

Optimizing design and performance assessment of a community-scale hybrid power system with distributed renewable energy and flexible demand response

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ABSTRACT

Modern urban energy system with renewable energy sources has become an effective solution to enhance energy security and promote carbon neutrality. This paper presents a holistic framework for the optimal design and management of such a flexible hybrid power system at the community scale. This framework integrates the potential assessment of rooftop PV and waste biomass, a general optimization approach with multi-perspective performance evaluation, as well as the impacts analysis of energy policy, demand response, and uncertain economic parameters. The proposed framework was applied to a small neighborhood area in Beijing, China. It was found that 100% utilization of available biomass and rooftop PV would satisfy 73% of local electricity demand with the levelized cost of electricity of 0.1030 \$/kWh and the embodied carbon emission of 0.5416 kg/kWh. The flexible shiftable load could lead to lower peak load and less electricity supply cost, and help to match the energy demand with the dispatchable rooftop PV output. However, the economic benefits caused by implementing demand response are more obvious than the environmental benefits. Furthermore, a higher electricity tariff and lower capital cost of PV technology would facilitate the investment in rooftop PV and achieve carbon emission reduction targets.

1. Introduction

Urban areas consuming about 75% of the world's total energy contribute 70% of worldwide carbon dioxide emissions (IEA, 2018). To date, most urban areas worldwide still heavily rely on the centralized energy supply of non-sustainable fossil fuels (Zhang et al., 2020). Driven by rapid urbanization and population growth, cities, especially in developing countries, are facing increased threats from rising energy demand, dwindling fossil energy, scarce land resources, and serious environmental pollution (Murray et al., 2020). Distributed renewable energy with the advantages of lower carbon emissions, reduced transmission and distribution losses, and avoided investments have been seen as effective solutions to achieve the decarbonization goal and sustainable development (Paiho et al., 2018; Luo et al., 2019). Optimal design and management of hybrid power systems with distributed renewable

energy generation is still a complex and challenging task considering the unique local resource conditions and competitive advantages of various technologies from different perspectives.

The studies on the urban hybrid energy system have started to embrace the tendencies from the building scale to the city scale. A lot of research has been done on the techno-economic-environmental assessment and optimal design of the urban energy system with new energy technologies (Yoon et al., 2018; Ugwoke et al., 2021). Prevalent technological options of hybrid energy systems in current research are usually PV arrays, wind turbines, battery systems, and combined heat and power (CHP) units in the form of turbines, engines, or fuel cells. For example, Maleki et al. (2017) developed an economic model and optimization method for a grid-connected hybrid energy system consisting of PV-wind turbine-fuel cells to satisfy the heat and power demand of the residents. Rajbongshi et al. (2017) focused on the optimal design of a

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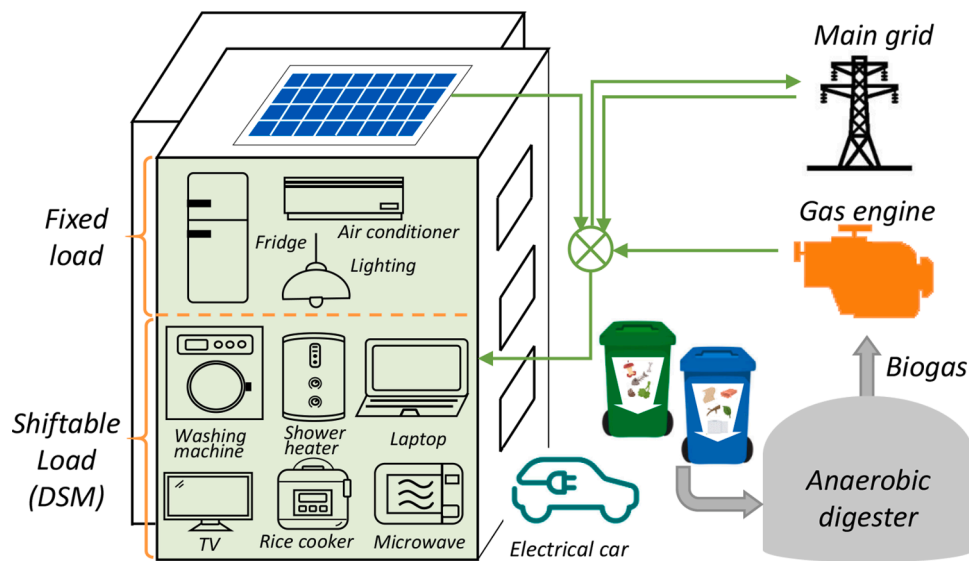
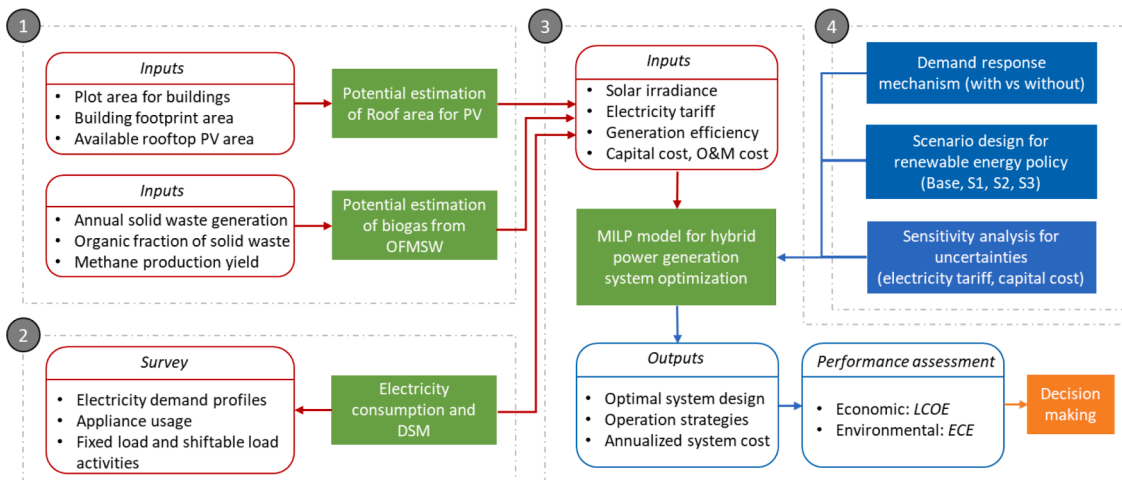
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Table 1

Summary of studies on optimal sizing of the residential hybrid energy system.

Articles	Technical components					Space potential for rooftop PV	DR	Operation modes
	PV	BIO	DG	BAT	Others			
Wang et al. (2015)	✓	-	✓	✓	-	-	✓	Stand-alone
Ren et al. (2016)	✓	-	-	-	✓	-	-	Grid-connected
Jafari & Malekjamshidi (2020)	✓	-	-	✓	✓	-	-	Grid-connected
Shivam et al. (2021)	✓	-	-	✓	-	-	-	Grid-connected
He et al. (2022)	✓	-	-	✓	✓	-	✓	Grid-connected
Khezri et al. (2022)	✓	-	-	✓	✓	✓	-	Grid-connected
Liu et al. (2022)	✓	-	-	✓	✓	-	-	Grid-connected
Navas et al. (2022)	✓	-	-	✓	✓	✓	-	Grid-connected
This paper	✓	✓	✓	✓	-	✓	✓	Grid-connected

Note: PV represents solar photovoltaic, not including rooftop PV; BIO is biomass generator, DG is diesel generator, BAT is battery storage, and DR denotes demand response.

**Fig. 1.** Configuration of a community-scale hybrid power system.**Fig. 2.** Research framework of the optimization of the hybrid power system.

hybrid energy system based on PV-biomass gasifier-diesel for a rural area by using the HOMER simulation tool. [Cremi et al. \(2020\)](#) proposed an optimization model for the techno-economic assessment of a hybrid energy system consisting of PV, diesel-fired and gas-fired combined-heat-and-power, and electric storage, and applied it to an exhibition center in Bari. [Liu et al. \(2021\)](#) studied the optimal energy planning for a

hybrid PV and wind energy system with battery and hydrogen vehicle storage technologies for a high-rise residential building.

In addition to the penetration of various distributed energy generation on the supply side, hybrid energy systems also face management challenges on the demand side especially due to the smart equipment and effective building automation systems. Flexible demand-side

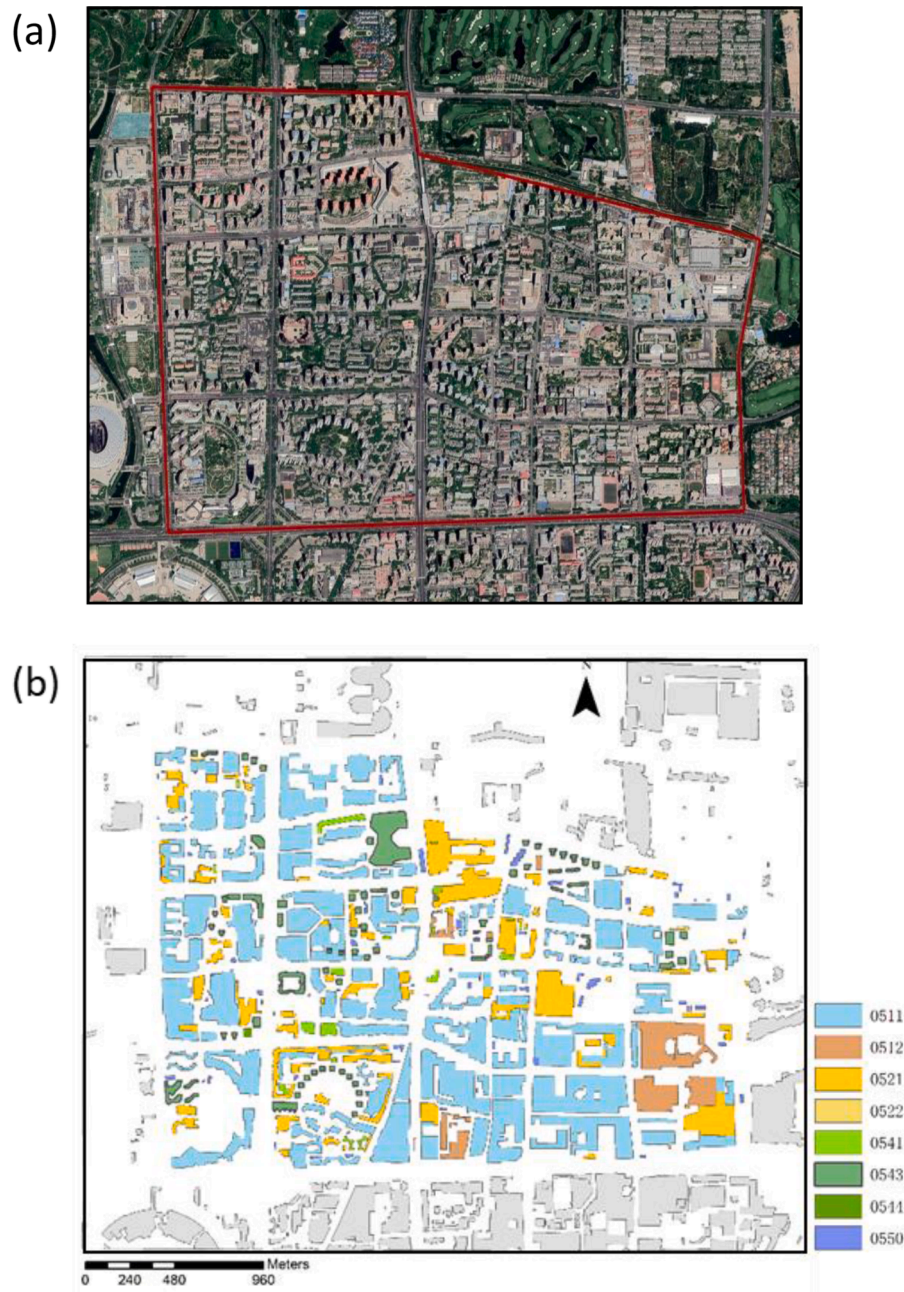


Fig. 3. Satellite image (a) and building footprint area (b) of the study area.

response actives of end-users play a significant role in balancing the less stable generation from renewables. Economic incentives and administrative measures are the main demand response schemes to reduce peak load or adjust demand curves. Some researchers have included demand response in the management of residential hybrid energy systems and highlighted the effectiveness of demand response in frequency control. For example, Wang et al. (2015) optimized a hybrid renewable energy system for a single-family residential home with a two-step demand response mechanism. The work of He et al. (2022) demonstrated that a demand response strategy could reduce the investment cost of the hybrid energy system by rearranging the deferrable loads.

Table 1 summarizes the research focuses of recent studies on optimal sizing of the residential hybrid energy system. It is found that PV technology is widely used due to the cost advantages. In practice, the deployment of PV panels requires sufficient land resources, which brings great challenges for densely built cities where the land resources are

scarce and expensive. Thus, rooftop photovoltaics is considered a promising solution to achieving greenhouse gas reduction targets at the community or neighborhood scale. However, few studies have evaluated the geographic potential for rooftop PV panels deployment in the urban hybrid energy system with PV penetration. In addition, with the rapid urban development, the increasing production of municipal solid waste (MSW) is one of the environmental issues associated with the growth of the economy and population (Fan et al., 2018). Waste-to-energy technology could be an attractive alternative for solid waste treatment to avoid landfill pressure and increase local energy security (Tan et al., 2015; Asher et al., 2019).

In general, few studies have evaluated the feasibility of a hybrid system with the consideration of both rooftop PV systems and waste-to-energy technology as electricity generation options as well as the demand response simultaneously. Motivated by the above-mentioned research gaps, this study proposed a versatile framework for the

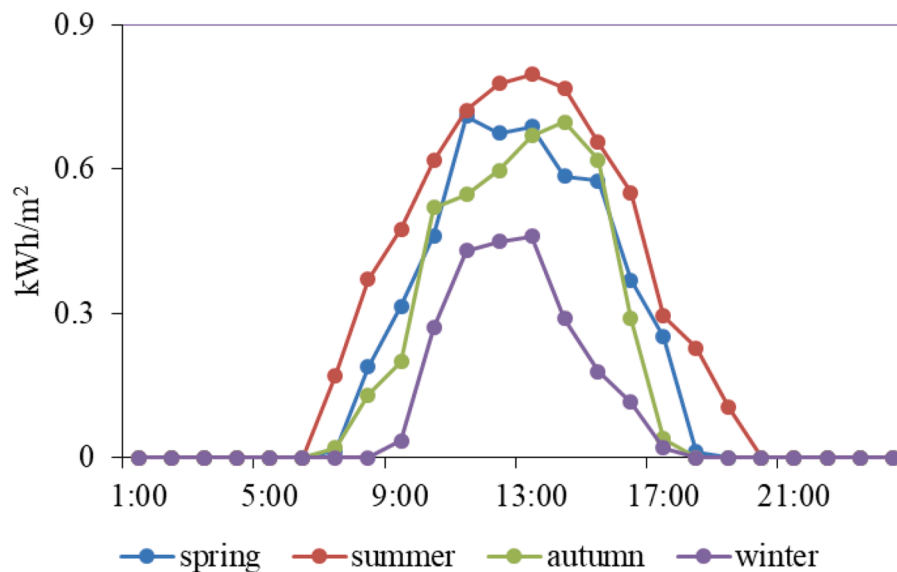


Fig. 4. Average solar irradiation profiles of different seasons.

Table 2

The classification of buildings and the corresponding utilization factor.

Code	Buildings' type	Utilization factor
0511	Housing construction area with high-density and multi-layers buildings	0.158
0512	Housing construction area with low-density and multi-layers buildings	0.136
0521	Housing construction area with high-density and low-rise buildings	0.286
0522	Housing construction area with low-density and low-rise buildings	0.235
0541	Multi-layers and stand-alone building	0.468
0543	High-rise and stand-alone building	0.439
0544	Super high-rise and stand-alone building	0.274
0550	Low-rise and stand-alone building	0.312

Note: Building density refers to the coverage rate of buildings, specifically the ratio of the total building footprint area to the total area. "high-density" refers to building density greater than or equal to 50%; otherwise, it is "low-density". Besides, "low-rise" indicates buildings with 1-3 floors, or building height less than 10 m, or without obvious shadows on high-resolution remote sensing images; "multi-layers" indicates buildings with 4 or more floors, or building height more than 10 m, or with obvious shadows on high-resolution remote sensing images; "high-rise" indicates buildings with 10 or more floors and building height less than 100 m; "super high-rise" refers to building height more than 100 m.

Table 3

Performance of shiftable loads.

Shiftable loads	Duration of operation (h)	Rated power (kWh)	Time interval range
Washing machine	0.5	0.4	7:00-21:00
Microwave	0.3	0.8	7:00-13:00
Rice cooker	0.5	0.6	6:00-19:00
Shower heater	1	3	6:00-24:00
Laptop	3	0.065	17:00-24:00
Television	3	0.18	9:00-23:00
Electrical car	4	3.5	18:00-8:00

optimal design and dispatch of a hybrid power system highlighting the integration of rooftop PV and biomass-based power generation. Under the integrated framework, the potential assessment of local renewable

energy at a community scale is primarily conducted from the energy supply perspective. In general, the main contributions of this paper are (1) assessing the potential of rooftop PV and solid waste biomass at the community scale with the assistance of a geographic information system tool; (2) developing a mixed-integer linear programming model for the optimal design and dispatch of a hybrid energy system with the utilization of localized renewable energy for fulfilling the electrical needs; (3) evaluating and comparing the influences of renewable energy policy and demand response on the system configuration, overall cost, and unit dispatch strategies; and (4) exploring the impacts of uncertainties in capital cost and electricity tariff through sensitivity analysis. The developed study framework could provide meaningful decision support for a community-scale hybrid system regarding renewable energy penetration targets and overall cost.

The remainder of this paper is structured as follows: the methodology of this study is outlined in Section 2; the case study is provided in Section 3 to illustrate its application; the main results and discussion on optimal strategies and sensitivity analysis are shown in Section 4; and finally, the conclusions and future research directions are presented in the final section.

2. Problem description

A community-scale hybrid energy system integrated with various renewable combinations has been developed on availability to ensure energy supply (Ashok, 2007). The configuration of the proposed system for local electricity demand is depicted in Fig. 1. In this study, the local electricity supply units include rooftop PV, biomass-based power generators, as well as battery storage. PV panels could be installed on the vacant space of the rooftop to generate. Since digesters or fermentation tanks are less expensive than gasifiers and more suitable for small-scale applications, these local wastes are collected to produce biogas through AD technology (Breitenmoser et al., 2018). The produced biogas serves as the feedstock of gas engines to provide electricity. Battery storage is applied to support the power supply during the peak load periods and adjust the dispatchable power output of PV. Besides, the hybrid power system could operate in a grid-connected mode, which allows purchasing electricity from the main grid to satisfy load demand and selling the excess energy back to the grid for gaining revenue.

As to the demand side of the hybrid power system, electricity consumption behaviors are also the key factors influencing the optimal design and management problems (Grubler et al., 2018). In most

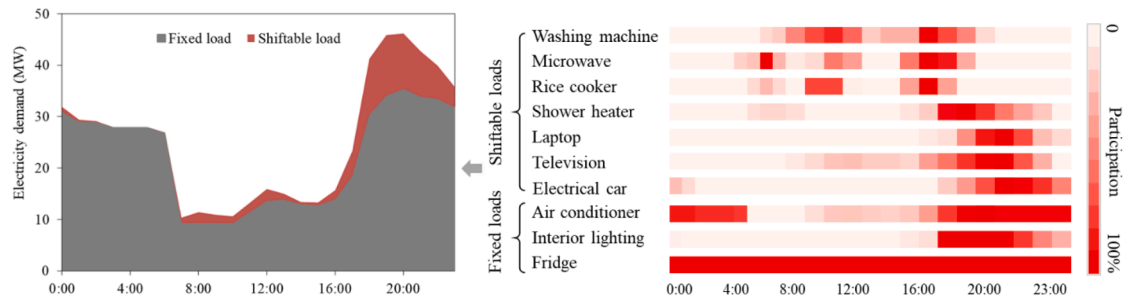


Fig. 5. Aggregated Electricity demand profile and operation activities of the appliances on a typical summer day.

Table 4
Technical and economic parameters considered for optimization.

Specification	Parameters	Value
Rooftop PV	Capital cost	1270 \$/kW
	O&M cost	20 \$/kW
	Lifetime	25 years
	Efficiency	14%
Biomass-based generator	Capital cost	1700 \$/kW
	O&M cost	0.3 \$/kWh
	Lifetime	20 years
	Efficiency	35%
Battery	Capital cost	250 \$/kWh
	O&M cost	1.4 \$/kWh
	Lifetime	10 years
	Charging/discharging efficiency	95%
	Maximum charging/discharging degree	52%

previous research, the electric demand is usually treated as an aggregated load profile (Majidi et al., 2017). With the application of intelligent electric meters and controllers, demand response could be introduced to encourage the end-users to shift their normal consumption behaviors to reshape the demand profiles and relieve the energy supply pressure. In the study of Taghizadeh et al. (2020), the maximum allowable limits for the participation of electrical load in demand response was assumed as 20% of the total load demand for simplification. In other studies, the energy requirements have been simulated separately with more details. For example, in the work of Rajbongshi et al. (2017), the local loads were classified into domestic, community,

and commercial loads. In the work of Jiang et al. (2017), the stimulated smart home appliances included constant power and variable power, and are further classified by interruption and transitivity to consider the demand response. In the simulation of (Wang et al., 2015), the residential electricity demand of a single-family house was divided into rigid loads and flexible loads. Referencing the above literature and survey, the electricity requirements in this study are classified into two types, i.e. fixed loads and shiftable loads. The former is non-dispatchable and fixed in time, such as lighting, fridge, and air conditioner. The latter with lower priority is flexible and dispatchable, including washing machine, TV, rice cooker, microwave, laptop, and shower heater, which can be considered as demand-side response resources. The residuals can adjust the schedule of the shiftable load to reduce electricity consumption at critical times and lower energy costs.

To achieve the optimal system design and operation management with various constraints, four critical steps should be implemented: (1) estimating the potential of rooftop PV installation and maximum available biomass from the organic fraction of MSW; (2) surveying the electricity consumption activities and the willingness to participate demand response programs; (3) optimizing the hybrid power generation system with economic and environmental performance assessment; (4) performing the sensitivity analysis of main economic parameters (e.g. electricity tariff and capital cost of renewable energy generation technology) to take uncertainties into account. The schematic diagram of the research framework is presented in Fig. 2. The implementing processes are further elaborated in the following section.

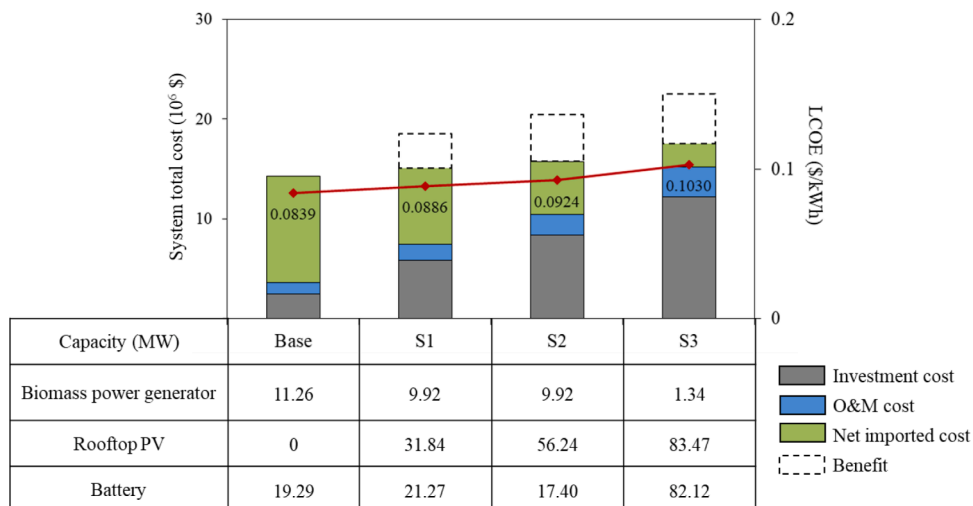


Fig. 6. Optimum configuration and cost of the hybrid system under different scenarios (Case I).

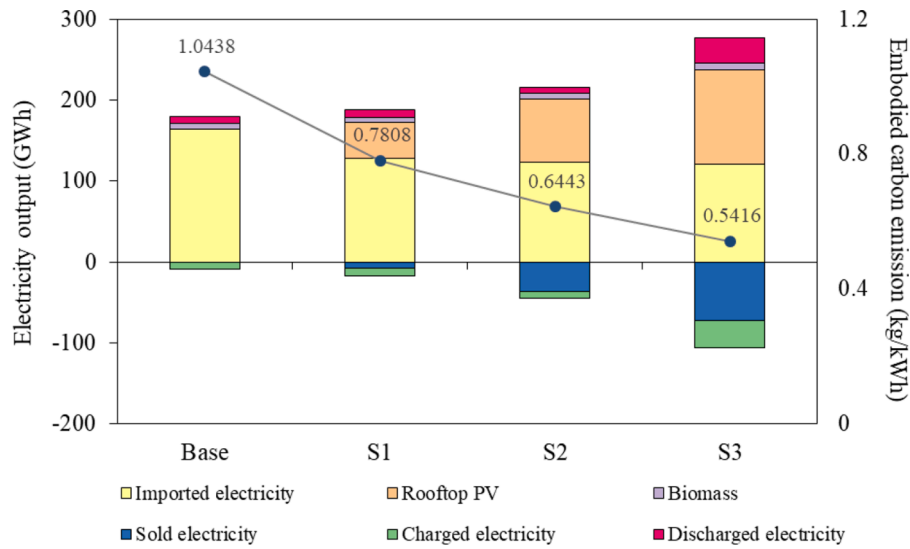


Fig. 7. Optimized electricity supply strategies and embodied carbon emission of electricity supply under different scenarios (Case I).

3. Mathematical model formulation

Compared with the evolutionary methods such as genetic algorithm (GA), particle swarm optimization (PSO), and tabu search, the mathematical optimization technique has the great advantages of shorter simulation time, more accuracy, independent of population size, and can solve the variable size of problems (Alberizzi et al., 2020; Kumar & Verma, 2021). Thus, a MILP model for the optimal design and dispatch of a hybrid power system is developed to minimize the total annualized cost while satisfying local power demand. Similar to the research done by Marquant et al. (2015), four seasonal patterns of load demand and solar irradiation are processed and used to reduce the computational dimension of the optimizations. Moreover, in order to investigate whether to implement a demand-side response mechanism to reduce peak load energy requirement, or invest in the energy storage device for balancing energy supply with demand, two cases are considered here:

3.1. Case I: hybrid power system without demand response

The total annualized system cost is the sum of the annualized capital cost (IC), operation and maintenance cost (OMC), and cost of electricity trade with the main grid (EC), which can be formulated as:

$$\text{Minf} = IC + OMC + EC \quad (1)$$

3.1.1. Annualized capital cost

The initial capital cost for each component is determined by the installed capacity (He et al., 2022), and the annualized capital cost during the lifetime is calculated by introducing the capital recovery factor (Zhang et al., 2019), as follows:

$$IC = C_{BIO}^{INV} \cdot CAP_{BIO} \cdot CRF_{BIO} + C_{PV}^{INV} \cdot CAP_{PV} \cdot CRF_{PV} + C_{BT}^{INV} \cdot CAP_{BT} \cdot CRF_{BT} \quad (2)$$

where, the subscript “BIO”, “PV” and “BT” are the abbreviations for biomass-based generator, rooftop PV, and battery storage, respectively. C^{INV} is the investment cost (\$/kW); CAP represents the installed capacity (kW).

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3)$$

where, i and n are the annual real interest rate and the expected lifetime of each component, respectively.

3.1.2. Operation and maintenance cost

Since little maintenance such as dust cleaning, routine inspections, and other necessary repairs are required, the operation and maintenance (O&M) cost for rooftop PV panels is assumed as an annual constant. Similarly, battery storage is also assigned a fixed annual maintenance cost (Rullo et al., 2019). The O&M cost of biomass generator is associated with the amount of power output. Thus, the total annual O&M cost can be written as:

$$OMC = FC_{PV} \cdot CAP_{PV} + FC_{BT} \cdot CAP_{BT} + \sum_s \sum_t N \cdot VC_{BIO} \cdot EG_{BIO,s,t} \quad (4)$$

where, FC_{PV} and FC_{BT} are the fixed cost of PV and battery (\$/kW); VC_{BIO} is the variable cost of the biomass-based generator, including the collection and production of biomass gas (\$/kWh); t is the time period ($t = 1, 2, \dots, 24$); s denotes the types of typical seasonal days ($s = 1, 2, 3, 4$); N is the number of days for each season, and $N = 90$.

3.1.3. Cost of electricity trade with the main grid

The cost of electricity trade with the main grid is the cost of purchasing electricity deducting the revenue of selling excess power back to the grid (Baraket et al., 2020; Khezi & Mahmoudi, 2020), and expressed as:

$$EC = \sum_s \sum_t N \cdot RP_t \cdot (EI_{s,t} - EX_{s,t}) \quad (5)$$

where, $EI_{s,t}$ and $EX_{s,t}$ are the amounts of purchased electricity and sold electricity, respectively (kWh); RP_t is the electricity exchange price (\$/kWh).

The constraints of the hybrid power system include:

3.1.4. Rooftop PV generation constraints

The hourly electricity output of the installed PV panels can be estimated by Eq. (6). Eq. (7) limits the maximum availability of the rooftop area (Allouhi et al., 2021).

$$EP_{t,s}^{PV} = G_{t,s}^{TOT} \cdot \eta_{PV} \cdot ARA \quad (6)$$

$$ARA \leq ARA_{total} \quad (7)$$

where, $EP_{t,s}^{PV}$ denotes the electricity output of rooftop PV (kWh); $G_{t,s}^{TOT}$ is the incident effective irradiance (kWh/m²); η_{PV} represents the efficiency of the PV panels; ARA is the utilized rooftop area for PV panels (m²).

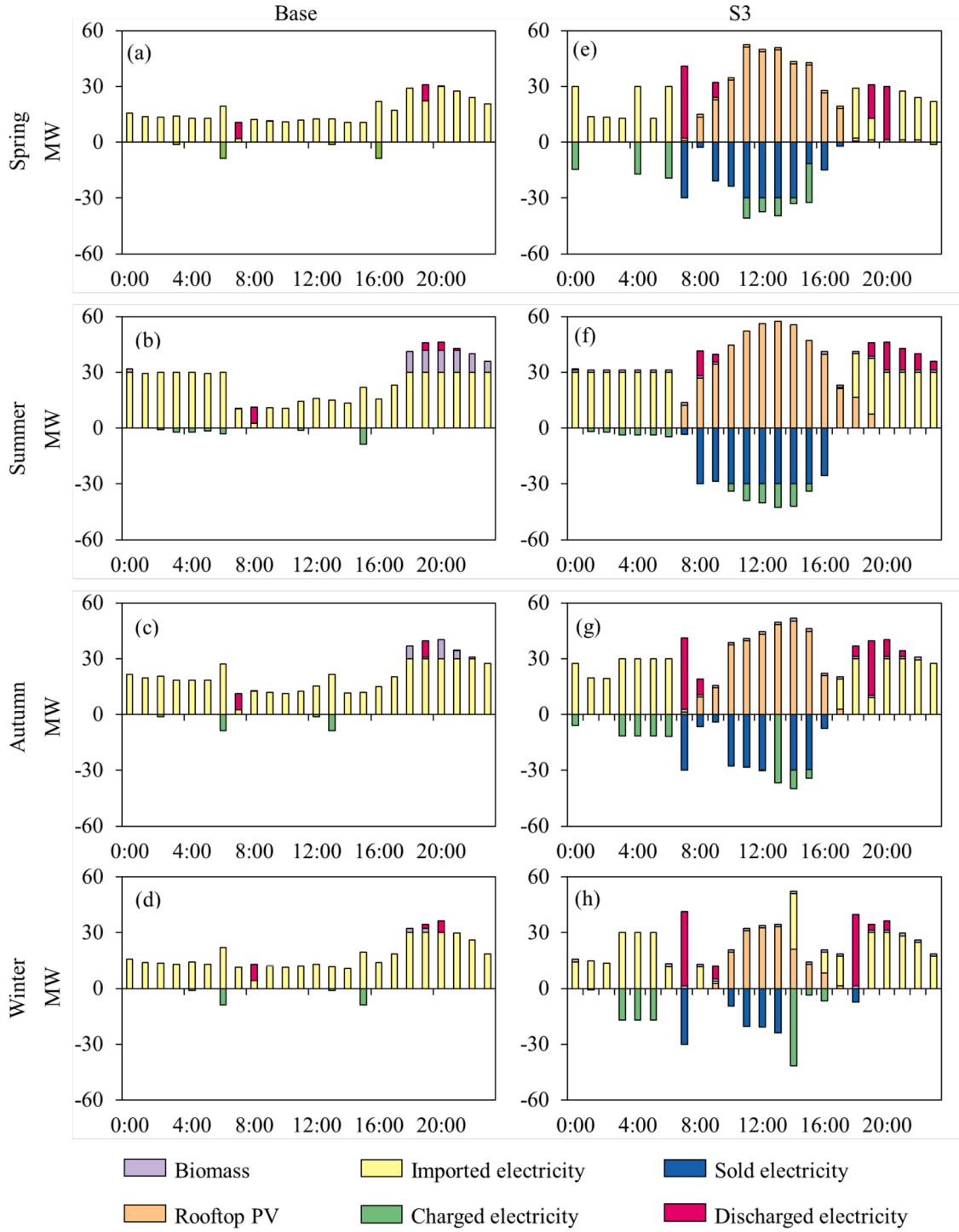


Fig. 8. Electricity supply profiles of typical days under the Base and S3 scenario (Case I).

3.1.5. Biomass-based generation constraints

Eq. (8) constrains the power output of biomass-based generators by its rated capacity and Eq. (9) implies the limitation of available biomass (Singh et al., 2016).

$$EG_{BIO,s,t} \leq CAP_{BIO}, \forall s, t \quad (8)$$

$$\sum_s \sum_t N \cdot \frac{EG_{BIO,s,t}}{\eta_{BIO} \cdot LHV_{biogas}} \leq MBIO \quad (9)$$

where, $MBIO$ is the amount of maximum available biogas produced from MSW (m^3); LHV_{biogas} is the low heat value of biogas (kWh/m^3), and η_{BIO} is the efficiency of biomass-based generator.

3.1.6. Battery storage operation constraints

The state of charge (SOC) characterizing the battery storage device at time t is expressed by Eq. (10), which is associated with the previous state, the charged and discharged energy with corresponding efficiencies (Liu et al., 2022). Meanwhile, the maximum limit of the SOC is expressed in Eq. (11). Further, the charging and discharging activities

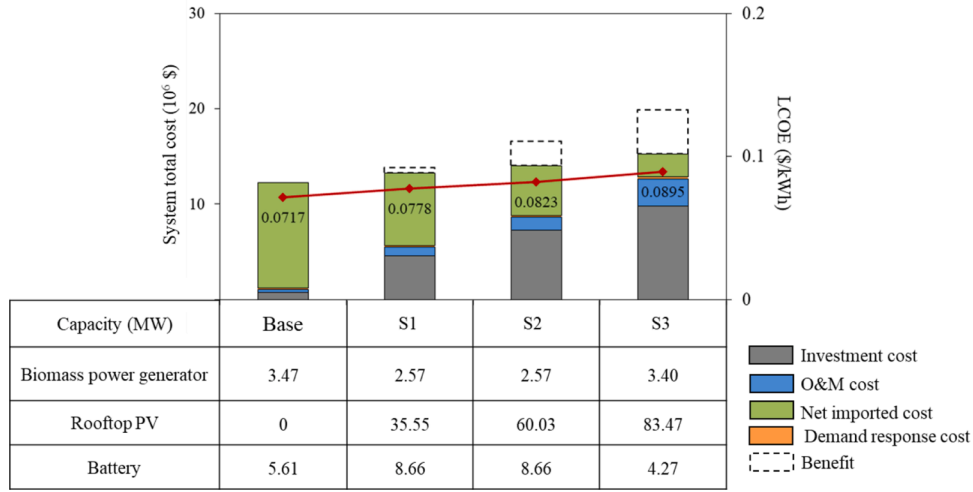


Fig. 9. Optimum configuration and cost of the hybrid system under different scenarios (Case II).

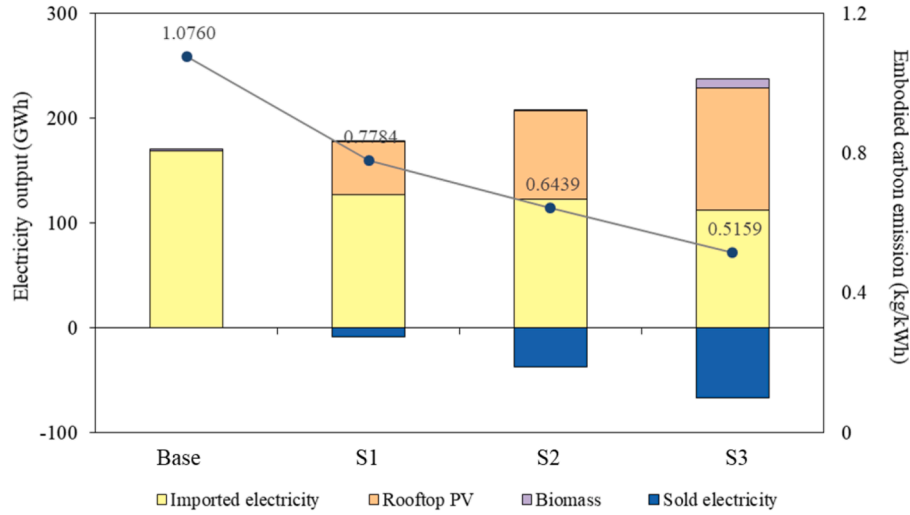


Fig. 10. Optimized electricity supply strategies and embodied carbon emission of electricity supply under different scenarios (Case II).

are constrained by Eqs. (12) and (13), respectively. Eq. (14) could avoid battery storage from charging and discharging simultaneously (Amrollahi and Bathaee, 2017).

$$SOC_{s,t} = SOC_{s,t-1} + ESC_{s,t} \cdot \eta_{ch} - \frac{ESD_{s,t}}{\eta_{dis}}, \forall s, t \quad (10)$$

$$SOC_{s,t} \leq SOC^{\max} \cdot CAP_{BT}, \forall t, s \quad (11)$$

$$0 \leq ESD_{s,t} \leq \vartheta_{dis} \cdot CAP_{BT} \cdot bd_{s,t}, \forall t, s \quad (12)$$

$$0 \leq ESC_{s,t} \leq \vartheta_{ch} \cdot CAP_{BT} \cdot bc_{s,t}, \forall t, s \quad (13)$$

$$bc_{s,t} + bd_{s,t} \leq 1, \forall s, t \quad (14)$$

where, $bc_{s,t}$ and $bd_{s,t}$ are the binary variables, $bc_{s,t} = 1$ represents charging, otherwise 0; $bd_{s,t} = 1$ for discharging, otherwise 0; $ESD_{s,t}$ is the discharged electricity from the battery to meet power demand (kWh); $ESC_{s,t}$ denotes the charged electricity (kWh); η_{ch} and η_{dis} are the charging and discharging efficiency; $SOC^{\max}$ is the maximum state of charging the battery energy storage system; ϑ_{ch} and ϑ_{dis} are maximum charging and discharging degree, respectively.

3.1.7. Transmission constraints

Eqs. (15)–(17) limit the amount of purchased and sold electricity from/to the grid by the capacity of the transmission line (Dali et al., 2010). Besides, Eq. (18) guarantees that purchasing and selling electricity could not occur at the same time.

$$EI_{s,t} \leq TC \cdot lc_{s,t}, \forall t, s \quad (15)$$

$$EX_{s,t} \leq TC \cdot ld_{s,t}, \forall t, s \quad (16)$$

$$lc_{s,t} + ld_{s,t} \leq 1, \forall t, s \quad (17)$$

where, TC is the capacity of transmission line (kW); $lc_{s,t}$ and $ld_{s,t}$ are the binary variables.

3.1.8. Energy demand constraints

The power demand should be met by the electricity derived from biomass generators, rooftop PV panels, net discharged power from battery storage, and net purchased electricity from the grid (Guo et al., 2021):

$$EG_{BIO,s,t} + EG_{PV,s,t} + (ESD_{s,t} - ESC_{s,t}) + (EI_{s,t} - EX_{s,t}) \geq D_{s,t}, \forall s, t \quad (18)$$

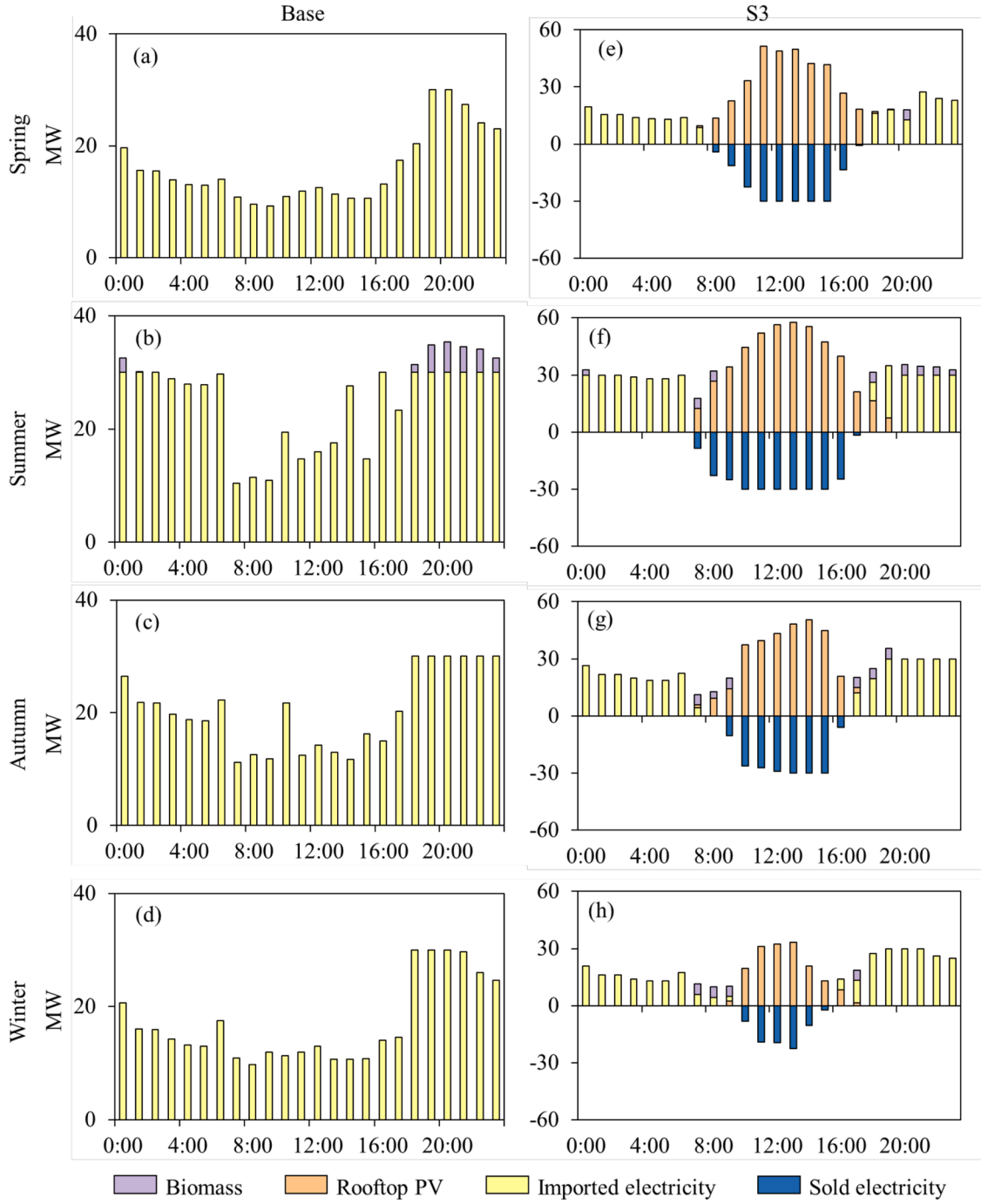


Fig. 11. Electricity supply profiles of typical days under the Base and S3 scenario (Case II).

where, $D_{s,t}$ is the electricity demand at time t (kWh).

3.2. Case II – hybrid power system with demand response

For a hybrid power system with demand response, except for the cost mentioned by Eq. (19), the cost of demand response (DSC) should be also taken into account. It is that extra cost should be paid to compensate for the inconvenience caused by shifting load. Thus, the objective function can be written as:

$$\text{Min} f = IC + OMC + EC + DSC \quad (19)$$

$$DSC = \sum_s \sum_t N \cdot PDS_t \cdot \max \{ D_{s,t} - D_{s,t}^0, 0 \} \quad (20)$$

where, PDS_t represents the compensation cost for demand-side response at time t (\$/kWh), $D_{s,t}^0$ is the original load demand (kWh), and $D_{s,t}$ is the adjusted load demand after demand response (kWh).

3.2.1. Load shifting constraints

Power demand is equal to the sum of fixed loads and shiftable loads and expressed by Eq. (21). Eq. (22) implies the total shiftable loads should be satisfied without cutting down. Considering the living habit

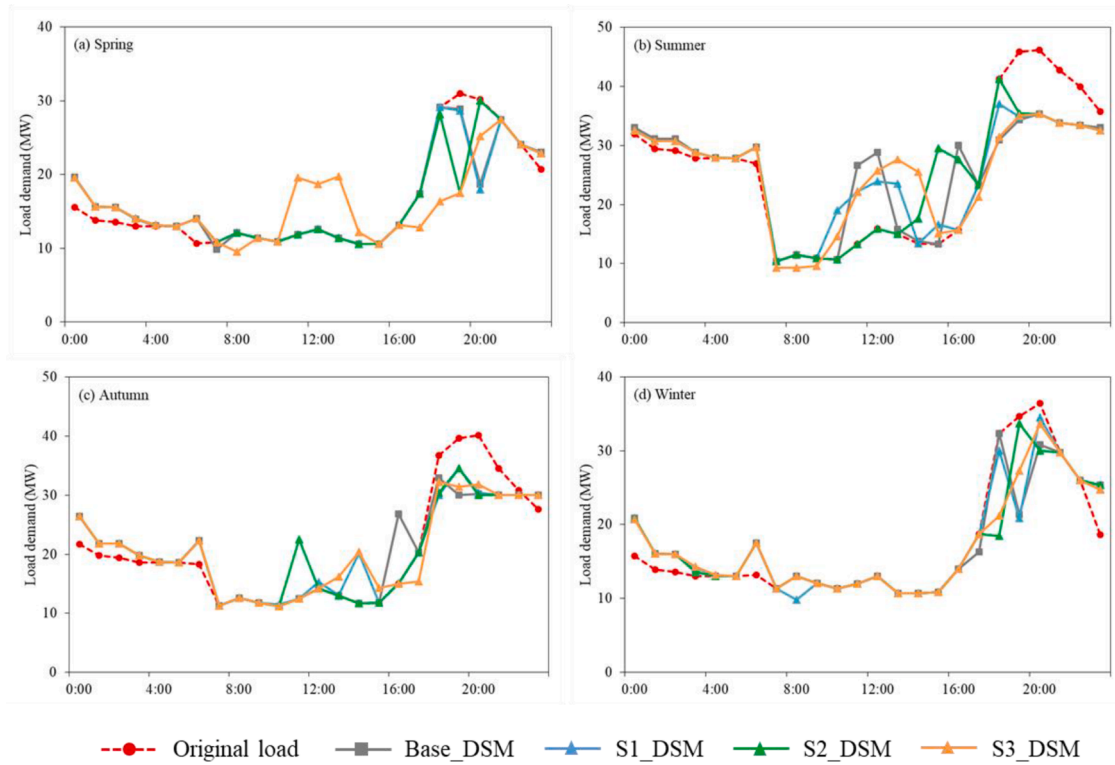


Fig. 12. Modified energy demand profiles with demand response under different scenarios (Case II).

and convenience, Eqs. (23) and (24) limit the shiftable loads should not be allocated to the time intervals earlier/later than the earliest start time/latest end time (Yuan et al., 2019; Lekvan et al., 2021).

$$D_{s,t} = FL_{s,t} + \sum_l SL_{l,s,t}, \forall s, t \quad (21)$$

$$\sum_l SL_{l,s,t} = TSL_{l,s}, \forall l, s \quad (22)$$

$$\sum_{t=0}^{T_l^{start}-1} SL_{l,s,t} = 0, \forall l, s \quad (23)$$

$$\sum_{t=T_l^{end}+1}^{23} SL_{l,s,t} = 0, \forall l, s \quad (24)$$

where, the subscript l denote the types of shiftable loads; $SL_{l,s,t}$ represents the shiftable load l at time t (kWh); $TSL_{l,s}$ is the total shiftable load (kWh); T_l^{start} and T_l^{end} are the earliest start time and the latest end time of shiftable load l , respectively.

And other constraints include Eqs. (7) and (19).

In addition, the levelized cost of electricity (LCOE), a commonly used metric to evaluate and compare the economic performance of different system options, is estimated by the total annualized cost and power production (Hwang et al., 2021). The carbon emission embodied in the electricity supply is also adopted to evaluate the environmental performance of the hybrid power system.

4. Case study

4.1. Overview of the study area

Beijing located at 39°56'N and 116°20'E in China is a metropolis with 21.53 million people and a GDP of RMB¥ 3,537 billion in 2019. Its

electricity consumption was 116.64 TWh, accounting for 26 % of the total energy consumption. However, its local electricity generation was only 44.30 TWh. Such a great gap between electricity supply and demand implies serious energy security risks (Beijing Bureau of Statistics, 2020a). Meanwhile, the output of local garbage keeps increasing with an annual growth rate of 4% in the recent ten years. In 2019, the total produced garbage was 10.11 million tons. Faced with the ambitious carbon neutrality target and heavy environmental pressures, the utilization of rooftop PV and waste biomass is expected to play a significant role in energy security, decarbonization, and waste management in Beijing. This study focuses on a small-scale hybrid power generation system for a residential area in the Chaoyang District of Beijing (seen in Fig. 3). The study area covers 6.05 km² with a building coverage rate of about 42.65% and a population density of 7,922 people per km² (Beijing Bureau of Statistics, 2020b).

4.1.1. Rooftop area for PV panels

The annual total solar radiation of the study area is about 1,669 kWh/m² with 2542 h of sunshine (<http://data.cma.cn/>). Fig. 4 presents the average solar radiation profiles of different seasons. Such an abundance of solar radiation indicates a great advantage for developing rooftop PV. For the geographical potential assessment of rooftop PV, the utilization factor, defined as a ratio of available roof area for PV panels to the building footprint area, is a key factor widely used. The value of utilization factors for different types of buildings are various due to the different geometrical and functional characteristics. According to the Content and Index of Fundamental Geographic Conditions Monitoring (CH/T 9029-2019) issued by the Ministry of Natural Resources of China, the buildings in this study area are classified into eight categories, i.e. "0511", "0512", "0521", "0522", "0541", "0543", "0544", and "0550", whose detail explanation can be found in Table 1. The average utilization factor for each type can be estimated by random image sampling. Firstly, the effective rooftop area of PV panel installation for the sampled buildings is measured by using the satellite image from Google Earth

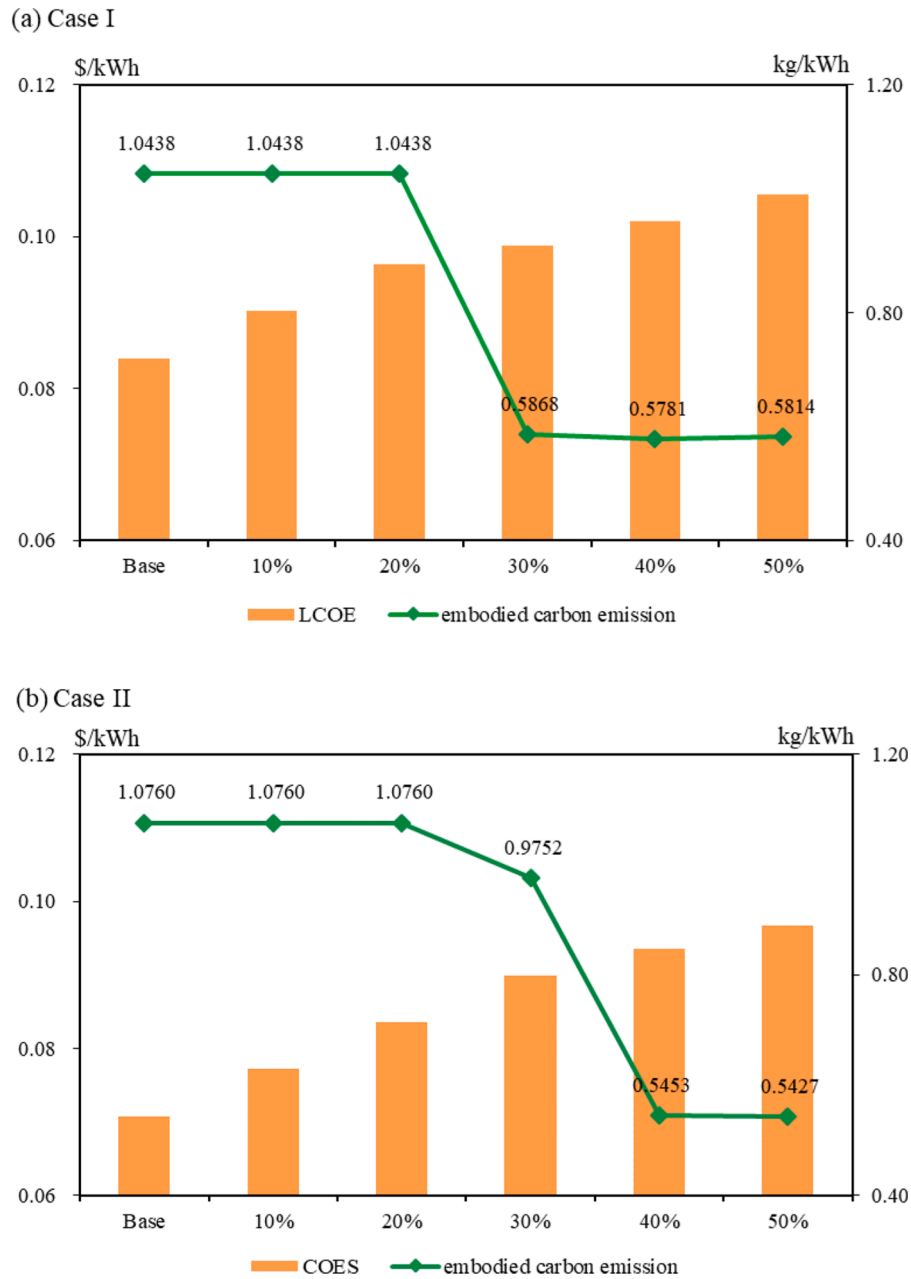


Fig. 13. Impacts of electricity tariff on the LCOE and the embodied carbon emission under the Base scenario.

with a 0.5 m spatial resolution. Facilities (*i.e.* stairwells, parapets, ventilation shafts, etc.) and equipment (*i.e.* cooling tower, water tank, antennas, etc.) are deducted during this process. Then the average utilization factors for different types of buildings are obtained and listed in Table 2. Finally, the total available rooftop area for PV panels (ARA_{total}) can be calculated by:

$$ARA_{total} = \sum_k PVR_k \times BFA_k \quad (25)$$

where, PVR_k is the utilization factor of the k^{th} type of building, and BFA_k is the corresponding building footprint area (m^2).

4.1.2. Waste biomass

From the survey done within the study area, it is found that the average annual solid waste generation per capita is 438 kg/person/a. Due to a high proportion of food residues, paper, and garden waste, the

organic fraction of solid waste in the study area is approximately 64%. The produced biogas is methane-rich, typically 50~75% CH_4 , 25~50% CO_2 , and trace gases, with a calorific value of 20~28 MJ/m^3 (Macias-Corral et al., 2008). Due to the different compositions and characteristics of MSW, the methane production rate for different areas are various. In this study, it is assumed that 1 kg of organic fraction of MSW can produce 0.268 m^3 of biogas with a proportion of methane of 60% (Khalid et al., 2011). Therefore, the estimated solid waste of the study area is about 21×10^3 tons with the maximum amount of available biogas $3.6 \times 10^6 m^3$.

4.1.3. Load demand

The electricity consumption of the study area is obtained from the primary survey data. Table 3 summarizes the commonly used appliances of the local residential households as well as the rated power, operation duration, and possible time range in a day based on the survey data. The

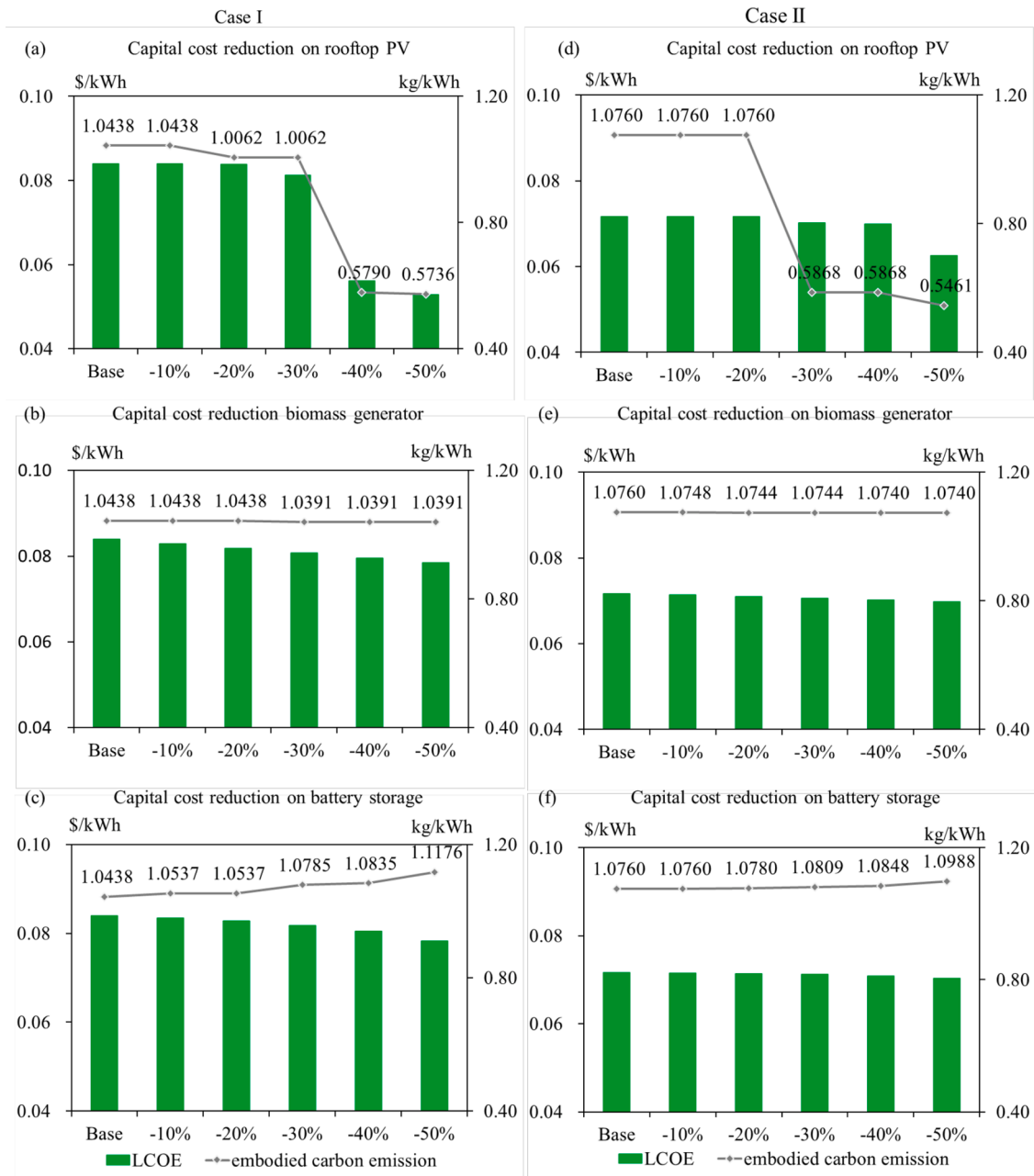


Fig. 14. Impacts of capital cost variation on the LCOE and the embodied carbon emission under the Base scenario.

average electricity consumption of the study area is 473 MWh/day with a peak load demand of 46.17 MW in summer. Fig. 5 illustrates the original activities of main appliances without demand response and the aggregated electricity demand profiles on a typical summer day.

4.2. Data and scenario description

The main economic and technical parameters for the components of the hybrid system are acquired from some existing literature (Fathima & Palanisamy, 2015; Kuang et al., 2016; Tiwary et al., 2019), and presented in Table 4. Besides, the time-of-use (TOU) electricity price is applied in this work, where the electricity exchange price is 0.0788 \$/kWh for the peak load period (i.e. 23:00-6:00), 0.0525 \$/kWh for the low load period (i.e. 7:00-9:00 and 17:00-20:00), and 0.0675 \$/kWh for rest periods. The compensation cost for demand response participation

is assumed as 20% higher than the electricity exchange price. The capacity limitation of the transmission line is 30 MW. In this work, rooftop PV and biomass-based generators are assumed as zero carbon emission technologies. According to the energy structure of Beijing, the carbon emission factor of the purchased electricity from the main grid is 1.088 kg/kWh. Furthermore, different scenarios are designed to explore the impact of renewable energy policy, whose detailed assumptions are described as follows:

- Base: without renewable energy generation penetration limitation;
- S1: at least 30% renewable energy generation penetration;
- S2: at least 50% renewable energy generation penetration;
- S3: all the local biomass and roof area are utilized for renewable energy generation.

The proposed optimal design and operation management models for the hybrid power systems without (Case I) or with demand response (Case II) have been implemented under different renewable energy policies, respectively.

5. Results and discussion

5.1. Optimal strategies for Case I

Fig. 6 presents the optimum configuration and system cost under different scenarios without demand response. Under the Base scenario, the hybrid system would be configured by 11.26 MW biomass-based power generator with 19.29 MW battery considering the lowest annualized system cost. With a higher renewable energy penetration level limitation, more investment in rooftop PV and battery storage would be required, as a result, the total system cost would increase greatly. Under S1 and S2 scenarios, 38% and 67% of the total available roof area would be utilized for PV system deployment, *i.e.* 31.84 MW and 56.24 MW, respectively. On the other hand, more electricity charged from PV generation output during the daytime (8:00–16:00) would be discharged at the evening peak hours (17:00–21:00) to relieve the power supply pressure. Therefore, the required capacity of the biomass power generator would reduce accordingly. Overall, the higher renewable energy penetration would lead to greater LCOE. The LCOE of the hybrid system would be 0.0839 \$/kWh, 0.0886 \$/kWh, 0.0924 \$/kWh, and 0.1030 \$/kWh under Base, S1, S2, and S3 scenarios, respectively.

Fig. 7 shows the optimized electricity supply strategies under different scenarios. Due to its relatively low cost, 93% of the available biomass would be used for power generation. Even so, it only accounts for a very small percentage (5%) of total electricity demand. Without a mandatory renewable energy policy, imported electricity would still be the main electricity supply for the community, about 163.55 GWh satisfying 96% of the total electricity demand. Limited by a higher renewable energy penetration level, the electricity output of rooftop PV would be 44.52 GWh under the S1 scenario and 78.64 GWh under the S2 scenario, which is about 26% and 46% of local electricity demand, respectively. When all of the local renewable energy is utilized (S3), the local renewable energy output would be 125.04 GWh, which is 73% of the total electricity demand. In this scenario, the imported and sold electricity would be 120.65 GWh (71% of total electricity demand) and 71.89 GWh (57% of total renewable energy output), respectively. Moreover, with higher penetration of rooftop PV, the annual throughput of the battery would increase accordingly. The charged electricity under the S3 scenario would be 34.40 GWh, almost four times that under the Base scenario (8.68 GWh). In general, the embodied carbon emission in electricity supply under Base, S1, S2, and S3 scenarios would be 1.0438 kg/kWh, 0.7808 kg/kWh, 0.6443 kg/kWh, and 0.5416 kg/kWh respectively.

As to the optimal operation management, the detailed 24 h electricity supply strategy for typical days under the Base and S3 scenario can be found in Fig. 8. Under the Base scenario, the biomass-based power generator would work as a supplement during the peak load period due to the constraint of electricity transmission. It would run 8 h in summer and even less in other seasons. Under the S3 scenario with the full utilization of renewable energy, the electricity consumption during daylight hours could be satisfied by the power output of rooftop PV with the biogas generators acting as backup. However, due to the mismatch of rooftop PV output and peak load demand, the expensive investment cost of battery storage, and the relatively low off-peak electricity tariff, only a small amount of rooftop PV power output would be stored in the battery to discharge at night, and the rest would be sold back to the grid. Moreover, with higher penetration of rooftop PV, the operation hour of biogas generators would increase.

5.2. Optimal strategies for Case II

With the consideration of demand response, the flexible dispatch of shiftable load could reduce the peak load and better match electricity supply and demand, thus the battery would be no longer required and the installed capacity of biomass-based power generator would decrease accordingly (Fig. 9). Compared with Case I, the total system cost of Case II would decrease greatly due to the avoided investment. For example, the total system cost of Case II under Base and S3 scenarios would be 12.21×10^6 \$ and 15.25×10^6 \$, which is 15 % and 13 % lower than that of Case I. Meanwhile, the implementation of demand response programs would also lead to lower LCOE, *i.e.* 0.0717 \$/kWh, 0.0778 \$/kWh, 0.0823 \$/kWh, and 0.0895 \$/kWh for the Base, S1, S2, and S3 scenarios, respectively.

Fig. 10 illustrates the optimized electricity supply strategies under different scenarios with demand response. Under the Base scenario, the imported electricity up to 168.60 GWh would play a dominant role in the electricity supply, nearly 99 % of the total electricity demand. The power output of a biomass-based generator would be only 2.09 GWh and the annual throughput of the battery would be 4.85 GWh due to the flexible load arrangement. With higher renewable energy penetration requirements, the electricity output of rooftop PV would increase but the power output of biomass-based generator would decrease. Especially, under the S3 scenario, the electricity exchanged with the main grid and the throughput of the battery of Case II would be more than that of Case I. The operation strategies for the Base and S3 scenarios are elaborately depicted in Fig. 11. Under the Base scenario, the biomass-based generator would only work from 19:00 to 0:00 in summer to meet night peak loads. The power supply in other seasons would still rely on the electricity from the main grid. Under the S3 scenario, with sufficient solar irradiation in spring and summer, the electricity output of rooftop PV could meet the local load demand during the daytime (9:00–16:00), meanwhile, the excess electricity would be sold to the grid. While the electricity requirements during the night-time (18:00–next 7:00) would be mainly supplied by electricity purchased from the grid. The biomass-based power generator would run when the solar is inadequate and the electricity tariff is not that low, for example, 7:00–8:00 and 18:00–21:00.

Fig. 12 illustrates the modified load profile with demand response under different scenarios. In general, the original shiftable load in the evening peak load period would be transferred to late night with lower electricity prices and the daytime with more output of rooftop PV. The total annual shifted load under Base, S1, S2, and S3 scenarios would be 10.38 GWh, 9.68 GWh, 9.25 GWh, and 13.29 GWh. Besides, the shifted load in summer would be greater than that in other seasons, due to more power generation of rooftop PV. For instance, for the Base scenario, the daily shifted load in summer would be 50.69 MWh, with a 23% reduction in peak load. The detailed performance of various shiftable loads under different scenarios can be found in Fig. A1.

5.3. Sensitivity analysis

In this section, sensitivity analysis is performed to better demonstrate the influences of uncertain economic parameters on decision-making under the Base scenario. To be more specific, considering the shortage of fossil fuels and the preliminary of the national carbon emission trading market, it is assumed that there would be an increasing tendency in the electricity tariff. With the rapid development of technology innovation, the capital cost of components is supposed to decrease in the future. The impacts of electricity tariff and capital cost on the LCOE and embodied carbon emission are shown in Figs. 13 and 14, respectively.

5.3.1. Influence of electricity tariff changes

Since the imported cost takes accounts for 75% of the total cost, the electricity tariff variations would bring a relatively obvious impact on system cost. For example, with a 20% increase in electricity tariff, the total annualized system cost of Case I would increase by 15%. An

expensive electricity tariff would stimulate the deployment of rooftop PV. For example, with a 30% increase in electricity tariff, the optimal system would consist of 9.59 MW biomass, 69.46 MW rooftop PV, and 17.60 MW battery. The imported electricity would be 120.38 GWh with a 26% reduction of that under the Base scenario. Meanwhile, with 46% of renewable energy penetration, the carbon emission embodied in the energy supply would also decrease to 0.5868 kg/kWh, which is 44% lower than that under the Base scenario. As a result, it would also decrease the embodied carbon emission in the electricity supply.

Since the energy supply of Case II would more heavily rely on imported electricity than that of Case I, there would be a more obvious increasing trend with the increase in electricity tariff. For example, with a 20% increase in electricity tariff, the total system cost would increase by 18%. Similar to Case I, modest growth in electricity tariff would only increase the cost of energy supply but bring no influence on the energy supply strategies. Dramatically increasing electricity purchasing costs would stimulate the penetration of renewable energy and decrease embodied carbon emissions.

5.3.2. Influence of capital cost changes

Besides, a slight reduction in the capital cost of rooftop PV technology has little effort to promote its investment from an economic perspective. For Case I, with a 20% reduction in its capital cost, rooftop PV would be selected to provide local energy, which implies that 6% of the available roof area would be used for PV technologies. With a 40% reduction, the utilization proportion of the rooftop area would be about 90%. Meanwhile, battery storage would also be considered in the hybrid energy system to balance the gap between energy supply and demand brought by rooftop PV. For example, with a 30% capital cost reduction, 8.67 MW biomass generator, 72.54 MW rooftop PV, and 23.60 MW battery would be the optimal system configuration. In general, the reduction of rooftop PV capital cost, the unit cost of energy supply and demand, as well as the carbon emission embodied in electricity supply would decrease.

Due to the limited biomass sources, the capital cost variation has little impact on the whole energy system. In general, with a slight reduction in the capital cost of biomass generators, the system configuration and operation strategies would remain the same. For Case I, when there is a 30% reduction, the installed capacity of the biomass generator would be 11.97 MW with 8.32 GWh annual output, which fully utilizes local biomass energy. Besides, the embodied carbon emission in the energy supply would decrease slightly to 1.0391 kg/kWh.

Similarly, capital cost reduction of battery storage would lead to a reduction in system cost. Moreover, with the time-of-use tariff, the cheaper capital cost of battery storage would lead to a higher capacity of battery and more exchange with the main grid. It has negative effects on the utilization of local renewable energy resources. It is that with a lower capital cost of battery the installed capacity of biomass generator would decrease with less power output. As a result, the carbon emission embodied in the energy supply would increase.

Overall, the influences of capital cost variation on Case II follow similar trends as Case I. More than a 20% reduction in the capital cost reduction of PV technologies would stimulate the utilization of rooftop PV panels and lead to a low-carbon energy supply strategy. Meanwhile, it would also reduce the amount of shifted load, especially in summer when the solar radiation is relatively high. For instance, with a 30% reduction in PV's capital cost, the annual shifted load would be 9.16 GWh, which is 12% less than that in the Base scenario. In the contrast, the capital cost reduction of biomass generators and battery storage would have little impact on the transformation of the power supply structure, and the caused economic benefits would be slight. Moreover, the capital cost reduction of battery storage would even bring negative effects to promote renewable energy penetration, unless restricting the trade with the main grid. It would also require less load shifting to keep the original habits.

6. Conclusions

This study presents a holistic framework for the optimal design and management of the community-scale hybrid power system with the integration of rooftop PV and biomass generation technologies. It can assist the decision-making on the identification of optimal system configuration and operation strategies with economic and environmental performance assessment. The influences of renewable energy policy, demand response, and uncertain economic parameters are analyzed and discussed to provide deeper management insights.

In summary, the obtained results show that for the study area biomass gas generator seems to be a more favorable option than rooftop PV technology to achieve the low-carbon transformation of energy supply. Even with a 100% utilization of collected biomass and available rooftop PV, it can only satisfy 73% of the local electricity demand. For economic purposes, electricity purchased from the public grid would still be the main supply to meet demand. It is also suggested that introducing demand response would reduce the economic cost of energy by avoiding more renewable energy investment but lead to less carbon emission reduction in the Base scenario. With a higher renewable energy generation penetration requirement, demand response would be more helpful to match the energy demand with the dispatchable rooftop PV output. This implies that under the current technical and economic conditions, mandatory renewable energy policies are required for realizing the transformation of the electricity supply structure and carbon-neutral goal. Furthermore, by performing the sensitivity analysis, it is found that higher electricity tariffs and lower capital cost of PV technology would make rooftop PV technology more attractive for the stakeholders. However, due to the time-of-use price mechanism, capital cost reduction of the battery would encourage charging electricity from the main grid at a low-price time rather than facilitate the renewable energy investment.

In general, it may act as a reference model for the customized hybrid power system planning of other regions or areas with localized data as input. However, there are still some problems that need to be addressed in the future. For example, the other potential economic and environmental impacts related to the by-products of anaerobic digestion are excluded in the current study. Besides, the components and characteristics of municipal solid waste should be estimated accurately to reflect reality. Moreover, the land requirement for the anaerobic digestion and the roof rent cost for PV installation could be further considered in practical cases. Last but not the least, except for the monetary-measured cost, other social or public issues such as the social acceptance of bio-energy and the willingness-to-pay to renewables are also important and need to be considered when implementing the hybrid power system in practice.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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Appendix

A.1 Performance of demand response activities.

Washing machine	Original	0	0	0	0	0	0	0	0	5%	10%	15%	12%	10%	3%	3%	4%	16%	12%	8%	2%	0	0	0	
	Base	0	0	0	0	0	1%	10%	0	0	18%	0	0	0%	0	0	31%	40%	0	0	0	0	0	0	
	S1	0	0	0	0	0	1%	0	15%	28%	0	0	0	0	0	0	0	0	0	26%	0	30%	0	0	
	S2	0	0	0	0	0	1%	0	15%	30%	0	0	0	0	0	0	0	0	0	24%	0	30%	0	0	
	S3	0	0	0	0	0	1%	0	0	30%	0	40%	0	29%	0	0	0	0	0	0	0	0	0	0	
Microwave	Original	0	0	0	0	0	0	5%	20%	6%	0	2%	10%	7%	0	0	10%	20%	20%	0	0	0	0	0	
	Base	0	0	0	0	0	5%	0	0	0	0	0	0	0	0	0	40%	45%	0	10%	0	0	0	0	
	S1	0	0	0	0	0	5%	0	0	0	0	0	33%	12%	0	0	45%	0	5%	0	0	0	0	0	
	S2	0	0	0	0	0	5%	0	45%	0	0	0	0	0	3%	27%	0	0	20%	0	0	0	0	0	
	S3	0	0	0	0	0	5%	0	0	6%	4%	10%	20%	0	20%	3%	0	29%	0	0	0	3%	0	0	
Rice cooker	Original	0	0	0	0	0	0	0	9%	4%	0	20%	21%	0	0	0	10%	26%	10%	0	0	0	0	0	
	Base	0	0	0	0	0	6%	0	0	0	4%	38%	42%	7%	0	3%	0	0	0	0	0	0	0	0	
	S1	0	0	0	0	0	6%	0	0	8%	4%	28%	51%	0	0	3%	0	0	0	0	0	0	0	0	
	S2	0	0	0	0	0	6%	0	0	0	0	28%	35%	0	0	3%	20%	0	0	8%	0	0	0	0	
	S3	0	0	0	0	0	6%	0	0	0	4%	0	0	7%	3%	3%	27%	50%	0	0	0	0	0	0	
Shower heater	Original	0	0	0	0	0	0	2%	3%	3%	2%	0	0	0	0	0	1%	2%	20%	22%	18%	12%	8%	7%	
	Base	5%	0	0	0	0	6%	1%	0	0	0.1%	0	0	1%	0	0	0	0	4%	25%	22%	16%	9%	10%	
	S1	5%	0	0	0	0	6%	2%	3%	0	3%	2%	0	0	0	0	3%	5%	0	25%	17%	11%	8%	10%	
	S2	5%	0	0	0	0	6%	0	0	0	2%	0	0	2%	0	0	0	7%	24%	18%	0	15%	12%	10%	
	S3	5%	0	0	0	0	6%	0	0	0	2%	15%	14%	13%	3%	2%	0	0	0	0	0	18%	12%	10%	
Laptop	Original	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5%	7%	58%	85%	93%	42%	10%	
	Base	7%	0	0	0	0	0	0	0	0	5%	10%	15%	12%	7%	2%	0	60%	60%	66%	6%	16%	17%	17%	
	S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4%	0	0	0	54%	0	30%	12%	0	
	S2	7%	0	0	0	0	0	0	0	0	5%	10%	15%	15%	12%	7%	2%	1%	61%	61%	60%	0	10%	17%	17%
	S3	7%	0	0	0	0	0	0	0	0	5%	8%	8%	3%	0	0	0	30%	75%	75%	45%	0	10%	17%	17%
Television	Original	0	0	0	0	0	0	0	0	0	0	3%	6%	11%	12%	9%	9%	7%	20%	29%	42%	49%	51%	36%	16%
	Base	12%	0	0	0	0	0	0	0	0	0	8%	8%	11%	13%	13%	10%	0	0	0	37%	67%	79%	42%	
	S1	12%	0	0	0	0	0	0	0	0	0	0	0	0	0	11%	11%	11%	0	0	47%	77%	89%	42%	
	S2	12%	0	0	0	0	0	0	0	0	7%	23%	23%	23%	13%	13%	6%	0	21%	21%	21%	0	30%	42%	42%
	S3	12%	0	0	0	0	0	0	0	0	4%	44%	44%	40%	0	14%	14%	14%	0	0	0	30%	42%	42%	
Electrical car	Original	39%	19%	9%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16%	36%	61%	81%	75%	64%	
	Base	100%	100%	100%	40%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60%	
	S1	94%	99%	100%	46%	6%	1%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54%	
	S2	94%	99%	100%	46%	6%	1%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54%	
	S3	94%	99%	100%	46%	6%	1%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54%	

Fig. A1. The performance of shiftable loads on a typical spring day in Case II under different scenarios. The number denotes the percentage of participants, and the darker color indicates more participants.

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