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LETTER TO THE EDITOR

Energy Efficiency Optimization of Integrated Energy System Considering Carbon Emissions

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With the increasing of energy consumption, it is important to improve energy efficiency and reduce carbon emissions. Integrated energy system can effectively improve energy efficiency by coupling multiple energy sources. In order to further improve energy efficiency and reduce carbon emissions, this paper proposes an energy efficiency optimization model with power to gas system (P2G). The energy supply cost and overall energy efficiency of integrated energy system are improved by hybrid energy storage system, which increases the system's wind power consumption rate by 11.2%. And the optimization strategy proposed in this paper increases the total energy efficiency of the system by 7.3% and reduces the total carbon emissions by 15.1%.

I Introduction

With the rapid development of the global economy, energy consumption has become more and more serious. How to protect the environment has become an important issue all over the world (Wei *et al.* 2014). In response to these problems, some researchers put forward the concept of integrated energy system (IES), expounded the concept of multi-energy collaborative operation (Moslehi *et al.* 2018).

Under the pressure of fossil energy crisis and environmental pollution, wind power generation has become an indispensable part of integrated energy system. But the fluctuation and intermittence of wind lead to serious problems of wind power utilization. In order to reduce the wind abandonment rate, it is especially important to study wind power utilization. In (Hirth *et al.* 2015), a unit with regulation capability is added to reduce the uncertainty of wind power output. As an important part of the integrated energy system, P2G can convert wind power which is difficult to use at electricity valley into natural gas which is easy to be stored on a large scale. Thereby achieving deep coupling of the power-gas network (Heinisch *et al.* 2015). Therefore, applying P2G technology to energy efficiency optimization of IES has become the focus of current research (Sun *et al.* 2017, He *et al.* 2017, Yu *et al.* 2018). At the same time, many scholars have carried out related research on the design and optimization of IES. Facci *et al.* proposed a dynamic programming model to optimize system operation by analyzing the operating mode of CHP (Facci *et al.* 2014, Cankurt *et al.* 2016). Based on the mixed integer linear programming theory, Bischi *et al.* used the minimum daily operating cost as the objective function to construct a model to optimize the integrated energy system, taking into account the factors such as energy prices and maintenance costs (Bischi *et al.* 2014, Watabe and Sassa 2016). The above research only optimizes the operation efficiency or cost of the system, and this paper considers two aspects to optimize the IES: reducing the carbon emissions and improving the system energy efficiency.

II Integrated Energy System Model

This paper introduces P2G to convert excess electricity into natural gas, and uses hybrid energy storage system to store energy, so as to improve the wind power consumption rate and reduce carbon emissions. The specific system structure is shown in Figure 1.

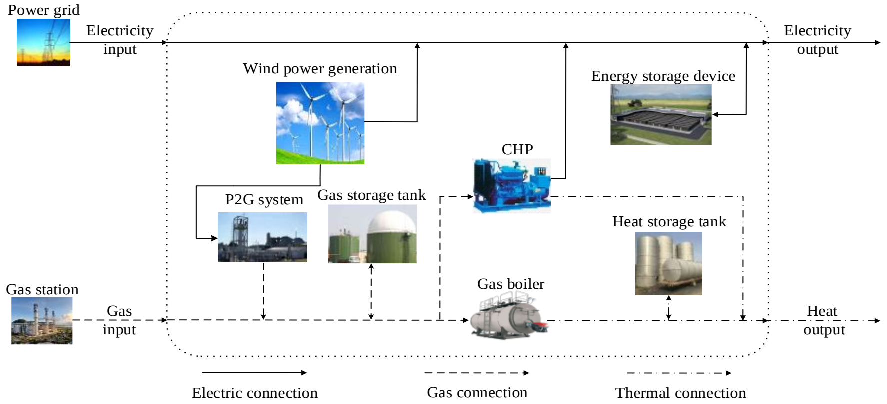

Fig. 1 Integrated energy system structure diagram

III Optimal Scheduling Model of System

This paper establishes the objective functions considering the cost of electricity and natural gas purchased from external system and the cost of carbon emissions, .

$$\min F = \sum_{t=0}^{24}(C_e + C_g + C_c) \tag{1}$$

$$C_c = p_c(S_{grid} \cdot EF_{grid} + S_{gas} \cdot EF_{gas}) \tag{2}$$

where C_e, C_g, C_c are the cost of electricity purchase, gas purchase and carbon emission. p_c is the carbon trade price, taken as 4$/t in this paper. S_{grid} and S_{gas} are the quantity of electricity and gas purchased from external system respectively. EF_{grid} and EF_{gas} are the average carbon emission factors of the grid and the average carbon emission factors of natural gas, respectively. In this paper, EF_{grid} and EF_{gas} are taken as 0.7143kgCO_2/kWh and 2.162kgCO_2/m^3 respectively.

The output expression of P2G is (Clegg *et al.* 2015):

$$P_{P2Go} = \eta_{P2G} \cdot P_{P2Gi} \tag{3}$$

$$Q_{P2G} = \frac{P_{P2Go}}{H_{gas}} \tag{4}$$

where η_{P2G} is the efficiency of P2G. P_{P2Gi} is the input power, P_{P2Go} is the output power, and H_{gas} is the heat value of natural gas. The output of P2G is limited by its maximum and minimum power:

$$P_{P2G\text{omin}} \le P_{P2Go} \le P_{P2G\text{omax}} \tag{5}$$

The output of CHP can be expressed as:

$$p_{CHPe} = \eta_e \cdot p_{CHPin} \tag{6}$$

$$p_{CHPh} = \eta_h \cdot p_{CHPin} \tag{7}$$

where P_{CHPin} is the input power of CHP, η_e is the efficiency of gas to electricity conversion, η_e is the efficiency of gas to heat, P_{CHPe} is the output electric power, P_{CHPe} is the output thermal power.

The output power of wind turbine system P_W can be can be expressed as (Li *et al.* 2018):

$$P_W = \begin{cases} 0 & v < v_c \text{ or } v > v_o \\ 0.5 \cdot \rho \cdot A \cdot \eta_w \min(v, v_{rated})^3 & v_c \le v \le v_o \end{cases} \tag{8}$$

In (8), A is the blade area of wind generator, η_w is power coefficient, v, v_{rated}, v_c and v_o are the actual wind speed, rated wind speed, the cut in and out speed of wind turbine system, respectively.

The output power of gas boiler P_{gb} an be expressed as (Salimi *et al.* 2015):

$$P_{gb} = \eta_{gb} \cdot P_{gbin} \tag{9}$$

$$\eta_{gb} = 100\% - l_1 - l_2 - l_3 \tag{10}$$

where η_{gb} is the thermal efficiency of gas boiler, P_{gbin} is the input power of gas boiler. l_1,l_2 and l_3 the heat loss of exhaust gas, heat loss of incomplete combustion of gas and loss of heat dissipation, respectively, which are taken as 8.62%, 0.83% and 1.92%, respectively. The operation of gas boiler is limited by its minimum and maximum operating power:

$$P_{gb\min} \le P_{gb} \le P_{gb\max} \tag{11}$$

where P_{gbmin} and P_{gbmax} are the minimum and maximum operating power of the gas boiler.

The capacity of the battery at any time in the battery energy storage system can be expressed as:

$$S_k = (1 - r_{self,d}) S_{k-1} - \Delta t \cdot P_h \tag{12}$$

In (12), k is the sampling time, S_k is the battery capacity at time k, $r_{self,d}$ is the self-discharge rate, Δt is the sampling time interval, P_h is the battery charging and discharging power.

The total heat energy stored in the heat storage tank at t time can be expressed as (Yuan *et al.* 2016):

$$E_H(t) = \begin{cases} E_H(t-1) + \eta_{H,ch} \cdot Q_H(t) \cdot \theta_H & Q_H(t) \ge 0 \\ E_H(t-1) + \eta_{H,dis} \cdot Q_H(t) \cdot \theta_H & Q_H(t) < 0 \end{cases} \tag{13}$$

where $Q_H(t)$ is the net heat power flow in / out the heat storage tank at time t. $\eta_{H,ch}$ is the heat storage charge efficiency. $\eta_{H,dis}$ is the discharge efficiency. θ_H is the time interval of analyzing heat storage tank.

The gas storage tank model can be expressed as:

$$P_{gs}(t) = P_{gs}(0) + \sum_{t=1}^{n} (P_{gsst}(t) - P_{gsre}(t)) \tag{14}$$

$$P_{gs\min} \le P_{gs}(t) \le P_{gs\max} \tag{15}$$

where $P_{gs}(0)$ is the gas volume of the tank at the initial time, $P_{gsst}(t)$ is the energy stored in the gas storage device at t time, $P_{gsre}(t)$ is the energy released by the gas storage device at t time. $P_{gs\min}$ and $P_{gs\max}$ are the minimum and maximum gas storage capacity respectively.

IV Case Study

This paper takes an industrial community in eastern China as an example for simulation and analysis. The equipment in community is shown in Figure 2, and the loads condition and wind speed change in a day are shown in Figure 2.

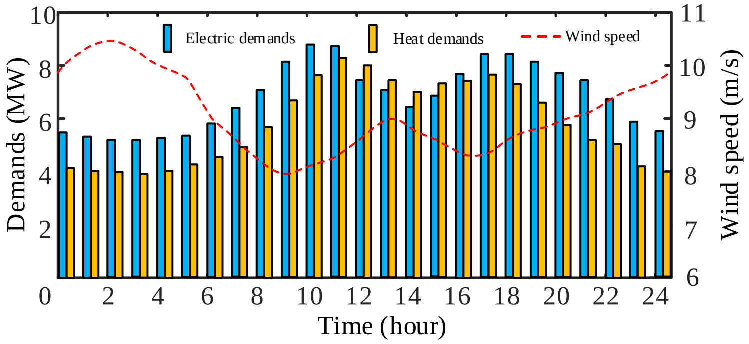

Fig. 2. Thermal, electrical loads and wind speed curves in community

The natural gas price in community is 0.42$/m^3, and the electricity price is shown in Table 1.

Table 1. 24-hour electricity price

time	electricity price($/kWh)
Peak hours(9:00-13:00；17:00-22:00)	0.206
Valley time(0:00-6:00；22:00-24:00)	0.055
Flat time(6:00-9:00；13:00-17:00)	0.129

V Results and analysis

Figure 3 shows the wind power generation output curve in community within 24 hours a day. As shown in the figure, curve a is the maximum output curve of wind power generation under ideal conditions (all generated electricity is consumed). Curve b is the actual wind power output curve in community before optimization. And curve c is the actual wind power output curve after optimization.

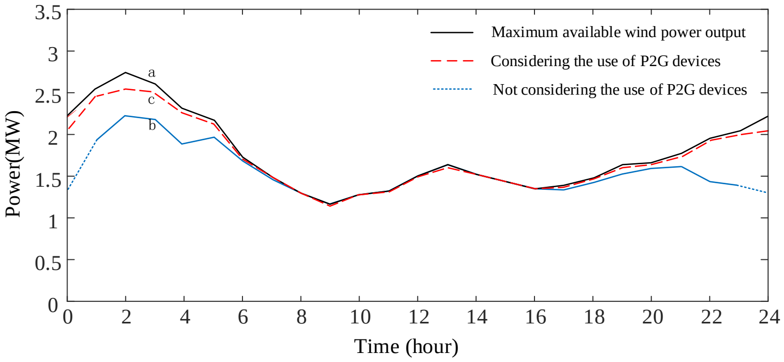

Fig. 3. Wind power output curves under different consumption conditions

As can be seen from Figure 3, the wind power generation output at night (22:00-5:00) is significantly higher than that at daytime (7:00-17:00) due to the wind speed, and the lower electrical loads at night leads to higher abandonment rate before optimization. In this paper, the excess electricity generated by wind power generation at night is converted into gas by P2G and stored in gas storage tank. And the stored gas is input to CHP for power generation to supply electrical loads at peak hours. The calculation shows that, the consumption rate of wind power increased by 11.2% after optimization. In addition, it can be seen that wind power is not completely absorbed after optimization. That is because complete wind power consumption needs to increase the P2G capacity (energy conversion power), which will greatly increase the purchase cost and reduce the utilization rate of equipment.

Therefore, this paper only consume part of wind power.

Figure 4 shows the electricity purchased from the grid before and after the optimization of the integrated energy system in community, and the curve of P2G output. It can be seen that the system needs to purchase electricity from the grid in 8:00-12:00 and 15:00-19:00 two periods due to the large increase of electrical loads. This paper consume excess wind power at night through P2G and gas storage tank, and supplies natural gas to CHP for power generation during peak loads period, which can significantly reduce the amount of electricity purchased from grid. According to the calculation results, the daily electricity purchased from grid can be reduced by 4.95 MWh by optimizing the community energy storage system.

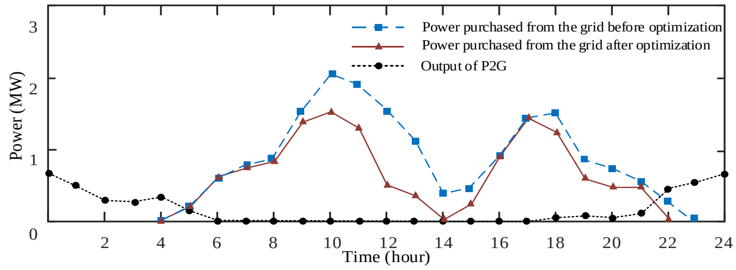

Fig. 4 Change of electricity purchased from grid and P2G Output curves before and after Optimizing

As mentioned above, the average carbon emission factor of grid is 0.7143kgCO_2/kWh in this paper. It can be seen from the data that reduce the electricity purchased from grid can reduce carbon emissions by 3535.8kg, which is about 15.1% of total carbon emissions of community system.

Figure 5 is the graph of natural gas purchased from gas station before and after the optimization of the integrated energy system in community. It can be seen from the figure that the purchase volume of gas before and after optimization between 10:00-12:00 and 17:00-19:00 periods is quite different. That is because the gas storage tank supplies the natural gas stored at night to CHP and gas boiler during the peak loads period to meet the electric loads and heat loads demand. The calculation shows that the daily purchase volume of gas can be reduced by 33.2MWh by adding P2G to optimize the integrated energy system.

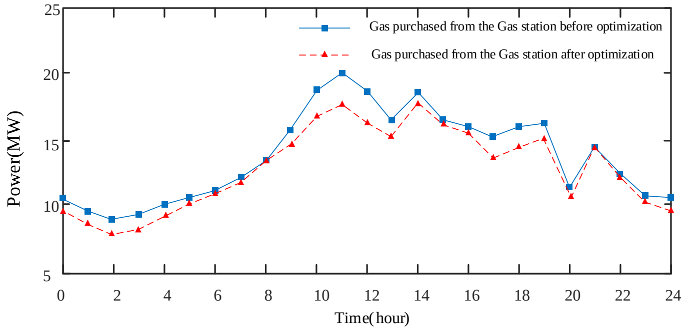

Fig. 5 Gas purchasing curve before and after optimization

In this paper. According to the calculation data, the energy efficiency of the integrated energy system increases from 77.8% to 85.1% by improving the wind power consumption rate.

VI Conclusion

This paper proposes an energy efficiency optimization model for integrated energy system, and improves the integrated energy system considering carbon emissions and energy efficiency. First, analyses the integrated energy system model including various energy conversion devices such as P2G based on the characteristics of the integrated energy system. Then, establishes the objective function by minimizing the energy supply cost and total carbon emission cost, and solves it by genetic algorithm. Finally, the wind power consumption rate in system, energy purchasing and system energy efficiency changes are analyzed in a community in eastern China.

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