Simulation of an On-grid Wind-Hydrogen Coupling System (Case Study: Mollo Selatan Subdistrict, Indonesia)

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Abstract : This study proposed a wind-hydrogen coupling systems control strategy to investigate its feasibility. The control strategy regulates the electrical energy generated by a wind turbine to meet the domestic load demand of a specific site. The remaining electrical energy is regulated to supply electrolyzer for producing hydrogen as energy storage. The stored energy in the form of hydrogen can be reconverted into electricity by utilizing fuel cells to meet the domestic load demand. Selecting proper sites for evaluating the control strategy is critical. Hence this study also conducts a wind resource assessment approach that considers the humidity effect to wind power density, wind turbine power curve, and annual energy production of a wind turbine. This approach achieved a better precise annual energy production estimation than other approaches that neglect the humidity. Proper wind resource assessment resulted in a site for the case study, Mollo Selatan Subdistrict for an on-grid system. The control strategy was modeled and evaluated with MATLAB Simulink. The simulation results show the possibility of storing energy generated by the wind into hydrogen and meeting the load demand of the case study location.

Keywords : Wind resource assessment; moist air density; wind hydrogen couple system; control strategy

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1. Pendahuluan

Changing climate drives global society for the energy transition, from fossil-fuelled energy to renewable-clean energy. Driven by various factors such as policy support, innovation, technological advancement, and sharp cost reductions, renewable energy usage has remarkably progressed over the past decade (IEA, IRENA, UNSD, WB, & WHO, 2019). Moreover, the energy transition aligns with United Nations Sustainable Development Goals (UN SDGs) – Goal 7: Affordable and Clean Energy.

Wind energy is one of the renewable energies projected to grow. In 2020, 154.3 MW of wind power generation had been installed in Indonesia (Kementerian ESDM, 2020). Two wind farms, both in Sulawesi Island, have already been operated since 2018. Based on data collected from 166 sites, about 35 sites have good wind energy potential, with an average annual wind speed is above six-meter per second. In addition, about 34 sites also have sufficient wind energy; the annual wind speed ranges between 4 – 5 m/s (Martosaputro & Murti, 2014).

The nature of renewable energy sources is intermittent and fluctuating (Gahleitner, 2013), including wind energy. Therefore, the need for energy storage is growing to meet the demand for

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nergy supply stability. Energy storage needs for large shares of wind power which will increase significantly in 2050, compared to today (IRENA, 2019). Power-to-gas electricity storage is to be considered, such as wind-to-hydrogen (W2H). The production of hydrogen from renewable power in combination with hydrogen storage can help provide long-term seasonal flexibility to the system (IRENA, 2019).

A study for Northern Europe concluded that despite the relatively low 45% cycle efficiency, power-to-gas electricity storage would be beneficial and economically viable in a high-renewables scenario for 2050. In addition, the study concludes that hydrogen storage and use for power generation is more profitable than its use for industry (IRENA, 2019). The electricity generated would produce hydrogen-based on water electrolysis (Widera, 2019) using an electrolyzer.

Hydrogen production based on water electrolysis using a renewable energy source is more environmentally friendly than the use of fossil fuels as a primary source of electricity (Zoulias & Varkaraki, 2004). The energy stored as hydrogen later can be reconverted to electricity based on hydrogen oxidation using fuel cells. The reconverting process only produces recyclable water (Zoulias & Varkaraki, 2004) which is harmless to the environment. Wind power generation system with hydrogen as its energy storage could be a long-term solution to reduce GHG emissions. Besides, it also increases flexibility in power systems (IRENA, 2019).

Indonesia has paid serious attention to wind energy. Two wind farms started to operate in 2018; one of them is the largest of its kind in Southeast Asia. In 2020, Indonesia installed 154.3 MW of wind power generation. The Indonesian government targets 1,800 MW of installed wind capacity (Kementerian ESDM, 2020). However, the nature of wind energy is intermittent and fluctuating. Therefore, the electric power output of wind power generation needs to be balanced with another power resource.

A wind hydrogen coupling system (WHCS) may solve such a problem. When the wind is highly available, the excess electricity generated by the wind generator would be stored in the form of hydrogen. When the wind energy potential is low, the hydrogen can be reconverted into electricity to feed into the end-users. Such a multi-stage energy conversion system requires control strategies to regulate energy flow. The present study focused on defining the WHCS and its control strategy. This process involved modeling the hypothetical structure of WHCS, identifying the characteristics of its variables, and simulating the modeled system in MATLAB Simulink to investigate its feasibility.

2. System Description

The system was investigated in the application for a remote location considering the wind energy potential. Hence the study assessed the case study locations using probability density function, wind power density (WPD), and annual energy production (AEP) approach for site-turbine matching. These methods aided the selection of a suitable wind turbine for the wind potential of the selected sites. Then the other components were modeled, and control strategies were evaluated using MATLAB Simulink.

The study is conducted using a mixed research method, including statistical method and computer simulation. The statistical method is essential to assess the wind energy potential. This study utilizes Weibull PDF (WPDF) to estimate critical parameters from the obtained hourly wind speed data. The computer simulation is conducted in a MATLAB Simulink environment. The simulation models are based on diagrams shown in Figure 1.

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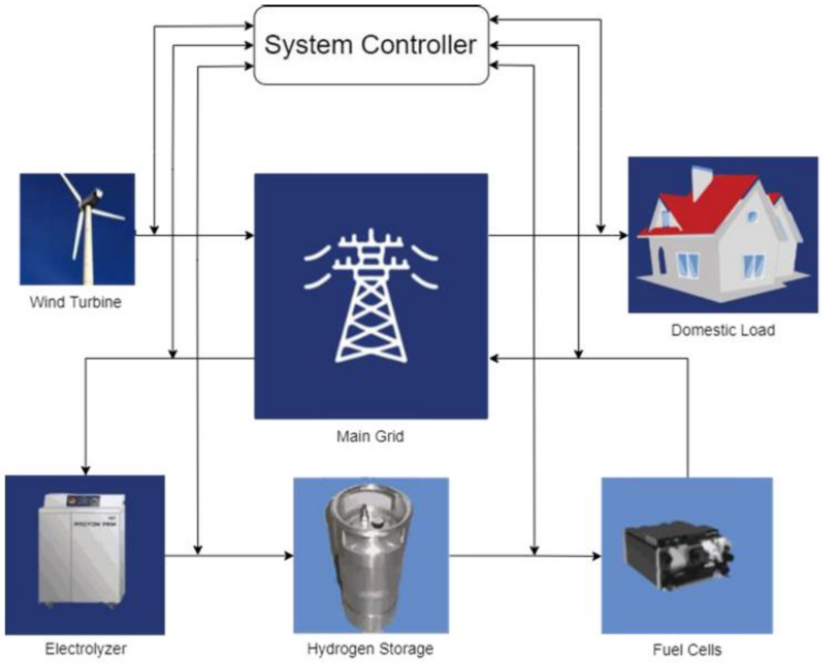

Figure 1. Block Diagram of an On-Grid Wind to the Hydrogen Coupling System

2.1. Wind Resource Assessment

Wind speed distribution for a particular site determines the wind energy available and the performance of an energy conversion system (Chang, 2011). PDF is the most used method to model wind variation on a particular location (Jangamshetti & Rau, 1999). Wind energy potential can be determined once the probability distribution of wind speed is obtained using PDF. WPDF is most widely adopted with its two parameters (Chang, 2011). WPDF fw of wind speed v is expressed by equation (1), where k and c are the shape parameter and the scale parameter, respectively.

$$f_w(v) = \left[\left(\frac{k}{c}\right) \times \left(\frac{v}{c}\right)^{k-1} \times \exp\left(-\frac{v}{c}\right)^k\right] \quad (1)$$

$$(k > 0, v > 0, c > 1)$$

Root mean square error (RMSE) goodness of fit is performed to check the accuracy of WPDF. The closer the value to zero, the better the results or the more accurate estimations are obtained (Parajuli, 2016). RMSE is expressed by equation (2) where n, y_i, and x_i are the number of observations, frequency of observations, and estimated frequency, respectively.

$$\text{RMSE} = \left[\left(\frac{1}{n}\right)\sum_{i=1}^{n}\left(y_i - x_i\right)\right]^{\frac{1}{2}} \quad (2)$$

The WPD is an essential index, where WPD indicates how much energy is available for WT conversion (Huang & Wan, 2012). The higher the WPD of a site, the higher the power output of the installed WTs (Saxena & Rao, 2016).

The total power P_w, defined by (1-7), is the total power that could be extracted from the wind. Hence, the total power presented by all possible wind speeds in a site complies with wind speed distribution f (v), available for the unit swept area of WT (Huang & Wan, 2012) can be expressed by equation (3).

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$$WPD = \frac{1}{A}\int_{0}^{\infty} P_w\left(v\right)\times f\left(v\right)dv \tag{3}$$

WED can be estimated once the WPD of a site is calculated. WED can be obtained by multiplying time t (t is taken as 8,760 hours for yearly basis WED) with previously given WPD (Huang & Wan, 2012), defined by equation (4) as follows.

$$WED = t\times WPD \tag{4}$$

2.2. Wind Turbine Power Curve and AEP Estimation

The power curve of WT indicates its performance. It reflects the power response of a WT to various wind speeds (Sohoni, Gupta, & Nema, 2016). Therefore, the WT power curve can be utilized to assess wind power. First, WRA, in terms of wind speed and WPD, needs to be done to identify a site suitable for a wind energy project (Mathew, 2007). Then the available wind data and WT power curve are selected to estimate the energy production.

The present study models the power curve of variable speed WT, which relies on the wind speed and works on three modes (idle, partial power, and rated power), based on the existing approach (Aghbalou, Charki, Elazzouzi, & Reklaoui, 2018; Song et al., 2021). The power output P (v) of variable speed WT is defined by equation (5), where v is the wind speed; P_p (v) and P_r are the partial power and the rated power, respectively; v_i, v_r, and v_o is the cut-in, rated, and cut-out wind speeds, respectively (Song et al., 2021).

$$P(v) = \begin{cases} P_p(v) & v_i \le v \le v_r \\ P_r & v_r \le v \le v_o \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

The partial power depends on several parameters. It includes wind speed v, cut-in wind speed v_i, rated wind speed v_r, and shape parameter k. Cubic approximation, to calculate partial power (Akorede, Mohd Rashid, Sulaiman, Mohamed, & Ab Ghani, 2013; Hu & Cheng, 2007; Yang, Lu, & Burnett, 2003; Yeh & Wang, 2008), is defined by equation (6).

$$P_{p4}(v) = P_r\left(\frac{v^3}{v_r^3}\right) \tag{6}$$

The current study used an approach proposed by (Al Mubarok, 2022), which takes humidity or moist air into consideration. The rated power of a WT is tested under a standard atmosphere, including standard air pressure and air density. The density of moist air is the ratio of the mass of moist air to its volume (Vestfálová & Šafařík, 2018) or the inverse of the specific volume V_{ma} of moist air (Toolbox, 2003), expressed by equation (7), where x is specific air humidity, the ratio of the mass of water to the dry air mass (Vestfálová & Šafařík, 2018). The air-vapor mixture's specific air humidity or humidity ratio can be obtained from the relative humidity RH parameter collected from a specific site using (8), where p is the ambient pressure (Vaisala, 2013).

$$\rho_{ma} = \frac{1}{V_{ma}} = \frac{\left(1+x\right)\times\frac{p}{R_a}}{\left(1+\left(\frac{x\times R_w}{R_a}\right)\right)} \tag{7}$$

$$x = 0.62198\times\left(\frac{RH}{100}\%\right)\times\left(\frac{p_w}{p-p_w}\right) \tag{8}$$

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The water vapor pressure p_w, ambient pressure p, and temperature T for a given altitude halt, standard temperature T_0, and standard pressure p_0 (Engineering Toolbox, 2004; Georgantopoulou & Georgantopoulos, 2018) are defined by equation (9), (10), and (11), respectively.

$$p_w = \frac{\exp\left(77.3450 + 0.0057 - \left(\frac{7,235}{T}\right)\right)}{T^{8.2}} \tag{9}$$

$$T = T_0 - \left(6.5 \times \frac{h_{alt}}{1,000}\right) \tag{10}$$

$$p = p_0 \times \left[1 - \left(0.0065 \times \frac{h_{alt}}{T}\right)\right]^{5.2561} \tag{11}$$

The Power, P, a WT can extract from wind is defined as wind energy over time, expressed by equation (12) (Wagner & Mathur, 2018). Based on equation (12), the power a WT can extract from wind is dependent on the air density. Hence, moist air density ρ_{ma} may affect the rated wind speed and power coefficient of a variable speed WT. The power coefficient and rated wind speed of a WT are represented by equations (13) and (14), respectively. Power coefficient C_{pr} equation is defined by equation (13) where the denominator represents the power available in the air (Burton, Sharpe, Jenkins, & Bossanyi, 2001).

$$P = \frac{1}{2} \times A \times \rho_a \times v^3 \tag{12}$$

$$C_{pr} = \frac{P_r}{\frac{1}{2} \times A \times \rho \times v_r^3} \tag{13}$$

$$v_r = \left(\frac{P_r}{\frac{1}{2} \times A \times \rho \times C_{pr}}\right)^{\frac{1}{3}} \tag{14}$$

Based on equation (14), the rated wind speed is increased for the high-moisture site with decreasing air density. On the other hand, based on equation (13), the power coefficient of a WT is decreased, which further increases the rated wind speed (Song et al., 2021).

The AEP of a specific WT (Hrafnkelsson, Oddsson, & Unnthorsson, 2016) can be estimated after obtaining the WT power curve by equation (15), where the hourly mean power production Pm is based on wind speed distribution (Song et al., 2021) is defined by equation (16).

$$AEP = t \times P_m \tag{15}$$

$$P_m = \int_0^\infty P(v) \times f(v) dv \tag{16}$$

2.3. Domestic Load Demand

The power curve of WT indicates its performance. It reflects the power response of a WT to various wind speeds (Sohoni et al., 2016). Therefore, the WT power curve can be utilized to assess wind power. First, WRA, in terms of wind speed and WPD, needs to be done to identify a site suitable for a wind energy project (Mathew, 2007). Then the available wind data and WT power curve are selected to estimate the energy production.

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The location chosen for this simulation is Mollo Selatan Subdistrict, which is in Timor Tengah Selatan Regency, East Nusa Tenggara Province, Eastern Indonesia. (Latitude: -9.83, Longitude 124.21, Altitude: 624 m). The meteorological data were obtained from (A/S, n.d.). Mollo Selatan area is 147.18 km2 and divided into seven villages. The population of the Mollo Selatan Subdistrict in 2019 was 15,970 (BPS, 2020). The total population of Mollo Selatan Subdistrict and national per capita electricity consumption (Direktorat Jenderal Kelistrikan Kementerian ESDM, 2020) are the basis for determining the assumed domestic load. The total consumer of State Electricity Company (PLN) in Mollo Selatan in 2019 was 3,453 families, the non-PLN user was 171 families, and non-electricity consumers was 557 families. Hence, this subdistrict is suitable for on-grid WHCS of current research as a case study site. Table 1 shows the load demand of the Mollo Selatan Subdistrict.

Table 1.

Load Demands of Mollo Selatan Subdistrict

Population	Per Capita Electricity Consumption	Annual Electricity Consumption
15,970	1.089 kWh	17,4 kWh

2.4. Specified Key Components

Key components of WHCS are specified in this section. The prescribed site-specific load shown in Table 2 determines which wind turbine to utilize for WHCS. Based on AEP estimation results in chapter 4, Aeolos-H 50kW (Aeolos, n.d.) with 25m hub height is sufficient to meet the demand of the Mollo Selatan Subdistrict. The electrolyzer is determined by the remaining energy available. It specified S10, a PEM electrolyzer by Nel Hydrogen (Nel Hydrogen, 2020), to be utilized in this simulation. It consumes about 6.1 kW each hour for the whole water electrolysis system, including the electrolyzer and its apparatus.

The overall system load is calculated by adding electrolyzer load and domestic load, becoming a combined load or cumulative load. The selected hydrogen storage tank is manufactured by Labtech (Labtech, n.d.). The stored hydrogen can be reconverted to electricity by fuel cell power modules when the wind is unavailable. Considering the domestic load demands, HyPM XR 12, a fuel cell power module manufactured by Hydrogenics (Hydrogenics, 2011), is selected for this simulation. Table 2 shows the specifications of the selected key components of WHCS. Table 3 shows the detailed specification of the selected WT.

Table 2.

Specified Key Components of WHCS at Mollo Selatan Subdistrict

Components	Brand – Model	Key Specifications
Wind Turbine	Aeolos-H 50kW	Pr = 50 kW
Electrolyzer	Nel Hydrogen S10	Pc = 6.1 kWh; H_{cp} = 0.27 Nm^3
Hydrogen tank	Labtech H-bond 45000 Nl H2	Capacity = 45 Nm^3
Fuel Cell	Hydrogenics HyPM XR 12	P_{fc} = 12.5 kW; Efficiency = 53%

Table 3.

Parameters of Studied WTs

Model	h_{wt} (m)	A (m^2)	v_i (m/s)	v_r (m/s)	v_o (m/s)	P_r (kW)	C_{pr}
Aeolos-H	25	254.5	3	10	25	50	0.3208

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3. Results and Discussion

WPDF is calculated with 2.247 as the shape parameter k and 7.557 as the scale parameter c. Hence, equation (1) yields the wind speed distribution based on wind data obtained from (A/S, n.d.). The goodness of fit of WPDF is calculated using equation (2), which is 0.0202. Figure 2 shows the wind speed distribution versus wind data.

The air density of humid air based on existing relative humidity data was investigated using equation (7). The moist air density of the Mollo Selatan site at 25 m hub height is 1.115 kg/m^3, lower than the standard air density 1.225 kg/m^3. The difference in air density is affecting the power a WT can extract and change the perspective of the wind resource assessment (Al Mubarok, 2022). WPD is calculated using equation (3) and WED is calculated using equation (4). Figures 3 dan 4 show the estimated WPD and WED, respectively.

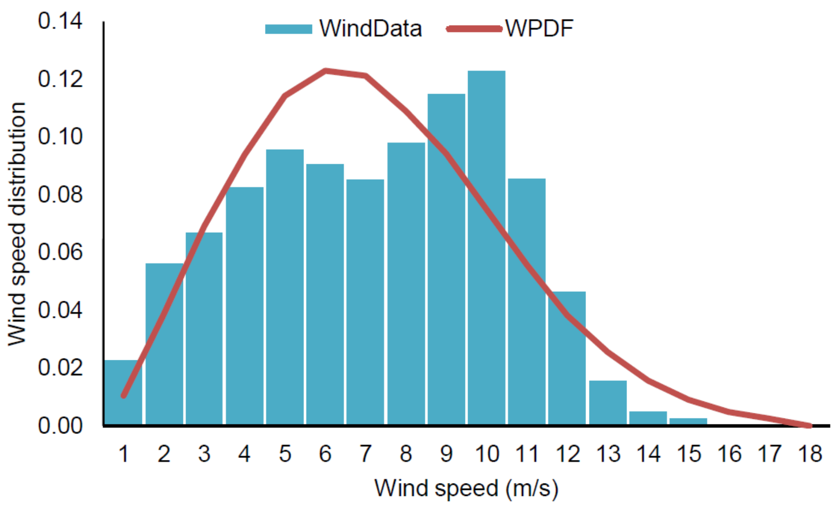

Figure 2. Wind Speed Distribution Using WPDF of Mollo Selatan Site at 25-Meter Hub-Height

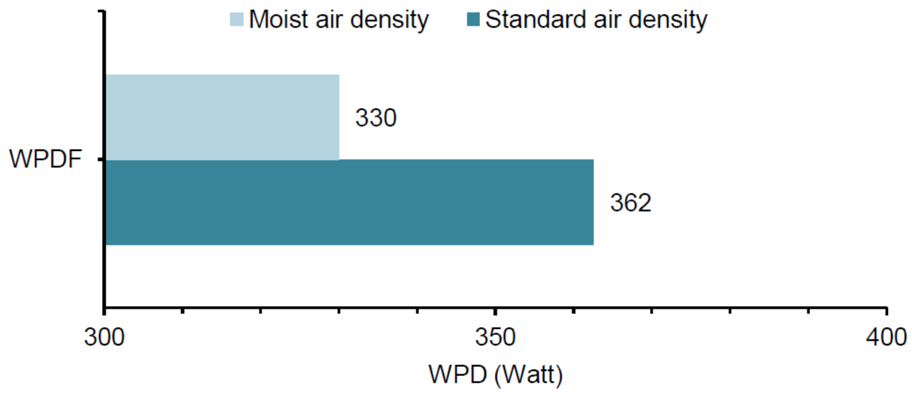

Figure 3. Wind Power Density Estimated using Standard and Moist Air Density

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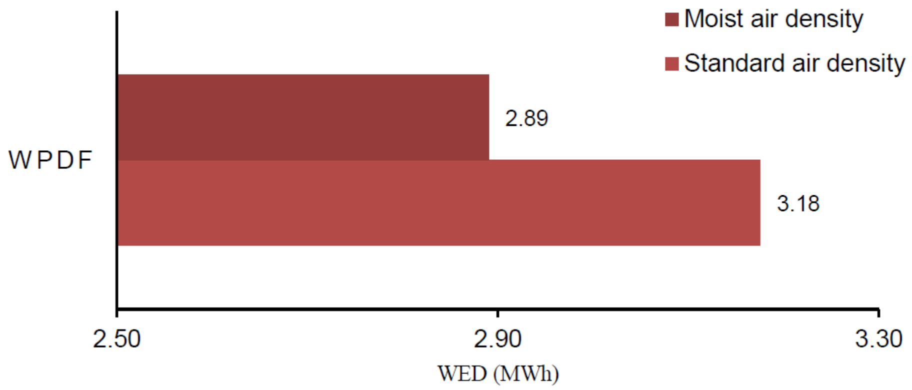

Figure 4. Wind Power Density Estimated using Standard and Moist Air Density

Considering humidity, the air density of the Mollo Selatan site at 25m hub height is 1.115 kg/m^3, lower than the standard air density, 1.225 kg/m^3. Hence, the rated wind speed of WT is also changed from 10 m/s to 10.32 m/s based on equation (5). Figure 5 shows the wind turbine power curve of Aeolos-H 50 kW modeled with standard and moist air density. Figure 6 shows the estimated AEP at 25m hub height using WPDF using standard air density and moist air density. By taking moist air density-based results as the reference, it is concluded that standard air density-based models invariably overestimate the AEP.

Figures 7, 8, 9, and 10 show the simulation results of stand-alone WHCS in Mollo Selatan subdistrict for a year on an hourly basis. The net power generated by WT is shown in Figure 10. The power generated by WT fluctuates due to the nature of intermittent wind speed. The fluctuation of generated wind power affected the state of the electrolyzer. Figure 8 shows no hydrogen production at some points because the electrolyzer was turned off. When the electrolyzer was turned off, the fuel cell was turned on and converted hydrogen into electricity. This can be seen in Figure 9, where hydrogen consumption gets a high value at some points. Figure 10 shows the cumulative load of the system. When the wind-generated power is low, the electrolyzer is turned off, and the cumulative load gets lower than the cumulative load with active hydrogen production. Hence, the power generated by fuel cells by converting hydrogen into electricity is sufficient to meet the domestic load demands.

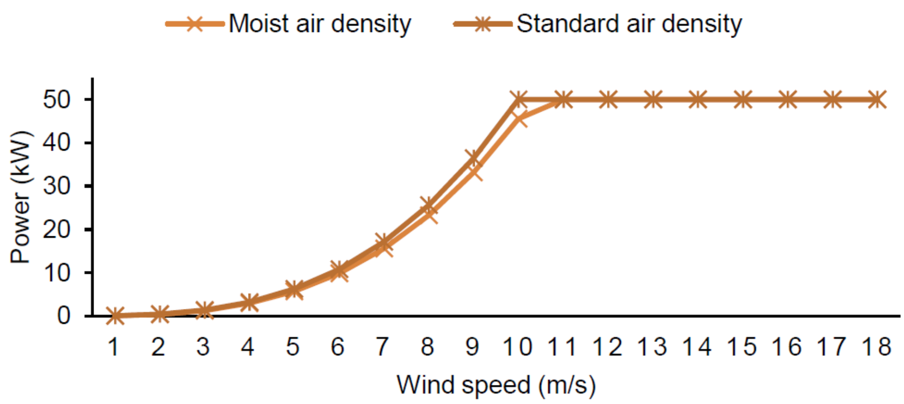

Figure 5. Wind Turbine Power Curve of Aeolos-H 50 KW Modelled with Standard and Moist Air Density

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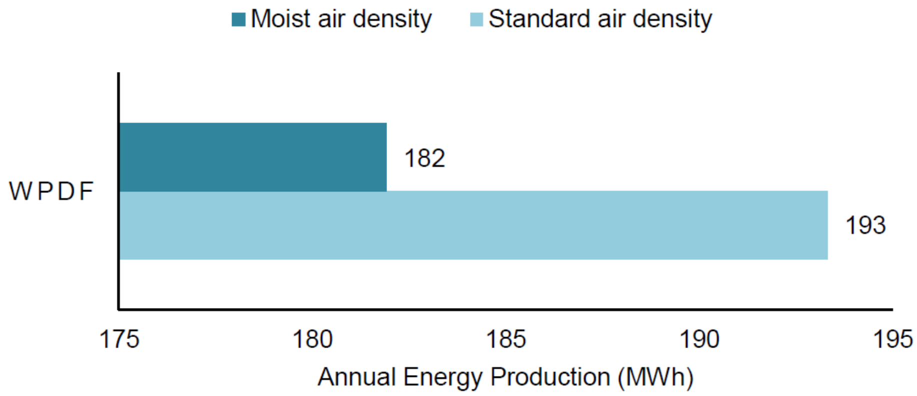

Figure 6. Annual Energy Production Estimated using Standard Air Density and Moist Air Density

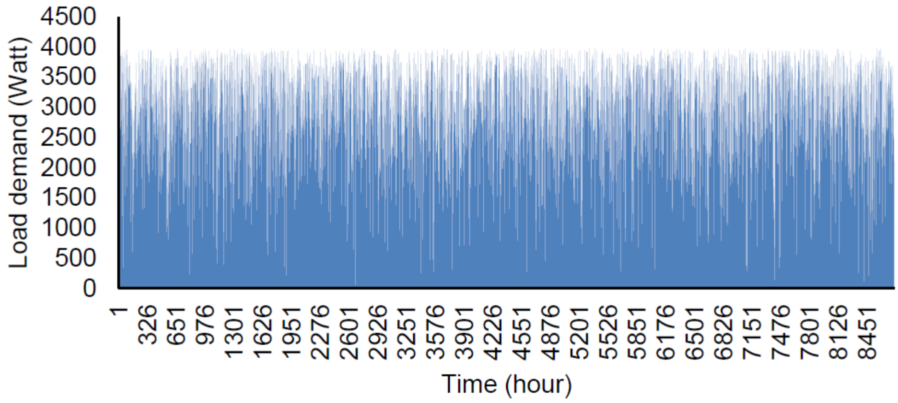

Figure 7. Hourly Load Demand of Mollo Selatan Subdistrict in a Year

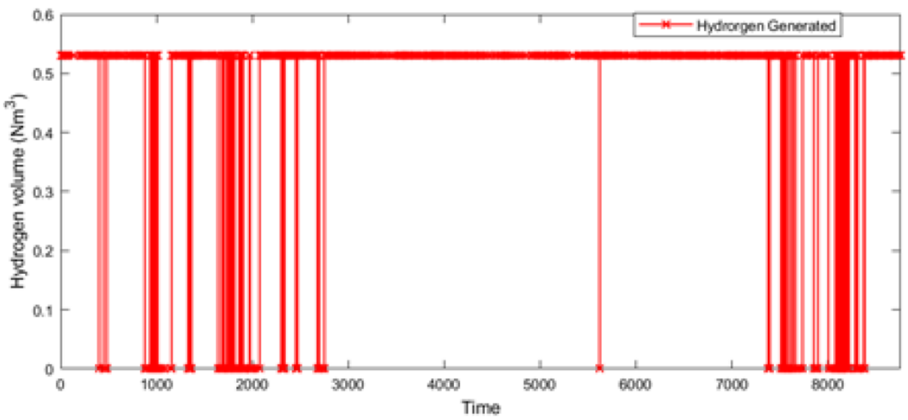

Figure 8. Hydrogen Generated by Electrolyzer at Mollo Selatan Site for a Year on an Hourly Basis

Figure 11 shows the generated power by WT versus cumulative load monthly. The lowest WT power output periods are February, March, and November. Low wind speed occurred during these periods. Generally, the generated electricity by WT is surplus, so the system contributes its power to the grid all year. The only deficit happened in November when the load demand was higher than the power generated by WT. However, the control system could anticipate this using backup power generated by the fuel cell so that the system did not give extra load and even managed to contribute to the main grid this month.

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Figure 12 shows the hydrogen produced versus hydrogen consumed by the system. The highest hydrogen consumption occurred during the low wind months of February, March, and November since fuel cells generated electricity to meet the load demand. At the end of the simulation, 204.66 Nm^3 or 18.4 kg of hydrogen remained in the hydrogen storage.

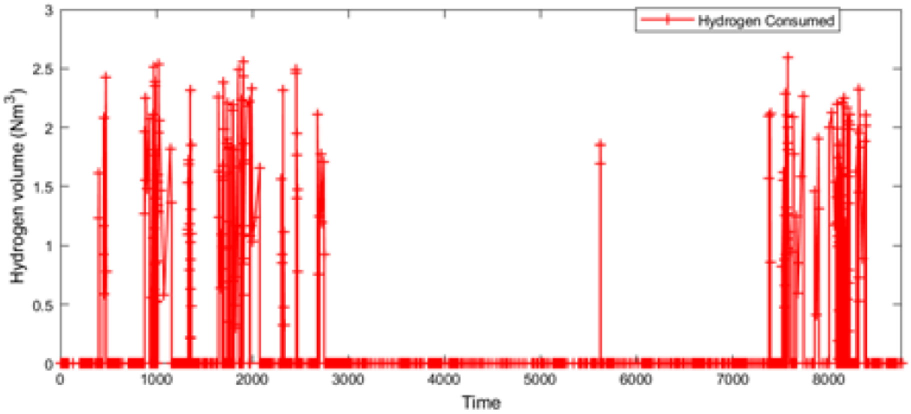

Figure 9. Hydrogen Consumed by Fuel-Cells at Mollo Selatan Site for a Year on an Hourly Basis

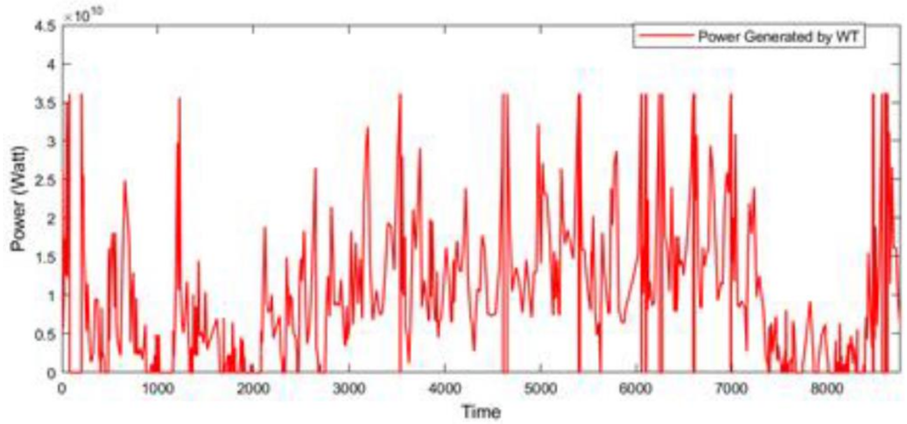

Figure 10. Net Electrical Power Generated by WT at Mollo Selatan Site for a Year on an Hourly Basis

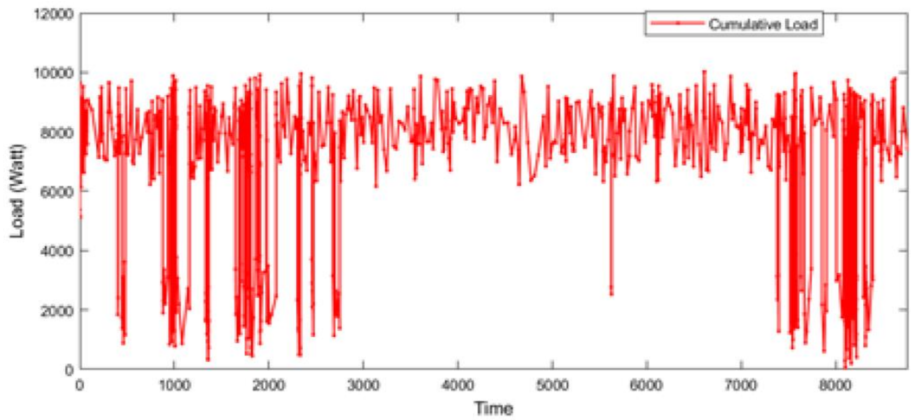

Figure 11. Cumulative System Load of Mollo Selatan Site for a Year on an Hourly Basis

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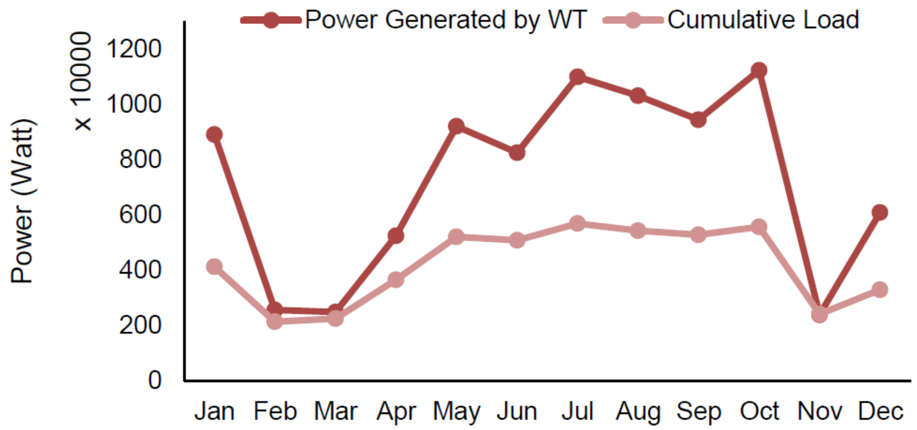

Figure 12. Power Generated by WT Versus a Cumulative Load of Mollo Selatan Site Monthly

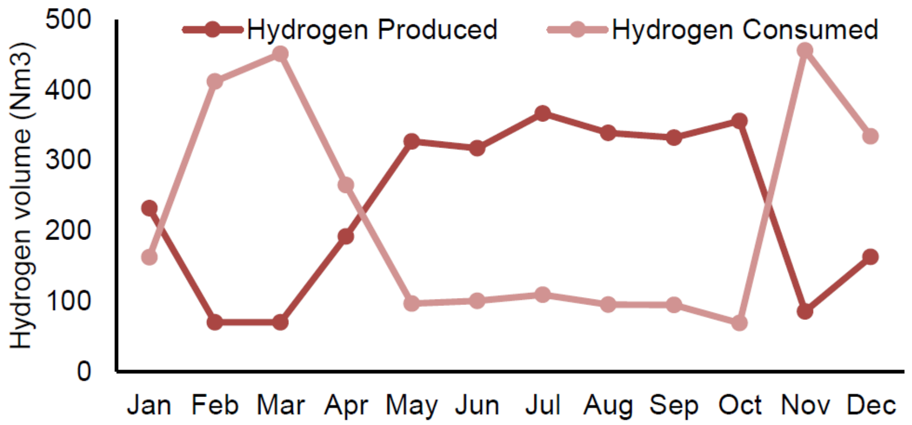

Figure 13. Hydrogen produced versus hydrogen consumed of Mollo Selatan site monthly

4. Conclusion

This study aimed to investigate the feasibility of an on-grid wind-hydrogen coupling system for a specific site. This study proposed a wind-hydrogen coupling system control strategy for the stand-alone system to investigate the feasibility. The control strategy regulates the flow of electrical energy generated by a wind turbine to meet domestic load demand and supply electrolyzer to produce hydrogen as energy storage. Hydrogen can be reconverted into electricity by utilizing fuel cells to meet the domestic load demand in case of low wind speed. This study also utilizes a novel wind resource assessment approach that considers the influence of moist air properties to wind power density, wind turbine power curve, and annual energy production of a wind turbine. This approach aided the assessment of selected sites for evaluating the control strategy. This approach achieved a better precise annual energy production estimation than other approaches that neglect the moist air property. The control strategy was modeled and evaluated with MATLAB Simulink. The simulation results show the possibility of storing energy generated by the wind into hydrogen and meeting the load demand of the Mollo Selatan subdistrict. An experimental study must validate the novel wind resource assessment approach. Finally, more in-depth simulation modeling of the key components may be investigated in future studies.

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