Capacity Optimization of a Renewable Energy System Coupled with Large-Scale Hydrogen Production and Storage

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Abstract. Hybrid renewable energy and hydrogen energy systems have been proved to be a reliable and cost competitive option for power generation and hydrogen supply. However, the inappropriate capacity of hydrogen production and storage may result in out-of-balance of the power supply side and the hydrogen consumption side. In this paper, a simplified mathematical modeling of the hybrid energy system, including power generation, hydrogen production and storage has been presented to optimize the capacity of alkaline electrolyzer and hydrogen storage tank. Multi-objective functions are adopted in the capacity optimization model, including abandoned rate of renewable power, hydrogen supply fluctuation, and utilization efficiency of electrolyzer and hydrogen storage tank. A meta-heuristic algorithm (*i.e.*, improved multi-objective particle swarm optimization algorithm) is chosen to solve the model. A hybrid energy system with a distributed photovoltaic power station with the rated power of 7000 kW has been designed to satisfy the hydrogen demand of 720 kg/d of a chemical plant. The results reveal that the optimal capacity configuration of the hybrid energy system is 4971 kW for the alkaline electrolyzer and 937 Nm^3 for hydrogen storage tank during a period of 8760 h. Compared with the empirical model and single-objective optimization model, the proposed multi-objective optimization model is found helpful to optimize the capacity of hybrid energy system and gives better results regarding renewable energy utilization rate, equipment usage rate, and hydrogen supply stability.

Keywords: Capacity optimization · Renewable energy system · Hydrogen · Simulation model

1 Introduction

The rapid depletion of fossil fuel resources, the massive carbon emission and the environmental problems related with their burning have generated growing interest in renewable energy. However, an essential feature of most renewable energy is their intermittency, that decreases the reliability of electricity supply and hinders their large-scale applications.

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One method of overcoming this disadvantage is to apply an energy storage system, such as pumped-storage power [1], electrochemical energy storage [2], and hydrogen energy [3]. Among these energy storage methods, hydrogen energy has several unique advantages including long term and large-scale energy storage, flexible hydrogen-electricity conversion, leading to increasing interest in hybrid renewable energy and hydrogen energy system [4, 5].

The focus on hybrid energy system is highlighted by many extensive studies, which cover economic analysis [6], system planning and design [7], and capacity optimization [8]. The capacity optimization of electrolyzer and hydrogen tank has a great effect on renewable energy utilization, hydrogen supply reliability, and net present cost. Much work so far has focused on capacity optimization of hybrid energy system using optimization algorithms and single-objective optimization. For example, flower pollination algorithm, particle swarm optimization (PSO) algorithm, and genetic algorithm are studied in previous studies, and show great results in capacity optimization [9]. However, single-objective optimization is difficult to take into account other requirements of hybrid energy system and to achieve simultaneous optimization [10], and the technical process concerning hydrogen is often oversimplified, which leads to distortion of optimization results for practical applications.

In this study, a distributed photovoltaic power station with rated power of 7000 kW and a chemical plant with hydrogen demand of 720 kg/d are chosen as the source side and hydrogen load side, respectively. Considering the energy utilization, hydrogen supply reliability, and the equipment usage rate, multi-objective optimization and PSO algorithm are used to optimize the capacity of electrolyzer and hydrogen tank. A comprehensive mathematical model of hybrid energy system is proposed to investigate the main parameters affecting the capacity optimization results during a period of 8760 h. The performance of proposed multi-objective optimization model is also compared with the empirical model and single-objective optimization model.

2 Mathematical Model of the Hybrid Energy System

The proposed hybrid energy system includes photovoltaic (PV) power, electrolyzer, hydrogen storage tank, compressor, power grid, and chemical plant, as shown in Fig. 1. The primary power source is PV power, and the power grid is the backup power source in case that the PV power is unable to fulfill the energy demand of the electrolyzer. Hydrogen produced by the electrolyzer is stored in the tank, and then compressed into high-pressure gas to meet the hydrogen demand of a chemical plant. The bi-converter acts as an inverter to convert AC power to DC to fulfill the DC load demand of electrolyzer. The detailed mathematical models of each part of the system are introduced as follows.

2.1 Solar Power System

The output power of PV panel (P_{sol}) depends on the solar radiation and atmospheric conditions, and it can be expressed as follows [11].

$$P_{pv}(t) = N_{pv} P_{rat} f_{loss} \frac{G_h(t)}{G_s}[1 + \alpha_P (T_c - T_s)] \tag{1}$$

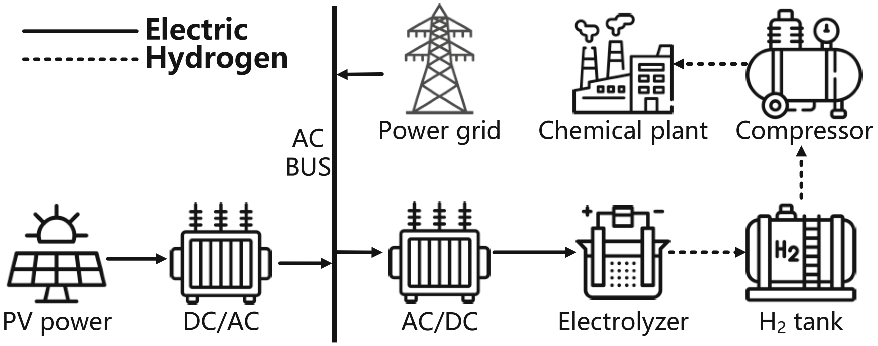

Fig. 1. Schematic diagram of the hybrid energy system.

where, N_{pv} is the number of PV panels, P_{rat} is the rated power of PV panel, f_{loss} is the loss factor of PV panel concerning shadow, dirt, and temperature, G_s is the standard incident radiation, $G_h(t)$ is the hourly solar radiation incident on the PV panel, α_P is the temperature coefficient of power, T_c is the PV cell real-time temperature, and T_s is the PV cell temperature under standard test conditions.

2.2 Electrolyzer

The electricity of solar system is used to produce hydrogen by electrolyzer. The power capacity of electrolyzer is considered as an optimization objective in this study.

The mass flow rate of produced hydrogen (ν_{e,H_2}) can be calculated as:

$$\nu_{e,H_2} = \frac{P_{pv}(t)\eta_{el} \times 3600}{HHV_{H_2}} \tag{2}$$

where, η_{el} is the efficiency of electrolyzer and HHV_{H_2} is the heating value of hydrogen.

2.3 Hydrogen Tank

Hydrogen generated by electrolyzer is stored in hydrogen tank, and hydrogen leakage during the storage is ignored. In terms of the capacity optimization, the storage capacity of hydrogen tank has been considered as an optimization objective.

2.4 Compressor

Power consumed by compressor (P_{comp}) is related with the inlet and output pressure of hydrogen, the flow rate of hydrogen, and the efficiency of compressor. It can be expressed as follow:

$$P_{comp} = C_{p,H_2} \frac{T_{comp}}{\eta_{comp}} \left[\left(\frac{P_{in}}{P_{out}} \right)^{\frac{k-1}{k}} - 1 \right] W_{comp} \tag{3}$$

where, $C_{p,\mathrm{H_2}}$ is the specific heat capacity of hydrogen, T_{comp} is the inlet ambient temperature, η_{comp} is the efficiency of compressor, P_{in} and P_{out} are the inlet and outlet pressure of hydrogen, k is the specific heat ratio of hydrogen at the standard condition, and W_{comp} is the gas flow rate.

3 Objective Functions, PSO Algorithm, and Constraints

3.1 Objective Functions

Considering the energy utilization rate of solar power, the hydrogen supply stability, and the equipment utilization rate of electrolyzer and tank, three objective functions (*i.e.*, abandonment rate of solar power, hydrogen supply shortage rate, and vacancy rate of equipment) are chosen and defined as:

$$\eta_{solar}^{AR} = \frac{1}{8760} \sum_{t=1}^{8760} \frac{P_{ex}(t)}{P_{pv}(t)} \tag{4}$$

$$\eta_{load}^{HSS} = \frac{1}{8760} \sum_{t=1}^{8760} \frac{M_{It,\mathrm{H_2}}(t)}{M_{load,\mathrm{H_2}}(t)} \tag{5}$$

$$\eta_{equ}^{vr} = 1 - \frac{1}{2 \times 8760} \left(\sum_{t=1}^{8760} \frac{M_{tank}(t)}{M_{rated,tank}} + \sum_{t=1}^{8760} \frac{P_{el}(t)}{P_{rated,el}} \right) \tag{6}$$

where, η_{solar}^{AR} is the abandonment rate of solar power, P_{ex} is the excess solar power, η_{load}^{HSS} is the hydrogen supply shortage rate, $M_{It,\mathrm{H_2}}$ is the insufficient mass of hydrogen supply, $M_{load,\mathrm{H_2}}$ is the hydrogen demand, η_{equ}^{vr} is the vacancy rate of electrolyzer and tank, M_{tank} is the mass of stored hydrogen in the tank, $M_{rated,tank}$ is the rated hydrogen mass of the tank, P_{el} is the power of electrolyzer, $P_{rated,el}$ is the rated power of electrolyzer.

3.2 PSO Algorithm

PSO algorithm is based on the population of swarms in which each individual particle is a potential solution of the problem [12]. The best solution is found by the swarm of particles in a search space. The moving path of a particle in a D-dimensional space is adjusted according its own optimal value as well as the swarm's optimal value. The principle and steps of PSO algorithm have been thoroughly introduced in previous studies [12–14], and the control parameters in this study are presented in Table 1. PSO algorithm has been run for a maximum number of iterations of 200 for 1 h time interval during a whole year data set, *i.e.*, 8760 h.

It is worthwhile mentioning that a linear weighting method is adopted to convert the multi-objective problem (*i.e.*, three objectives in this study) into a single-objective one by using the following equation:

$$F_{mul} = w_1 \eta_{solar}^{AR} + w_2 \eta_{load}^{HSS} + w_3 \eta_{load}^{HSS} \tag{7}$$

where, w_1, w_2, and w_3 are the weights of three objective functions, respectively, and the sum of three weights is equal to 1.

Table 1. Control parameters used in PSO algorithm

Parameters	Symbol	Value
Dimension of the problem	D	3
Population size	NS	200
Maximum iteration number	$IT_{\max}$	200
Weighting factors	c_1, c_2	1.5
Maximum inertia weight	$W_{\max}$	0.8
Minimum inertia weight	$W_{\min}$	0.4
Number of objective functions	OB	3

3.3 Constraints

Constraints including energy balance, hydrogen flow balance, input power and hydrogen storage capacity constraint should be carefully considered to ensure the accuracy of the model concerning practical applications.

Energy balance. It involves in solar power, auxiliary electricity from grid, and power consumed by electrolyzer and compressor at time t. It can be expressed as follow:

$$P_{pv}(t) + P_{ex}(t) = P_{el}(t) + P_{comp}(t) \tag{8}$$

where, P_{ex} is the auxiliary electricity from grid, P_{el} is the electrolyzer power.

Hydrogen flow balance. It is related to the supply, storage, and consumption of hydrogen, which can be further calculated as follow.

$$M_{e,\mathrm{H_2}}(t) = M_{tank}(t+1) - M_{tank}(t) + M_{load,\mathrm{H_2}}(t) - M_{ss,\mathrm{H_2}}(t) \tag{9}$$

where, $M_{\mathrm{e,H_2}}$ is the hydrogen generated by electrolyzer, M_{tank} is the stored hydrogen, $M_{\mathrm{load,H_2}}$ is the needed hydrogen of chemical plant, $M_{ss,\mathrm{H_2}}$ is the supply shortage of hydrogen.

Capacity constraints. The input power of electrolyzer cannot exceed the maximum power or be lower than the minimum starting power. The stored hydrogen in the tank cannot exceed its maximum capacity.

$$P_{el,\min} \le P_{el} \le P_{el,\max} \tag{10}$$

$$0 \le M_{\mathrm{tank}} \le M_{\mathrm{tank,max}} \tag{11}$$

where, $P_{el,\min}$ and $P_{el,\max}$ are the minimum and maximum power of electrolyzer, respectively, and $M_{\mathrm{tank,max}}$ is the maximum storage capacity of hydrogen tank.

4 Results and Discussions

The output power of PV system and hydrogen demand of the chemical plant in a typical week are shown in Fig. 2. The output power of PV system shows a strong volatility, which reaches the highest power at midday. The average hydrogen demand is about 30 kg/h, and the curve of hydrogen demand indicates the relatively small fluctuation. The resource data are further used in the capacity optimization.

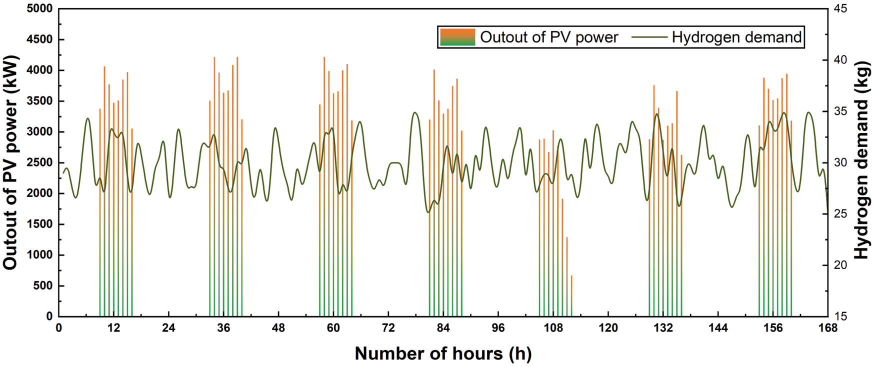

Fig. 2. Output power of PV system and hydrogen demand in a typical week.

Figure 3 reveals convergence characteristic of PSO algorithm with different objective functions. It is obvious that all the simulations converge in almost preliminary 30–100 iterations. Table 2 shows the capacity optimization results with different optimization methods, and the capacity configuration based on empiric value (*i.e.*, 80% of the rated PV power for electrolyzer power, and hydrogen yield in 12 h at the rated electrolysis power for the storage capacity of hydrogen tank) is also tested using the simulation model. The results show that the single-objective function is able to reach its corresponding optimal solution, but leads to the unbalance of other objective functions. For example, when selecting η_{equ}^{vr} as the objective function, the optimization results are 2942 kW for electrolyzer and 106 Nm^3 for hydrogen tank, and the η_{equ}^{vr} reaches the lowest. However, the storage capacity of hydrogen tank is too low to satisfy the electricity storage demand, resulting in a high abandonment rate of solar power. Compared with empiric value and single-objective function, multi-objective optimization shows a better performance, and the weighting factors of three objective functions (i.e., w_1, w_2, and w_3) are 0.3557, 0.3427, and 0.3016, respectively. Based on the simulation results of multi-objective optimization, the optimal capacity values are 4971 kW for electrolyzer and 937 Nm^3 for hydrogen tank. The η_{solar}^{AR}, η_{load}^{HSS}, and η_{equ}^{vr} for multi-objective optimization are 0.1737, 0.2484, and 0.7389, respectively, indicating the good performance of multi-objective optimization. It should be pointed out that even after the capacity optimization, the η_{equ}^{vr} is still too high because of the low annual utilization hours of solar power, and hybrid wind-photovoltaic complementary power generation is suggested to improve the usage rate of electrolyzer and hydrogen storage tank [15].

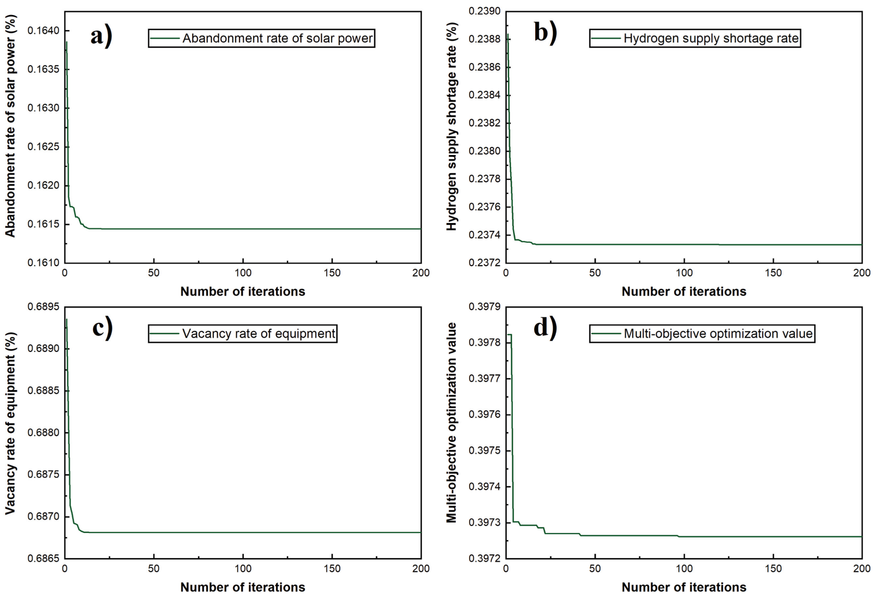

Fig. 3. Convergence characteristic of PSO algorithm with different objective functions. (a. abandonment rate of solar power, b. hydrogen supply shortage rate, c. vacancy rate of equipment, d. multi-objective function)

Table 2. Capacity optimization results with different optimization methods

Optimization method		Electrolyzer power (kW)	Capacity of tank (Nm^3)	η_{solar}^{AR}	η_{load}^{HSS}	η_{equ}^{vr}
Single-objective optimization	η_{solar}^{AR}	5078	2000	0.1617	0.2384	0.7833
	η_{load}^{HSS}	5313	2000	0.1622	0.2375	0.7845
	η_{equ}^{vr}	2942	106	0.3893	0.4566	0.6868
Multi-objective function		4971	937	0.1737	0.2484	0.7389
Empiric value		5600	823	0.1932	0.2640	0.7436

For further discussion, the capacity configuration obtained by multi-objective optimization has been chosen because of its better results. Figure 4 depicts the power input and output of the hybrid energy system in a typical week. It can be observed that the power of electrolyzer mainly depends on solar power generation, and when the PV power is insufficient or zero, auxiliary power from the grid is needed to supply power to the compressor. When the output power of PV is less than the minimum power of electrolyzer (*i.e.*, 40% of the rated power in this study), the electrolyzer is shut down, and the hydrogen supply mainly depends on the hydrogen stored in hydrogen tank.

In order to gain insight into the hydrogen management of the hybrid energy system, a complete data for a typical week concerning the hydrogen flow balance has been

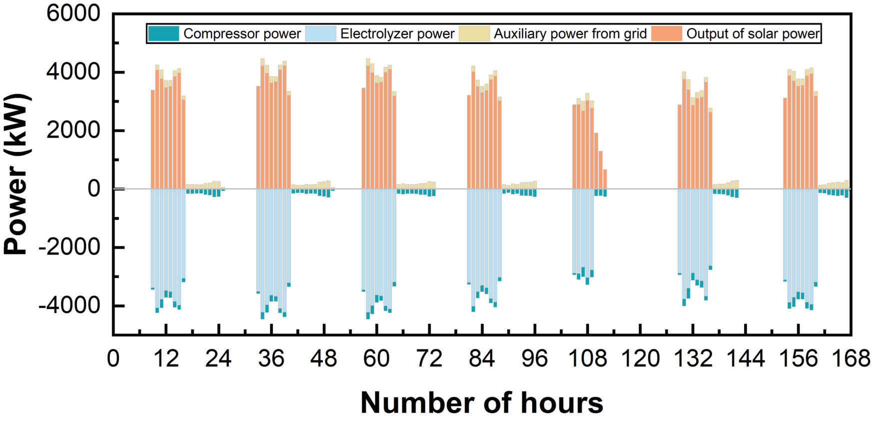

Fig. 4. Power input and output of hybrid energy system in a typical week.

selected. As shown in Fig. 5, the supply shortage of hydrogen usually occurs during the shortage of PV power generation or the startup stage of electrolyzer. Besides, the hydrogen produced by electrolyzer is significantly influenced by the remaining hydrogen stored in hydrogen tank, the hydrogen demand, and the output power of PV power system. As for 4971 kW electrolyzer, a maximum of 87.6 kg/h can be produced, and the highest hydrogen storage capacity of hydrogen tank is 1347 kg. Further, it can be concluded that with the increase of electrolyzer power and the storage capacity of hydrogen tank, the hydrogen supply shortage rate and the energy utilization rate of solar power increases, however, accompanied with the decrease of equipment utilization rate, *i.e.*, electrolyzer and hydrogen tank.

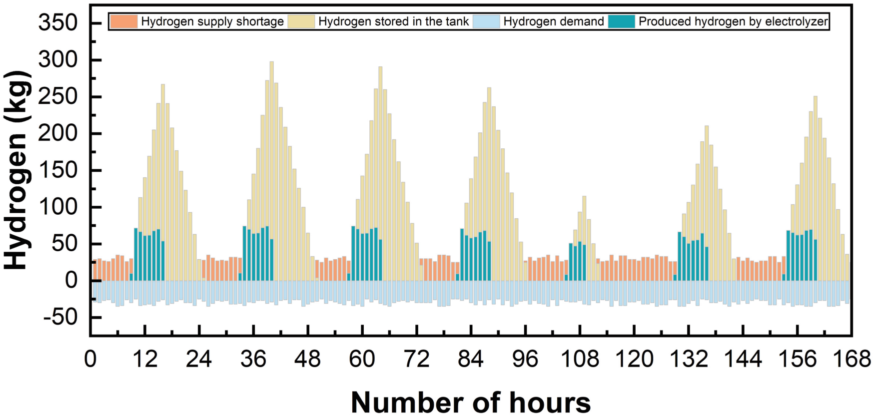

Fig. 5. Hydrogen balance of hybrid energy system in a typical week.

5 Conclusion

Based on PSO algorithm and multi-objective optimization, a hybrid energy system including solar energy and hydrogen energy is proposed. The optimization functions and the mathematical model are key issues in designing of high-efficiency and stable hybrid energy system. Compared with single-objective function optimization and empirical algorithm, multi-objective function optimization shows a better performance in terms of the balance of different optimization objectives. As to a 720 kg/d chemical plant with a distributed photovoltaic power station with rated power of 7000 kW, the optimal capacity configuration for the hybrid system is 4971 kW for electrolyzer and 937 Nm^3 for hydrogen tank according to the capacity optimization results. The proposed optimization model is promising in the capacity planning of hybrid energy system, which promotes large-scale applications of hydrogen energy in power industry.

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