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Peer-to-peer energy trading of net-zero energy communities with renewable energy systems integrating hydrogen vehicle storage

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Abstract

This study presents peer energy trading management approaches in a net-zero energy community with fundamental units of university campus, commercial office and high-rise residential building groups as per actual energy consumption and simulation data. Hybrid solar photovoltaic and wind turbine systems are developed for power supply to the diversified community integrated with three hydrogen vehicle storage groups based on the TRNSYS platform. An individual peer energy trading price model is proposed for the diversified community to allocate an individual peer trading price to each building group according to its intrinsic energy characteristic and grid import price. The time-of-use peer trading management strategies are further developed for both uniform and individual energy trading price modes to improve the grid flexibility and economy. The study results indicate that the peer energy trading management in the individual trading price mode improves the renewable energy self-consumption ratio by 18.76% and load cover ratio by 11.23% for the net-zero energy community compared with the peer-to-grid trading. The time-of-use trading management in the individual trading price mode can reduce the net grid import energy by 8.93%, grid penalty cost by 142.87%, annual electricity cost by 14.54%, and equivalent carbon emissions by 8.93% (982.36 tCO_2), respectively. This comprehensive feasibility study on the typical community with the proposed peer trading price model and management strategies provides significant guidance for renewable energy and hydrogen storage applications in large-scale communities within high-density urban contexts.

Keywords: solar photovoltaic; wind turbine; hydrogen vehicle storage; net-zero energy community; peer-to-peer energy trading

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1. Introduction

1.1. Background

The global energy-related CO_2 emissions grew 1.7% in 2018 to a record high due to the increasing fossil fuel consumption, and nearly two-thirds of the growth is attributed to the power sector [1]. The world is still not on track to limit global warming to well below 2ºC stipulated by the Paris agreement, although the CO_2 emissions remained relatively stable in 2019 [2]. A compound reduction rate of 3.8%/year in CO_2 emissions is anticipated to keep the expected temperature rise well below 2ºC by 2050. Over half of the necessary CO_2 emission reductions are expected from renewable energy, predicting to share up to 86% of total electricity generation by 2050 [3].

The accelerating renewable energy development [4] and advanced energy storage technology [5] are important contributors to promote renewable applications in the future energy framework [6]. It is anticipated that the total solar photovoltaic (PV) capacity would rise over thirteen-fold in 2050 to 8519 GW based on 2019 [7]. Dramatic decline in the installed cost of solar PV is observed of about 74% between 2010 and 2018, expecting to be reduced to 165 - 481 US$/kW by 2050 [8]. The global wind power installations expanded 19% in 2019 [2], predicting to rise to 6044 GW by 2050 [9]. The onshore wind power is expected to drop to 650 - 1000 US$/kW by 2050, becoming the cheapest power generation sources [8]. The installed cost of offshore wind systems would also decrease greatly to be globally competitive with fossil fuels by 2030 [8]. Meanwhile, energy storage technology improves the dispatch flexibility [10] and utilization efficiency [11] of renewable energy generation. About 30 GWh of stationary storage and 200 GWh of mobile vehicle storage are installed globally, which would be expanded to over 9000 GWh and 14145 GWh respectively by 2050 [12]. Renewable hydrogen is experiencing unprecedented momentum as a clean energy carrier available for a variety of sectors such as transport, heating and industrial raw materials [13]. The compressed hydrogen storage is the most economic storage option at the discharge duration longer than 20 - 45 hours in terms of the costs of storage electricity [14]. It is estimated that about 160 Mt of renewable hydrogen could be produced annually by 2050 (only 1.2 Mt in 2018), and the production cost is expected to be decreased from 4.0 - 8.0 to 0.9 - 2.0 US$/kg [3]. Over 400M hydrogen cars, 15 - 20M hydrogen trucks and 5M hydrogen buses are anticipated by 2050 with short refueling time (3 - 5 minutes) and long cruise range (400 - 500 km) [15].

In order to promote the cleaner power production, mitigation on carbon emission and solution for energy shortage crisis, this study develops peer energy trading management approaches for a diversified net-zero energy community with hybrid renewable energy and hydrogen vehicle (HV) storage systems.

1.2. Literature review

The peer-to-peer (P2P) energy trading in communities with renewable energy sources has aroused increasing attention in recent years to accelerate distributed renewable energy developments, especially in regions with large-scale household PV and battery storage applications such as Australia, Germany, America and England. The energy trading pricing schemes, grid integration with P2P trading, and performance improvements by P2P trading are widely investigated by researchers on the P2P trading management in renewable energy communities.

Different energy trading pricing schemes of P2P energy trading in communities have been studied to balance trading benefits of major stakeholders. For example, a supply demand ratio based pricing scheme is proposed for P2P energy trading among neighboring PV prosumers in microgrids, based on the total supply demand distribution of the community. The results show that the PV prosumers can achieve effective cost saving compared with peer-to-grid (P2G) trading, and the on-site consumption of PV energy can be improved [16]. A proper compensation price is introduced to modify the supply demand ratio based pricing scheme to balance the P2P sharing economic benefits of prosumers and consumers in household communities. A case study in a community with 100 homes installed with PV and private battery storage in the UK shows that a 30% reduction of energy bills can be achieved, together with improvements on PV self-consumption by 10 - 30% and self-sufficiency by about 20% [17]. Additionally, a near-optimal energy cost optimization algorithm is proposed to determine the P2P energy trading price in household communities. The microgrid energy price is obtained with the Pareto optimality, which ensures a household cost participating in P2P trading not higher than that of no participation. The authors reported that the cost saving is not always in a linear increase with the renewable energy and storage penetration rate, where a saturation point is observed in a case study of a 40-home community with PV and private battery storage systems in Canada [18]. Experimental surveys are also adopted to study the impact of community electricity prices on the P2P trading preference of prosumers in a 301-homeowner community in Germany [19]. It should be noted that a same peer selling/buying price is allocated to all peers in the community for most of previously developed community P2P trading pricing schemes, and the grid import price should also be kept the same for all building peers.

Various methods have been developed by researchers to facilitate the grid integration in building communities with P2P energy trading. Specifically, an ancillary service provision mechanism is developed for a P2P energy trading community to achieve ancillary services for the utility grid, and its effectiveness is clarified by a case study of a 20-home community with PV and/or electric vehicle systems in the Great Britain [20]. A novel blockchain-based P2P trading framework is presented to achieve regional energy balance and carbon mitigation on distribution networks. The results show that the proposed P2P trading framework outperforms the aggregator-based trading and centralized trading, in terms of daily grid export and carbon emission reduction [21]. And a bi-level optimization model is also proposed to manage the peer and storage revenue for a 10-home community with rooftop PV and central battery storage units in Australia. It is shown that the grid pricing scheme is an important factor affecting the peer sharing revenue in the community [22]. It can be found that few studies consider the time-of-use P2P energy trading management based on grid penalty cost business models to maintain the power grid flexibility and economy.

Furthermore, the performances of P2P energy trading management in community applications have been widely assessed regarding the technical, economic and environmental aspects. For example, a three-layer P2P trading framework is proposed for a 36-home community with distributed PV systems, indicating that the PV self-consumption ratio can be improved with the P2P trading scheme [23]. The P2P energy transaction with real-time double auction market is investigated for a diversified community with 90 homes and 4 enterprises in China, to maintain the energy and economic effectiveness without sacrificing privacy preservation and robustness [24]. The total cost of a community with 68 homes installed with rooftop PV systems in Portugal is optimized by adopting the mixed integer liner programming model, and the research results shown that 28% and 55% of economic savings can be achieved for consumers and prosumers, respectively [25]. The similar optimization model is also adopted to study the P2P trading cost saving potential of a 500 households community with rooftop PV and private battery storage systems in Australia. The authors reported that a maximum of 28% cost saving can be obtained by households with large PV-battery installations on weekdays [26]. And a motivational psychology framework of P2P trading in communities installed with PV systems is proposed by game-theoretic methods. The authors reported that about 18.38% and 9.82% of daily carbon emissions in Summer and Winter can be reduced by the proposed energy trading model, compared with the feed-in-tariff scheme in a household community in Australia [27]. The multiclass energy management is proposed to study the peer energy trading of prosumers with heterogeneous preferences according to the energy sources including the green prosumer with/without a PV source and battery, philanthropic prosumer with a PV source and battery, and low-income household. The developed peer trading market platform manages the energy trading between prosumers and the utility grid to minimize the costs considering the losses and battery depreciation [28]. It can be identified that most of existing research on the P2P energy trading management focuses on home community applications with household solar PV and battery/electric vehicle units, without considering the P2P energy trading of communities with diversified building groups, hybrid renewable energy and HV storage systems, and different grid price schemes.

Based on the above literature review, research gaps on P2P energy trading in communities with renewable energy sources are observed that a same peer selling/buying price is allocated to all peers in the community for most of previously developed community P2P trading pricing schemes, and the grid import price needs to be kept the same for all building peers. So these peer trading pricing schemes are not suitable for studying P2P trading of diversified communities with building groups who want to set an individual peer selling/buying price, rather than co-determined by the community peers. Furthermore, few studies consider the time-of-use P2P energy trading management based on grid penalty cost business models to maintain the power grid flexibility and economy. And most of existing research on the P2P energy trading management focuses on home community applications with household solar PV and battery/electric vehicle units, without considering the P2P energy trading of communities with diversified building groups, hybrid renewable energy and HV storage systems, and different grid price schemes.

Therefore, an individual P2P energy trading pricing scheme needs to be developed for large-scale diversified communities to allocate the individual P2P trading price to each different building group, according to its intrinsic supply demand feature and grid import price. As the P2P energy trading in the net-zero energy communities may bring pressure to the utility grid with higher net grid imported energy compared to that with only P2G trading, the time-of-use P2P energy trading management considering grid penalty cost business models needs to be developed to maintain the power flexibility and economy of the utility grid. The techno-economic-environmental performance assessment of P2P energy sharing of net-zero energy communities with diversified building groups, and hybrid renewable energy and HV storage systems is worthy to be investigated, given the promising potential of renewable energy and HV technologies for achieving carbon neutrality. The lifetime economic analysis in the future cost scenario of renewable energy and HV storage systems for power supply to net-zero energy communities with P2P trading is also important to provide a clear economic reference for potential stakeholders to accelerate carbon neutrality of urban areas in the near future.

1.3. Scope and contribution

To fill the above research gaps, this study develops peer energy trading management approaches for a diversified net-zero energy community in urban areas consisting of campus, office and residential building groups according to actual energy consumption and simulation data. The hybrid solar photovoltaic and wind turbine systems integrated with three groups of hydrogen vehicle storage are installed for power supply to the net-zero energy community based on the TRNSYS platform. An individual peer energy trading price model is proposed to study the peer-to-peer energy trading management of the net-zero energy diversified community to allocate an individual peer selling/buying price to each building group. And the time-of-use P2P energy trading management strategies are also developed based on the time-of-use grid penalty cost model to improve the power flexibility and economy of the utility grid in large-scale community applications. The main contribution of this study is shown as below:

(1) This study proposes an individual peer energy trading price model for dynamic peer-to-peer energy management of net-zero energy communities with diversified building groups, hybrid renewable energy and hydrogen vehicle storage systems, and different grid price schemes. An individual peer selling/buying price is allocated to each building group according to its intrinsic supply demand feature and grid import price. The superiority and economic benefits of the proposed individual peer energy trading price model for diversified building communities are demonstrated in comparison with the uniform peer trading price model generally for home building communities.

(2) The time-of-use peer-to-peer energy trading management strategies for both uniform and individual peer trading price models are developed, based on the time-of-use grid penalty cost model, to improve the power flexibility and economy of the utility grid connecting with large-scale community within urban contexts.

(3) The developed peer energy trading management approaches are applied to a diversified net-zero energy community in a high-density urban city (Hong Kong) consisting of university campus, commercial office and high-rise residential building groups according to actual energy consumption and simulation data. The techno-economic-environmental performances of peer-to-peer energy trading management cases in the net-zero energy community are clarified compared with the baseline peer-to-grid case, involving the system supply, grid integration, electricity bill and carbon emissions. The lifetime net present value of hybrid renewable energy and hydrogen vehicle storage systems in the current cost and future cost scenarios is further discussed to provide economic references for relative stakeholders to develop net-zero energy communities in urban areas.

2. Methodology

This study develops a diversified net-zero energy community powered by hybrid renewable energy systems integrated with three groups of HV storage to study the P2P energy trading with the overall framework shown in Fig. 1. The net-zero energy community means the diversified community installed with renewable energy and storage systems, achieving a net-zero energy operation with annual balanced electrical demand and renewable energy generation. The utility grid is connected with the community allowing surplus renewable energy export and grid import for unmet electrical load, as there is time mismatch between the electrical demand and on-site renewable generation/storage supply. Fundamental units are integrated in the net-zero energy community including the university campus building group (the Hong Kong Polytechnic University - PolyU), commercial office building group (the International Commerce Center - ICC) and high-rise residential building group (public residences with standard layout - Resid). The load profiles of three building groups are obtained from actual annual energy consumption data and dynamic simulation data as per local surveys and codes. Hybrid renewable energy sources of solar PV and wind turbine systems with advantageous and complementary characteristics are developed for the net-zero energy community. 1000 HVs following different cruise schedules are allocated to three building groups serving as both the daily cruise and energy storage tools. An individual peer energy trading price model is proposed for the diversified community to allocate an individual peer selling/buying price for each building group, according to their intrinsic energy surplus-demand features and grid import prices. The uniform peer trading price model, with a same peer trading price for all peers developed for household communities, is also adapted for the net-zero energy community for comparison analysis. And time-of-use P2P trading management strategies based on the time-of-use grid penalty cost model are further developed for the two peer trading price modes to improve the power flexibility and economy of the utility grid in community applications.

Five peer trading cases with different energy trading management strategies are developed to study the P2G and P2P energy trading behavior of three building groups in the net-zero energy community. Case 1 serves as the baseline case where the building groups only trade energy with the utility grid rather than trade with their peers. Case 2 adopts P2P energy trading in the uniform price mode where the building groups trade surplus energy with their peers prior to the utility grid, and a uniform energy selling/buying price is utilized for P2P trading in the community depending on the dynamic total energy surplus and demand. Case 3 adopts P2P energy trading in the individual price mode where the building groups trade surplus energy with their peers prior to the utility grid, and an individual energy selling/buying price is set for each building group community depending on its own energy surplus and demand. Different P2P energy trading rules should be followed in the uniform and individual energy trading price models. Case 4 and Case 5 further consider time-of-use energy trading management on top of Case 2 and Case 3 based on the time-of-use grid penalty cost model to improve grid power flexibility and economy in large-scale net-zero energy community applications.

To assess the peer trading management in the net-zero energy community with hybrid renewable energy and HV storage systems, the energy sharing flow and energy trading cost saving of the net-zero energy community of typical P2P trading cases are analyzed. And the detailed techno-economic-environmental performances of the peer trading cases with different peer trading price modes and management strategies are compared, including renewable energy self-consumption and on-site load coverage, annual energy trading flow, time-of-use grid penalty cost, annual electricity cost and equivalent carbon emissions. Furthermore, the lifetime net present value (NPV) of hybrid renewable energy and HV storage systems under the current and future cost scenarios is evaluated to provide economic references to develop net-zero energy communities in the near future.

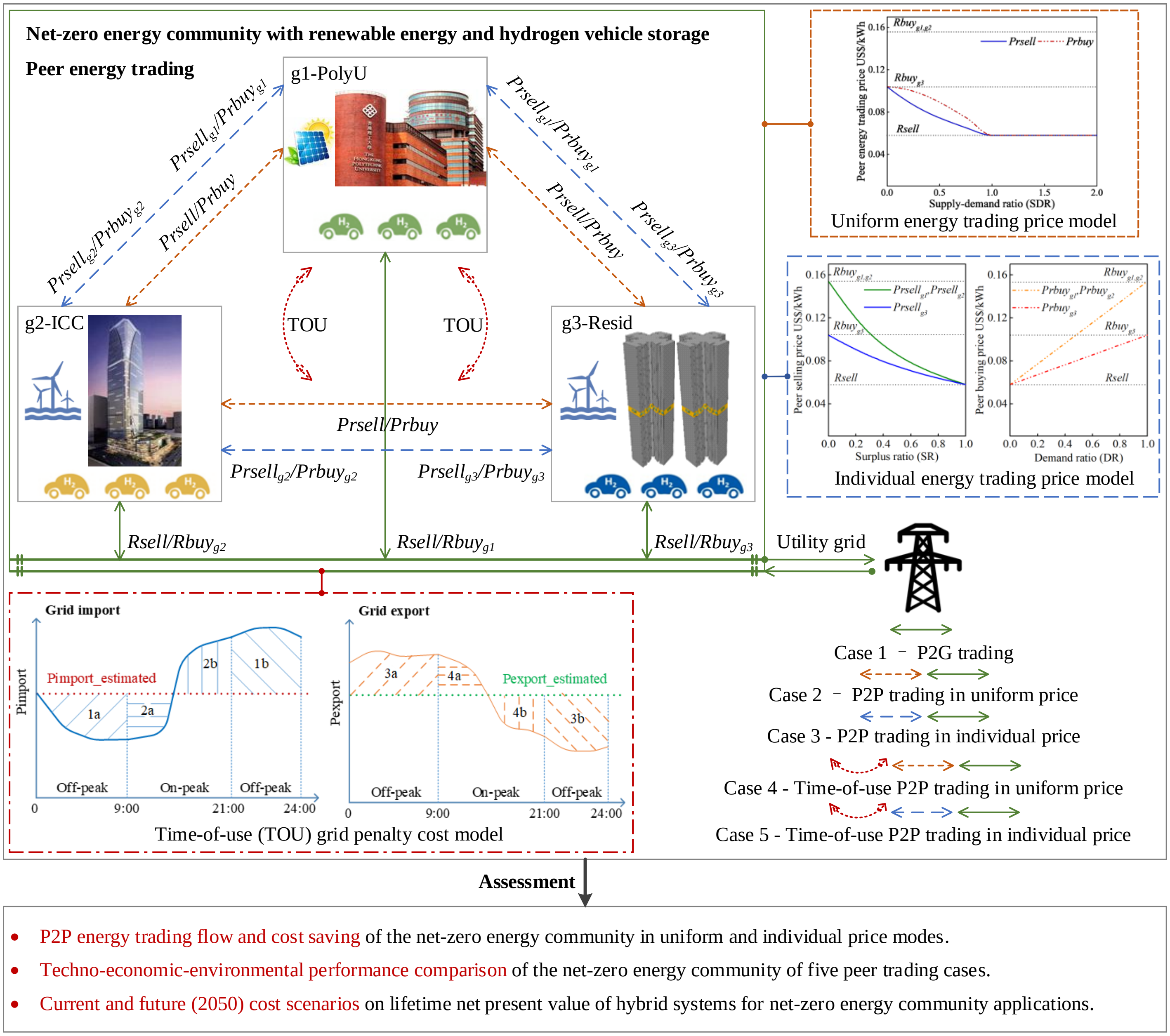


Fig. 1 Framework of peer energy trading of a net-zero energy community with hybrid renewable energy and HV storage systems

2.1. Net-zero energy community with hybrid renewable energy and hydrogen vehicle storage systems

(1) Electrical load of the net-zero energy community

A typical building community with the university campus building group, commercial office building group and high-rise residential building group is developed with hybrid renewable energy and HV storage systems. The electrical load of the campus building group is obtained from the on-site collected energy consumption data of the Phase I - Phase V of the Hong Kong Polytechnic University (PolyU) for about 149260 m^2 with an annual electrical load of 52740 MWh. The electrical load of the office building group is based on the practical collected data of commercial offices in the International Commerce Center (ICC) in Hong Kong for about 268800 m^2 with an annual electrical load of 39767 MWh. And the electrical load of the residential building group (Resid) is obtained from the dynamic simulation on ten high-rise public residential buildings with standard layouts in Hong Kong according to local building codes [29, 30] and on-site surveys [31]. The building area of the residential buildings is about 192095 m^2 with an annual electrical load of 27206 MWh. The monthly electrical load of three building groups is shown in Fig. 2, with a similar trend indicating higher electricity demand in summer with large cooling load.

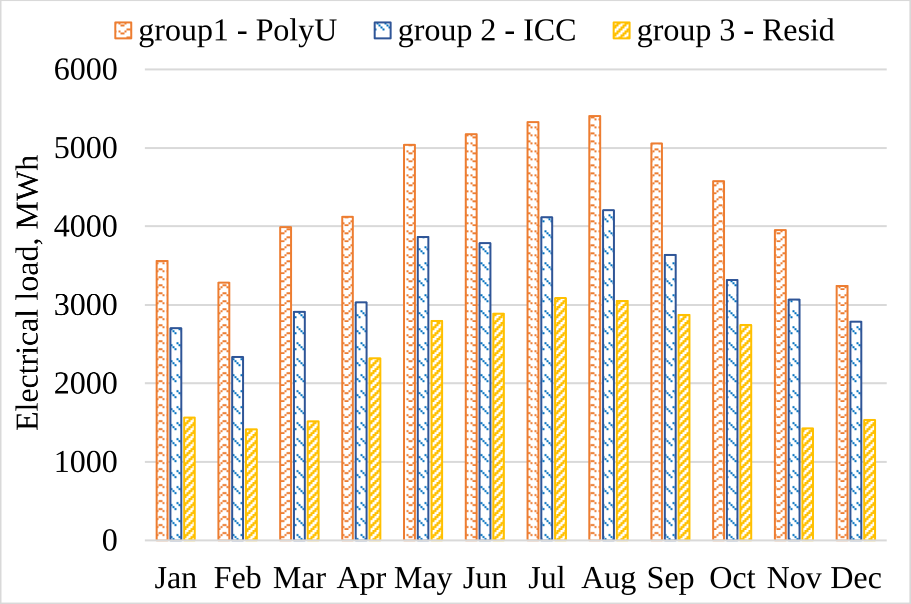


Fig. 2 Electrical load of three building groups in the net-zero energy community

(2) Hybrid renewable energy and hydrogen vehicle system

Hybrid renewable energy and HV systems are developed for power supply to the typical community for a net-zero energy operation with annual balanced electrical demand and renewable energy generation as shown in Fig. 3. The rooftop solar PV system of 41200 kW is installed for electricity supply to the campus building group with a titled angle of 22° employing maximum power point tracking devices. The TRNSYS Type 103 is adopted to predict the current-voltage characteristics of the PV module via an empirical equivalent circuit model. The offshore wind turbine systems of 13500 kW and 9200 kW are developed for electricity supply to the office and residential building groups given the advantageous costal conditions of the location [32]. Type 90 is used to simulate the power generation of wind energy conversion systems based on a power versus wind speed characteristic according to the datasheet of wind turbine manufacturers [33, 34].

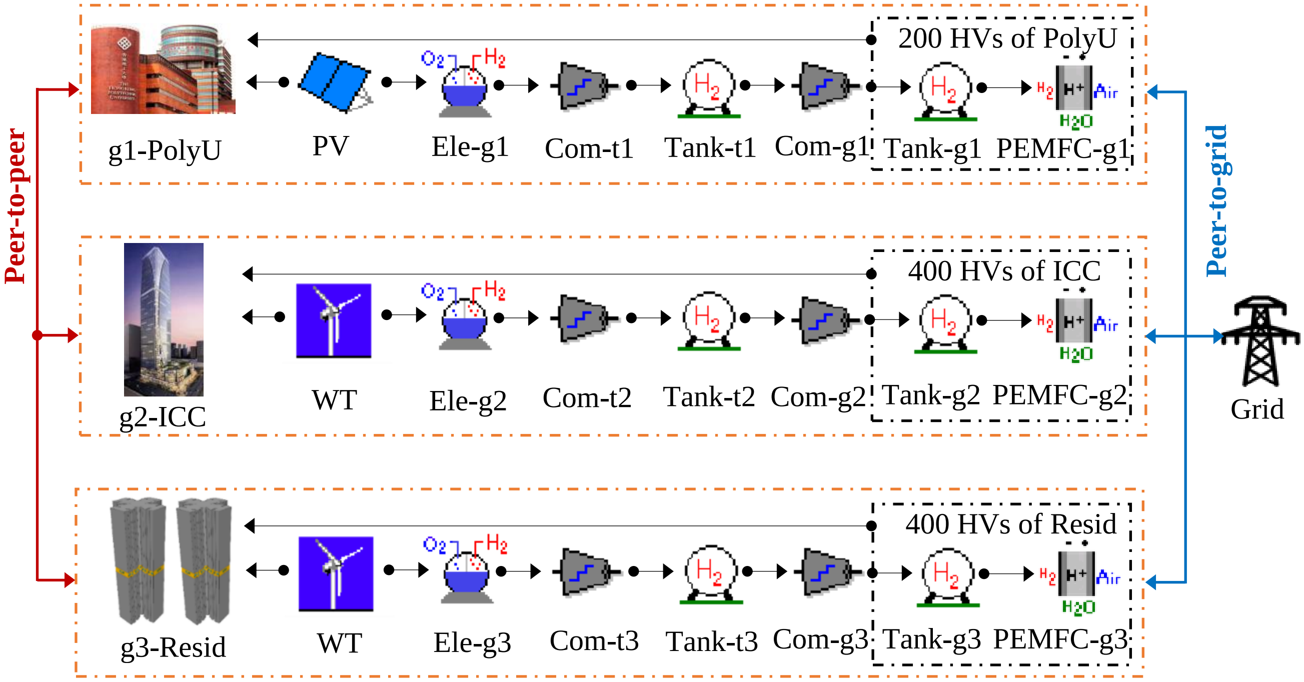


Fig. 3 Hybrid renewable energy and HV systems for the net-zero energy community

A hydrogen vehicle (HV) system is allocated to each building group in the community serving as both the energy storage unit and daily cruise tool. Specifically, the HV system can store surplus renewable energy by driving the advanced alkaline electrolyzers to generate hydrogen, which is then compressed and stored in hydrogen storage tanks based on the van der Waals equation of state for real gas. Meanwhile, the HV system can supply power for the load shortage of the community, by consuming the stored hydrogen in the proton exchange membrane fuel cells where converting the chemical energy of hydrogen and oxygen to electrical currents. Moreover, the HV system can meet the daily cruise requirement of building occupants, which integrates the building and transport sectors in the community with renewable energy supply. The integration of HV storage with renewable energy systems is different from that of battery vehicle storage. Battery vehicle 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.

200 HVs are equipped in the campus building group parking during 10:00 - 18:00 in weekdays, 400 HVs are equipped in the office building group parking during 9:00 - 17:00 in weekdays and 400 HVs are equipped in the residential building group during 19:00 - 8:00 from Monday to Saturday and all hours in Sunday. The daily cruise range of each HV is about 49.25 km based on the local traffic census [6]. The hydrogen consumption system is installed in the mobile vehicle modelled by a proton exchange membrane fuel cell (*PEMFC-g*) using Type 170d and a hydrogen storage tank (*Tank-g*) using Type 164b with a full hydrogen storage of 5 kg at 700 bars, which can support for 502 km cruise range based on a commercialized product “2019 Toyota Mirai” [35]. The hydrogen generation system is fixed in the building simulated by an alkaline electrolyzer (*Ele-g*) using Type 160a, primary compressor (*Com-t*) using Type 167 and stationary storage tank (*Tank-t*). And a secondary compressor (*Com-g*) is also equipped to delivery hydrogen from the stationary hydrogen storage tank to the mobile hydrogen storage tank. The generated heat during the HV system operation is recovered from the electrolyzers, compressors and fuel cells for domestic hot water application in the residential building group. The utility grid supplies power to the HV system when the charge state of the mobile hydrogen storage tank is not able to cover the next day’s cruise.

(3) Five energy trading cases in the net-zero energy community

Three building groups with different operational functions and renewable energy configurations in the net-zero energy community can not only exchange power with the utility grid, but also make P2P energy trading among the community. Five net-zero energy community cases with different energy trading price modes and energy trading management strategies are presented to demonstrate the feasibility and superiority of the proposed individual peer trading price model and the developed time-of-use peer trading management strategies. The reason of adopting five cases is that, there are two factors with two variables for each factor (four cases), i.e. peer trading price modes (uniform and individual) and time-of-use peer trading management strategy (with and without), and a baseline case is firstly presented with only P2G energy trading among the building groups serving as the comparison benchmark (Case 1). Two cases with P2P energy trading in the uniform and individual peer trading price modes respectively (Case 2 and Case 3) are then established to study the feasibility of P2P energy trading on top of the P2G energy trading and highlight the differences of various energy trading price schemes. And another two cases with time-of-use P2P energy trading in the uniform and individual peer trading price modes respectively (Case 4 and Case 5) are further developed to indicate the superiority of the proposed time-of-use peer trading management strategies on top of the baseline case and P2P energy trading cases without time-of-use management. The detailed comparison results of these five cases are shown in Section 3.2 regarding the detailed techno-economic-environmental aspects. Five cases with varied energy trading modes are developed as shown in Fig. 4.

(1) In Case 1 (baseline P2G case), three building groups make energy trading only with the utility grid and do not share energy with peers in the community as per Fig. 4(a).

(2) In Case 2 and Case 3, the P2P energy trading among the community is managed prior to the P2G energy trading as per Fig. 4(b). And a uniform price is adopted for the community P2P energy trading in Case 2, while an individual price is assigned to each building group in Case 3 according to the proposed individual peer trading price model in Section 2.2.

(3) Case 4 and Case 5 are further developed considering grid time-of-use operation in the P2P energy trading management to improve the power flexibility and economy of the utility grid as per Fig. 4(c). A uniform peer energy trading price mode is adopted in Case 4 and an individual peer energy trading price mode is adopted in Case 5.

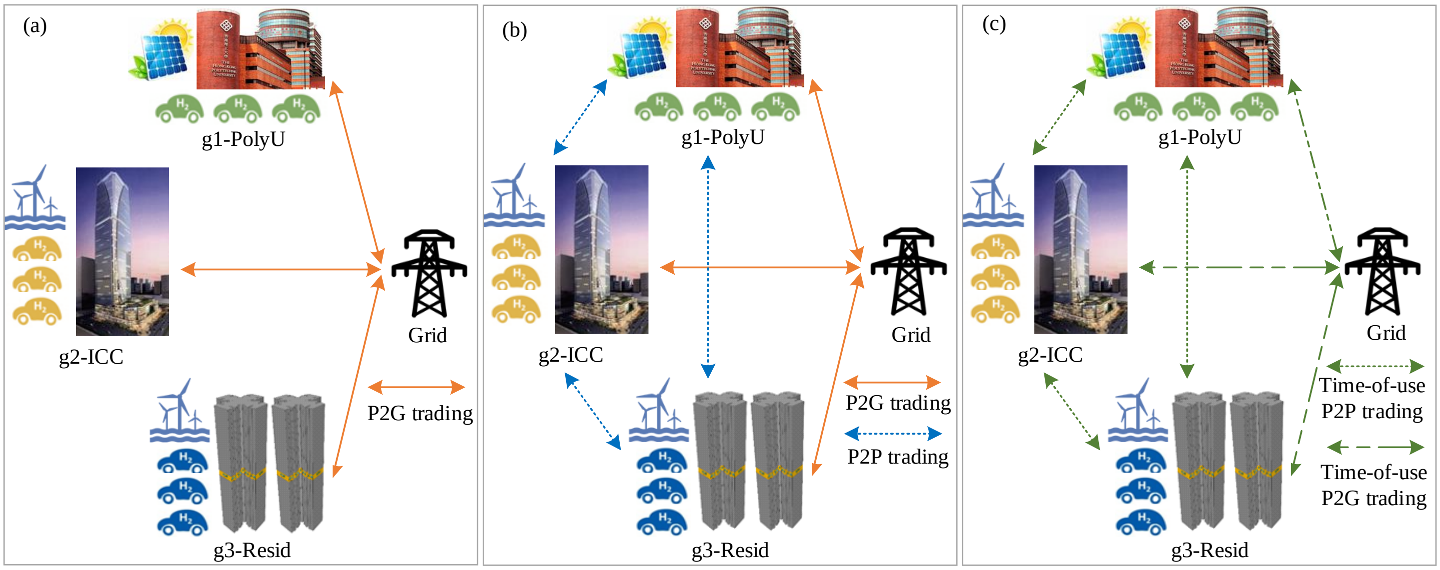


Fig. 4 Schematic of energy trading in the net-zero energy community of five cases

Note: (a) only P2G trading (Case 1); (b) P2P trading in uniform price mode (Case 2) and in individual price mode (Case 3); (c) time-of-use P2P trading in uniform price mode (Case 4) and in individual price mode (Case 5).

2.2. Uniform and individual peer energy trading price models in the net-zero energy community

(1) Uniform peer energy trading price model

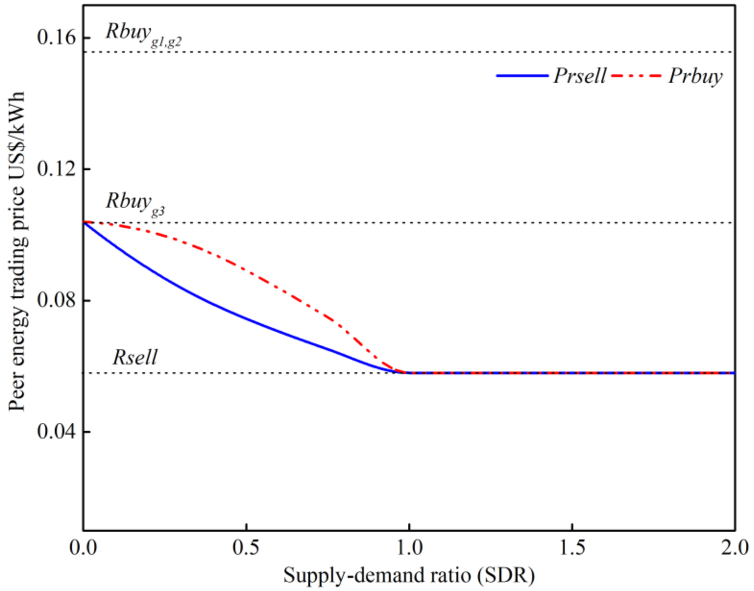


Fig. 5 Uniform peer energy trading price model in the net-zero energy community

The uniform peer energy trading price model in the net-zero energy community with three different functional building groups is developed based on the total supply-demand ratio (*SDR*) of the community assuming that the relationship between the price and *SDR* is inverse-proportional [16] as per Fig. 5.

The dynamic energy supply available for peer energy selling of the net-zero energy community is the sum of surplus renewable energy after the self-consumption of three building groups. And the dynamic demand needing peer energy buying of the net-zero energy community is the sum of electrical load shortage after the self-sufficiency of three building groups. So the *SDR* is formulated by Eq. (1) as shown below.

$$SDR = \frac{\sum P_{REgi\_sur}}{\sum P_{Loadgi\_shor}} \tag{1}$$

where P_{REgi_sur} is the surplus renewable energy after the self-consumption of building group i, kW. P_{Loadgi_shor} is the electrical load shortage after the self-sufficiency of building group i, kW.

The P2P energy selling price (*Prsell*) in the net-zero energy community can be formulated as the piecewise function of *SDR* as Eq. (2) [16].

$$Prsell = f(SDR) = \begin{cases} \dfrac{Rsell \cdot Rbuy_{g3}}{\left(Rbuy_{g3} - Rsell\right) \cdot SDR + Rsell}, & 0 \leq SDR \leq 1 \\ Rsell & , \ 1 < SDR \end{cases} \tag{2}$$

where *Rsell* is the grid feed-in tariff rate of renewable energy and it is the same for all building groups, 0.058 \$/kWh [36]. $Rbuy_{gi}$ is the grid electricity buying rate of group i in \$/kWh which is different with building types (i.e. 0.154 \$/kWh for non-residential buildings and 0.104 \$/kWh for residential buildings [37]). Here a lower electricity rate of $Rbuy_{g3}$ is adopted for the uniform trading price model to ensure the peer energy selling price lower than the grid energy selling price.

The P2P energy buying price (*Prbuy*) in the net-zero energy community is also formulated as the piecewise function of *SDR* as per Eq. (3), and it is dependent on the selling price considering the economic balance [16].

$$Prbuy = f(SDR) = \begin{cases} Prsell \cdot SDR + Rbuy_{g3} \cdot (1 - SDR), 0 \leq SDR \leq 1 \\ \quad Rsell \quad , 1 < SDR \end{cases} \tag{3}$$

(2) Individual peer energy trading price model

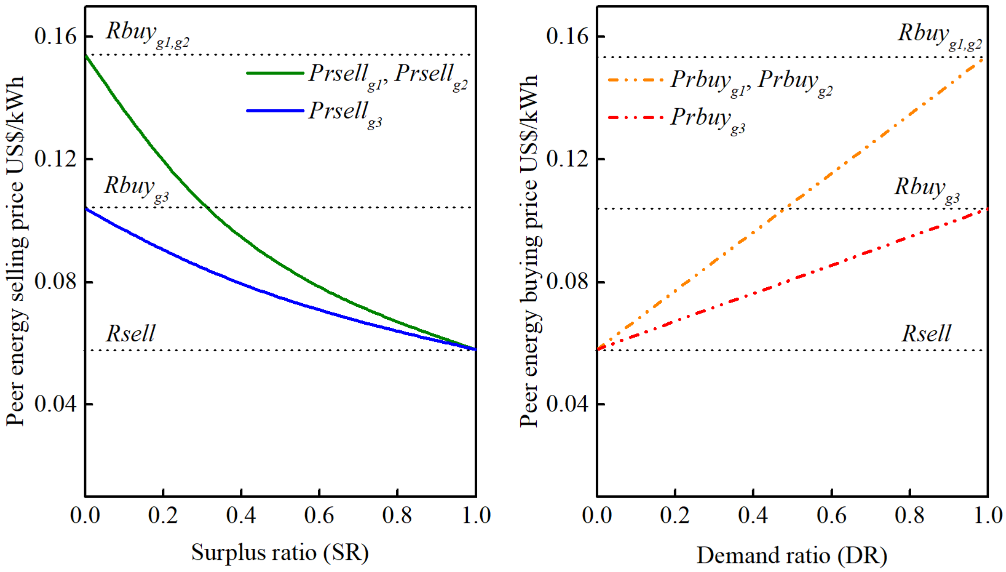


Fig. 6 Individual peer energy trading price model in the net-zero energy community

An individual peer energy trading price model allocating an individual trading price to each building group is proposed to study the P2P energy trading behavior of the diversified community, consisting of building groups with different energy distributions and grid pricing schemes. The peer selling price of each building group is determined by its own surplus renewable energy with an inverse-proportional relation, and the peer buying price of each building group is determined by its own demand shortage with a proportional relation as per Fig. 6.

The surplus renewable energy of an individual building group for peer trading is indicated by the surplus ratio (*SR*) as per Eq. (4).

$$SR_{gi\_sur} = \frac{P_{REgi\_sur}}{P_{REgi}} \tag{4}$$

where P_{REgi} is the dynamic renewable energy generation of building group i, kW.

The demand shortage of an individual building group for peer trading is indicated by the demand ratio (*DR*) as per Eq. (5).

$$DR_{gi\_shor} = \frac{P_{Loadgi\_shor}}{P_{Loadgi}} \tag{5}$$

where P_{Loadgi} is the dynamic electrical load of building group i, kW.

The peer selling price and peer buying price of each building group are developed as shown in Eqs. (6-7), dependent on the *SR* and *DR*. It should be noted that the peer selling price and peer buying price of an individual building group are independent, as its renewable energy surplus and demand shortage could be not positive values at the same time. And the peer energy trading prices vary with the dynamic renewable energy generation and electrical load of the building group.

$$Prsell_{gi} = f\left(SR_{gi\_sur}\right) = \frac{Rsell \cdot Rbuy_{gi}}{\left(Rbuy_{gi} - Rsell\right) \cdot SR_{gi\_sur} + Rsell} \tag{6}$$

$$Prbuy_{gi} = f\left(DR_{gi\_shor}\right) = \left(Rbuy_{gi} - Rsell\right) \cdot DR_{gi\_shor} + Rsell \tag{7}$$

2.3. Energy management of five net-zero energy community cases with hybrid renewable energy and hydrogen vehicle storage systems

(1) Energy management strategy of baseline peer-to-grid case (Case 1)

The energy management strategy of the hybrid renewable energy and HV storage system in Case 1 is shown in Fig. 7, where the building groups in the net-zero energy community do not share energy with other peers but only trade with the utility grid. Specifically, the renewable energy generation of each building group is firstly used on-site to cover the building electrical load. Then surplus renewable energy is used to drive electrolyzers of the hydrogen storage system to generate and store hydrogen, when the fractional state of charge (FSOC) of the stationary hydrogen storage tank is lower than its maximum level ($FSOC_{ti\_max}$ at 0.95). And the dynamic charging power is also limited by the electrical current density of electrolyzers (within 40 - 400 mA/cm^2 [38]). The residual renewable energy is lastly exported to the utility grid. For the unmet building load supplied by the on-site renewable energy, the parked HVs can be operated to supply power, when the FSOC of the mobile hydrogen storage tank is higher than its minimum level ($FSOC_{gi\_min}$ at 0.1005) to support one-day cruise and keep above the atmosphere pressure. Finally, the utility grid supplies power for unmatched load.

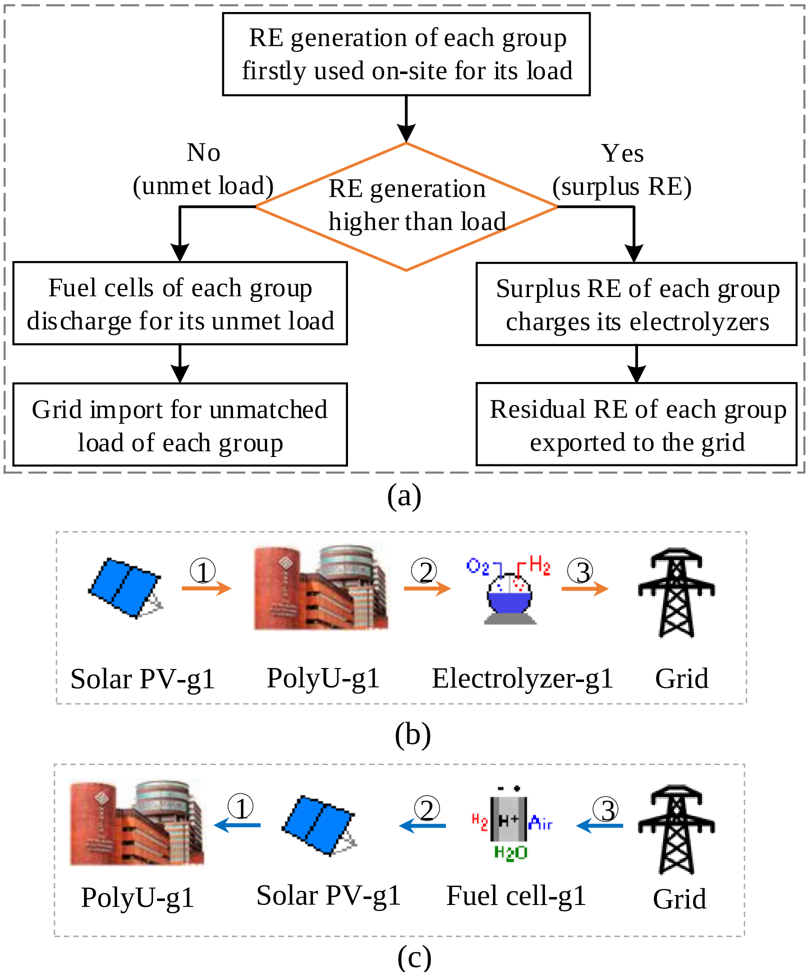


Fig. 7 Energy management strategy of Case 1 (a) simplified diagram (b) renewable generation flow priority of building group 1 (c) load matching flow priority of building group 1

The detailed energy management strategy of the hybrid renewable energy and HV storage system in Case 1 with only peer-to-grid trading is shown in Fig. 8.

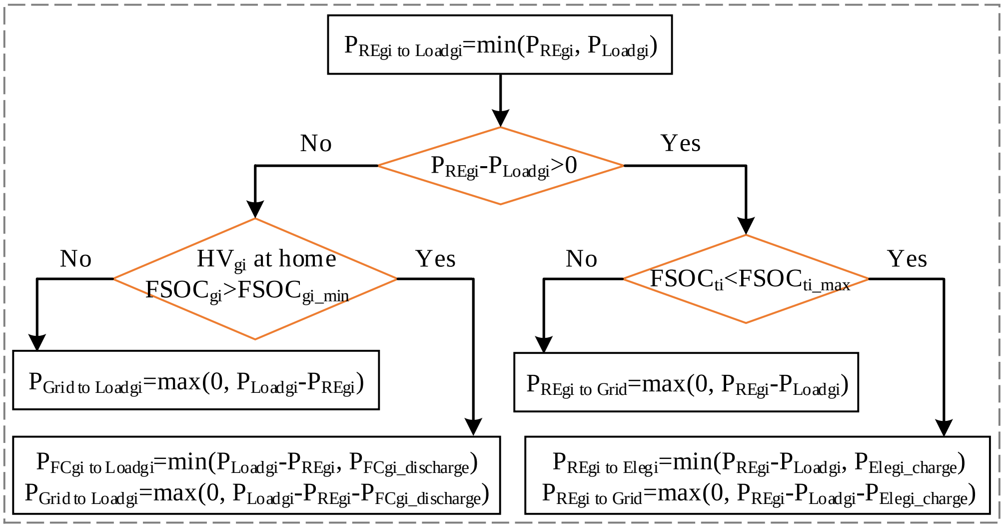
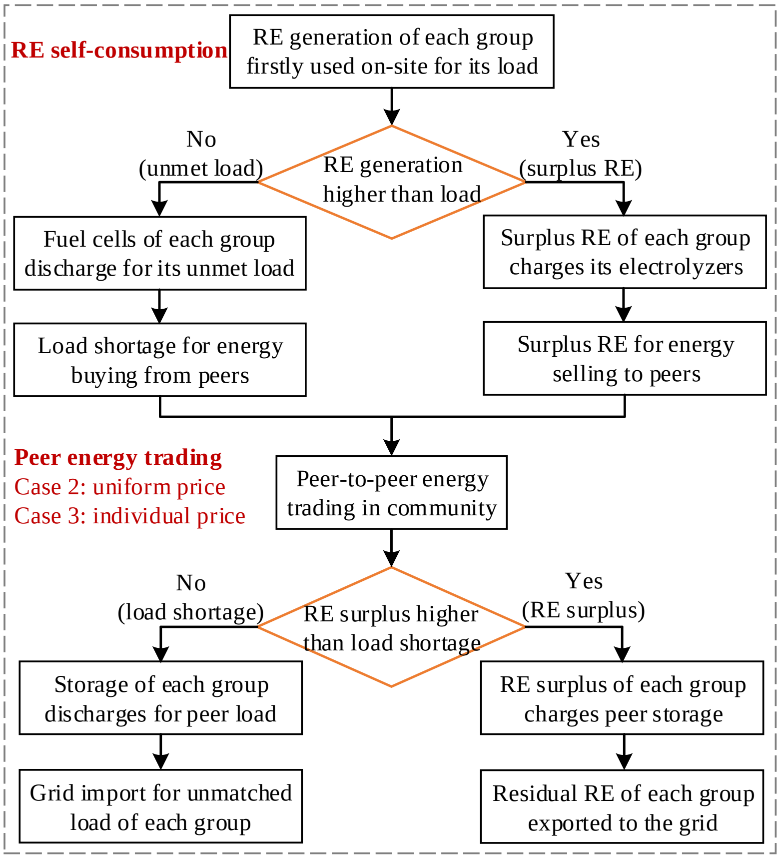


Fig. 8 Detailed energy management strategy of Case 1

(2) Energy management strategy of peer-to-peer energy trading cases (Case 2 in uniform price mode and Case 3 in individual price mode)



(a)

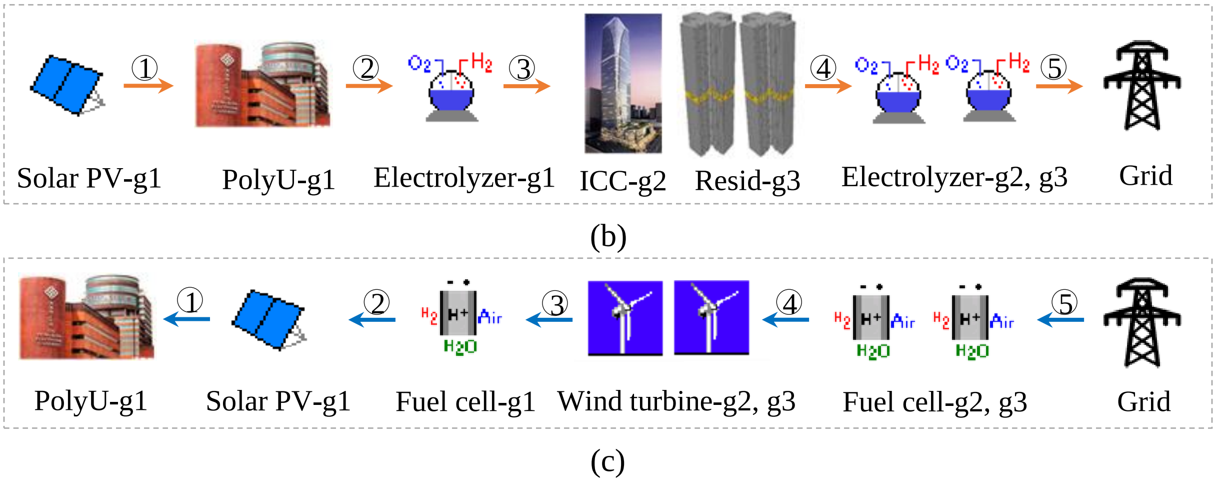


Fig. 9 Energy management strategy of Case 2 and Case 3 (a) simplified diagram (b) renewable generation flow priority of building group 1 (c) load matching flow priority of building group 1

The energy management strategy of the P2P energy trading cases (Case 2 in uniform price and Case 3 in individual price) is presented in Fig. 9. Renewable energy generation of each building group is firstly utilized on site for the building itself including electrical load and electrolyzers. Then surplus renewable energy of each building group after self-consumption is shared to meet the unmet load of other community peers. Afterwards, the residual renewable energy of each building group is delivered to charge the hydrogen storage systems of other community peers before being exported to the grid. The building group with load shortage after buying peer renewable energy can also buy energy from the hydrogen storage systems of its peers. The detailed energy flow priority of renewable energy generation and load matching in Case 2 and Case 3 is shown in Fig. 9 (b-c), taking group 1 as a detailed demonstration. Renewable energy of building group 1 is firstly utilized on site for the building itself, then surplus renewable energy is used for peer load and peer storage before being exported to the grid. The building load is firstly met by self-produced renewable energy and self-available hydrogen storage, then it can buy electricity from peer renewable sources and peer storage.

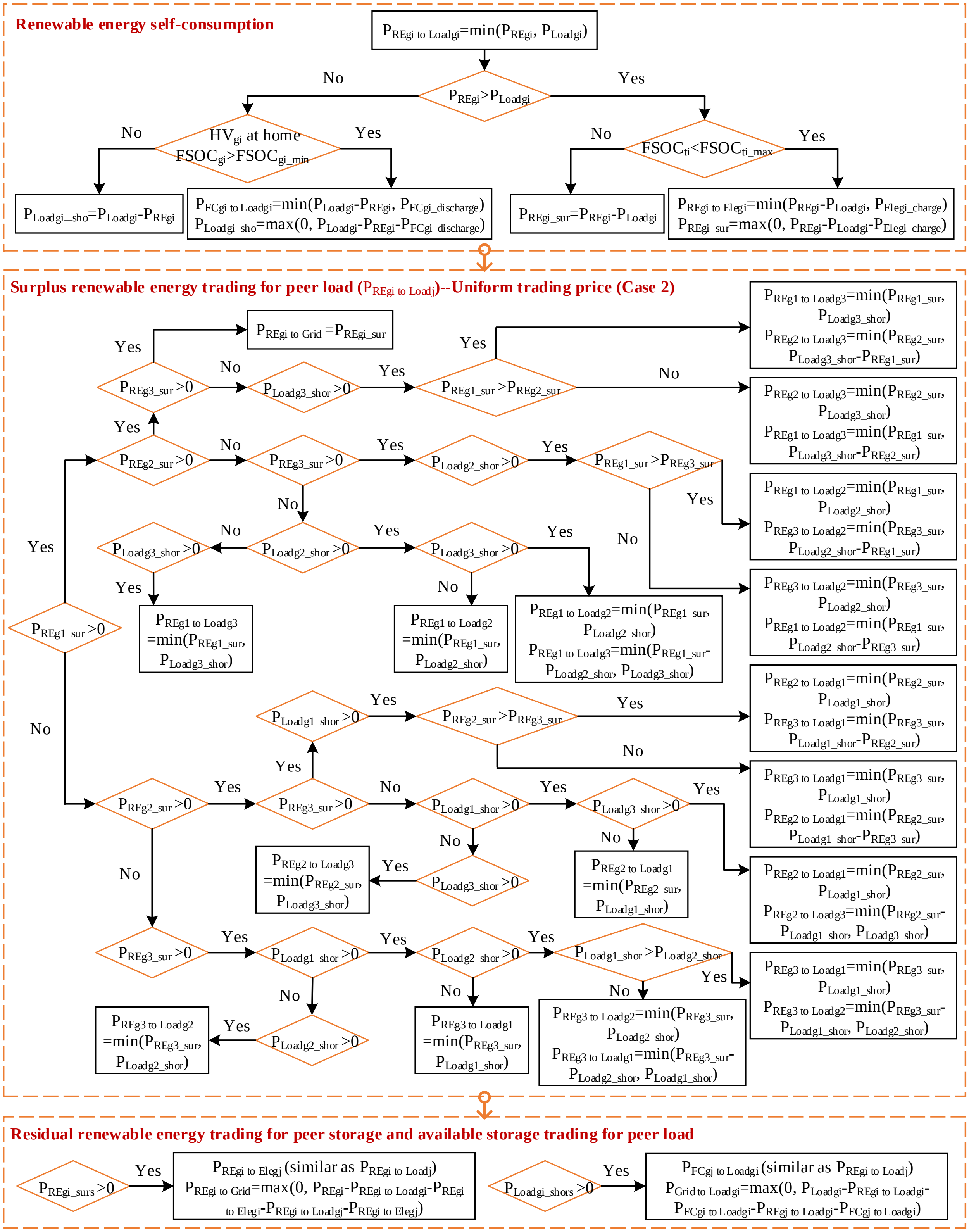


Fig. 10 Detailed energy management strategy of Case 2

The detailed energy management strategy of the hybrid renewable energy and HV storage system in Case 2 with P2P energy trading in the uniform price mode is shown in Fig. 10. The basic trading rules should be followed in the P2P energy trading process in the uniform price mode:

1) Surplus energy from renewable sources (PV/wind) or storage sources (fuel cells) of one peer is shared to meet the unmatched load of other peers prior to electrolyzers of other peers.

2) When more than one peer with surplus renewable power or storage power are available for sharing to the third peer, the peer with higher surplus power has the peer trading priority considering the energy trading convenience.

3) When more than one peer with unmatched demand need to buy energy from the third peer, the peer with a higher grid electricity price has the peer trading priority, so as to reduce the overall electricity bills of the community.

The detailed energy management strategy of the hybrid renewable energy and HV storage system in Case 3 with P2P energy trading in the individual price mode is shown in Fig. 11. As an individual trading price is allocated to each building group according to its own renewable energy surplus and load shortage, the P2P trading rules in Case 3 are different from Case 2 as below:

1) When more than one peer with surplus renewable power or storage power are available for sharing to the third peer with unmatched demand, the peer with a lower selling price has the energy trading priority.

2) When more than one peer with unmatched demand need to buy energy from the third peer with surplus energy, the peer with a higher buying price has the peer trading priority.

3) The dynamic trading price is the minimum value of selling price of the seller and buying price of the buyer to encourage internal energy sharing in the net-zero energy community.

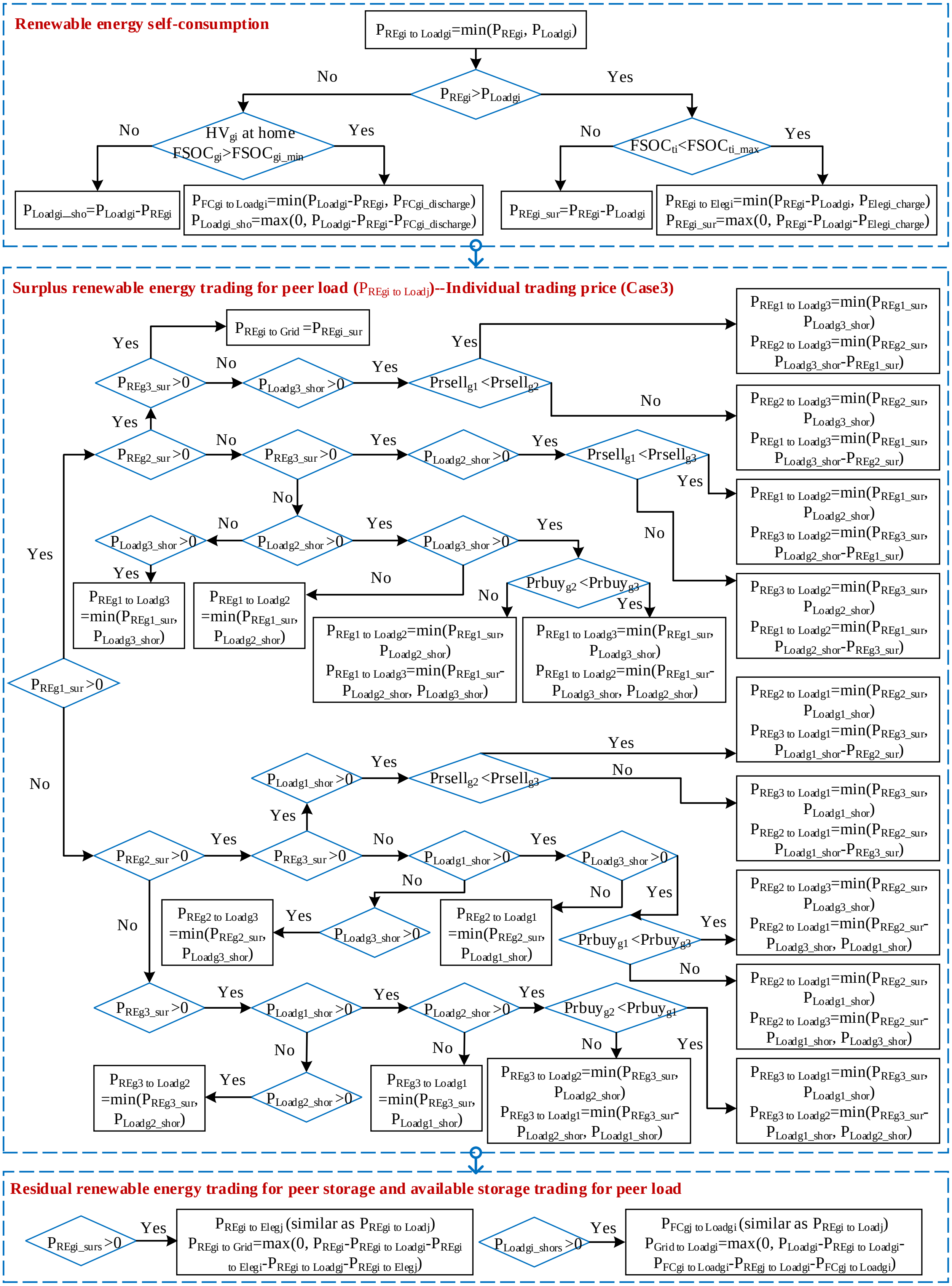
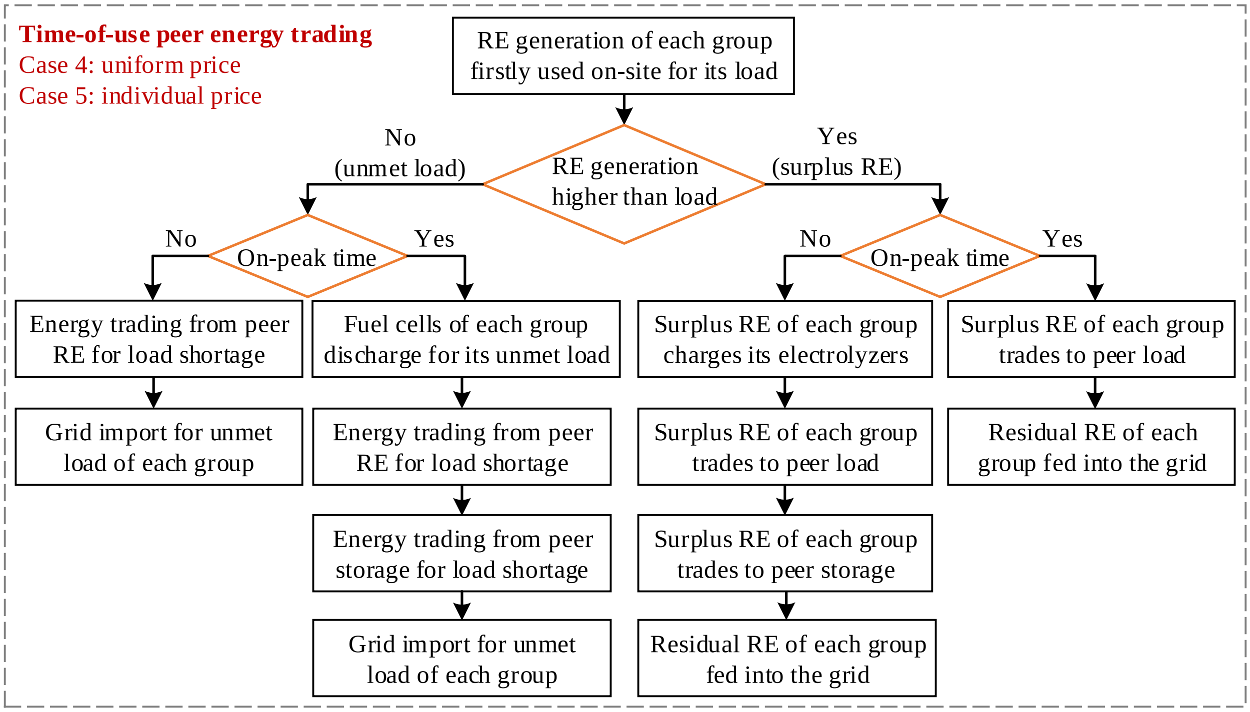


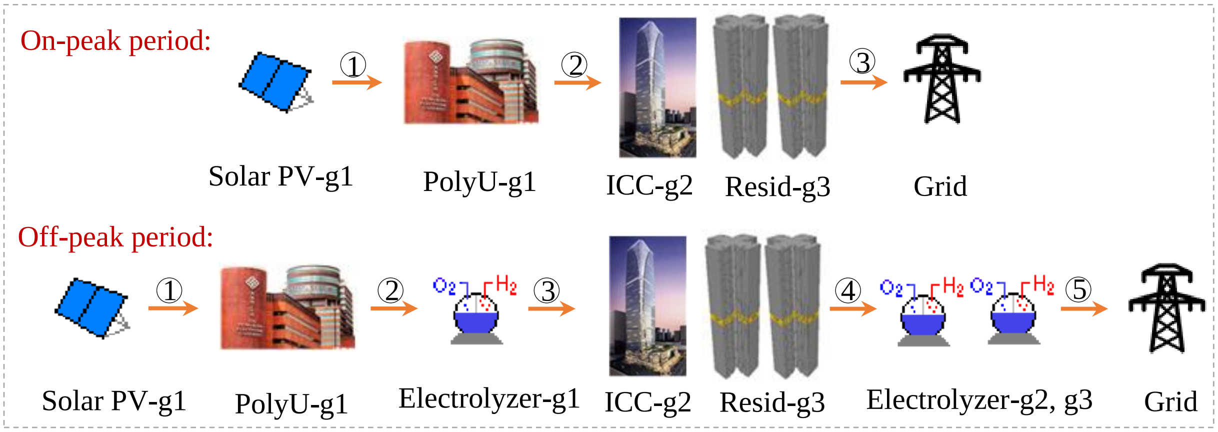
Fig. 11 Detailed energy management strategy of Case 3

(3) Energy management strategy of time-of-use peer-to-peer energy trading cases (Case 4 in uniform price mode and Case 5 in individual price mode)

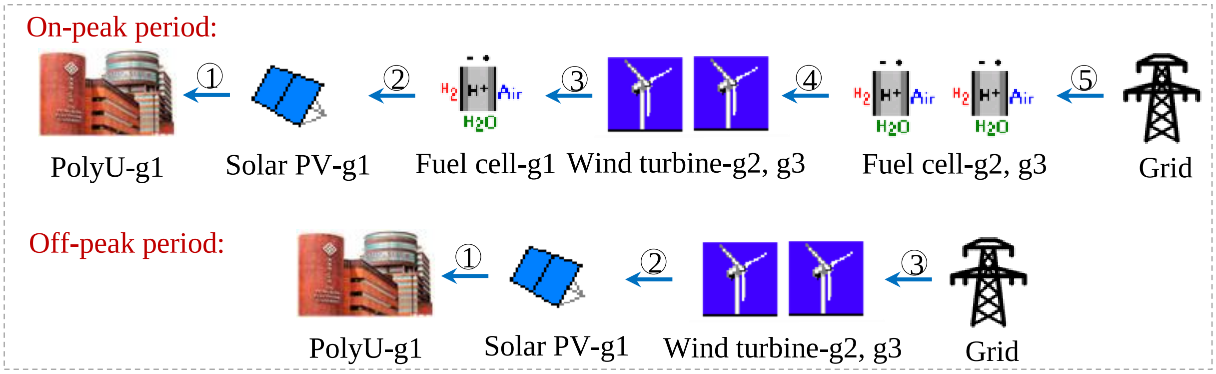
The time-of-use P2P energy trading is proposed to improve the power flexibility and economy between the net-zero energy community and utility grid, with the simplified diagram shown in Fig. 12 (a). The renewable energy generation is exported into the grid after supplying to electrical load of three building groups during on-peak time, while it is also available for hydrogen storage systems of three building groups during off-peak time. Because a higher energy export during on-peak time and a lower energy export during off-peak time are preferred by the utility grid. Both renewable energy and hydrogen storage are available for the electrical load of buildings during on-peak time, while only renewable energy is utilized for meeting building load during off-peak time. Since a lower energy import during on-peak time and a higher energy import during off-peak time are encouraged by the utility grid, to address the power congestion and improve the economic performance through power shifting. The detailed energy flow priority of renewable energy generation and load matching in Case 4 and Case 5 is shown in Fig. 12(b-c), taking group 1 as a detailed demonstration.



(a)



(b)



(c)

Fig. 12 Energy management strategy of Case 4 and Case 5 (a) simplified diagram (b) renewable generation flow priority of building group 1 (c) load matching flow priority of building group 1

Therefore, the surplus renewable energy available for peer load sharing and the load shortage for peer energy trading in the time-of-use P2P trading process can be formulated as Eqs. (8-9).

$$P_{REgi\_sur} = \left(P_{REgi} - P_{REgi\ to\ Loadgi}\right) \cdot T_{onpeak} + \left(P_{REgi} - P_{REgi\ to\ Loadgi} - P_{REgi\ to\ Elegi}\right) \cdot T_{offpeak} \quad (8)$$

$$\begin{aligned} P_{Loadgi\_shor} = {} & \left(P_{Loadgi} - P_{REgi\ to\ Loadgi} - P_{FCgi\ to\ Loadgi}\right) \cdot T_{onpeak} \\ & + \left(P_{Loadgi} - P_{REgi\ to\ Loadgi}\right) \cdot T_{offpeak} \end{aligned} \quad (9)$$

where $P_{REgi\ to\ Loadgi}$ is the self-consumed renewable power of group i to meet its electrical load, kW. $P_{REgi\ to\ Elegi}$ is the self-consumed renewable power of group i to charge its electrolyzers, kW. T_{onpeak} is the on-peak time and $T_{offpeak}$ is the off-peak time. $P_{FCgi\ to\ Loadgi}$ is the energy from hydrogen storage of group i to meet its electrical load, kW. It is assumed that the on-peak period is the daily period between 9:00 and 21:00 and the off-peak period comprises all other hours according to the local power grid company [39].

The energy trading of renewable energy sharing for peer storage only operates in off-peak period to enhance the grid flexibility. The residual renewable energy after self-consumption and supplying to peer load (P_{REgi_surs}) is available for trading to peer storage as per Eq. (10). The energy shortage of the hydrogen storage system after self-sufficiency (P_{Elegi_shor}) is formulated as Eq. (11).

$$P_{REgi\_surs} = \left(P_{REgi} - P_{REgi\ to\ Loadgi} - P_{REgi\ to\ Elegi} - P_{REgi\ to\ Loadgj}\right) \cdot T_{offpeak} \tag{10}$$

$$P_{Elegi\_shor} = \left(P_{Elegi} - P_{REgi\ to\ Elegi}\right) \cdot T_{offpeak} \tag{11}$$

where $P_{REgi\ to\ Loadgj}$ is the peer trading renewable power of group i to meet the electrical load of group j, kW.

The energy trading of hydrogen storage sharing for peer load only operates during on-peak period to relieve the power grid. The load shortage after self-sufficiency and peer renewable energy trading (P_{Loadgi_shors}), that needs to be met by the peer storage, is shown in Eq. (12). And the hydrogen storage after self-consumption (P_{FCgi_avai}) available for peer sharing is formulated as Eq. (13).

$$P_{Loadgi\_shors} = \left(P_{Loadgi} - P_{REgi\ to\ Loadgi} - P_{FCgi\ to\ Loadgi} - P_{REgj\ to\ Loadgi}\right) \cdot T_{onpeak} \tag{12}$$

$$P_{FCgi\_avai} = \left(P_{FCgi} - P_{FCgi\ to\ Loadgi}\right) \cdot T_{onpeak} \tag{13}$$

where $P_{REgj\ to\ Loadgi}$ is the peer trading renewable power of group j to meet the electrical load of group i, kW.

Finally, the energy trade between building group i with the utility grid is formulated as Eqs. (14-15).

$$\begin{aligned} P_{REgi\ to\ Grid} &= \left(P_{REgi} - P_{REgi\ to\ Loadgi} - P_{REgi\ to\ Loadgj}\right) \cdot T_{onpeak} \\ &+ \left(P_{REgi} - P_{REgi\ to\ Loadgi} - P_{REgi\ to\ Elegi} - P_{REgi\ to\ Loadgj} - P_{REgi\ to\ Elegj}\right) \cdot T_{offpeak} \end{aligned} \tag{14}$$

where $P_{REgi\ to\ Grid}$ is the energy from renewable sources of building group i to the grid, kW. $P_{REgi\ to\ Elegj}$ is the peer trading renewable power of group i to charge the electrolyzers of group j, kW.

$$P_{Grid\ to\ Loadgi} = \left(P_{Loadgi} - P_{REgi\ to\ Loadgi} - P_{FCgi\ to\ Loadgi} - P_{REgj\ to\ Loadgi} - P_{FCgj\ to\ Loadgi}\right) \cdot T_{onpeak}$$

$$+\left(P_{Loadgi} - P_{REgi\ to\ Loadgi} - P_{REgj\ to\ Loadgi}\right) \cdot T_{offpeak} \tag{15}$$

where $P_{Grid\ to\ Loadgi}$ is the energy from the utility grid to meet the electrical load of building group i, kW. $P_{FCgj\ to\ Loadgi}$ is the peer trading energy from hydrogen storage of group j to meet the electrical demand of group i, kW.

2.4. Assessment indicators of hybrid renewable energy and hydrogen vehicle storage systems

(1) Self-consumption of renewable energy sources

The renewable energy self-consumption ratio (SCR) is formulated to evaluate the on-site application efficiency of renewable energy generation for electrical load and storage in the net-zero energy community as per Eq. (16).

$$SCR = \frac{\sum E_{REgi\ to\ Loadgi} + \sum E_{REgi\ to\ Elegi} + \sum E_{REgi\ to\ Loadgj} + \sum E_{REgi\ to\ Elegj}}{\sum E_{REgi}} \tag{16}$$

where i is a specific building group in the net-zero energy community and j is the other two building groups. $E_{REgi\ to\ Loadgi}$ is the self-consumed renewable energy of group i to meet its electrical load, kWh. $E_{REgi\ to\ Elegi}$ is the self-consumed renewable energy of group i to charge its electrolyzers, kWh. $E_{REgi\ to\ Loadgj}$ is the peer trading renewable energy of group i to meet the electrical load of group j, kWh. $E_{REgi\ to\ Elegj}$ is the peer trading renewable energy of group i to charge the electrolyzers of group j, kWh. E_{REgi} is the renewable energy generation of group i, kWh.

(2) Community load coverage by renewable energy and storage

The load cover ratio (LCR) is developed to assess the on-site community load coverage by hybrid renewable energy and HV storage systems as shown in Eq. (17).

$$LCR = \frac{\sum E_{REgi\ to\ Loadgi} + \sum E_{FCgi\ to\ Loadgi} + \sum E_{REgj\ to\ Loadgi} + \sum E_{FCgj\ to\ Loadgi}}{\sum E_{Loadgi}} \tag{17}$$

where $E_{FCgi\ to\ Loadgi}$ is the energy from HV storage of group i to meet its electrical load, kWh. $E_{REgj\ to\ Loadgi}$ is the peer trading renewable energy of group j to meet the electrical load of group i, kWh. $E_{FCgj\ to\ Loadgi}$ is the peer trading energy from HV storage of group j to meet the electrical demand of group i, kWh. E_{Loadgi} is the total electrical load of group i including the building load and compressor load of hydrogen compressors, kWh.

(3) Net energy import of the utility grid for the net-zero energy community

The net grid import is calculated to assess the grid power integration of the net-zero energy community as shown in Eq. (18).

$$Net\ grid\ import = \sum E_{Grid\ to\ Loadgi} + \sum E_{Grid\ to\ Elegi} - \sum E_{REgi\ to\ Grid} \tag{18}$$

where $E_{Grid\ to\ Loadgi}$ is the imported energy from the utility grid to meet the electrical load of group i, kWh. $E_{Grid\ to\ Elegi}$ is the imported energy from the utility grid to drive the electrolyzers of group i to produce hydrogen for daily cruise when the $FSOC$ of HV storage tank is lower than its minimum level, kWh. $E_{REgi\ to\ Grid}$ is the renewable energy of group i exported to the utility grid, kWh.

(4) Time-of-use grid penalty cost evaluating the grid flexibility

A time-of-use grid penalty cost (PC_{TOU}) business model is proposed to evaluate the power interaction flexibility between the net-zero energy community and utility grid, to encourage grid import and limit grid export during off-peak time as well as to encourage grid export and limit grid import during on-peak time. A fine will be imposed on the building community when the calculated penalty cost is positive and a bonus can be gained when the penalty cost is negative, aiming to achieve higher power resilience and flexibility of the utility grid. It is formulated as per Eq. (19) covering the penalty cost of grid import in off-peak time ($PC_{import\_offpeak}$), penalty cost of grid import in on-peak time (PC_{import_onpeak}), penalty cost of grid export in off-peak time ($PC_{export\_offpeak}$) and penalty cost of grid export in on-peak time (PC_{export_onpeak}) [40].

$$\begin{aligned} PC_{TOU} &= PC_{import\_offpeak} + PC_{import\_onpeak} + PC_{export\_offpeak} + PC_{export\_onpeak} = \\ &\left(\int P_{import\_estimated} - \int P_{import\_offpeak}\right)\cdot PF_{offpeak} + \left(\int P_{import\_onpeak} - \int P_{import\_estimated}\right)\cdot PF_{onpeak} + \\ &\left(\int P_{export\_offpeak} - \int P_{export\_estimated}\right)\cdot PF_{offpeak} + \left(\int P_{export\_estimated} - \int P_{export\_onpeak}\right)\cdot PF_{onpeak} \end{aligned} \tag{19}$$

where $P_{import\_estimated}$ is the estimated grid import power defined as the ratio of peak electrical demand of buildings, $0.5\cdot P_{Loadgi\_max}$ in kW. $P_{import\_offpeak}$ is the dynamic grid import power during off-peak time, kW. $PF_{offpeak}$ is the penalty factor during off-peak time defined as the ratio of the electricity tariff, $0.1\cdot Rbuy_{gi}$ in US\$/kWh. P_{import_onpeak} is the dynamic grid import power during on-peak time, kW. PF_{onpeak} is the penalty factor during on-peak time defined as the ratio of the electricity tariff, $0.1\cdot Rbuy_{gi}$ in US\$/kWh. $P_{export\_offpeak}$ is the dynamic grid export power during off-peak time, kW. $P_{export\_estimated}$ is the estimated grid export power defined as the ratio of rated renewable energy capacity, $0.2\cdot P_{REgi\_rated}$ in kW. P_{export_onpeak} is the dynamic grid export power during on-peak time, kW. The ratios on the time-of-use grid penalty cost model can be set according to the grid power availability and renewable energy system capacity, and typical ratios are adopted for a case analysis in the present study.

(5) Annual net electricity bill of the net-zero energy community

The annual net electricity bill (NB_a) of the community is formulated in Eq. (20) counting the electricity bill of buying energy from peers and utility grid of three building groups and electricity profit of selling surplus energy to peers and utility grid of three building groups.

$$NB_a = \sum E_{Grid\ importgi} \cdot Rbuy_{gi} + \sum E_{peer\ buygi} \cdot Prbuy_{gi} - \sum E_{Grid\ exportgi} \cdot Rsell - \sum E_{peer\ sellgi} \cdot Prsell_{gi} \tag{20}$$

where $E_{Grid\ importgi}$ is the total grid imported energy of group *i* including the grid imported energy to electrical load ($E_{Grid\ to\ Loadgi}$) and to electrolyzers ($E_{Grid\ to\ Elegi}$), kWh. $E_{peer\ buygi}$ is the energy buying from peers' renewable sources and storage for the electrical load and storage of group *i* including $E_{REgj\ to\ Loadgi}$, $E_{REgj\ to\ Elegi}$ and $E_{FCgj\ to\ Loadgi}$, kWh. $Prbuy_{gi}$ is the electricity buying price group *i* in \$/kWh, dependent on the dynamic energy surplus and demand as explained in Section 2.2, and it is different in the uniform and individual trading price cases. $E_{Grid\ exportgi}$ is grid exported energy from renewable sources of group *i*, kWh. $E_{peer\ sellgi}$ is the energy from renewable sources and storage of group *i* selling to its peers for the electrical demand and storage including $E_{REgi\ to\ Loadgj}$, $E_{REgi\ to\ Elegj}$ and $E_{FCgi\ to\ Loadgj}$, kWh. $Prsell_{gi}$ is the electricity selling price of group *i* in \$/kWh, dependent on the dynamic energy surplus and demand as explained in Section 2.2.

(6) Lifetime net present value assessing the system economic performance

The lifetime net present value (NPV) of hybrid renewable energy and HV storage systems for power supply to the net-zero energy community is formulated as Eq. (21) covering the present value of initial cost (PRV_{ini}), replacement cost (PRV_{rep}), operation and maintenance cost ($PRV_{O\&M}$), residual cost (PRV_{res}), and net electricity bill (PRV_{nb}). The system NPV under the current cost scenario and future cost scenario (projected in 2050) is compared.

$$\begin{aligned} NPV &= PRV_{ini} + PRV_{O\&M} + PRV_{rep} - PRV_{res} + PRV_{nb} \\ &= C_{ini} + \sum_{n=1}^{n=N} \frac{f_{mai} \cdot C_{ini}}{(1+i)^n} + \sum_{j=1}^{j=J} C_{ini} \left(\frac{1-d}{1+i}\right)^{j \cdot l} - C_{ini} \frac{l_{res}}{l} \cdot \frac{(1-d)^N}{(1+i)^N} + \sum_{n=1}^{n=N} \frac{NB_a \cdot (1+\gamma)^{n-1}}{(1+i)^n} \end{aligned} \tag{21}$$

where C_{ini} is the initial investment of the hybrid renewable energy and HV storage system, US\$. f_{mai} is the annual ratio of operation and maintenance cost to the initial cost of each component. *N* is the calculated serving time of the hybrid system for 20 years, and *n* is a specific year. *i* is the annual real discount rate, 5.8%/year. *J* is the total times of a system component needing to be replaced, and *j* is a specific replacement time. *d* is the annual price degression rate of a specific component. *l* is the serving lifetime of a specific component, and l_{res} is the residual lifetime at the end of the calculated system serving time. *γ* is the annual electricity rising rate, 1.4%/year. The economic parameters of hybrid renewable energy and HV storage systems are shown in Table 1.

Table 1 Economic parameters of hybrid renewable energy and HV storage systems

Components	Initial cost (current scenario)	Initial cost (2050 future scenario)	O&M ratio (of initial cost)	Lifetime, year
PV [41]	3500 US$/kW	323 US$/kW [7]	2%	20
Wind turbine [41]	4000 US$/kW	2100 US$/kW [9]	1%	20
Inverter/converter [41]	700 US$/kW	280 US$/kW [42]	1%	10
Electrolyzer	1400 US$/kW [14]	700 US$/kW [14]	2% [43]	20 [44]
Compressor	15000 US$/Set [45]	5300 US$/Set [14]	2% [46]	20 [47]
H_2 storage tank [43]	50 US$/N m^3	18 US$/N m^3 [14]	0.5%	25
HV [48]	58500 US$/HV	35100 US$/HV [14]	2%	8

(7) Annual equivalent carbon emissions assessing the system environmental performance

The annual equivalent carbon emission (CE_a) is formulated as shown in Eq. (22) to evaluate the environmental performance of the hybrid renewable energy and HV storage systems applied in the net-zero energy community with three building groups.

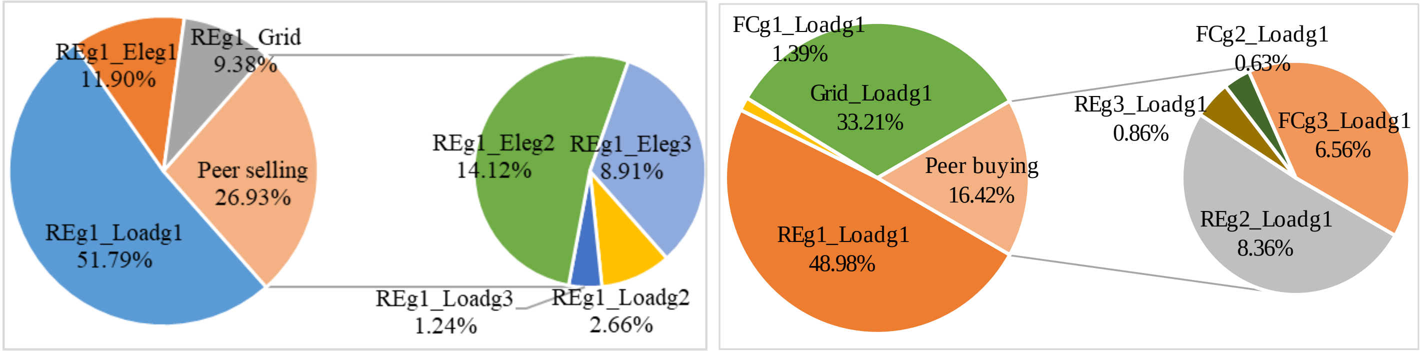
$$CE_a = \left(\sum E_{Grid\ importgi} - \sum E_{Grid\ exportgi}\right) \cdot CEF_{eq} \tag{22}$$

where CEF_{eq} is the equivalent CO_2 emissions of the utility grid, 0.572 kg CO_2/kWh [49].

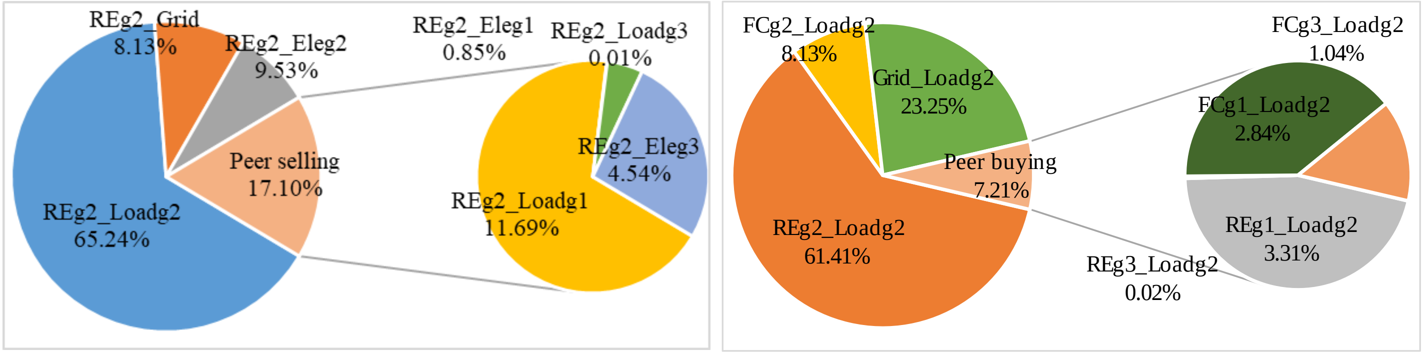
3. Results and discussion

This section firstly analyzes the energy sharing flow and trading cost saving of typical P2P trading cases in the net-zero energy community. Then detailed techno-economic-environmental performances of five cases are discussed, including the renewable energy self-consumption and load coverage, energy trading flow, time-of-use grid penalty cost, annual electricity cost and carbon emissions. Finally, the system lifetime NPV is evaluated under the current and future cost scenarios.

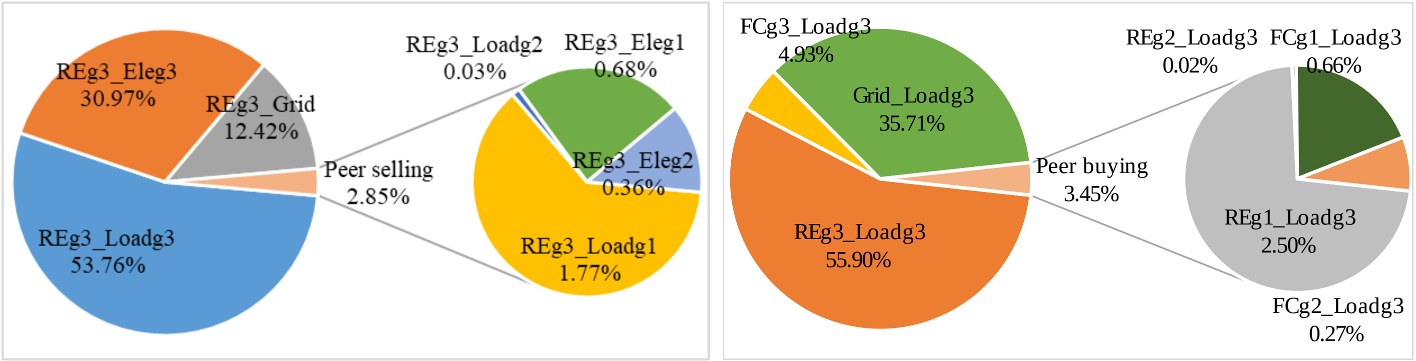
3.1. Analysis on typical peer-to-peer energy trading cases of the net-zero energy community



Renewable energy flow of group 1 Load matching flow of group 1



Renewable energy flow of group 2 Load matching flow of group 2



Renewable energy flow of group 3 Load matching flow of group 3

Fig. 13 Annual renewable energy flow and load matching flow in Case 2 (uniform price mode)

The renewable energy generation and load matching flow of the net-zero energy community in Case 2 with P2P energy trading in the uniform price mode are discussed as per Fig. 13. It is indicated that about 26.93% of renewable energy generation (13488.01 MWh) in the campus building group is shared to peers, which otherwise needs to be fed into the utility grid if the P2P energy trading is not adopted. The peer selling energy in the office and residential building groups accounts for about 17.10% and 2.85% of its renewable energy generation respectively, lower than that in the campus building group with good complementarity. Majority of peer selling energy is traded for storage charging in the campus building group while more peer selling energy is shared for peer load matching in the office and residential buildings. Because less peer load of the office and residential buildings is in demand when surplus renewable energy generation of the campus buildings is available. The on-site self-consumption of the renewable supply is significantly improved with P2P sharing by 18.19% in the net-zero energy community. Building groups can also buy energy from peers with available renewable and storage power, where about 16.42% of electrical load (8696.27 MWh) of the campus buildings is supported by peers. The peer buying energy of office and residential buildings takes for 7.21% and 3.45% of the annual load respectively, which is lower than that of the campus building group with the maximum annual load. The annual average load coverage of the net-zero energy community is also enhanced with peer energy sharing by about 10.55%.

The P2P trading energy and cost of three building groups in the net-zero energy community of Case 2 with the uniform price mode are shown in Fig. 14 (a). The peer selling cost of the trading energy is not higher than the peer buying cost, as the P2P energy selling price is not greater than the P2P energy buying price as explained in the uniform price model in Section 2.2. The P2P selling cost keeps above the P2G selling cost and the P2P buying cost keeps below the P2G buying cost, to effectively encourage peer energy trading in the net-zero energy community. The P2P trading energy and cost of three building groups in the net-zero energy community of Case 3 with the individual price mode are shown in Fig. 14 (b). There is little cost difference between the P2P selling cost and P2P buying cost as the dynamic trading price is the minimum value of selling price of the seller and buying price of the buyer, as explained in trading rules of the individual price model in Section 2.3. And it can be found that the P2P trading cost is not lower than the P2G selling cost but not higher than the P2G buying cost.

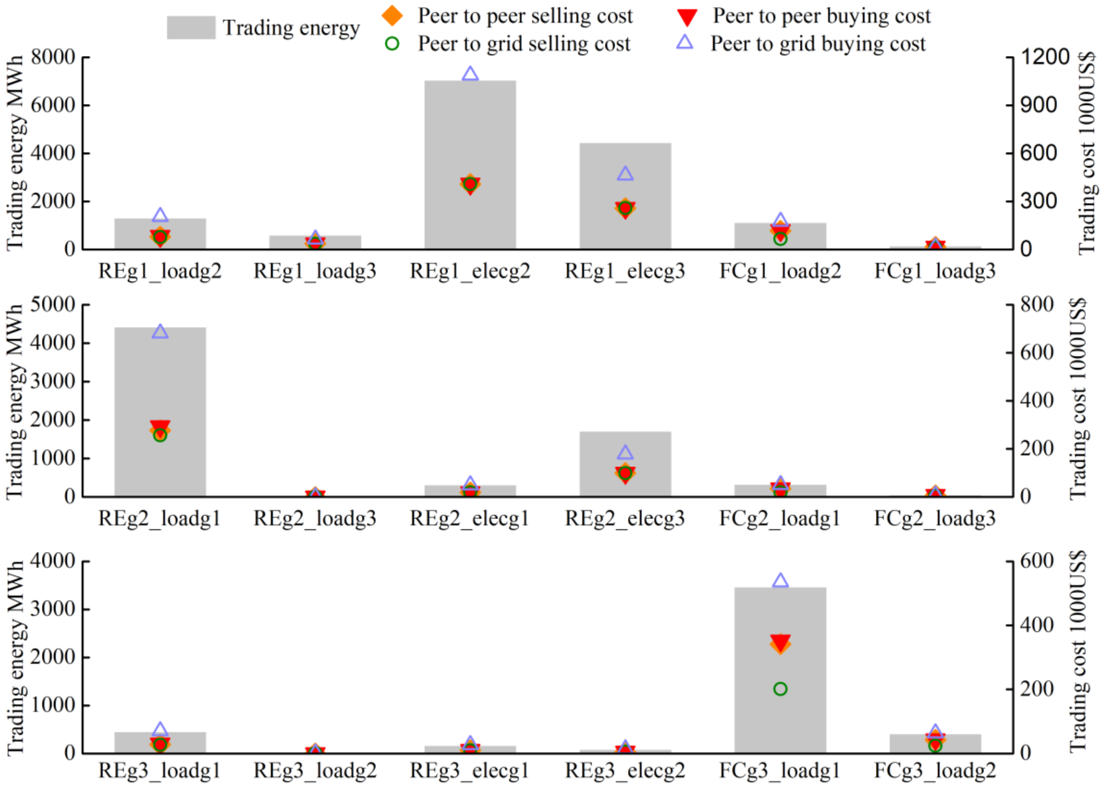


Fig. 14(a) P2P trading energy and cost in Case 2 (uniform price mode)

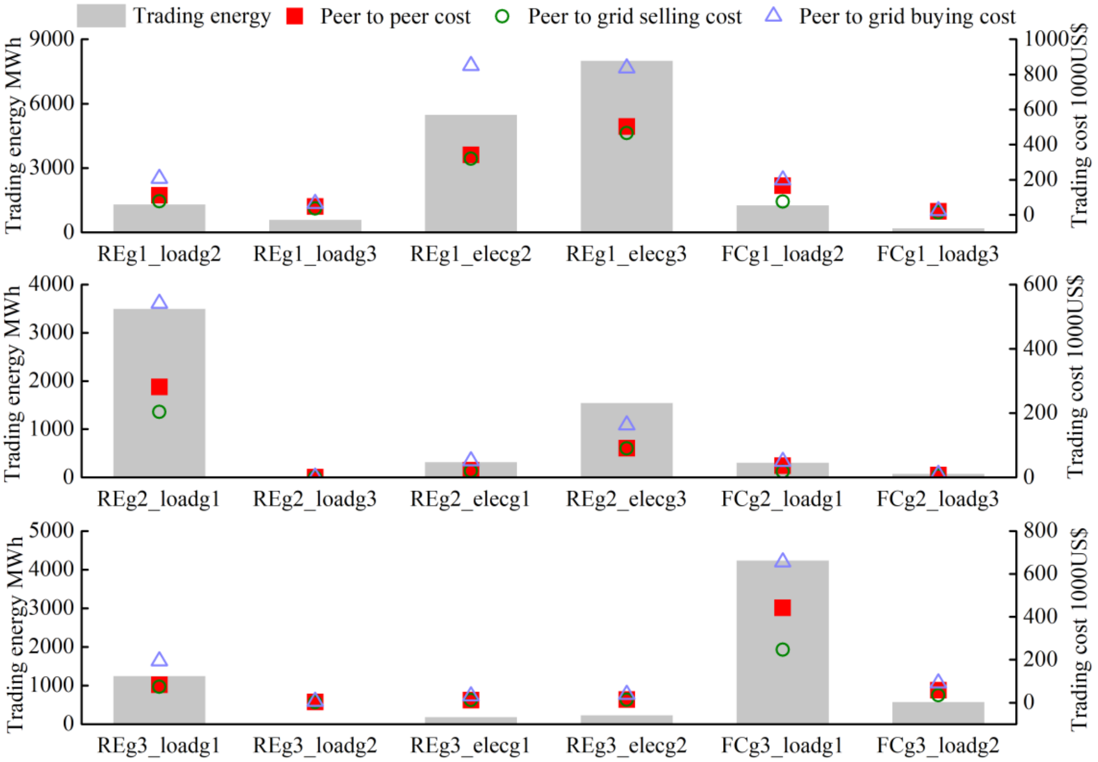


Fig. 14(b) P2P trading energy and cost in Case 3 (individual price mode)

Large amounts of economic profits can be achieved in the P2P energy trading management compared with the P2G energy trading management in Case 2 as per Fig. 15(a), where up to US$ 888.18k of electricity bill can be saved in the office building group (g2) by the P2P buying. The total cost saving resulted from P2P energy trading (selling and buying) of the campus and office building groups is about US$ 739.97k and US$ 927.23k respectively, which is much higher than that of the residential building group at US$ 474.14k. Because a smaller grid electricity rate ($Rbuy_{g3} < Rbuy_{g1,\, g2}$) is adopted for the uniform price model to ensure the peer energy selling price lower than the grid energy selling price as explained in Section 2.2. The peer selling earning of about US$ 263.63k and peer buying saving of US$ 1877.72k can be obtained with the total trading profits of US$ 2141.34k in the net-zero energy community with the P2P trading management.

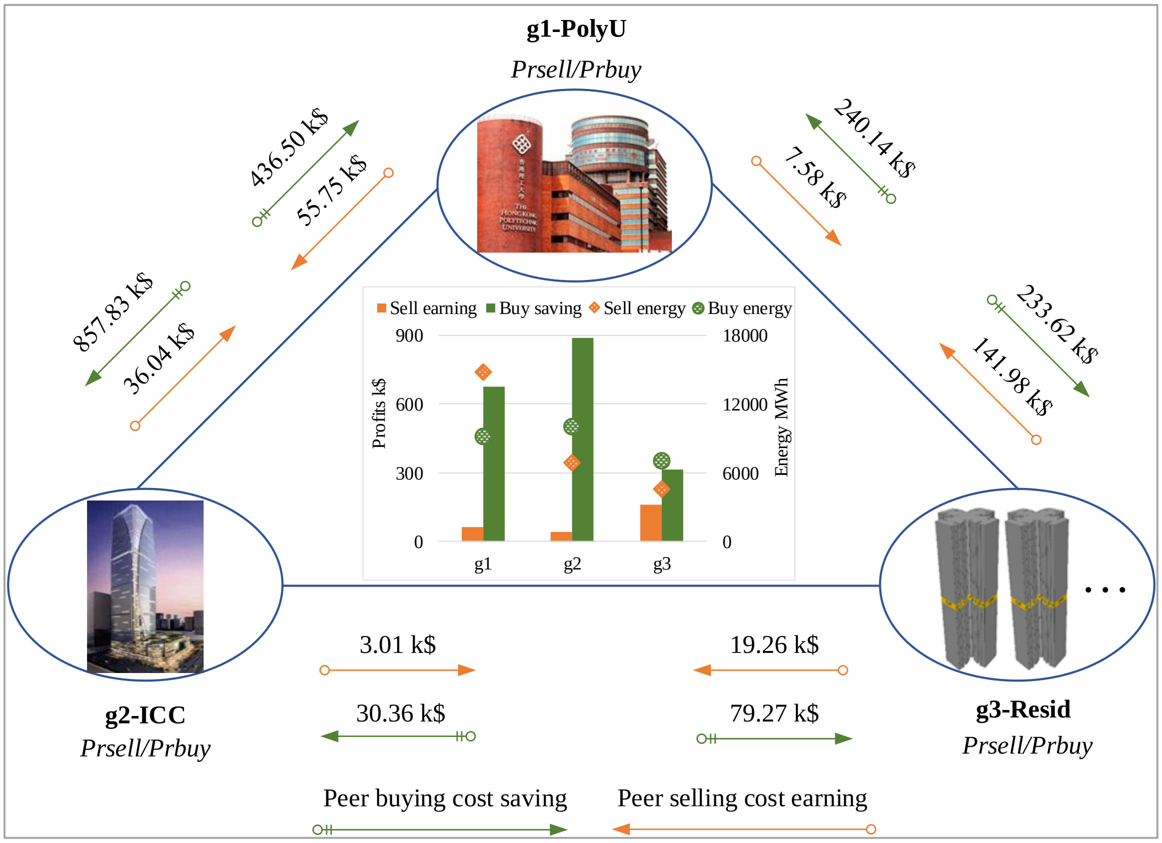


Fig. 15(a) P2P trading cost saving in Case 2 (uniform price mode)

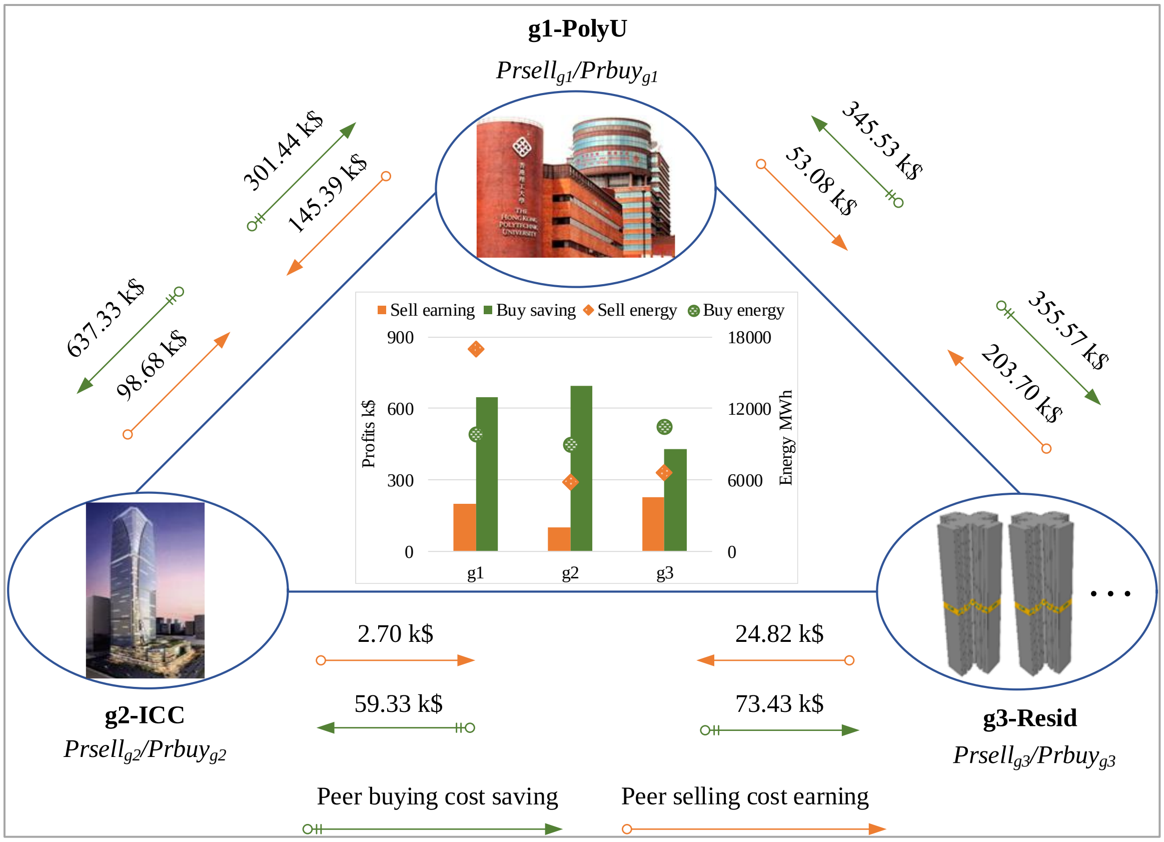
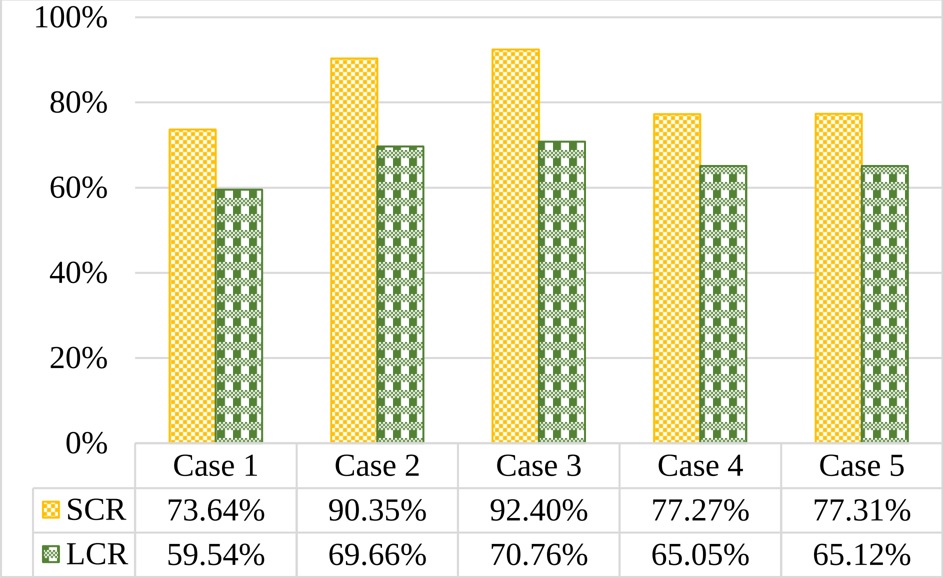


Fig. 15(b) P2P trading cost saving in Case 3 (individual price mode)

A relatively balanced energy trading profit among three building groups in the net-zero energy community is observed in Case 3 adopting the individual price mode as per Fig. 15(b). The peer energy buying saving of the campus and office building groups is higher than that of the residential building group, as the grid electricity buying price of non-residential buildings is higher than that of residential buildings in the community. And the P2P selling saving of the residential building group is the highest of about US$ 228.53k, although the P2P selling energy of the campus building group is the highest of 17037.06 MWh. About US$ 2301.01k of energy trading profits can be obtained in the net-zero energy community with US$ 528.38k of peer selling earning and US$ 1772.63k of peer buying saving. The energy trading profits of Case 3 in the individual trading price mode are 7.46% higher than that in Case 2 in the uniform trading price mode.

3.2. Comparison of five peer trading cases of the net-zero energy community

The self-consumption ratio (*SCR*) of renewable energy supplied to the community load and storage of five net-zero energy cases is compared as per Fig. 16 together with the load cover ratio (*LCR*) of the community met by on-site renewable energy and storage. It is indicated that Case 1 with only P2G trading has the minimum *SCR* and *LCR* of 73.64% and 59.54%, respectively. The *SCR* and *LCR* can be improved by 16.71% and 10.12% in Case 2 with P2P trading in the uniform price mode, as more renewable energy generation is utilized on site for peer sharing. And both *SCR* and *LCR* can be further enhanced in Case 3 with P2P trading in the individual price mode by 18.76% and 11.23% on top of the P2G trading (Case 1). The *SCR* and *LCR* are decreased when considering grid time-of-use management in the P2P trading (Case 4 and Case 5) since the energy trading is limited by the time-of-use management, but it is still higher than that of the baseline P2G case (Case 1).



	Case 1	Case 2	Case 3	Case 4	Case 5
▨ SCR	73.64%	90.35%	92.40%	77.27%	77.31%
▨ LCR	59.54%	69.66%	70.76%	65.05%	65.12%

Fig. 16 Renewable energy self-consumption and load coverage of five cases

The energy supply of each building group with the hybrid renewable energy and HV storage system can be used to meet its internal electrical load, trade with the community peers and the utility grid, according to the management strategies as compared in Fig. 17. The internal consumption indicates the annual energy supply from the renewable energy generation and hydrogen storage of each building group to meet its internal electrical load. The peer trading energy means the annual energy exchange among peers in the net-zero energy community, and the grid trading energy indicates the net grid imported energy. It is found that the internal consumption of Case 1 with only P2G trading is higher than other cases with P2P trading as the renewable sources and storage in Case 1 are not shared among community peers. Both peer trading energy and grid trading energy of cases considering time-of-use management (Case 4 and Case 5) are lower than cases without time-of-use management (Case 2 and Case 3) to maintain the grid power flexibility. Specifically, reductions of 52.40% on the peer trading energy and 32.06% on grid trading energy are observed in the uniform trading price case when considering time-of-use management (Case 4 compared with Case 2). And reductions of 56.66% and 34.24% on the peer trading energy and grid trading energy are achieved in the individual trading price case considering time-of-use management (Case 5 compared with Case 3). The grid trading energy in Case 4 and Case 5 considering time-of-use operation is also lower than Case 1 with only P2G trading by 8.78% and 8.93% respectively. Therefore, the time-of-use trading management cases achieve the best grid power flexibility.

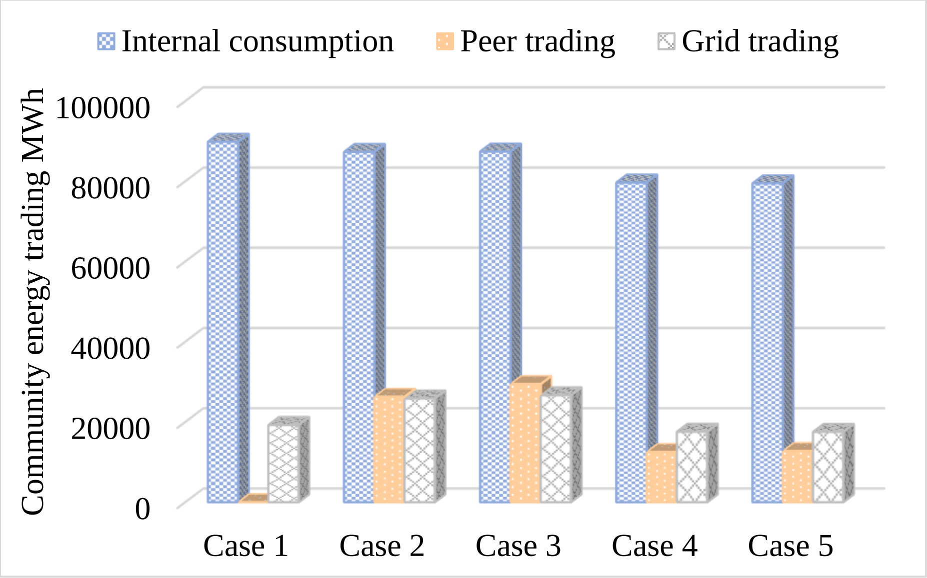


Fig. 17 Annual energy trading of five net-zero energy community cases

The time-of-use grid penalty cost covering the grid import and export during the on-peak and off-peak periods of five net-zero energy community cases is compared in Fig. 18. The penalty cost of grid import in off-peak time and grid export in on-peak time is positive with an economic fine, as the grid imported energy in off-peak time is less than the import estimation and the grid exported energy in on-peak time is also under the export estimation. While the penalty cost of grid import in on-peak time and grid export in off-peak time is negative with an economic bonus, as the grid imported energy in on-peak time and grid exported energy in off-peak time are below the import and export estimation. The total penalty cost in Case 1 with only P2G trading is about US$ -168.99k, and the bonus is reduced to US$ -40.96k in Case 2 and to US$ -3.52k in Case 3 when considering P2P trading in the net-zero energy community with more power exchange with the utility grid. While the grid penalty cost in Case 4 and Case 5 considering time-of-use P2P trading management is the minimum at about US$ -409.26k and US$ -410.43k with the maximum bonus. The grid penalty cost in Case 4 and Case 5 is reduced by 142.18% and 142.87% compared with the P2G case, indicating the best grid economic flexibility.

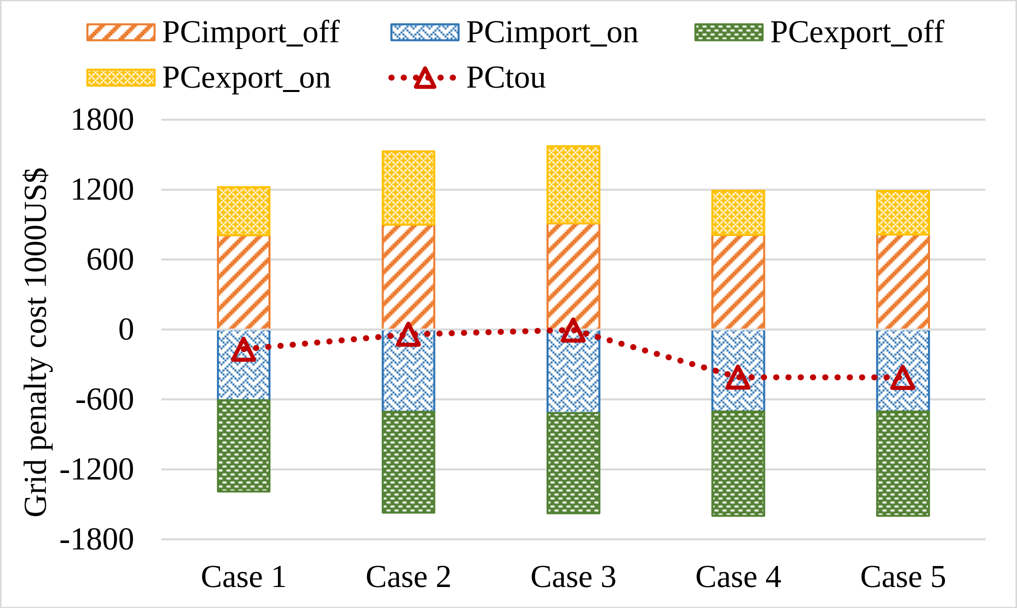


Fig. 18 Time-of-use grid penalty cost of five net-zero energy community cases

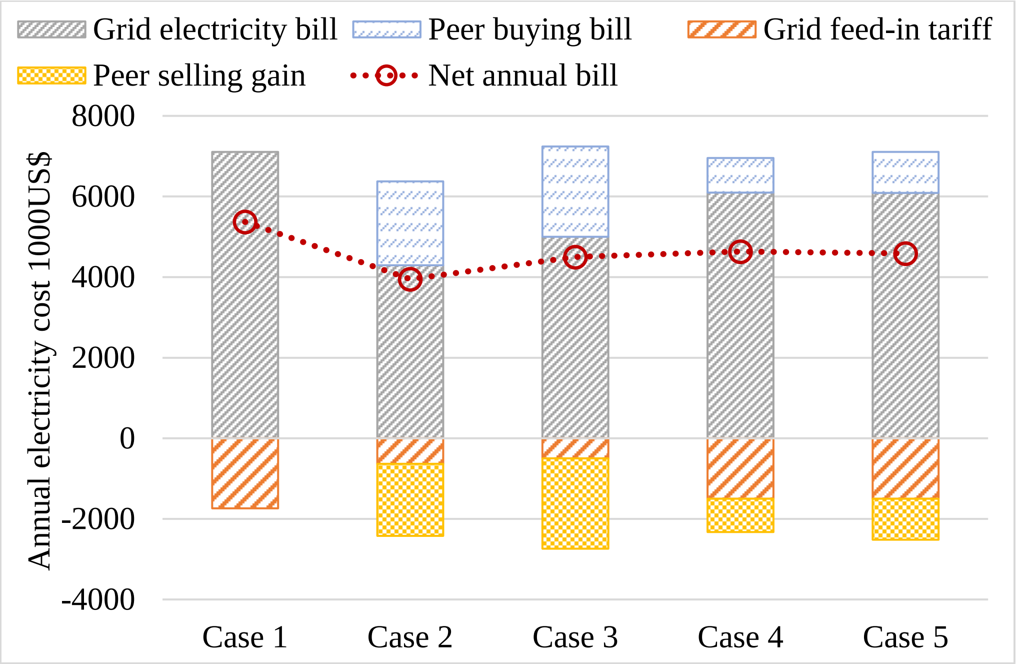


Fig. 19 Annual electricity cost of five net-zero energy community cases

The annual electricity cost of five net-zero energy community cases, indicating the net annual bill of energy selling and buying cost from both peers and utility grid, is compared as per Fig. 19. The net annual bill of Case 1 in the P2G trading operation is the maximum of about US$ 5370.04k, and it is reduced by 26.47% and 16.16% in Case 2 and Case 3 with P2P trading in the uniform and individual trading price modes. The annual electricity cost of Case 4 and Case 5 considering grid flexibility management is higher than that of Case 2 and Case 3, as the peer trading is limited by the grid time-of-use consideration. But the net annual cost in Case 4 and Case 5 is still less than that of Case 1 with only P2G trading by 13.75% and 14.54% for the uniform price mode and individual price mode, respectively.

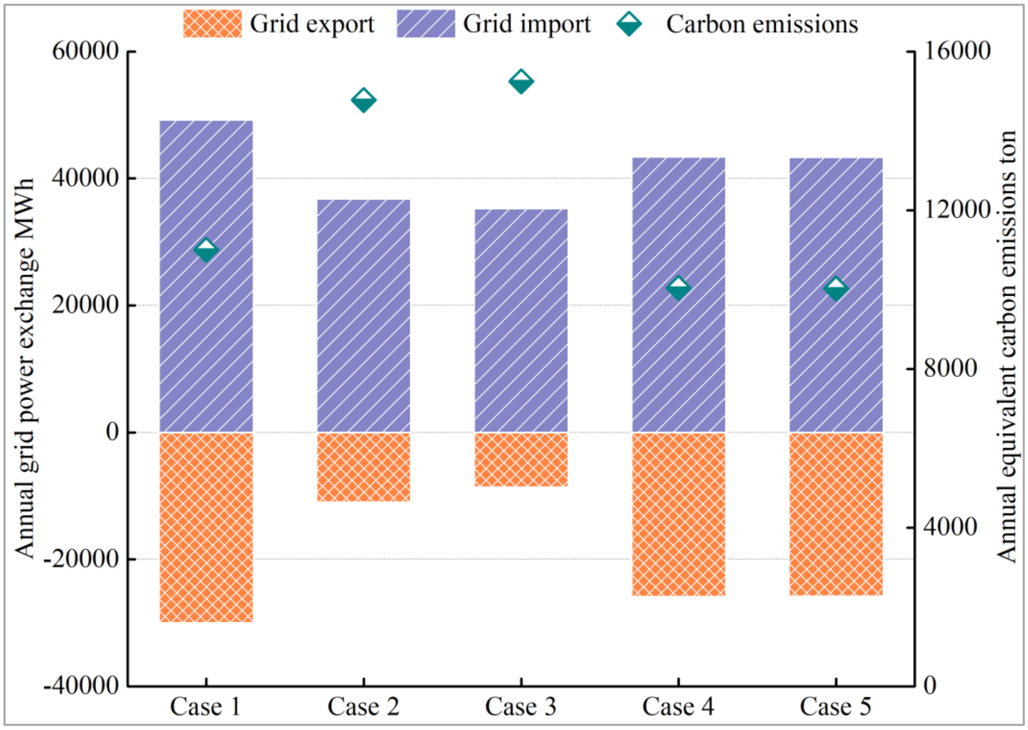
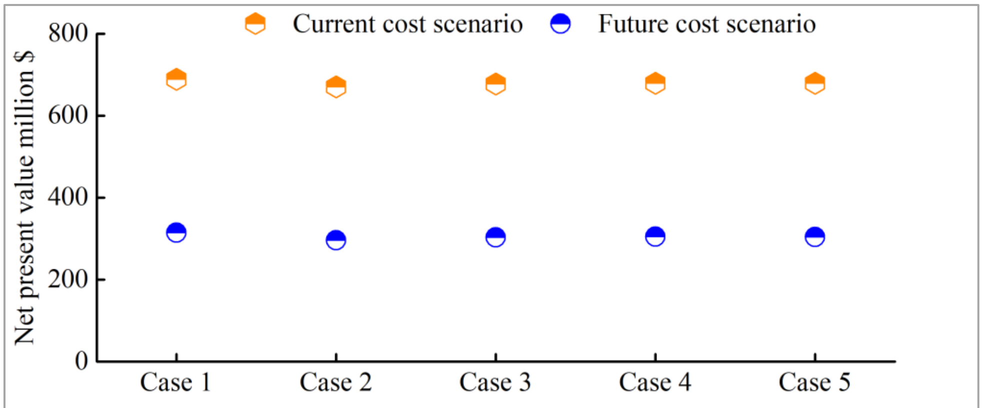


Fig. 20 Annual equivalent carbon emissions of five net-zero energy community cases

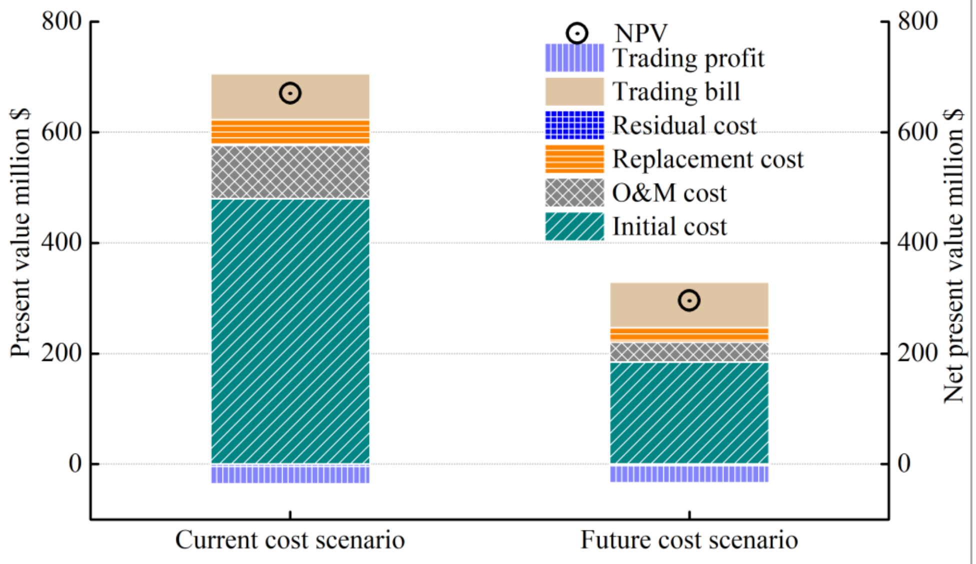
The annual equivalent carbon emissions calculated from the annual power exchange between the net-zero energy community and the utility grid of five cases are shown in Fig. 20. The annual equivalent carbon emissions of Case 1 with only P2G trading are about 11006.08 tons. It is increased by 34.26% and 38.50% in Case 2 and Case 3 with P2P trading in the uniform and individual price modes although the grid import and export energy are reduced. Because the net grid imported energy of Case 2 and Case 3 is higher than that of Case 1. The carbon emissions in Case 4 and Case 5 considering the grid time-of-use P2P trading are the minimum of about

10039.35 tons and 10023.72 tons, lower by 8.78% and 8.93% than that in Case 1 with only P2G trading management. This is because that the grid import during on-peak time and grid export during off-peak time are limited by the time-of-use management.

3.3. Lifetime net present value of hybrid renewable energy and hydrogen vehicle storage systems in current and future cost scenarios



(a) Net present value of five cases in current and future cost scenarios



(b) Present value of Case 2 in current and future cost scenarios

Fig. 21 Lifetime NPV of five cases in current and future cost scenarios

The hybrid renewable energy and HV storage systems are projected for large penetrations for building power supply in urban areas with significant cost decline in the near future, supported by advanced technology development and increased governmental subsidy. The lifetime NPV of the net-zero energy community powered by the hybrid renewable energy and HV storage systems in the current cost scenario and future cost scenario (2050) is compared as per Fig. 21. It is indicated that the system NPV in the current cost scenario of five net-zero energy community cases is about US$ 670.53 - 689.02M, and it is reduced by 54.40% - 55.90% in the future cost scenario to US$ 295.71 - 314.20M. Case 2 with the P2P energy trading in the uniform price mode shows the minimum lifetime NPV with the lowest grid trading cost with detailed items shown in Fig. 21(b). The initial cost accounts for 71.62% of the lifetime NPV of the hybrid renewable energy and HV storage system for the community power supply in the current cost scenario, followed by the maintenance cost at 14.34% and trading bill at 12.37%, respectively. The system initial cost and maintenance cost can be reduced by 61.49% and 63.11% when considering the cost reduction in the future scenario in 2050, with a total cost reduction of 55.90% on the lifetime NPV in Case 2.

3.4. Research significance, limitations and future work

This study presents peer-to-peer energy trading management approaches for a diversified net-zero energy community with hybrid renewable energy and hydrogen vehicle storage systems. An individual peer energy trading price model is proposed for the diversified community to allocate an individual peer selling/buying price for each building group, according to their intrinsic energy surplus-demand features and grid import prices. The uniform peer trading price model, with a same peer trading price for all peers developed for household communities, is also adapted for the net-zero energy community for comparison analysis. The time-of-use peer trading management strategies for the proposed individual trading price model and the adapted uniform trading price model are further developed to improve the power flexibility and economy of the utility grid. And the lifetime net present value of hybrid renewable energy and hydrogen vehicle storage systems in the current cost and future cost scenarios is further discussed as an economic reference for future applications. The improved techno-economic-environmental performance results of peer-to-peer energy trading cases (compared with the baseline peer-to-grid trading case), can provide significant guidance for peer energy management in large-scale diversified communities within urban contexts. However, this research conducts peer energy trading analysis based on a diversified community with three building groups of university campus, commercial office and high-rise residential buildings. Further studies need to be conducted on generalizing the developed individual energy trading price model and time-of-use peer energy trading management strategies to city-scale diversified building communities such as the whole Hong Kong. Furthermore, only the deterministic schedules of vehicles are assumed for the energy interaction with buildings, without the consideration on stochastic driving schedules. Future study will focus on the quantification of stochastic schedules of vehicles and associated techno-economic performances [50].

4. Conclusions

This study develops peer-to-peer energy trading management approaches for a net-zero energy community with fundamental units of university campus, commercial office and high-rise residential building groups based on actual energy consumption and simulation data. The hybrid solar photovoltaic and wind turbine systems are developed for power supply to the net-zero energy community integrated with three hydrogen vehicle groups for both daily commuting and energy storage based on the TRNSYS platform. Important findings of the present study are summarized as below:

(1) An individual peer-to-peer energy trading price model is proposed for peer energy sharing in diversified communities to allocate an individual peer selling/buying price to each building group according to its intrinsic energy surplus-demand characteristic and grid import electricity price. The superiority and economic benefits of the proposed individual peer energy trading price model for diversified building communities are demonstrated in comparison with that of the uniform peer trading price model generally for home building communities. The time-of-use peer energy trading management strategies in the uniform and individual peer trading price modes are further developed to improve the power flexibility and economy of the utility grid.

(2) The peer-to-peer energy trading improves the renewable energy self-consumption and on-site load coverage of the net-zero energy community compared with the baseline peer-to-grid energy trading, by 18.76% and 11.23% respectively for the individual peer trading price mode, as more renewable energy generation is utilized on site for peer sharing. The individual trading price mode can improve the peer-to-peer energy trading profits of the net-zero energy community by 7.46% with increased peer trading energy and increased peer selling earnings, compared with the uniform trading price mode. The proposed time-of-use peer trading management strategies achieve significant improvements in both the grid power flexibility and grid economy on top of the peer-to-grid trading, with reductions of 8.93% in the net grid import energy and 142.87% in the annual grid penalty cost for the individual trading price mode, since the grid import during on-peak time and grid export during off-peak time are limited by the time-of-use management.

(3) The time-of-use peer-to-peer trading reduces the annual electricity cost of the net-zero energy community with less net grid import energy compared with the baseline peer-to-grid trading, by 14.54% for the individual trading price mode. Obvious environmental benefits are obtained in the time-of-use peer trading management with reduced net grid import energy, with about 8.93% (982.36 tCO_2) of carbon emission reductions for the individual price mode. The lifetime net present value of the hybrid renewable energy and hydrogen vehicle system applied in the net-zero energy community can be reduced by 54.40% - 55.90% in the future cost scenario compared with the current cost scenario, showing a promising application potential in the near future.

(4) The peer trading management in a net-zero energy community with hybrid renewable energy and hydrogen vehicle storage systems is presented. The detailed techno-economic-environmental performance comparison on the net-zero energy community in different peer trading price modes and management strategies provides clear guidance for renewable energy installation and management within high-density urban contexts. The proposed individual peer energy trading price model and time-of-use peer trading management strategies provide significant references for relative stakeholders for peer trading management in large-scale diversified urban communities.

Nomenclature

Acronyms	
DR	demand ratio
FC	fuel cell
FSOC	fractional state of charge
HV	hydrogen vehicle
LCOE	levelized cost of electricity
LCR	load cover ratio
NPV	net present value
PC	penalty cost
PEMFC	proton exchange membrane fuel cell
PRV	present value
PV	photovoltaic
P2G	peer-to-grid
P2P	peer-to-peer

SCR	self-consumption ratio
SDR	supply-demand ratio
SR	surplus ratio
TOU	time-of-use

List of symbols

$P_{export\_estimated}$	grid exported power estimation, kW
$P_{export\_offpeak}$	grid exported power of off-peak time, kW
P_{export_onpeak}	grid exported power of on-peak time, kW
P_{Elegi_shor}	energy shortage of hydrogen storage system after self-sufficiency of group *i*, kW
P_{FCgi_avai}	hydrogen storage after self-consumption available for peer sharing, kW
$P_{FCgi\ to\ Loadgi}$	energy from hydrogen storage of group *i* to meet its electrical load, kW
$P_{FCgj\ to\ Loadgi}$	peer trading energy from hydrogen storage of group *j* to meet load of group *i*, kW
$P_{Grid\ to\ Loadgi}$	energy from grid to meet load of group *i*, kW
$P_{import\_estimated}$	grid imported power estimation, kW
$P_{import\_offpeak}$	grid imported power of off-peak time, kW
P_{import_onpeak}	grid imported power of on-peak time, kW
P_{Loadgi}	dynamic electrical load of group *i*, kW
P_{Loadgi_shor}	load shortage after self-sufficiency of group *i*, kW
P_{Loadgi_shors}	load shortage after self-sufficiency and peer renewables trading of group *i*, kW
P_{REgi}	dynamic renewable energy generation of group *i*, kW
P_{REgi_sur}	surplus renewable energy after self-consumption of group *i*, kW
P_{REgi_surs}	residual renewable energy after self-consumption and supplying to peer load of group *i*, kW
$P_{REgi\ to\ Elegi}$	self-consumed renewable power of group *i* to charge its electrolyzers, kW
$P_{REgi\ to\ Elegj}$	peer trading renewable power of group *i* to charge electrolyzers of group *j*, kW
$P_{REgi\ to\ Grid}$	energy from renewable sources of group *i* to grid, kW
$P_{REgi\ to\ Loadgi}$	self-consumed renewable power of group *i* to meet its load, kW
$P_{REgi\ to\ Loadgj}$	peer trading renewable power of group *i* to meet load of group *j*, kW
$P_{REgj\ to\ Loadgi}$	peer trading renewable power of group *j* to meet load of group *i*, kW
$PC_{export\_offpeak}$	penalty cost of grid exported power of off-peak time, US$
PC_{export_onpeak}	penalty cost of grid exported power of on-peak time, US$
$PC_{import\_offpeak}$	penalty cost of grid imported power of off-peak time, US$
PC_{import_onpeak}	penalty cost of grid imported power of on-peak time, US$
PC_{TOU}	time-of-use grid penalty cost, US$
$PF_{offpeak}$	penalty factor of off-peak time, US$/kWh
PF_{onpeak}	penalty factor of on-peak time, US$/kWh
$Prbuy$	peer-to-peer energy buying price, US$/kWh
$Prsell$	peer-to-peer energy selling price, US$/kWh

Rbuy	grid electricity buying rate, US$/kWh
Rsell	grid feed-in tariff rate of renewable energy, US$/kWh

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