Analysis of Carbon Reduction Strategy on Distributed Combined Cooling, Heating and Power (CCHP) Systems Design in Rural Area

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Abstract. An optimal design model of distributed CCHP systems is established based on the minimum system cost. Renewable energy is added as auxiliary energy. By proposing carbon emission reduction constraints, the influence for optimal design of the system could be analysed, which generated by the changes in carbon emission reduction rate. Some reasonable results would be achieved, such as: 1. A trade-off among system cost, building energy consumption and carbon emission reduction can be received, and optimization schemes under different carbon emission reduction strategies are obtained. 2. System lowest carbon reduction rate is 20%, and the highest is 50%; systems lowest primary energy saving rate is 4.91%, and the highest is 19.09%. 3. With the change of carbon emission reduction strategy, energy consumption and costs of the distributed CCHP systems show diversity differences at the same time. This article suggests the carbon emission reduction rate of CCHP systems is 40% in Ankang rural.

1. Introduction

In 2015, the Paris climate change conference adopted the Paris agreement to address global climate change after 2020[1]. Due to the large consumption of Chinese building energy, it accounts for about 1/3 of the total energy consumption of the society[2,3]. Zeng et al. proposed that increase the proportion of renewable energy in building energy consumption can effectively reduce carbon emission[4]. Distributed combined cooling, heating, and power (CCHP) system is a form of distributed energy system, which can simultaneously use primary energy and a variety of renewable energy sources to supply cold energy, heat energy, and electric power[5,6]. Therefore, how to balance the relationship between system cost, building energy consumption and carbon emission reduction is particularly important. Many scholars have studied the environmental benefits of distributed CCHP[7-11]. As proportion of renewable energy consumption continues to decline because of the lack of technical support[12,13,14]. Therefore, this paper will build the optimization model of distributed CCHP systems for rural residential buildings, taking Qiyan community, Dazhuyuan town, Hanbin district, Ankang city, Shaanxi Province, China as an example to verify the practicability of the model.

2. Statement of the Problems

Ankang municipality in the new rural community construction is fully rolled out [15,16]. This paper takes Community Qiyan, Dazhuyuan, Hanbin as the case study area, which is a rural community reconstructed after the disaster and plans to resettle 567 households[17](Figure 1). The authors used EnergyPlus8.6 to generate typical daily load(Figure 2). In this study, the peak power of PV panels is 0.17 kW and each PV panel covers an area of 1.3 m^2. The area available for mounting PV panels is 3900 m^2. The maximum installed PV panels capacity is 510 kW. Solar radiation is based on relevant meteorological data[18]. Total biomass available for 518,400 tons[19]. The price of natural gas is 2.5 yuan/m^3 in Ankang, and heat value is 10.6 kWh/m^3. Efficiency of internal combustion engine generator is 0.35, the fuel price per unit of electricity generated is 0.671 yuan/kWh. The carbon emission factor of natural gas under the standard conditions is 2.1622 kg CO_2/m^3, carbon emission per unit of electricity generated by this device is 0.583 kgCO_2/kWh. The residential electricity price is 0.4983 yuan/kWh in Shaanxi Province, the carbon emission factor of power grid is 0.89 kgCO_2/kWh[20]. Based on early distributed CCHP systems[20,21], this study developed a variety of renewable energy and energy storage technologies for the system, where L, R and D corresponding means cold, heat and electricity three forms of energy [22, 23].
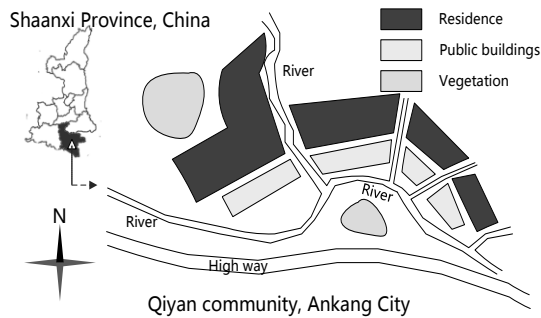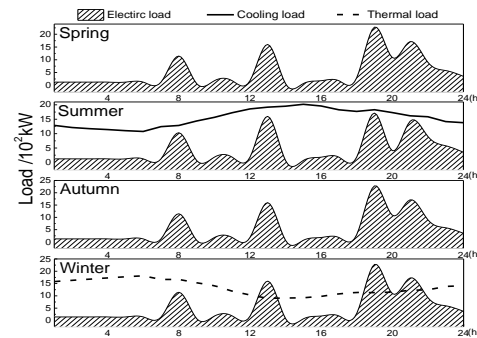

Figure 1. Community map.

Figure 2. Typical daily load.

3. Modelling formulation

3.1 Objective function

The model is the target function of the total cost of CCHP system. This daily economic cost, given in Equation (1) involves the following terms: installation cost (C_{INV}), operational and maintenance cost (C_{OM}), purchasing electricity cost (C_{ELEC}), fuel cost (C_{FUEL}), and government subsidies (C_{SUB}).

$$\min\left(C_{INV} + C_{OM} + C_{ELEC} + C_{FUEL} - C_{SUB}\right) \tag{1}$$

Equipment system can be divided into 4 categories: a. use of primary energy production equipment; b. first-level energy conversion equipment; c. secondary energy conversion equipment; and d. storage of energy storage devices.

$$C_{INV} = 4/365 * \left(\begin{array}{l} \sum_k \sum_n CAG_{k,n} * UG_k * COG_{k,n} * IR \big/ \left(1 - 1\big/(1+IR)^{LG_k}\right) + \sum_n CAH_n * UH * COH_n * IR \big/ \left(1 - 1\big/(1+IR)^{LH}\right) \\ + \sum_n CAC_n * UC_n * COC_n * IR \big/ \left(1 - 1\big/(1+IR)^{LC_n}\right) + \sum_n CAS_n * US_n * COS_n * IR \big/ \left(1 - 1\big/(1+IR)^{LS_n}\right) \end{array} \right) \tag{2}$$

Where $CAG_{k,n}$, CAH_n, CAC_n and CAS_n respectively is design capacity of class a, b, c and d equipment, kW; $UG_{k,n}$, UH_n, UC_n and US_n respectively is number of class a, b, c and d equipment; $COG_{k,n}$, COH_n, COC_n and COS_n respectively is capacity cost of class a, b, c and d equipment, yuan/kW; IR is the depreciation rate, specified at 10% in this study; LG_k, LH, LC_n and LS_n respectively is lifetime of class a, b, c and d equipment, year.

$$C_{OM} = \sum_s \sum_h \sum_k \sum_n OMG * G_{s,h,k,n} + \sum_s \sum_h \sum_n OMC_n * CG_{s,h,n}$$
$$+ \sum_s \sum_h \sum_n OMH * HG_{s,h,n} + 4/365 \times \sum_n OMS_n * CAS_n \tag{3}$$

Where $OMG_{k,n}$, OMH_n, OMC_n and OMS_u respectively is the running cost of class a, b, c and d equipment, yuan/kWh; $G_{s,h,k,n}$, $HG_{s,h,n}$ and $CG_{s,h,n}$ respectively is energy production of class a, b and c equipment, kWh; s stand for season; and h represents hour.

$$C_{ELEC} = \sum_s \sum_h PE_h * EP_{s,h} \tag{4}$$

Where PE_h is hourly electricity price, yuan/kWh; $EP_{s,h}$ is electricity form the grid, kWh.

$$C_{FUEL} = \sum_s \sum_h \sum_k \sum_n PF_{k,n} * G_{s,h,k,n} / \eta_{k,n} \tag{5}$$

Where $PF_{k,n}$ is price of fuel, yuan/kWh; $\eta_{k,n}$ is capacity efficiency of production equipment.

$$C_{SUB} = 4/365 * \sum_k \sum_n SUB_{k,n} * CAG_{k,n} / LG_k + \sum_s \sum_h \sum_k \sum_n SUBV_{k,n} * G_{s,h,k,n} \tag{6}$$

Where $SUB_{k,n}$ is one-time investment subsidy for equipment, yuan/kW; $SUBV_{k,n}$ show device running subsidy, yuan/kWh.

3.2 Constrains

The energy produced during the operation of the device cannot exceed its capacity, given in Equation (7), (8), (9).

$$G_{s,h,k,n} \leq UG_k * CAG_{k,n} \tag{7}$$

$$CG_{s,h,n} \leq UC_k * CAC_{k,n} \tag{8}$$

$$HG_{s,h,n} \leq UH_k * CAH_{k,n} \tag{9}$$

Electricity generated by the internal combustion engine is fixed with the residual heat generated, given in Equation (10). Where ζ is ratio of power generation and surplus heat of gas combustion engine; ζ is specified at 0.7 in this study.

$$\zeta * G_{s,h,k=NG,n=R} = G_{s,h,k=NG,n=D} \tag{10}$$

Solar PV power generation is limited to equipment capacity and solar radiation intensity, given in Equation (11). Where RS is the surface area of the PV panel, m^2; $SI_{s,h}$ is direct solar radiation, kW/m^2.

$$G_{s,h,k=PV,n=D} \leq UG_{k=PV} * RS * SI_{s,h} * \eta_{k=PV,n} \tag{11}$$

The secondary energy conversion equipment needs to convert the heat energy into the cold energy during the summer, which is converted into heat by the heat exchanger during the spring and autumn period. The constrains of energy conversion is given in Equation (12), (13). Where θ_n is the efficiency of energy conversion equipment.

$$\theta_{n=L} * \sum_k G_{s=sum,h,k,n=R} = CG_{s=sum,h,n=L} \tag{12}$$

$$\theta_n * \sum_k G_{s=spr/aut/win,h,k,n} = CG_{s=spr/aut/win,h,n} \tag{13}$$

The energy storage device at h=1, the storage energy is 0, there may be energy input ,energy output is 0, given in Equation (14), (15), (16). Where $EST_{s,h,n}$ is energy in energy storage devices, kWh; $IST_{s,h,n}$ is energy to enter the energy storage devices, kWh; $OST_{s,h,n}$ is energy flowing out of the energy storage devices, kWh.

$$EST_{s,h=1,n} = 0 \tag{14}$$

$$IST_{s,h=1,n} \geq 0 \tag{15}$$

$$OST_{s,h=1,n} = 0 \tag{16}$$

When the energy storage device is at h > 1, its operation can be represented by the Equation (17), (18), (19). Where β_n is the efficiency of energy storage.

$$EST_{s,h,n} = EST_{s,h-1,n} + \beta_n * IST_{s,h-1,n} - OST_{s,h-1,n} \tag{17}$$

$$0 \leq EST_{s,h,n} + \beta_n * IST_{s,h,n} - OST_{s,h,n} \leq CAS_n \tag{18}$$

$$0 \leq EST_{s,h,n} \leq CAS_n \tag{19}$$

The system energy supply of each moment must meet the needs of the user load, the consumption of electricity the absorption chiller and the ground source heat pump (20), (21). Where $ED_{s,h,n}$ is user loads, kWh; σ is the power consumption coefficient of absorption chiller; $\varepsilon_{s,n}$ is the power consumption coefficient of ground source heat pump.

$$CG_{s,h,n=D} + EP_{s,h} + OST_{s,h,n=D} \geq IST_{s,h,n=D} + ED_{s,h,n=D} + \sigma * CG_{s,h,n=L} + \sum_n HG_{s,h,n} * \varepsilon_{s,n} \tag{20}$$

$$CG_{s,h,n=R/L} + HG_{s,h,n=R/L} + OST_{s,h,n=R/L} \geq IST_{s,h,n=R/L} + ED_{s,h,n=R/L} \tag{21}$$

The carbon emission reduction rate of the system is given in Equation (22). Where *CEG* is electricity carbon emissions, kgCO$_2$/kWh; $CEF_{k,n}$ is the carbon emissions of system equipment, kgCO$_2$/kWh; *CENG* is natural gas carbon emissions, kgCO$_2$/kWh; φ is the efficiency of electric chiller, specified at 5[24]; *RT* is the carbon emission reduction rate, set by the decision-maker.

$$\sum_s \sum_h EP_{s,h} * CEG + \sum_s \sum_h \sum_k \sum_n G_{s,h,k,n} / \eta_{k,n} * CEF_{k,n}$$
$$\leq \left(1-RT\right)\left(\sum_s \sum_h ED_{s,h,n=D} * CEG + \sum_s \sum_h ED_{s,h,n=L} / \phi * CEG + \sum_s \sum_h ED_{s,h,n=R} / \psi \times CENG\right) \tag{22}$$

4. Results and Discussions

Based on the above-mentioned, this paper sets six scenarios as follow: the carbon emission reduction rate of 0, 10%, 20%, 30%, 40%, 50%. Comparing the Scenarios, weighing the relationship between cost of distributed CCHP systems, residential building energy consumption and carbon emission reduction, obtaining the optimal configuration of the distributed CCHP systems under different carbon reduction rate. The following will analyze the change rule of optimal configuration, energy consumption, energy saving rate of primary energy and cost under different carbon emission reduction rate.

4.1 Change rule of optimal configuration

Optimal configuration under different carbon emission reduction rate is shown in Table 1. According to the table, when set of carbon emission reduction rate lower than 20%, the system configuration does not change, that is, the value of the minimum system carbon reduction rate by calculation, set of carbon emission reduction rate exceeds 50%, the model has no solution, namely the value for the system to achieve the highest rate of carbon emissions. Because of the renewable energy equipment does not produce carbon emissions, with the increase of carbon reduction rate, the demand will increase, but the utilization of biomass and solar power is limited, so the biomass boiler and the equipment capacity of solar photovoltaic panels have no change. On the whole, the capacity of the ground heat pump is on the rise. There are unpredictable changes in the capacity of all other technologies, indicating that the optimal configuration of the system is extremely complex.

System cost under different carbon emission reduction rate described in Figure 3. With the increase of the consumption of natural gas, the amount of waste heat generated by the internal combustion engine is gradually increasing, so the consumption of biomass energy is gradually reduced. PV panels power generation has neither fuel cost nor carbon emission, resulting in the device running at full load, so the utilization of solar resources is unchanged under all scenarios. The utilization of geothermal

energy is only related to the capacity of ground source heat pump. Combined with Table 2, consumption of geothermal energy varies with the change of the capacity of ground source heat pump. The reference object of energy saving rate of primary energy is the traditional energy system. Lowest energy saving rate of primary energy of the system is 4.91%, and the highest energy saving rate of primary energy of the system is 19.09%. Cost under different carbon emission reduction rate is shown in Figure 4. Because the optimal configuration does not change under the carbon emission reduction rate of 20%, the cost is invariable. In this system, only PV panels are subsidized, and its capacity and operation mode do not vary with the change of carbon emission rate, so the subsidy cost will not change.

Table 1. Optimal configuration under different carbon emission reduction rate.

Technologies	Carbon emission reduction rate, Capacity /kW					
	0	10%	20%	30%	40%	50%
NG ICG	781	781	781	766	598	1043
PV	510	510	510	510	510	510
BB	450	450	450	450	450	450
GP	154/171	154/171	154/171	173/192	385/427	351/390
AC	1713	1713	1713	1658	1346	1589
HE	1535	1535	1535	1514	1279	1901
IS	382	382	382	553	2177	198
HS	725	725	725	725	340	901
BA	404	404	404	456	873	2170

5. Conclusions

Based on the early distributed CCHP systems, conclusions generated as follow: 1. Lowest carbon emission reduction rate was 20% and highest was 50%. The lowest energy saving rate of primary energy was 4.91% and the highest was 19.09%. 2. As carbon emission reduction rate increased from 20% to 50%, natural gas consumption increased 47,441 kWh, grid power purchase reduced 23838 kWh, solar energy consumption remained unchanged, biomass energy consumption decreased by 3322 kWh, and energy consumption of geothermal showed an irregular upward trend. 3. As carbon emission reduction rate increased from 20% to 50%, total cost increased 13,200 yuan, of which C_{INV}, C_{OM}, C_{FUEL} increased, C_{ELEC} reduced, C_{SUB} remain unchanged.
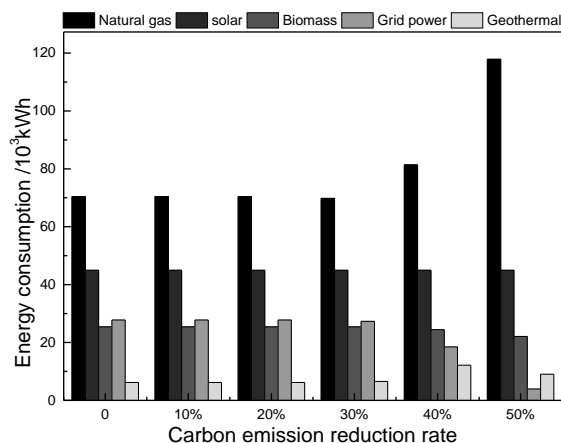

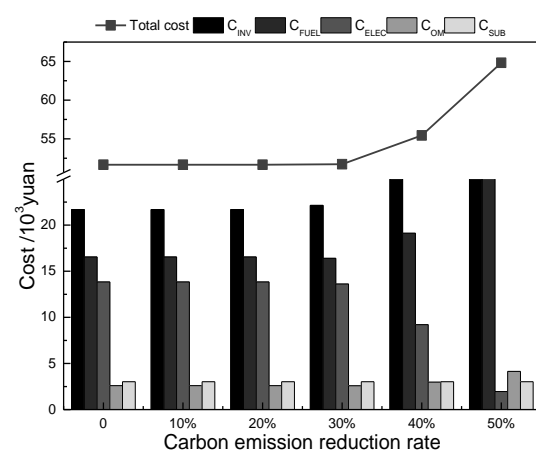**Figure 3.** System energy consumption under different carbon emission reduction rate.

Figure 4. Costs under different carbon emission reduction rate.

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