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Economic and Environmental Optimization for Distributed Energy System Integrated with District Energy Network

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Abstract: The purpose of this research is to develop a mixed integer linear programming model for optimization of a distributed energy system integrated with electricity network. In this model, the optimal configuration of the selected equipment and dynamic intelligent control of the hourly electricity interchange among end-users were determined. The multi-objective function was to maximize the total cost saving and pollutant emission reduction. As an illustrative example, the model was applied to a neighborhood level containing hotel, office and residential buildings in Dalian, China. According to the results, with the installation of the electricity network, the load rate of the power generating unit in the hotel and office were improved and the power generate unit (PGU) often operated at full loads during the daytime with the surplus electricity distributed to the residential buildings. Furthermore, the overall performance was enhanced leading to a more than 30–40% reduction compared to the only distributed energy system (20–30%). In addition, the advancement of the electricity network was reflected in its application in office, where most of the excess electricity is transferred from office to residential building during the daytime in winter, while during the night time, the phenomenon was reversed, so that the office received electricity from residential buildings and no generated unit was at work in office.

Keywords: multi-objective optimization; district energy network; electricity exchange; hourly running schedule

1. Introduction

Energy has been one of the fundamental human needs with the development of human civilization. Recently, uncontrolled growth of energy demands, environmental concerns, and multi-carrier energy systems have been attracting significant attention. Energy Internet is known as a new form of multi-carrier energy system which can achieve the deep integration of energy production, transmission, storage, and consumption in energy revolution [1–3]. "Energy Internet" connects devices, machines and systems with advanced sensors, controls and software applications at the energy production end, the energy transmission end and the energy consumption end, forming the "Internet of things" foundation of the energy Internet. Based on the concept of Energy Internet, at present, the thermal exchange among users is given more attention in terms of the networked application of distributed energy system (DES). In foreign countries, the energy network of DES is mainly promoted by gas companies, and most of the equipment is deployed in the form of gas-fired internal combustion engine and direct-fired gas turbine with natural gas as fuel, etc., while photovoltaic and photothermal equipment is given as the supplement.

Distributed energy systems (DESs) located in or near end users have been widely applied in urban areas due to high energy generation efficiency and avoidance of transmission and distribution losses. This system can also provide electricity, cooling, and heating to meet the demands of local end-users [4–7]. As a comprehensive generated energy system, the operation strategy and energy management of DES are especially complicated. Many studies have indicated that, in certain circumstances, the energy consumption could not be reduced and the annual total cost is even higher than that of the conventional system. Therefore, it is important to improve the performance of the DES with the optimization of the load fluctuation and energy management, which seriously affects the entire performance of system.

The complex rate is further increased when the DES is designed for satisfying the demands of multiple end-users in the neighborhood level. Therefore, a DES integrated with an energy network which allows for energy sharing between various users has been investigated [8–10]. Many research papers have already been focused on the design and optimization of this aspect. Soderman and Pettersson [11] proposed a mix integer linear programming (MILP) model for structural and operational optimization of DES with district heating pipelines. The model required the involved producer, consumers, and authorities to form a unit for decision making. Sameti and Haghighat [12] modeled a mathematical program to obtain the optimal design and planned a new district heating system, which can optimize the best way to select the equipment among various candidates and their electrical connections among the pipeline network of the buildings. Varasteh et al. [13] addressed the network expansion planning of active Combined Cooling, Heating and Power (CCHP) systems with their heating and cooling network. The studied method used a bi-level iterative optimization for optimal expansion and operational planning of the system, with each zone being able to transact electricity with the upward utility. Kang et al. [14] proposed a new configuration of distributed energy system (DES) with a district cooling system, which facilitated a design for DES that used real site energy demands.

Generally, as regards district heating and cooling networks, each of the aforementioned analysis refers to the heating pipe line or both heating and cooling networks. It is seen less frequently that the performance and advancement of electricity networks are considered, which allows for electricity transfer among the users. Even though electricity transfer is allowable between buildings in a Greek neighborhood through an existing power transmission network in [15], the model is developed for the optimization of a distributed energy resource (DER) system that is combined with the design of a heating network. However, in China, the first Energy Internet demonstration projects are mostly constructed by power companies. This is mainly because the concept of Energy Internet in China was first put forward by the state grid corporation, and the smart grid is the core support of the Energy Internet. In China, no matter the project of multi-energy complementarity system, nor the project of Energy Internet, the regional electricity matching and coordination are the key points of construction. In addition, considering the basic physical characteristics of electricity and heat, the transmission loss of heat energy is much greater than that of electricity. Therefore, as a measure for balancing the electricity between the supply and demand sides, it is necessary to analyze the electricity interchanges between the distributed generators, due to our national conditions [16].

According to the above discussion, it can be summarized that, although many studies have been focused on the optimization of the DES with heating and cooling network [17,18], the majority of the literature focuses on the annual operation strategy and the overall performance improvement of the whole DES; therefore, there is still a lack of in-depth discussion on the hourly interactive operation strategy between the producers and consumers in the network. Meanwhile, load allocation of all district end-users and hourly energy generation of each producer as well as the effect of energy reciprocity (energy exchange among the buildings) has been given little attention and will be detailed in this study. The purpose of this analysis is to determine the optimal configuration of the selected equipment and the interchange way of hourly electricity transfer among end-users. To be specific, dynamic intelligent control of its hourly operation can be obtained from optimal running scheduling viewpoint.

This paper presents an integrated approach for designing DES, which can optimize the DES configuration in combination with electricity network satisfying time-varying use demands. A multi-objective optimization model is developed to optimize and evaluate the economic and environmental performance of a DES integrated with hourly electricity interchange at the neighborhood level. As an illustrative example, the proposed mathematical method is applied to three types of buildings (hotel, office and residential building) located in Dalian, China.

The paper is organized as follows. The problem definition is described in Section 2. The mathematical model is summarized in Section 3. Section 4 describes an optimization and analysis with multiple objectives. The results are also reported in this section. Finally, in Section 5, the conclusions are reported.

2. Problem Definition

2.1. Numerical Study

In order to investigate various aspects for the design and operation of the DES integrated with district electricity network, an optimization model was developed and optimized. The model was applied to an urban area in Dalian City, North China. The energy loads of three typical buildings of DES in respective days are shown in Figure 1. The distance between buildings is shown in Table 1. In this study, three typical days per year, namely winter, summer and mid-season days, were introduced regarding hourly variations in energy demands.

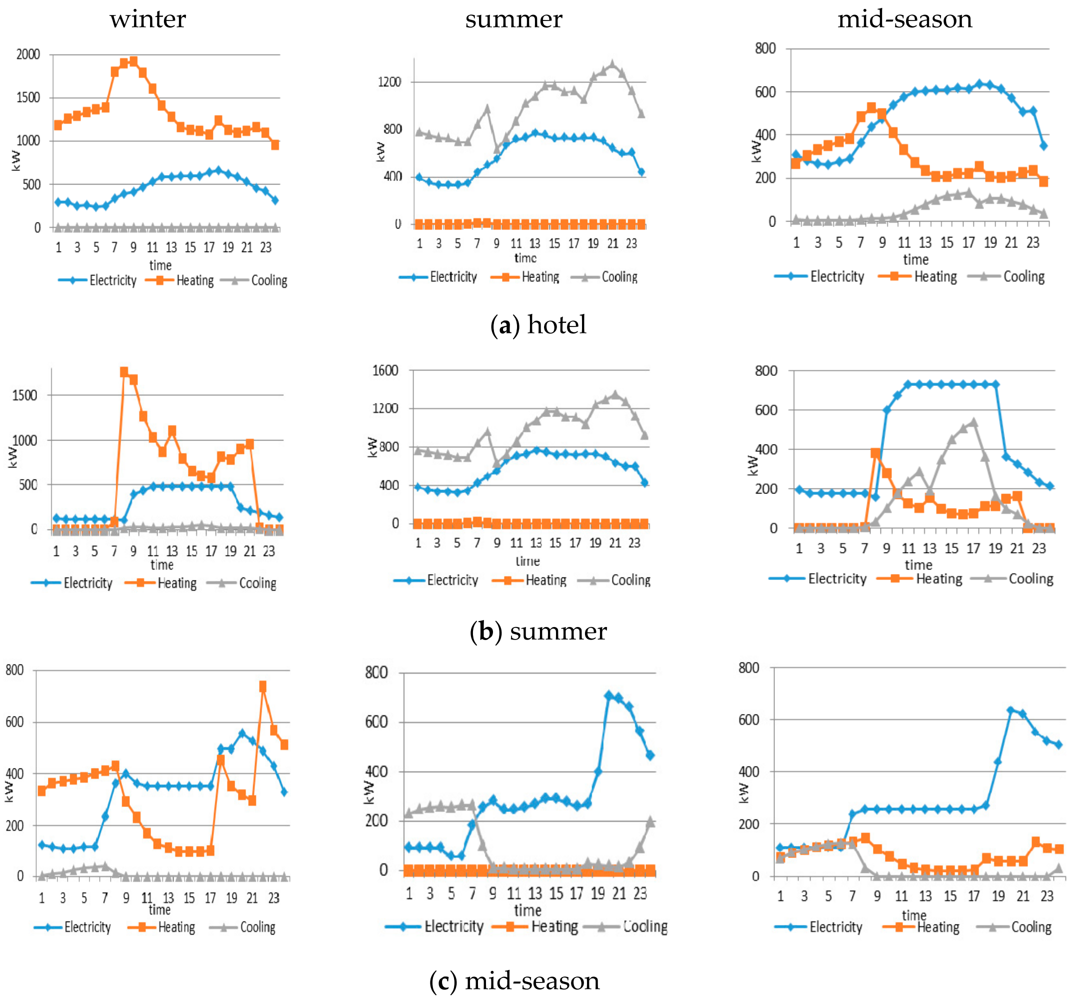


Figure 1. The energy loads of typical buildings of distributed energy system (DES) in respective day.

In the reference conventional system, all electricity demands are served by the local electricity grid. Gas boiler and electric chiller will satisfy the thermal demands including space heating and cooling load respectively. In DES, electricity consumption can come from the electricity grid or the power generator unit. The exhaust gas of high-temperature from the DES is recovered to meet the heating demands through the heat exchanger and the cooling load through the absorption chiller. In the DES with a network, electricity demands can be produced by the PGU, or purchased from the utility grid, or interchanged with other users through the electricity network. Cooling demands are satisfied by absorption and electric chillers units, and heating is recovered from PGU and the deficit heat is supplied by gas boilers. The superstructure of DES and DES integrated with electricity network are shown in Figure 2.

Table 1. Distance between buildings (m).

Building Types	Hotel	Office	Residential Buildings
hotel	0	200	180
office	200	0	150
residential buildings	180	150	0

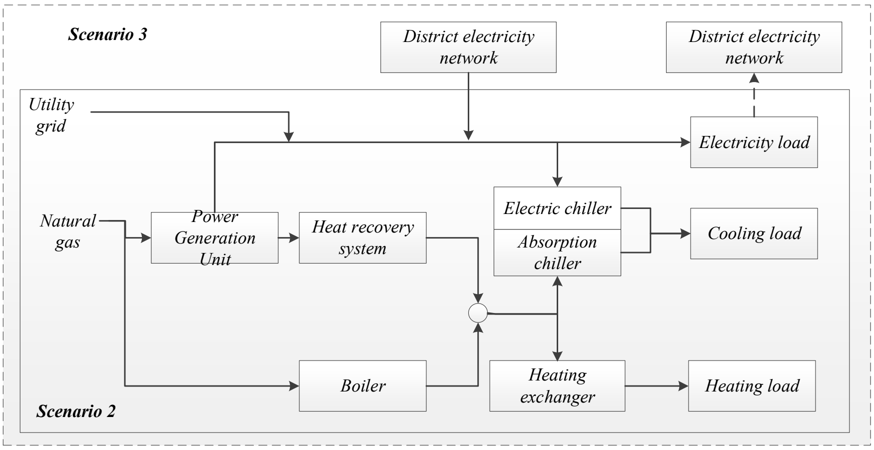


Figure 2. The superstructure of distributed energy system (**scenario 2**) and system integrated with electricity network (**scenario 3**).

2.2. Setting of Scenarios

In this optimization, a comparative analysis was studied through the following scenarios. The model presented in this paper has been optimized for three scenarios:

Scenario 1 (CON): Conventional system. It is the basic scenario which presents the conventional energy supply system. The electricity demand is satisfied by utility grid, heating demand by gas boilers and cooling load by the electric chiller. No DES technology or electricity network was considered.

Scenario 2 (DES): In this region, most of the energy demand including electricity, heating and cooling systems can be satisfied by the installed DES in each producer, and a small part from boilers and utility grids.

Scenario 3 (DES+EN): In this scenario, the electricity network was added to the DES of this region. Meanwhile, the optimal operating schedule was obtained through real-time control of actual electricity demand, which implies that each building can exchange electricity with other buildings through intelligent control.

2.3. Other Assumptions

The following assumptions have been made before the optimization:

(1) The average electricity losses during electricity distribution are 5% of the total distributed electricity.
(2) The electricity network already exists among the buildings in scenario 3.
(3) The interest rate is assumed as 3%, based on which the investment costs can be calculated according to Equation (3).
(4) The weighting coefficients τ_1, τ_2, referring the multi-objective function introduced in Section 3, are assumed be 1/2.

3. Mathematical Model

The problem proposed in Section 2 was constructed as a MILP model. The typical daily load curves of hotels, offices and residential buildings were chosen as the study case to verify the feasibility of the presented methodology. The model contains a multi-objective function, technology design constraints and energy balance constraints. The conventional system in scenario 1 was introduced as the basis to evaluate the performance of the DES. The basic structure of this analysis is shown in Figure 3.

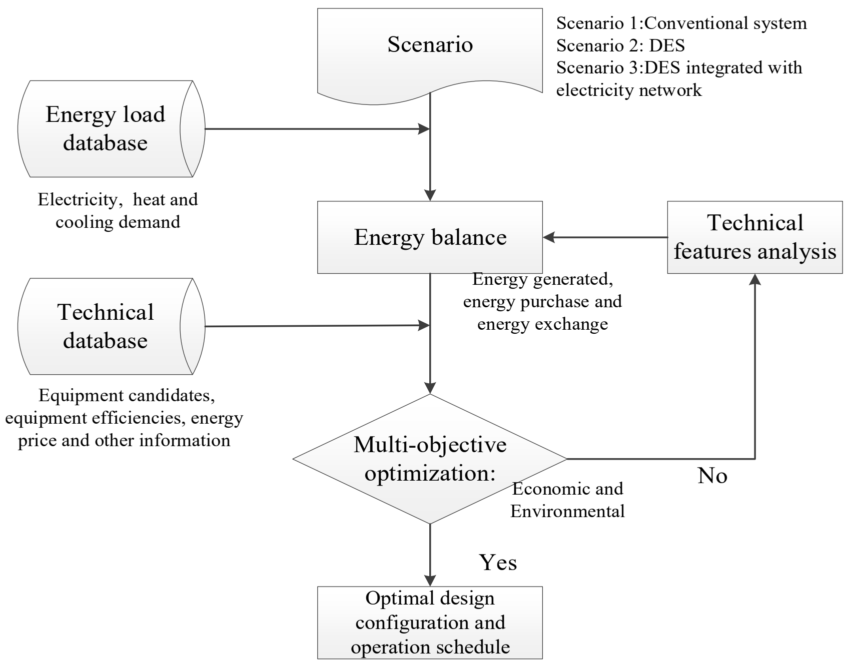


Figure 3. The basic structure of this analysis.

3.1. *Objective Function*

3.1.1. Economic Objective

The total cost $COST_{DES}$ consists of involving equipment and network capital and installation cost ($C_{inv,eq}$ and $C_{inv,net}$), operation and maintenance (OM) cost ($C_{om,eq}$ and $C_{om,net}$), fuel and grid electricity purchased cost (C_{fuel} and C_{grid}) [19,20].

$$COST_{DES} = C_{inv,eq} + C_{inv,net} + C_{om,eq} + C_{om,net} + C_{fuel} + C_{grid} \tag{1}$$

The investment cost of equipment ($C_{inv.eq}$) can be expressed as follows:

$$C_{inv,eq} = \sum_{i \in I} \sum_{l \in L} R_i C_{cap,i} P_{i,l} \tag{2}$$

where C_{cap} is the unit capital cost of the equipment. P is the capacity of generated unit and i is the type of equipment. l is the building.

The capital recovery factor of each equipment, R, is:

$$R = \frac{r \cdot (1+r)^v}{(1+r)^v - 1} \tag{3}$$

The capital cost of district power networks $C_{inv.net}$ is:

$$C_{inv,net} = \sum_{l,l'} R \cdot C_{net} \cdot D_{l,l'} \tag{4}$$

where C_{net} is the unit cost of the district power network, and $D_{l,l'}$ is the distance between buildings l and l'.

The operation and maintenance (OM) costs of the equipment, $C_{om.eq}$, contain the fixed (function of the unit capacity) and variable (function of the annual energy generation of the unit) costs.

$$C_{om,\mathrm{eq}} = \sum_{i \in I} \sum_{l \in L} C_{fix,i} \cdot p_{i,l} + \sum_{i \in I} \sum_{l \in L} C_{var,i} \cdot Out_{i,l} \tag{5}$$

In Equation (5), C_{fix} and C_{var} is the unit fixed cost of the equipment and unit variable cost of the equipment, respectively. *Out* is the output energy of the equipment.

The OM cost of the distribution network can be calculated by multiplying its capital cost ($C_{net,i}$), and the distance between buildings ($D_{l,l'}$) as follows:

$$C_{om,net} = \sum_{i \in I} \sum_{l,l' \in L} C_{net,i} \cdot D_{l,l'} \tag{6}$$

The fuel cost is the unit price of fuel (C_{ft}) multiplied with the consumption of fuels (F_{fuel}) as follows:

$$C_{fuel} = \sum_{i \in I} \sum_{l \in L} C_{ft,i} \cdot F_{fuel,i,l} \tag{7}$$

The grid electricity cost is the unit price of electricity (C_{grid}) multiplied with consumption of the fuel (E_{grid}):

$$C_{grid} = \sum_{i \in I} \sum_{l \in L} C_{grid,i,l} \cdot E_{grid,i,l} \tag{8}$$

3.1.2. Environmental Objective

With the increasing concern of global warming, pollutant emissions have received much attention in the analysis of distributed energy systems. Environmental effect (*GAR*) including global warming effect (*GWE*), acidification effect (*AE*) and $PM_{2.5}$ emission effect (*RE*), is calculated as:

$$GAR = \alpha_1 GWE + \alpha_2 AE + \alpha_3 RE \tag{9}$$

α_1, α_2, α_3 is assumed as 1/3, respectively, referring to [21,22]. The pollutant emissions (E_m), is calculated as:

$$Em = F_{fuel,j} \xi_Z \tag{10}$$

$F_{fuel,i}$ is the consumption of fuels j; ξ_Z is the emission factor [23] (see Table 2).

Table 2. Emission conversion factors and global warming effect (GWE), acidification effect (AE) and emission effect (RE) of some substances.

Emission	Natural Gas (g/KWh)	Coal (g/KWh)	GWE (gCO_2-equiv./g)	AE (gSO_2-equiv./g)	RE ($gPM_{2.5}$-equiv./g)
CO_2	203.74	326.37	1		
CH_4	0.015	0.003	21		
N_2O	0.0004	0.01	310	0.7	
SO_2	0.011	3.14		1	1.9
NO_X	0.202	1.134		0.7	0.3
$PM_{2.5}$	0.0012	0.055			1

The *GWE* presents the emission contributions to the greenhouse effect, and the other emissions should be changed into equivalent quantities of CO_2. *AE* and *RE*, which are explained as SO_2 equivalent emission and $PM_{2.5}$ equivalent emission. The conversion equivalent factors for *GWE*, *AE* and *RE* are $\lambda_{z,co_2\text{-}equiv}$, $\lambda_{z,so_2\text{-}equiv}$ and $\lambda_{z,PM_{2.5}\text{-}equiv}$, respectively. The values are also shown in Table 2 [21,22].

$$GWE = \sum_{Z}^{6} Em_z \lambda_{z,CO_2-equiv} \tag{11}$$

$$AE = \sum_{Z}^{6} Em_z \lambda_{z,SO_2-equiv} \tag{12}$$

$$RE = \sum_{Z}^{6} Em_z \lambda_{z,PM_{2.5}-equiv} \tag{13}$$

3.1.3. Multi-Objective Optimization

In previous studies, the MILP model has been widely used for the optimization of DES with economic objective function. Recently, due to growing concerns for the environmental issues, a purely single economic criteria optimization has become insufficient due to growing environmental concerns. However, the minimization of overall cost and pollutant emission has simultaneously become more challenging since the economic and the environmental objectives may be contradictory, i.e., for being expensive to utilize environmentally friendly technologies. To resolve such problems and find the global optimum of the conflicting objective functions, the multi-objective optimization method can be useful and has been widely applied by the authors of [19].

Referring to the economic objective function (Equation (1)) and the environmental function (Equation (9)), this problem has two objective functions to be optimized. A single objective function U is formulated as a weighted sum of the cost savings, *COST*, and the pollution emission reduction, *GAR*, to be maximized as follows [10]:

$$U = MAX\left\{\tau_1 \frac{COST_{CON} - COST_{DES}}{COST_{CON}} + \tau_2 \frac{GAR_{CON} - GAR_{DES}}{GAR_{CON}}\right\} \tag{14}$$

In Equation (14), τ_1 and τ_2 are the weights, and $\tau_1 + \tau_2 = 1$. In this paper, τ_1 and τ_2 is assumed as 1/2, respectively. Actually, the weightages should not be assumed to be the same value 1/2. However, at the present stage, we cannot determine the exact weightages of economic effect and environmental effect. $COST_{CON}$ and $COST_{DES}$ are the total costs of the reference energy system and DES, respectively. GAR_{CON} and GAR_{DES} are the environmental impacts, respectively.

3.2. Design Constraints

3.2.1. Power Generate Unit

The PGU is often operated at part-load condition. Therefore, electric load fraction, an on-off coefficient, of 25% was set to avoid the low PGU efficiency at a relatively low load. And the recovered heat can be calculated through heat to power ratio [24–26]. P_{cap} is the capacity of power generate unit (PGU), and m, d, h means month, day and hour respectively. E_{pgu} is the electricity generated by PGU. HE is the heat recovered from PGU and μ_{rec} is the recovery factor.

$$P_{cap} \cdot 25\% \leq E_{pgu,m,d,h} \leq P_{cap} \tag{15}$$

$$HE_{pgu,m,d,h} = E_{pgu,m,d,h} \mu_{rec} \tag{16}$$

3.2.2. Electrical Chiller

The cooling generated from electrical chiller (CO_{ec}) should not exceed its rated capacity (CO_{cap}). The electricity (E_{ec}) can be illustrated as shown in Equation (18):

$$CO_{ec,m,d,h} \leq CO_{cap} \tag{17}$$

$$E_{ec,m,d,h} = CO_{ec,m,d,h} / COP_{ec} \tag{18}$$

3.2.3. Gas Boiler

The heat output of a boiler (HE_{bo}) to the rated capacity (HE_{cap}) is shown in Equation (19):

$$HE_{bo,m,d,h} \leq HE_{cap} \tag{19}$$

3.2.4. Power Networks

Although the buildings can interchange electricity with each other through power lines, only one direction of electricity flow, χ, is allowed in every period [15,27]:

$$\chi_{l,l'}^{line} + \chi_{l',l}^{line} \leq 1 \tag{20}$$

Moreover, the electricity flows in the network (E_{ex}) cannot exceed the maximum transmission capacity (Max_{line}):

$$Eex_{l,l'} \leq \chi_{l,l'}^{line} \cdot Max_{line} \tag{21}$$

3.3. Energy Balance

3.3.1. Electricity Balance

The energy balance of electricity is represented in Equation (22), in which the left part is the electricity input flows from PGU (E_{pgu}), the utility grid (E_{grid}) and the exchange electricity ($E_{ex\text{-}in}$) from other buildings and the right part refers to the output flows including electrical chiller for cooling demand (E_{demand}, CO_{demand}) and the interchange electricity ($E_{ex\text{-}out}$) transported to other buildings. COP is the coefficient of performance:

$$\left(\sum_{l} E_{pgu,m,d,h,l}\right) + E_{pur,i,m,d,h} + E_{ex-in,i,m,d,h} = E_{demand,i,m,d,h} + CO_{demand,i,m,d,h} + E_{ex-out,i,m,d,h} \tag{22}$$

3.3.2. Heating Balance

As shown in Equation (23), heating flows inwards contain feed flows of all producers (PGU, HE_{pgu} and boiler, HE_{bo}). On the other hand, heating flows outwards include heating demand HE_{demand}.

$$(\sum_{l} HE_{pgu,m,d,h,l}) + HE_{bo,i,m,d,h} = HEdemand_{i,m,d,h} \tag{23}$$

4. Results and Discussion

4.1. Optimal System Design and Corresponding Performance

4.1.1. Optimal System Design of Hourly Energy Demand

An optimal PGU capacity can be obtained according to the energy demands based on technical parameters, which is one of the most significant outputs of the proposed model. For these evaluations, the variables used in the model are listed in Tables 3–5, referring to [28–30].

Table 3. Technical features of the power generate unit (PGU).

Rated Capacity (kW)	Rated Efficiency (%)	Unit Capital Cost
230	27	1905.6 $/kW
470	33	1699.7 $/kW
633	34.5	1790 $/kW
800	37.6	1625 $/kW
1121	36.8	1475 $/kW
1460	41.4	679 $/kW
2020	37.4	734 $/kW

Table 4. Technical features of other equipment.

Equipment	Rated Efficiency (%)/COP	Unit Capital Costs
Electrical chiller	4	127.5 $/kW
Absorption chiller	0.8	173.5 $/kW
Heat recovery system	0.8	124 $/kW
Gas boiler	0.8	100 $/kW
Power pipeline		147 $/m

Table 5. Information of energy prices ($/kWh).

Energy Type		Average Time	Peak Load Time	Low Load Time
electricity price	residential buildings	−0.08	0.115	−0.04
	Commercial building	0.134	0.2	0.07
natural gas price			0.03	

1 $ = 6.5 yuan.

For the conventional system (scenario 1), the electricity, heating and cooling demands are provided through the utility grid, gas-fired boiler and electrical chillers, respectively. The capacity of boiler and electrical chiller of each building was chosen as shown in Table 6, while with the DES (scenario 2 and scenario 3) in the region, the optimal capacities of PGU of the three typical buildings were selected from the candidates in Table 3. The capacity of PGU candidates are [230, 470, 633, 800, 1121, 1460, 2020]. According to the optimization results, the optimal configuration of system was suggested to install as follows: the PGU capacity was selected through the optimization, the capacity of 633 kW was installed in hotel, 800 kW was allocated in office, and 470 kW was installed in residential buildings. And the optimal capacity of boiler, absorption chiller and electrical chiller were also selected as shown in Table 6. Referring to scenario 3, the electricity output of PGU through hourly dynamic control for each building in three typical days was optimized and indicated in Tables 7–9. The hourly PGU optimization boundary was [0, 630], [0, 800] and [0, 470] in hotel, office and residential buildings respectively. The multi-objective values with respect to hourly costs and pollutant emissions reduction were also summarized in Tables 7–9. The positive value referred to the reduction of hourly costs and pollutant emissions, whereas the negative value referred to the increase.

Table 6. Installed capacities of equipment.

	Scenario 1				Scenario 2				Scenario 3			
	PGU	Boiler	Absorption Chiller	Electrical Chiller	PGU	Boiler	Absorption Chiller	Electrical Chiller	PGU	Boiler	Absorption Chiller	Electrical Chiller
Hotel	–	1914	–	337	633	1392	823	173	633	1826	823	318
Office	–	1762	–	441	800	1762	959	249	800	748	813	233
Residential buildings	–	738	–	66	470	378	245	66	470	283	318	57

Table 7. The results of optimal system design of hourly energy demand in typical winter day.

	Scenario 2 (DES)				Scenario 3 (DES + Electricity Network)			
	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value
1	292	128	126	10.21%	547	0	0	15.87%
2	299	116	118	10.18%	268	0	265	14.97%
3	252	116	110	9.09%	240	0	238	13.95%
4	257	116	110	8.92%	240	0	242	13.65%
5	239	116	118	8.49%	235	0	237	13.20%
6	250	116	118	18.39%	243	0	240	22.49%
7	335	116	236	23.05%	312	66	308	24.36%
8	388	104	362	25.35%	54	800	0	27.84%
9	413	393	401	30.07%	402	800	6	34.19%
10	470	442	362	33.60%	469	800	6	37.87%
11	528	479	354	36.52%	556	800	6	41.50%
12	587	479	354	29.56%	633	687	99	35.73%
13	582	479	354	28.77%	608	800	7	35.58%
14	593	479	354	30.56%	633	643	150	35.72%
15	596	479	354	31.48%	633	720	76	34.55%
16	595	479	354	31.67%	633	672	123	33.80%
17	633	497	354	32.51%	633	765	77	33.41%
18	633	479	496	42.52%	633	650	350	45.28%
19	615	479	496	42.08%	633	686	271	45.38%
20	584	238	559	36.96%	555	713	114	44.50%
21	531	214	527	35.36%	551	721	0	43.13%
22	460	188	488	13.95%	633	22	470	18.37%
23	425	153	433	13.80%	630	0	381	18.66%
24	311	140	331	12.65%	393	0	388	17.99%

Table 8. The results of optimal system design of hourly energy demand in typical summer day.

	Scenario 2 (DES)				Scenario 3 (DES + Electricity Network)			
	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value
1	389	216	92	−8.30%	0	0	0	0.80%
2	353	177	92	−6.78%	0	0	0	0.71%
3	333	177	92	−6.75%	0	0	0	0.68%
4	333	177	92	−6.80%	0	0	0	0.68%
5	329	177	57	−6.83%	0	0	0	0.63%
6	350	177	57	20.67%	439	0	214	28.67%
7	434	177	185	23.28%	402	193	308	24.69%
8	495	196	256	35.28%	504	457	97	44.27%
9	553	600	284	39.40%	628	800	61	44.89%
10	633	660	249	39.26%	632	800	273	42.60%

Table 8. *Cont.*

	Scenario 2 (DES)				Scenario 3 (DES + Electricity Network)			
	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value
11	633	721	249	38.89%	633	800	455	40.96%
12	633	800	256	24.78%	633	800	470	25.01%
13	633	800	270	25.16%	633	800	470	25.34%
14	633	800	292	23.96%	633	800	470	24.16%
15	633	800	292	23.81%	633	800	470	24.01%
16	633	800	277	23.82%	633	800	470	24.04%
17	633	800	263	23.99%	633	800	470	24.24%
18	633	800	270	36.62%	633	800	470	38.36%
19	633	780	398	37.79%	633	800	470	38.79%
20	633	376	470	30.67%	633	800	470	39.14%
21	633	376	470	33.83%	633	800	453	38.97%
22	633	296	470	−18.23%	0	14	0	1.34%
23	633	277	470	−18.81%	0	0	0	1.29%
24	633	236	462	−17.13%	0	0	0	1.15%

Table 9. The results of optimal system design of hourly energy demand in typical mid-season day.

	Scenario 2 (DES)				Scenario 3 (DES + Electricity Network)			
	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value	Hotel (kW)	Office (kW)	Residential Buildings (kW)	Objective Value
1	309	196	112	−6.56%	216	0	122	8.04%
2	284	177	112	−1.41%	241	0	160	10.08%
3	269	177	112	1.49%	260	0	0	8.96%
4	263	177	112	2.20%	275	0	89	9.30%
5	278	177	112	2.82%	289	0	0	9.73%
6	291	177	112	27.19%	301	50	229	32.85%
7	365	177	238	30.54%	382	131	266	31.06%
8	437	159	259	41.48%	387	328	139	47.03%
9	477	601	259	40.98%	402	800	135	41.79%
10	541	676	259	38.37%	619	800	57	38.89%
11	577	733	259	37.03%	628	800	140	37.31%
12	602	733	259	20.38%	633	800	162	20.69%
13	606	733	259	19.29%	633	800	164	19.63%
14	610	733	259	20.63%	633	800	170	20.93%
15	610	733	259	22.11%	633	800	169	22.43%
16	621	733	259	23.05%	633	800	179	23.38%
17	616	733	259	23.84%	633	800	175	24.13%
18	637	733	272	37.65%	633	800	210	37.94%
19	632	733	440	34.27%	633	800	376	34.50%
20	616	364	470	33.51%	628	800	188	35.14%
21	572	327	470	31.74%	629	800	93	35.56%
22	508	287	470	−29.17%	251	0	101	4.41%
23	511	234	470	−31.22%	234	0	82	4.61%
24	350	214	503	−29.82%	179	0	110	4.28%

Examining the above tables, compared with scenario 2 (DES), it can be concluded that the load rate of the PGU in the hotel and office are improved in scenario 3, with the electricity network and the generated units often operated at full loads with 633 kW and 800 kW, which is higher than the hourly demand. This is because of the application of the electricity network; the surplus electricity can distribute to the residential buildings. This situation is quite different in residential building. Lower electricity is optimally generated in residential building.

A comparative study has also been proceeded in order to evaluate the performance of integrating distributed generation system with electricity network among buildings. Figure 4 illustrates the multi-objective values of the economic saving and pollutant emission reduction in scenario 2 and scenario 3, respectively. It can be found that, in general, the objective reduction values in scenario 2 and scenario 3 have the same variation tendency. It can be also noted that the adoption of the DES+

Electricity Network in scenarios 3 allows for higher objective values. The application of the DES technologies in scenario 2 as well as in scenario 3 DES with the installation of the power network, leads to a average 20–30% and 30–40% reduction compared to scenario 1, respectively. In scenario 2, the DES system has the biggest reduction value with 42.52% at 6 p.m. on a winter day, when the capacity of PGU is optimized as 633 kW, 479 kW and 496 KW in the three typical buildings. As shown in Figure 2 for scenario 3, in typical days, the reduction rate increases gradually and reaches the peak value at about 8 a.m. to 11 a.m., then decreases at 12 a.m. Furthermore, as a result of the generated electricity of the buildings gradually increasing, the optimal reduction of objective value calculated through simulation is presented as increasing during 6 p.m. to 9 p.m. period. In addition, it can be also observed from Tables 7–9 and Figure 4, as the optimal generated electricity of buildings changes, the biggest reduction value in scenario 3 is presented 47.03% at 8 a.m. on a mid-season day.

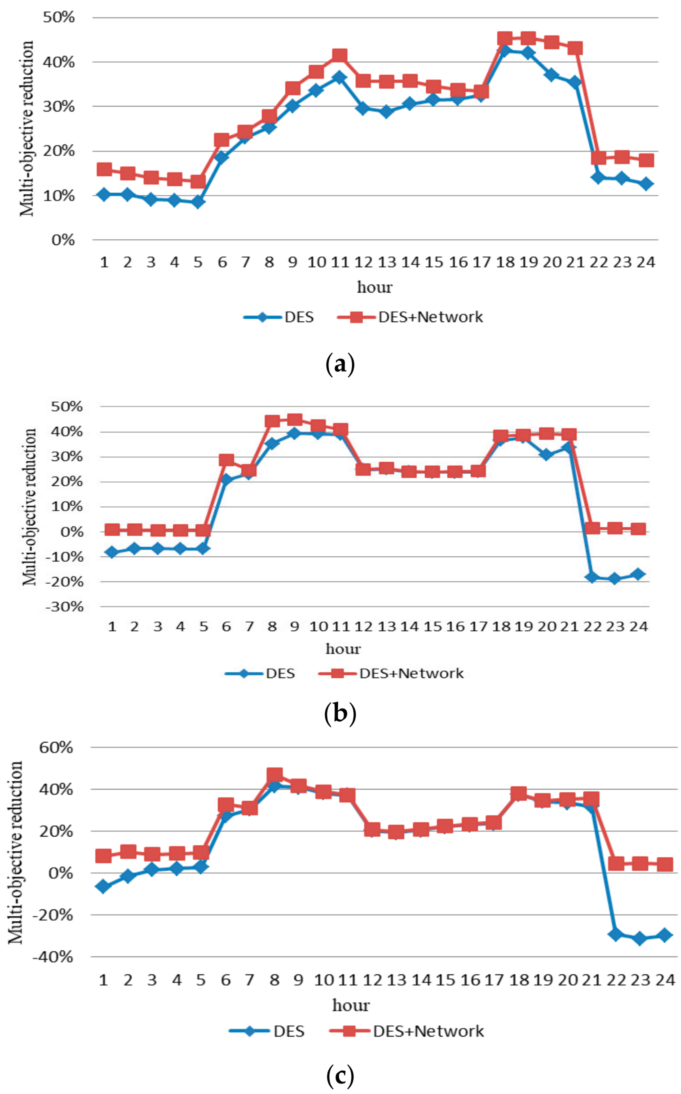
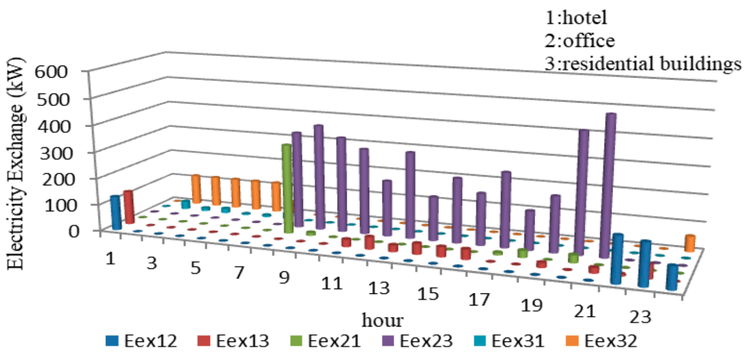


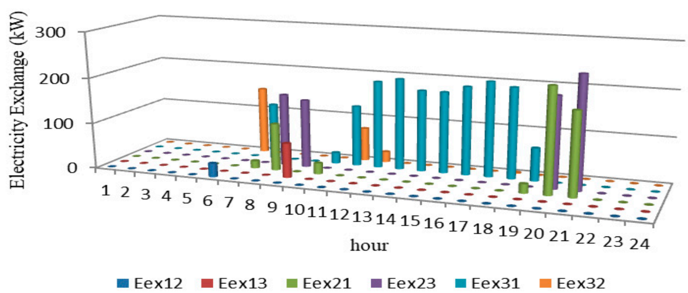
Figure 4. The objective values in DES (scenario 2) and DES + Network (scenario 3) in typical winter (**a**), summer (**b**) and mid-season (**c**) days.

4.1.2. Optimal Electricity Network Interchange of Buildings

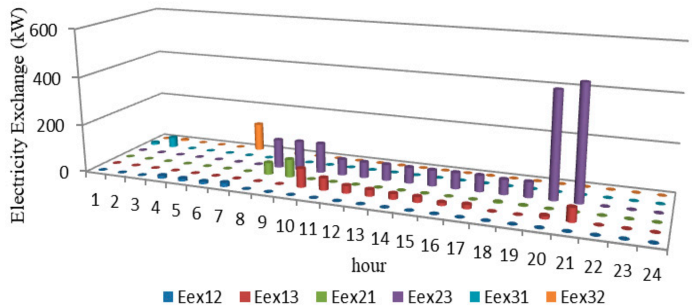
Each building, in which a PGU is installed, can be regarded as an energy producer since a certain amount of electricity is transferred to other buildings. Therefore, it is also important to investigate the electricity interchange between each building through the distribution grid. The hourly optimal interchange between the three typical buildings in scenario 3 is presented in Figure 5. It reflects the cooperative relationship of end-users within the electricity network. For example, the value of E_{ex12} implies the electricity supply from hotel to office, whereas the E_{ex21} is the deficit part that is from office to hotel.



(**a**)



(**b**)



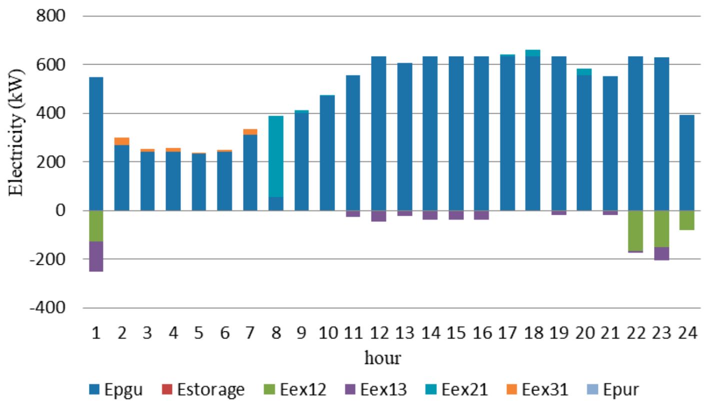
(**c**)

Figure 5. Optimal electricity interchange of buildings in typical winter (**a**), summer (**b**) and mid-season days (**c**).

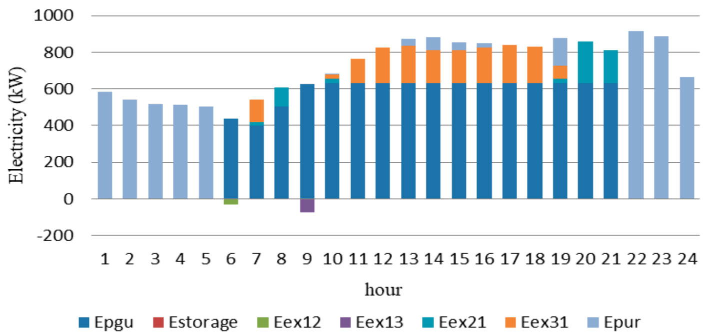
It is necessary to analyze the hourly electricity interchange between each building connected by network in the three typical days. According to Figure 5, on a winter day, the electricity produced by the DES can satisfy all electricity requirements of the office, and most of the excess electricity is transferred through the electricity network from office to residential building (Eex23) to cover their electricity loads. Meanwhile, partial excess electricity of the hotel is also transferred to residential buildings (Eex13). This is mainly due to the higher electricity-grid price for offices and hotels in the daytime and the PGU produce much electricity, which is higher than the electrical demand to avoid purchasing electricity from grid. Hence, the surplus of produced electrical energy is injected into other building power lines. While during night time, the phenomenon is reversed, so that the hotel and office receives electricity from residential buildings (Eex31 and Eex32). Especially in an office, no CCHP unit is on and the electricity demands are all satisfied from the electricity transferred from residential buildings through the power network. On a summer day, the PGU allocated in the three buildings operates at full load in accordance with the higher electricity demand from 9 a.m. to 9 p.m. This is because the cooling demand in peak hours is so high that the recovered thermal energy is not enough for cooling, thus the electrical chiller is also used to cover the deficiency. In the hotel, the deficiency of electricity is also transferred from the residential building during the daytime (Eex31), while on a mid-season day, the electricity demand of residential buildings is satisfied by hotel and office during the daytime due to its lower requirements (Eex23 and Eex13).

4.2. Optimal Energy Supply Strategy

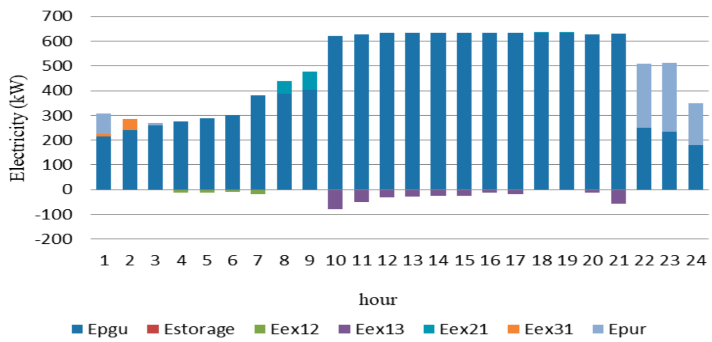
Figure 6 summarizes the hourly electricity balances for the hotel, considering typical winter, summer and mid-season days.



(**a**)



(**b**)



(**c**)

Figure 6. Hourly electricity balance of hotels in typical winter (**a**), summer (**b**) and mid-season days (**c**).

For the hotel, PGU almost operates the entire day on a typical winter day. According to Figure 6, electricity demand is also almost evenly served by electricity generated by the PGU for self-use on a winter day. However, on a summer and mid-season day, the electricity loads are satisfied by electricity generated by the PGU and purchased from the grid. When the install capacity of prime mover units cannot satisfy the higher demand, the electricity demands are also supplemented from the electricity which is transferred from residential buildings.

In the following, a typical day representing winter, summer and mid-season in an office is selected to show the hourly electricity supply strategy (see Figure 7). The optimal operation schedule of electricity interchange from office to other buildings is shown in scenario 3. It can be concluded that, during the daytime, the electricity demand is mainly satisfied by the DES unit and the excess electricity is transported to residential buildings, especially on a winter day. During the night time, electricity demand is mostly purchased from the grid on a summer and mid-season day; whereas, on a winter day, most of the electricity demand is supplied by a combination of interchange from hotel and residential buildings.

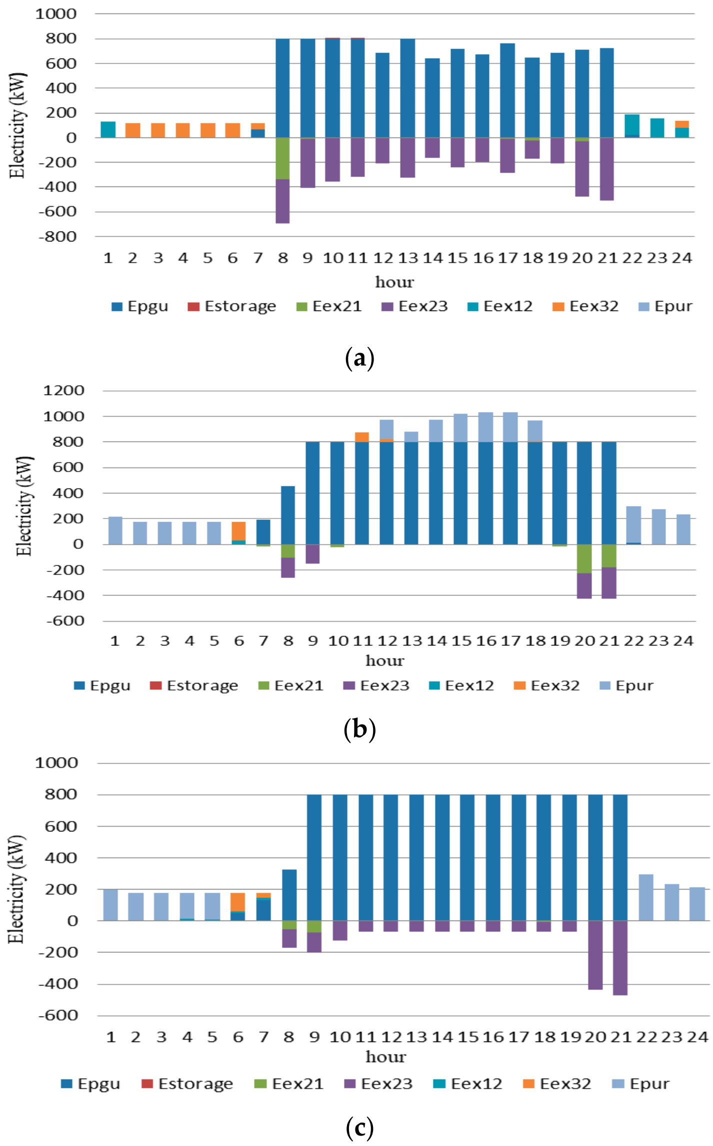
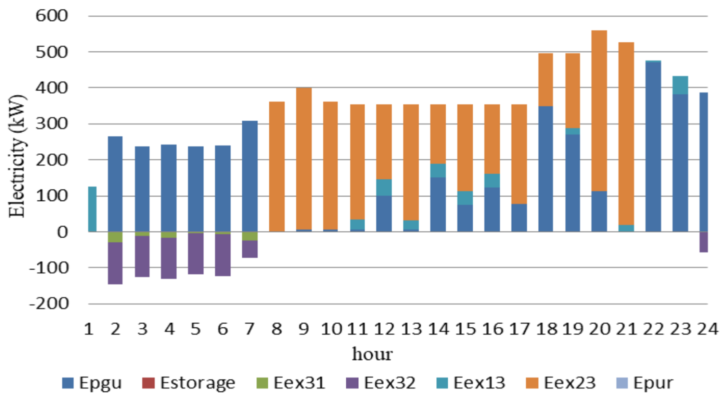


Figure 7. Hourly electricity balance of office in typical winter (**a**), summer (**b**) and mid-season days (**c**).

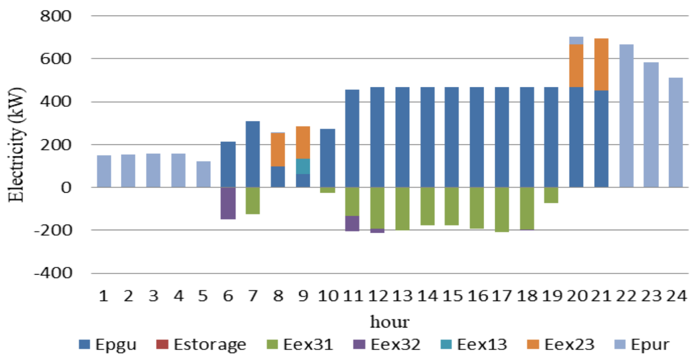
Figure 8 shows the electricity balancing results in typical days for residential buildings in scenario 3. Compared with that in scenario 2, the total installed capacity of PGU for residential buildings is decreased. One reason for this is that the application of electricity networks eliminates some of the strong coupling relationship between electricity demand and producer, which increases the load rate of the PGU and thus causes an increase of electricity in office and residential buildings with higher electricity price from utility grid.

From Figure 8, the main supplier of electricity demand is the PGU, followed by interchanged energy from other buildings on a typical mid-season day. While on a winter day, interchanged energy meets most of the electricity demands, followed by that which is generated by PGU. On a summer day, as to the electric balance, mostly excess electricity is transported to hotels during the daytime.

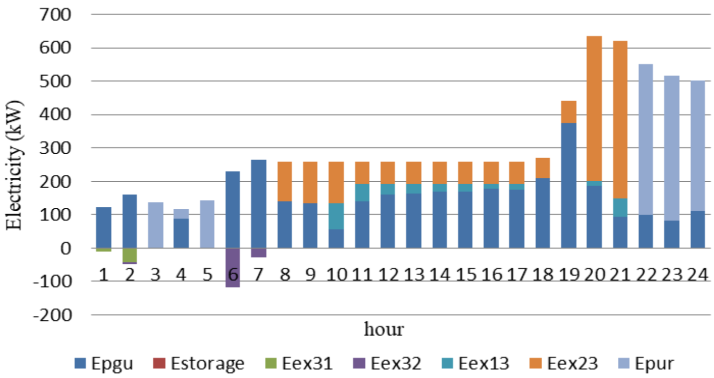
As a widely used measure for balancing electricity between the supply and demand sides, electricity storage has been usually applied as a complement to the distributed generators [31,32]. The storage can store/release energy in/from storage tank to balance supply and demand in a single customer. However, in a region, the surplus/insufficient electricity can be delivered/interchanged to the neighborhoods through electricity network to solve the mismatch problem. According to above Figures 5–7, the results also showed that the stored electricity was almost zero in three studied buildings for 24 h in each typical day.



(**a**)



(**b**)



(**c**)

Figure 8. Hourly electricity balance of residential building in typical winter (**a**), summer (**b**) and mid-season days (**c**).

5. Conclusions

In this research, a MILP model has been developed for the determination of optimal system unit capacity and hourly operation schedules of a DES and a DES+EN. The model was applied in a neighborhood level containing hotel, office and residential buildings in Dalian, China. According to the discussion and results, the conclusion can be deduced as follows:

(1) With the installation of the power network, the load rate of the PGU in hotel and office were improved and the PGU often operated at full loads during the daytime, with the surplus electricity distributed to the residential buildings.
(2) The adoption of the DES+ Electricity Network scenarios allowed for the higher objective reduction values. The application of the DES technologies in scenario 2 as well as in scenario 3 with the installation of the power network, led to a average 20–30% and 30–40% reduction compared to the conventional system respectively.
(3) On a winter day, the advancement of DES + Electricity Network was reflected in its application in the office, most of the excess electricity was transferred from office to residential building through the electricity network during the daytime, while during night time, the phenomenon was reversed, so that the hotel and office received electricity from residential buildings (Eex31 and Eex32), since no PGU units were on in the office.

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Nomenclature

DES	Distributed energy system	subscripts	
DES-EN	Distributed energy system integrated with electricity network	*inv*	Investment cost
CON	Conventional system	om	operation and maintenance costs
PGU	power generation unit	net	network
COST	Total cost	eq	equipment
GAR	Pollutant emissions	ec	Electric chiller
Symbols		fuel	fuel
COP	Coefficient of performance	pgu	power generation unit
τ	Weight factor of objective function	cap	capital cost
C	cost	bo	boiler
R	the capital recovery factor of the equipment	e	electricity
P	the capacity of generated unit	i	types of equipment.
D	distance between buildings	fix	fix costs
OM	operation and maintenance costs	var	variable costs
Out	output energy of the equipment	rec	recovered thermal energy for heating and cooling
F	consumption of the fuel	line	Electricity wire
CO	Cooling demand	ex	Exchange of electricity
HE	Heat consumption		
E	electricity	in	input
L,	The types of building	out	output
GWE	global warming effect	demand	demand load
AE	acidification effect	l	The types of building
RE	$PM_{2.5}$ emission	m	month
		h	hour

α	weighting factors	d	day
λ	conversion factors	Ex12	Electricity transferred from hotel to office
χ	direction of electricity flow	Ex13	Electricity transferred from hotel to residential building
E_{ex}	electricity flows in the network	Ex21	Electricity transferred from office to hotel
Max	the maximum transmission capacity	Ex23	Electricity transferred from office to residential building
r	interest rate	Ex31	Electricity transferred from residential building to hotel
v	the service life of the equipment	Ex32	Electricity transferred from residential building to office
Em	Pollutant emission		
F_j	fuel consumption		
ξ_z	emission factor		

References

1. Liu, G.W.; Qu, L.; Zeng, R.; Gao, F. *The Energy Internet*; Woodhead Publishing: Cambridge, UK, 2019; pp. 265–282.
2. Rao, B.V.; Kupzog, F.; Kozek, M. Phase Balancing Home Energy Management System Using Model Predictive Control. *Energies* **2018**, *11*, 3323. [CrossRef]
3. Barbato, A.; Capone, A.; Barbato, A.; Capone, A. Optimization Models and Methods for Demand-Side Management of Residential Users: A Survey. *Energies* **2014**, *7*, 5787–5824. [CrossRef]
4. Yang, Y.; Zhang, S.J.; Xiao, Y.H. Optimal design of distributed energy resource systems coupled with energy distribution networks. *Energy* **2015**, *85*, 433–448. [CrossRef]
5. Wu, Q.; Ren, H.B.; Gao, W.J.; Ren, J.X. Multi-objective optimization of a distributed energy network integrated with heating interchange. *Energy* **2016**, *109*, 353–364. [CrossRef]
6. Ackermann, T.; Andersson, G.; Soder, L. Distributed generation: A definition. *Electr. Power Syst. Res.* **2001**, *57*, 195–204. [CrossRef]
7. Song, X.H.; Shu, M.D.; Wei, Y.M.; Liu, J.P. A Study on the Multi-Agent Based Comprehensive Benefits Simulation Analysis and Synergistic Optimization Strategy of Distributed Energy in China. *Energies* **2018**, *11*, 3260. [CrossRef]
8. Dong, M.; He, F.L.; Wei, H.R. Energy supply network design optimization for distributed energy systems. *Comput. Ind. Eng.* **2012**, *63*, 546–552. [CrossRef]
9. Obara, S.Y.; Morizane, Y.; Morel, J. A study of small-scale energy networks of the Japanese Syowa Base in Antarctica by distributed engine generators. *Appl. Energy* **2013**, *111*, 113–128. [CrossRef]
10. Rieder, A.; Christidis, A.; Tsatsaronis, G. Multi criteria dynamic design optimization of a small scale distributed energy system. *Energy* **2014**, *74*, 230–239. [CrossRef]
11. Soderman, J.; Pettersson, F. Structural and operational optimization of distributed energy systems. *Appl. Therm. Eng.* **2006**, *26*, 1400–1408. [CrossRef]
12. Sameti, M.; Haghighat, F. Optimization of 4th generation distributed district heating system: Design and planning of combined heat and power. *Renew. Energy* **2019**, *130*, 371–387. [CrossRef]
13. Varasteh, F.; Nazar, M.S.; Heidari, A.; Shafie-khah, M.; Catalao, J.P.S. Distributed energy resource and network expansion planning of a CCHP based active microgrid considering demand response programs. *Energy* **2019**, *172*, 79–105. [CrossRef]
14. Kang, J.; Wang, S.W.; Yan, C.C. A new distributed energy system configuration for cooling dominated districts and the performance assessment based on real site measurements. *Renew. Energy* **2019**, *131*, 390–403. [CrossRef]
15. Mehleri, E.D.; Sarimveis, H.; Markatos, N.C.; Papageorgiou, L.G. A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level. *Energy* **2012**, *44*, 96–104. [CrossRef]
16. Mehleri, E.D.; Sarimveis, H.; Markatos, N.C.; Papageorgiou, L.G. Optimal design and operation of distributed energy systems: Application to Greek residential sector. *Renew. Energy* **2013**, *51*, 331–342. [CrossRef]
17. Li, L.X.; Mu, H.L.; Nan, L.; Miao, L. Economic and environmental optimization for distributed energy resource systems coupled with district energy networks. *Energy* **2016**, *109*, 947–960. [CrossRef]
18. Wu, Q.; Ren, H.B.; Gao, W.J.; Ren, J.X.; Lao, C.S. Profit allocation analysis among the distributed energy network participants based on Game-theory. *Energy* **2017**, *118*, 783–794. [CrossRef]

19. Somma, M.D.; Yan, B.; Bianco, N.; Luh, P.B.; Graditi, G.; Mongibello, L.; Naso, V. Multi-objective operation optimization of a Distributed Energy system for a large-scale utility customer. *Appl. Therm. Eng.* **2016**, *101*, 752–761. [CrossRef]
20. Lesse, J.A.; Su, X. Design of an economically efficient feed-in tariff structure for renewable energy development. *Energy Policy* **2008**, *36*, 981–990. [CrossRef]
21. Jing, Y.Y.; Bai, H.; Wang, J.J. Multi-objective optimization design and operation strategy analysis of BCHP system based on life cycle assessment. *Energy* **2012**, *37*, 405–416. [CrossRef]
22. Li, M.; Mu, H.L.; Li, N.; Ma, B.Y. Optimal design and operation strategy for integrated evaluation of CCHP (combined cooling heating and power) system. *Energy* **2016**, *99*, 202–220. [CrossRef]
23. Ebrahimi, M.; Keshavarz, A. Sizing the prime mover of a residential micro-combined cooling heating and power (CCHP) system by multi-criteria sizing method for different climates. *Energy* **2013**, *54*, 291–301. [CrossRef]
24. Fumo, N.; Mago, P.J.; Chamra, L.M. Emission operational strategy for combined cooling, heating, and power systems. *Appl. Energy* **2009**, *86*, 2344–2350. [CrossRef]
25. Wang, J.J.; Zhai, Z.Q.; Zhang, C.F.; Jing, Y.Y. Environmental impact analysis of BCHP system in different climate zones in China. *Energy* **2010**, *35*, 4208–4216. [CrossRef]
26. Liu, M.X.; Shi, Y.; Fang, F. A new operation strategy for CCHP systems with hybrid chiller. *Appl. Energy* **2012**, *95*, 164–173. [CrossRef]
27. Liu, X.; Wu, J.; Jenkins, N.; Bagdanavicius, A. Combined analysis of electricity and heat networks. *Appl. Energy* **2016**, *162*, 1238–1250. [CrossRef]
28. Wang, J.J.; Zhai, Z.Q.; Jing, Y.Y.; Zhang, X.T.; Zhang, C.F. Influence analysis of building types and climate zones on energetic, economic and environmental performances of BCHP systems. *Appl. Energy* **2011**, *88*, 3097–3112. [CrossRef]
29. Wang, J.J.; Zhang, C.F.; Jing, Y.Y. Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China. *Appl. Energy* **2010**, *87*, 1247–1259.
30. Wang, J.J.; Jing, Y.Y.; Zhang, C.F.; Zhai, Z.Q. Performance comparison of combined cooling heating and power system in different operation modes. *Appl. Energy* **2011**, *88*, 4621–4631. [CrossRef]
31. Steen, D.; Stadler, M.; Cardoso, G.; Groissbock, M.; DeForest, N.; Marnay, C. Modeling of thermal storage systems in MILP distributed energy resource models. *Appl. Energy* **2015**, *137*, 782–792. [CrossRef]
32. Zahedi, A. Maximizing solar PV energy penetration using energy storage technology. *Renew. Sustain. Energy Rev.* **2011**, *15*, 866–870. [CrossRef]