A Photovoltaic-Assisted in-Situ Hydrogen Refueling Station System and Its Capacity Optimization Method

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***Abstract*—In order to accelerate the popularization of hydrogen vehicles, it is urgent to reduce the cost of hydrogen refueling stations. This paper proposes a photovoltaic-assisted in-situ hydrogen refueling station (PA-HRS) system. Compared with the traditional HRS, the assistance from PV reduces the dependence of PA-HRS with the power grid. The PA-HRS system also includes alkaline electrolytic cells and storage batteries, which can make it more flexible to operate and regulate based on the peak-valley difference of electricity price. Finally, the case study based on real data shows that with the increase of PV construction capacity, the annual operating cost of the system gradually decreases. Moreover, the proposed PA-HRS system can achieve an annual cost reduction of 13.31% with the assistance of 600kW PV.**

Keywords-Photovoltaic, Hydrogen refueling station, Capacity configuration, PA-HRS

I. INTRODUCTION

Hydrogen energy has attracted much attention in recent years because of its cleaning properties[1]. Hydrogen-powered vehicles are also replacing gas-powered vehicles and electric vehicles. The popularization of hydrogen energy vehicles needs the hydrogenation station as the guarantee[2]. As a commercial unit, the cost and income of hydrogenation station are the key to determine its viability[3].

The cost of hydrogenation station can be divided into construction cost and operation cost, and the construction cost is often determined by its area, location, equipment configuration and equipment capacity[3]. The operation cost includes depreciation cost, labor cost, power cost and so on, among which the power cost accounts for the majority of the operation cost, and also accounts for 40%~60% of the total cost[4].

Aiming at the problem of how to reduce the cost of hydrogenation station, some scholars designed the optimal capacity configuration of each equipment of hydrogenation station from the perspective of construction cost, so as to reduce the initial investment of hydrogenation station[5]. Starting from the operation cost, some researchers put forward the optimization operation strategy[6], which is to make use of the peak valley difference of electricity price, run the electrolytic cell at low electricity price, temporarily store the hydrogen into the hydrogen storage tank, stop the operation of the electrolytic cell at high electricity price, and use the hydrogen energy in the hydrogen storage tank to supply hydrogen[7].

In order to fundamentally solve the problem of high operation cost of hydrogenation station caused by high electricity price, some scholars proposed to use photovoltaic or wind power to produce hydrogen to achieve the purpose of reducing operation cost[8]. They assume that the power generation cost of new energy is almost zero. However, although the power generation cost of distributed energy is very low, the construction cost is high. Therefore, the construction cost of photovoltaic equipment should be taken into account when studying the hydrogen production by photovoltaic power generation.

The main findings and innovations of this study are summarized as follows.

1) A photovoltaic-assisted in-situ hydrogen refueling station (PA-HRS) system is proposed in this paper. The photovoltaic power is used for hydrogen production in the electrolytic cell, and the hydrogenation station is connected to the large power grid. The redundant photovoltaic power can be sold to the power grid.

2) Based on the data results of local radiation intensity, peaking valley difference of electricity price, and estimation of hydrogen energy demand of hydrogenation station based on user behavior, this paper puts forward a system optimization configuration method considering construction and operation costs, and puts forward a capacity configuration strategy to minimize the annual system costs.

3) The optimal capacity configuration of PA-HRS with different capacity of PV is proposed. The impact of PV capacity on the annual cost is analyzed.

II. MODELING OF PA-HRS

A. *Structure of PA-HRS*

Fig.1 shows the structure of PA-HRS. As can be seen, the electricity used for electrolysis to produce hydrogen may come from the grid, photovoltaics or batteries, and the hydrogen produced by electrolysis of water in the electrolyzer is stored in a hydrogen storage tank by a compressor or supplied to hydrogen vehicles. The electricity generated from PV may be directly connected to the grid, deposited in batteries or used directly in electrolyzers for hydrogen production, depending on the power purchase price of the grid. Correspondingly, there is also a two-way flow of electrical energy between the battery and the grid, as well as a possible direct supply to the electrolyzer, depending on the power purchase price of the grid and the current demand for hydrogen energy. The hydrogen energy from the hydrogen refueling station is supplied to the hydrogen vehicles, so the hydrogen refueling behavior of the hydrogen vehicles determines the hydrogen energy demand of the station, and the capacity of each equipment in the station should be optimized based on the hydrogen energy demand.

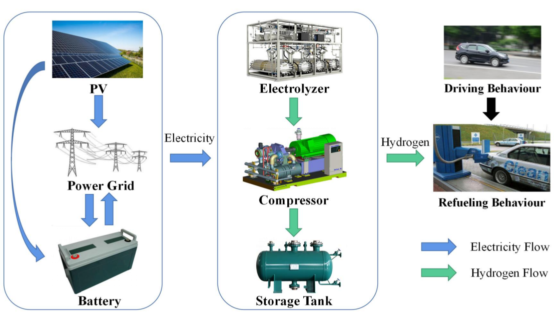


Fig.1 The structure of the proposed PA-HRS system.

B. *Equipment Modeling*

1) *Basic models of PV*

Generally, the output power of photovoltaic power generation device is related to the solar irradiation intensity and temperature, which can be calculated as follows[9]:

$$P_{PV}(t) = P_{STC} f_{PV} \frac{G_{PV}(t)}{G_{STC}} (1 - \alpha_p (T_e(t) - T_{ref})) \tag{1}$$

Where P_{STC} represents the rated power output(kW) of the PV under standard test condition(STC), G_{STC} and T_{ref} are the STC irradiation (W/m^2) and temperature(℃), $G_{PV}(t)$ represents the real-time solar irradiation intensity(W/m^2) at time t, f_{PV} is the discount factor of the power output, α_p is the temperature coefficient(℃$^{-1}$)， while $T_e(t)$ is real-time panel temperature(℃).

$$T_e(t) = T_a(t) + G_{PV}(t) \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{NOCT}} \tag{2}$$

The panel temperature $T_e(t)$ can be determined by (2), where $T_a(t)$ is the actual ambient temperature at time t, $T_{c,NOCT}$ and $T_{a,NOCT}$ are the nominal operating cell temperature (NOCT) of the PV panels and the NOCT of ambient temperature, and G_{NOCT} is the NOCT of irradiation intensity[9].Technical parameters of PV panels of PA-HRS is shown in Table 1. P_{STC} one of the variables to be optimized.

TABLE I. PV PANEL PARAMETERS.

Parameters	***Values***	**Parameters**	***Values***
G_{STC}	1 kW/m^2	$T_{c,NOCT}$	20 ◦C
T_{ref}	25 ◦C	G_{NOCT}	0.8kW/m^2
α_p	0.005 ◦C^{-1}	$T_{a,NOCT}$	25 ◦C
f_{PV}	80%		

2) *Electrolysis and Stored Procedure*

The proposed PA-HRS system applies Alkaline electrolytic cell because of its mature technology. The input variable of an alkaline electrolytic cell is the operating power, and the output variable is the hydrogen energy generated by its electrolysis. Part of the energy is dissipated in the form of heat energy, so the efficiency of an alkaline electrolytic cell is usually set as 75%[9].Due to the existence of minimum starting voltage, there is a minimum operating power of alkaline electrolyzer, and its operating power is constrained from 20% to 100%. Thus, the hydrogen production model of the electrolytic cell is shown in (3).

$$V_{ele,out}(t) = \frac{\eta_{EL} P_{ele}(t)}{LHV_{H_2}} \tag{3}$$

Where $V_{ele,out}(t)$ represents the hydrogen generated from eletrolyzer at time t, $P_{ele}(t)$ represents the electricity consumed by eletrolyzer at time t, LHV_{H2} is the low heating value of hydrogen gas. Technical parameters of electrolytic cell[11] of PA-HRS is shown in Table 2.

TABLE II. ELECTROLYTIC CELL PARAMETERS.

Parameters	***Values***
η_{EL}	75%
LHV_{H2}	39.7 kWh/kg

The storage model of hydrogen storage tank is shown in (4).

$$SOHT(t) = (Q_{HT}(t-1) + \eta_{h,in} V_{ele,out}(t) - \frac{V_{store,out}(t)}{\eta_{h,out}}) / Q_{H,N} \quad (4)$$

Where SOHT(t) is the state of hydrogen of storage tank at time t, $Q_{HT}(t-1)$ is the hydrogen stored in tank at time t-1(kg), $V_{store,out}(t)$ is the hydrogen output of tank(kg), and $Q_{H,N}$ is the rated storage capacity of tank, which is one of the variables to be optimized.

3) Battery Energy Flow and Loss

The battery of the proposed PA-HRS system absorbs redundant PV output and sells them to the grid at times of high electricity prices. The model the battery is shown in (5).

$$SOC(t) = (Q_{BE}(t-1) + \eta_{BE,in} P_{BE,in}(t) - \frac{P_{BE,out}(t)}{\eta_{BE,out}}) / Q_{BE,N} \quad (5)$$

Where SOC(t) is the state of charge at time t, $Q_{BE}(t-1)$ is the hydrogen stored in tank at time t-1(kWh), $P_{BE},out(t)$ is the power output of battery(kWh), and $Q_{BE,N}$ is the rated storage capacity of battery, which is one of the variables to be optimized. Parameters of hydrogen storage tank and battery of PA-HRS is shown in Table 3. $Q_{H,N}$ and $Q_{BE,N}$ are the variables to be optimized.

TABLE III. TANK AND BATTERY PARAMETERS.

Parameters	***Values***
$\eta_{h,in}$	90%
$\eta_{h,out}$	90%
$\eta_{BE,in}$	95%
$\eta_{BE,out}$	95%

III. OPTIMIZATION METHOD

A. Operation Strategy

The operation strategy of PA-HRS is shown in Fig.2. Firstly, the hydrogen energy demand of HRS is estimated based on user behavior, and try to ensure the hydrogen storage tank is full. On this basis, the electric energy from PV firstly meets the hydrogen energy demand of users, and if the PV power is higher than the rated hydrogen production power of electrolyzer or the hydrogen storage tank is full, the electricity will be sold to the grid when the power purchase price of grid is high, and stored into the battery when the power purchase price of grid is low; if the PV power is lower than the rated hydrogen production power of electrolyzer and the power sale price of grid is low, the priority is to take electricity from the grid to produce hydrogen; when the power sale price of grid is high, the priority is to take electricity from the battery to produce hydrogen.

In the operation process, the maximum exchange power with the grid, the charging and discharging power range of the battery, and the system power balance constraints are also taken into account.

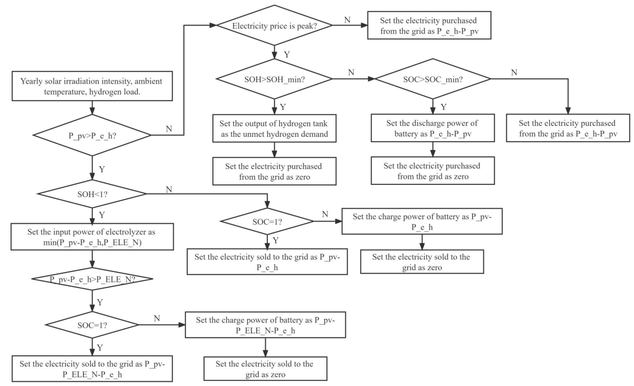


Fig.2 The operation strategy of PA-HRS.

B. Data preparation

The operation and capacity planning results of the PA-HRS system are closely related to the solar radiation intensity and hydrogen demand. The irradiation intensity data and ambient temperature in this paper were obtained from the 2017 meteorological dataset of Golo station, which recorded the hourly average radiation intensity, as shown in Fig.3.

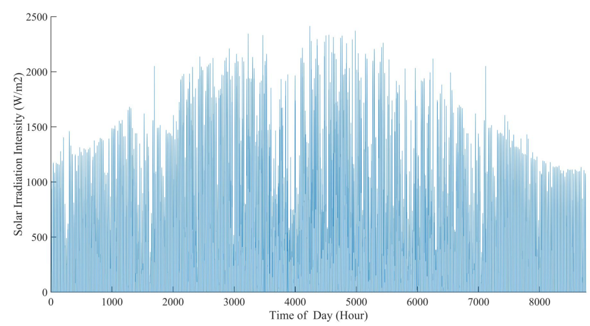


Fig. 3 Hourly average solar irradiation intensity.

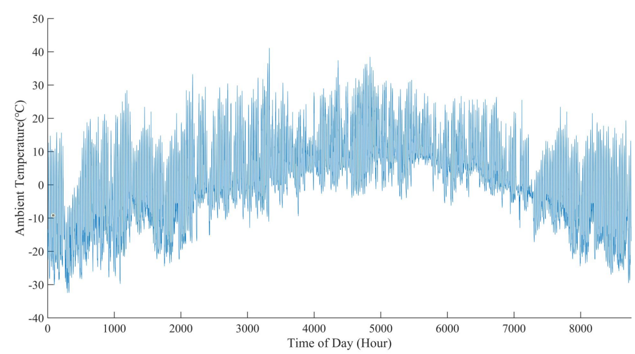


Fig. 4 Hourly average ambient temperature.

The hydrogen energy demand estimation method is derived from [10]. In order to simplify the demand-side analysis, the hydrogen energy vehicles served by the hydrogen refueling station in this paper are assumed to be only private cars, and the parameters are consistent with

[10]. The PA-HRS system serves 25 private HVs and the yearly hydrogen demand estimation is shown in Fig.5.

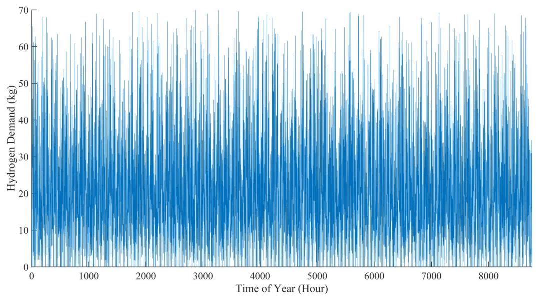


Fig. 5 Hourly average hydrogen demand estimation.

C. Objective Function

The proposed PA-HRS system is to satisfy the hydrogen demand of HVs with minimum costs, including operation and installation.Therefore, the optimization objective is to minimize the annual cost of the system, as shown in (6). The optimized variables for minimizing the annual cost are the capacities of PV, electrolyzer, battery, and hydrogen storage tank.

$$\begin{aligned} & C_{ins} = (A/P,r,n)(c_{pv}P_{STC} + c_{ele}P_{ELE,N} + c_{store}Q_{H,N} + c_{BE}Q_{BE,N}) \\ & (A/P,r,n) = \frac{r \times (1+r)^n}{(1+r)^n - 1} \\ & C_{ope} = \sum_{t=1}^{T}(P_{EX,out}c_{e,out} + P_{EX,in}c_{e,in}) \\ & \min C = C_{ins} + C_{ope} \end{aligned} \tag{6}$$

The optimization goal of the optimization method proposed in this paper is the cost of the system for a whole year, so Present-Value Interest factors of Annuity (PVIFA) should be considered. r represents the annual rate, and n represents the lifetime of HRS. c_{pv},c_{ele},c_{store},c_{BE} represent the unit cost of corresponding devices in PA-HRS respectively. $P_{EX,out}$ and $P_{EX,in}$ represent the power sold to the grid and purchased from the grid. $c_{e,out}$ and $c_{e,in}$ represent the electricity price of the power sold to the grid and purchased from the grid. There parameters are shown in Table 4[12]. The prices of electricity purchase and sale at different periods are shown in Table 5. The peak period of electricity price is 8:00-12:00 and 19:00-22:00, and the valley period is 00:00-8:00 [11].

TABLE IV. PARAMETERS IN OBJECTIVE FUNCTION.

Parameters	***Values***
c_{pv}	818 $/kW
c_{ele}	784 $/kW
c_{store}	124 $/kg
c_{BE}	100 $/kWh
r	5%
n	15

TABLE V. TIME-OF-USE ELECTRICITY PRICE.

	Peak period($/kWh)	***Normal period($/kWh)***	***Valley period($/kWh)***
purchase	0.23	0.10	0.06
sale	0.09	0.04	0.02

D. Constraints

The system constraints considered are divided into equation constraints and inequality constraints. The equation constraints include: hydrogen energy supply and demand balance constraints(7) and electric energy power balance constraints(8); the inequality constraints take into account the operating power range constraints of electrolyzer(9), the maximum hydrogen storage capacity of hydrogen storage tank(10) and capacity of battery(11), and the maximum power constraints of the contact line interacting with the grid (both power extraction from the grid and residual power feed-in are considered)(12). $P_{EX,max}$ is set as a sufficiently large value in this paper. Moreover, in order to reduce the energy loss of the system operation, the electric energy flow of the grid and the system must be one-way at the same time(13), and the battery cannot be charged and discharged simultaneously(14).

$$V_{store,out}(t) = V_{demand}(t) \tag{7}$$

$$P_{EX,in}(t) + P_{PV}(t) = P_{BE,in}(t) + P_{ELE}(t) + P_{EX,out}(t) \tag{8}$$

$$20\% P_{ELE,N} < P_{ELE}(t) < P_{ELE,N} \tag{9}$$

$$0 < SOH(t) < 1 \tag{10}$$

$$0 < SOC(t) < 1 \tag{11}$$

$$0 \le \max(P_{EX,in}, P_{EX,out}) < P_{EX,\max} \tag{12}$$

$$P_{EX,in} \cdot P_{EX,out} = 0 \tag{13}$$

$$P_{BE,in} \cdot P_{BE,out} = 0 \tag{14}$$

IV. RESULTS AND ANALYSIS

A. Capacity Configuration results and analysis

Since the time scale studied in this paper is one year, there are many variables involved and complicated control steps, so this paper uses heuristic algorithms to solve the optimization problem. Genetic algorithm (GA) is used to solve the above optimization problem, and the variables to be optimized are the capacity of PV, electrolyzer, hydrogen storage tank and battery. GA is developed with python language and executed in a computer with the following specifications: Core i5-8265U, 3.40GHz CPU, 8GB RAM, and 64-b system.

Table 4 shows the optimal capacity configuration of the equipment for the PA-HRS system under different PV capacity configurations, and the upper limits of configuration for the electrolyzer, the hydrogen storage tank and the battery are respectively 2000kW, 1000kg and 1000kWh. As can be seen, the annual costs of PA-HRS system are less than Non-PA-HRS system, moreover, with the increase of the capacity of PV, the annual costs of the system decrease. However, since the power exchange of

PA-HRS and the grid is limited, it is unreasonable to increase PV infinitely. At the same time, too much PV power needs batteries with larger capacity for storage, and the replacement and abandonment of batteries may bring environmental pollution. Fig.6 shows the relationship between PV capacity and annual cost, which shows that with the increase of PV capacity, the annual costs of PA-HRS gradually decrease. Compared with Non-PA-HRS, PA-HRS with 600kW PV realizes 13.31% reduction.

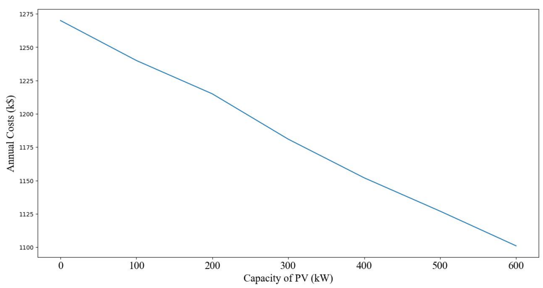


Fig. 6 The relationship between PV capacity and annual cost.

TABLE VI. OPTIMIZED CAPACITY CONFIGURATION OF PA-HRS AND NON-PA-HRS.

		Non-PA-HRS	PA-HRS					
Capacity	PV/kW	0	100	200	300	400	500	600
	Electrolyzer/kW	424	423	469	403	409	402	420
	Hydrogen tank/kg	459	450	477	632	425	569	426
	Battery/kWh	126	174	215	142	234	512	612
Annual costs /k$		1270	1240	1215	1181	1152	1127	1101

B. Operation analysis of PA-HRS

Fig. 7 shows the hourly storage state of hydrogen and electricity of PA-HRS with PV capacity as 1000kW, in which the blue line is for hydrogen tank and the orange one is for battery. As can be seen, the hydrogen storage state fluctuates in the safety range of storage tank, while the battery stores redundant PV to achieve full absorption of photovoltaic.

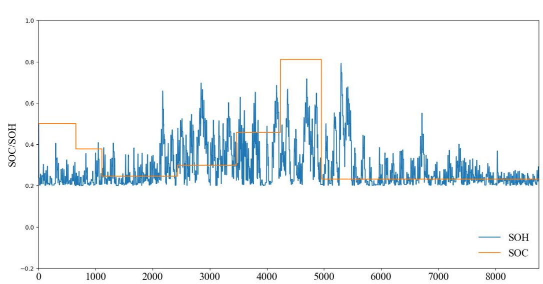
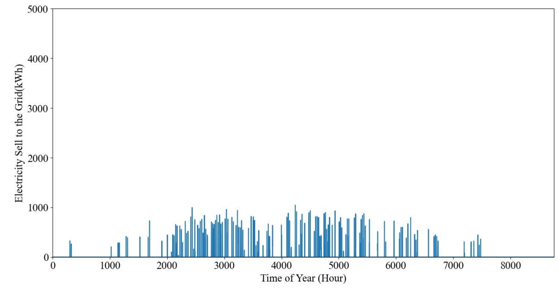
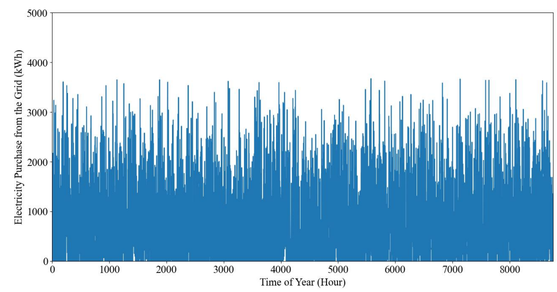


Fig.7 Hourly storage state of hydrogen tank and battery of PA-HRS.

The annual energy exchange between the system with 1000kW PV and the grid is shown in Fig. 8, and it can be seen that the system realizes the optimization of the operation process through the two-way energy exchange with the grid.



(a) Electricity sell to the grid.



(b) Electricity purchase from the grid.

Fig. 8 Hourly storage state of hydrogen and electricity of PA-HRS

V. CONCLUSION

This paper proposes a PA-HRS system to realize the reduction of total costs for hydrogen refueling station. With the assistance of PV, PA-HRS system has less dependence on the power grid. The system includes alkaline electrolytic cells and storage batteries, which can be more flexible to operate and regulate based on the peak-valley difference of electricity price. The results of the case study based on real data show that the proposed PA-HRS system can achieve an annual cost reduction of 13.31% with the assistance of 600kW PV. At the same time, the study concludes that within a certain range, with the increase of PV construction capacity, the annual operating cost of the system gradually decreases.In the future work, the authors of this paper will also evaluate the impact of larger scale PV on hydrogen refueling stations.

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