Energy Proceedings
Vol 38, 2024
ISSN 2004-2965

Research on Capacity Configuration of Wind Solar Off-grid Hydrogen Production System

Xuesong Chang[1], Yingzi Xian[1], Bolong Mao[1],Jiawei Chen[1],Xiumin Li[1],Xin Du[2],Lei Wang [1*]

1 College of Automation, Chongqing University, Chongqing, 400044, PR China

2 Goldwind Technology Co., LTD, Wulumuqi, 830000, PR China
(*Corresponding Author: leiwang08@cqu.edu.cn)

ABSTRACT

This paper mainly studies the configuration issues of the wind solar off-grid hydrogen production system. The system consists of a WT, PV array, energy storage batteries, an alkaline electrolyser, and a proton exchange membrane (PEM) electrolyser. The addition of PEM electrolyzer aims to reduce wind and solar power curtailment and improve the energy utilization efficiency of the system.Firstly, the study establishes simplified mathematical models for each device, designs a power-flow strategy, and develops an economically optimal objective function. The model is solved using the optimized sparrow optimization algorithm to obtain the system configuration and other important indicators such as annual energy output power and H_2 production.For a scenario with a 1 MW WT and a 1 MW PV panel hydrogen production, the system configuration is determined as follows: EES with a capacity of 244 kWh, alkaline electrolyser with a power of 863 kW, PEM electrolyser with a power of 198 kW, and hydrogen storage tank capacity of 3060 kg. The energy utilization efficiency is 51% and the investment cost is approximately 2.38 million$.

- **Keywords:** hydrogen production system, configuration capacity, off-grid wind solar system, electrolyser model

NONMENCLATURE

Abbreviations	
WT	Wind Turbine
WSOHPS	Wind Solar Off-grid Hydrogen Production System
MPPT	Maximum Power Point Tracking
PV	Photovoltaic

1. INTRODUCTION

Fossil fuels such as coal, oil, and natural gas have been the primary sources of energy and they have driven rapid economic growth and spurred social development. However, due to their limited reserves around the world and the fact that they mainly produce carbon dioxide as a byproduct, issues related to energy shortages and climate change will seriously impact people's quality of life while also constraining economic and social development [1]. Therefore, researching and developing new types of clean energy as soon as possible is an inevitable trend for future energy structure transformation.

Hydrogen is a clean renewable secondary energy source with advantages such as low density, high calorific value, high storage density, no pollution or contamination. It is an important approach to solve problems related to energy shortages and climate change [2]. Renewable methods for producing hydrogen not only have zero environmental impact but also generate highly pure hydrogen which makes it very suitable for future environmental protection trends. [3] mentioned that since hydrogen production efficiency is closely related to wind-hydrogen coupling system optimization scheduling strategies, it proposed a wind-hydrogen system optimization scheduling method considering wind power hydrogen production efficiency. [4] in order to fully utilize renewable energy sources, it proposed a new joint optimization scheme where wind-hydrogen systems were coupled with power transmission so that wind power could be distributed reasonably for grid connection and hydrogen production purposes. [5] considered startup constraints of water electrolysis devices while respectively minimizing annual total cost or normalized cost per unit produced as planning objectives for integrated hydrogen-electricity

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

energy systems based on decomposition algorithms used to solve double-layer planning models. Optimizing hydrogen storage deployment helps reduce leveling costs in the hydrogen system but does not give specific allocation methods. Although many countries are now studying off-grid technology using solar-wind-generated electricity for hydrogen production, there are few studies related to allocation. Therefore, this paper aims to conduct an economic study of the WSOHPS from the perspective of allocation.

2. SYSTEM DESCRIPTION

Fig.1 presents the structure of WSOHPS, the system consists of a PV array connected to the DC/DC converter, WT linked to the DC bus bar via AC/DC rectifier,. A lithium battery bank used as an energy storage system (ESS), the ALK and PEM electrolyser to produce hydrogen and a gas tank for hydrogen storage. All the energy sources, ESS and hydrogen production devices are connected together to a common DC bus bar. DC/AC inverter ensures the adaptation of the electrolyser voltage level.

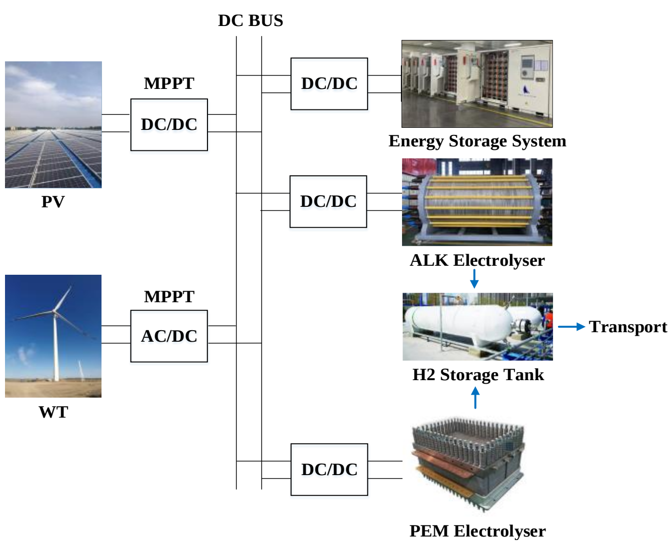

Fig. 1. Structure of WSOHPS

3. SYSTEM MODELLING

3.1 WT Model

Model used to calculate the output power of WT can be given as follow:

$$P_{WT} = N_{WT} \times \eta_{PV} \times P_{WT\_one} \quad (3\text{-}1)$$

$$P_{WT} = \begin{cases} 0 & V_t < 0, V_t > V_{c\_out} \\ P_{wt\_rated} \times \dfrac{V_t^3}{V_{rated}^3} & V_{c\_in} \le V_t \le V_{rated} \\ P_{wt\_rated} & V_{rated} \le V_t \le V_{c\_out} \end{cases} \quad (3\text{-}2)$$

Where V_t is the wind speed at time t, P_{wt_rated} is the rated power of WT, V_{c_in} is the cut-in speed of the WT, V_{c_out} is the cut-out speed of the WT, V_{rated} is the rated wind speed of the WT; P_{WT} is the output power of the WT.

3.2 PV Array Model

The solar panel output power P_{pv} is given by following equations :

$$P_{PV} = N_{PV} \times \eta_{PV} \times A_m \times G_t \quad (3\text{-}3)$$

$$\eta_{PV} = \eta_{ref} \times \eta_{pc} \times \lfloor 1 - \beta(T_c - T_{cref}) \rfloor \quad (3\text{-}4)$$

$$T_c = T_a + (\frac{\text{NOCT} - 20}{800}) \times G_t \quad (3\text{-}5)$$

Where N_{PV} is the number of PV panels; η_{PV} is the panel efficiency; A_m is the total area of the panel module; G_t is the incident global irradiance; T_a is the surrounding temperature of solar PV; T_a is the ambient temperature; β is the maximum power temperature coefficient of the PV array, -0.35%,NOCT is the normal PV working temperature; T_{cref} is the standard test temperature, 25℃.

3.3 ALK Electrolyser Model

The relationship between the voltage and current of a ALK electrolyser cell as a function is given by following equations:

$$U_{cell} = U_{rev} + \frac{r_1 + r_2 \cdot T_{el}}{A_{el}} I_{el} + (s_1 + s_2 \cdot T_{el} + s_3 \cdot T_{el}^2) \times \ln\left[\left(\frac{t_1 + {t_2}/{T_{el}} + {t_3}/{T_{el}^2}}{A_{el}}\right) \mathrm{I}_{el} + 1\right] \quad (3\text{-}6)$$

$$n_{H_2} = \eta_F \frac{n_{cell} \cdot I_{el}}{z \cdot F} \quad (3\text{-}7)$$

Where the r_1 and r_2 are the ohm resistance parameters of the electrolyser, 7.33×10^{-5},-1.11×10^{-7}; T_{el} is the temperature of the electrolyser, I_{el} is the input current, s_1, s_2 and s_3 are the electrode overvoltage coefficient, 0.159,1.38×10^{-3},-1.61×10^{-5}; t_1, t_2 and t_3 are the electrode overvoltage coefficient, 0.016, -1.302, 421.The n_{cell} is the number of series modules in the electrolyser, I_{el} is the input current, *z* is the number of electrons transferred per reflection, 2, and *F* is Faraday's constant, 96485.

3.4 PEM Electrolyser Model

A PEM electrolyser voltage can be approximately described as sum of represents reversible potential V_{rev}, ohmic overpotential V_{ohm}, activation overpotential V_{act}

and concentration overpotential V_{con}. The PEM electrolyser model is as follows:

$$V_{cell} = V_{rev} + V_{ohm} + V_{act} + V_{con} \tag{3-8}$$

$$V_{ohm} = i_{el} \, R_{eq} \tag{3-9}$$

$$V_{act} = V_{act.an} + V_{act.cat} \tag{3-10}$$

$$V_{on} = i_{el}\left(\beta_1 \frac{i_{el}}{i_{\lim}}\right)^{\beta_2} \tag{3-11}$$

$$n_{H_2} = \frac{i_{el} A}{2F} \tag{3-12}$$

R_{eq} represent the resistance of the membrane, $V_{act.an}$,$V_{act.cat}$ is the activation overpotential for the anode and cathode; i_{lim} is the limiting current density, β_1 is a function of temperature and pressure of oxygen and β_2 is a constant; n_{H2} represents the hydrogen production rate ,i_{el} represents the electrolyzer current density; F stands for the Faraday constant; A is the surface area.

3.5 ESS Model

The model of energy storage battery is divided into Charge and discharge model and life model. This project adopts the State of Charge (SOC) model of battery.The SOC model of energy storage battery charge and discharge process is as follow:

$$SOC(t) = SOC(t-1) \times (1-\sigma) + \left[E_{Gen(t)} - \frac{E_L(t)}{\mu_{inv}}\right] \times \mu_B \tag{3-13}$$

$$SOC(t) = SOC(t-1) \times (1-\sigma) + \left[\frac{E_L(t)}{\mu_{inv}} - E_{Gen(t)}\right] \times \mu_B \tag{3-14}$$

Where the SOC model of the charging and discharging process of the energy storage battery is shown in Eq.(3-13) and Eq.(3-14). $SoC(t)$ is the SoC of the energy storage battery at time t, where E_L is the load,σ is the self-discharge rate an hour, and E_{Gen} is the energy generated; μ_B is the charging and discharging efficiency of battery. The battery optimally operates between the allowable discharge limit, denotedas SOCmin, and the allowable maximum charge limit, denoted as SOCmax.

3.6 Hydrogen Tank Model

The hydrogen tank model is shown by the following equation:

$$C_T(t+1) = C_T(t) + C_{AEL}(t) + C_{PEM}(t) \tag{3-15}$$

Where $C_T(t+1)$ is the capacity of the hydrogen tank at time t+1, $C_{AEL}(t), C_{PEM}(t)$ is the amount of hydrogen produced by the electrolyser at time t.

4. CAPACITY OPTIMIZATION SCHEME OF WIND SOLAR HYDROGEN PRODUCTION SYSTEM

4.1 Operation Strategy

The input power of an ALK electrolyser is less than 30% of the rated power, not only will the hydrogen production efficiency of the electrolyser be reduced, but also the purity of the produced hydrogen gas will be affected, and even explosions may occur if the purity of hydrogen gas does not meet requirements. The operating range of PEM electrolyser is from 10% to 110% of rated power. Due to its expensive price, it has a low cost-effectiveness ratio and a low installation rate. The main purpose for including PEM electrolysers is to reduce wind and solar abandonment rates. When input power is low and ALK electrolysis cannot produce hydrogen, PEM electrolysis can absorb this electrical power.

Case1: When WT and PV output exceeds the rated capacity of the ALK electrolyzer, it runs at full capacity while excess electrical energy supplies PEM electrolysers for producing H_2. If there is still excess electrical energy after running both electrolysers at their full capacity, then any remaining energy charges batteries until SoC=SoCmax; thereafter excess electricity dissipates as waste.

Case2: If source side output power falls below 30% but remains over 10% above ALK's rated capacity, then ALK electrolyser runs in low-power mode with no battery operation.

Case3: If source side output falls below 30%, but still above 10% below PEM's rated capacity, then ALK electrolysis shuts down so that PEM can absorb this energy.

Case4: If the source side power output is less than 10% of the rated power of the PEM electrolyzer, if the battery SoC is greater than SoCmin, and the battery discharge power is greater than the difference in power between the ALK electrolyser and the source side output, the electrolyser will be powered by battery discharge at 30% of the rated power; if the battery SoC is equal to SoCmin, the electrolyzer stops and the battery is charged; if the difference power is greater than the battery's maximum discharge power, the excess power is used to charge the battery. The system operation diagram is shown in Fig.2.

4.2 Economic Model

For the WSOHPS, the total objective function is shown in the equation, where the PRO is total system revenue, E_{H2} is hydrogen sales revenue, A_{AEL} is hydrogen production,P_{H2} is hydrogen price, 22¥/kg, C_{AEL}, C_{BAT}, C_{TANK},

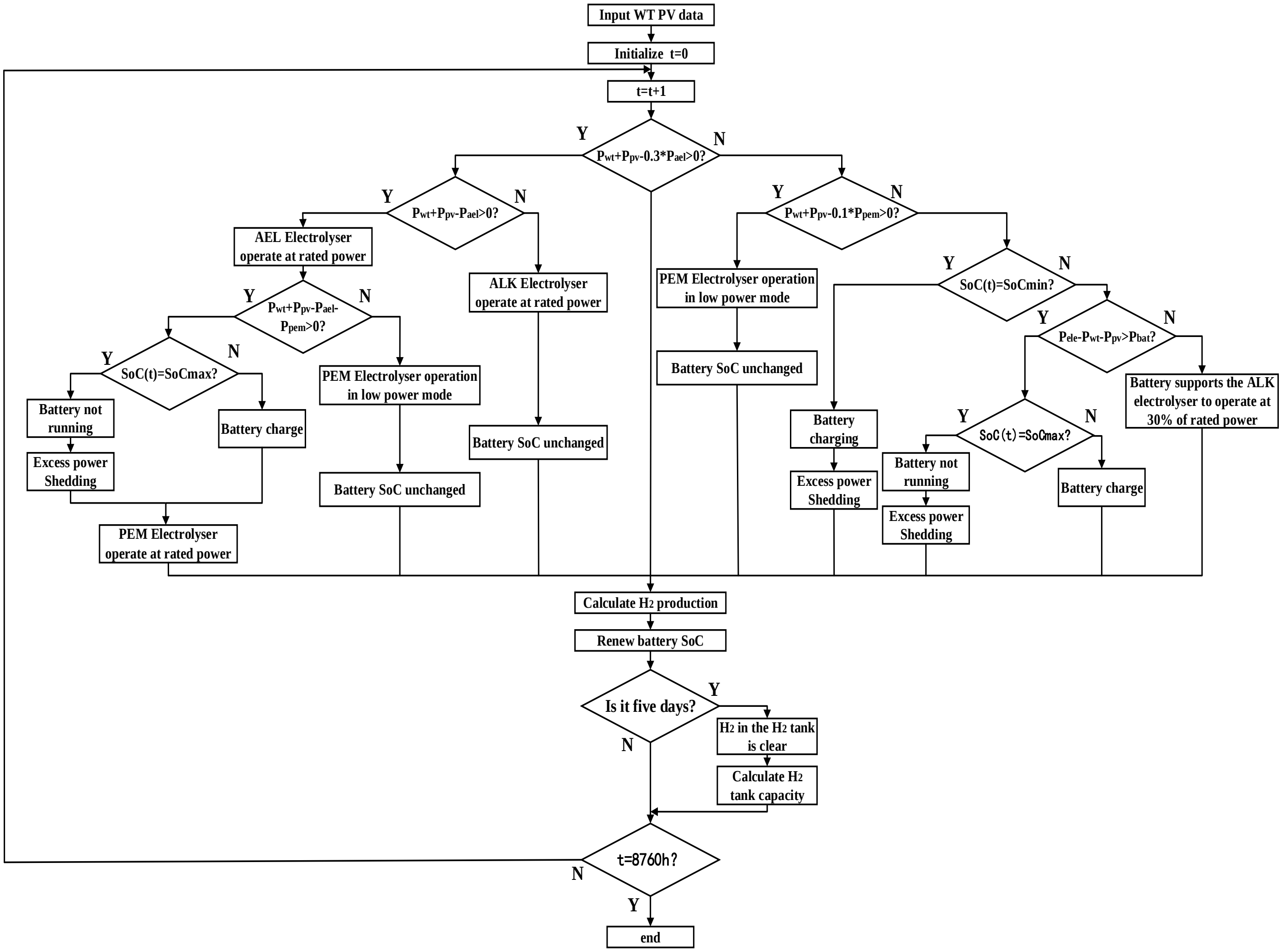

Fig. 2. System operation diagram

C_{WT}, C_{PV} is cost of electrolyser, batteries, hydrogen tanks, WT, and PV respectively; C_{AELa}, C_{BATa}, C_{TANKa}, C_{WTa}, C_{PVa} are construction costs of electrolyser, batteries, hydrogen tanks, WT, and PV respectively; C_{AELm} , C_{BATm} , batteries, hydrogen tanks, WT, and PV respectively. C_{TANKm}, C_{WTm},C_{PVm} are M&O costs of electrolyser, DAEL, DBAT, DTANK , DWT ,DPV are cost recoveries of electrolyser, batteries, hydrogen tanks, WT, and PV respectively.Tab.1 recaps the economic data taken from the paper.

$$R_{total} = E_{H_2} - C_{BAT} - C_{AEL} - C_{PEM} - C_{WT} - C_{PV} \quad (4\text{-}1)$$

$$E_{H_2} = (A_{ael} + A_{pem}) \times P_{H_2} \quad (4\text{-}2)$$

$$C_{BAT} = C_{BATa} + C_{BATm} - D_{BAT} \quad (4\text{-}3)$$

$$C_{AEL} = C_{AELa} + C_{AELm} - D_{AEL} \quad (4\text{-}4)$$

$$C_{PEM} = C_{PEMa} + C_{PEMm} - D_{PEM} \quad (4\text{-}5)$$

$$C_{WT} = C_{WTa} + C_{WTm} - D_{WT} \quad (4\text{-}6)$$

$$C_{PV} = C_{PVa} + C_{PVm} - D_{PV} \quad (4\text{-}7)$$

Tab.1 Economic data of system

Components	capital cost ($/kW)	replacement cost ($/kW)	O&M cost ($/kW)	lifetime (year)
PV array	547	503	27/y	20
Wind turbine	273	218	13.5/y	20
Battery	273	218	13.5/y	10
AEL	328	262	16.4/y	15
PEM	1780	1246	89/y	10
H_2 tank	391.5 $/kg	391.5 $/kg	0	20

4.3 Optimization Algorithm

The system optimization variables are batteries capacity, electrolyser capacities, and H2 tank capacity. The Sparrow Optimization Algorithm (SOA) has the advantages of good convergence, fast computation speed and fewer parameters that need to be adjusted compared to other algorithms.The SOA process diagram is shown in Fig.3.

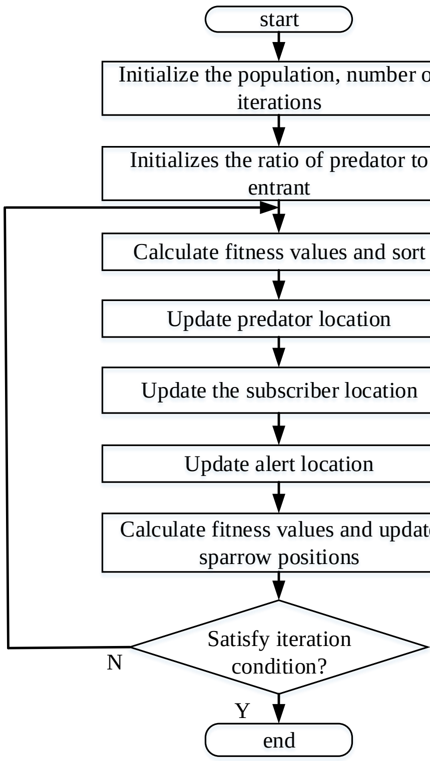

Fig. 3. SOA process diagram

5. RESULTS AND DISCUSSION

5.1 Data Input

Energy data were measured in Chongqing(30.54'N Latitude, 107.11'E Longitude).Meteorological data for the year of 2022,taken from the meteorological and radiometric station of CDER at Chongqing required in the simulation, are depicted in Fig.4 and Fig.5. The wind speed data is shown in Fig. 6.

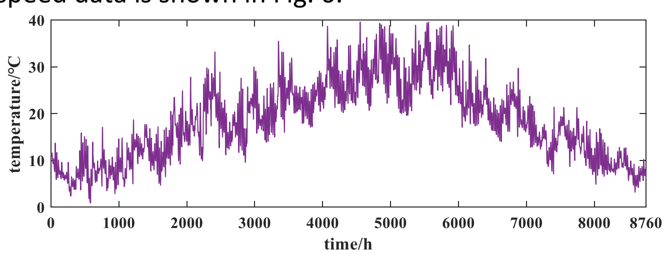

Fig. 4. Temperature data for one year

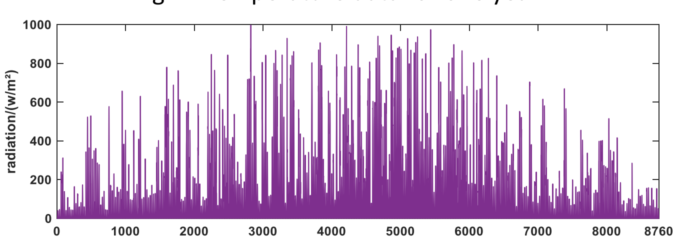

Fig. 5. Radiation data over one year

The rated power of the PV is 1MW, and the rated power of the WT is 1MW. Fig.7 and Fig.8 show the output power of PV array and WT in 2022.

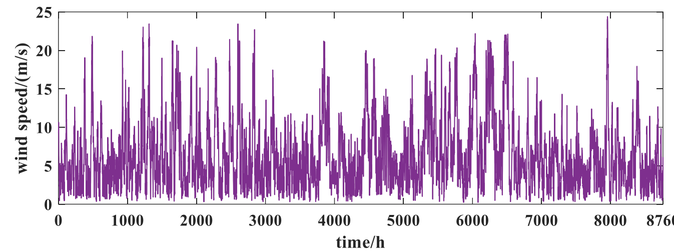

Fig. 6. Wind speed data over one year

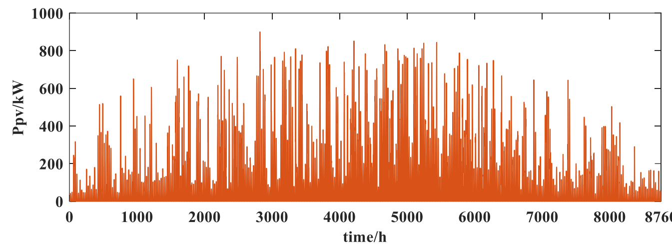

Fig. 7. PV output power over one year

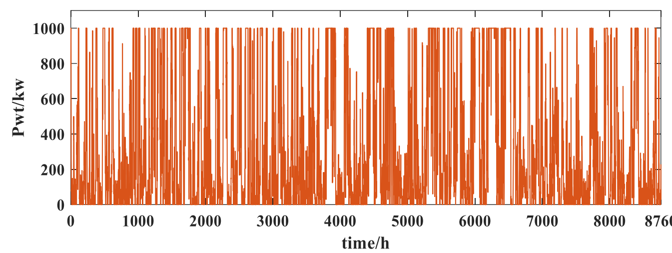

Fig. 8. WT output power over one year

5.2 Capacity Optimization Results Analysis

The capacity optimization allocation of ALK electrolyser, PEM electrolyser, energy storage system and hydrogen storage tank are shown in Tab.2. Due to the need to calculate and the capacity of the cases, and need to set more parameters, so the model and code into software, convenient for subsequent capacity configuration calculation.

Tab.2 Capacity configuration result

Unit	Capacity
PV array(kW)	**1000**
Wind turbine(kW)	**1000**
Battery(kWh)	244
AEL Electrolyser(kW)	863
PEM Electrolyser(kW)	198
H_2 tank(kg)	3060

When 1MW PV array equipped with 1MW WT hydrogen prodeuction, the capacities of the PEM electrolyser, ALK electrolyser, battery, and hydrogen storage tank are 244kW, 863kW, 198kWh, and 3060 kg, respectively. With this capacity configuration, the system achieves the highest benefit.

5.3 Economic Results Analysis

Tab.3 Economic indicators

Economic index	WT(1MW)+PV(1MW)
Generated Energy(kWh)	3062179
Revenue(million $)	5830.7
H_2 Production(kg)	63095
Operation time	20y
H_2 sales income(million $)	475.4
System efficiency	51%

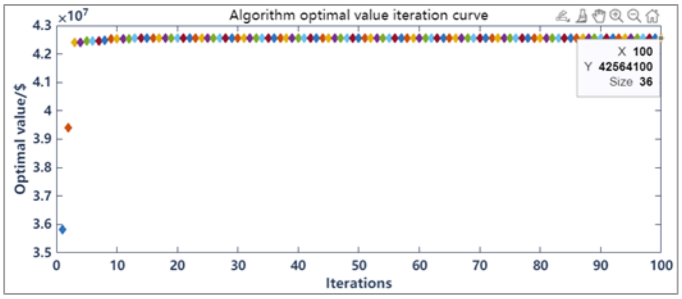

Fig.9. Algorithm optimal value iteration curve

Set the number of iterations of the SOA to 100, and the iterative optimization process of the algorithm is as shown in the Fig.9. The revenue, Generated energy, hydrogen production and other improtent indicators are shown in Tab.3. WT and PV generate 3,062,179 kWh of electricity annually. By the 20 year of operation, the system's profit can reach up to 5830.7 million $ with a system energy utilization rate of 51%. Additionally, every year it produces 63,095 kg of hydrogen which can be sold at a price of $5 per kg. The annual income from selling hydrogen is estimated to be around 475.4 million $.

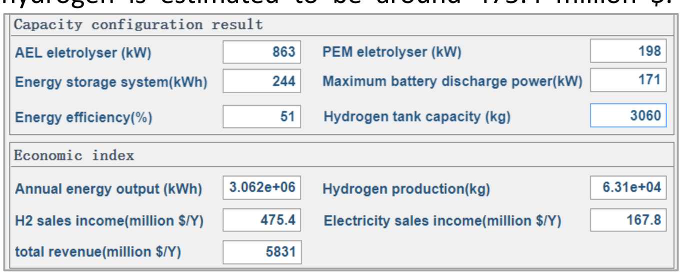

Fig. 10. Software calculation result

Fig.11 shows a comparison of input power from the source and battery SoC. When the input power from the source is greater than the electrolyzer's power, any excess power will be used to charge the battery, causing its SoC to increase. Conversely, when the input power from the source is less than the minimum start-up power required by the electrolyser, energy will be discharged from the battery in order to support its operation, thus causing its SoC to decrease.

Fig.12 is a profit chart for the system from its 1st to 30th year. The construction cost of the system is 2,382,608 dollars and it can generate positive income in the 8th year of operation. By the thirtieth year, the earnings could reach up to 7,601,890 dollars with a higher replacement cost considered. This calculation is based on a higher replacement cost for the system.

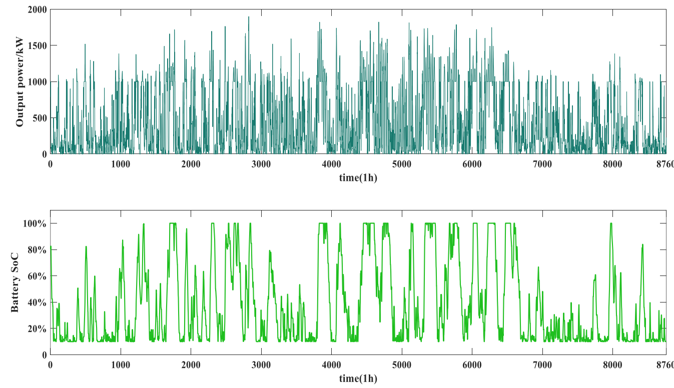

Fig. 11. Comparison of and battery SoC

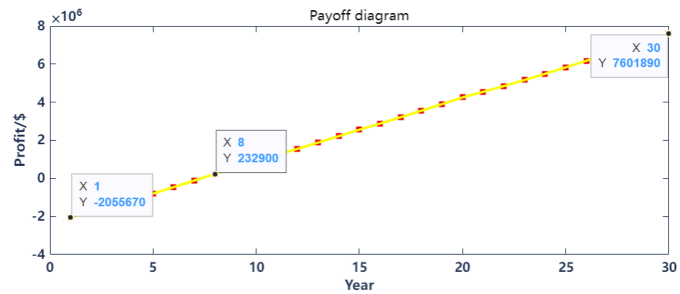

Fig. 12. Revenue from 1st year to 30th year

6. CONCLUSIONS

This paper studies the WSOHPS in the perspectives of capacity allocation. Based on the fluctuations of WT and PV, this paper designed a system operation strategy with low voltage and high current characteristics for an electrolyzer. Secondly, considering the costs of the electrolyzer, battery, WT, and PV systems comprehensively, an objective function was established. The economic model was solved using a SOA to obtain the appropriate allocation for each component in the system. Taking Chongqing's weather as an example, wind speed and temperature data were imported into the analysis. Under conditions where 1 MW WT and 1 MW PV are combined to produce hydrogen, the configurations of PEM electrolyser, AEL electrolyser, energy storage system and hydrogen storage tank are 244 kW, 863 kW, 198kWh, and 3060 kg respectively; This results in an annual hydrogen production rate of 63,095 kg, which can generate revenue up to $475.4 million annually through hydrogen sales. The investment cost can be recouped in eight years after construction begins with total earnings reaching 5.831 billion$ by year twenty of operation.The overall energy conversion efficiency rate is 51%.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (NO.51875058), Central University Frontier Discipline Special Project (NO. 20 19CDQYZDH025), Chongqing Basic Science and Front ier Technology Research Special (NO.CSTC2018jcyjAX0 414) and Chongqing Municipal Education Commission Science and Technology Research Project (NO. KJQN20180118).

REFERENCE

[1] Izadi A, Ahmadi P, Bashiri S. A comparative optimization of a trigeneration system with an innovative integration of solar Heliostat towers and Hydrogen production unit. Sustain Energy Technol Assess 2021;47:101522.

[2] Furat Dowood, Martine Anda. Hydrogen production for energy:An overview. International Journal of Hydrogen Energy. 2020,45:3847-3869.

[3] Z. P. HONG, Z. X. WEI, X. J. HAN. Optimization Scheduling Control Strategy of Wind-Hydrogen System Considering Hydrogen Production Efficiency. Journal of Energy Storage, 2022,47: 103609-103624.

[4] Z. H. DENG, Y. W. JIANG. Optimal Sizing of Wind-Hydrogen System Considering HydrogenDemand and Trading Modes. International Journal of Hydrogen Energy, 2020, 45(20): 11527-1153.

[5] Pan G, Gu W, Qiu H, et al. Bi-level mixed-integer planning for electricity-hydrogen integrated energy system considering levelized cost of hydrogen[J]. Applied Energy, 2020, 270: 115176.