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Study on hybrid renewable energy with battery and hydrogen vehicle storage applications in a zero-energy building community in Hong Kong

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Abstract

This study develops hybrid renewable energy systems for applications in zero-energy buildings and their community integrated with stationary battery storage and mobile hydrogen vehicles following different cruise schedules. The educational, office and residential building groups in Hong Kong are selected for zero-energy building case studies based on on-site collected energy consumption data and simulated load data as per local surveys and codes. And a zero-energy community integrating the three building groups is also developed for comparison to evaluate the supply, load cover, storage efficiency, grid integration, system cost and carbon emission indicators. The study results indicate that the renewable energy self-consumption ratio of four zero-energy scenarios varies between 88.10% - 96.01%. The community microgrid performs best in the load cover ratio of 74.96% with shared renewables and storages and achieves positive grid integration performance with a peak-to-average power ratio of 7.65 due to the complementary load characteristics of three building groups. The hydrogen storage efficiency of four zero-energy building scenarios varies between 37.42% - 55.62%. The levelized cost of energy of hybrid systems applied in four zero-energy scenarios varies within 0.48 - 0.63 US$/kWh, and it can be reduced to 0.09 - 0.24 US$/kWh considering the local feed-in tariff. The CO_2 emission of the zero-energy community is about 13631.82 tons, higher than the sum of three buildings by 4.32%, as its power exchange with the utility grid is reduced for more renewable energy self-consumption with higher energy losses. The detailed techno-economic-environmental feasibility analysis offers valuable references for relevant stakeholders to develop renewables applications in zero-energy building communities of urban areas.

Keywords: solar photovoltaic, wind turbine, hydrogen vehicle, battery storage, zero-energy building community

NOMENCLATURE

CEa	Annual carbon emission
FiT	Feed-in tariff
HSE	Hydrogen system efficiency
HV	Hydrogen vehicle
LCR	Load cover ratio
LCOE	Levelized cost of energy
PAR	Peak to average ratio
PV	Photovoltaic
SCR	Self-consumption ratio

1. Introduction

Renewables grew rapidly in recent years adding over 200 GW installations in 2019 and spread to all corners of the world providing about 27.3% of global electricity generation by the end of the year [1]. It is significant to promote renewable energy applications in the building and transport sectors with high carbon emission and energy consumption [2]. Renewables development in buildings is limited by policy although it is the fastest growing energy source in buildings, while the transport sector has the lowest share of renewable energy despite increased growth of electric vehicles. The building sector and transport sector account for majority of carbon emission in Hong Kong of about 63% and 16%, respectively, which need to be greatly reduced to achieve the ambitious climate action plan of reducing absolute carbon emission by 26% - 36% by 2030 based on 2005's level [3]. The hybrid solar photovoltaic (PV) and wind energy systems with stationary battery storage and mobile hydrogen vehicle storage are developed for a typical zero-energy building community within the urban context integrating the building and transport sectors. Three different types of buildings covering educational, office and residential functions are considered in the community based on on-site collected energy consumption data and simulated data as per local surveys and codes.

Amounts of research has been conducted on renewable energy and storage systems for building community applications. The hybrid cogeneration, electric and hydrogen storages and battery storage are compared to improve the local self-consumption of PV plants in a district, showing that the synergistic operation of energy networks helps to reduce the power ramp [4]. An optimal design model of district smart renewable energy systems with electricity, thermal and hydrogen demands is proposed to minimize the total annual cost. Case studies on smart energy systems applied in both urban and rural districts are conducted with a range of levelized cost of energy (LCOE) between 0.43 - 0.65 \$/kWh [5]. An energy management strategy based on a novel multi-agent system is developed to optimize the cost, grid imported power consumption and power quality of microgrid communities with renewables and electric vehicles. The authors report that communities with energy storage capacity covering 30% of total load achieve best optimization results [6]. The battery energy storage is optimized for communities to achieve renewable energy shifting and demand load shifting, and case studies on a single family and a multi-home community indicate that batteries are more beneficial applied in communities than single homes [7]. Novel business models for community microgrids integrated with renewable energy and storage systems are proposed to optimize the configuration and management strategy to achieve a minimum electricity costs. Case studies in 17 locations in Chile are conducted showing that community microgrids can achieve more profits compared with single-dwellings and higher benefits and self-sufficiency levels can be obtained in rural areas [8]. A multi-criterion energy system model is developed to size renewable energy and storage configurations applied in remote communities in Canada to help policy makers to evaluate the complex trade-offs in designing systems [9]. It can be found that few studies on hybrid renewable energy and storage systems for urban community applications consider the zero-energy scenarios integrating the building sector and transport sector according to on-site energy consumption data. And the comprehensive techno-economic-environmental performance covering the energy supply, storage, consumption and grid integration aspects under of zero-energy building scenarios needs further analysis.

This study mainly aims to investigate the techno-economic-environmental performance of hybrid PV-wind-battery-hydrogen systems applied in zero-energy building communities integrated with hydrogen vehicles following different cruise schedules. Four zero-energy scenarios of educational buildings, office buildings, residential buildings and building community are analyzed and compared evaluating the supply, load cover, storage efficiency, grid integration, LCOE and carbon emission indicators. The comprehensive feasibility analysis of hybrid renewable energy and storage systems integrating building and transport sectors provides relevant stakeholders with valuable references to further develop renewables in urban communities.

2. Methodology

The schematic of the building community with hybrid renewable energy and storage systems is shown in Fig. 1 including the building community, renewable energy supply, hybrid storage and energy management strategy. ***Building community:*** A typical community is established for renewable energy application as the case study covering educational buildings, office buildings and residential buildings in Hong Kong. The practical annual load consumption of Phase I - Phase V buildings in the Hong Kong Polytechnic University (PolyU) is collected as the educational buildings data. And the operational annual load consumption of the office zone of the International Commerce Centre (ICC) in Hong Kong is collected as the office buildings data. Ten typical high-rise buildings with 40 floors each based on a standard design layout for public residential buildings (RES) in Hong Kong are adopted as the residential buildings data, and it is simulated according to the local building codes [10, 11] and onsite survey energy use data [12].

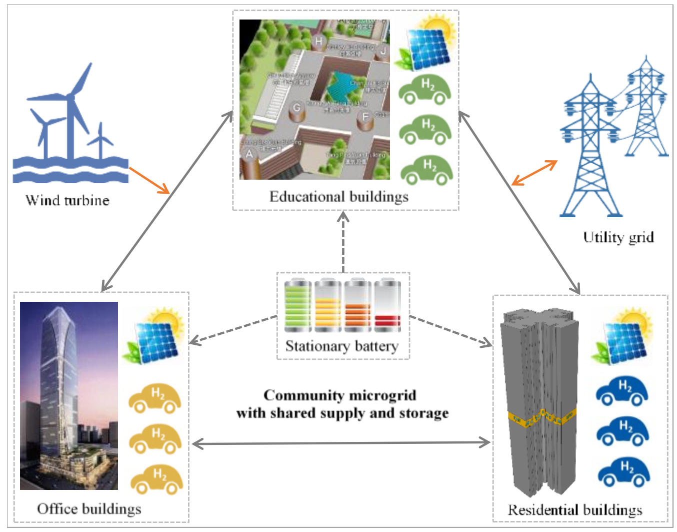

Fig. 1 Schematic of the zero-energy building community with hybrid renewable energy and storage systems

Renewable energy supply: A hybrid PV-wind-battery-hydrogen system is developed for the building community microgrid integrating three groups of hydrogen vehicles following different cruise schedules for different buildings based on the TRNSYS platform. Rooftop PV panels are installed on each building considering the maximum available installation area based on the empirical equivalent circuit model with a titled angle of 22° close to the local latitude. The offshore wind turbine is also adopted as the supplementary supply based on the power-speed characteristic curve tested by manufacturers as wind power has good complementary nature with PV power applied in Hong Kong [13]. The wind turbines are sized to achieve a zero-energy building scenario.

Hybrid hydrogen and battery storage: Three groups of hydrogen vehicles (HVs) following different cruise schedules are developed for the community based on a commercialized product “2019 Toyota Mirai” with a full storage of 5 kg hydrogen at the maximum pressure of 7 bar offering a cruise range of about 502 km [14]. The hydrogen storage system in each group includes electrolyzers, compressors, hydrogen storage tanks and fuel cells. 200 HVs are assumed for staff and students from the PolyU buildings parking between 10:00 - 18:00 during working days (group 1), and 400 HVs are assumed for the business workers from the ICC buildings parking between 9:00 - 17:00 during working days (group 2), and 400 HVs are assumed for the residents from the residential buildings with the parking period of 19:00 - 8:00 from Monday to Saturday and all time in Sunday (group 3). The daily average cruise range of these vehicle is about 49.25 km according to the annual traffic census from Transport Department in Hong Kong [15]. HVs are discharged to meet the building load with available stored hydrogen when parking at the buildings, and the utility grid offers power to the electrolyzer to generate hydrogen when HVs are not able to cover the daily cruise on the next day. A stationary battery storage tank is also equipped in the community microgrid, and the hybrid storage of both HVs and battery can store surplus renewable energy and cover the unsatisfied building load of three buildings groups via the microgrid.

Energy management strategy: Renewable energy generation from the PV panels and wind turbines is firstly controlled to meet the electrical load of the community, and then charge the parked HVs to maximum storage states. The surplus renewable energy is used to charge the battery tank and finally fed into the utility grid. When renewable energy cannot meet all the electrical load of the community, fuel cells of the parked HVs are controlled to discharge to the load prior to the stationary battery tank. And the utility grid can meet the unsatisfied load after using renewable supply and storage energy. The detailed validation of the hybrid systems can be found in the previous publication of the authors [16].

Four zero-energy building scenarios with equal amount of annual renewable energy generation and building electrical load are developed as shown in Table 1. The PV capacity is determined according to the maximum available installation area of the corresponding buildings. And the wind turbine is sized based on the difference of collected building load and PV capacity.

Table 1 Sizing of hybrid PV-wind-battery-hydrogen of four zero-energy building scenarios

Zero-energy building scenarios	PV kW	Wind kW	Battery kWh	HV number
Case 1 Educational buildings (PolyU)	250	21700	1000	200
Case 2 Office buildings (ICC)	300	16300	2000	400
Case 3 Residential buildings (RES)	650	11000	2000	400
Case 4 Community microgrid (COM)	1200	49000	5000	1000

The techno-economic-environmental performance of these four zero-energy building scenarios with hybrid renewable energy and storage systems is analyzed and compared. To evaluate the supply side performance, the renewable energy self-consumption ratio (SCR) is formulated as per Eq. (1).

$$SCR = \frac{\textit{on-site RE consumption}}{\textit{total RE generation}} = \frac{E_{RE\ to\ load}+E_{RE\ to\ battery}+E_{RE\ to\ electro}}{E_{RE}} \tag{1}$$

where $E_{RE\ to\ load}$ is the supplied renewable energy to the electrical load, kWh. $E_{RE\ to\ battery}$ is the charging energy from renewables to the battery, kWh. $E_{RE\ to\ electro}$ is the provided energy from renewables to the electrolyzer, kWh. E_{RE} is the total energy generation of PV panels and wind turbines, kWh.

The load cover ratio (LCR) is developed to assess the covering performance of the on-site supply from hybrid renewable energy systems as per Eq. (2).

$$LCR = \frac{\textit{on-site supply}}{\textit{total electrical load}} = \frac{E_{RE\ to\ load}+E_{battery\ to\ load}+E_{FCs\ to\ load}}{E_{load}} \tag{2}$$

where $E_{battery\ to\ load}$ is the discharging energy from the battery to the electrical load, kWh. $E_{FCs\ to\ load}$ is the energy from fuel cells of HVs to the electrical load when HVs are parked at the buildings, kWh. E_{load} is the total electrical load, kWh.

The hydrogen system efficiency (HSE) is calculated to evaluate the storage performance of the vehicle integrated hydrogen storage system as shown in Eq. (3).

$$HSE = \frac{H_2\ \textit{system supply}}{H_2\ \textit{system consumption}} = \frac{E_{FCs\ to\ road}+E_{FCs\ to\ load}+E_{HR\ to\ res}}{E_{RE\ to\ electro}+E_{grid\ to\ electro}+E_{comp}} \tag{3}$$

where $E_{FCs\ to\ road}$ is the energy from fuel cells to drive the motor of HVs when used on the road, kWh. $E_{HR\ to\ res}$ is the heat energy recovered from the hydrogen system to meet the air-conditioning reheat and domestic hot water demand of residential buildings, kWh. $E_{grid\ to\ electro}$ is the refueled energy from the utility grid to drive the electrolyzer to generate hydrogen to ensure the HVs' daily cruise, kWh. E_{comp} is the energy consumption of compressors in the hydrogen system, kWh.

The peak to average ratio (PAR) of the grid power consumption as shown in Eq. (4) is established to show the grid integration between the utility grid and the studied zero-energy buildings or community.

$$PAR = \frac{\textit{grid imported peak power}}{\textit{grid imported average power}} = \frac{Pgrid\_imported_{peak}}{Pgrid\_imported_{average}} \tag{4}$$

where $Pgrid\_imported_{peak}$ is the peak power imported from the utility grid, kW; $Pgrid\_imported_{average}$ is the average power imported from the utility grid, kW.

The levelized cost of energy (LCOE) of the hybrid renewable energy and storage systems are considered for cost evaluation as per Eq. (5).

$$LCOE = \frac{PRV_{ini}+PRV_{rep}+PRV_{O\&M}-PRV_{res}-PRV_{fit}}{\sum_{n=1}^{n=N}\frac{E_{PV}\cdot(1-\delta_{PV})^{n-1}}{(1+i)^{n}}+\sum_{n=1}^{n=N}\frac{E_{WT}\cdot(1-\delta_{WT})^{n-1}}{(1+i)^{n}}} \quad (5)$$

where PRV_{ini} is the present value of system initial cost covering major system components (i.e. PV panels, wind turbines, batteries, inverters, hydrogen vehicles, electrolyzers, compressors and storage tanks), US$; PRV_{rep} is the present value of replacement cost, US$; $PRV_{O\&M}$ is the present value of operation and maintenance cost including components maintenance and operational electricity bill cost, US$. PRV_{res} is the present value of residual cost, US$. PRV_{fit} is the present value of renewable energy feed-in tariff (FiT), US$. n is a certain year in the lifetime and N is the total system service lifetime, 20 years. E_{PV} is the PV energy generation in the first year, kWh. δ_{PV} is the annual degradation rate of the PV system, 1%/year. E_{WT} is the wind energy generation in the first year, kWh. δ_{WT} is the degradation rate of the wind turbine system, 1.5%/year. i is the annual real discount rate, 5.8%/year.

Furthermore, the annual operational equivalent CO_2 emission (CE_a) of the hybrid renewable energy and storage systems applied in the four building scenarios is calculated for environmental assessment as per Eq. (6) [17].

$$CE_a=(E_{grid\ import}-E_{grid\ export})\cdot CEF_{eg} \quad (6)$$

where $E_{grid\ import}$ is the annual energy imported from the utility grid, kWh. $E_{grid\ export}$ is the annual energy exported to the utility grid, kWh. CEF_{eg} is the equivalent CO_2 emission of the utility grid, 0.572 kg CO_2/kWh.

3. Results and discussion

3.1. Technical performance analysis

The technical performance of four zero-energy building scenarios with hybrid PV-wind-battery-hydrogen applications is compared including self-consumption of renewable supply, on-site cover percentage of electrical load, application efficiency of hydrogen storage system and grid integration indicators as shown in Fig. 2. It is indicated that the renewable energy self-consumption performance in Case 1 applied in the educational buildings is the minimum of about 88.10% as the hydrogen system capacity is less than that in the office group and residential group. And Case 3 has the maximum SCR of up to 96.01% with more hydrogen vehicles and longer parking time than other groups so that more surplus renewable energy can be used in the hydrogen storage system. The SCR in Case 4 of community microgrid is about 93.88% which is higher than Case 1 and Case 2 but lower than Case 3 as renewable energy supply and energy storage is shared in the community. The on-site load cover ratios of the hybrid system of these four zero-energy building scenarios are within 71.12% - 74.96% indicating an obvious mismatch between the renewable energy supply and electrical load. And Case 3 of residential buildings has the minimum LCR as the installed renewable energy capacity is the minimum, while Case 4 integrating three types of building as a community microgrid performs best in on-sit covering of building load.

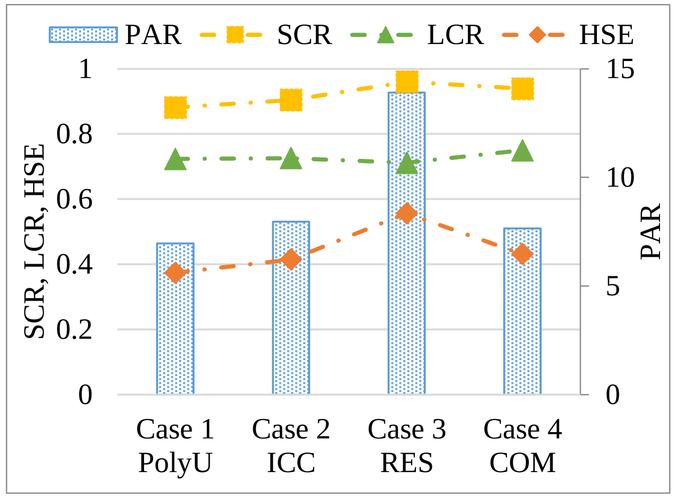

Fig. 2 Technical results of four zero-energy scenarios

In terms of grid integration between the utility grid and the zero-energy buildings, Case 1 of educational buildings has the minimum PAR of about 6.96 which is much lower than that in Case 3 of residential buildings of 13.91. An obvious seasonal difference of electrical load is observed in residential buildings with high air-conditioning load during April to October in the hot-summer and cold-winter region, while the electrical load in educational and office buildings is less sensitive to the season. And the PAR in the community is about 7.65 indicating a positive grid integration performance when integrating these three buildings with different load characteristics into a community with shared supply and storage. The HSE in Case 1 is the lowest of about 37.42% with the minimum number of hydrogen vehicles while Case 3 has the highest HSE of 55.62% as the generated heat of the hydrogen systems from electrolyzer, compressors and fuel cells is recovered to cover the reheat and domestic hot water demand of the residential buildings. The HSE in the community microgrid is about 43.14% which is much lower than that of battery vehicles and further study will be conducted to recover heat from the hydrogen storage system of educational and office buildings to enhance its overall efficiency.

3.2. Economic performance analysis

The economic results of four zero-energy building scenarios are compared as per Fig. 3 showing the lifetime present value of the hybrid renewable energy and storage system. It is shown that the lifetime present value of investment cost in Case 1 of educational buildings is higher than that of office buildings and residential buildings as the electrical load in PolyU is the maximum so that more wind turbines installation is needed. It is assumed that renewable energy generation can get 3 HK$/kWh FiT subsidy and any unit of renewable electricity used at the premises is charged at the tariff rates based on the FiT scheme in Hong Kong [18]. So the renewable energy FiT is Case 1 is also higher with more renewable energy generation. The electricity bill of the buildings is calculated according to the peak-valley electricity pricing scheme in Hong Kong for large power tariff covering demand charge, energy charge, fuel cost adjustment, rent and rates special rebate [19].

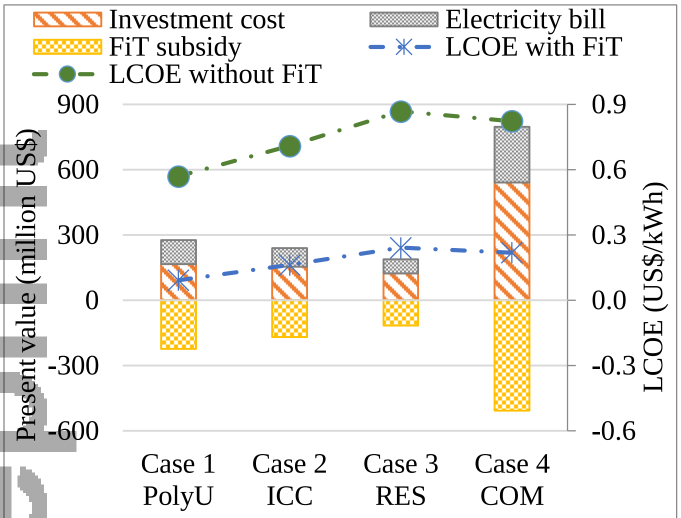

Fig. 3 Economic results of four zero-energy scenarios

The LCOE in Case 1 of educational buildings considering FiT is about 0.09 US$/kWh, much lower than that in Case 2 (0.16 US$/kWh) and Case 3 (0.24 US$/kWh) as more renewable energy generation is available in Case 1. And the LCOE in Case 1 is increased from 0.09 US$/kWh to 0.48 US$/kWh when FiT subsidy is not considered. The LCOE of the community is about 0.22 US$/kWh with FiT and increased to 0.60 US$/kWh without FiT, which is promising to be reduced with the marketing development of renewable energy and storage technologies.

3.3. Environmental performance analysis

Fig. 4 shows the annual operational equivalent CO_2 emission of four zero-energy building scenarios to evaluate the environmental performance of the hybrid renewable energy and storage system applications. The CO_2 emission in Case 3 is about 3963.95 tons which is much lower than that in Case 1 (4876.49 tons) and Case 2 (4227.01 tons), as the imported power from the utility grid in Case 3 is the minimum with lowest electrical demand compared with the other two building groups. The CO_2 emission of the community is about 13631.82 tons and it is higher than the sum of three buildings by 4.32%, as the energy exchange between the community and the utility grid reduces and more renewables generation is used by on-site hybrid systems with higher energy losses. Further study on improving the overall efficiency of the hybrid storage systems should be conducted to improve the environmental performance.

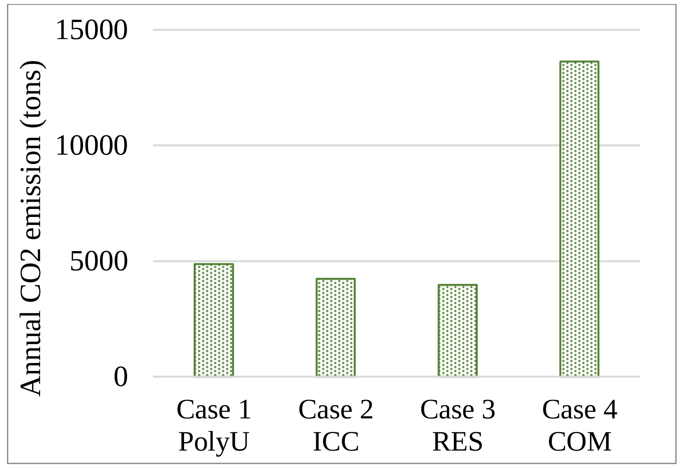

Fig. 4 Environmental results of four zero-energy scenarios

4. Conclusions

This study investigated the techno-economic-environmental performance of hybrid renewable energy and storage systems for applications in zero-energy buildings and community integrated with stationary battery storage and mobile hydrogen vehicles following different cruise schedules. Three typical kinds of buildings in Hong Kong are selected for zero-energy building case studies including educational buildings, office buildings, residential buildings based on on-site collected energy consumption data and simulated load data as per local surveys and codes. And the zero-energy building community integrating three building groups is also developed for comparison evaluating the supply, load cover, storage efficiency, grid integration, levelized cost of energy and CO_2 emission indicators. Important findings are summarized as below:

(1) The renewable energy self-consumption ratio of four zero-energy building scenarios varies between 88.10% - 96.01% reaching its maximum in Case 3 of residential buildings with more hydrogen vehicles and longer parking time. The community microgrid case (Case 4) integrating three types of buildings achieves the best performance in load covering by on-site renewables and storages of 74.96% with shared renewable supply and energy storage among buildings. A positive grid integration performance is also observed in the community microgrid case with the peak-to-average power ratio of 7.65, lower than that in Case 3 of residential buildings by 45.04%, due to the complementary load characteristics of educational, office

and residential buildings. The overall hydrogen storage efficiency of four zero-energy building scenarios varies within 37.42% - 55.62% and further study on recovering the generated heat from hydrogen systems of educational and office buildings will be conducted to enhance the storage efficiency.

(2) The levelized cost of energy of the hybrid renewable energy and storage systems applied in four zero-energy scenarios varies within 0.48 - 0.63 US$/kWh, and it can be reduced to 0.09 - 0.24 US$/kWh when considering the encouraging feed-in tariff in Hong Kong. A minimum levelized cost of energy is obtained in Case 1 of educational buildings with more available renewable energy generation.

(3) The annual operation equivalent CO_2 emission of the zero-energy educational, office and residential buildings is about 4876.49 tons, 4227.01 tons and 3963.95 tons, respectively. And the CO_2 emission of the zero-energy community is about 13631.82 tons which is higher than the sum of three buildings by 4.32%, as the energy exchange between the community and the utility grid reduces and more renewables generation is used by on-site hybrid systems with higher energy losses.

(4) The development of hybrid renewable energy systems integrating the stationary battery storage and mobile hydrogen vehicle storage is analyzed and compared for typical buildings and communities covering educational, office and residential types to achieve zero-energy scenarios. The detailed and in-depth technical, economic and environmental performance analysis offers valuable references for relevant stakeholders to develop renewables applications in zero-energy building communities within urban contexts.

Acknowledgement

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References

[1] REN 21. Renewables 2020 global status report. 2020.
[2] Liu J, Chen X, Cao S, Yang H. Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings. Energy Conversion and Management. 2019;187:103-21.
[3] Electrical and Mechanical Services Department. Hong Kong Energy End-user Data 2019. 2019.
[4] Bartolini A, Carducci F, Muñoz CB, Comodi G. Energy storage and multi energy systems in local energy communities with high renewable energy penetration. Renewable Energy. 2020;159:595-609.
[5] You C, Kim J. Optimal design and global sensitivity analysis of a 100% renewable energy sources based smart energy network for electrified and hydrogen cities. Energy Conversion and Management. 2020;223:113252.
[6] Xiong L, Li P, Wang Z, Wang J. Multi-agent based multi objective renewable energy management for diversified community power consumers. Applied Energy. 2020;259:114140.
[7] Parra D, Norman SA, Walker GS, Gillott M. Optimum community energy storage for renewable energy and demand load management. Applied Energy. 2017;200:358-69.
[8] Avilés A C, Oliva H S, Watts D. Single-dwelling and community renewable microgrids: Optimal sizing and energy management for new business models. Applied Energy. 2019;254:113665.
[9] Quitoras MR, Campana PE, Rowley P, Crawford C. Remote community integrated energy system optimization including building enclosure improvements and quantitative energy trilemma metrics. Applied Energy. 2020;267:115017.
[10] Hong Kong Building Environmental Assessment Method Society. An envrionmental assessment for new buildings Version 4/04. 2004.
[11] Hong Kong Electrical and Mechanical Services Department. Guidelines on Performance-based Building Energy Code. 2007.
[12] Qin H, Pan W. Energy use of subtropical high-rise public residential buildings and impacts of energy saving measures. Journal of Cleaner Production. 2020;254:120041.
[13] Ma T, Yang H, Lu L, Peng J. Optimal design of an autonomous solar–wind-pumped storage power supply system. Applied Energy. 2015;160:728-36.
[14] Toyota USA NEWSROOM. Toyota Mirai product information. 2019.
[15] Transport Department in Hong Kong. The annual traffic census. 2018.
[16] Liu J, Wang M, Peng J, Chen X, Cao S, Yang H. Techno-economic design optimization of hybrid renewable energy applications for high-rise residential buildings. Energy Conversion and Management. 2020;213:112868.
[17] Cao S. The impact of electric vehicles and mobile boundary expansions on the realization of zero-emission office buildings. Applied Energy. 2019;251:113347.
[18] Electrical and Mechanical Services Department. Introduction to feed-in tariff of renewable energy in Hong Kong. 2018.
[19] China Light and Power Hong Kong Limited. Large power tariff. 2020.