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Comparison of renewable energy systems with battery vehicles and hydrogen vehicles for application in a zero-energy community in Hong Kong

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ABSTRACT

This study develops hybrid renewable energy systems integrated with battery vehicles and hydrogen vehicles for application in a typical zero-energy community based on the TRNSYS platform. The load files of the community including school campus, office and residential buildings are obtained according to on-site collected energy use data and simulation data as per local surveys. Three groups of battery vehicles and hydrogen vehicles following different cruise schedules are integrated as both cruise tools and energy storage technologies. The study results find that the renewables self-consumption ratio of the zero-energy community with hydrogen vehicles is up to 94.45%, much higher than that of the battery vehicles integrated system of 75.84%. The load cover ratio of hydrogen vehicles integrated system is about 69.86%, slightly lower than that of the zero-energy community with battery vehicles of 70.21%. The lifetime net present value of the zero-energy community with battery vehicles is US$ 256.79m, smaller than that of the zero-energy community with hydrogen vehicles by 44.08%. And the net present value of the zero-energy community with battery vehicles is lower than its baseline case by about 27.54%, while the net present value of the zero-energy community with hydrogen vehicles is higher than its baseline case by 31.91%. Obvious decarbonisation potential of the zero-energy community with battery vehicles and hydrogen vehicles is achieved of about 92.71% and 75.96% respectively compared with the corresponding baseline cases. The detailed techno-economic-environmental feasibility study provides stakeholders with valuable guidance for integrating renewable supply and clean transportation in urban communities.

Keywords: Solar photovoltaic; Wind turbine; Battery vehicle; Hydrogen vehicle; Zero-energy community

NOMENCLATURE

BSE	Battery vehicle system efficiency
BV	Battery vehicle
CEa	Annual carbon emission
FiT	Feed-in tariff
HSE	Hydrogen vehicle system efficiency
HV	Hydrogen vehicle
LCR	Load cover ratio
NPV	Net present value
O&M	Operation and maintenance
PV	Photovoltaic
SCR	Self-consumption ratio

1. INTRODUCTION

The integration of renewable energy and clean transportation is experiencing an unprecedented development in recent years contributing to the sustainable energy transformation [1, 2]. Amounts of research have been conducted on renewable energy systems for power supply to buildings and communities integrating with battery vehicles (BVs) and hydrogen vehicles (HVs). The energy sharing network integrating office and hotel buildings with vehicles-to-building interactions is analyzed proposing an advanced cycling aging model of battery degradation. The authors analyze the lifecycle technical and economic feasibility of renewable energy systems [3]. The real-time energy management model of renewable energy systems applied in a community microgrid with battery swapping of electric vehicles is proposed to improve system economy and supply flexibility [4]. The energy supply and environmental performance of renewable energy systems with a HV and BV is compared for application in a zero-energy building. The author reports that the HV integrated system is more demanding compared with the BV integrated system as the system efficiency of the HV system is smaller [5]. The techno-economic-environmental feasibility of hybrid renewable energy systems with HVs for high-rise residential buildings is analyzed optimizing the supply, grid and system cost [6]. This study mainly aims to develop and compare the system supply, lifetime economy and decarbonisation performance of renewable energy systems with BVs or HVs applied in a typical zero-energy community in Hong Kong. The comprehensive technical, economic and environmental analysis provides guidance for stakeholders to promote renewables in high-density cities.

2. METHODOLOGY

This study develops hybrid renewable energy systems for a typical zero-energy community consisting of campus buildings, office buildings and residential buildings integrating with three groups of BVs or HVs in different schedules. The supply and economic performance as well as decarbonisation potential of the renewable energy system are analyzed and compared with baseline cases without renewable supply. The annual load file of the campus buildings is obtained from the on-site collected operational data of Phase I - Phase V buildings in the Hong Kong Polytechnic University. The practical annual electricity consumption of the International Commerce Centre, the tallest building in Hong Kong, is also collected as input load of office buildings. And the residential buildings load is simulated based on the local building codes [7] and on-site survey energy use data [8].

The solar photovoltaic (PV) panels and wind turbines are installed as the hybrid renewable supply for the community with a good complementary nature connected to the external weather file based on the Meteonorm data of Hong Kong [9]. The BVs are modeled by TRNSYS Type 47a based on a commercialized electric vehicle product "Tesla Model S" with a battery capacity of 85 kWh at the full cruise range of about 426 km [10]. The HVs are developed from a commercialized product "2019 Toyota Mirai" with a full hydrogen storage of 5 kg supporting the cruise range of 502 km [11]. The HV is modelled with the mobile hydrogen storage tank and proton exchange membrane fuel cell. The application of HVs for the storage of renewable energy in the zero-energy community case is supported by electrolyzers, compressors and stationary hydrogen storage tanks installed in buildings. 200 vehicles are assumed for the campus building group with the parking period of 10:00 - 18:00 in weekdays; 400 vehicles are assumed for the office building group according to the car parking setting of the building and the parking period is 9:00 - 17:00 in weekdays; and 400 vehicles are assumed for the residential building group according to a local survey on the car owner ratio in public housing and the parking time is 19:00 - 8:00 from Monday to Saturday and all hours in Sunday. The average daily driving distance of these vehicles is 49.25 km according to the local transport report [12]. The utility grid is connected to the community as the backup for electrical load and also take in surplus renewable generation. The grid also supply power to charge BVs or drive electrolyzers in zero-energy cases to ensure the vehicles' daily cruise range. And the daily cruise demand of BVs and HVs in baseline cases is met in external electric car stations and hydrogen stations. The renewable energy systems are established in the TRNSYS 18 simulation platform [13] at a timestep of 0.125 h to get the annual operational data for further analysis. The detailed validation of the hybrid systems can be found in the previous publication of the authors [14]. Four cases of the community are studied including zero-energy community with BVs, zero-energy community with HVs, baseline community with BVs and baseline community with HVs.

The system supply, economic and decarbonisation performance of the zero-energy community is analyzed by developing technical, economic and environmental indicators. The on-site consumption ratio of renewable energy generation is evaluated by self-consumption ratio (SCR) as Eq. (1) [15]:

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

The load coverage of electrical load of the community by the renewable energy systems is also evaluated as Eq. (2):

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

The overall efficiency of BV system and HV system is formulated to compared the application efficiency of vehicles in the zero-energy community as per Eqs. (3 - 4):

$$BSE = \frac{\text{BV system supply}}{\text{BV system consumption}} = \frac{E_{BVs\ to\ road}+E_{BVs\ to\ load}}{E_{RE\ to\ BVs}+E_{grid\ to\ BVs}} \tag{3}$$

$$HSE = \frac{\text{HV system supply}}{\text{HV system consumption}} = \frac{E_{FCs\ to\ road}+E_{FCs\ to\ load}+E_{HR}}{E_{RE\ to\ electro}+E_{grid\ to\ electro}+E_{comp}} \tag{4}$$

The lifetime net present value (*NPV*) of the zero-energy community with renewable energy systems and vehicle is assessed for economic analysis as shown in Eq. (5) including present value of initial cost (PRV_{ini}), present value of operational and maintenance cost ($PRV_{O\&M}$), present value of replacement cost (PRV_{rep}), present value of residual cost (PRV_{res}) and present value of feed-in tariff (PRV_{FiT}) [14]. And the *NPV* of baseline community entirely relying on the utility grid and integrating vehicles relying on external refuel is also calculated for comparison.

$$NPV = PRV_{ini} + PRV_{O\&M} + PRV_{rep} - PRV_{res} - PRV_{FiT} = C_{ini} + \sum_{n=1}^{n=N} \frac{f_{mai}\cdot C_{ini}}{(1+i)^n} + \sum_{j=1}^{j=J} C_{ini}\left(\frac{1-d}{1+i}\right)^{j\cdot l} - C_{ini}\frac{l_{res}}{l}\cdot\frac{(1-d)^N}{(1+i)^N} - \sum_{n=1}^{n=N}\frac{\left(E_{PV}\cdot(1-\delta_{PV})^{n-1}+E_{WT}\cdot(1-\delta_{WT})^{n-1}\right)\cdot c_{fit}}{(1+i)^n} \tag{5}$$

In terms of decarbonisation potential of zero-energy community compared with baseline community without renewable energy, the annual carbon emission is formulated for evaluation as per Eq. (6) [16]:

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

3. RESULTS AND DISCUSSION

3.1. System supply performance comparison of renewable energy systems

The on-site renewable energy consumption performance of two hybrid renewable energy systems integrating three groups of BVs or HVs for application in a zero-energy community with campus buildings, office buildings and residential buildings is compared as per Fig. 1. It is indicated that the *SCR* of the renewable energy system with HVs is up to 94.45% with about 35.47%

contributed to the electrolyzers. While the *SCR* of the renewable energy system with BVs is about 75.84% with only 7.49% used to charge the BVs. The *SCR* of the zero-energy community with HVs is higher than that of the zero-energy community with BVs by 18.61% because the stationary hydrogen storage tanks are installed in the buildings to store hydrogen even though HVs are not parked.

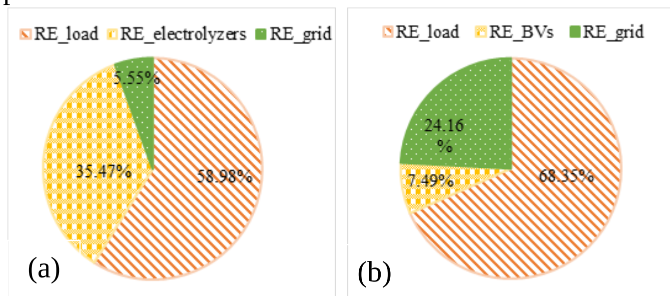

Fig. 1 Self-consumption ratio of zero-energy community with HVs (a) and BVs (b)

The on-site load coverage by renewable energy systems in the two zero-energy community cases is compared in Fig. 2. The *LCR* of the zero-energy community with HVs is about 69.86%, which is slightly lower than that of the zero-energy community with BVs of about 70.21%. The load coverage of HVs is about 11.70% of 13508.84 MWh, much lower than the supplied energy from renewables of 40378.16 MWh due to a relatively low energy efficiency of the hydrogen system of about 53.82%. And the overall efficiency of the vehicles integrated hydrogen system counting the vehicle-to-building energy exchange and road cruise would be further reduced to 39.20% when the generated heat from electrolyzer, compressors and PEMFCs is not recovered. The load coverage of BVs is about 5.22% of 6253.64 MWh with a relatively high efficiency of about 88.42%.

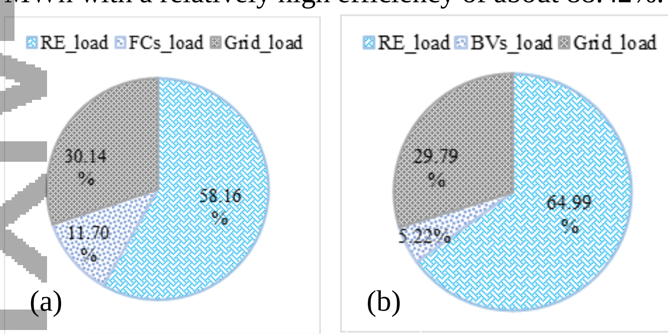

Fig. 2 Load cover ratio of zero-energy community with HVs (a) and BVs (b)

3.2. Economic and decarbonisation performance comparison of renewable energy systems

The lifetime *NPV* of renewable energy systems with BVs or HVs for power supply to a typical zero-energy community in Hong Kong is shown in Fig. 3. It is indicated that the initial cost of both renewable energy systems with BVs and HVs accounts to the majority of the total system investment cost of 75.00% and 77.55%, respectively. A large amount of FiT subsidy can be obtained of about US$ 489.18m according to the encouraging local FiT scheme with an FiT rate of 3 HK$ for all units of electricity generated by the renewable energy system, and the on-site consumed renewable generation is charged at the time-of-use electricity rate counted in the O&M cost [17]. The total lifetime *NPV* of the zero-energy community with BVs is US$ 256.79m, which is smaller than that of the zero-energy community with HVs (US$ 459.19m) by 44.08%. Because the initial cost of renewable energy systems with HVs is much higher including electrolyzers, compressors and storage tanks in the buildings.

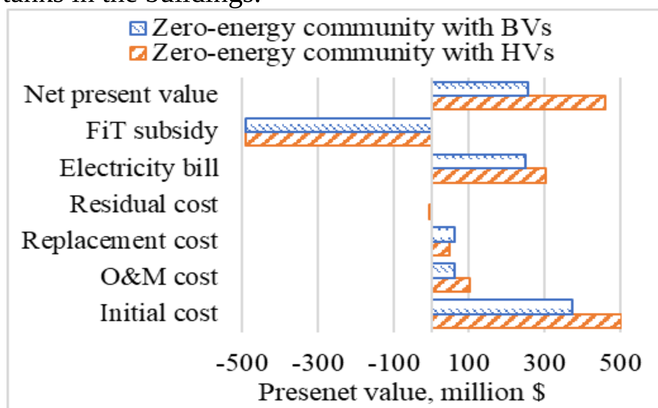

Fig. 3 Lifetime net present value of renewable energy systems with BVs and HVs

To further investigate the economic saving potential of the zero-energy community with BVs or HVs, the lifetime *NPV* of baseline community without renewable supply is also analyzed as per Fig. 4. Three groups of BVs or HVs are still integrated with the community to meet the daily cruise demand of building occupants. The BVs or HVs are refueled in external battery vehicle stations at the cost of 0.18 US$/kWh [18] or hydrogen vehicle stations at the cost of 16.51 US$/kg [19], and the cost of refueling vehicles is included in the item of O&M cost.

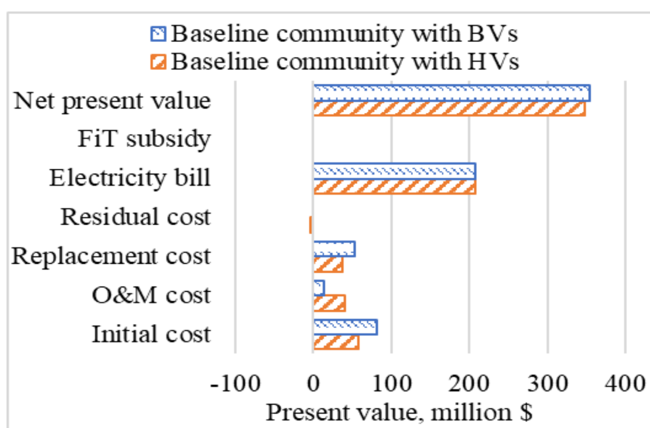

Fig. 4 Lifetime net present value of baseline cases without renewable energy

It is indicated that the initial cost and replacement cost of BVs are higher than those of HVs in the baseline community. The lifetime *NPV* of the baseline community with BVs is about US$ 354.39m, 1.80% higher than that of the baseline case with HVs of US$ 348.11m. And it is also compared that the lifetime *NPV* of the zero-energy community with BVs is lower than the baseline case with BVs by about 27.54%, while the *NPV* of zero-energy community with HVs is higher than the baseline case with HVs by 31.91%.

The decarbonisation potential of the zero-energy community with BVs or HVs is analyzed by comparing with the baseline case without renewable energy supply as shown in Fig. 5. The minimum carbon emission is observed in the zero-energy community with BVs (4989.91 tCO_2) with more renewable generation feeding into the utility grid, and its carbon emission is 69.69% lower than that in the zero-energy community with HVs (16460.91 tCO_2). The carbon emission in the two baseline cases is the same of about 68476.43 tCO_2 due to the equal electrical load. The decarbonisation potential of the zero-energy community with BVs is about 92.71% compared with the baseline case with BVs, while the decarbonisation potential of the zero-energy community with HVs is lower of 75.96% compared with the baseline case with HVs.

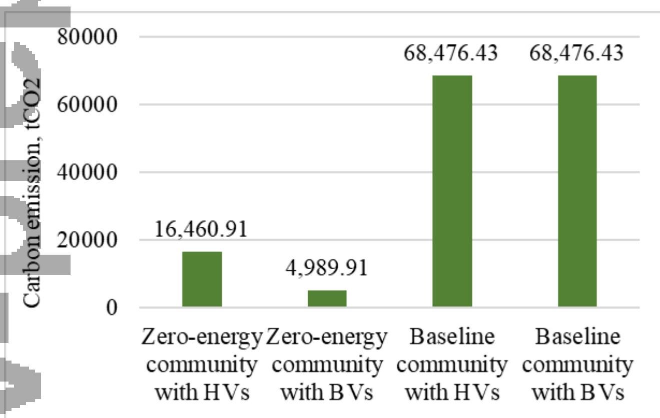

Fig. 5 Carbon emission of zero-energy community and baseline community without renewables

4. Conclusions

This study analyzes the energy supply, economic and decarbonisation performance of renewable energy systems integrating three groups of battery vehicles or hydrogen vehicles following different cruise schedules for power supply to a typical zero-energy community. The baseline community without renewable energy is also developed for comparison and important findings are summarized as below:

(1) The self-consumption ratio of the renewable energy system with hydrogen vehicles in the zero-energy community is up to 94.45%, much higher than that of the renewable energy system with battery vehicles of 75.84%. While the load cover ratio of hydrogen vehicles integrated system is about 69.86%, slightly lower than that of the zero-energy community with battery vehicles of 70.21%. The overall efficiency of hydrogen vehicle system is relatively low of about 53.82%, and it is reduced to 39.20% when the generated heat from electrolyzer, compressors and fuel cells is not recovered, much lower than that of the battery vehicle system of about 88.42%.

(2) The lifetime net present value of the zero-energy community with battery vehicles is US$ 256.79m, which is smaller than that of the zero-energy community with hydrogen vehicles (US$ 459.19m) by 44.08%. And the lifetime net present value of the zero-energy community with battery vehicles is lower than the baseline case without renewables by about 27.54%, while the net present value of zero-energy community with hydrogen vehicles is higher than its baseline case by 31.91%.

(3) The decarbonisation potential of the zero-energy community with battery vehicles is about 92.71% compared with its baseline case, while the decarbonisation potential of the zero-energy community with hydrogen vehicles is lower of 75.96% compared with its baseline case.

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