Analysis of hydrogen production capacity of off-grid photovoltaic system based on PVsyst software simulation

Jiantao Li¹, Yongguang Li¹,*, Boxu Zhu¹, Xinxia Ma¹

¹College of Energy and Mechanical Engineering, Shanghai University of Electric Power, No.2103 Pingliang Road, Yangpu District, Shanghai, 200090, China;
* E-mail: liyongguang@shiep.edu.cn

Abstract. As a typical green energy, hydrogen energy has many advantages. The traditional hydrogen production methods are more polluting. However, the use of electricity generated by photovoltaic systems to produce hydrogen can not only make full use of local solar energy resources, but also achieve environmentally friendly hydrogen production. In this work, we use PVsyst software to model and simulate a 30kW off grid photovoltaic power plant in a region of Shanghai, and calculate its power generation. Combined with the energy consumption of hydrogen production equipment, we evaluated the hydrogen production capacity and pollutant emission reductions, and we also analyzed the performance ratio and power loss of photovoltaic system, which verifies the environmental protection of photovoltaic hydrogen production, and provides a reference for photovoltaic hydrogen production researchers.

1. Introduction
With the increase in global energy demand and environmental protection awareness, people in the world are increasingly yearning for green energy. As a renewable secondary energy source, hydrogen energy has an energy density of 140MJ/kg, which is the highest energy density fuel except nuclear fuels. Its calorific value of combustion is about three times that of gasoline. And hydrogen as an energy resource, only generates pure water when chemical reaction occurs without polluting substances such as carbon oxides, nitrogen oxides and sulfur oxides, and one of the main raw materials for hydrogen production is water, which has the characteristics of universal accessibility and high recyclability[1, 2]. Moreover, the use of hydrogen is not limited to energy sources, but is also widely used in ammonia synthesis, petroleum refining, metal refining, biopharmaceuticals and food processing.

The main methods of hydrogen preparation are: hydrogen from methane reforming, hydrogen from coal gasification, hydrogen from biomass, hydrogen from nuclear energy and hydrogen from electrolysis of water, among which only hydrogen from electrolysis of water can achieve zero pollution and also produce oxygen as a by-product[3]. According to Faraday's theorem of hydrogen production from water electrolysis, the theoretical power consumption for producing 1 Nm³ of hydrogen from water electrolysis is 2.95 kWh under standard conditions, while the conventional commercial electrolyzer, considering the power consumption caused by various losses, consumes about 6 kWh of electricity to produce 1 Nm³ of hydrogen from water electrolysis in a commercial electrolyzer[4]. If the electricity generated by thermal power generation in traditional power grid is used to produce hydrogen, carbon dioxide will be produced. By comparison, it can be found that the use of photovoltaic electricity to produce hydrogen has no emissions of pollutants, and the cost of electricity has also decreased.

China's solar energy resources are mainly distributed in the northwest area, while the energy demand is mainly concentrated in the central and eastern regions, a large amount of solar energy resources have
not been fully developed, and the electrolyzed water hydrogen production equipment can match the fluctuation and intermittence of photovoltaic power generation\[1\]. Therefore, China has a large amount of undeveloped solar energy resources that can be used for photovoltaic hydrogen production. In this work, we use PVsyst software to model and simulate 30kW off-grid photovoltaic system, which comprehensively consider the impact of the above factors on photovoltaic power generation. Combined with the relevant parameters of electrolytic water hydrogen production equipment, we calculated the hydrogen production, and analyzed the emission reduction of pollutants compared with the traditional power grid hydrogen production, which can provide reference for researchers in related fields, and promote the development and utilization of green energy.

2. PVsyst software review
The PVsyst software package was developed at the University of Geneva for study, simulation, and design of PV systems. It supports 3D modeling environment and takes into account the obstruction and shading effects of surrounding objects such as trees, buildings and other structures\[5\]. PVsyst can import meteorological data from Meteonorm and NASA, as well as user-defined data from many different sources, combined with specific terrain and environmental data, photovoltaic module data, etc. to realize the simulation of photovoltaic hourly power generation.

Petros J. Axaopoulos et al. compared PVsyst software with actual photovoltaic power plant data and found that although the data obtained by PVsyst simulation is slightly smaller than the actual value, it can reflect the characteristics of photovoltaic power generation and the deviation can be reduced by optimization of PVsyst module modeling\[6\].

Mounir Bouzguenda et al. used PVsyst software to design an off-grid 2 kW solar photovoltaic system. After analyzing the simulation results, they found that the shadows caused by nearby buildings and trees have limited impact on system performance, and despite the abundant solar resources in summer, high temperature environment seriously affects the overall performance of system components\[5\].

Nallapaneni Manoj Kumar et al. analyzed the simulation performance of a 100kWp grid-connected photovoltaic system based on PVsyst to evaluate the feasibility of the system to provide energy for educational institutions. After analyzing the effective energy output of the photovoltaic array and the annual losses, they found that PVsyst can indeed assist in improving the performance of photovoltaic power generation and benefit the installer or owner of the photovoltaic system\[7\].

Hartmut Nussbaumer et al. selected days with different light intensities and diffuse radiation shares for the experiment, and compared experimental measurement data, PVsyst simulation data, and data from simulation tools developed by ISC Konstanz and ECN.TNO. Finally, they found that the trends of the tripartite data are similar, which indicate that it is reasonable to use these two software to evaluate the potential of double-sided photovoltaic power generation\[8\].

Brahim belmahdi et al. simulated photovoltaic power generation based on PVsyst to study the possibility and feasibility of installing 1MW photovoltaic grid connected power generation system in different cities in northern Morocco, with fixed tilt angle, or seasonal tilt adjustment. After the performance analysis of the two configurations, it was found that the fixed inclined panel is better than the seasonally adjusted inclined panel\[9\].

Krzysztof mik et al. studied the electrical and chemical characteristics of four new types of silicon light photovoltaic modules produced by Xdisc company, carried out experiments and measured data, and then used PVsyst to assist in modeling verification. By analyzing the power generation, energy loss and economic calculation, it was found that the four new types of light photovoltaic modules had higher profits than traditional photovoltaic modules in terms of current prices\[10\].

In summary, PVsyst can be used to simulate the annual output of photovoltaic power plants by considering factors such as shadows, meteorological conditions, photovoltaic module layout, geographic location, inverter settings, etc. the mathematical relationships between different influencing factors can be found in the literature \[11\], and the modeling in PVsyst of photovoltaic plants can be realized by combining the relevant settings with the help files that come with the software. After combining the mathematical relationship between the power consumption of electrolytic water and the amount of
hydrogen produced, the hydrogen production capacity of a photovoltaic plant with a fixed installed capacity can be analyzed.

3. Case study

3.1. Analysis of simulation principle
The principle of this simulation is to determine the installed capacity of photovoltaic power plants based on the hydrogen production and load demand of the hydrogen production equipment. According to this principle, the scheme of photovoltaic hydrogen production is realized by using an off-grid photovoltaic systems with the use of batteries to ensure that the load demand of the electrolyzer is met, so that the analysis of hydrogen production volume, etc. can be carried out, and the general flow of the off-grid PV system for hydrogen production is shown in Figure 1.

![Figure 1 Sketch of hydrogen production from electrolytic water in off-grid photovoltaic plant](image)

3.2. Simulation description
In this work, we plan to use a commercial electrolyzer CHE-1000 with a power supply of 6 kW. Under standard operating conditions, the hydrogen output of the electrolyzer is 1Nm³/h. It is assumed that the load demand is the power supply of the electrolyzer and the daily operating time is 12h. The project site of the simulation is a region in Shanghai. The number of consecutive request autonomy days is assumed to be 4 days, the probability of insufficient load of hydrogen production equipment is assumed to be 5%, and the self-consumption power of the system is assumed to be 6W.

PVsyst can perform trial calculations based on the annual load demand and local solar energy resources, which can give the recommended value of photovoltaic power (29295Wp) and battery capacity (7073Ah). So we finally determined to select 120 Generic Si-poly modules, and the inclination of the modules is the fixed value 41°, the module spacing is 2 meters, the nominal power of each photovoltaic module is 250Wp, every 20 photovoltaic modules form a string, the entire off-grid system has a total of 6 strings, so the nominal capacity of the off-grid PV system is 30KW, and a universal controller is configured, it is set to use MPPT type operation mode, and its allowable voltage range is 526V-874V. In addition, the system also includes 284 generic batteries with a voltage of 12V and a capacity of 100Ah, each string consisting of 4 batteries, and there are 71 strings in total, the electricity generated by the system is transmitted to the electrolysis water hydrogen production equipment through transformers and other equipment.

3.3. Analysis of simulation results
Table 1 describes the global horizontal irradiation of a region in Shanghai, the effective global radiation considering IAM loss and shadow loss, and the solar energy that can be used by photovoltaic arrays, the power abandoned due to the battery being fully charged, the power that does not meet the load demand, the actual power available for users, the planned load demand of users, and the load satisfaction rate. It can be seen that the load demand is not fully satisfied only in January, and the annual load demand satisfaction rate is 99.3%, which meets the requirement that the annual load demand deficiency rate of hydrogen production equipment is less than 5%.
Table 1: Balance and main results of 30kWp stand alone photovoltaic system

| Month   | GlobHor (kWh/m²) | GlobEff (kWh/m²) | E_Avail (kWh/m²) | E Unused (kWh/m²) | E_Miss (kWh) | E_User (kWh) | E_Load (kWh) | SolFrac ratio |
|---------|------------------|------------------|------------------|------------------|-------------|-------------|-------------|---------------|
| January | 66.6             | 85.6             | 2277             | 116.6            | 193.9       | 2043        | 2236        | 0.913         |
| February| 75.8             | 81.5             | 2294             | 170              | 0           | 2020        | 2020        | 1             |
| March   | 96.6             | 92.9             | 2575             | 366.1            | 0           | 2236        | 2236        | 1             |
| April   | 119.1            | 103.6            | 2830             | 553.2            | 0           | 2164        | 2164        | 1             |
| May     | 140.9            | 111.2            | 2984             | 632.7            | 0           | 2236        | 2236        | 1             |
| June    | 124.5            | 95.2             | 2480             | 279.5            | 0           | 2164        | 2164        | 1             |
| July    | 154.5            | 120.3            | 3094             | 725.9            | 0           | 2236        | 2236        | 1             |
| August  | 147.1            | 127.4            | 3302             | 999.9            | 0           | 2236        | 2236        | 1             |
| September| 119.2           | 112.2            | 2963             | 813.6            | 0           | 2164        | 2164        | 1             |
| October | 102.2            | 110.8            | 2967             | 569.2            | 0           | 2236        | 2236        | 1             |
| November| 74.6             | 90.4             | 2379             | 221.9            | 0           | 2164        | 2164        | 1             |
| December| 67               | 83.6             | 2193             | 0.6              | 0           | 2236        | 2236        | 1             |

Year 1288.1 1214.7 32338 5431.2 193.9 26135 26328 0.993

When we know the off-grid system available electricity ($E_{user}$), off-grid system self-consumption through the calculation of simulation results ($E_{loss}$), combined with the electrolyzer energy consumption ($P_{H2}$), hydrogen production rate ($V$), the annual hydrogen production ($V$) can be calculated according to equation (1), while the production of oxygen is half of hydrogen production.

$$V = \frac{E_{user} - E_{loss}}{P_{H2}} \times V$$ (1)

After converting the electricity into standard coal, it is found that 1kWh of electricity is equivalent to approximately 0.000997t CO₂, 0.00003t SO₂, 0.000015t NOₓ and other pollutants. Then, combined with the aforementioned principles, the calculation results of the electricity consumption of photovoltaic hydrogen production, the energy saving and emission reduction relative to thermal power hydrogen production are shown in Table 2.

Table 2: Analysis of products, energy saving and emission reduction

| Month     | E_System loss (kWh) | E_H₂ (kWh) | H₂ Production (Nm³) | O₂ Production (Nm³) | CO₂ Reduction (t) | SO₂ Reduction (t) | NOₓ Reduction (t) |
|-----------|---------------------|------------|---------------------|---------------------|-------------------|-------------------|-------------------|
| January   | 4.464               | 2038.536   | 339.756             | 169.878             | 2.032             | 0.061             | 0.031             |
| February  | 4.032               | 2015.968   | 335.995             | 167.997             | 2.010             | 0.060             | 0.030             |
| March     | 4.464               | 2231.536   | 371.923             | 185.961             | 2.225             | 0.067             | 0.033             |
| April     | 4.320               | 2159.680   | 359.947             | 179.973             | 2.153             | 0.065             | 0.032             |
| May       | 4.464               | 2231.536   | 371.923             | 185.961             | 2.225             | 0.067             | 0.033             |
| June      | 4.320               | 2159.680   | 359.947             | 179.973             | 2.153             | 0.065             | 0.032             |
| July      | 4.464               | 2231.536   | 371.923             | 185.961             | 2.225             | 0.067             | 0.033             |
| August    | 4.464               | 2231.536   | 371.923             | 185.961             | 2.225             | 0.067             | 0.033             |
| September | 4.320               | 2159.680   | 359.947             | 179.973             | 2.153             | 0.065             | 0.032             |
| October   | 4.464               | 2231.536   | 371.923             | 185.961             | 2.225             | 0.067             | 0.033             |
| November  | 4.320               | 2159.680   | 359.947             | 179.973             | 2.153             | 0.065             | 0.032             |
| December  | 4.464               | 2231.536   | 371.923             | 185.961             | 2.225             | 0.067             | 0.033             |

Year 52.560 26082.440 4347.073 2173.537 26.004 0.782 0.391

From the calculation results of the whole year, it can be seen that a 30kWp off-grid photovoltaic system in a region of Shanghai can produce 4347.073 Nm³ of H₂ and 2173.537 Nm³ of O₂ in a specific
area of Shanghai for a whole year, which can reduce the emission of polluting gases by about 27t compared to the thermal power generation of hydrogen.

3.4. Loss analysis

![Loss diagram over the whole year](image)

**Figure 2 Loss diagram over the whole year**

$PR$ is the ratio of the total radiation received on the 1m$^2$ square array surface without considering any shading ($Y_f$) to the radiation received in the STC case ($Y_r$), indicating the performance ratio of the whole photovoltaic plant, which can be described as:

$$PR = \frac{Y_f}{Y_r}$$  \hspace{1cm} (2)

$SF$ is the ratio of the power available to the customer ($E_{sol}$) to the customer's planned load demand ($E_{load}$) and represents the load satisfaction rate of the whole system, which can be described as:

$$SF = \frac{E_{sol}}{E_{load}}$$  \hspace{1cm} (3)

From Figure 2(a), it can be seen that part of the energy generated by the monthly photovoltaic array per unit installed capacity is lost due to the layout of photovoltaic array and storage battery. Combined with figure 2(b), the $PR$ value of the whole year is 0.662, which is lower than that of conventional photovoltaic plant, on the one hand, this phenomenon is due to the existence of the above losses, on the other hand, in order to consider the load demand of hydrogen production equipment in winter, the off-grid photovoltaic system is not designed and calculated according to the optimal inclination angle of the
whole year, but simulated and calculated according to the inclination angle with the minimum loss in winter, so that the annual load demand rate of the system is as high as 99.3%. If the inclination angle of modules is adjusted to the optimal value of the whole year, the PR value will rise, however, it will reduce the hydrogen production capacity of the hydrogen production system.

4. Conclusion & Prospect
In this paper, we study the rationality and effectiveness of using PVsyst to simulate the hydrogen production capacity of an off-grid photovoltaic system in a region of Shanghai, and finally, the simulation results of the off-grid photovoltaic system are used to analyze the hydrogen production capacity of photovoltaic, energy saving and emission reduction, so as to provide reference for engineering and scientific researchers.

In this work, the principle of hydrogen-determined electricity was used to conduct the simulation. In the future research, the principle of electricity-determined hydrogen combined with the method described in this paper can be considered to design a PVsyst simulation scheme, i.e., to determine the local photovoltaic hydrogen production capacity according to the solar energy resources of a certain place, and to conduct the analysis of the economics and environmental protection of the scheme to promote the development of green energy such as solar energy and hydrogen energy.

Acknowledgements
This work was supported by Shanghai Municipal Science and Technology Commission Supported Local Capacity Building Project (122505010000) and Shanghai Municipal Education Commission Boosting Plan (12ZT11).

References
[1] CHI J, YU H. (2018) Water electrolysis based on renewable energy for hydrogen production[J]. Chinese Journal of Catalysis,39(3): 390-394.
[2] PIAN S, SUN B.X, YANG H. (2020) Prospect of Hydrogen Production by Electrolysis of Pure Water Based on Renewable Energy[J]. SHANDONG CHEMICAL INDUSTRY,49(15): 64-65.
[3] KHAN M A, ZHAO H, ZOU W, et al. (2018) Recent Progresses in Electrocatalysts for Water Electrolysis[J]. Electrochemical Energy Reviews,1(4): 483-530.
[4] BADWAL S P S, GIDDEY S S, MUNNINGS C, et al. (2014) Emerging electrochemical energy conversion and storage technologies[J]. Frontiers in Chemistry,2.
[5] BOUZGUENDA M, AL OMAIR A, AL NAEEM A, et al. Design of an off-grid 2 kW solar PV system In: 2014 9th International Conference on Ecological Vehicles and Renewable Energies, EVER 2014.
[6] AXAOPOULOS P J, FYLLADITAKIS E D, GKARAKIS K. (2014) Accuracy analysis of software for the estimation and planning of photovoltaic installations[J]. International Journal of Energy and Environmental Engineering,5(1).
[7] KUMAR N M, KUMAR M R, REJOICE P R, et al. (2017) Performance analysis of 100 kWp grid connected Si-poly photovoltaic system using PVsyst simulation tool[J]. Energy Procedia,117: 180-189.
[8] NUSSBAUMER H, JANSSEN G, BERRIAN D, et al. (2020) Accuracy of simulated data for bifacial systems with varying tilt angles and share of diffuse radiation[J]. Solar Energy, 197: 6-21.
[9] BELMAHDI B, BOUARDI A E. (2020) Solar Potential Assessment using PVsyst Software in the Northern Zone of Morocco[J]. Procedia Manufacturing,46: 738-745.
[10] MIK K, ZAWADZKI P, TARŁOWSKI J, et al. (2021) Multifaceted Analyses of Four Different Prototype Lightweight Photovoltaic Modules of Novel Structure[J]. Energies,14(8): 2239.
[11] JIANG H.Q., HE G.L, LAN Y.P. (2013) GUANGFU DIANZHAN SHEJI JISHU. CHINA ELECTRIC POWER PRESS, Beijing.