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Optimal Investment Strategies for Solar Energy Based Systems

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Abstract: Solar energy, as an inexhaustible renewable energy, can be used to produce heat and electricity. It is of great importance to examine the strategy for investment on solar energy technology. In response to varying electricity price in the electricity market, the battery energy storage system (BESS) can be used to get price arbitrage. This paper proposes an optimal configuration model for a photovoltaic (PV) system, solar heating system, and BESS in order to obtain maximum profit for investors. The investment potential of these systems is compared and analyzed based on return on investment (ROI) index which is defined to evaluate economic profitability. A bi-level programming is adopted to optimize the operation strategy of batteries (inner layer), the size of PV system and solar heating system, and the size of batteries (outer layer) including their maximum discharge/charge power and capacity. Sequential quadratic programming (SQP) method and particle swarm optimization (PSO) are used as optimization methods. In the case study, five investment strategies are investigated in order to decide how to invest in PV modules, batteries, and solar thermal collectors. The results show that the BESS may be a preferable choice for the investors if the investment cost of BESS goes down a lot in the future. Investing in solar energy for both heat and power may be not reasonable because the ROI of this strategy is always higher than either investing in heat or in power. The optimal strategy may be changed with the fluctuation of heat and electricity prices.

Keywords: solar energy; investment strategies; bi-level optimization; batteries; return on investment (ROI)

1. Introduction

Solar energy as a rich sustainable energy source, has been considered to be one of the most promising solutions to meet the increasing demand for energy [1]. Besides, it is also one of the most suitable solutions to cut carbon dioxide emissions which can effectively overcome the global warming crisis [2]. In this case, much attention from strategic investors has been paid on the solar industry. Solar energy is mainly used to generate power and produce heat to meet heating demands such as heating and drying [3]. Investors may make tradeoffs between the heat and power when making decisions on investment in solar energy.

In this century, photovoltaic (PV) technology which is known as converting solar energy directly into power by semiconductors has matured and experienced massive growth [4]. In 2017, installed PV capacity rose to 402.5 GW globally. Solar PV accounts for a high proportion in new renewable energy installations [5]. The benefits of investing in solar power generation are related to the electricity market. There are three main electricity markets in Northern Europe: spot market (Elspot), balancing market

(Elbas), and regulating market [6]. These markets work in different time periods and ensure that the completion of the transaction meets all demands.

Due to the fluctuation of the electricity market, people would like to use energy storage installations when the hourly spot market price is available one day ahead [7]. Battery energy storage system (BESS) is one of the best choices, and rated power of global electro-chemical storage installations from the US Department of Energy database is 3297 MW [8]. Plenty of studies have studied the operating schedule of BESS to get maximum profit in the electricity market. Several optimization methods, such as dynamic programming [9] and nonlinear programming [10], were adopted to optimize the operation of BESS. Reference [11] calculated the levelized cost of energy for PV systems with storage, but it does not consider the profit of investment.

As for supplying heat by solar energy, solar water heating is one of the most famous solar thermal applications and has been used in 70 million houses [12]. It can reduce the cost of fuel consumption and CO_2 equivalent emissions [13]. In some countries, the integration of solar thermal systems in district heat (DH) systems is widely used [14]. Heat price largely determines the yield of the investors who invest the solar heat which involves the DH market. Around the world, the DH market can be divided into regulated market and deregulated market [15]. In a deregulated DH market, the pricing method based on marginal cost is commonly utilized to determine the price of DH. In a regulated DH market, the price of DH is usually regulated by the government which depends on the operation cost, annual depreciation, and permitted profits for DH companies [16]. This method is called the cost-plus pricing method.

This paper analyzes investment strategies for solar energy based on PV system, solar heating system, and BESS with a real situation at Xiaojin, Sichuan, China (latitude: 30.76477°, longitude: 102.11929°) as case of study. The return on investment (ROI) is used to calculate the profits of systems. A bi-level programming is adopted to optimize the operation strategy of batteries in the inner layer, area allocation of PV system and solar heating system, and the size of batteries in the outer layer. In the case study, four cases from the present and future perspectives are investigated to decide how to invest in PV modules, batteries, and solar thermal collectors; notably, each case contains five strategies.

The subsequent sections in this paper are organized as follows. Section 2 presents the modelling of electricity/heating and battery hybrid systems. Section 3 studies the proposed optimization methods and optimized framework. The case study is presented in Section 4, and the performances of the proposed optimal strategies at present and in future are studied. Finally, conclusions and outlooks are given in Section 5.

2. System Models

The model of solar energy based electricity/heating and battery hybrid systems is composed of a PV model, solar heating system model, and batteries model. The schematic diagram of the model is shown in Figure 1. The cost of each sub-system is also proposed in this section. The power generated by the PV system is sold to the electricity market or stored in the battery energy storage system. Additionally, the heat supplied by solar thermal collectors is sold to the DH market directly through heat networks. The power from the PV system is sold to the electricity market to bring profits. The electricity generated from the PV system is directly sold to the electricity market through the inverter, but the electricity price may be quite low. With the aid of batteries, the power can be stored when the electricity price is relatively low. In addition, when the electricity price is high, the batteries discharge and the electricity is sold to the electricity market. In this way, price arbitrage can be realized. This is the reason why we consider integrating the BESS into the system to increase the profits of selling electricity supplied by the PV system. Investment strategies for solar energy based electricity/heating and battery hybrid systems are optimized.

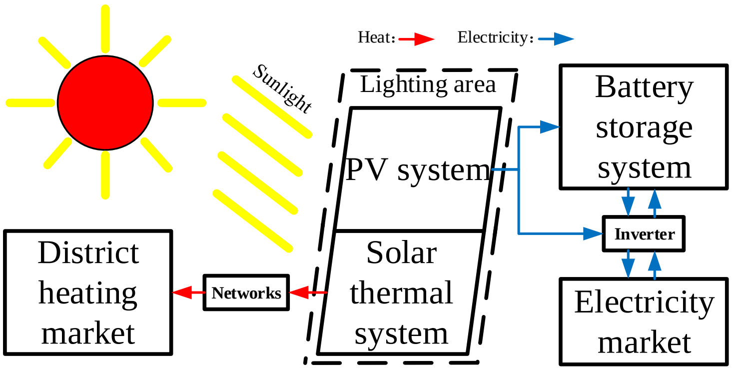

Figure 1. Electricity/heating and battery hybrid systems model.

2.1. Photovoltaic System Model

A PV cell is a semiconductor diode which can convert the energy from sunlight into direct current electricity. The solar radiation and ambient temperature are the two essential parameters to decide the PV cell output. The output power of PV system can be presented by using Equation (1) [17]:

$$P_{pv} = P_n \times \frac{G_\beta}{G_{ref}} \times \left[1 + K_t \times (T_c - T_{ref})\right] \tag{1}$$

The PV module is tilted to capture more solar radiation. In this paper, the tilt angle is set as 30°. PV panels are oriented south for best azimuth angle since they are in the northern hemisphere. The total solar radiation can be calculated by the sum of beam radiation, diffuse radiation, and ground-reflected radiation. They can be represented by [18]:

$$G_\beta = G_{\beta,b} + G_{\beta,d} + G_{\beta,r} \tag{2}$$

$$G_{\beta,b} = G_b \times \frac{\max\,(0,\ \cos\theta)}{\max\,(0.087,\ \cos\theta_z)} \tag{3}$$

$$G_{\beta,d} = G_d \times [(1 - F_1) \times \cos^2(\frac{\beta}{2}) + F_1 \times \frac{\max\,(0,\ \cos\theta)}{\max\,(0.087,\ \cos\theta_z)} + F_2 \times \sin\beta] \tag{4}$$

$$G_{\beta,r} = \rho \times (G_b + G_d) \times \frac{1 - \cos\beta}{2} \tag{5}$$

The temperature of the PV cell is calculated by Equation (6):

$$T_c = T_a + (0.0256 \times G_\beta) \tag{6}$$

The PV module efficiency is assumed to have a 0.5% reduction each year. The cost of the PV system changes all the time, but it has declined gradually in these years. In this study, the initial capital cost of a PV module is assumed as \$705/kW and \$141/m^2 based on the rated power of PV panels, including the installation cost and operation cost [19]. The direct current supplied by PV modules is converted to alternating current by inverters and then exported to the electricity market. The inverter efficiency is assumed to be 95% [20].

2.2. Battery System Model

The battery system is connected with the PV system. The electricity price in the market is not always high. In the low electricity price period, the power can be stored by the batteries. The batteries discharge when the electricity price is high. The electricity price in an example day is shown in Figure 2. In the morning, the grid prices reach the maximum of this day. More electricity is willingly exported to the electricity market. If the batteries are in the state of charging or they are empty at that time, the profits may decrease. The profits depend on the operation of the batteries. In this paper, the operation of batteries in a year is optimized considering various electricity prices in different days.

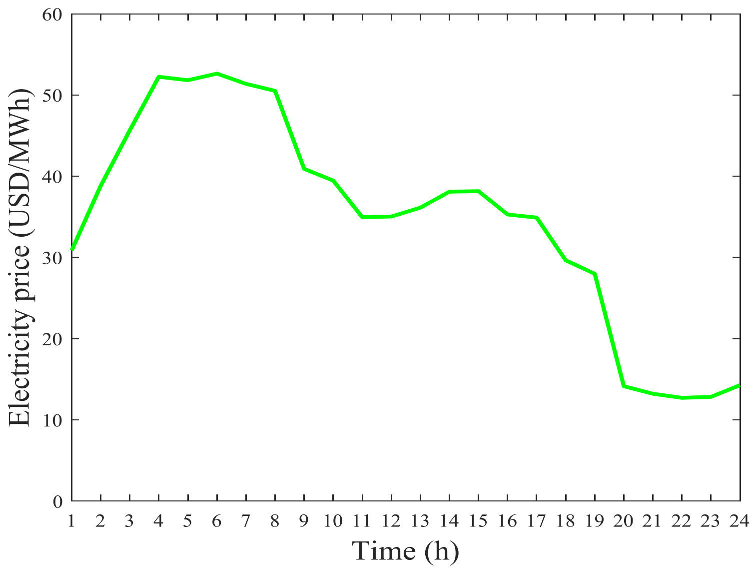

Figure 2. Electricity price in an example day.

The energy stored in the BESS depends on the sum of the discharge/charge power and can be expressed as Equation (7):

$$E_{t+1} = \begin{cases} E_t + \eta P_t \times (1\text{hour}) & P_t > 0 \\ E_t + (P_t/\eta) \times (1\text{hour}) & P_t < 0 \end{cases} \tag{7}$$

When BESS is charged/discharged, P_t is positive/negative.

The energy of BESS that is bought from/sold to the electricity market will also go through the inverters. Batteries can be charged using the power from PV modules. Hence, discharge/charge power of the batteries can be expressed as Equation (8):

$$P_t = \begin{cases} P_{fpv-t} + \eta_{inv} P_{trade-t} & P_{trade} \geq 0 \\ P_{trade-t}/\eta_{inv} & P_{trade} < 0 \end{cases} \tag{8}$$

The BESS system can bring more income via price arbitrage, and its capital cost must be considered. Maximum discharge/charge power and capacity determine the BESS capital cost, and it can be expressed as Equation (9) [21]:

$$C_{bs} = C_p P_{\max} + C_w W_{\max} \tag{9}$$

The operation of batteries is limited by Equations (10) and (11):

$$-P_{\max} \leq P_t \leq P_{\max} \tag{10}$$

$$W_{\max} \times (1 - \text{DOD}) \leq E_t \leq W_{\max} \times \text{DOD} \tag{11}$$

The discharge/charge power is limited by the BESS power. The energy stored in batteries is not less than 20% and no more than 80% according to an assumption that depth of discharge (DOD) is 80%.

The profits of the BESS system not only depend on its capital cost but also depend on the hourly batteries performance (discharge/charge power). The operation of batteries is related to the electricity price, which has a great influence on revenue. The daily income depends on the operation mode. Hence, a bi-level optimization is used to find the optimal operation mode which is modeled in Section 3.

Polysulfide-bromine (PSB) with a low investment cost is used as the BESS in this research. Technical specifications of the PSB are presented as follow [21,22]: the capital power cost is 150 USD/kW and the capital energy cost is 65 USD/kWh. The efficiency is 65% and the lifespan is 15 years.

2.3. Solar Heating System Model

In this model, the heat produced by solar is from solar thermal collectors. The technology for solar thermal collector is flat plate collector (FPC). The efficiency of the solar thermal collector depends on many parameters and can be calculated by Equations (12) and (13) [23]:

$$\eta_c(t) = \eta_0 - a_1 \frac{(T_m(t) - T_a(t))}{G_\beta(t)} - a_2 \frac{(T_m(t) - T_a(t))^2}{G_\beta(t)} \tag{12}$$

$$T_m = \frac{T_{out} + T_{in}}{2} \tag{13}$$

Hence, specific net solar gain is:

$$Q_t = \eta_c(t) \times G_\beta(t) \tag{14}$$

The solar thermal system is connected to heat networks. Heat from solar thermal collectors is used to heat water and transported through heat networks. For the various heat users, the temperature requirements of water are different. The collector outlet temperature is assumed equal to heating network water supply temperature. Collector inlet temperature is assumed as 40 °C and outlet temperature is assumed as 60 °C. Heat loss is considered in the networks.

The investment cost of solar thermal collectors depends on the actual collector price per m^2. Its cost is calculated by regression analysis and is shown in Figure 3. The total system investment cost of solar heating system can be calculated according to Equation (15) [24]:

$$C_{shs} = (-48.22 \times \ln S_{shs} + 785.67) \times S_{shs} + C_{ins} + C_{os} \tag{15}$$

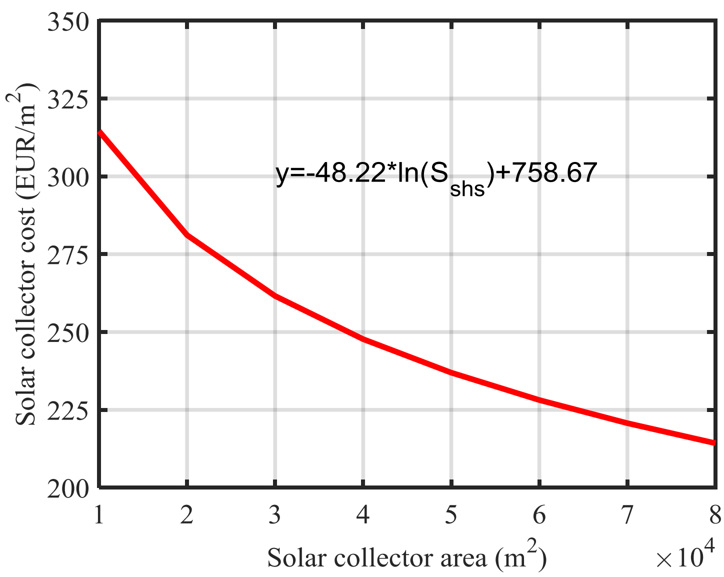

Figure 3. Solar thermal collector costs under different areas [24].

3. Optimization Methods

3.1. Optimization Methodology

The sequential quadratic programming (SQP) method and particle swarm optimization (PSO) are used as optimization methods in this paper.

3.1.1. Sequential Quadratic Programming (SQP) Method

SQP is a classic approach based on mathematical programming theory. It is also one of the best algorithms to solve the small or medium scale nonlinearly constrained optimization problems. Under the constrains, a lot of iterations are made to get the best optimization. At each iteration, the Quasi-Newton updating method is adopted to get an approximation of the Hessian matrix of the Lagrangian function. This approximation is used to get the solution of a quadratic programming sub-problem, and this solution is adopted to update the approximation [25].

3.1.2. Particle Swarm Optimization (PSO)

The PSO approach simulates the hunting behavior of birds. It was first proposed in 1995 by Kennedy and Eberhart [26]. This evolutionary algorithm can be a good choice to solve this non-convex optimization problem [27]. In PSO, each particle has a fitness value determined by the optimized function and a speed that determines the direction and distance. The position (x) and velocity (v) are constant updated by Equations (16) and (17):

$$v_{ij}^{t+1} = w \times v_{ij}^{t} + c_1 \times r_1(p_{ij}^{t} - x_{ij}^{t}) + c_2 \times r_2 \times (g_j^{t} - x_{ij}^{t}) \tag{16}$$

$$x_{ij}^{t+1} = v_{ij}^{t+1} + x_{ij}^{t} \tag{17}$$

c_1 and c_2 are set as equivalent in this paper. The strategies of linear inertia weight reduction are used in this paper [28].

3.2. Optimization Approach

The aim of this paper is to find the best investment strategies for solar energy based electricity/heating and battery hybrid systems. A bi-level programming is adopted to optimize the operation strategy of batteries (inner layer), the size of batteries including their maximum discharge/charge power and capacity, and the area of the PV system and solar heating system (outer layer).

3.2.1. Outer Layer Optimization

The size of batteries and area of PV system can be obtained in this layer. BESS capacities and power decide the capital costs of batteries. PSO is used as the optimization method in this layer. The total area of PV system and solar heating system is constant in this paper:

$$S_{total} = S_{pv} + S_{shs} \tag{18}$$

The ROI index is defined to evaluate economic profitability [29]. It is adopted as the objective function in this layer to evaluate and compare the efficiency of investment strategies in this research. The ROI can be written as Equation (19) in this paper:

$$\min(ROI) = \min\left(\frac{C_{bs} + C_{bp} + C_{pv} \times S_{pv} + C_{shs} + \sum_{n=1}^{T} \frac{C_{OM}}{(1+r)^T}}{I_{ave}}\right) \tag{19}$$

3.2.2. Inner Layer Optimization

While each parameter is determined in the out layer, the optimal strategy is decided in this layer. Equation (7) describes the energy and operation mode of the BESS. When P_t is positive/negative, the BEES is on charging/discharging mode. The value of P_t is restricted in this layer and SQP is adopted as the optimization algorithm. The optimization objective function in this layer is chosen as maximum annual income without considering the capital cost, and is given by Equation (20):

$$\max\{I_r^n\} = \max\left\{\sum_{t=1}^{8760}\left\{HP_t \times P_{sc} + EP_t \times \left[\left(P_{pv-n} - P_{fpv-t}\right) \times \eta_{inv} - P_{trade}\right]\right\}\right\} \quad (20)$$

The algorithm flow chart is shown in Figure 4.

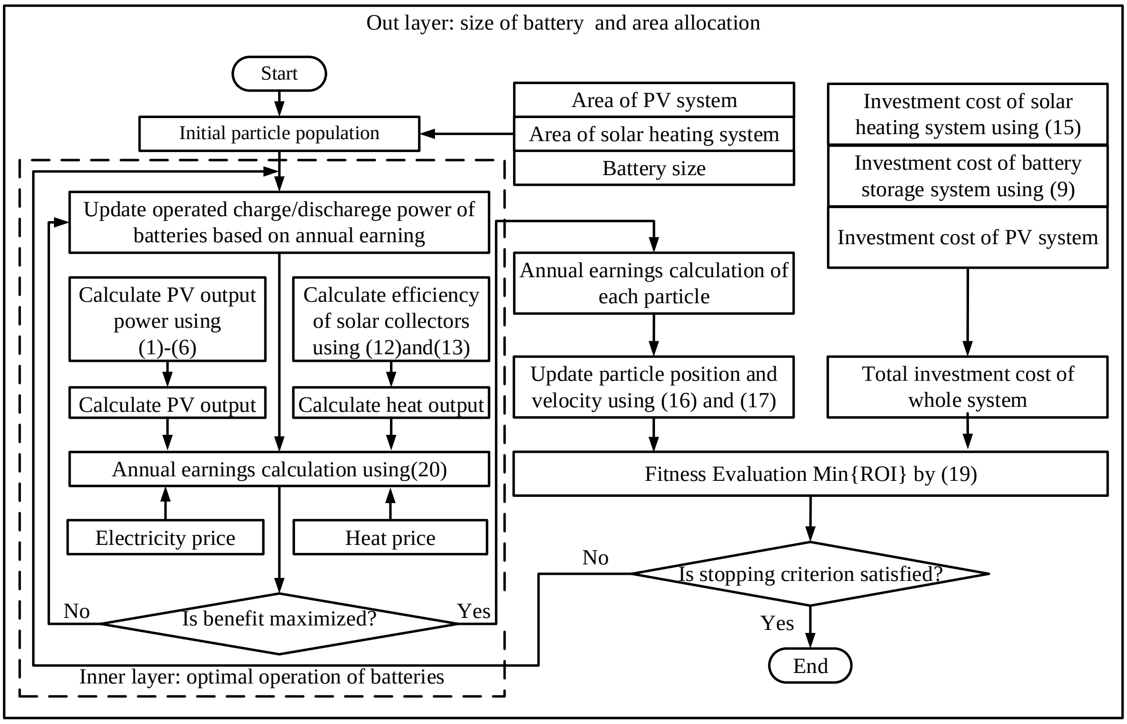

Figure 4. Flowchart of the bi-level programming.

3.3. Assumptions

In order to implement the program, some necessary assumptions are made as follow:

- Buying electricity from the electricity market is considered in the optimization of batteries. The energy in batteries are from the PV system and electricity market. Due to the impact of taxes, the price of buying electricity is assumed to be 1.2 times of price in the electricity market. The price of selling electricity is equal to the price in the electricity market.
- The charge/discharge power of the BESS is small, and it is assumed that the spot prices are not changed by the operation of the BESS. At the beginning of a day, the state charge of batteries is assumed to be 50%. The storage energy in batteries should be more than 50% at the end of the day.
- The heat produced by solar is supposed to be sold to the heat market. In order to simplify the model, regulated market is chosen as the DH market. Its price is assumed as a constant (10 USD/GJ in this paper). The trade of heat will not change the heat price. Without considering demand and price fluctuation, heat storage is not involved in this paper.
- The construction area is assumed to be 100,000 m^2 including solar thermal collectors and PV. The room for batteries is not considered, because they do not occupy the field for receiving light.

4. Case Study

4.1. Reference Solar Radiation, Ambient Temperature, and Electricity Price

The situation studied in this paper is Xiaojin, Sichuan, China (latitude: 30.76477°, longitude: 102.11929°). Total solar radiation during a year is shown in Figure 5. The daily average value of total solar radiation is 334 W/m^2, and the solar energy is abundant to be transformed to electrical energy and heat. The ambient temperature data is also necessary to calculate both heat and electricity. It is shown in Figure 6. Annual minimum temperature is −3.8 °C, and annual maximum temperature is 26.7 °C.

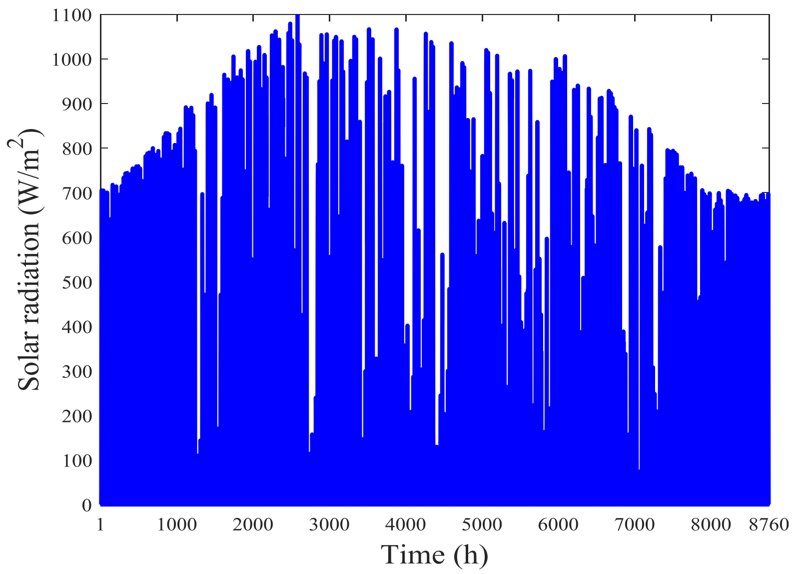

Figure 5. Total solar radiation.

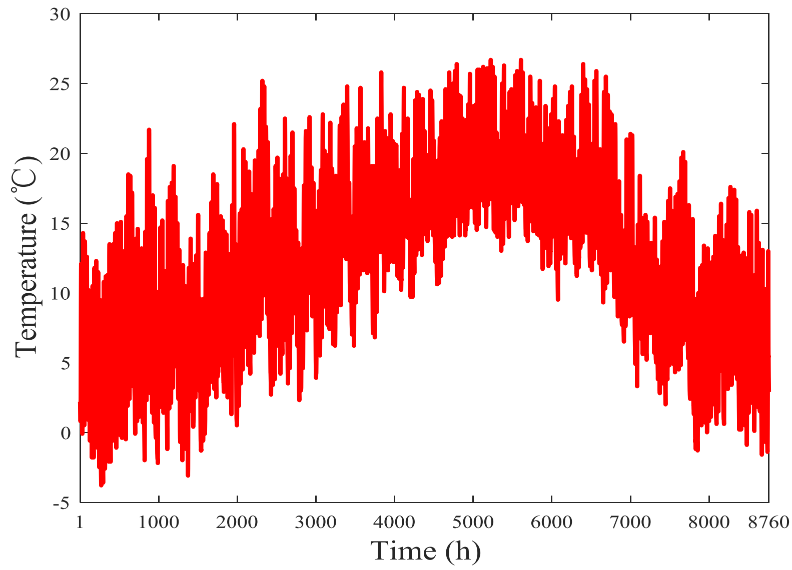

Figure 6. Ambient temperature.

The behaviors of selling electricity are determined by the electricity prices. The data of electricity prices selected in this paper is shown in Figure 7 which has a high fluctuation. The highest electricity prices occur in winter and the electricity prices are zero in some hours. The heat price is assumed to be 10 USD/GJ in the regular heat market.

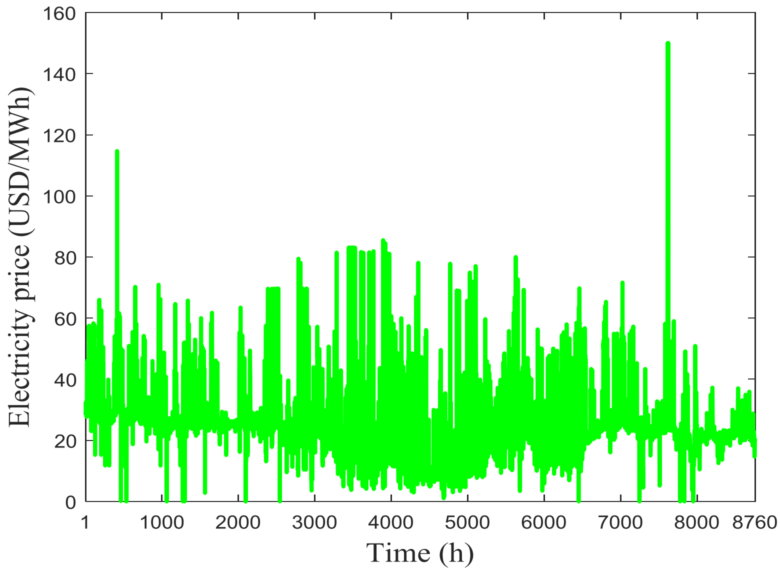

Figure 7. Electricity price.

4.2. Optimization Results of Investment on the Photovoltaic System and Solar Heating System at Present and Future

In order to decide how to invest in PV modules for selling electricity and solar thermal collectors for selling heat, the following five investment strategies are investigated in the case study:

- Strategy 1: investing in PV system (Bench mark). Investors sell the electricity supplied by the PV system to the electricity market.
- Strategy 2: investing in solar heating system (Bench mark). Investors sell the heat from the solar heating system to the DH heat market.
- Strategy 3: investing in PV system and BESS. This strategy considers price arbitrage with the aid of PSB to earn more money from the electricity market.
- Strategy 4: investing in PV and solar thermal heating systems based on optimal area allocation. Income of investments may from the heat market and electricity market.
- Strategy 5: investing in PV system with BESS and solar thermal heating system. Income of investments may be from selling heat and power directly and price arbitrage. Due to the high cost of the batteries and because the power will be lost during the charge process of batteries, the size of batteries cannot be too large. It is important to optimize the size of the batteries.

Four cases are investigated in the following section which includes the present and future investment condition (2030, 2040, 2050). The best optimal strategy varies in different cases. In the future, the data adopted in this paper like electricity price and heat price will be changed. The optimal strategy may also be changed in the future. In this case, the investment strategies on solar energy of the years 2030, 2040, and 2050 are compared and analyzed. In this paper, the electricity price will increase significantly in 2030 and keep stable in the period of 2030 to 2040 [30]. The electricity may decrease in 2050 according to [31]. Based on [32], the heat price in Europe has increased a lot in past 30 years. Its growth trend is adopted to predict the heat price in the future in this paper. The electricity prices and heat prices from 2030 to 2050 are shown in Figure 8. For the solar heating system, we consider a reduction in its cost from present to 2030/from 2030 to 2040/from 2040 to 2050 of 8%/6%/4% [19]. The investment cost of the PV system will be reduced. The reduction trend of PV system is assumed to be to the same as the solar heating system.

With the development of technology, the cost of batteries will decrease in the future. From [33], the cost of batteries may be reduced by 40% for the 2020–2030 period. In order to analyze the investment potential of the batteries in this system, an assumption is made in this case: the capital cost of batteries will have a decline of 40% in 2030, have a decline of 50% in 2040 and have a decline of 55 % in 2050. The efficiency of PSB increases to 75%. The DOD increases to 90%.

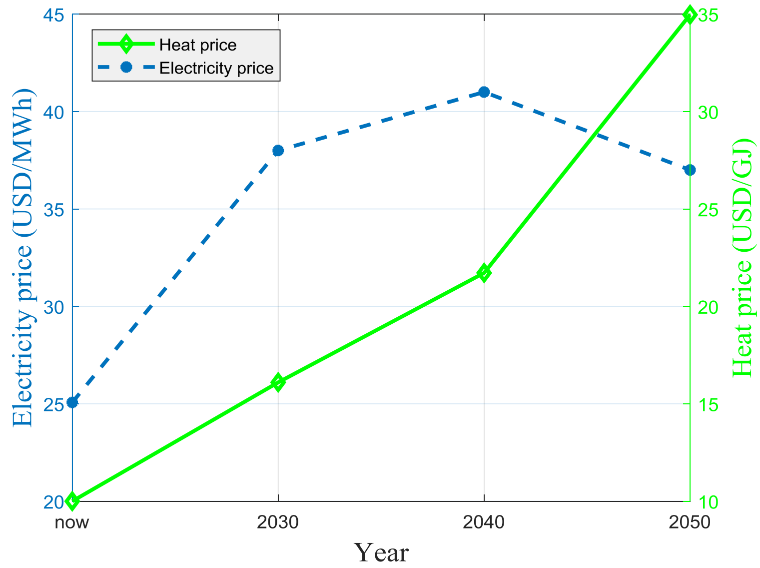

Figure 8. Electricity price and heat price in the future.

The optimal results include ROI, annual income, and area allocation of these strategies are compared in Table 1. The cost of each strategy includes BESS cost, PV system cost, and solar heating system cost are also given in Table 1.

Table 1. Optimization of the four cases.

Case		Now					2030				
Strategy number		1	2	3	4	5	1	2	3	4	5
Annual income ($\times 10^5$/USD)		6.03	10.06	6.03	6.03	6.03	9.15	16.21	11.60	9.15	11.60
ROI		27.12	32.83	27.12	27.12	27.12	16.46	18.75	15.83	16.46	15.83
Area of PV ($\times 10^5$/m^2)		1	-	1	1	1	1	-	1	1	1
Area of STS ($\times 10^5$/m^2)		-	1	-	0	0	-	1	-	0	0
Batteries size	Power (MW)	-	-	0	-	0	-	-	16.92	-	16.92
	Energy capacities (MWh)	-	-	0	-	0	-	-	48.30	-	48.30
Batteries cost	Power cost coefficient (USD/kW)	-	-	150	-	150	-	-	90	-	90
	Energy cost coefficient (USD/kWh)	-	-	65	-	65	-	-	39	-	39
Total batteries cost ($\times 10^5$/USD)		-	-	0	-	0	-	-	34.07	-	34.07
PV cost ($\times 10^5$/USD)		163.64	-	163.64	163.64	163.64	150.55	-	150.55	150.55	150.55
Solar heating system cost ($\times 10^5$/USD)		-	330.44	-	0	0	-	304.00	-	0	0
Case		**2040**					**2050**				
Strategy number		1	2	3	4	5	1	2	3	4	5
Annual income ($\times 10^5$/USD)		9.87	21.87	13.37	21.87	21.87	8.91	35.21	12.61	35.21	35.21
ROI		14.34	13.07	13.39	13.07	13.07	15.26	7.79	13.93	7.79	7.79
Area of PV ($\times 10^5$/m^2)		1	-	1	0	0	1	-	1	0	0
Area of STS ($\times 10^5$/m^2)		-	1	-	1	1	-	1	-	1	1
Batteries size	Power (MW)	-	-	20.85	-	0	-	-	22.60	-	0
	Energy capacities (MWh)	-	-	67.25	-	0	-	-	84.02	-	0
Batteries cost	Power cost coefficient (USD/kW)	-	-	75	-	75	-	-	67.5	-	67.5
	Energy cost coefficient (USD/kWh)	-	-	32.5	-	32.5	-	-	29.25	-	29.25
Total batteries cost ($\times 10^5$/USD)		-	-	37.49	-	0	-	-	39.83	-	0
PV cost ($\times 10^5$/USD)		142.55	-	142.55	0	0	136.85	-	136.85	0	0
Solar heating system cost ($\times 10^5$/USD)		-	285.76	-	285.76	285.76	-	274.33	-	274.33	274.33

4.2.1. Analysis of Investment Strategies at Present

At present, the optimal result of strategies 3, 4, and 5 are the same as strategy 1. The strategy of investing in the PV system can obtain the minimum ROI. In strategy 2, though selling heat to the heating market can bring more annual incomes than selling electricity to the electricity market, capital cost per square meter of solar heating system is more expensive than that of the PV system when the total area is 100,000 m^2. Therefore, the optimal area of solar thermal collectors is zero. In strategy 3 and strategy 5, there is no need to install the PSB batteries since the cost of PSB batteries is high and its charge/discharge efficient is low. Investing only in the PV system can be the best investment strategy at present.

4.2.2. Analysis of Investment Strategies in 2030

In 2030, the RIO of strategy 5 is the same as that of strategy 3 with the minimum ROI. Investing in the PV system and BESS may be the best strategy. Though the heat price has a significant increase (from 10 to 16.1 USD/GJ), annual mean of electricity price also increases a lot (from 25 to 38 USD/MWh). Though the ROI of strategy 2 is close to the minimum ROI of five strategies, the optimal area of solar thermal collectors is still zero in strategies 4 and 5.

Compared to strategies 1 and 3, the ROI is reduced by using batteries though it decreases significantly. It is due to the decrease of batteries' cost. The optimal sizes of batteries in strategy 3 in 2030 are 16,924.7 kW and 48,300.7 kWh. Hourly batteries performance in a year is given in Figure 9. Batteries often operate at the maximum charge/discharge power. While, batteries do not operate at the time that the fluctuation of electricity price is less like the period from 8041 to 8760 h. The electricity bought from the electricity market in a year is shown in Figure 10.

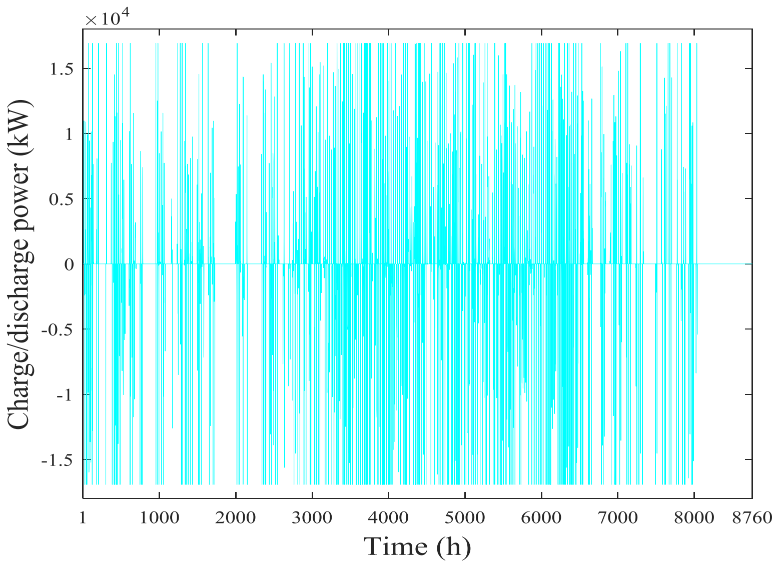

Figure 9. Hourly batteries performance in a year.

Day 5 was chosen as an example. Ambient temperature and solar radiation on day 5 are shown in Figure 11. The solar energy can be captured only from 7 a.m. to 6 p.m. The solar radiation peak is at 12 a.m. The trend of temperature curve is similar to that of solar radiation. The peak ambient temperature is 10.2 °C at 4 p.m.

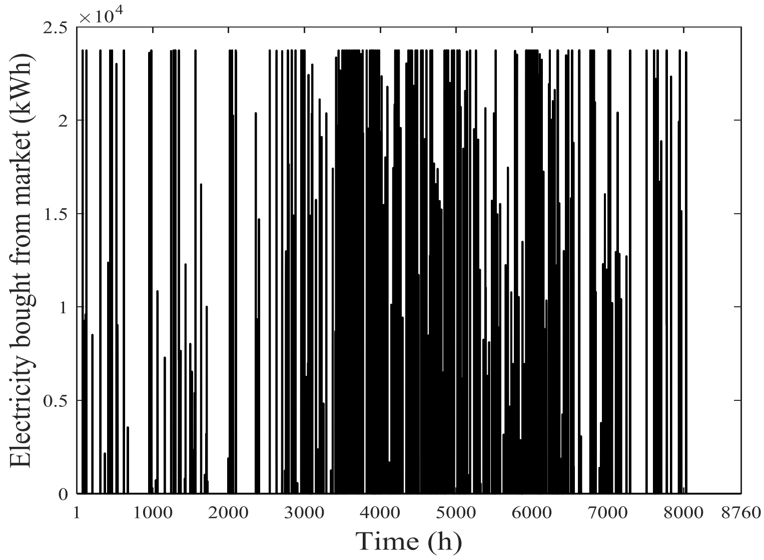

Figure 10. The electricity bought from the electricity market over a year.

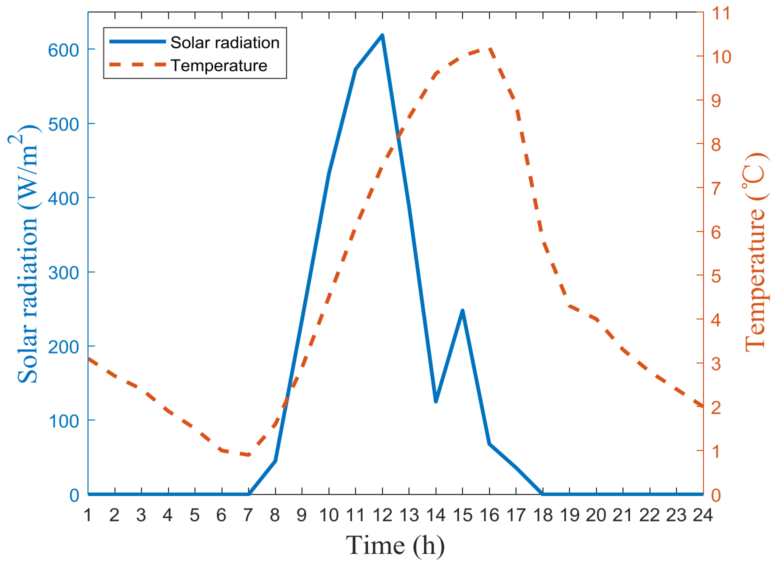

Figure 11. Solar radiation and ambient temperature on day 5.

The electricity bought from the electricity market on day 5 is shown in Figure 12. The electricity is bought from the electricity market at 5 a.m. and from 1 p.m. to 6 p.m. since the electricity price at that time is relatively low compared to the other hours on the day. At 5 p.m., the electricity price is lowest in day 5. No power is bought from the electricity market at other hours. One reason is that the electricity price is high. The other reason is that solar energy is sufficient to be converted into electricity, and it is more economic that batteries can be charged by the power from PV modules. For a year, investors still prefer to buy the electricity from the electricity market most of the time, as seen in Figure 10.

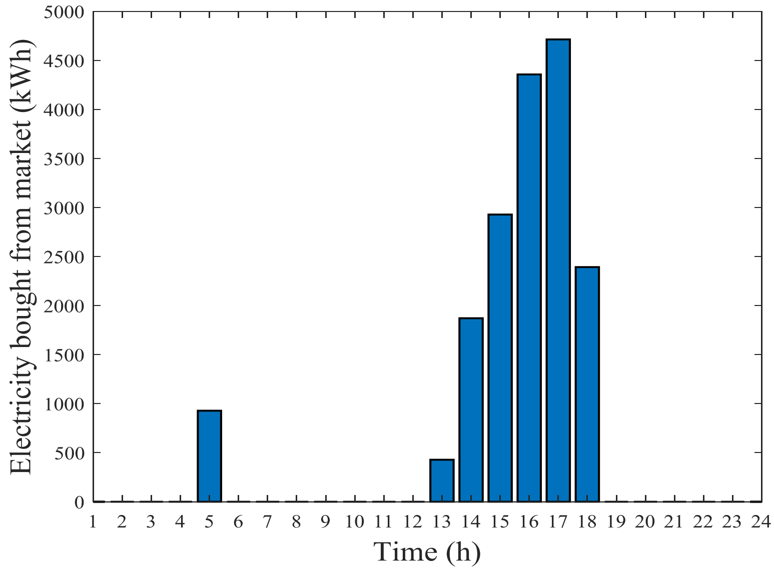

Figure 12. The electricity bought from electricity market on day 5.

The energy stored in batteries and electricity price on day 5 are given in Figure 13. Since electricity price is relatively low, the batteries are charged by the power bought from the electricity market at 5 a.m. However, PSB cannot buy too much electricity from the electricity market. This is because the price of buying electricity from the electricity market is more expensive than that of selling electricity to the electricity market. Then the electricity stored in the batteries is sold to electricity market from 6 a.m. to 8 a.m. since the electricity price is relatively high. The electricity stored in the batteries cannot be sold out with the highest electricity price (at 7 a.m.) in that period, because the maximum discharge power of the batteries is 16,924.7 kW. In addition, the electricity stored in the batteries cannot be sold out due to the limit of DOD. This is also the reason why the batteries do not run from 9 a.m. to 11 a.m. From 12 a.m. to 6 p.m., the electricity price is relatively low. The batteries are charged by the power from PV modules and the electricity market until they reach the upper limit. From 9 p.m. to 12 p.m., the electricity price is relatively high, and the batteries are discharged until their energy gets to the half of the maximum capacity.

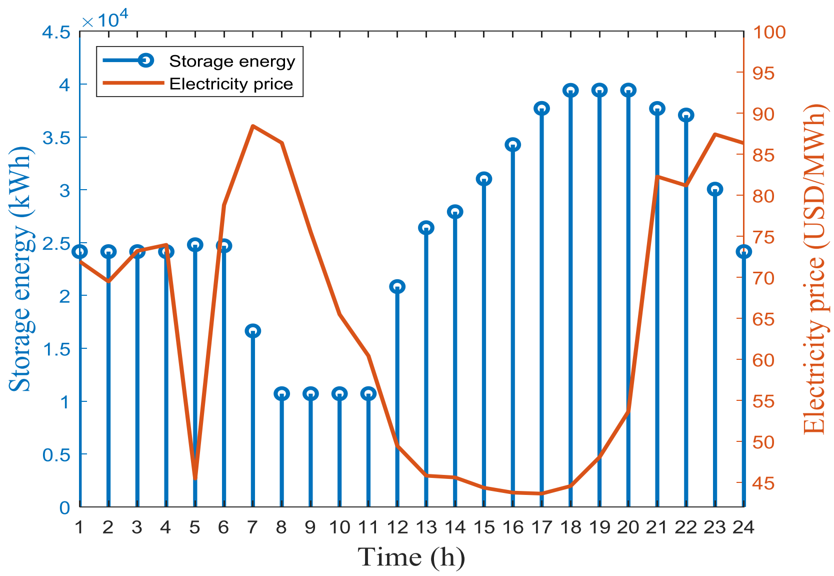

Figure 13. The energy stored in batteries and electricity price on day 5.

Sometimes the power from PV system is sold to the electricity market directly, though the price is relatively low. Batteries do not charge and discharge frequently to achieve price arbitrage. Since the charge efficient of batteries cannot reach to 100%, part of the energy will be lost in the process of charge and discharge. The batteries will operate if the extra benefits from the price arbitrage can be obtained after offsetting the energy loss caused by the batteries and the difference between buying and selling electricity.

Results show that the BESS have a considerable investment potential in the future. If the discharge/charge efficiency of batteries can be improved significantly, less power will be lost which can get more profits.

4.2.3. Analysis of Investment Strategies in 2040

In 2040, the ROI of strategies 4 and 5 are the same as that of strategy 2, which means investing in solar heating system can get the minimum ROI. Heat price has increased a lot in 2040 while electricity price has no significant change from 2030 to 2040. The difference value of ROI between strategy 1 and 3 is not large. Compared to strategy 1, the optimal result of strategy 3 shows that BESS can decrease the RIO and make more profits. However, its ROI is still higher than the strategy of investing in solar heating systems. Hence, the investing in the PV system is not a good choice.

4.2.4. Analysis of Investment Strategies in 2050

In 2040, investing in solar heating system is the optimal strategy for investors. In 2050, heat price increases and becomes more than that in 2040. It even exceeds the heat price of present by factors of 3.5. Investing in solar heating systems has become the best investment strategy undoubtedly. The optimal area for the PV system in strategies 4 and 5 are both zero because the annual income of investment on the PV system is much lower than that of investing in solar heating systems. The ROI of strategy 2 even becomes half of the RIO of the suboptimal strategy 3. Compared to strategies 3 and 1, BEES can help investors get more profits from the electricity market. It means batteries have a great investment potential. In 2050, when investors invest in PV system, BESS might be worth taking into consideration. However, the RIO of investing in solar heating systems is the lowest one.

As shown in Table 1, at present, investors are more expected to invest in PV systems; in 2030, they are more expected to invest in PV system and BESS. With the heat price increasing a lot in 2040 and 2050, the RIO of strategy 2 decreases a lot. Strategies 4 and 5 are the same as strategy 2 which means investing in solar energy for heat is better. The best investment strategy varies with the cost of the whole system, electricity price of the electricity market, and heat price of the heat market. However, investing in solar energy for both heat and power is not reasonable. From the optimal results, either the area of the PV system or the area of the solar heating system will be zero. In the future (from 2030 to 2050), the RIO of strategy 3 is always lower than strategy 1, though it may not be lowest in five strategies. It means BESS can decrease the RIO when it works with the PV system. BESS holds great potential. The size of batteries increases constantly from 2030 to 2050. One reason is their costs decrease constantly and the other reason is that the cost of the PV system decreases.

However, the performance of the batteries will be depreciated after several years. Calculation of batteries' lifespan is very complex. It depends on many factors which include DOD, ambient temperature, discharge rate, charging regime, and battery maintenance procedures [34]. Hence, the lifespan and operation strategies of batteries vary greatly from case to case. The reduction of batteries' lifetime is not considered in this paper.

5. Conclusions and Future Works

This paper investigated the investment strategies for solar energy based electricity/heating systems and battery systems. First, the models of the PV system, solar heat system, and batteries storage system were established. Second, a bi-level optimization was proposed to optimize the size of batteries and area size of the PV system and solar heating system. The battery system cannot decrease the ROI unless the cost falls by 40% in 2030. Third, investors investing in solar energy for both heat and power may be unreasonable. Determined by heat price and electricity price, whether investing in heat or power can bring more profit is influenced by the electricity market and DH market. This research establishes the relationship of the two markets. Investment strategies reveal heat price in the heat market can be affected by electricity market, which means the setting of heat price in a regulated heat market should consider electricity price. Heat pumps and combined heat and power can link the heat and electricity. Further study will investigate the relationship between heat price and electricity price. The depreciated performance of the batteries by the optimal operational strategies after several years will also be studied in the future.

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Nomenclature

P_{pv}	output power of PV system (kW)
P_n	rated power of PV (kW)
G_β	solar radiation on a tilted surface (W/m^2)
β	tilt angle (°)
G_{ref}	reference value of solar radiation (W/m^2)
K_t	temperature coefficient of the maximum power (°C)
T_c	temperature of PV cell (°C)
T_{ref}	temperature of PV cell at reference conditions (°C)
$G_{\beta,b}$	beam radiation on a tiled surface (W/m^2)
$G_{\beta,d}$	diffuse radiation on a tiled surface (W/m^2)
$G_{\beta,r}$	ground-reflected radiation (W/m^2)
G_b	horizontal direct radiation (W/m^2)
θ	incidence angle (°)
θ_z	zenith angle (°)
G_d	horizontal diffuse radiation (W/m^2)
F_1	coefficient expressing the degree of circumsolar (-)
F_2	coefficient expressing the degree of horizon anisotropy (-)
ρ	albedo of the ground which is 0.2 in this paper (-)
T_a	ambient temperature (°C)
E_t	energy stored in the BESS at hour t (kWh)
E_{t+1}	energy stored in the BESS at hour $t + 1$ (kWh)
η	efficiency of the BESS (-)
P_t	power output of the BESS at hour t (kW)
P_{fpv-t}	power that batteries charged by PV at hour t (kW)
η_{inv}	inverter efficiency (-)
$P_{trade-t}$	power that bought from/sold to electricity market at hour t (kW)
C_{bs}	BESS capital cost (USD)
C_p	power cost coefficient (USD/kW)
$P_{\max}$	BESS power (kW)
C_w	energy cost coefficient (USD/kWh)
$W_{\max}$	energy capacities (kWh)
DOD	depth of discharge (-)

η_c	efficiency of solar thermal collector (-)
η_0	maximal efficiency of thermal collector (-)
a_1,a_2	coefficients of the collector heat losses (W/(m^{2}k))
T_m	medium collector temperature (°C)
T_{out}	collector outlet temperature (°C)
T_{in}	collector inlet temperature (°C)
Q_t	specific net solar gain (kWh/m^2)
C_{shs}	total investment cost of solar heating system (USD)
S_{shs}	area of solar heating system (m^2)
C_{ins}	installation cost of solar heating system (USD)
C_{os}	cost of other elements in solar heating system (USD)
r_1,r_2	random numbers in the range [0, 1] (-)
c_1	a cognitive, standing for how much the particle is drawn by its personal best (-)
c_2	a social constant, standing for how much the particle is drawn by the swarm's best point (-)
w	the inertia weight (-)
S_{pv}	area of PV system (m^2)
C_{pv}	capital cost of PV cells per m^2 (USD)
C_{bp}	capital replacement cost (USD)
C_{OM}	operation and maintenance cost (USD)
r	interest rate which is 0.05 in this paper (-)
I_{ave}	average annual earnings (USD)
T	project lifetime (year)
I_r^n	income obtained from electricity market and heat market in year n (USD)
P_{sc}	heat energy generated from solar collectors (kJ)
HP_t	heat price in regulated heat market (USD/GJ)
EP_t	electricity price at hour t (USD/MW)
P_{pv-n}	PV output power at year n (kW)

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