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Peer-to-peer trading optimizations on net-zero energy communities with energy storage of hydrogen and battery vehicles

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Abstract

This study develops peer-to-peer energy trading management and optimization approaches of renewable energy systems integrated with energy storage of hydrogen and battery vehicles for power supply to a diversified net-zero energy community. Typical net-zero energy community models are developed and compared with different storage vehicle types (hydrogen vehicle/battery vehicle) and energy trading modes (peer-to-grid/peer-to-peer). Multi-objective peer-to-peer trading optimizations of the net-zero energy community with both hydrogen and battery vehicles are developed to explore the optimal interactive impact of vehicle numbers and management strategies. An improved peer-to-peer trading management strategy is further proposed considering the peer trading priority and complementary operations of hybrid vehicle storage. The study results indicate that the hydrogen vehicle-integrated system achieves superior supply performances, while the battery vehicle-integrated system performs better on the grid integration, economic and environmental aspects. The time-of-use peer trading strategy should be adopted when the battery vehicle number in office buildings is relatively small, and the strategy without time-of-use management is preferred when the vehicle numbers in diversified building groups are relatively large for a techno-economic-environmental optimization. Obvious improvements can be achieved by the improved peer trading strategy, with reductions on the net grid import by 18.54%, carbon emissions by 1594.13 tons, net electricity bill by 8.31% and lifetime net present value by US$ 458.69k. This comprehensive feasibility study on the diversified net-zero energy community provides significant references for stakeholders to install and manage renewable energy and green vehicle storage systems towards carbon neutrality in integrated building and transport sectors in urban areas.

Keywords: Renewable energy; Hydrogen vehicle energy storage; Battery vehicle energy storage; Diversified net-zero energy community; Peer-to-peer trading optimizations

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1. Introduction

1.1. Background

Over 55% of the global population stay in cities which contribute around 75% of CO_2 emissions from global final energy use [1]. More than 1300 cities set renewable energy targets covering more than 1 billion people, and around 800 cities committed to net-zero emissions by the end of 2020 [1] to achieve a carbon-neutral urban living environment [2]. The building and transport sectors are dominated energy consumers in cities with large amounts of carbon emissions [3]. It is reported that the building sector accounts for about 28% of global energy-related CO_2 emissions [4], and renewable energy is the fastest growing energy source for buildings supplying around 26% of its electricity end-uses in 2018 [5]. Around 150 cities issued policies to achieve the decarbonisation in the building sector through renewable energy by the end of 2020 [1]. And 28 cities signed the Net Zero Carbon Buildings Commitment to promote renewable energy applications towards the net-zero energy/carbon buildings in 2020 [6]. With regard to the transport sector, the global urban transport accounts for around 40% of total transport-related CO_2 emissions, while the share of renewable energy in global transport remains low at only 3.7% currently. Over 67 cities adopted e-mobility targets by the end of 2020 to increase renewable energy penetration in the transport sector and to expand the use of battery vehicles or hydrogen vehicles [1].

Green vehicles are enjoying unprecedented development in recent years towards the decarbonisation in the transport sector [7], which contributes to nearly 25% of global energy-related direct CO_2 emissions [8]. Multiple environmental, societal and health benefits are delivered by green vehicles including high energy efficiency and security [9], reduced air pollution and carbon emissions [10], as well as good noise control. Electric cars, mainly referring the battery electric cars and plug-in hybrid electric cars, experienced an annual average expansion of 60% during 2014 - 2019, reaching 7.2 million in 2019 with 47% contributed by the Chinese market. The battery vehicle (BV) accounts for around 67% of global electric car sales with an annual growth of 14% in 2019, and significant increments are observed in many markets such as Europe (risen by 80%) and Canada (risen by 43%) [11]. And the global electric vehicle stock is anticipated to reach 245 million (excluding two/three-wheelers) in 2030 to achieve climate goals of the Paris Agreement [8]. About 2 million electric vehicle charging points were installed globally in 2019, accumulating to 7.5 million including both private and public chargers [12]. The hydrogen vehicle

(HV) is experiencing an emerging and notable development as a potential carbon-free vehicle, with the global stock of 25210 units in 2019, doubled the figure from 2018, stimulated by the policy momentum and escalating markets. The U.S. dominates the global stock of HVs with a share of about 32%, followed by China of about 25%. About 470 hydrogen refuelling stations were in operation worldwide by the end of 2019, increased by 20% from the previous year, and Japan has the most installations at 113 [13]. It is projected that over 420 million HVs will be equipped worldwide by 2050 according to the Hydrogen Council [14].

A promising development status has been observed on promoting renewable energy and green vehicle technologies for achieving carbon neutrality in the building and transport sectors in urban areas with continuously increased energy consumption and carbon emissions. While, the spatial-temporal mismatch between the intermittent renewable energy supply and stochastic electrical demand of end-users proposes great challenges. And the optimal integration of renewable energy systems with green vehicles (serving with both daily cruise and energy storage functions) also needs in-depth research. Therefore, it is important to study the design optimization and management approaches of hybrid renewable energy and green vehicle storage systems for power supply to the integrated building and transport sectors in cities. This study aims to develop peer-to-peer (P2P) energy trading optimization and management approaches of hybrid renewable energy systems integrated with energy storage of hydrogen vehicles (HVs) and battery vehicles (BVs) for applications in diversified net-zero energy communities in urban areas, to help achieve carbon neutrality in the near future. Three innovations are presented including: (1) The transient simulation models of four net-zero energy community cases are developed integrated with HVs or BVs in either peer-to-grid (P2G) energy trading or P2P energy trading managements. The comprehensive techno-economic-environmental performances of HV-integrated renewable energy systems and BV-integrated renewable energy systems are compared for applications in the diversified net-zero energy community. (2) The multi-objective P2P energy trading optimizations on the net-zero energy community integrated with both HVs and BVs are developed, to explore an optimum interactive impact between the equipped vehicle numbers and P2P trading management strategies for a comprehensive system optimization. (3) An improved P2P energy trading management strategy of hybrid renewable energy systems with HV and BV energy storage is further proposed considering the peer trading priority and complementary operations of hybrid vehicle storage, to enhance the grid integration, decarbonisation and economy.

1.2. Literature review

The integration of hydrogen vehicles (HVs) and battery vehicles (BVs) in renewable energy systems has attracted increasing attentions in recent years, as the decarbonisation potential of the emerging green vehicle technologies contributes to the acceleration of carbon neutrality on the transport and power sectors [15]. The differences of HV systems and BV systems have been compared regarding the technical and decarbonisation performances. And optimization approaches have been adopted to achieve the system economy and robustness of HV and BV integrated renewable energy systems. The P2P energy trading management of hybrid renewable energy and storage systems has been investigated from perspectives of different stakeholders.

Research has been conducted on comparing HV systems and BV systems in terms of the energy efficiency [16, 17], energy consumption [18], greenhouse gas emissions [19] and demand uncertainties [20]. Specifically, the energy and environmental impact of renewable energy systems integrated with a HV or a BV is compared applied in a zero-energy building in Finland. The results indicate that the BV-integrated renewable energy system is easier to achieve the annual net-zero energy balance than the HV-integrated system, as the utilization efficiency of the BV system (0.88 - 0.90) is much higher than that of the HV system (0.45 - 0.65) [16]. The energy efficiency of the HV system and the BV system during the whole life cycle from the raw material stage to the wheel stage is investigated, by an energy matching method based on the source energy consumption rate. This method can provide references for the evaluation and design of new green vehicles in renewable energy systems [17]. A flexible vehicle simulation model is also presented to assess the energy consumption and range of vehicles powered by the battery, fuel cell and ultra-capacitor. It is indicated that the BV consumes the least energy (23%), followed by the HV (65%) compared with the internal combustion engine vehicle in real world conditions [18]. The dynamic greenhouse gas emission of HVs and BVs from a well-to-wheel perspective is analyzed by examining the power mix and the resulting change of vehicle market share in South Korea. The numerical results show that the introduction of HVs helps to reduce carbon emissions and affects the BV market [19]. An autonomous hybrid charging station is proposed with a PV system supply assisted by a diesel generator to provide electricity for both BVs and HVs. The uncertainties of hydrogen and electricity demand are considered based on the information-gap decision theory, to provide the investor with three strategies following different risk constraints [20]. It can be found that few studies compare the comprehensive techno-economic-environmental performances of HV systems and BV systems for integration with hybrid renewable energy systems applied in diversified net-zero energy communities, especially under different peer trading modes (P2G/P2P).

The optimization approaches have been adopted to minimize the cost [21, 22] and achieve the system robustness [23] of renewable energy systems integrated with hybrid HV and BV units. Specifically, a unified model of the hybrid renewable energy and battery storage system is developed for a home building integrated with a HV and a BV to minimize the cost of energy consumption, considering the uncertainties of wind and solar power generation. The authors reported that the BV and HV can reduce the carbon emissions by 56.24% and 12.5%, respectively [21]. The minimum system cost is also searched for a set of distributed energy resources supplying power for BV charging and HV refuelling, through optimizing the component sizes and energy management strategy simultaneously. It is indicated that the system optimal cost depends on the weather and electricity pricing schemes [22]. A robust optimization approach is proposed to design a standalone hybrid HV and BV charging station with PV power and diesel generator sources, considering the stochastic operations of solar irradiance, electricity and hydrogen loads. The annual system cost and system robustness are optimized by searching the optimal capacities of PV power and diesel generation based on the mixed-integer linear programming [23]. It is indicated that the techno-economic-environmental performance optimizations of renewable energy systems with hybrid HV and BV units, serving as both energy storage and cruise tools, are seldom involved to explore the optimal interaction between equipped vehicle numbers and time-of-use management, considering the real-time P2P trading in diversified net-zero energy communities.

The P2P energy trading management of communities with renewable energy and storage systems has been widely investigated to improve the energy autonomy and grid flexibility of building communities [24], with regard to the battery management [25, 26], agent management [27], and prosumer management [28]. The optimal P2P energy trading management is studied considering optimal battery sizing and operation under different battery storage ownership structures. The results indicate that the user owned battery storage system achieves the highest economic benefits applied in campus buildings compared with other ownership structures [25]. The role of battery storage in the P2P energy community is also studied by comparing the contribution of batteries located at the consumer level versus a central shared battery applied in a small community in London. And the results show that an end-user potential saving of 31% can be achieved by the P2P trading and private storage [26]. A novel multi-agent deep reinforcement learning method is proposed for the coordinated management of the large-scale P2P energy trading community, and experiments based on 300 residential households demonstrated the effectiveness of the proposed approach in terms of the system operation cost, demand peak and computational time [27]. A distributed P2P energy transaction model based on the double auction market is proposed for dynamic P2P trading management of urban community microgrid systems with diversified prosumers. The case study based on 90 residential prosumers and 4 enterprise prosumers demonstrated the technical and economic superiority of the proposed approach, compared with existing centralized approaches [28]. It can be identified that the P2P trading management of renewable energy systems with hybrid HV and BV storage units applied in diversified net-zero energy communities has been seldom studied, especially considering the optimal P2P energy trading orders and complementary charging of hybrid vehicle storage.

The research gaps and research problems can be found based on the above literature review on renewable energy and storage systems in terms of the comparison between HV systems and BV systems, optimization on HV and BV integrated renewable energy systems, and P2P energy trading management. Firstly, few studies compared the comprehensive techno-economic-environmental performances of HV-integrated renewable energy systems and BV-integrated renewable energy systems applied in diversified net-zero energy communities with P2P energy trading. Secondly, an optimum interactive relationship between the equipped vehicle numbers and P2P trading management strategies of hybrid HV and BV integrated renewable energy systems needs further investigation, to guide its applications in diversified urban communities. Thirdly, improved P2P energy trading management strategies need to be developed to improve the grid integration, decarbonisation and economic cost of hybrid HV and BV integrated renewable energy systems. Therefore, three major research problems of the present study are proposed as follows:

(1) Finding the technical, economic, environmental application superiorities of HV-integrated renewable energy systems and BV-integrated renewable energy systems for power supply to a typical diversified net-zero energy community under the P2G trading or P2P trading management by developing transient simulation models.

(2) Exploring the optimum interactive impact between green vehicle numbers and P2P energy trading management strategies in the net-zero energy community by developing multi-objective P2P energy trading optimizations on the renewable energy and hybrid HV and BV storage systems.

(3) Improving the grid integration, decarbonisation and economy of renewable energy and hybrid HV and BV storage systems applied in the net-zero energy community by proposing an improved P2P energy trading management strategy considering the peer trading priority and complementary operations of hybrid vehicle storage.

1.3. Research aims and objectives

This study presents peer-to-peer energy trading optimizations of hybrid renewable energy systems for power supply to a diversified net-zero energy community integrated with hydrogen vehicles and battery vehicles, serving as both energy storage and daily cruise tools in different operation schedules. The hybrid solar photovoltaic and wind turbine system models are firstly developed in the TRNSYS 18 environment applied in a typical diversified net-zero energy community consisting of university campus, commercial office, and high-rise residential buildings, based on actual energy use and simulation data. Multi-objective optimizations are conducted to study the interactive impact of vehicle numbers and time-of-use management on the techno-economic-environmental performances of hybrid renewable energy systems, based on the coupled simulation and optimization methods. Three research aims and objectives are investigated in the present study:

(1) To compare the techno-economic-environmental performances of four net-zero energy community cases with hydrogen vehicles or battery vehicles in either peer-to-grid energy trading or peer-to-peer energy trading management, regarding the on-site renewable energy self-consumption, on-site load coverage, grid integration, annual equivalent carbon emissions, annual electricity bill and lifetime net present value.

(2) To develop multi-objective peer-to-peer trading optimizations on the net-zero energy community integrated with both hydrogen vehicles and battery vehicles, to explore the optimal configurations of vehicle numbers in the diversified building groups and time-of-use management operations for a comprehensive system optimization. The technical, economic, and environmental indicators are adopted as the optimization multi-criteria, including the on-site renewable energy self-consumption, annual net electricity bill and annual equivalent carbon emissions of the diversified net-zero energy community.

(3) To propose an improved peer-to-peer energy trading management strategy of the renewable energy and hybrid vehicle energy storage system on top of the optimum solution, in

terms of enhancing the peer energy trading priority and making complementary charging operations on the hybrid hydrogen vehicle and battery vehicle storage. Significant improvements can be achieved for the typical diversified net-zero energy community, regarding the grid integration, decarbonisation benefits, electricity bills and system lifetime cost.

2. Methodology

This study presents the peer-to-peer (P2P) energy trading management and optimization approaches on a diversified net-zero energy community integrated with hydrogen vehicle (HV) and battery vehicle (BV) storage, with the overall framework as shown in Fig. 1. The diversified community locates in a high-density urban city consisting of three fundamental building groups of the university campus, commercial office and high-rise residential buildings, based on actual energy use data and simulations. Hybrid solar photovoltaic (PV) and offshore wind turbine systems, with advantageous and complementary characteristics, are developed for power supply to the net-zero energy community, with annual balanced electrical loads and renewable energy generations. The HV and BV groups with different cruise schedules are integrated with the hybrid renewable energy systems, serving as both energy storage units and cruise tools for the building occupants.

Firstly, four net-zero energy community cases are developed with different energy storage vehicles and peer trading management strategies, to compare the application feasibility of HV-integrated and BV-integrated renewable energy systems in either P2G or P2P trading operation. Specifically, Case 1 allocates three HV groups to the diversified net-zero energy community with only P2G trading management. Case 2 allocates three BV groups to the diversified net-zero energy community with only P2G trading management. Case 3 allocates three HV groups and introduces P2P energy trading in the diversified community. And Case 4 allocates three BV groups in the community with P2P energy trading management. Detailed techno-economic-environmental performances of these four cases are compared to explore the superiority of HV storage and BV storage systems in either P2G or P2P trading management strategy, in terms of the on-site renewable energy self-consumption, on-site load coverage, grid integration and carbon emissions, annual electricity bill and lifetime net present value (NPV).

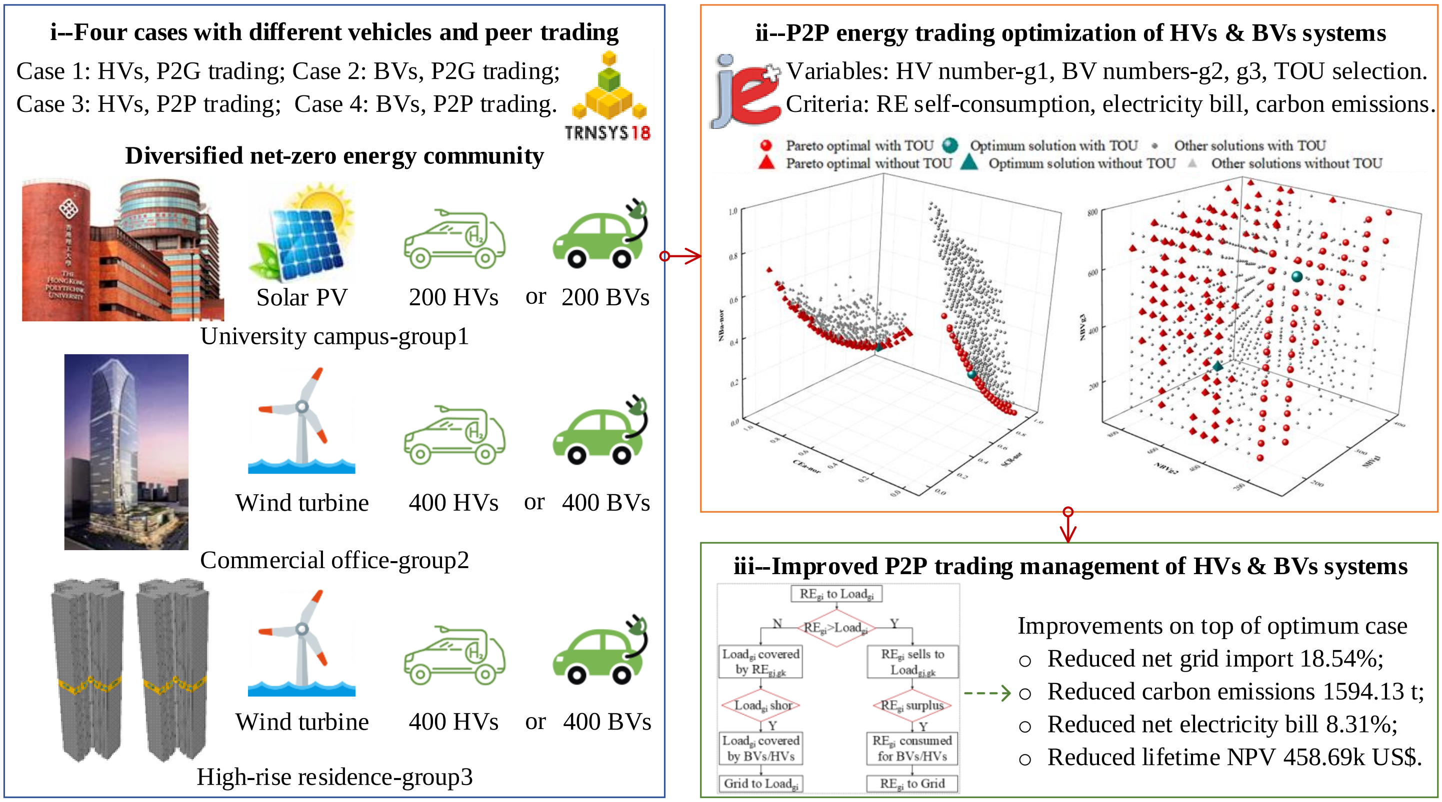


Fig. 1 Framework of peer trading optimizations on a diversified net-zero energy community integrated with HVs and BVs

Secondly, the P2P energy trading optimizations are conducted on the diversified net-zero energy community integrated with both HV and BV storage units, to investigate the interactive impact of vehicle numbers and time-of-use (TOU) management on the techno-economic-environmental performances of hybrid renewable energy systems. Four optimization variables are assigned including the number of integrated HVs in the university campus buildings, the number of integrated BVs in the commercial office buildings, the number of integrated BVs in the high-rise residential buildings, and the TOU management selection signal. And the technical, economic and environmental performance indicators of the renewable energy and hybrid vehicle storage systems are adopted as optimization criteria, including the on-site renewable energy self-consumption, annual net electricity bill, and annual equivalent carbon emissions. The application conditions of the TOU management strategy on optimizing the techno-economic-environmental performances of hybrid renewable energy and vehicle storage systems are clearly presented, based on the distribution of the Pareto optimal set of optimization objectives. And the optimal interactive relationship of the TOU management strategy and equipped vehicle numbers in three diversified building groups is reported for a comprehensive optimization, based on the distribution of the Pareto optimal set of optimization variables. The multi-objective P2P energy trading optimization results can provide guidance for the application and management of renewable energy and green vehicle storage systems for achieving carbon neutrality in integrated building and transport sectors.

Based on the final optimum solution obtained from the decision-making strategy of the minimum distance to the utopia point method, an improved P2P energy trading management strategy is further proposed to enhance the dynamic peer energy trading of the hybrid renewable energy system with both HVs and BVs for the diversified net-zero energy community. The surplus renewable energy of each building group is shared and traded for the load shortage of other building peers prior to its vehicle storage, to increase the on-site load coverage and reduce grid power pressure. And the storage charging and discharging of BV systems is prior to HV systems to make complementary operations of hybrid storage units in the diversified community. The underlying mechanism for the complementary operations is that, BV systems have a higher utilization efficiency and a lower charging starting power but a smaller charging rate limit and lower charging availability, while HV systems have a larger charging rate and higher charging availability but a higher charging starting power and a lower efficiency. The techno-economic-environmental superiority of the improved P2P trading management strategy is demonstrated, through the comparison with the optimum solution of the multi-objective optimization. And significant reductions can be achieved in the net grid import, annual equivalent carbon emissions, annual net electricity bill and lifetime NPV for the net-zero energy community.

2.1. Hybrid renewable energy systems for the diversified net-zero energy community integrated with hydrogen vehicles or battery vehicles

(1) Load profiles of a typical diversified community

A typical diversified community is established consisting of fundamental building groups of university campus buildings, commercial office buildings and high-rise residential buildings, based on actual energy consumption data and simulations as per local surveys and building codes. Specifically, the annual hourly power consumption data of the Phase I - Phase V in the Hong Kong Polytechnic University (PolyU) are collected as the load profile of the university campus building group, with a building area of about 149,260 m^2. The annual hourly power consumption data of the commercial office zone in the International Commerce Center (ICC) in Hong Kong are collected as the load profile of the commercial office building group, with a building area of about 268,800 m^2. And the annual hourly energy consumption data of ten high-rise residential buildings (Resid) at standard layouts in Hong Kong are modelled based on the TRNSYS platform according to local surveys [29] and building design codes [30, 31], to get the load profile of the residential building group with a building area of about 192,095 m^2. The monthly electrical load of the diversified community with three building groups is shown in Fig. 2, with an annual electrical load of about 119,714.05 MWh, and the maximum monthly load is achieved in August at 12664.94 MWh with a relatively high air-conditioning demand in the hot-summer region.

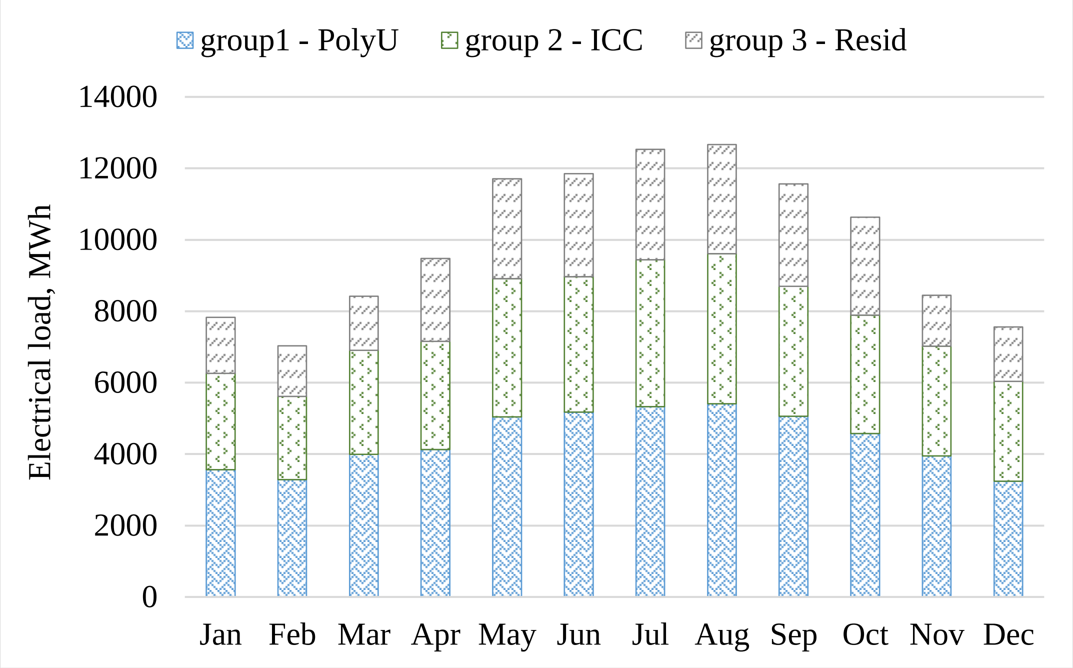


Fig. 2 Monthly electrical load of the diversified community with three building groups

(2) Hybrid renewable energy systems with HVs or BVs

This study develops HV-integrated renewable energy systems and BV-integrated renewable energy systems for power supply to a typical diversified net-zero energy community, given the promising development of HVs and BVs as the most widely used green vehicles. Multiple functions are served for the green vehicles when integrated with hybrid renewable energy systems, including storing surplus renewable energy as the energy storage unit, supplying power for load shortage as the energy supply unit, as well as serving as the daily cruise tools of occupants in the corresponding building group. The simulation models of renewable energy systems with HVs or BVs are firstly established based on the TRNSYS 18 platform [32], with either P2G or P2P trading managements as shown in Fig. 3 and Fig. 4. The PV systems are installed for power supply to the university campus buildings (group 1) with the rated capacity of 41200 kW, to achieve an annual energy balance with its electrical load for a net-zero energy operation. The TRNSYS Type 103 is utilized for the PV module modelling employing equations for an empirical equivalent circuit model to predict the current-voltage characteristics. The wind energy conversion systems are installed for power supply to the commercial office buildings (group 2) and high-rise residential buildings (group 3) with the rated capacity of 13500 kW and 9200 kW, respectively. The mathematical model of Type 90 is adopted to calculate the power output of the wind turbine system based on the power versus wind speed characteristic from the testing datasheet of manufacturers, and the impact of air density changes and wind speed increases with height is also considered.

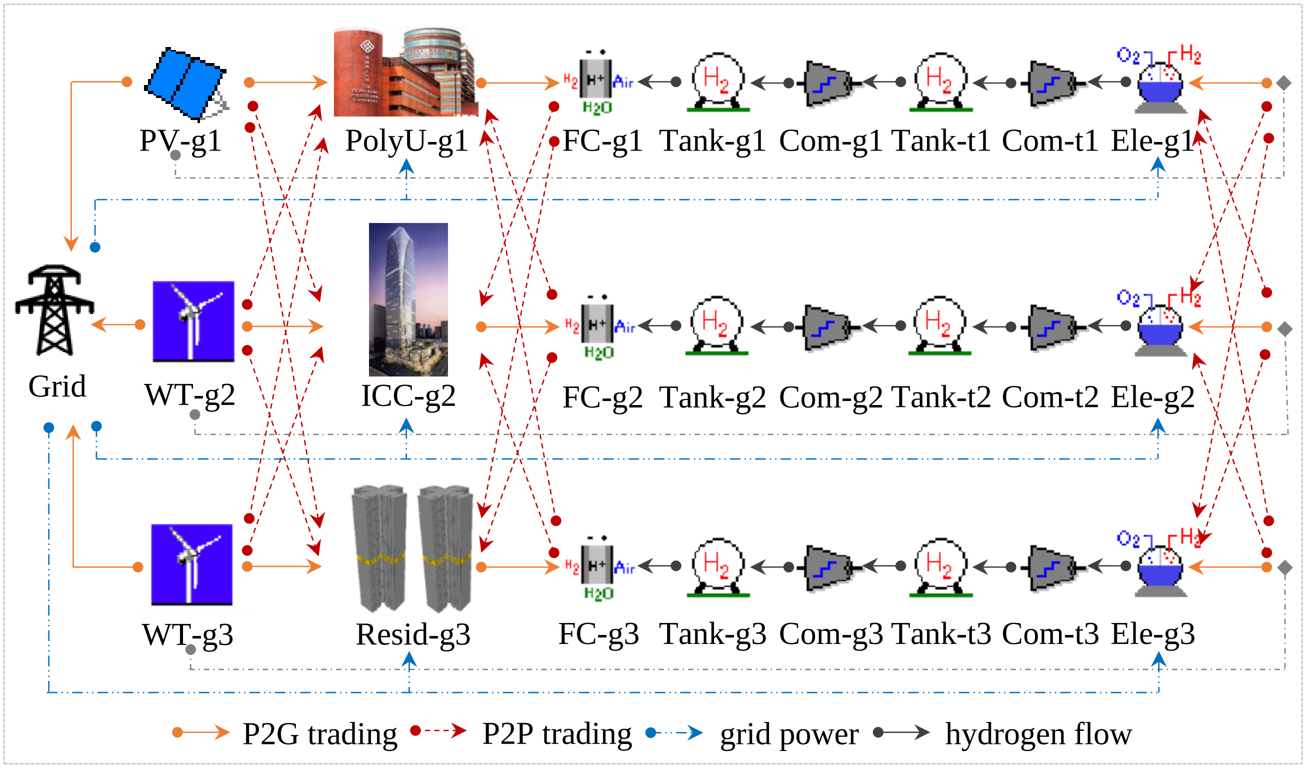


Fig. 3 Schematic of HV-integrated renewable energy systems with P2G trading (Case 1) and P2P trading (Case 3) in the net-zero energy community

The hybrid renewable energy system model integrated with three HV storage groups is developed for power supply to the diversified net-zero energy community, considering the P2G trading (Case 1) and P2P trading (Case 3) managements as shown in Fig. 3. Three groups of HV systems are installed in the net-zero energy community with a fixed vehicle number for each building group at a typical operation schedule for these cases, while the vehicle numbers are adopted as the optimization variables in the peer energy trading optimization in Section 2.2. 200 HVs are allocated for the campus buildings parking during 10:00 - 18:00 in working days, 400 HVs are allocated for the office buildings parking during 9:00 - 17:00 in working days, and 400 HVs are allocated for the residential buildings with the parking schedule of 19:00 - 8:00 from Monday to Saturday and all hours in Sunday. An average daily cruise range of 49.25 km is adopted for the vehicles based on the local traffic report [33].

The HV system is consisted of components for hydrogen generation, compression, storage, and consumption. The high-pressure alkaline water electrolyzer, based on the datasheet of an advanced alkaline electrolyzer "Phoebus", is equipped for producing hydrogen driven by electrical power from surplus renewable energy or the utility grid. It is modelled by Type 160a considering the fundamental thermodynamics, heat transfer, dynamic thermal model, and empirical electrochemical relationships [34]. The cell number of the electrolyzer is determined by the input power to keep the operational current density within the range of 40 - 400 mA/cm^2 [35]. The multistage polytropic compressor, modelled by Type 167, is utilized to compress hydrogen for storage when the pressure of entering hydrogen is lower than that of storage tanks based on a quasi-equilibrium compression process. Two sets of compressors are equipped in each HV system, serving for transporting hydrogen from electrolyzers to stationary storage tanks in buildings and delivering hydrogen from stationary storage tanks to mobile storage tanks in vehicles. And Type 164 is adopted for the compressed hydrogen storage tanks based on the van der Waals equation of state for real gases. The stationary hydrogen storage tanks are equipped on-site together with electrolyzers, while mobile hydrogen storage tanks are equipped in vehicles together with fuel cells. The hydrogen is consumed by the proton exchange membrane fuel cell (PEMFC), modelled by Type 170, considering the electrochemical and thermal dynamic processes of converting the chemical energy of hydrogen and oxygen to electrical current [34]. The mobile hydrogen vehicle is modelled by the mobile hydrogen storage tanks and PEMFCs, according to the commercial product of "2019 Toyota Mirai", with a full hydrogen stock of 5 kg at 700 bars supporting a cruise range of 502 km [36].

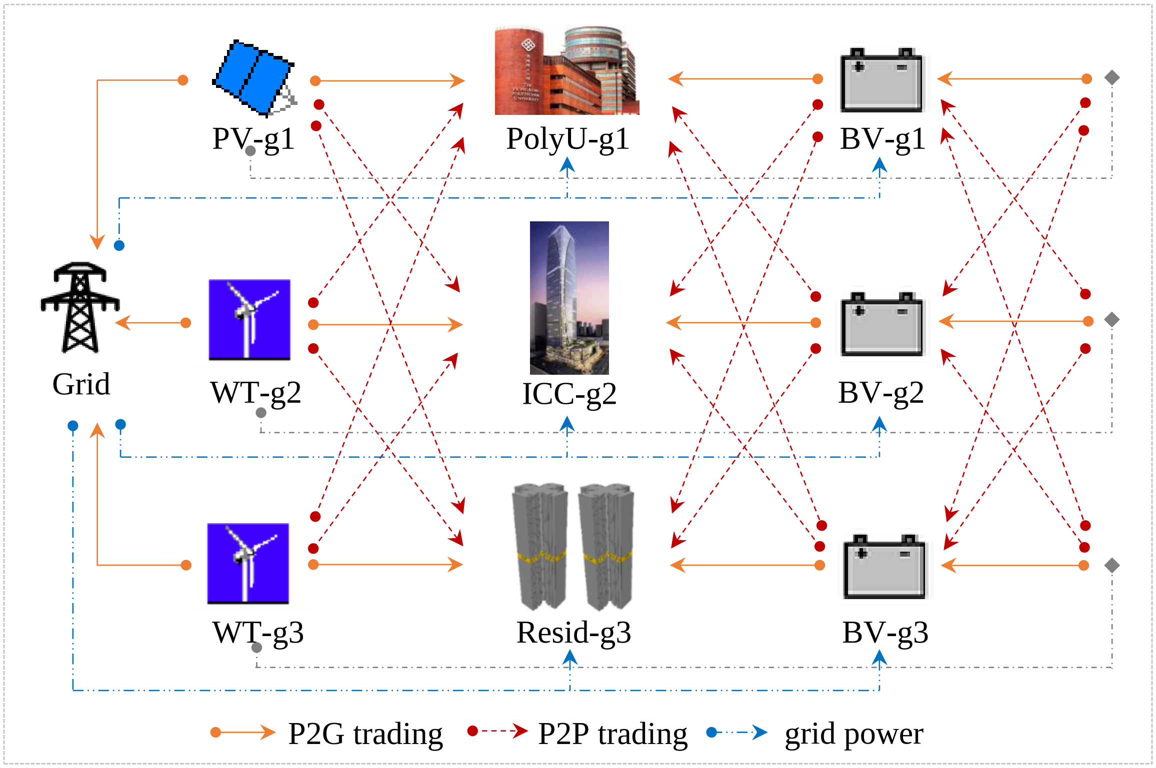


Fig. 4 Schematic of BV-integrated renewable energy systems with P2G trading (Case 2) and P2P trading (Case 4) in the net-zero energy community

The hybrid renewable energy system integrated with three BV storage groups is also developed for power supply to the diversified net-zero energy community with P2G energy trading (Case 2) and P2P energy trading (Case 4) as shown in Fig. 4. The vehicle number and operation schedule in each group keep the same with that in the HV-integrated renewable energy systems. And the storage capacity of each BV is 75 kWh, as comparable to that of the HV. Type 47a is adopted to model the battery vehicle based on the energy balance mechanism, according to the commercial product of "Tesla Model S 75" [36]. A maximum electricity storage state of charge at 0.95 is set for the BV, and a minimum storage state of charge at 0.39 is set to cover one-day cruise and keep above the minimum vehicle storage level.

Obvious differences between the BV storage system and HV storage system are considered in the energy management of hybrid renewable energy systems applied in the diversified net-zero energy community. On the one hand, the HV system has superior performances than the BV system for the charging time availability and charging rate limit. Renewable energy can be stored in the HV system via driving stationary electrolyzers to generate hydrogen and store in the stationary storage tanks, so the HV system can store surplus renewable energy even though HVs are not parked in buildings. While, only parked BVs can be charged for the BV system. And the charging rate limit of the BV system (1C for the lithium-ion battery) is stricter than the HV system (current density of 400 mA/cm^2 for the advanced alkaline electrolyzer). On the other hand, the BV system has superior advantages than the HV system in terms of the initial charging power, energy efficiency and investment cost. The electrolyzers can be started when the input power is above its initial charging power (current density of 40 mA/cm^2 for the advanced alkaline electrolyzer), while BVs can be started without strict power limitations. Moreover, the utilization efficiency of the BV system is much higher than that of the HV system.

(3) Energy management strategy of P2G and P2P trading of the diversified community

The building groups in the diversified net-zero energy community can not only exchange power with the utility grid, but also trade energy with other building peers for higher grid flexibility and system economy. The detailed energy management strategies of hybrid renewable energy and vehicle storage systems under the P2G trading and P2P trading in the individual peer energy trading price mode are explained and compared as per Fig. 5 and Fig. 6.

For the P2G trading management, the building groups in the diversified zero-energy community exchange energy only with the utility grid as per Fig. 5. Renewable energy generation of each building group is firstly delivered to meet its electrical load, and then to charge the vehicles (HVs in group 1, BVs in group 2 and group 3) according to the available storage state. The BV charging is controlled by the maximum fractional state of charge of BVs ($FSOC_{max}$ at 0.95) and the BV charging rate limit (1C for the lithium-ion battery). And the HV charging is controlled by the maximum storage state of stationary hydrogen storage tanks ($FSOC_{max}$ at 0.95) and the electrolyzer charging power limit (40 - 400 mA/cm^2 for the advanced alkaline electrolyzer). Finally, the surplus renewable energy is exported into the utility grid. In terms of the load shortage of each building group, the vehicle storage is utilized before importing energy from the utility grid. The BV discharging is controlled by the minimum storage state of BVs ($FSOC_{min}$ at 0.39 to cover one-day cruise and keep above the minimum vehicle storage level) and the BV discharging rate limit (1C for the lithium-ion battery). The HV discharging is controlled by the minimum storage state of mobile hydrogen storage tanks ($FSOC_{min}$ at 0.1005 to support one-day cruise and keep above the atmosphere pressure) and the rated power output of the PEMFC.

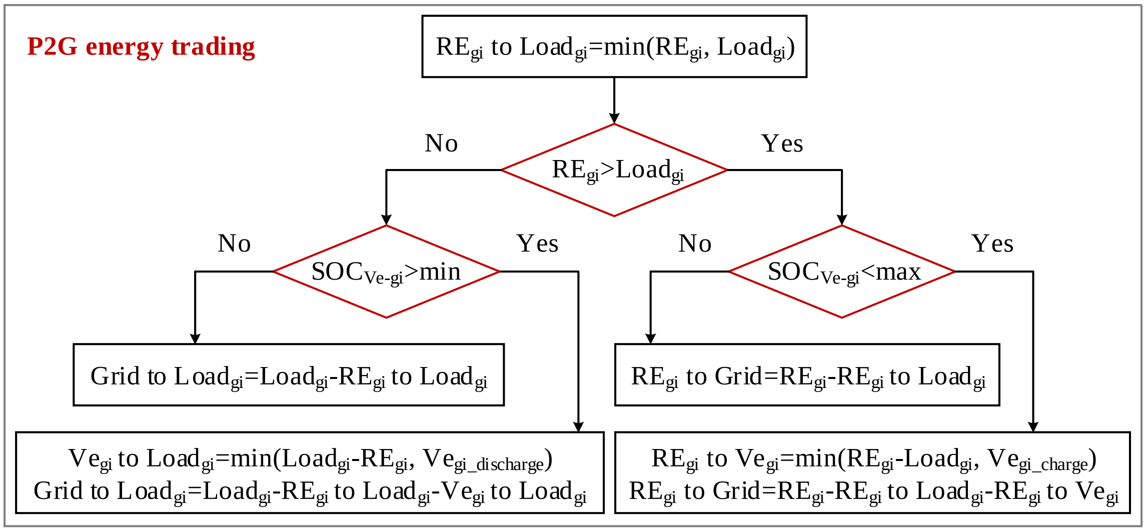


Fig. 5 Flowchart of renewable energy and vehicle storage systems with P2G trading

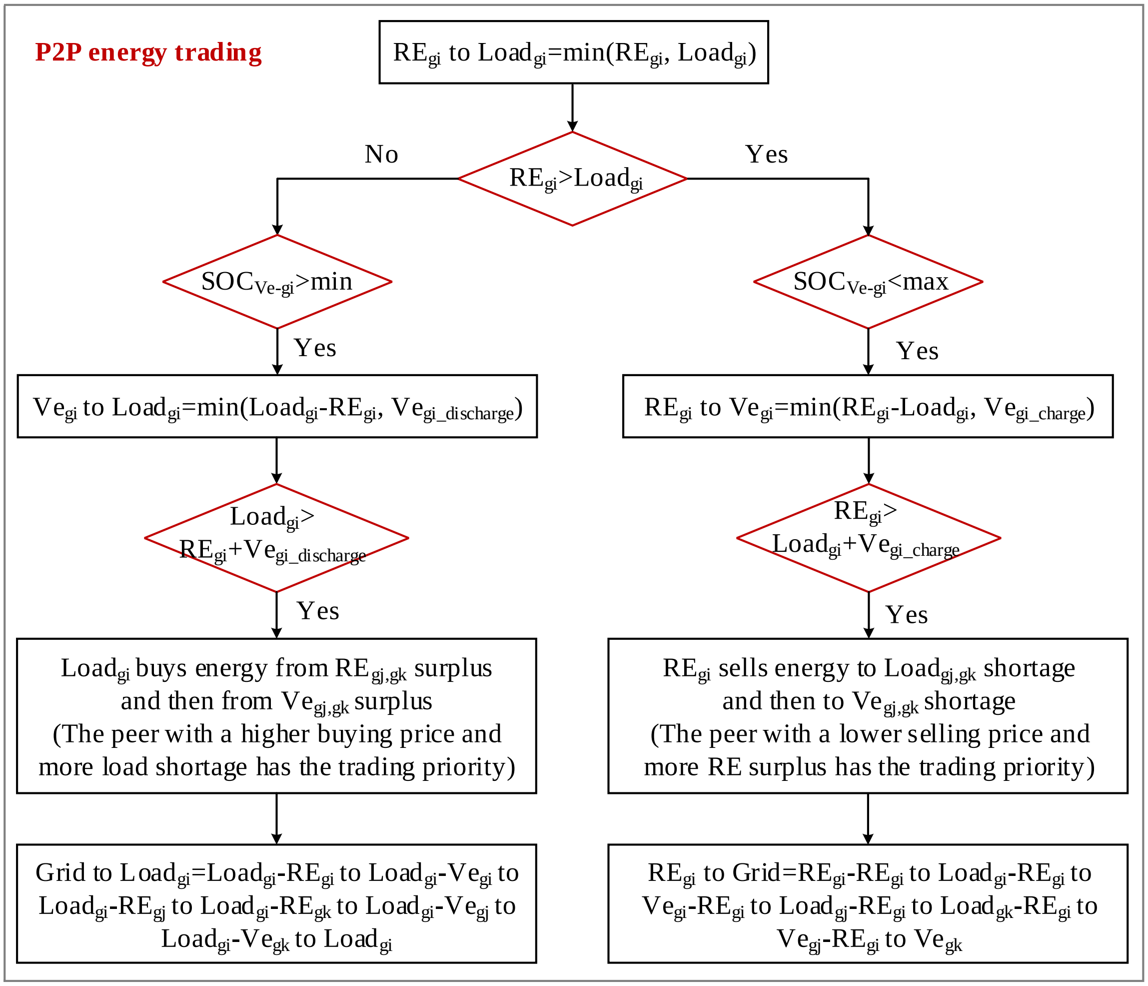


Fig. 6 Flowchart of renewable energy and vehicle storage systems with P2P trading

For the P2P trading management, the building groups in the diversified zero-energy community share energy with other building peers before exchanging with the utility grid as per Fig. 6. Renewable energy of each building group is firstly consumed by its own electrical load and vehicle storage, then the surplus renewable energy is shared to cover the load shortage and vehicle shortage of other building peers. The building peer with a lower selling price and higher surplus renewable energy catches the energy trading priority. And finally, the residual renewable energy after meeting the load and storage shortage of all building groups in the community is exported into the utility grid. As for the load shortage of the building group after being covered by its own renewable energy and vehicle storage supply, the surplus renewable energy and vehicle storage of other building peers can be utilized. And the building peer with a higher buying price and higher load shortage enjoys the energy trading priority. Lastly, energy is imported from the utility grid to cover the unmet load shortage in the community.

An individual peer energy trading price model is adopted to study the P2P trading of the diversified net-zero energy community to allocate an individual trading price to each building group based on its intrinsic supply demand feature and grid export price [37], as shown in Fig. 7. The peer selling price and peer buying price of an individual building group are independent, since its renewable energy surplus and demand shortage could not exist at the same time.

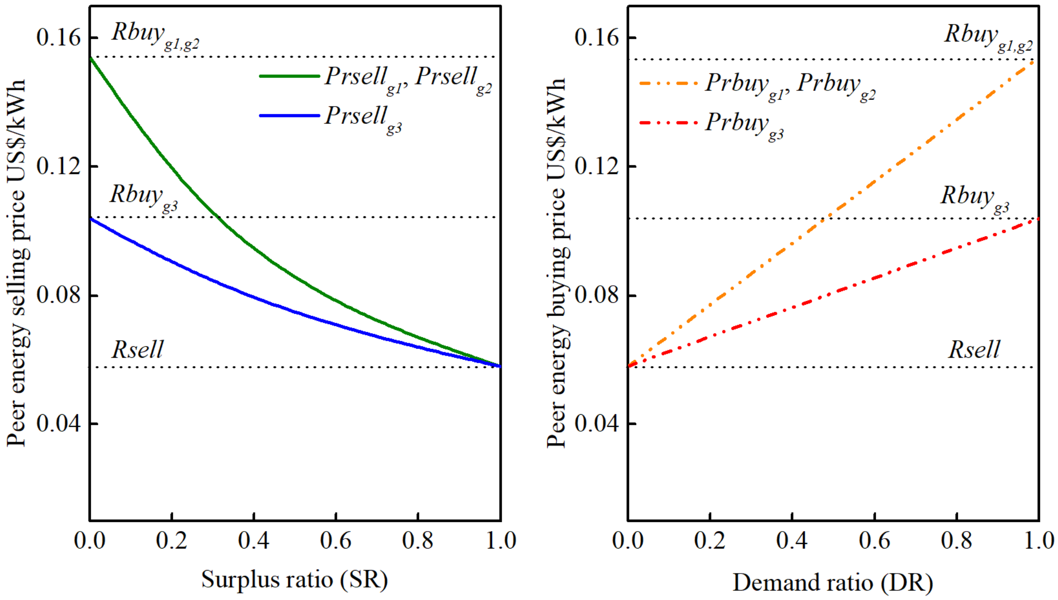


Fig. 7 Individual peer energy trading price model for the diversified community

The P2P energy selling price of each building group shows an inverse-proportional relation with its dynamic renewable energy surplus ratio (SR) as shown in Eq. (1).

$$Prsell_{gi} = f\left(SR_{gi\_sur}\right) = \frac{Rsell \cdot Rbuy_{gi}}{\left(Rbuy_{gi} - Rsell\right) \cdot SR_{gi\_sur} + Rsell} \tag{1}$$

where $Prsell_{gi}$ is the peer energy selling price of building group i, US$/kWh. SR_{gi_sur} is the renewable energy surplus ratio of building group i, expressed by the ratio of surplus renewable energy to the dynamic renewable energy generation. $Rsell$ is the electricity rate of renewable energy exported into the utility grid, 0.058 US$/kWh. $Rbuy_{gi}$ is the electricity rate of energy imported from the grid of building group i, at 0.154 US$/kWh for non-residential buildings and 0.104 US$/kWh for residential buildings according to the local electric company [38].

The P2P energy buying price of each building group shows a proportional relation with its dynamic demand shortage ratio (DR) as shown in Eq. (2).

$$Prbuy_{gi} = f\left(DR_{gi\_shor}\right) = \left(Rbuy_{gi} - Rsell\right) \cdot DR_{gi\_shor} + Rsell \tag{2}$$

where $Prbuy_{gi}$ is the peer energy buying price of building group i, US$/kWh. DR_{gi_shor} is the demand shortage ratio of building group i, expressed by the ratio of load shortage to the dynamic electrical load.

Table 1 Four community cases with different storage vehicles and energy trading strategies

Net-zero energy community cases	Case 1	Case 2	Case 3	Case 4
Three HV groups	√	--	√	--
Three BV groups	--	√	--	√
P2G trading only	√	√	--	--
P2P trading management	--	--	√	√

Four net-zero energy community cases are developed and compared with different storage vehicles and energy trading strategies as shown in Table 1. Namely, Case 1: HVs are installed in each building group with only P2G trading in the community; Case 2: BVs are installed in each building group with only P2G trading in the community; Case 3: HVs groups are installed in each building group with P2P trading in the community; Case 4: BVs groups are installed in each building group with P2P trading in the community. The vehicle number in each building group of these four cases keeps the same, with 200 vehicles in the university campus buildings (group 1), 400 vehicles in the commercial office buildings (group 2) and 400 vehicles in the high-rise residential buildings (group 3) according to the building functions and scales. And the vehicle numbers in the diversified building groups will be specifically studied as the optimization variables for the multi-objective optimizations in the following Section 2.2.

2.2. Peer-to-peer energy trading optimization and evaluation of the diversified net-zero energy community with both hydrogen vehicles and battery vehicles

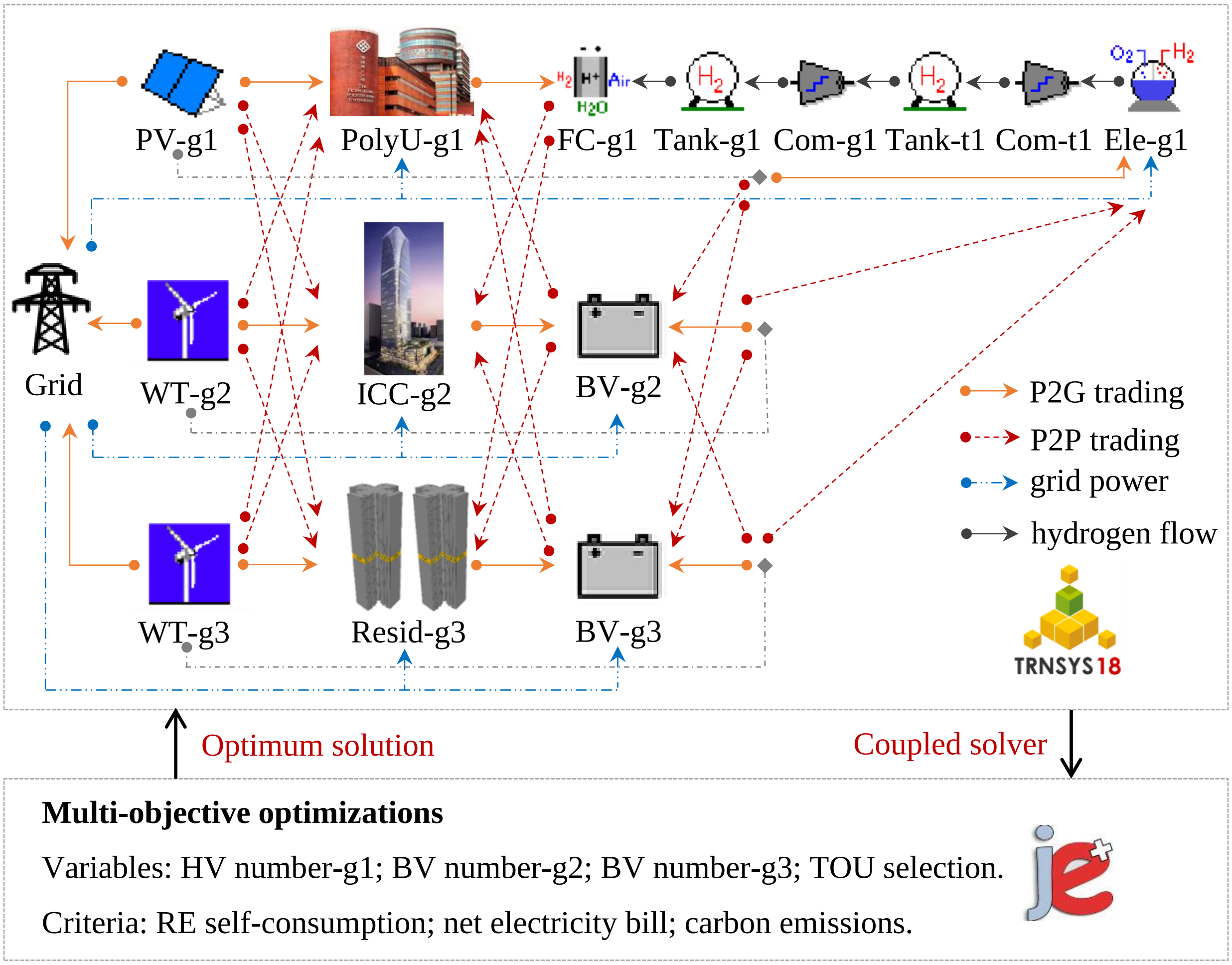


Fig. 8 Multi-objective optimization on hybrid renewable energy systems with both HVs and BVs

The P2P energy trading optimization of the diversified net-zero energy community with both HVs and BVs is further developed, to explore the optimal interactive impact of vehicle numbers and TOU management strategies on the techno-economic-environmental performances of hybrid renewable energy systems, with the schematic as shown in Fig. 8. The hybrid renewable energy system model integrated with HVs (group 1 campus buildings) and BVs (group 2 office buildings and group 3 residential buildings) is firstly established in the TRNSYS 18 platform. The building groups in the diversified net-zero energy community trade energy with both building peers and the utility grid.

Then, multi-objective optimizations on the diversified net-zero energy community are conducted based on the coupled TRNSYS and jEplus+EA platform. The Non-dominated Sorting Genetic Algorithm II (NSGA-II) is adopted as a robust and elite multi-objective genetic algorithm with fast non-dominated sorting approach, fast crowded distance estimation procedure and simple crowded comparison operator [39]. NSGA-II solves the multi-objective optimization problems with the following steps: population initialization, non-dominated sort, crowing distance, binary tournament selection, genetic operators with a high crossover rate (0.9) and a low mutation rate (0.05), recombination and selection for the Pareto optimal set [40]. A population size of 10 and a maximum generation of 200 are adopted for an exhaustive solution searching. The vehicle numbers integrated with three building groups and the TOU management selection signal are adopted as optimization variables. The HVs are integrated with the university campus buildings (group 1) searching within the range of 150 - 400 at an increment of 50. The BVs are integrated with the commercial office buildings (group 2) and high-rise buildings (group 3), both searching within the range of 150 - 800 at an increment of 50. And the TOU management selection signal is searched between the value 0 (with TOU management) and 1 (without TOU management).

The detailed energy management strategy with TOU management in the P2P energy trading of the diversified net-zero energy community is shown in Fig. 9. During on-peak periods, surplus renewable energy after meeting its electrical load is shared with other building peers with load shortage, where the building peer with a lower selling price and more surplus renewable energy enjoys the energy trading priority. And residual renewable energy after covering the load shortage of all buildings is exported into the utility grid for higher power flexibility and economy during on-peak time. While during off-peak periods with the grid preference of a low energy export, surplus renewable energy after meeting internal electrical demand is utilized to charge storage vehicles and shared with other building peers with load shortage and storage shortage. The residual renewable energy after covering all the load shortage and storage shortage of buildings in the community is finally fed into the grid. In terms of covering the load shortage of the building during on-peak time, after being met by the self-owned renewable energy sources, the vehicle storage of the building group is utilized. Afterwards, the load shortage can be covered via buying energy from other building peers with surplus renewable energy and surplus vehicle storage, following the rule that, the building peer with a higher buying price and higher load shortage catches the energy trading priority. The remaining load shortage after being satisfied by all surplus renewable energy and storage is finally supported by the utility grid. While during off-peak time with the grid preference of a high energy import, the building group with load shortage buys energy from other building peers with surplus renewable energy, and then imports energy from the utility grid.

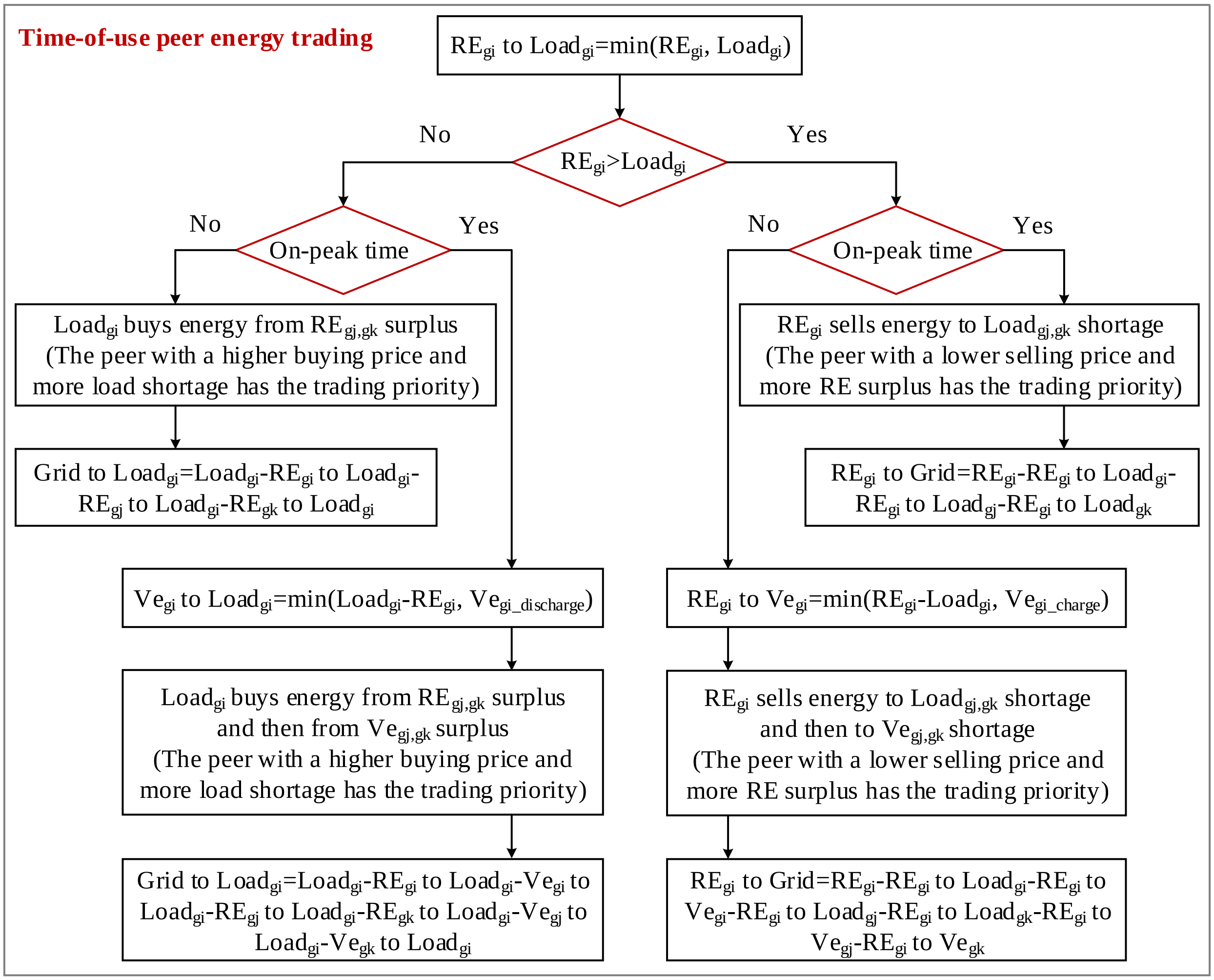


Fig. 9 Flowchart of renewable energy and vehicle storage systems with time-of-use P2P trading

The technical, economic and environmental performance indicators of renewable energy and hybrid vehicle storage systems are adopted as the optimization criteria, including the renewable energy on-site consumption, annual net electricity bill and annual equivalent carbon emissions.

(1) On-site renewable energy self-consumption ratio (SCR) of the diversified community:

$$SCR = \frac{on\text{-}site\ RE\ consumption}{total\ RE\ generation} = \frac{E_{RE\ to\ load} + E_{RE\ to\ BV} + E_{RE\ to\ HV}}{E_{RE}} \tag{3}$$

where $E_{RE\ to\ load}$ is the renewable energy produced by PV panels and wind turbines to meet electrical demand of buildings including peer sharing, kWh. $E_{RE\ to\ BV}$ is the utilized renewable energy for charging BVs, kWh. $E_{RE\ to\ HV}$ is the utilized renewable energy for driving electrolyzers to generate hydrogen in the HV system, kWh. E_{RE} is the total renewable energy generation from PV panels and wind turbines in the diversified community, kWh.

(2) Annual net electricity bill (NBa) of the diversified community:

$$NB_a = E_{grid\ import} \cdot Rbuy + E_{peer\ import} \cdot Prbuy - E_{grid\ export} \cdot Rsell - E_{peer\ export} \cdot Prsell \tag{4}$$

where $E_{grid\ import}$ is the annual imported energy from the grid for electrical load, HV and BV systems in the diversified community with three building groups, kWh. $E_{peer\ import}$ is the annual imported energy from both renewable energy sources and vehicle storage of peers in the community, kWh. $E_{grid\ export}$ is the annual exported energy from renewable energy sources to the grid, kWh. $E_{peer\ export}$ is the annual exported energy for electrical load and vehicle demand of peers in the community, kWh.

(3) Annual equivalent carbon emissions (CEa) of the diversified community:

$$CE_a = \left(E_{grid\ import} - E_{grid\ export}\right) \cdot CEF_{eq} \tag{5}$$

where CEF_{eq} is the equivalent carbon emissions of the utility grid, 0.572 kg CO_2/kWh [41].

Furthermore, other significant indicators are also formulated to evaluate the hybrid renewable energy and vehicle storage systems for power supply to the diversified net-zero energy community, including the on-site load coverage, net grid import, vehicle system utilization efficiency and lifetime net present value.

(4) On-site load cover ratio (LCR) of the diversified community:

$$LCR = \frac{on\text{-}site\ supply}{total\ electrical\ load} = \frac{E_{RE\ to\ load} + E_{HV\ to\ load} + E_{BV\ to\ load}}{E_{load}} \tag{6}$$

where $E_{HV\ to\ load}$ is the supplied energy from HV systems by consuming hydrogen in PEMFCs to generate electricity to cover electrical load including peer trading energy, kWh. $E_{BV\ to\ load}$ is the supplied energy from BV systems to electrical load including peer trading energy, kWh. E_{load} is the total electrical load of the community, kWh.

(5) Hydrogen vehicle storage system efficiency:

$$HVE=\frac{HV\ system\ supply}{HV\ system\ consumption}=\frac{E_{HV\ to\ road}+E_{HV\ to\ load}+E_{HV\ recovery}}{E_{RE\ to\ HV}+E_{grid\ to\ HV}+E_{compressor}+E_{H_2\ tank}} \tag{7}$$

where $E_{HV\ to\ road}$ is the energy consumption of HVs for daily cruises, kWh. $E_{HV\ recovery}$ is the recovered energy from HV systems for applications in domestic hot water in residential buildings, kWh. $E_{grid\ to\ HV}$ is refuelling energy from the utility grid to drive electrolyzers of HV systems to generate hydrogen to ensure daily cruises, when the storage level of hydrogen tanks in HVs is lower than the minimum threshold, kWh. $E_{compressor}$ is the energy required for hydrogen compression of HV systems, kWh. $E_{H2\ tank}$ is the energy change in hydrogen storage tanks, kWh.

(6) Battery vehicle storage system efficiency:

$$BVE=\frac{BV\ system\ supply}{BV\ system\ consumption}=\frac{E_{BV\ to\ road}+E_{BV\ to\ load}}{E_{RE\ to\ BV}+E_{grid\ to\ BV}+E_{BV\ store}} \tag{8}$$

where $E_{BV\ to\ road}$ is the energy consumption of BVs for daily cruises, kWh. $E_{grid\ to\ BV}$ is refuelling energy from the utility grid to BVs to ensure daily cruises, when the storage level of BVs is lower than the minimum threshold, kWh. $E_{BV\ store}$ is the energy change of BV storage, kWh.

(7) Net grid import of the diversified community:

$$NGI = E_{grid\ to\ load} + E_{grid\ to\ HV} + E_{grid\ to\ BV} - E_{RE\ to\ grid} \tag{9}$$

where $E_{grid\ to\ load}$ is the annual imported energy from the utility grid to meet electrical load of community buildings, kWh. $E_{RE\ to\ grid}$ is the annual exported renewable energy into the utility grid in the community, kWh.

(8) Lifetime net present value (NPV) of hybrid renewable energy and vehicle storage systems:

$$\begin{aligned} NPV &= PRV_{ini} + PRV_{O\&M} + PRV_{rep} - PRV_{res} + PRV_{nb} \\ &= C_{ini} + \sum_{n=1}^{n=N}\frac{f_{mai}\cdot C_{ini}}{(1+i)^n} + \sum_{j=1}^{j=J} C_{ini}\left(\frac{1-d}{1+i}\right)^{j\cdot l} - C_{ini}\frac{l_{res}}{l}\cdot\frac{(1-d)^N}{(1+i)^N} + \sum_{n=1}^{n=N}\frac{NB_a\cdot(1+\gamma)^{n-1}}{(1+i)^n} \end{aligned} \tag{10}$$

where the NPV calculation considers the 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 net electricity bill (PRV_{nb}), during a service lifetime of 20 years. The specific cost of main components in the hybrid renewable energy and vehicle storage systems are included, namely, PV panels, wind turbines, inverters/converters, electrolyzers, compressors, hydrogen storage tanks, HVs, and BVs. C_{ini} is the initial cost of a component, US$. n is a specific year, and N is the system service lifetime at 20 years. i is the annual real discount rate at 5.8%/year. f_{mai} is the ratio of maintenance cost to the initial cost and it differs with the component. j is a specific replacement time, and J is the total replacement times during the system lifetime. l is the service lifetime of a component, year. l_{res} is the residual lifetime of a component at the end of the system lifetime, year. d is the annual price degression rate of a component. γ is the annual electricity rising rate at 1.4%/year. The specific economic parameters of the main system components are shown in Table 2.

Table 2 Economic parameters of hybrid renewable energy and vehicle storage systems

System components	Initial cost	O&M ratio (of initial cost)	Lifetime, year
PV [42]	3500 US$/kW	2%	20
Wind turbine [42]	4000 US$/kW	1%	20
Inverter/converter [42]	700 US$/kW	1%	10
Electrolyzer	1400 US$/kW [43]	2% [44]	20 [45]
Compressor	15000 US$/Set [45]	2% [46]	20 [47]
Hydrogen storage tank [44]	50 US$/N m^3	0.50%	25
Hydrogen vehicle [48]	58500 US$/HV	2%	8
Battery vehicle [49]	81070 US$/BV	2%	8

2.3. Improved peer-to-peer energy management on the diversified net-zero energy community with both hydrogen vehicles and battery vehicles

An improved P2P energy management strategy is proposed to further enhance the dynamic peer energy trading of the hybrid renewable energy system integrated with both HVs and BVs for power supply to the diversified net-zero energy community. Its superiority in the technical, economic and environmental performances is demonstrated in comparison with the final optimum solution obtained by the multi-objective optimizations. The main improvements of the improved P2P management strategy on top of the optimization P2P management strategy of hybrid systems with both HVs and BVs lie in two aspects: (1) Surplus renewable energy of the building group is shared and traded for the load shortage of other building peers prior to its vehicle storage, to increase the community on-site load coverage and reduce grid power pressure. (2) The storage charging and discharging of the BV system are prior to the HV system to make complementary operations of the hybrid vehicle storage, as the BV system has a higher utilization efficiency and a lower charging starting power but a smaller charging rate limit and lower charging availability, while the HV system has a larger charging rate and higher charging availability but a higher charging starting power and a lower efficiency.

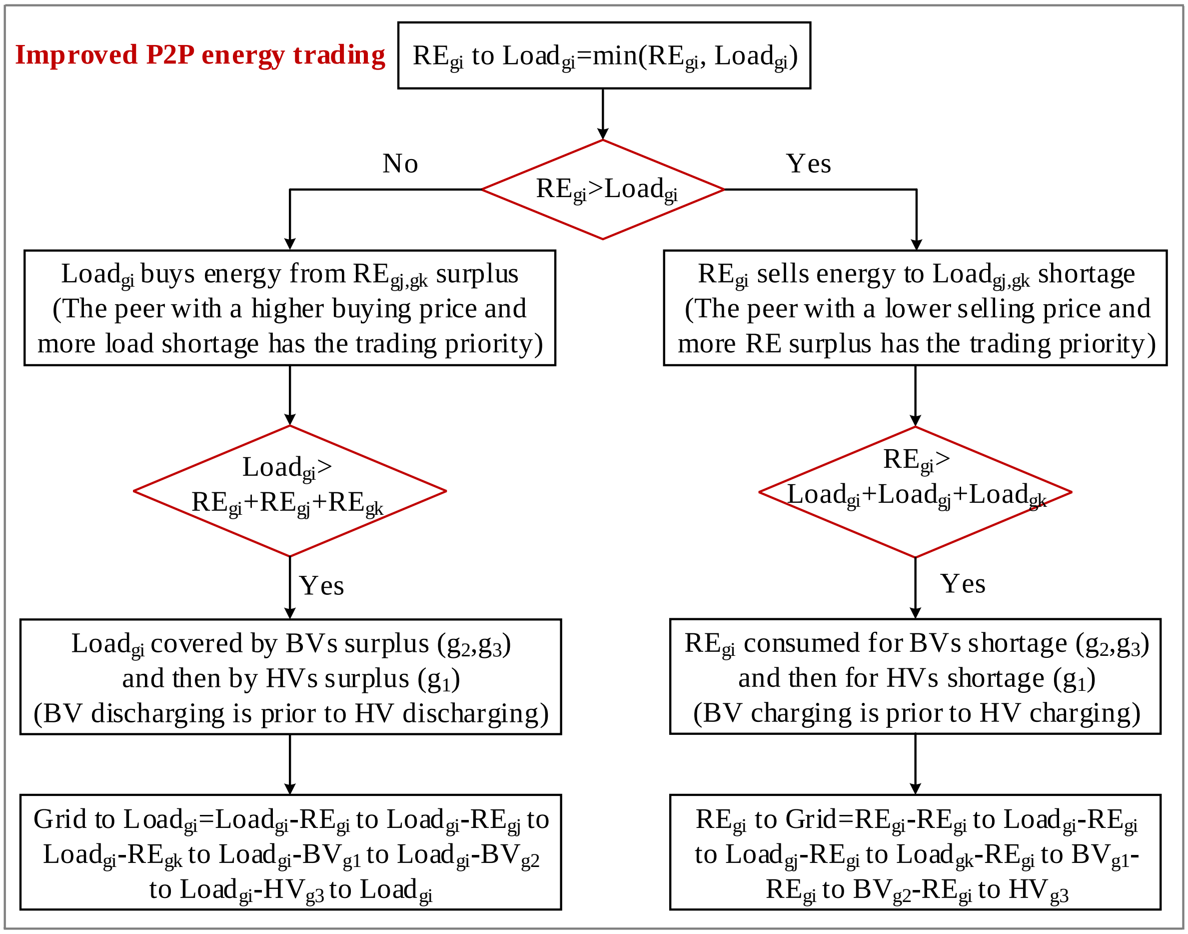


Fig. 10 Flowchart of improved P2P trading strategy of the community with both HVs and BVs

The detailed energy management strategy of the improved case is explained in Fig. 10. Surplus renewable energy generation of the building group after meeting its own electrical load is shared with other building peers with load shortage, where the building peer with a lower selling price and higher renewable energy surplus has the energy trading priority. And residual renewable energy after meeting all load demand of community peers is then utilized to charge three groups of storage vehicles, where the BV charging is prior to the HV charging to make complementary operations of the hybrid vehicle storage. Finally, extra renewable energy is exported into the utility grid. As for the load shortage of the building group after being satisfied by its renewable energy sources, it is then covered by the shared energy from other building peers with surplus renewable energy, where the building peer with a higher buying price and more load shortage enjoys the trading priority. The building group still with load shortage can then be met by storage vehicles, where the BV discharging is prior to the HV discharging. And the remaining load shortage is lastly covered by the utility grid.

3. Results and discussion

3.1. Comparison of hydrogen vehicles-integrated and battery vehicles-integrated renewable energy systems for the diversified net-zero energy community

Four hybrid renewable energy and vehicle storage systems are developed for power supply to the diversified net-zero energy community with different energy storage vehicle types (HV/BV) and energy trading modes (P2G/P2P). The technical, economic and environmental performances of four net-zero energy community cases are compared, concerning the on-site renewable energy self-consumption, on-site load coverage, grid integration, carbon emissions, annual electricity bill and lifetime net present value.

(1) On-site renewable energy self-consumption of four net-zero energy community cases

The renewable energy supply from solar PV and wind sources for the net-zero energy community is firstly utilized to meet electrical load and charge vehicle storage in the building itself, then to be either exported into the grid in the P2G trading management (Case 1 and Case 2), or shared to peer load and vehicle storage before being exported into the grid in the P2P trading management (Case 3 and Case 4). So the renewable energy consumption for self-load in the four cases is almost the same, while consumption for other parts differs greatly as shown in Fig. 11. It is indicated that more renewable energy is utilized on site for the HV-integrated system for both P2G trading (Case 1) and P2P trading (Case 3) with a SCR increment of 13.09% and 16.82% respectively, compared with the BV-integrated cases (Case 2 and Case 4). The main reason is that the charging availability of HVs is higher than BVs which only can be charged when parking in buildings. So the utility grid needs to absorb much more renewable energy in the BV-integrated system, higher by 49.67% in the P2G trading and 171.30% in the P2P trading compared with the HV-integrated system. It is also found that the P2P energy trading improves the on-site renewable energy consumption for both the HV-integrated system (Case 3) and the BV-integrated system (Case 4), where the SCR is increased by 16.54% and 12.82% respectively on top of the P2G trading cases (Case 1 and Case 2), as more renewable energy can be shared for peer load and storage.

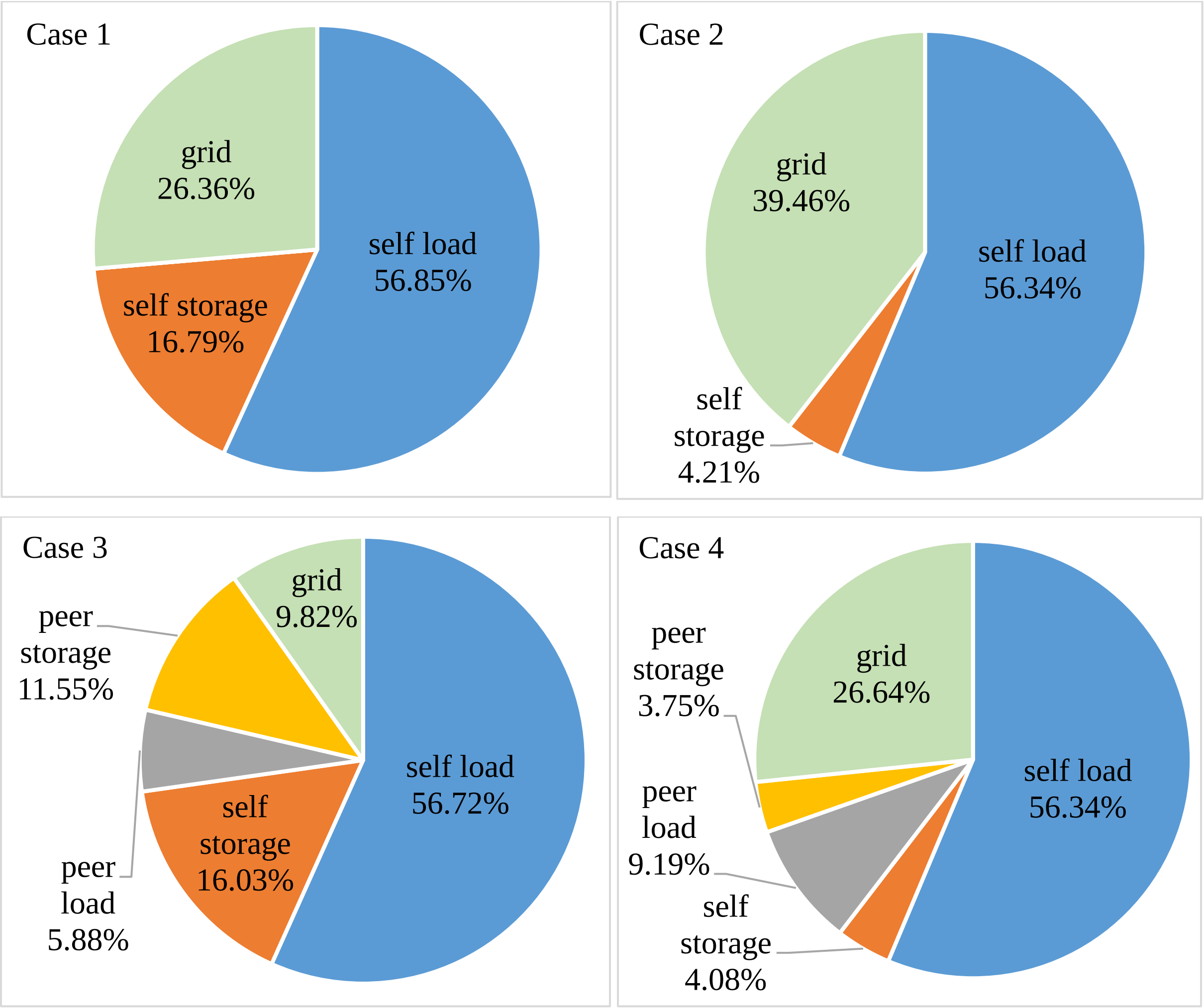


Fig. 11 Comparison of renewable energy self-consumption of four cases with HVs or BVs

(note: Case 1: HVs-integrated system in P2G trading; Case 2: BVs-integrated system in P2G trading; Case 3: HVs-integrated system in P2P trading; Case 4: BVs-integrated system in P2P trading.)

(2) On-site load coverage of four net-zero energy community cases

The renewable energy systems integrated with vehicle storage units are developed for meeting electrical demand of buildings in the net-zero energy community, with the on-site load coverage comparison as shown in Fig. 12. It is indicated that the on-site load coverage of the HV-integrated system is slightly higher than that of the BV-integrated system, by 3.45% for the P2G trading (Case 1 vs. Case 2) and 1.64% for the P2P trading (Case 3 vs. Case 4), as more renewable energy is absorbed by the HV storage. And obvious enhancements on the LCR of the net-zero energy community is observed by introducing P2P trading compared with P2G trading, higher by 10.10% for the HV-integrated system (Case 3 vs. Case 1) and 11.91% for the BV-integrated system (Case 4 vs. Case 2), since part of building load can be covered by surplus energy of peer renewable generation and storage for the P2P trading management. Therefore, less grid power import is needed by adopting the P2P trading, reduced by 25.62% for the HV-integrated system (Case 3 vs. Case 1) and 27.13% for the BV-integrated system (Case 4 vs. Case 2).

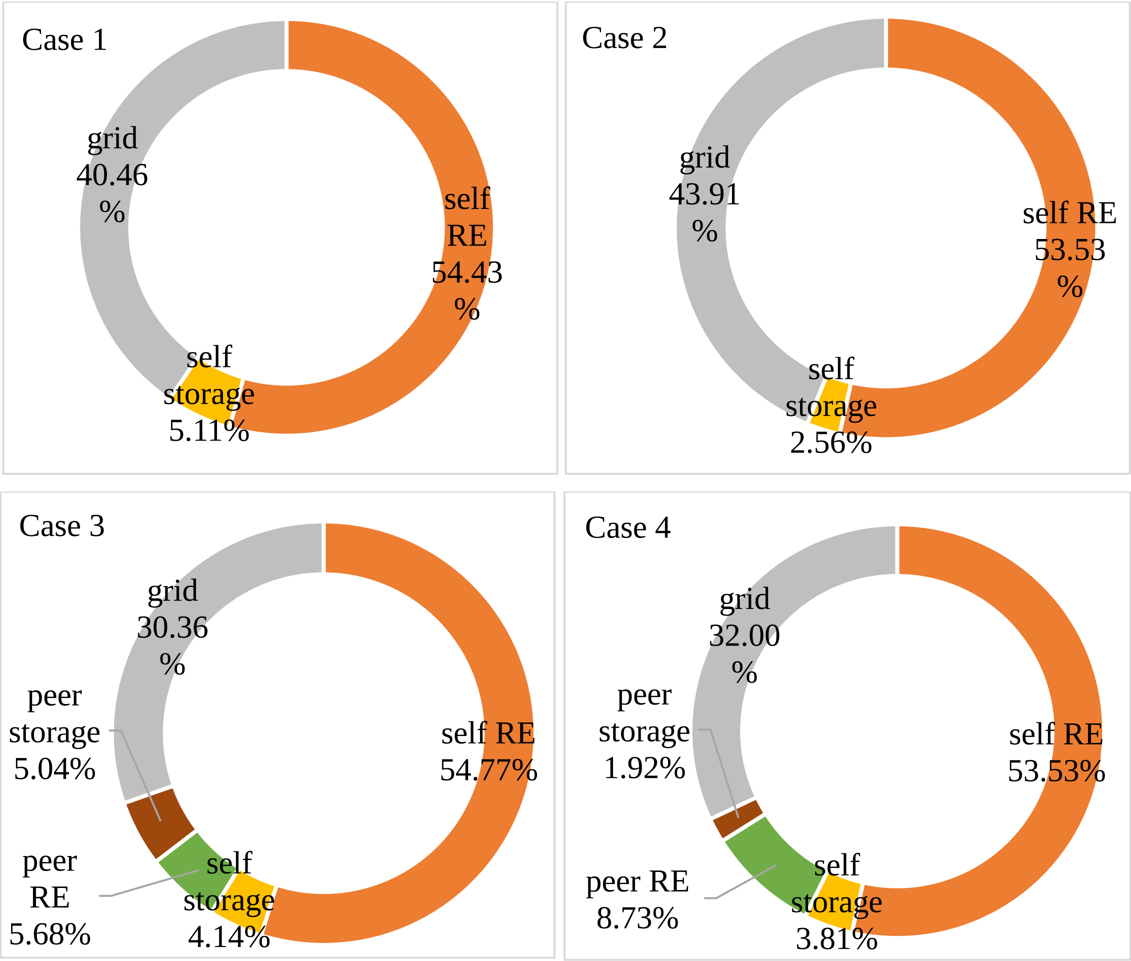


Fig. 12 Comparison of on-site load coverage of four cases with HVs or BVs

(note: Case 1: HVs-integrated system in P2G trading; Case 2: BVs-integrated system in P2G trading; Case 3: HVs-integrated system in P2P trading; Case 4: BVs-integrated system in P2P trading.)

(3) Grid integration and carbon emissions of four net-zero energy community cases

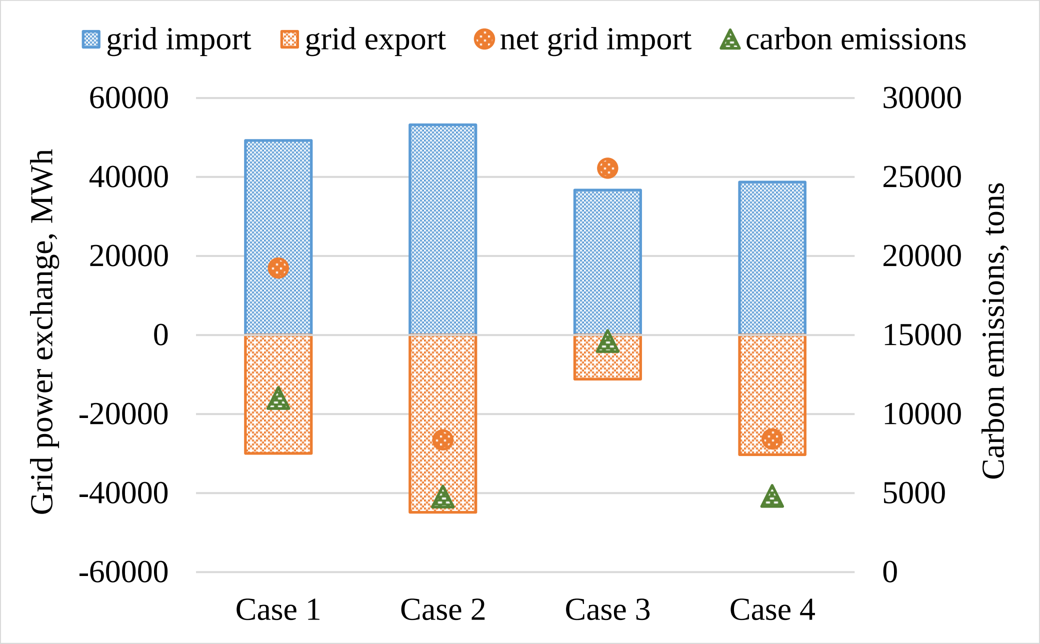


Fig. 13 Grid integration and carbon emissions of four cases with HVs or BVs

(note: Case 1: HVs-integrated system in P2G trading; Case 2: BVs-integrated system in P2G trading; Case 3: HVs-integrated system in P2P trading; Case 4: BVs-integrated system in P2P trading.)

The power integration between the diversified net-zero energy community and the utility grid varies with the storage vehicle types and energy trading management modes as shown in Fig. 13. It is indicated that the BV-integrated system performs better in the grid integration, with much less net grid import than the HV-integrated system by 56.60% for the P2G trading (Case 2 vs. Case 1) and 67.05% for the P2P trading (Case 4 vs. Case 3). This is mainly because more renewable energy generation is exported into the utility grid in the BV-integrated system with less storage charging availability. And the utilization efficiency of the BV storage system (90.06% - 93.55%) is much higher than the HV storage system (40.81% - 42.42%), considering both energy storage and transportation functions. While, the P2P energy trading increases the net grid import for both HV and BV storage systems, with less grid export compared with P2G trading cases. Significant decarbonisation benefits are observed in the BV-integrated systems induced by lower net grid import compared with the HV-integrated systems, reduced by 6229.02 tons for the P2G trading

(Case 2 vs. Case1) and 9803.21 tons for the P2P trading (Case 4 vs. Case 3). But the P2P energy trading increases carbon emissions of the diversified community compared with the P2G trading, especially for the HV storage system higher by 32.85% at 3615.37 tons (Case 3 vs. Case 1), as more renewable energy is used for peer load and storage rather than exported into the grid.

(4) Annual electricity bill of four net-zero energy community cases

The building groups in the net-zero energy community pay electricity bills for both the utility grid imported energy and peer bought energy, and achieve electricity gains for the grid exported energy and peer sold energy as shown in Fig. 14. It is indicated that the BV-integrated systems enjoy lower net annual bill than the HV-integrated systems, reduced by 6.60% (US$ 354.35k) for the P2G trading (Case 2 vs. Case 1) and 20.50% (US$ 931.52k) for the P2P trading (Case 4 vs. Case 3), as more renewable energy is available for feeding into the grid with export gain in the BV-integrated systems. And the P2P trading reduces the annual electricity bill of the diversified community, lower by 15.37% (US$ 825.34k) for the HV-integrated system (Case 3 vs. Case 1) and 27.96% (US$ 1402.50k) for the BV-integrated system (Case 4 vs. Case 2). The main reason is that less electricity is needed from the utility grid with a higher cost than the peer trading energy.

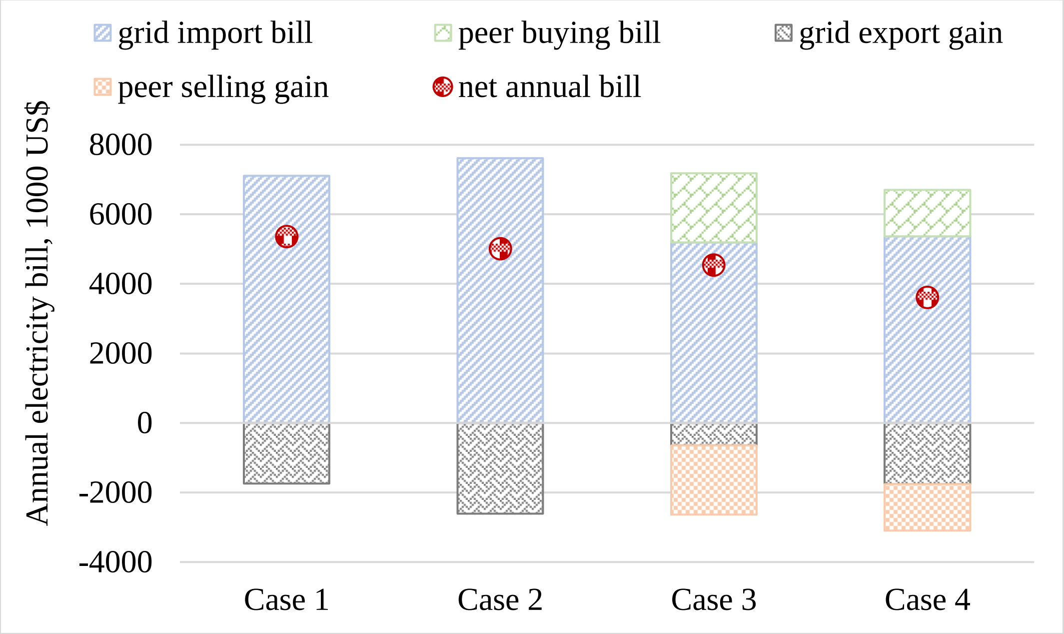


Fig. 14 Annual electricity bill of four cases with HVs or BVs

(note: Case 1: HVs-integrated system in P2G trading; Case 2: BVs-integrated system in P2G trading; Case 3: HVs-integrated system in P2P trading; Case 4: BVs-integrated system in P2P trading.)

(5) System lifetime net present value of four net-zero energy community cases

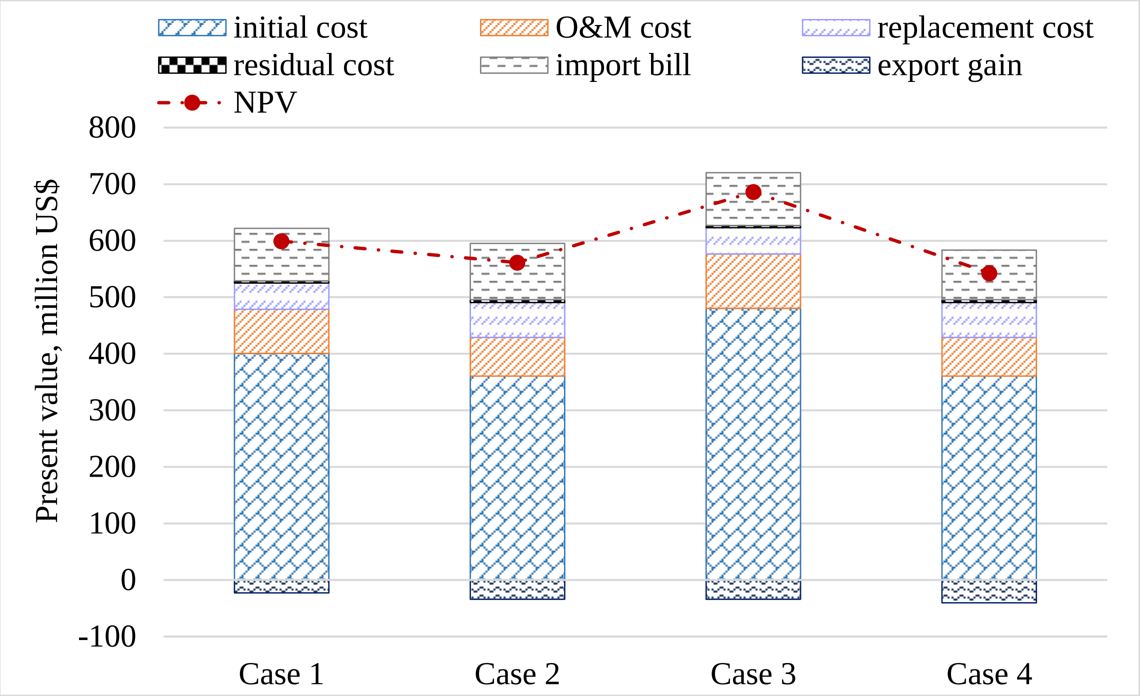


Fig. 15 System lifetime net present value of four cases with HVs or BVs

(note: Case 1: HVs-integrated system in P2G trading; Case 2: BVs-integrated system in P2G trading; Case 3: HVs-integrated system in P2P trading; Case 4: BVs-integrated system in P2P trading.)

The system NPV of the hybrid renewable energy systems integrated with three groups of HVs or BVs during a service lifetime of 20 years is analysed, considering the initial cost, O&M cost, replacement cost, residual cost, electricity import bill and electricity export gain, as per Fig. 15. The comparison results show that the present value of initial cost of HV-integrated systems is higher than that of BV-integrated systems, as more components are installed in HV storage systems including electrolyzers, compressors, hydrogen storage tanks and hydrogen vehicles. And the present value of net electricity bill of HV-integrated systems is higher than that of BV-integrated systems with higher grid export gains. So the lifetime NPV of HV-integrated systems is higher than that of BV-integrated systems, by 6.74% (US$ 37.81M) for the P2G trading (Case 1 vs. Case 2) and 26.38% (US$ 143.22M) for the P2P trading (Case 3 vs. Case 4). The present value of initial cost and O&M cost of HV-integrated systems with P2P trading (Case 3) is increased by 19.80% and 23.83% compared with that with only P2G trading (Case 1), since more electrolyzers need to be installed in the community with higher charging power. The present value of electricity export gain (including grid export gain and peer selling gain) with P2P trading is higher by 51.42% than that without P2P trading. So the lifetime NPV of HV-integrated systems with P2P trading (Case 3) is higher than that with only P2G trading (Case 1) by 14.55% for US$ 87.16M. In terms of BV-integrated systems, the present value of investment cost with P2P trading (Case 4) is the same with that with only P2G trading (Case 2). While, the present value of net electricity bill of BV-integrated systems with P2P trading is 27.96% lower than that with P2G trading. So the lifetime NPV of BV-integrated systems with P2P trading (Case 4) is lower than that with only P2G trading (Case 2) by 3.25% for US$ 18.25M.

3.2. Multi-objective optimizations on the net-zero energy community integrated with both hydrogen vehicles and battery vehicles

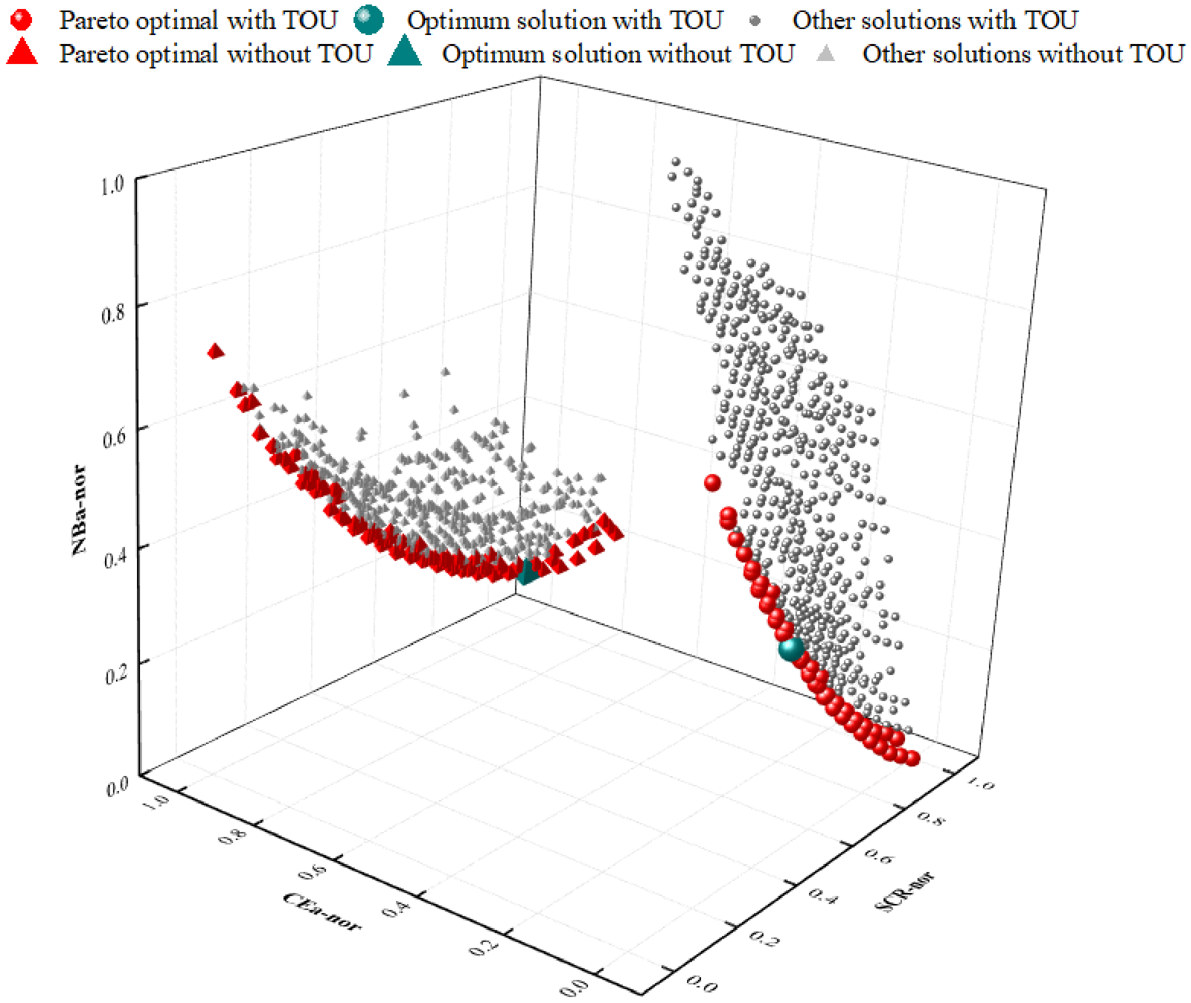


Fig. 16 Pareto optimal and final optimum results of hybrid PV-wind-HV-BV systems under TOU and non-TOU management strategies

The three-dimensional Pareto optimal and final optimum results of the multi-objective optimization on hybrid PV-wind-HV-BV systems are shown in Fig. 16, optimizing three groups of vehicle numbers and TOU management selection signals, considering the on-site renewable energy utilization, annual electricity bill and carbon emissions. Two obvious Pareto optimal surfaces are observed for TOU and non-TOU management approaches, with a clear trade-off conflict among the focused technical, economic, and environmental criteria in normalized values. Namely, both TOU management and non-TOU management strategies can be selected in the hybrid renewable energy systems with different vehicle numbers for a comprehensive techno-economic-environmental optimization in the net-zero energy community. The final optimum solutions of TOU and non-TOU management approaches as highlighted in the cyan ball and tetrahedron are obtained using the decision-making strategy of the minimum distance to the utopia point method [50].

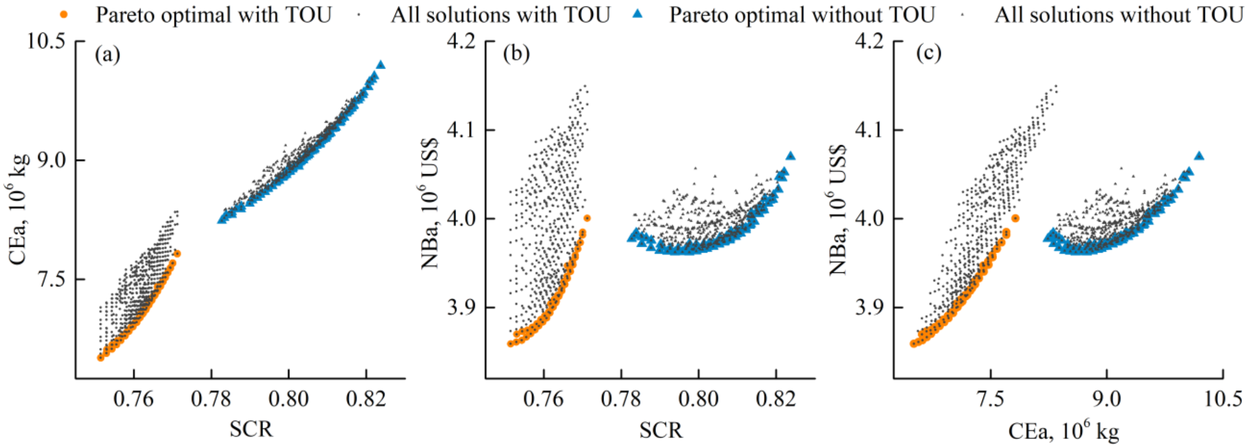


Fig. 17 Projection distribution of Pareto optimal and final optimum results

The two-dimensional projections of Pareto optimal solutions under TOU and non-TOU managements are shown in Fig. 17 for a clear demonstration. It is indicated that the Pareto optimal solutions with TOU management achieve lower SCR than that without TOU management, as per Fig. 17(a) and (b), since the on-site utilization of renewable energy is limited by the time-of-use power management to increase grid export and reduce grid import during on-peak periods, and to increase grid import and reduce grid export during off-peak periods. While most Pareto optimal solutions of TOU management obtain lower carbon emissions and lower annual electricity bill compared with that of non-TOU management as per Fig. 17(c), as the net grid imported energy is reduced with TOU management. Therefore, TOU management should be adopted when solely focusing on the economic and environmental performances (*CEa-NBa*) of the hybrid PV-wind-HV-BV systems applied in the net-zero energy community. While, both TOU and non-TOU management approaches can achieve balanced results when considering the techno-economic (*SCR-CEa*) or techno-environmental (*SCR-NBa*) performances, with appropriate vehicle numbers in diversified building groups.

The distribution of sizing vehicle numbers of three building groups in the net-zero energy community of Pareto optimal and final optimum solutions under TOU and non-TOU managements is shown in Fig. 18, with the two-dimensional projections as shown in Fig. 19. The results indicate that the Pareto optimal solutions of TOU management are obtained with a relatively low BV number in group 2, as per Fig. 19(a) and (c), since BVs in group 2 (commercial office buildings) are assumed to be parked in buildings only during on-peak periods, and only parked BVs have charging or discharging availability. And less vehicles in group 2 with lower charging availability has relatively lower impact on decreasing renewable energy *SCR* under TOU management, so a relatively superior performance can be achieved in decreasing *CEa* and *NBa*. It is also found that most of optimal solutions of non-TOU management are obtained with large vehicle numbers with higher charging availability for a higher *SCR*. The final optimum solution under TOU management obtained from the minimum distance to the utopia point method is achieved with the vehicle numbers of three groups for 200, 150, 700, respectively. And the final optimum solution under non-TOU management is achieved with 150 HVs in group 1, with 350 BVs in group 2 and 400 BVs in group 3. It can be found that TOU management should be adopted when the number of integrated BVs in building group 2 is relatively small, for achieving a comprehensive optimal results in technical, economic and environmental performances (*SCR-CEa-NBa*). While TOU management is not preferred when the BV number in building group 2 is relative large.

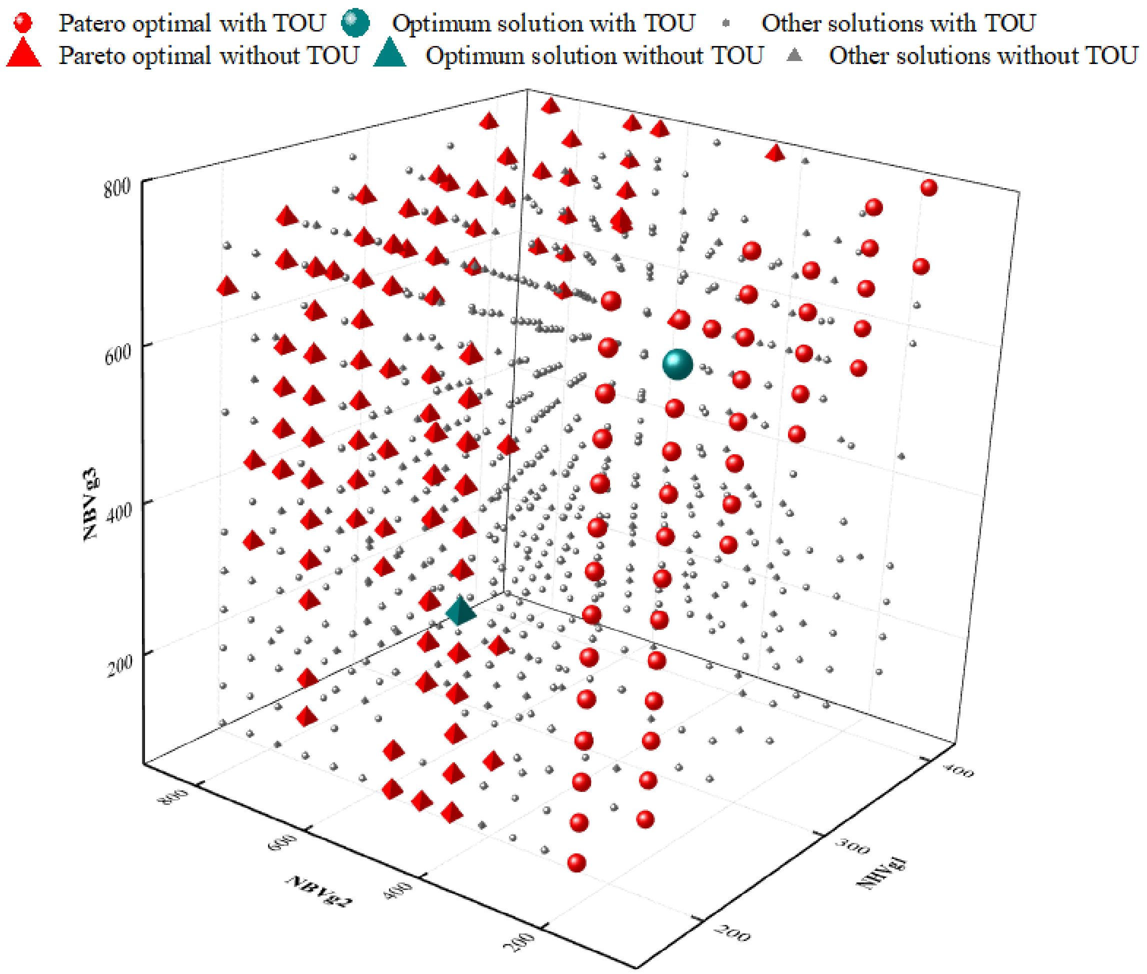


Fig. 18 Distribution of sizing vehicle numbers of Pareto optimal and final optimum solutions under TOU and non-TOU management strategies

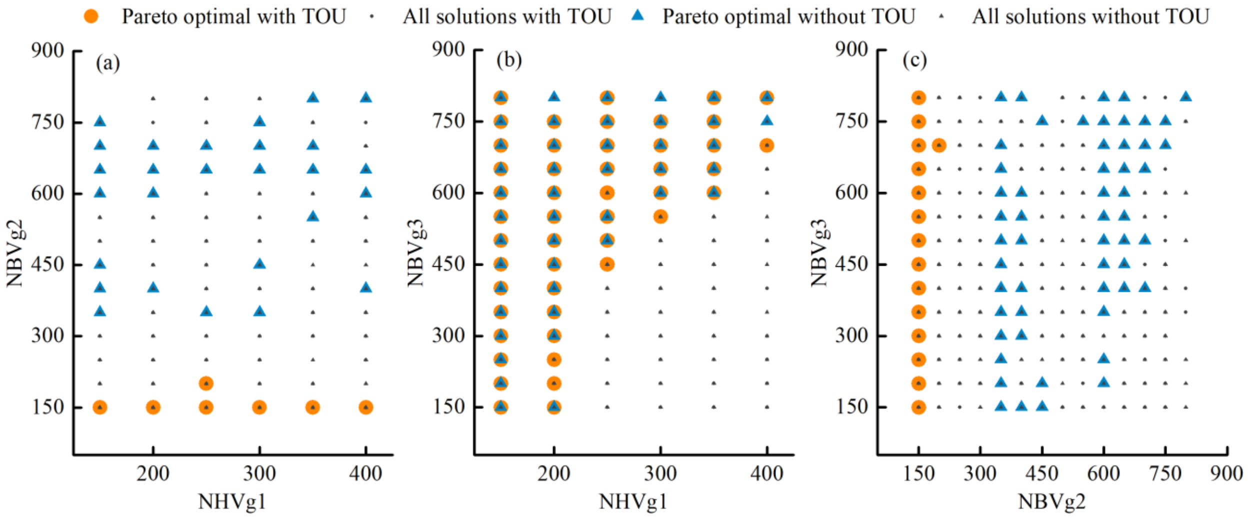
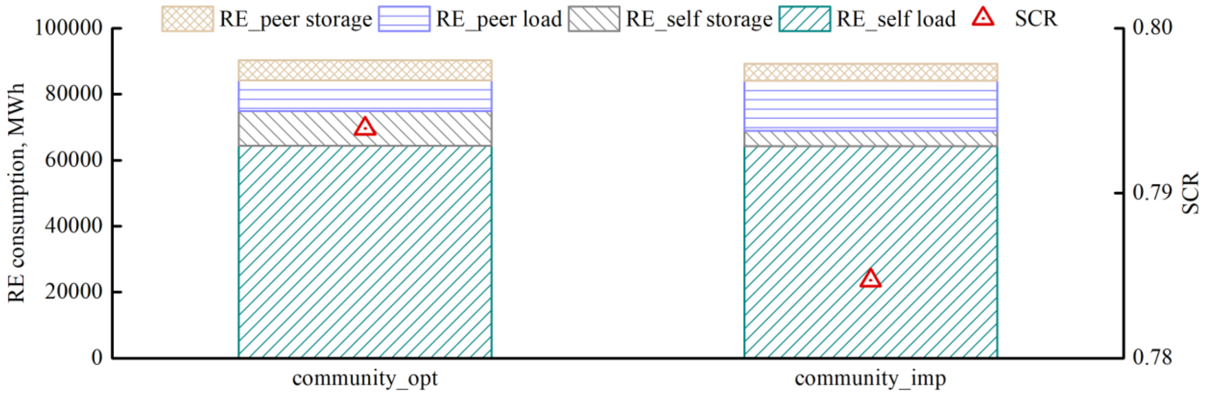


Fig. 19 Projection distribution of sizing vehicle numbers under TOU and non-TOU strategies

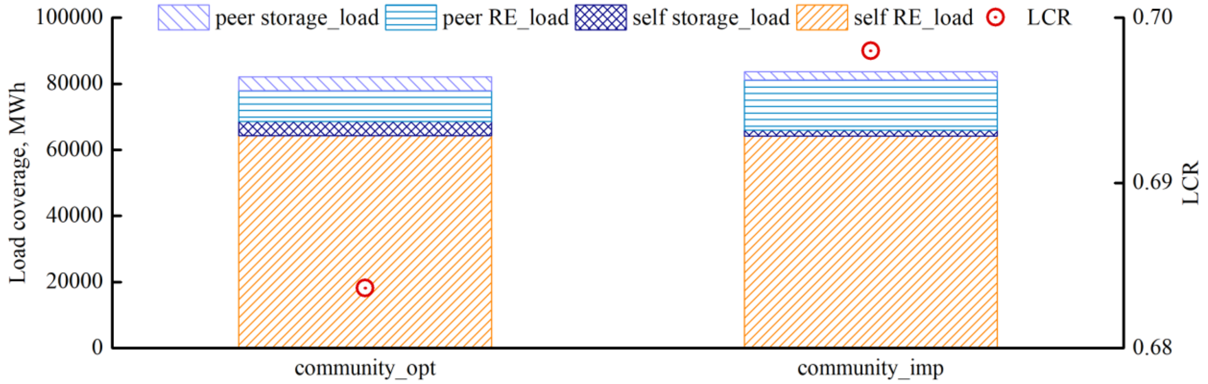
3.3. Improved peer-to-peer energy trading management of the net-zero energy community integrated with both hydrogen vehicles and battery vehicles

In this section, an improved P2P trading management strategy is proposed, and the techno-economic-environmental superiority is demonstrated through the comparative analysis with the multi-objective optimum case. The underlying mechanism and working principles of the improved P2P trading management strategy are specifically described in Section 2.3.

(1) Power flow of optimum and improved cases



(a) Renewable energy consumption



(b) On-site load coverage

Fig. 20 Renewable energy consumption and load coverage of optimum and improved cases

(note: the ‘opt’ and ‘imp’ are abbreviations of the optimum case and the improved case)

The annual energy flow of the hybrid PV-wind-HV-BV system for power supply to the net-zero energy community for the optimum and improved cases is firstly analyzed to compare the on-site renewable energy consumption and load coverage. It is indicated that the more renewable energy is consumed for meeting the peer load in the net-zero energy community for the improved case, 61.43% higher than the optimum case as per Fig. 20(a). While less on-site renewable energy is available for the self-storage and peer storage, lower by 55.42% and 14.10% respectively. The main reason is that the on-site renewable energy is utilized for peer load prior to storage vehicles in the improved case, while a reversed priority is adopted in the optimum case as explained in Section 2.3. The SCR of renewable energy for the improved case is slightly lower than the optimum case by 0.92% in the net-zero energy community, changing from 79.39% to 78.47%. Regarding the on-site load coverage of the net-zero energy, a 1.44% improvement in the LCR is observed for the improved case compared with the optimum case as per Fig. 20(b). The peer trading energy is improved by 31.19% on top of the optimum case, and less demand is required from storage vehicles. Meanwhile, the utilization efficiency of the hybrid vehicle storage is reduced from 68.27% in the optimum case to 58.23% in the improved case with less charging availability.

(2) Improvement in grid integration and decarbonisation benefits

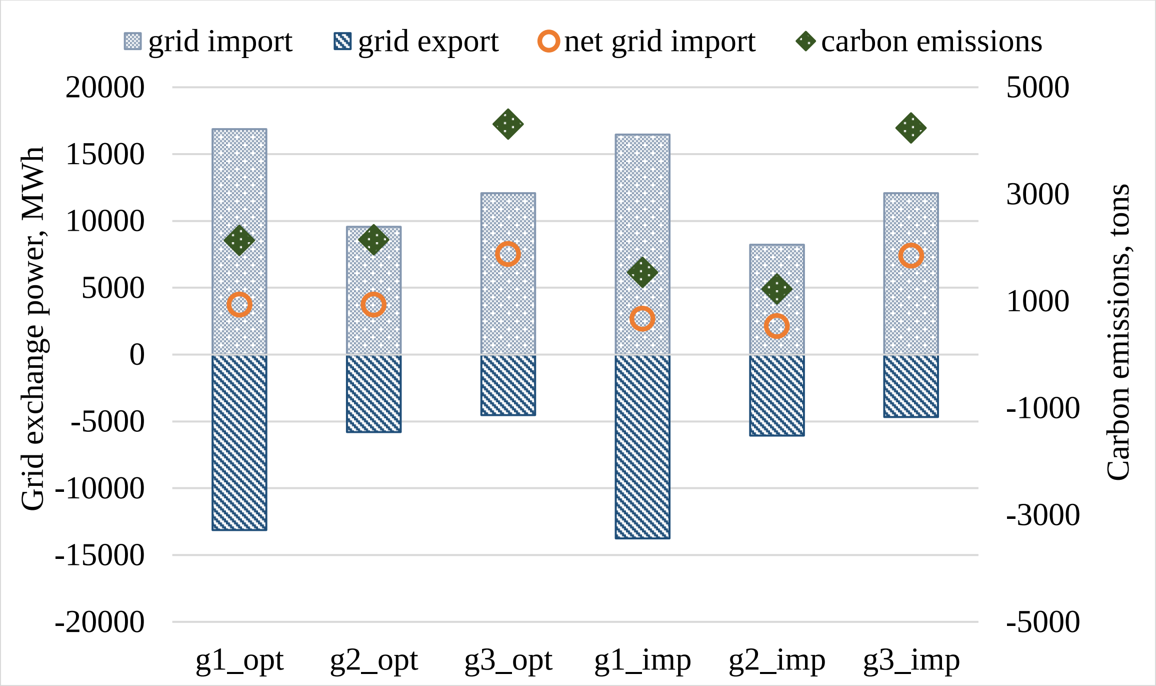
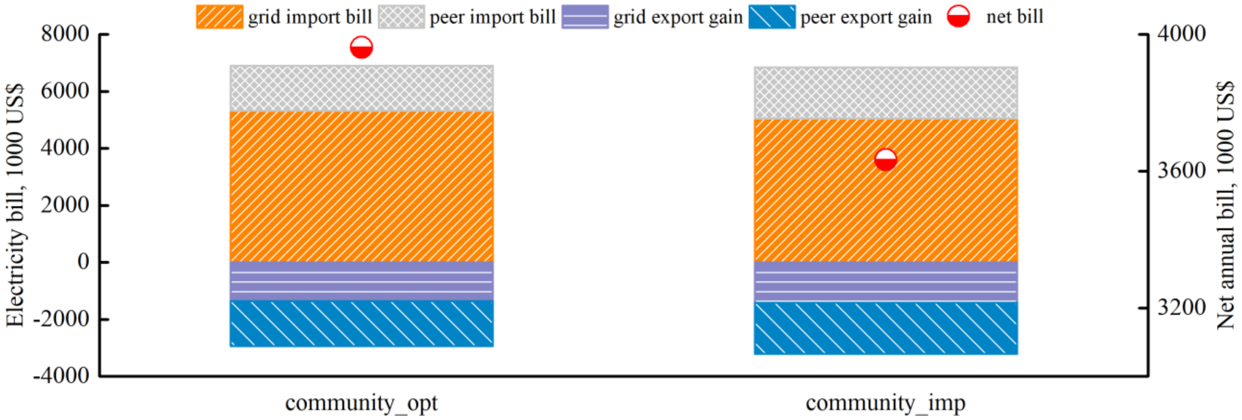


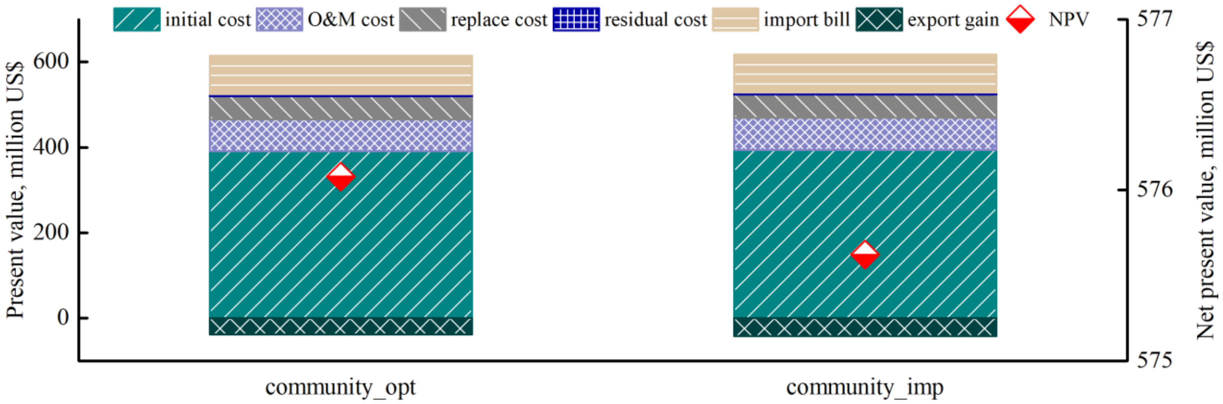
Fig. 21 Annual grid power exchange and carbon emissions of the optimum and improved cases (note: the ‘opt’ and ‘imp’ are abbreviations of the optimum case and the improved case)

The grid integration and decarbonisation performances of the hybrid PV-wind-HV-BV system can be significantly improved by prioritizing energy trading to peer load before energy consumption to self-storage, compared with the optimum case with a reversed energy flow as shown in Fig. 21. The results show that the grid export of three building groups in the net-zero energy community all increases for the improved case with a rising range of 2.93% - 4.88%, compared with the optimum case. And an overall reduction in the community grid import of about 4.53% (1741.36 MWh) and an overall increment in the community grid export of about 4.46% (1045.58 MWh) are observed for the improved case. The net power import from the utility grid of the net-zero energy community is therefore markedly reduced in the improved case by around 18.54% of 2786.94 MWh. Meanwhile, obvious decarbonisation benefits are achieved by adopting the improved P2P trading management strategy in the net-zero energy community, with the annual equivalent carbon emissions reduced by 18.54% for 1594.13 tons.

(3) Improvement in annual electricity bill and lifetime NPV



(a) Annaul electricity bill



(b) Lifetime net present value

Fig. 22 Annual electricity bill and lifetime NPV of the optimum and improved cases

(note: the ‘opt’ and ‘imp’ are abbreviations of the optimum case and the improved case)

In addition to achieving improvements in technical and environmental aspects of the hybrid PV-wind-HV-BV system, the economic improvement is also observed in the proposed improved case on top of the optimum case as per Fig. 22. As shown in Fig. 22(a), it is indicated that the annual electricity bill of grid imported energy is reduced in the improved case by US$ 268.45k, while the annual electricity bill of peer imported energy is increased by US$ 217.08k. Because less energy is imported from the utility grid and more energy is imported from the community peers, and the peer trading cost is more favorable than the grid trading cost in the individual peer trading price mode. And both the grid export gain and peer export gain are increased in the improved case by US$ 60.64k and 217.08k, respectively. A total reduction in the net annual electricity bill of about US$ 329.09k is achieved, lower by 8.31% compared with the optimum case. Moreover, the lifetime NPV of the hybrid PV-wind-HV-BV system with the improved P2P energy trading management strategy is also cut down as shown in Fig. 22(b). The system investment cost is slightly higher in the improved case by US$ 3.82M as more electrolyzers are needed, while the system electricity bill is lower by US$ 4.28M. So the system lifetime NPV of the improved case is lower than that of the optimum case by US$ 458.69k, mainly contributed by the reduced electricity bills.

3.4. Results comparison with the existing literature

The research results show that the P2P energy trading in the net-zero energy community improves the on-site renewable energy consumption for both the HV-integrated system by 16.54% and the BV-integrated system by 12.82% compared with the corresponding P2G energy trading, as more renewable energy can be shared for peer load and storage. And obvious enhancements on the on-site load coverage are also observed by introducing P2P trading, higher by 10.10% for the HV-integrated system and 11.91% for the BV-integrated system, since part of the building load can be covered by surplus energy of peer renewable generation and storage for the P2P trading management. And the P2P trading also reduces the annual electricity bill of the diversified community, lower by 15.37% (US$ 825.34k) for the HV-integrated system and 27.96% (US$ 1402.50k) for the BV-integrated system. The main reason is that less electricity is needed from the utility grid with a higher cost than the peer trading energy. Similar improvements are also reported by Chao et al. [51] by studying the P2P energy sharing in a 100-home community with PV and private battery storage in the U.K., with increases on the PV self-consumption by 10 - 30% and self-sufficiency by about 20%, as well as a reduction of energy cost in the community by 30%.

In terms of comparing the grid integration performance of the HV-integrated system and BV-integrated system applied in the net-zero energy community, this study indicates that the BV-integrated system achieves much less net grid import than the HV-integrated system by 56.60% for the P2G trading and 67.05% for the P2P trading. This is mainly because more renewable energy generation is exported into the utility grid in the BV-integrated system with less storage charging availability. And the utilization efficiency of the BV storage system (90.06% - 93.55%) is much higher than the HV storage system (40.81% - 42.42%), considering both energy storage and transportation functions. It agrees well with a previous study showing that the BV-integrated system is easier to achieve the annual net-zero energy balance than the HV-integrated system applied in a zero-energy building in Finland, as the utilization efficiency of the BV system (0.88 - 0.90) is much higher than that of the HV system (0.45 - 0.65) [16].

Additionally, this study also found that the BV-integrated system with lower net grid import achieves better decarbonisation benefits than the HV-integrated system applied in the net-zero energy community, reduced by 6229.02 tons for the P2G trading and 9803.21 tons for the P2P trading. A similar finding was also demonstrated indicating that BVs reduce carbon emissions more than HVs for integration with renewable energy and battery storage systems applied in a home building [21].

3.5. Research implications, limitations and future work

This study proposes novel P2P energy trading management and optimization approaches for a diversified net-zero energy community integrated with energy storage of hydrogen and battery vehicles, to provide references for policy makers to achieve carbon neutrality in the integrated transport and building sectors within urban contexts. Detailed research implications regarding the social, economic and environmental aspects are presented as below:

(1) It is promising to integrate green vehicle storage with renewable energy systems for applications in net-zero energy communities. The HV-integrated systems achieve higher self-consumption and load coverage with higher charging availability, while the BV-integrated systems perform better in the grid integration, decarbonisation, electricity bill and lifetime NPV with a higher utilization efficiency. Further improvements can be expected for integrating green vehicles with the building sector, with the advancing commercialized technologies and motivating carbon-neutral policies.

(2) The P2P energy trading can be adopted in large-scale diversified net-zero energy communities powered by hybrid renewable energy systems integrated with HV storage or BV storage, for increasing renewable energy self-consumption and on-site load coverage as well as reducing the electricity bill compared with P2G energy trading.

(3) Suggestions on applying renewable energy systems integrated with HV and BV storage are provided for power supply to the diversified net-zero energy community, based on the multi-objective peer trading optimizations. The TOU peer trading management should be adopted when the BV number in commercial office buildings is relatively small, and the strategy without TOU management is preferred when the green vehicle numbers in diversified building groups are relatively large. And the TOU peer trading management is recommended when focusing on the system economic and environmental performances, while both management approaches can achieve balanced results when considering the techno-economic or techno-environmental performances.

(4) The developed improved peer trading management strategy considering the optimal peer trading priority and complementary operations of hybrid vehicle storage can effectively guide the P2P energy trading for improving the grid integration, decarbonisation and economy of net-zero energy communities in urban areas.

However, there are limitations in the present study, for example, these research findings on the P2P trading management and optimizations are concluded based on the case study of a typical diversified net-zero energy community with university campus, commercial offices and high-rise residences in Hong Kong based on actual energy use data and simulations. The detailed research findings may be different for applications in other sites with different weather conditions, renewable energy and storage configurations, and grid electricity tariffs. While, the proposed novel P2P trading optimization frameworks and improved P2P trading management strategy are still applicable for developing net-zero energy communities in various sites. Moreover, the fixed vehicle cruise schedules are utilized for the vehicle groups integrated with the community, without considering the real stochastic operations. Future work on the P2P trading management and optimizations will be conducted considering numbers of diversified building groups and practical green vehicle schedules to guide the acceleration of carbon neutrality in the integrated transport and building sectors in cities.

4. Conclusions

This paper presents the newly developed peer-to-peer energy trading management and optimization approaches of hybrid renewable energy systems for power supply to a typical diversified net-zero energy community integrated with hydrogen vehicles and battery vehicles based on actual energy use data and simulations. Firstly, four net-zero energy community cases are developed and compared with different vehicle types and peer trading management approaches, to explore the techno-economic-environmental performance superiority of hydrogen vehicle-integrated and battery vehicle-integrated renewable energy systems under peer-to-grid trading and peer-to-peer trading managements. Secondly, multi-objective peer-to-peer trading optimizations of renewable energy systems with hybrid energy storage of hydrogen vehicles and battery vehicles are developed, to find optimal configurations of vehicle numbers in diversified building groups and time-of-use management operations, for a comprehensive optimization considering the system supply, electricity cost and decarbonisation benefits. Furthermore, an improved peer-to-peer trading management strategy is proposed on top of the optimum solution obtained by the multi-objective optimizations, to further enhance the system grid integration, decarbonisation and economy, via improving the peer trading priority and making complementary operations on the hybrid vehicle storage. Important conclusions of the present study are drawn as follows:

(1) The hydrogen vehicle-integrated hybrid renewable energy systems achieve superior performances on the renewable energy self-consumption (higher by 16.82%) and on-site load coverage (higher by 1.64%), compared with the battery vehicle-integrated systems under the peer-to-peer trading management. While the battery vehicle-integrated systems perform better in terms of the grid integration (67.05% less net grid import), decarbonisation benefits (9803.21 tons CO_2 reduced), net annual electricity bill (lower by 20.50%) and lifetime net present value (lower by 26.38%). And the utilization efficiency of the battery vehicle-integrated system (90.06% - 93.55%) is much higher than the hydrogen vehicle-integrated system (40.81% - 42.42%) considering both energy storage and transportation functions.

(2) The peer-to-peer energy trading management improves the technical performances and electricity bill of the diversified net-zero energy community in terms of the renewable energy self-consumption (higher by 16.54%), load coverage (higher by 10.10%) and annual electricity bill (lower by 15.37%) for the hydrogen vehicle-integrated systems compared with the peer-to-grid

trading. But carbon emissions of the net-zero energy community are increased by 32.85% (3615.37 tons), as more renewable energy is utilized for peer load and storage rather than being exported into the utility grid.

(3) The multi-objective peer trading optimizations indicate an optimal interactive relationship between the time-of-use management selection and equipped vehicle numbers in the net-zero energy community with hybrid renewable energy systems integrated with both hydrogen vehicles and battery vehicles. For the techno-economic-environmental optimization in the typical net-zero energy community, the time-of-use management strategy should be adopted when the battery vehicle number in commercial office buildings is relatively small, and the strategy without time-of-use management is preferred when the green vehicles numbers in diversified building groups are relatively large. And the time-of-use management strategy should be adopted when focusing on the system economic and environmental performances, while both management approaches can achieve balanced results when considering the techno-economic or techno-environmental performances, with appropriate vehicle numbers in diversified building groups.

(4) Obvious improvements can be achieved by the proposed improved peer-to-peer energy trading management strategy of renewable energy and hybrid vehicle storgae systems applied in the diversified net-zero energy community, including the grid integration (18.54% less net grid import), decarbonisation benefits (1594.13 tons less carbon emissions), net electricity bill (lower by 8.31%) and lifetime net present value (reduced by US$ 458.69k) on top of the optimum solution.

(5) The present study develops peer energy trading approaches for a diversified community, via comparing four typical net-zero energy cases with different storage vehicles and peer trading managements, developing multi-objective peer trading optimizations, and proposing an improved peer trading management strategy. The techno-economic-environmental superiority of hydrogen vehicle-integrated and battery vehicle-integrated renewable energy systems is distinguished, and the optimal interactive relationship between the vehicle numbers and system management strategies is demonstrated. The comprehensive results provide significant guidance for stakeholders to install and manage renewable energy and green vehicle systems for net-zero energy communities towards carbon neutrality in integrated building and transport sectors in urban areas.

Nomenclatures

Acronyms

BV	battery vehicle
CEa	annual equivalent carbon emissions
DR	demand ratio
FSOC	fractional state of charge
HV	hydrogen vehicle
LCR	load cover ratio
NBa	annual net electricity bill
NPV	net present value
NSGA-II	Non-dominated Sorting Genetic Algorithm II
PEMFC	proton exchange membrane fuel cell
PRV	present value
PV	photovoltaic
P2G	peer-to-grid
P2P	peer-to-peer
SCR	self-consumption ratio
SR	surplus ratio
TOU	time-of-use
WT	wind turbine

List of symbols

$E_{BV\ store}$	energy change of battery vehicle storage, kWh
$E_{BV\ to\ load}$	energy from battery vehicles to electrical load, kWh
$E_{BV\ to\ road}$	energy consumption of battery vehicles for daily cruises, kWh
$E_{compressor}$	energy required for hydrogen compression, kWh
$E_{grid\ export}$	exported energy from renewable sources to the grid, kWh
$E_{grid\ import}$	imported energy from the grid, kWh

$E_{grid\ to\ BV}$	energy from the grid to battery vehicles, kWh
$E_{grid\ to\ HV}$	energy from the grid to hydrogen vehicles, kWh
$E_{HV\ recovery}$	recovery energy from hydrogen vehicle systems, kWh
$E_{HV\ to\ load}$	energy from hydrogen vehicle systems to electrical load, kWh
$E_{HV\ to\ road}$	energy consumption of hydrogen vehicles for daily cruises, kWh
$E_{H2\ tank}$	energy change in hydrogen storage tanks, kWh
E_{load}	total electrical load, kWh
$E_{peer\ export}$	exported energy from peers, kWh
$E_{peer\ import}$	imported energy from peers, kWh
E_{RE}	total renewable energy generation, kWh
$E_{RE\ to\ BV}$	energy from renewable sources to charge battery vehicles, kWh
$E_{RE\ to\ load}$	energy from renewable sources to meet electrical load, kWh
Prbuy	peer energy buying price, US$/kWh
Prsell	peer energy selling price, US$/kWh
Rbuy	electricity rate of energy imported from the grid, US$/kWh
Rsell	electricity rate of renewable energy exported to the grid, US$/kWh

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