Dynamic simulation of a hydrogen-fueled system for zero-energy buildings using TRNSYS software

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Abstract. As a result of global warming and environmental pollution over the past few decades, life on Earth has been adversely affected. For this reason, large-scale zero-energy buildings have garnered considerable attention for utilizing clean energy resources. Hydrogen is a green and sustainable fuel with remarkable features of having high efficiency, higher energy content than diesel and gasoline, and producing only water as waste. Hydrogen can be integrated with a hybrid renewable energy system as safe and reliable energy storage for a longer time in net zero energy buildings compared to batteries with short-time energy storage capability. The focus of this study is to find the optimum design for a hydrogen storage system to isolate a small lab building from grid power by providing its hourly energy needs with renewable resources located in Toronto, Canada. Hence, a model using TRNSYS software is developed to study the behaviour of an energy system that could supply electricity to the lab building. To conduct a case study, TRNSYS is used to extract the solar irradiance during one year for climate data of Toronto. The system mainly comprises solar panels, an electrolyzer, a fuel cell, and a hydrogen storage tank. According to the results, renewable energy system reliability can be increased throughout the entire year period, and grid dependency reduced by adding a hydrogen storage system. Based on the optimized simulation results the system can supply the load demands of the lab in a year with the solar panel electricity production and the hydrogen storage unit without requiring grid power.

1 Introduction

According to studies, almost a third of all energy consumption is attributed to the building sector, however increasing household equipment and new buildings for various applications are contributing to the growth of this amount [1]. Increasing energy consumption leads to a rise in greenhouse gas emissions, which is one of the most significant adverse impacts [2]. Solar energy is a clean and abundant renewable energy source and integration of it into buildings is one of the promising methods toward net-zero energy buildings. However, storing solar energy is critical to utilize this clean energy source. In recent years, hydrogen has become more popular as a way to store renewable energy [3]. It is expected that by 2050, hydrogen demand will increase significantly on a global scale [4]. Hydrogen, with its high calorific value, lightweight, and high gravimetric energy density, is a renewable energy source to help phase out the use of fossil fuels [5]. As a result of the high demand for a hydrogen energy source in terms of clean and carbon-free energy, there have been many efforts to integrate it into buildings as a long-term energy storage source [6]. A hydrogen energy system is mainly compromised of solar panels for generating the required electrical load of the building, an electrolyzer for producing hydrogen, a hydrogen tank to store the generated hydrogen, and a fuel cell to convert the electrochemical energy to electrical energy. As part of a low-carbon community, Parra et al. [7] developed a hydrogen energy storage system that included a polymer electrolyte membrane electrolyzer, a metal hydride tank, and a proton-exchange membrane fuel cell unit. In addition to being flexible, the system was efficient for long-term and mid-term energy storage, achieving a 52% round-trip efficiency. As a result of investigating hybrid renewable energy systems integrated with buildings in four different locations, Izadi et al. [8] created zero-energy buildings. The simulated system was in TRNSYS and comprised solar panels, wind turbines, and a hydrogen storage unit. PV panels and wind turbines could produce 35% and 49% of the electricity required by buildings in each city, respectively, according to simulation results, while renewable resources and hydrogen storage systems can produce 70% to 88% of the electricity needed by buildings. In another study, Wei et al. [9] used the TRNSYS software to evaluate the potential, storage, and consumption of electricity in the Canadian city of Saskatoon, which has a high potential for solar and wind power. According to the results, solar panels can generate higher energy, indicating that solar panels have a much greater potential than wind turbines. To study the transient behaviour of a residential energy system, a model was developed by Mansir et al. [10] using TRNSYS software to supply the heating, cooling, domestic hot water, and electricity demands of a residential building. Comparative studies of hydrogen fuel cells and conventional batteries are presented in this study. Based on the results, the capital cost of an HVAC system using hydrogen storage is twice that of an HVAC system using batteries. Using hydrogen storage systems with larger capacities leads to better performance. This study aims to find an optimal configuration for the hydrogen energy system for an off-grid small lab located in Toronto, Canada, and supply the hourly energy demand of the lab with renewable resources. An energy system simulation was performed using TRNSYS software to simulate the transient behaviour of the system throughout the year.
2 System description

For this study, a renewable energy system is simulated for a small-sized lab building located in Toronto, Canada (43°39.7’N, 79°26.5’ W). The lab building has one story with a total area of 45 m². The heating and cooling system is comprised of an air-source heat pump and a hydronic radiant floor system. Creating a zero-energy building with no grid dependency is the main objective of this study.

The considered renewable energy system, which is simulated transiently compromise of an electrolyzer, hydrogen storage unit, and fuel cell coupled with a photovoltaic system. When the photovoltaic array generates more energy than the electricity demand, surplus energy is injected into the electrolyzer to generate hydrogen. Once the hydrogen is generated, it will be stored in the hydrogen storage tank until it is required. The stored hydrogen in the tank will be transferred to the fuel cell if the primary system is insufficient to meet the load; as long as there is a power deficit, this may continue. In addition, the main controller is considered to monitor the performance of the system and check if generated energy through the solar panels covers the electrical load demand of the building.

3 TRNSYS Modelling

TRNSYS is used to simulate the performance of the mentioned system in a year with its ability to model transient systems, such as those associated with solar power. For this study, TRNSYS 18 is used to simulate the system. Simulations are performed at hourly intervals for a total of 8760 hours. As mentioned previously, this system mainly consists of solar panels, an electrolyzer, a hydrogen tank, and a fuel cell and will be discussed in this section. As shown in Figure 1, a schematic simulation of renewable energy is shown using TRNSYS software.

Solar panel- In PV panels, solar irradiation is converted into DC electricity. As solar irradiation enters the system, only a portion of it is converted into electricity, and the remainder is created as heat [11]. The PV panels are installed on the rooftop of the lab building. Selected PV panels have a nominal maximum power of 450 W. Type 103a provides a model for photovoltaic panels in this study.

Electrolyzer- An electrolyzer is used to convert water into hydrogen and oxygen in water electrolysis in order to produce green hydrogen. Hydrogen is produced with an alkaline electrolyzer in this research. The alkaline electrolyzer was simulated using a Type160a component in TRNSYS.

Fuel cell- A fuel cell generates electricity primarily by consuming hydrogen from a hydrogen storage tank. TRNSYS models alkaline fuel cells using Type173a, which is a simple mathematical model. For developing the electrochemical model, current-voltage characteristics at standard operating temperatures are taken into account.

Compressed gas tank- The gas storage tank stores hydrogen generated by the electrolysis of water and supplies it to the fuel cell. In order to simulate compressed gas storage tanks, the Type164b in the software is used, in which the simulation is based on a model based on the Van der Waals equation of state applied to real gases, therefore calculating the pressure for each tank by performing a mass balance application based on the mass of hydrogen contained therein [12].

The technical features of the solar panels, electrolyzer, hydrogen tank, and fuel cell are represented in Table 1.

![Fig. 1. Schematic of the hydrogen system in TRNSYS software.](image)

<table>
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<tr>
<th>No.</th>
<th>System Component</th>
<th>Type</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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</table>

2 Electrolyzer Alkaline (Type160a) |   |   |
| **Electrode surface area** | m² | 0.02 |
| **Working temperature** | °C | 80 |
| **Working pressure** | bar | 7 |

3 Fuel cell Alkaline (Type173a) |   |   |
| **Electrode area** | cm² | 100 |
| **Working temperature** | °C | 70 |
| **Open circuit voltage** | V | 5.6 |
| **Minimum allowable cell voltage Stack** | V | 0.4 |

4 Hydrogen tank Compressed real gas storage (Type164b) |   |   |
| **Maximum pressure** | bar | 200 |
| **Tank volume** | m³ | 1 |
| **Molar weight of gas** | g/mol | 12.9 |
| **Critical temperature of gas** | °C | -240 |
| **Critical pressure of gas** | - | 12.9 |

### 4 Results and discussion

This section presents the performance of the hydrogen storage system based on the energy analysis, to provide a comprehensive insight into the system’s operation. A dynamic simulation of the system is conducted using TRNSYS software during different hours and months of the year. For this simulation, the time step is 1 hour. The time scale used for this simulation is a full year and runs from January 1 to December 31.

This simulation mainly involves the input of weather data as well as load demand information. Hydrogen from water decomposition is produced using the generated electricity from the PV module for the electrolyzer. When the fuel cell is operating, hydrogen is produced and stored in the hydrogen storage tank. Storage of hydrogen in a tank makes it possible to use it later when solar radiation is unavailable. Fuel cells produce energy by converting hydrogen stored in the hydrogen tank into electrical energy.

As this system consists of a PV solar collector, both the solar radiation intensity and the ambient temperature are required for the development of the system. An annual average of Toronto’s ambient temperature and solar radiation intensity can be found in Figure 2. The average annual solar radiation intensity in Toronto is 3.53 kWh/m²/day which the highest solar radiation observed in July and the lowest in the year happening in December. Also, there is a significant increase in solar radiation intensity in the summer season than the cold days of the year. This difference in solar radiation intensity increases the potential for the application of a hydrogen storage system to provide electricity load demand for the entire year.

The PV collector's output power is shown in Figure 3. The annual total power produced in photovoltaic panels is 2792.7 kW. It is evident from Figure 3 that the PV output power is higher during hot days of the year due to the higher solar radiation intensity.

Figure 4 shows the results of the simulation of power provided by the fuel cell, required power by the electrolyzer, and grid power. As shown in the graph for the load power required by the electrolyzer, at the largest electrical load demand period, the electrolyzer required 42.5 kW, in contrast with 12 kW at the lowest demand of the electricity. Based on the provided power by the fuel cell during the peak period of power consumption, the power generated by the fuel cell is between 29 kW-30 kW. In periods of low electricity consumption, the fuel cell produces 6 kW of power. It is evident from the electrolyzer and fuel cell power graphs when the electrolyzer is operating, the fuel cell is on the idling power however, in the fuel cell operation period, the electrolyzer is set on the idling power. In addition, Figure 4 shows the grid power for the system. As can be seen, the simulated hydrogen system is a stand-alone system that neither requires power from the grid nor supplies power to the grid.

**Fig. 2.** Solar radiation intensity and ambient temperature over a year in Toronto.
5 Conclusions

In the current study, a hydrogen system is simulated and studied using TRNSYS software. The system mainly consists of a solar panel that produces electricity, an electrolyzer that produces hydrogen, and a fuel cell that uses the stored hydrogen and produces electricity in case the sun is not available. An understanding of the effects can be gained by analyzing the dynamic analysis results and examining how design parameters affect the performance of the system. The results show that, based on the climate of Toronto, during hot days of the year, the proposed renewable integrated system can provide electricity and meet the load demand of the building. However, due to the lack of solar radiation on cold days of the year, the application of hydrogen energy storage provides long-term and seasonal energy storage and can be beneficial to supply the load demand in winter. Based on analysis results, the system typically provides enough energy to meet the lab's load demand throughout the year which can facilitate the net-zero energy buildings in Toronto, Canada.

References