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Investigation of residential heat and transport electrification considering grid flexibility within existing zero energy houses

Wenya Xu¹, Yingjun Ruan^{1*}, Tingting Xu¹, Yuting Yao¹, Hua Meng¹ and Yanxue Li^{2,3}

¹ College of Mechanical Engineering, Tongji University, Shanghai, 201800, China

² Innovation Institute for Sustainable Maritime Architecture Research and Technology, Qingdao University of Technology, Qingdao, 266033, China

³ Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China

*E-mail: ruanyj@tongji.edu.cn

Abstract. The development of distributed energy resources (DERs) provides favorable conditions for building energy systems decarbonization. However, the rising penetration of DERs has led to many challenges, such as supply-demand imbalances and sharp increases in net loads. Tapping demand-side flexibility and developing building sector electrification are effective approaches to facilitate the transition to decarbonized and decentralized building energy systems. This study proposes a comprehensive dispatch model to explore the potential for residential electrification flexibility. It is validated through real-world data measured from zero energy houses (ZEHs) in Kyushu, Japan. It assesses the benefits of collaboration between heat pumps and electric vehicles within ZEHs across varied dispatch strategies, including scenarios reflecting the impact of tariff structures and optimization objectives. Furthermore, the seasonal characteristics of the multi-energy coupling are analyzed. The results validate the potential of building electrification, leading to operating cost savings of over 66%. Additionally, a self-consumption rate of more than 77% for photovoltaics is achieved through the deployment of hot water and transportation electrification. When utilizing fixed feed-in and time-of-use tariffs, PV on-site consumption and operating costs show opposite trends.

1. Introduction

To mitigate climate change, many countries have set their ambitious decarbonization targets. The building sector accounts for 30%-40% of final energy consumption [1], and carbon emissions from energy consumption have emerged as a pivotal challenge for environmental sustainability. The operational stage of a building accounts for 70% of total carbon emissions [2]. There is an accelerating transition to decarbonized and decentralized building energy systems [3]. Zero energy houses (ZEHs) are one strategic energy-saving concept that produce as much energy as they consume and plays an important role in carbon neutrality by mitigating carbon emissions [4, 5]. The basic ways to achieve ZEHs can be summarized as minimizing demand from buildings and maximizing consumption of variable renewable energy resources [6]. Renewable energy



resources, particularly solar photovoltaics (PV) generation, play a critical role in increasing the ZEH energy independence. The increasing penetration of renewable energy resources, in particular solar PV generation, is one of the key technologies to promote the development of ZEHs [7]. Additionally, solar PV and wind renewable powers exhibit steep cost reductions in levelized cost, accelerating their developments in distributed networks. Distributed energy resources (DERs) are characterized by their intermittent nature and fluctuating availability, which can present opportunities and risks in planning and operating low-carbon energy systems [8, 9]. As the intermittent PV penetration rises, it results in the transient energy supply-demand mismatch on the demand side, and it also brings about challenges for the stability and reliability of grid operations due to the integration of a large amount of PV generation into the power grid. For example, the "duck curve" phenomenon has been extensively concerned which is characterized by a significant increase in net electricity load in periods of low PV generation [10].

In recent years, DERs, such as PV, heat pumps (HP), battery storage, and electricity vehicles (EVs), have developed quickly. For example, the installed capacity of HPs in Japan, recognized as one of the most mature markets for this technology, has consistently increased to reach 36GW [11]. Previous works have suggested that electrification of heating and transportation and sustainable energy supply are cornerstones of the success of the global energy transition and world decarbonization [12]. The integration of DERs in the building with the grid inevitably leads to increased peak demand for electricity and grid capacity reduction and congestion. The rising penetration of electrification creates a higher demand for grid flexibility and multi-energy coupling [13, 14]. Tamara Knittel et al. [15] analyze heat electrification in residential and commercial buildings located in British Columbia, Canada. The study aimed to assess the impact of various levels of heating electrification on peak electricity demands and ramping events. The results indicate that with a 50% HP penetration, moderate improvements in envelope efficiency can lead to a 60% increase in peak electricity demand, while minimal improvements in envelope efficiency can result in a ramping rate increase of up to 144%. The adoption of large-scale HP penetration would further strain grid flexibility. However, recent efforts have also highlighted the value of EVs for the decarbonization of buildings. Annamaria Buonomano et al. [16] study the energy and economic potential of vehicle-to-building (V2B) energy management for various users. The analysis of the proposed case demonstrates that residential buildings can achieve energy demand reductions of up to 82%, while office buildings can achieve reductions of up to 62%. The scenario involving an integrated energy storage system combining home energy storage and EVs shows the most favorable economic outcomes. Improving the matching between on-site renewable generation and energy consumption is important to ensure high energy self-sufficiency and improve energy flexibility.

Transitioning to decarbonized and decentralized building energy systems requires attention to the electricity market dynamics. Previous research finds that the market value of renewable generation can evolve with grid decarbonization and tends to decline as the penetration level of renewables increases. For example, Japan's fixed feed-in tariff (FIT) was 19 yen in 2019, decreasing to 7 yen in 2024 [17]. Zero and even negative prices have also been observed in spot markets [10, 18]. Time-of-use tariffs (TOU) are usually used to incentivize users to shift their energy demand to off-peak hours. However, building electrification can generate new peak hours and unpredictable load demand fluctuations in time series [15, 19]. The electricity price can impact the user's electricity consumption behaviors. It is crucial to clarify the electricity market's role in the interaction between buildings and the grid and necessary to assess the impact of electricity markets on the scheduling of building energy systems.

In the management of building energy systems, minimizing operating costs [20] or carbon emissions [21] or maximising on-site self-consumption of renewable energy [22] is often used as an optimization objective for the system. Previous research has revealed that different optimization objectives do not always exhibit the same results and may have opposite results [23]. The diverse objectives may have led to the difference between the electrification deployment and economic benefits. These all emphasize the need for policymakers to address tariff reforms or technological advancements accordingly. Therefore, achieving a sustainable decarbonization pathway for the energy system with large-scale development of DER is indeed a complex task that involves balancing conflicting objectives [24]. Relying solely on the widespread development of energy efficiency measures is also not sufficient; it is essential to transform the energy system towards greater flexibility and resilience.

This research develops a comprehensive bottom-up dispatch model to unlock the flexibility potential of residential electrification fully. The validity of the model is cross-validated using energy system operational data measured in existing ZEHs. The study evaluates the benefits of the cooperation between HPs and EVs in ZEHs under different dispatch strategies. The different dispatch strategies encompass scenarios based on realistic spot market electricity prices and TOU tariff schemes, as well as scenarios where optimization objectives focus on minimizing operating costs, reducing grid fluctuations, or both. Subsequently, the study investigates dispatch results, grid flexibility, and economic benefits under these scenarios. Key performance indicators include grid netload, PV self-consumption rate, and energy costs. Comprehensive analyses and comparisons offer valuable insights into energy system flexibility and resilience with the increasing penetration of DER.

2. Objective and data resource

2.1 Research objective

Due to its proximity to the equator, the Kyushu region has significant solar investment potential. Initially, curtailment issues were the first to occur in the region due to limited grid flexibility [25]. This paper focuses on the energy system of ZEHs, which primarily consists of rooftop PV, bidirectional EV systems, and air-source heat pumps with hot water storage tanks, as shown in Figure 1. Two scheduling scenarios are proposed to explore the flexibility potential of different sector couplings in the existing ZEHs. One scenario emphasizes optimizing energy cost minimization using grid-imported TOU tariffs and fixed PV feed-in tariffs. At the same time, the other focuses on energy cost minimization through grid import/export based on spot price profiles. Additionally, the study compares and evaluates two optimization objectives: minimizing energy costs and minimizing grid volatility.

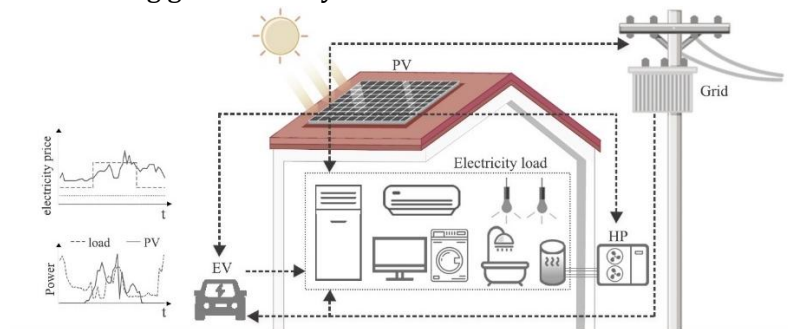


Figure 1. Diagram of the hybrid energy system in zero energy houses.

2.2 Data resource

The residential operation data in this study were obtained from two ZEHs in a zero-carbon community in Kyushu, Japan. Energy system operational data, including total power consumption, PV power generation, PV power sales, grid-purchased power, and heat pump power consumption, were collected in real-time at 30-minute intervals over one year through an installed cloud-based collection platform. Table 1 provides an overview of the annual operation of the energy systems in the examined ZEHs. The results indicate that the local consumption rates of PV energy in the two ZEHs are only 21.1% and 35.3%, with excess PV power sold to the public grid. Notably, heat pumps account for 21.1% and 16.7% of the annual electricity consumption, respectively, highlighting the significant potential for regulation. The study utilizes FIT and TOU prices employed in the Kyushu region obtained in [17]. Additionally, the spot price has been taken from [26].

Table 1. Annual operational data of the examined zero energy houses

Variables	ZEH1	ZEH2
Load / kWh	7301	10168
PV generation / kWh	6644	6651
Grid import / kWh	5902	7821
Grid feed-in / kWh	5245	4304
HP consumption / kWh	1537	1701
Operation cost / Yen	341697	394115

The ambient temperature data are taken from the Japan Meteorological Agency [27]. Existing research indicated that HPs' coefficients of performance (COP) vary with temperature. The HP power consumption and heat production data are fitted with the ambient temperature data. According to the reference [4], the dynamic COP for the measured year is obtained by fitting the relationship between heat pump power consumption and ambient temperature. It is shown in Figure 2. Before the study, data regarding the purpose of EV trips, return times home, and the probability distribution of travel distances were collected through an in-depth examination of residential EV traffic in the Kyushu region. Utilizing the Monte Carlo algorithm simulation, annual travel hourly discharge curves for EVs were generated, as shown in Figure 3.

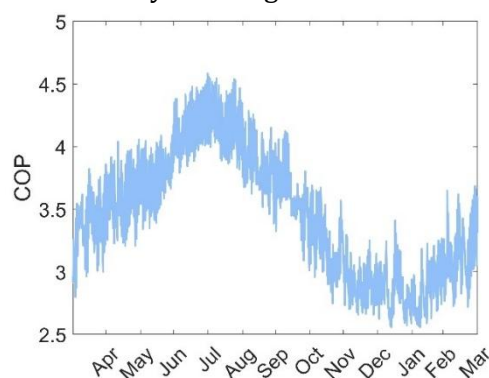


Figure 2. Calculated COP.

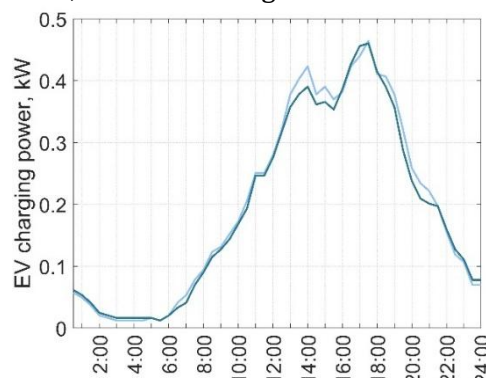


Figure 3. Average half-hourly EV charging power.

3. Methodology

The balance between the fluctuating demand for electricity and hot water in the operation of the residential building energy system can be described by Eq.1 and Eq.2. The other electrical loads are satisfied by PV, EV and the power grid. It can be described as Eq.3.

$$P_{load}(i) = P_{pv}(i) + P_{ev}(i) + P_{grid}(i) \quad (1)$$

$$P_{load}(i) = P_{load_oth}(i) + P_{hp}(i) \quad (2)$$

Where, P_{pv} presents the PV power generation, P_{ev} is the charging or discharging power of EV. P_{grid} denotes the electricity exported to/imported from the grid. P_{load} represents the total energy load for residential buildings. P_{load_oth} is the other electricity demands of users except hot water load. P_{hp} presents the HP power consumption. The power balance of HP can be described by Eq.3:

$$SOC_{hp}(i) = [P_{hp}(i) \times cop(i) \times \Delta i \times \eta_{hp} - Q_{load}(i) \times \Delta i \times \eta_Q + E_{hp_init}(i-1)] / cap_{hp} \quad (3)$$

Where, η_{hp} presents the efficiency of HP charging. Q_{load} is the hot water demand, cop is the COP of HPs which is used to calculate the electricity consumption for hot water production. η_Q is the coefficient of heat loss, where it is set to 0.98. E_{hp_init} present the energy status of the HP system at the time $i-1$. cap_{hp} is the nominal storage capacity of thermal tanks. Eq.4 show the minimum and maximum power charging and discharging constraints of the HP. As for the regulation of energy systems, the state of charge (SOC) of HP is always within the security constraints. It is expressed as Eq.5.

$$P_{hp_min} \leq P_{hp}(i) \leq P_{hp_max} \quad (4)$$

$$SOC_{hp_min} \leq SOC_{hp}(i) \leq SOC_{hp_max} \quad (5)$$

The bidirectional EV system can be expressed by:

$$P_{ev}(i) = P_{ev_cha}(i) + P_{ev_load}(i) - P_{ev_dis}(i) - P_{evd_load}(i) \quad (6)$$

$$\sum_{(i-1)*48+1}^{i*48} P_{evd_load}(i) = \sum_{(i-1)*48+1}^{i*48} P_{ev_load}(i), i = 1, 2, 3, \dots, N \quad (7)$$

Where, P_{ev_cha} and P_{ev_dis} are the EV charging and discharging power. P_{ev_load} is the total charging power of EV after getting home. It is generated by EV load sampling based on the Monte Carlo. P_{evd_load} is the discharging power of EV when driving. The sum of P_{ev_load} and P_{evd_load} should remain constant throughout the day, as both are resulted by the same driving behaviours. The real-time energy of EV at time i is satisfied as Eq.8. To ensure safe operation of the EVs, the charging and discharging power and SOC also need to be constrained. They can be described as Eq.9 and Eq.10.

$$SOC_{ev}(i) = \left[\left(P_{ev_cha}(i) + P_{ev_load}(i) \right) \times \Delta i \times \eta_{ev_cha} - \left(P_{ev_dis}(i) + P_{evd_load}(i) \right) \times \Delta i \times \eta_{ev_dis} + E_{ev_init}(i-1) \right] / cap_{ev} \quad (8)$$

$$P_{ev_min} \leq P_{ev}(i) \leq P_{ev_max} \quad (9)$$

$$SOC_{ev_min} \leq SOC_{ev}(i) \leq SOC_{ev_max} \quad (10)$$

Where, E_{ev} present the energy status of EVs at time i . Similarly, E_{ev_init} is the energy status of the EV system at the time $i-1$. η_{ev_cha} and η_{ev_dis} are the efficiency of EV charging and discharging. cap_{ev} is the battery nominal storage capacity of EVs.

The energy cost focuses on real-time transactions between the home and the grid, representing the sum of electricity purchase costs and PV feed-in revenue over a specified period.

Grid volatility pertains to the fluctuations in grid import. The final optimization objective aims to find a balance between these two factors. They can be described as follows:

$$P_{grid}(i) = P_{grid_buy}(i) - P_{grid_sell}(i) \quad (11)$$

$$object_1 = \sum_{i=1}^I (P_{grid_buy}(i) \times \Delta t \times pri_b(i) - P_{grid_sell}(i) \times \Delta t \times pri_s(i)) \quad (12)$$

$$object_2 = \sum_{i=2}^I (P_{grid_buy}(i) - P_{grid_average}(i-1))^2 \quad (13)$$

$$\min F = object_1 + object_2 \times f \quad (14)$$

Where, P_{grid_buy} denotes the electricity from grid import, P_{grid_sell} denotes the electricity from grid export. pri_b presents TOU tariff and pri_s presents the feed-in tariff in electricity market. $P_{grid_average}$ denotes the average hourly load. f is the weight.

The simulation is solved by using MATLAB on a laptop with Intel(R) Core(TM) Ultra 9-185H (2.50 GHz), 16.0 GB of memory, under Windows 10 64-bit operating system.

4. Results and discussion

4.1 Operating comparisons of different coupling scenarios

Figure 4 depicts typical coupling scenarios of the building energy system on a typical weekday in winter and summer. The blue line presents the status of the HP operation. The positive value shows the power of hot water generation, and the negative value shows the hot water consumption. The green line presents the status of the EV operation, in which the positive value denotes the charging power, and the negative value denotes the discharging power. The grey line shows the transaction between the grid and the ZEHs. The positive value means the users purchase the electricity from the grid, and the negative value means the electricity sold to the grid. The typical winter day is characterized by high load demand and low PV generation. In the PV-EV-HP coupling and PV-HP coupling scenarios, the HP concentrates on hot water storage during the low tariff hours in the morning. The EV also chooses charging during the low tariff hours. It discharges to satisfy the building load during the high tariff hours. Due to non-home hours such as EV trips, EV discharges alone cannot achieve building load balance. As a result, there is a large electricity demand to purchase from the grid on this typical winter day.

In the chosen summer typical day, PV generation of daytime is much higher than the building load. In the PV-EV-HP coupling scenario, it can be observed that the HP operation is shifted to the high PV generation period compared to the PV-poor day, and the PV power is utilized to run the stored hot water. A comparison of the two coupled scenarios shows that the HP operation exhibits the same pattern. However, the feed-in electricity shows an understandable decrease in the PV-HP scenario. This is mainly because this power is stored by the EV charging. Some of the stored PV power is used for EV traveling power consumption, and some are released to satisfy the user's demand in the evening, i.e., when the EV is at home. In the two typical daytime coupling scenarios, the SOCs of the EV and HP are always within the set safe range. By observing the two coupled scenarios, it can be found that the bidirectional EV system can effectively improve on-site PV consumption.

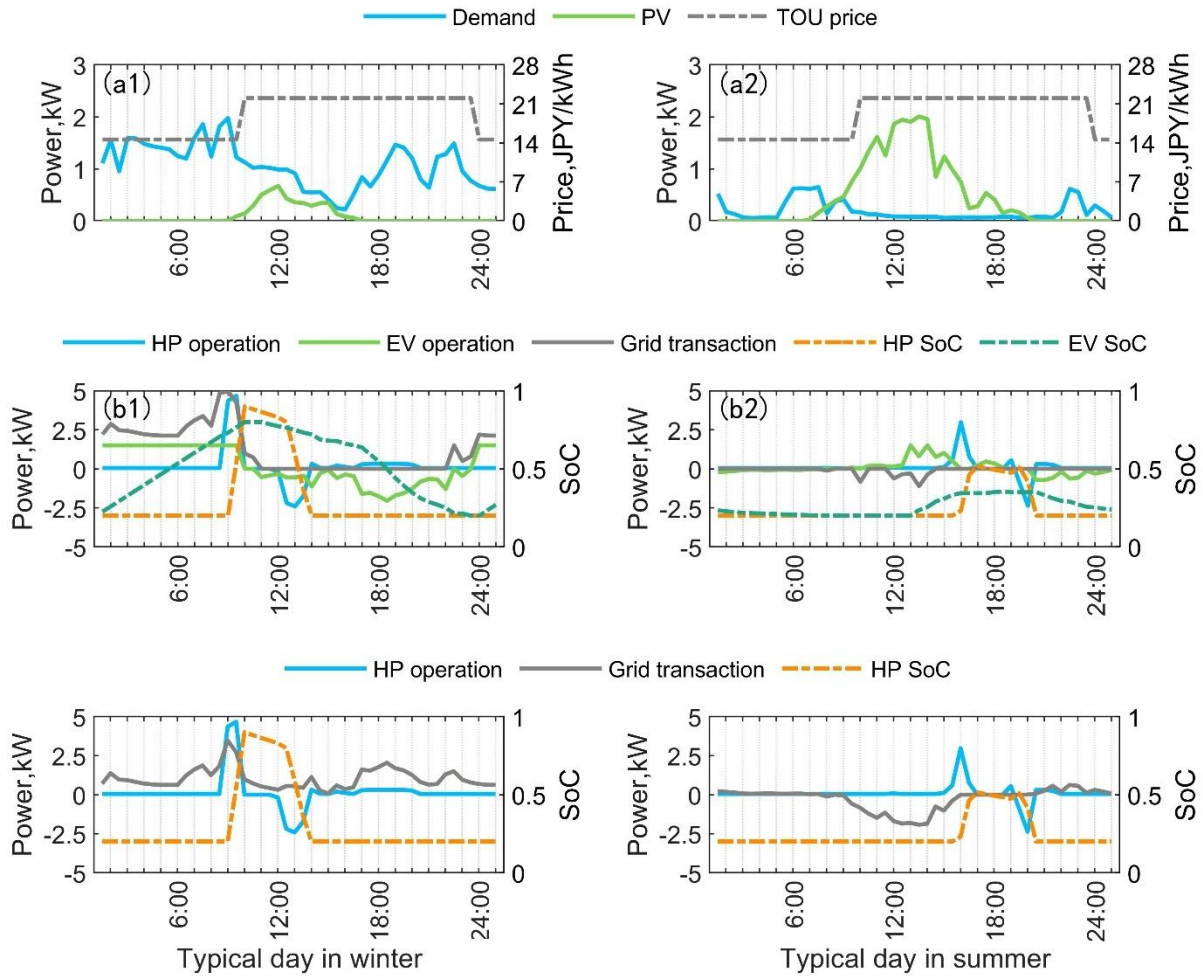


Figure 4. Operation of the residential building energy system on typical weekend in winter and summer: (a) Demand for the renewable energy supply of residential buildings; (b) Operation of energy system coupled with EV and HP; (c) Operation of energy system coupled with HP.

4.2 Dispatch result comparisons of different tariff strategies

Figure 5 shows the dispatch results of two ZEHs on one typical mid-season day, considering different tariff strategies. (b1) and (b2) demonstrate the operation profiles based on the TOU tariffs, and (c1) and (c2) depict the operation profiles based on the spot market price. When the PV generation is surplus, it can be seen that the surplus PV is used by HP to store hot water. The grid mainly offers the charging demand of EVs. The discharging actions of EVs mainly result from daily driving needs. The load demand in the night is served by electricity from the EV discharging and grid import. The grid import mainly shows in the low tariff hours. However, based on the spot price strategy, the operation shows a larger demand for grid import. An amount of electricity is transacted according to the peak-valley values of electricity prices. HP's operation also shows the difference between the different tariff strategies. HP consumes PV for hot water storage and operates low spot price hours. This means that the electricity imported from the grid during the low-price hours can be used, and the PV generation during the high-price hours can be sold at the spot market price.

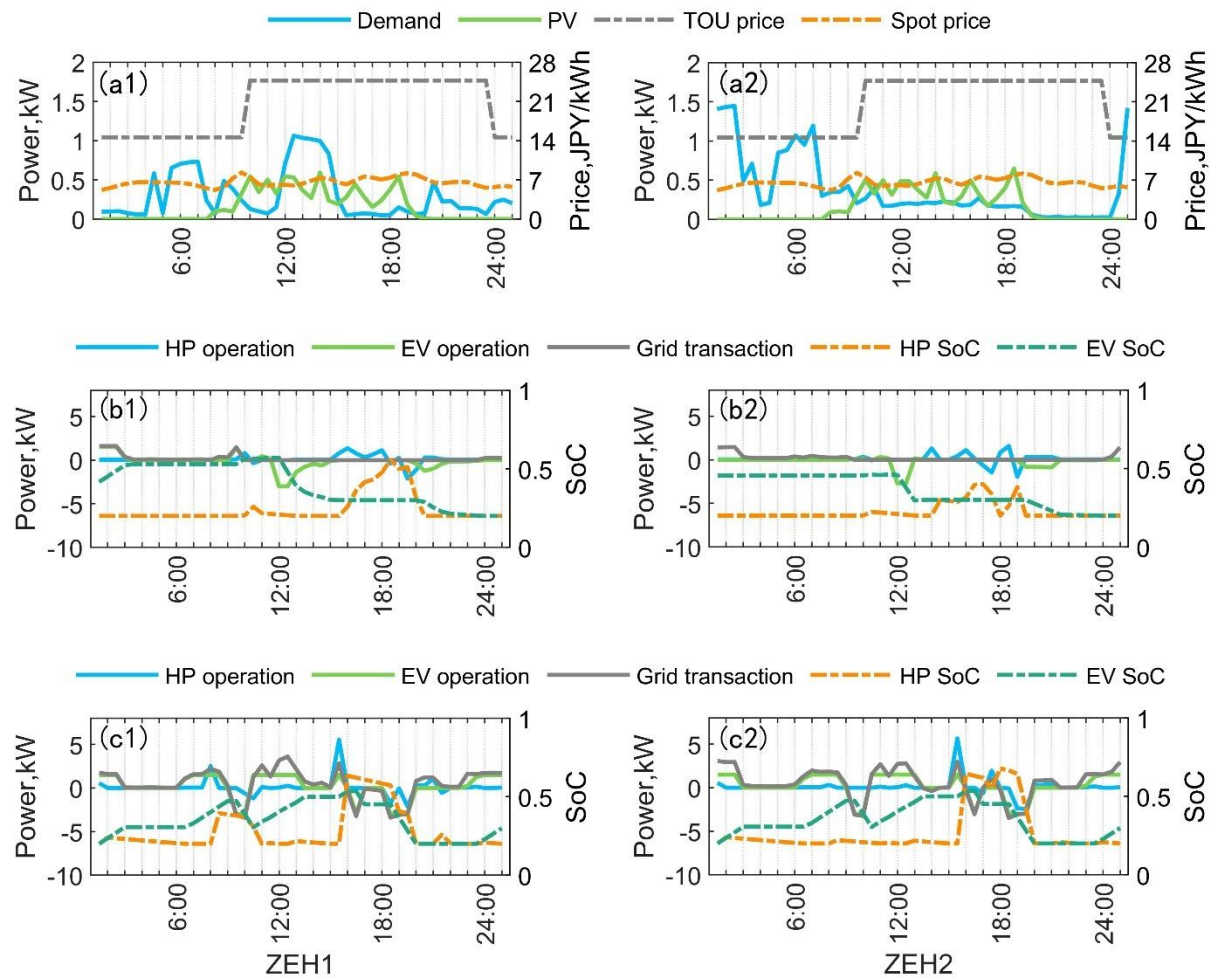
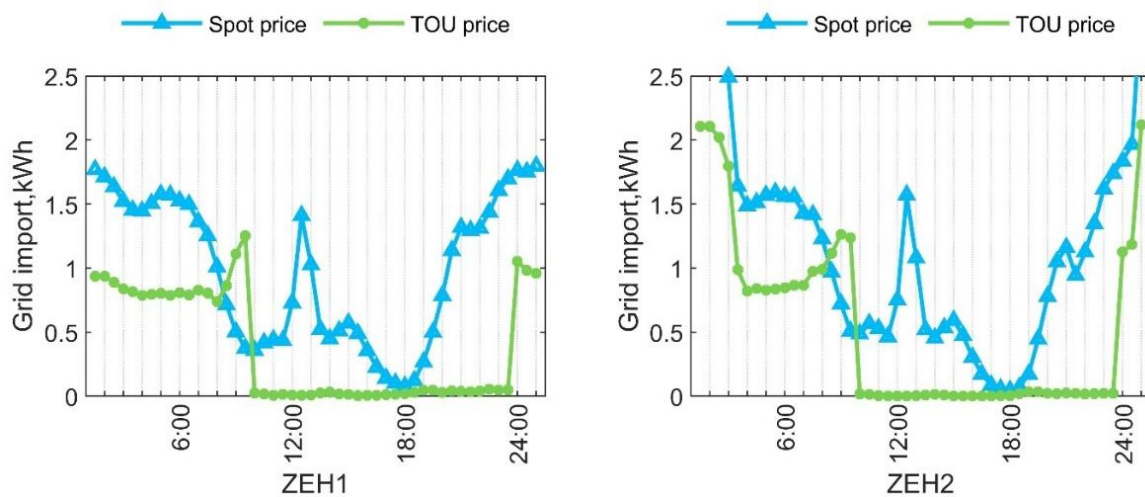


Figure 5. Operation of the residential building energy system on typical day within different tariff strategies: (a) Demand for the renewable energy supply of residential buildings; (b) Operation of energy system based on TOU tariff; (c) Operation of energy system based on spot price.

Table 2 shows the chosen key indicator values of two ZEHs within the different tariff strategies. As mentioned in the previous analysis, under the spot price strategy, ZEH may sell excess PV generation during high tariff periods for more arbitrage. The results show that two ZEHs show a smaller self-consumption ratio within the spot price strategy. It also has a higher grid import, so the energy system can arbitrage more to take advantage of the differences between real-time prices. The ZEHs achieve optimal operational cost savings based on the spot price strategies. In all scenarios, operational cost savings of more than 66% are achieved compared to the real-time monitoring data of ZEHs. Figure 6 demonstrates the comparison of grid import profiles within different tariff strategies. It can be seen that the spot price strategy shows higher grid import demand than the TOU strategy. It also means higher net load and grid dependence. Based on the TOU price, it generates two electricity demand peaks in 0:00-9:00 and 23:00-24:00. However, there is another demand peak in 12:00-13:00. It results from the low price in the periods. Additionally, the amount of electricity imported from the grid within the spot price is 1.5 times as large as that within the TOU price strategy, which will pose great challenges to grid operation.

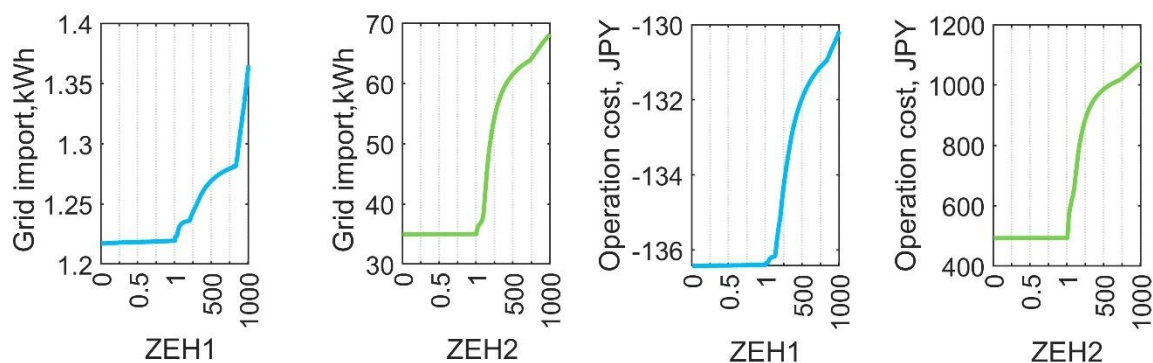
Table 2. Key indicators comparison of the ZEHs within the different tariff strategies.

	TOU tariff strategy			Spot price strategy		
	Self-consumption ratio	Grid import (kWh)	Operation cost (JPY)	Self-consumption ratio	Grid import (kWh)	Operation cost (JPY)
ZEH1	0.95	6738	98561	0.77	17326	9295
ZEH2	0.99	9222	135153	0.83	19914	26348

**Figure 6.** Comparison of grid import profiles within different tariff strategies.

4.3 Impact of different optimisation objectives on the grid flexibility

Figure 7 compares key indicators as the weight changes with the TOU tariffs. As illustrated in Section II, the first part of the objective function represents the operational cost, with a smaller value indicating greater cost savings. The second part of the objective function represents grid stability, where a smaller value indicates reduced grid fluctuation and more stable operation. As renewable energy penetration increases, grid stability becomes an important consideration. The impact of the weights on the self-consumption ratio is not shown in the figure due to the unclear nature of the changes. The figure shows that when grid stability is included in the optimization objective, the grid import and operational costs remain relatively stable when the weight is between 0 and 1. However, when the weight exceeds 1, the grid import and operational costs increase significantly.

**Figure 7.** Comparison of key indicators with the weight f changes.

5. Conclusions

This study utilizes the hourly measured data of exiting ZEHs to examine the potential of electrifying transport and hot water and its impact on the residential energy system operation. This study proposes a bottom-up integrated scheduling model for the operation of ZEH energy systems and evaluates their electrification potential. A comprehensive comparison of coupling scenarios is investigated, considering different tariff mechanisms and operation objectives. The main findings are summarized as follows:

Across all simulation scenarios, there is a notable enhancement in PV on-site consumption capacity and a reduction in net load demand with over 66% savings in operating costs. Based on the scheduling results, the HP operation time is adjusted from the morning to peak PV generation hours. During periods of insufficient PV generation, the HP prioritizes utilizing low-cost hourly power to heat water. The EV performs superior as a mobile energy storage system within the scheduling framework. Grid importation rises significantly under the spot price tariffs, with different tariff structures showing nearly a 1.5-fold variation in net load peaks. However, for the ZEHs' users, operating cost savings are nearly doubled under the current spot price. Moreover, the relative weights between these objectives significantly impact system performance when optimizing operations with concurrent objectives such as operational cost and grid stability. In this research, the results suggest that the weight ranging from 0 to 1 is optimal.

Acknowledgments

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