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Energy Storage Through a Regenerative Hydrogen Fuel Cell in a Hybrid System of Renewable Energy for Power Generation

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From the perspective of reducing the use of fossil fuels, there has been recent interest in hybridizing the renewable energy system for power generation. Energy storage systems are an integral part of hybrid renewable energy systems, and hydrogen storage is one of the newest storage systems. In this study, a new emerging energy storage system called hydrogen storage is integrated into the hybrid system of photovoltaics and wind turbines for power generation in a stand-alone application. This integration was verified using mathematical and dynamic models in MATLAB/Simulink. The results depend on factors such as solar radiation, wind speed, hydrogen stored, and the energy consumption of a rural house over two days. The findings showed that combining two energy sources for power generation was more effective than using a single source. The maximum combined output voltage and current of the photovoltaic and wind turbine systems were 351.6 V and 16.84 A, compared to 180 V and 10 A provided by each energy source separately. For one day of self-sufficient operation, the hydrogen stored in the tank was used to power a Proton Exchange Membrane fuel cell, ensuring a continuous power supply regardless of solar radiation or wind speed fluctuations. This study will catalyze further research by providing information about the hybrid hydrogen storage system for power generation. It aims to improve the reliability and cost-effectiveness of renewable energy and demonstrate the competitiveness of hydrogen storage compared to battery storage, ultimately contributing to its commercialization.

1. Introduction

Energy is necessary for all living things' evolution, growth, and survival. Thus, there is no single action that is not reliant on energy. Energy can be captured, converted into a usable form, and used for various applications. Energy sources can be broadly classified as renewable or non-renewable (Sadeghi, 2018). Non-renewable energy comes from finite resources that eventually will dwindle, becoming too expensive or too environmentally damaging to retrieve, and the continued use of non-renewable resources has clear implications for our health and well-being (Sadeghi, 2018). According to Neha & Rambeer (2021), renewable energy sources are the most essential and effective answer for the future since they are environmentally friendly, renewable, and sustainable. For illustration, renewable energy sources are solar, wind, biomass, geothermal, hydropower, and tidal power (Babu & Ashok Kumar, 2021). Wind and solar energy are the most effective among many rentable renewable energy resources and have achieved rapid and significant innovation in the previous year (Ceran et al., 2017). However, they are unreliable since the sun doesn’t always shine, and the wind doesn’t always blow (Sadeghi, 2018). Hybrid systems are one of the answers to this challenge, consisting of renewable power generation and storage systems (Sadeghi, 2018). Cruzatt Quispe et al. (2022) also pointed out that the combination of solar and wind energy is more effective in generating energy throughout the year when compared to individual sources.Electrical energy storage is used in various electrical systems, including on-grid and off-grid power generation, to convert electrical energy to a storable form that can be converted back to electricity when needed and provide supplementary services such as voltage and frequency stability, guaranteeing reliable energy supply and increasing the transmission of renewable energy technology (Hossain et al., 2020). For this purpose, researchers and designers often use traditional batteries (Siddiqui & Dincer, 2020).

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However, a battery is associated with usage that includes short storage times, the energy in the battery cannot be fully discharged, the battery's capacity decreases with each charging and discharging cycle, and the storage medium needs to be replaced regularly (Siddiqui & Dincer, 2020). Hydrogen energy storage technology is a promising option to alleviate these problems (Torma et al., 2023). It has a greater energy density and less generation of pollutants (Gomes et al., 2022). The hydrogen stored in the tank is unaffected by temperature or self-discharge issues because the fuel is kept outside the electrochemical cell stack. Furthermore, this method can store more energy for about 1000 Wh/kg, costs less, and is clean and environmentally friendly (Hossain et al., 2020).Hence, this paper's main contribution is to design and analyse a working simulation through mathematical and dynamic modeling that reflects the outline and conditions of the existing hybrid renewable energy system that can use hydrogen storage as a backup for power generation in a stand-alone application.

2. Methodology

The schematic diagram of the hybrid renewable energy system for power generation in a stand-alone application is shown in Figure 1, which mainly includes the photovoltaic (PV), the wind turbine (WT), the electrolyser, the hydrogen storage tank, the fuel cell, the controller, the DC-to-AC inverter, and the variable load system. The inputs of the hybrid system are solar irradiation and wind speed, which are converted into direct current via the photovoltaic and wind turbine systems. The hybrid system's output is a variable load representing the rural house's energy demand. The controller controls the voltage flow from the primary source into the DC-to-AC inverter, the flow of current from the PV and WT into the electrolyser, the hydrogen fuel in the hydrogen storage tank, and finally, the voltage flow from the fuel cell into the DC-to-AC inverter. The hydrogen produced by the electrolyser is conserved in the hydrogen storage tank and is used to power the fuel cell. The fuel cell supplies the variable load whenever there is a fluctuation in wind and/or solar energy or high demand from the variable load. The DC-to-AC inverter converts the direct current (DC) into alternating current (AC) to power the variable load, which requires explicitly alternating current.

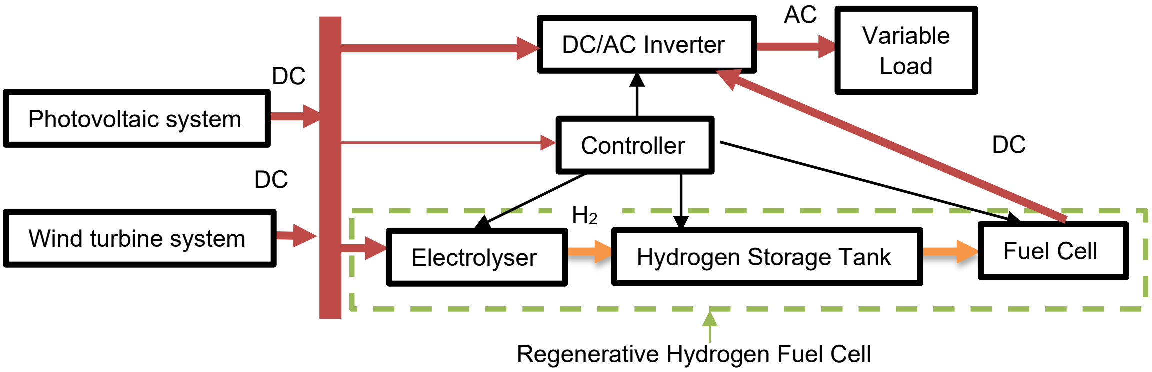

Figure 1: Simplified setup configuration of the hybrid system project

2.1 Direct current-to-alternative current inverter and Variable load

South Africa uses 230 V as the average phase-to-neutral AC voltage, with the voltage root mean square (V_{rms}) of 163 V. The average daily energy consumption for rural households cooking with electricity is 7 kWh (Gerro et al., 2016). A minor amount of energy consumption characterizes this consumption during the night, with an energy peak in the morning, followed by a more prominent energy peak in the late afternoon and evening. The DC-to-AC inverter obtained from a MATLAB file was used for designing and simulation purposes to convert the Direct Current from the photovoltaic, wind turbine, and fuel cell system into an Alternating Current (S. Adam & A. Fashina, 2019). Furthermore, a saturation block was used to limit the maximum voltage of 200 V applied to the input DC-to-AC inverter.

The variable load is inversely proportional to the energy demand of South Africa's rural houses cooking with electricity. The variable load, shown in Table 1 for different hours of the day, was calculated using Equation 1 and was built in Simulink using mathematical modeling (1-D Lookup with the help of the clock) (Franklin, 2019).

$$Variable\ Load(R) = \frac{{V_{rms}}^2}{ED}\ (\Omega) \tag{1}$$

Table 1: Average energy demand and variable load in terms of the time of day

Time (hour)	Energy demand (kW)	Variable Load (Ω)
00:00-05:00	0.05	531
05:00-07:00	0.375	71
07:00-08:00	1	27
08:00-14:00	0.1625	164
14:00-16:00	0.25	106
16:00-17:00	0.5	53
17:00-20:00	0.75	35
20:00-22:00	0.25	106
22:00-00:00	0.1875	146
Total	7.1	

2.2 Photovoltaic system

A solar cell, also known as a photovoltaic (PV) cell, is an electrical device that uses the photovoltaic effect, a physical and chemical phenomenon, to alter solar energy directly into electricity (Guerra et al., 2018). The irradiance data collected for one day in Vanderbijlpark was built into Simulink using mathematical modeling to influence the photovoltaic system's output voltage and current (Nsasak et al., 2021).

The PV system's power (PV array) was sized using Equation 2. The peak sunshine ($\mathrm{P_{sun}}$) for the Vaal triangle was 4.74, the temperature losses (T) were 0.88 °C, the derating factor was (Df) 0.774, and the inverter efficiency (η_{inv}) was 98 % (Franklin, 2019). The PE320M-BBB Panasonic photovoltaic array Simulink-built model was selected with a maximum output power ($\mathrm{P_{max}}$) of 319.68 W. The number of PV modules calculated using Equation 3 was 8. The model was designed in Simulink and organized into two parallel strings and four series strings with two inputs: the irradiation and the temperature (fixed at 25 °C) (Franklin, 2019).

$$PV\ array\ (kW) = E_C \div P_{Sun} \div T \div n_{inv} \div Df \tag{2}$$

$$N_{PV} = PV\ array \div P_{max} \tag{3}$$

2.3 Wind turbine system

A wind turbine is a device that transforms the wind's kinetic energy into mechanical energy, which drives a generator to produce electricity (Neha & Rambeer, 2021). Wind speed, air density, and rotor blade diameter influence the mechanical energy obtained from wind kinetic energy (Chong et al., 2021). The wind speed profile collected for one day in the Vaal Triangle was built into Simulink using mathematical modeling. A Permanent Magnet Synchronous Machine (PMSM) wind turbine type obtained from the MATLAB File Exchange was also used for designing purposes (Ali et al., 2017). The mechanical power and torque of the wind turbines were modified using Equations 4 and 5 to comply with the desired wind turbine power of 1 kW. The blade radius (R) was 3.3 m, the average wind speed (V) was 4.5 m, the maximum power coefficient ($\mathrm{C_P}$) was 0.45, the air density was 1.223 kg/m³, and the torque was 4.7 Nm (Sultan et al., 2021).

$$P_{wt} = \frac{1}{2} * \rho * \pi * R^2 * C_p * V^3 \tag{4}$$

$$T = \frac{P_{wt}}{\omega} \tag{5}$$

2.4 Hydrogen storage system

Hydrogen storage is a technology used to store electrical power in chemical form. It is renewable, cleanest, lightest, and most efficient (Hossain et al., 2020). In hydrogen storage systems, electricity is converted to hydrogen through an electrolyser (EL) and stored in pressurised tanks. The stored hydrogen can produce electricity in a fuel cell (FC) (Guo & Sepanta, 2021).

2.4.1 Electrolyser

The electrolysis method uses electricity to break down water into its components: oxygen and hydrogen. The oxygen is released into the environment, while the hydrogen is preserved for future generations to utilise (Guo & Sepanta, 2021). The PEM Electrolyser system selected for this project was built in Simulink through mathematical modeling using Equation 6. The number of cells in series (N_C) was 50, the Faraday constant (F) was 96485 C/mol, the universal gas constant (R) was 0.00831 J/kmol*K, and the temperature inside the electrolyzer was 62 °C. The working pressure (P) was 30 bar (Möller & Krauter, 2022) (Sultan et al., 2021). The current study immediately transferred the created hydrogen to the hydrogen tank.

$$V_{H_2}(m^3/s) = \frac{V_m*N_c*I}{2*F} \ with \ V_m(m^3/mol) = \frac{R(273.15+T)}{P} \tag{6}$$

2.4.2 Fuel cell

The fuel cell is an energy conversion device that transforms hydrogen and oxygen into water and electricity (Macedo & Peyerl, 2022). Thus, the hydrogen stored in the tank is used to feed the fuel cell and supply the load when there are fluctuations in wind velocity and/or solar radiation intensities or peak load demand (Guo & Sepanta, 2021). A model example of the PEM fuel cell in Simulink was used and modified according to the maximum average variable load power of 1 kW (Jadhav & Thakare, 2022). This model is incorporated with a boost DC-to-DC converter, which increases the voltage from 45 to 100 (Babu & Ashok Kumar, 2021).

The minimum amount of hydrogen (0.00182 kg of H_2/hour) needed to run the PEM fuel cell was calculated using Equation 7, considering the efficiency of the PEM fuel cell as 55 % (Olubukunmi, 2011).

$$N_{H2} = i * \frac{3.77*10^{-5}KgH_2}{hour*Amp} = \frac{26.66*3.77*10^{-5}KgH_2}{H*Amp} = \frac{0.001005\ kgH_2}{H} \times 55\% = 0.00182\ kgH_2/H \tag{7}$$

2.4.3 Hydrogen Storage Tank

The hydrogen storage tank system was used to store the hydrogen produced by a PEM electrolyser, which can then be reused in the fuel cell to regenerate electricity (Sultan et al., 2021). The hydrogen storage tank was built in Simulink through mathematical modeling using Equation 8 (Möller & Krauter, 2022). The molar mass of hydrogen (M_{H2}) was 0.00201588 g/mol, the volume of the tank (V_b) was 3 $m^{3,}$ and the initial pressure (P_{bi}) was 1.5 bar. The lowest and maximum mass of stored hydrogen in the tank, stated in terms of pressure at any point throughout the hybrid system's operation, were limited to 745.65 bar and 17906.22 bar, respectively, knowing the minimal quantity to run the PEM fuel cell and the autonomy of one day taken into consideration.

$$P_b - P_{bi} = Z\frac{N_{H2}*R*T_b}{M_{H2}*V_b} \ with \ Z = \frac{P_b*V_m}{R*T_b} \ ; \ N_{H2} = V_{H2}*\rho_{H2} \ and \ V_m = \frac{R(273.15+T)}{P} \tag{8}$$

2.5 Controller

A controller system was used to control the flow of voltage, current, and hydrogen in the hybrid system. It was built using a state flow chart in Simulink and consisted of four states, respectively ON and OFF, depending on the transitions or conditions applied to the hybrid system. The minimum current set for the PEM electrolyser to start producing electricity was 3.5 A. For the PEM fuel cell to operate, the output voltage from the photovoltaics and wind turbine system must be less than 150 V, and the hydrogen stored in the tank must be more excellent than 745.65 bar (hydrogen expressed in terms of pressure).

3. Results and Discussion

The simulation results presented in Figure 2 were done in the MATLAB/Simulink environment by creating each component separately and evaluating the hybrid renewable energy system for the power generation model. The validity of the hybrid system modeled in Simulink was analyzed using a variable load representing the power consumption of rural houses in South Africa and the solar radiation and wind speed profiles throughout the day. Table 2 illustrates the output summary of the correlation between the solar radiation intensity, wind speed, output voltage, and current of the photovoltaic and wind turbine systems. It also includes the hydrogen produced by the PEM electrolyser, hydrogen stored in the tank, the output voltage of the PEM fuel cell, the variable load, and the AC output current consumption after 48 hours of simulation.

The output voltage and current of the photovoltaic and wind turbine systems were altered depending on the amount of solar irradiation and wind speed. The AC consumption was observed only when the DC-to-AC inverter supplied the variable load through the PV, WT, or PEMFC output voltage. A minimum of 150 V from the output voltage of the PV and WT systems or 100 V from the PEMFC is required to supply the variable load. Additionally, for the PEMFC to operate, a minimum of 745.65 bar (hydrogen expressed in terms of pressure) stored in the storage tank is required. The output voltage from the PV and WT systems must be less than 150 V. To produce hydrogen with the PEMEL, a minimum current of 3.5 A from the PV or WT systems is needed, and the hydrogen stored in the storage tank should be less than 17906.2 bar.

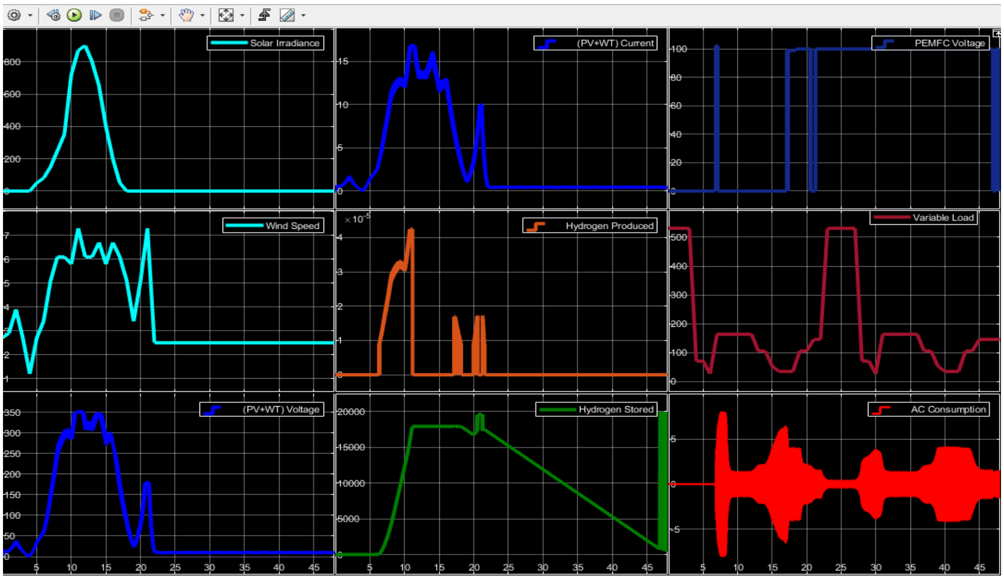

Figure 2: Simplified setup configuration of the hybrid system project

Table 1: Summary results of the hybrid system model simulated for 48 hours.

Time (hours)	Solar Irradiation (W/m^2)	Wind Speed (m/s)	PV+WT Voltage (V)	PV+WT Current (A)	PEMEL (m^3/s)	Storage Tank (bar)	PEMFC (V)	Variable Load (Ω)	AC Current (A)
0	0	2.7	16.8	0.723	0	1.5	0	531	0
6.809	136.6	4.775	131.6	5.61	1.4 10^{-5}	748.3	102.4	137.8	±0.216
11.107	873.2	7.17	351.6	16.84	4.2 10^{-5}	17870	0	164	±1.061
16.376	143.6	6.47	245.7	11.18	0	17906.2	0	35	±6.007
21.553	0	4.646	70.8	3.202	0	17460	100	146	±1.
23	0	2.5	10.16	0.459	0	15850	100	531	±0.091
29.966	0	2.5	10.16	0.459	0	11910	99.99	28.47	3.869
38.95	0	2.5	10.16	0.459	0	5983	100	55.66	3.596
46.909	0	2.5	10.16	0.459	0	737.4	0	146	0

The power generated throughout the day by two renewable energy sources was more effective than each, as seen in Table 2, around 11.107 hours into the simulation (Sawle et al., 2018). This was due to the solar radiation intensity of 873.2 W/m^2, while the wind speed was 7.17 m/s. The combination of the output current generated from the photovoltaic and wind turbine systems was 16.84 A, and the output voltage was 351.6 V. This high current also influenced hydrogen production, which rose to 4.2 10^{-5} m^3/s. The PEMFC maintained power flow whenever the output voltage from the PV and WT was below 150 V, and a minimum of 745.65 bar was stored in the storage tank. According to Table 2, at approximately 21.553 hours into the simulation, the hydrogen stored in the tank was 17460 bar. This amount of hydrogen in the storage tank was sufficient to supply the PEMFC and sustain the power flow to the variable load until around 46.909 hours (the second day). This confirms that hydrogen storage systems can be used as backups instead of traditional batteries (Siddiqui & Dincer, 2020).

4. Conclusion

This study introduces and formulates a hydrogen storage system tailored for a hybrid renewable energy framework using MATLAB/Simulink. The simulation framework integrates mathematical and dynamic modeling techniques, meticulously considering the specifications and selections of individual components. Additionally, the model incorporates empirical data concerning solar irradiation, wind speed, and energy consumption derived from a rural residence in South Africa. The simulation outcomes were systematically tabulated and graphically illustrated, and a thorough evaluation was performed spanning 48 hours (equivalent to two days). Notably, the results elucidate a direct correlation between the combined output voltage and current with solar radiation and wind speed. The attained peak values surpassed those achieved by singular energy sources.

Moreover, the hydrogen reservoir sustained between 21.553 and 46.909 hours, empowering the PEMFC to ensure uninterrupted electricity supply to variable loads amid daily solar irradiance and wind speed fluctuations. The study concludes that a hydrogen storage system exhibits the potential to mitigate the limitations associated with battery usage. Nonetheless, it is imperative to acknowledge that these observations are grounded in simulations, thus potentially diverging from real-world operational scenarios.

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