Numerical Study of Solar Hydrogen Production System for Rural Areas Employing TRNSYS

Zhipeng Sun
China Datang Corporation Science and Technology Research Institute Thermal Power Technology Research Institute, Beijing 100040, China
Email: 444095258@qq.com

Abstract. In this study, solar heating water system and hydrogen production were modeled and simulated by using System Simulation Software TRNSYS. What’s more the system was optimized by TRNSYS/GenOpt. The electricity grid was the auxiliary electrical energy for the system. Hot water was generated by solar collector and then transported to a hold-up vessel with supplementary heat source. Photovoltaic (PV) panels generated electricity which was used to product hydrogen by electrolyzing water. Alkaline Fuel Cell used the hydrogen to generate electrical energy for the supplementary heating source of hold-up vessel. The systems for north-China rural areas in Hebei Province were designed and the hourly system operating characteristic using the optimum volume of vessel was investigated. According to the experimental hot water load of one farmhouse, the hourly and annual electrolytic hydrogen volume, the hourly electrical energy generated by photovoltaic panels, the energy conversion characteristic of the system, the hourly pressure in the storage tank of hydrogen were studied by TRNSYS. According to the simulation results, the most covering rate of solar energy varied from 20% appearing in January to 80% appearing in August.

Keywords. Hydrogen generation; system simulation; solar hot water; system optimum.

1. Introduction
Traditional fossil fuel not only causes global warming and related environmental problems but also is non-renewable energy [1]. On the contrary the utilization of hydrogen will not bring about harmful emissions such as NOx [2]. What’s more hydrogen has been produced by employing variable renewable energy. As a result, investigations on hydrogen system and coupling with various clean energy have significantly increased in recent period.

Surer and Arat [3] introduced the brief history about hydrogen being used in social productions as clean fuel and the efficiency analysis, the key difficulty and core technology were studied. The results showed that the application prospect of hydrogen in aviation will be more and more widely such as green productions. And the hydrogen generation-storage system will play the key role in future industrial manufacture. In the recent years, the system simulation of electrolysis of water where hydrogen was produced and stored was implemented by employing TRNSYS program, and many related systematic investigations were also conducted in this software. Ulleberg and Morner [4] modeled a solar-hydrogen system using TRNSYS in which the numerical study about a Norwegian house was conducted. The investigation showed that the parameters of the clean energy system need to be magnified to satisfy the high requirement of energy. Assaf and Shabani [5] carried out a study where a coupled heating and electric system using solar-hydrogen energy was studied by TRNSYS program. The numerical data showed that the system can meet almost all the hot water demand. Ozden and Tari [6] proposed a coupled
solar-hydrogen energy system and the annual simulation was conducted using TRNSYS program. The results showed that the clean energy system using hydrogen have met the energy and economic demand fully. Topriska et al. [7] experimentally investigated a hybrid solar-hydrogen energy system. Duc et al. [8] proposed an optimization for 20 kW class load in which the photovoltaic and electrolyzer was coupled. The system efficiency of photovoltaic and electrolyzer were respectively 17% and more than 80%. The investigation of an all-day test showed that the production capacity of hydrogen has achieved 18.6 Nm³ using the electrolyzer.

What’s more, the numerical and experimental researches about clean energy system including solar, biomass and energy storage for rural areas have been increasing in the recent years. Gao Xinyu [9] modeled a solar heating system for the new countryside construction and studied the applications.

However the study about hybrid hydrogen system design and optimizing for the countryside by using TRNSYS/GenOpt program is still shortcoming.

In this study, for one mountain village which locates in north-east rural areas of HeBei province, a solar-hydrogen system which was designed based on the grid was modeled using TRNSYS/GenOpt program. Annual and hourly hot water and hydrogen production were simulated and investigated. The optimum volume of hot water hold-up vessel, which minimized the annual operating cost, also has been calculated.

2. Main Theoretical Model

2.1. Photovoltaic Array
In the photovoltaic array the electrical production characteristics of photovoltaic array are modeled. The photovoltaic array model is used in simulations about utility grid connections, direct load coupling, and electrical storage batteries. Empirical equations are employed when the electric circuit features are calculated. A DC electric source, diode and resistors are included in the circuit. What’s more the PV current is calculated according to the load. The calculation of circuit parameters such as current and voltage at various conditions are all carried out.

In this study the photovoltaic electrical energy was used to electrolyze water. The equation (1)[10] gives the energy calculation for the PV array:

\[ E_{rad} = E_{et} + E_{loss} \]  

where \( E_{rad} \), \( E_{et} \) and \( E_{loss} \) are the total radiation energy obtained by the PV, the electrical energy production on the PV and the energy loss respectively.

2.2. Electrolyzer
The heat conduction equations, fundamental thermodynamics and some related empirical theory are integrated to calculate the performance of electrolyzer in this paper.

The equation (2) [11] shows the total reaction for decomposition:

\[ H_2O + E_{et} \rightarrow H_2 + \frac{1}{2}O_2 \]  

3. System Modeling and Simulations
The hybrid solar-hydrogen system was designed and optimized by employing the TRNSYS/GenOpt program. In terms of key transient operational characteristics the TRNSYS/GenOpt program performs outstandingly in simulating variable energy systems such as the solar heating, hydrogen generation-storage, heat pump system and energy storage and so on. GenOpt is the optimization program which is modeled to obtain the optimal value based on a simulation program.

3.1. Meteorological and Load Data
The annual hourly ambient temperature data and radiation data were calculated by using TRNSYS, and the hot water load for a farm house(108m2) was also obtained by experimental statistics under all-day
hot supporting. Summer solstice (4104h-4128h), autumn equinox (6336h-6360h) and winter solstice (8496h-8520h) were selected to study the system operational characteristics.

Figure 1 shows the hourly temperature data in ShiJiaZhuang which is a typical north-China city. The highest temperature and lowest temperature are 39℃ and -10℃.

As shown in figure 2 the annual radiation energy is relatively abundant. However the highest radiation energy appearing in June and July is more than twice as much as the lowest radiation energy appearing in January.

As shown in figure 3, the hourly hot water load of the farm house in typical days were collected experimentally considering of the bathing, washing, and house cleaning.

![Figure 1](image1.png)

**Figure 1.** The annual hourly ambient temperature of the rural area located in north-China.

![Figure 2](image2.png)

**Figure 2.** The annual hourly radiation of the rural area located in north-China.

![Figure 3](image3.png)

**Figure 3.** The hourly hot water load of the farm house in typical days.

### 3.2. System Modeling

The coupled solar-hydrogen system mainly includes control equations, PV arrays, hold-up vessel, electrolyzer and gas tank, and the system components parameters are listed in table 1 and the system model is shown in figure 4.
Table 1. Main theoretical relations and technical parameters.

| Item                                | Value |
|-------------------------------------|-------|
| Area of solar collector (m²)        | 15    |
| Areas of farm house (m²)            | 108   |
| Cell of PV array                    | 50    |
| Electrolyzer area (m²)              | 0.25  |
| Volume of hydrogen storage (m³)     | 10    |

Figure 4. The hybrid solar-hydrogen system in TRNSYS.

According to the hourly load of hot water, the solar-hydrogen system is firstly employed to meet the load. Meanwhile the electrical energy generated on PV array is used to electrolyze water when the solar energy is abundant, and the hydrogen is stored and used to the AFC to support the hot water storage tank after 16 p.m. The hourly data of hot water generated by solar collector, hydrogen generation, hot water load was calculated.

4. Results and Discussions
Firstly the volume of hot water storage tank was optimized based on the annual hourly simulations. And the system operation cost was minimized by the optimum volume.

Figure 5 presents the annual hydrogen production in the electrolyzer.

As shown in figure 5, the annual rule of hydrogen generation acts according to the radiation energy distribution law. The highest hydrogen generation speed is 3000L/h which appears in August.

Figure 6 presents the system operation characteristics in the three typical days.

Figure 6a presents the hourly in/out flow temperature of water tank in the three typical days. The temperature of hot water supported to farm house was set to 60°C and the inlet water temperature equals to the ambient temperature. Along with the decreasing ambient temperature, more energy was needed to heat the water and the radiation energy also decreased significantly.
Figure 5. The annual hydrogen production in the electrolyzer.

Figure 6. The system operation characteristics in the three typical days.

Figure 6b presents the hourly hot water load which was met by the solar heating water system, hydrogen energy and electrical energy based on electrical grid. In Summer solstice (1h-24h) the radiation energy is abundant. The total hot water load was met by solar heating collector and hydrogen AFC except little hot water load appeared from 0h to 9h. After 16 pm all of the hot water load was met by hydrogen energy and the system operation cost was decreased significantly by 27%. The cleaning energy covering rate was highly closed to 80%.

In autumn equinox (25h-48h) the radiation energy decreased relative to Summer solstce. The hydrogen energy generated and stored between 10am to 16 pm cannot meet the hot water load needed after 16 pm. After 22 pm to meet the hot water load the electrical grid was employed.

In winter solstice (49h-72h) day, the radiation energy comes to the lowest point. As shown in figure 6b almost 80% of water load was met by electrical grid.
According to the annual simulation results, the hydrogen generation efficiency of the system was calculated by considering the hydrogen generation speed and the total solar energy. The highest hydrogen generation efficiency reached 10%.

5. Conclusion
(1) The hybrid solar-hydrogen system was modeled by employing the TRNSYS/GenOpt program. The annual radiation energy distribution law, the hydrogen generating speed and the system hot water load balance were investigated according to the simulation results.
(2) The radiation energy in July is more than twice as much as that in January.
(3) The most covering rate of solar energy varied from 20% appearing in January to 80% appearing in August. And the system hydrogen generating efficiency is about 10%.

References
[1] Abe J O, Ajenifuja E and Popoola O M 2019 Hydrogen energy, economy and storage: Review and recommendation Int. J. Hydrogen Energy 44 15072.
[2] Dincer I 2002 Thermal Energy Storage MA. Systems and Application. (New York: Wiley).
[3] Surer M G and Arat H T 2018 State of art of hydrogen usage as a fuel on aviation Eur. Mech. Sci. 2 (1) 20-30.
[4] Ulleberg Q and Morner S O 1997 TRNSY simulation models for solar-hydrogen systems Sol. Energy 59 4.
[5] Assaf J and Shabani B 2016 Transient simulation modelling and energy performance of a standalone solar-hydrogen combined heat and power system integrated with solar thermal collectors Appl Energy 178 66.
[6] Ozden E and Tari I 2016 Energy and economic analyses of a hybrid solar hydrogen renewable energy system in Ankara, Turkey Appl. Therm. Eng. 99 169-78.
[7] Topriska E, Kolokotroni M, Dehouche Z, Novieto D T and Wilson E A 2016 The potential to generate solar hydrogen for cooking applications: Case studies of Ghana, Jamaica and Indonesia Renew. Energy 95 495-509.
[8] Duc T N, Goshome K, Endo N and Maeda T 2019 Optimization strategy for high efficiency 20 kW-class direct coupled photovoltaic electrolyzer system based on experiment data Int. J. Hydrogen Energy 44 (49) 26741-52.
[9] Gao X, Fan B and Zhang H 2009 Study on application of solar heating system in new countryside construction Acta Energiae Solaris Sinica 30 (12) 1653-1657.
[10] Saleem M S, Abas N and Kalair A R 2020 Design and optimization of hybrid solar-hydrogen generation system using TRNSYS Int. J. Hydrogen Energy.
[11] Karacavus B and Aydin K 2020 Hydrogen production and storage analysis of a system by using TRNSYS Int. J. Hydrogen Energy.