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Original Research Article

Viability of Green Hydrogen Production at Benguela Wind Energy Community Project in Lüderitz, Namibia

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ABSTRACT

The use of renewable energy-generated hydrogen can be an effective solution to reduce the impact of carbon emissions on global climate change. Water electrolysis is a crucial technology for producing green hydrogen due to its scalability, which can help balance the gap between energy demand and supply. This study evaluates the technical feasibility of integrating an additional electrolysis component into a stand-alone community wind energy system. The wind power generated by the system charges a battery bank used for community business activities. The results showed significant excess energy that can be used to produce hydrogen. By integrating a 7 kW electrolyser, annual hydrogen production of up to 235 kg can be achieved without compromising the electrical load demand. Hydrogen can be used as a clean fuel to meet the usual unmet loads in off-grid systems like cooking, without requiring system upsizing.

KEYWORDS

Wind energy, Green hydrogen, Electrolysis, Sustainable community system.

INTRODUCTION

The awareness and use of alternative energy sources other than traditional fossil fuels have in the past two decades increased significantly [1]. Recently, there has been much interest in the use of green hydrogen as a synthetic fuel and energy carrier to accelerate the transition to alternative energy sources [2]. While the focus is on the large green hydrogen production plants to meet regional and international energy demands, there is an opportunity to maximize the utilisation of off-grid Renewable Energy (RE) systems, mainly solar photovoltaics (PV) or wind for remote areas applications [3]. Due to the nature of these RE systems, storage in the form of charging batteries is usually required to cater for when the renewable energy source is unavailable. Battery technologies are still expensive, and if the storage capacity is not optimized properly, the system may become high-priced. This can lead to large excess energy also known as dump load by the RE system [3]. The incorporation of the hydrogen production subsystem offers a good solution to utilise the excess energy by integrating an electrolyser to produce green hydrogen which can be stored in hydrogen tanks for later use.

The three well-known types of electrolysis systems are alkaline electrolysis, proton exchange membrane (PEM), and solid oxide (SO) electrolysis. These technologies follow

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different methods of achieving electrolysis, mainly with how they use different charge carriers and environments in which the electrolysis takes place [4]. The PEM electrolysis systems, in comparison to the aforementioned technologies, can respond rapidly to varying power inputs and therefore can be easily integrated with renewable energy systems [5]. The PEM technology also offers lower operating temperatures, robustness, flexibility in fuel types, high power density, fast start-up and fewer problems with corrosion and leaks [6]. The PEM model, unlike the alkaline and SO systems exhibits a high level of precision in its depiction of the electrochemical phenomenon occurring within the fuel cell [7]. The model incorporates various characteristics, including the compressor dynamics, the dynamics of manifold filling, and subsequently the partial pressures of the reactants. In contrast, empirical models [7] prioritise the characterization of fuel cells under specified operating circumstances. One prominent limitation is the constrained ability to forecast outcomes outside the defined operational parameters. Nevertheless, these models typically exhibit lower computational intensity and offer greater ease of development and utilisation.

The literature provides information on the incorporation of hydrogen generation from both grid-connected and off-grid renewable technologies. Nevertheless, there is a lack of comprehensive studies on various configurations and applications of hybrid renewable energy systems (HRES) that incorporate batteries, wind energy-based storage units, and hydrogen-based storage units [8]. Scamman *et al.* [9] investigated a prototype solar-hydrogen production system design using a PEM electrolyser. The results demonstrate the electrolyser's ability to closely follow PV's highly variable output in all different seasonal operation conditions of a year, indicating positive integration of an electrolyser into changing RE output nature.

In their study, Awan *et al.* [10] conducted a performance analysis of different hybrid renewable energy systems that incorporate storage units such as batteries, hydrogen, and pumped hydro at Sharurah, Saudi Arabia. The simulations and optimization processwas employed to determine the optimum sizes of the system components. The PV-diesel-fuel cell system has been demonstrated to be the least economically viable solution [10]. The wind-diesel-fuel cell configuration represents the most cost-effective option within the hydrogen-based storage classification. In other words, from this study, hybrid renewable energy systems (HRES), wind energy ‐ based, and hydrogen ‐ based storage units seem to be the most economical option. Rezk *et al.* [11] did a sensitivity analysis on a PV-fuel cell-battery system design using the HOMER software and evaluated it to supply a small community in Saudi Arabia. The authors varied the PV array tilt angle and the derating factor of the converter to optimise the system performance. Compared to the grid extension option and diesel generator, the designed system was found to be at least 67 % more cost-effective. In another off-grid RE hydrogen production study, Tebibel [12] developed a multi-objective methodology for maximizing hydrogen production from the system while avoiding energy dumping by diverting excess wind energy to the electrolyser but allowing a bi-directional converter kick-in to assist during low wind regime. This type of system requires a significant battery capacity to cater for the electrolyser nominal power and may exacerbate system cost. Al-Buraiki *et al*. [13] assessed the techno-economic viability of residential house PV and wind with battery storage to meet electricity demand and electrolyser to produce hydrogen for a vehicle. Last, but not least, Janssen *et al.* [14] did cost projections for green hydrogen production through off-grid systems in Europe. The main finding was that the cost of green hydrogen production systems differs depending on different technologies, locations, and points in time. Furthermore, the authors discovered that at present hybrids of wind-based hydrogen production systems seem to be more cost-effective compared to solar PV systems.

In their review of HRES, Come Zebra *et al.* [15] highlighted barriers to the increased market uptake of off-grid renewable energy applications in developing countries. Among these barriers are low awareness, high initial costs, lack of demo projects, maintenance issues, and no follow-up programs. In a study by Nyarko *et al.* [16], the drivers and challenges of off-grid renewable-based systems in West Africa demonstrated similar findings regarding technological, social, and economic challenges. The existing body of literature examines three distinct approaches to supplying power to remote regions: grid-extension, mini-grids, and decentralised independent systems. Mini grids are widely regarded as a favourable solution [17] for the electrification of rural areas, when compared to alternative solutions. However, just like grid-extension, the feasibility of expanding the grid to rural areas is hindered by the considerable expenses associated with connecting sparsely populated and dispersed households.

In Namibia, not only access to electricity is a challenge but also affordability largely because of a sparse population over a widespread area, making it expensive to reach remote areas via the grid extension [18]. Standalone solutions are exclusively appropriate for singular families or community. Wind energy is a notable form of renewable energy in Namibia [19]. Most favourable wind resources are located in the coastal region of Namibia [20]. Off-grid systems may make sense in such settings. The ability to store electricity can contribute to the advancement of decentralised electricity generation, which is particularly appealing for isolated areas facing challenges in grid expansion due to difficulties and lack of economic viability [21].

This research aims to examine the technical viability of small-scale renewable energy systems that rely solely on wind power as the energy source, along with battery and hydrogen production. The primary focus of the study is to determine the potential of such systems to store excess energy in the form of hydrogen, without interconnecting the electrolyser with the system battery. This analysis will be beneficial for independent system configurations in remote areas with abundant renewable energy sources. The study compares different sizes of PEM-based electrolysers and determine the most suitable electrolyser size for integrating into a wind-battery-based system for hydrogen production. This is done while ensuring that the electrolyser size would have little impact on the electrical load demand. The analysis estimates annual hydrogen production by altering the nominal power of the electrolyser using projected wind energy output from wind speed data collected over twelve months. This serves as a reliable metric to demonstrate the capacity of independent systems to accommodate anticipated increase in electrical load demand or without requiring much additional financial investment in the system.

MATERIALS AND METHODS

This section describes the project site, the data collected and the analysis methods.

Project description

The study is based on a small-scale community-run wind energy system. The system is situated in Lüderitz, Namibia, and supplies electricity to a sewing group of women from Benguela Township to generate income for themselves [19]. The township is characterised by none to low-income residents who mainly depend on the saturated fishing and surrounding mining industries for employment. As a result, many cannot afford electricity tariffs and do not have electricity in their shacks. The current wind energy system consists of three small-scale turbines rated at 3.5 kW each with a combined capacity of 10.5 kW. **Figure 1** shows the project setup. There is a separate workshop on the premises where electricity generated is supplied to sewing machines. The total load demand is only 11 kWh/day (about 4 MWh per year), consisting of five sewing machines, a chest freezer, an air conditioner and lights. The project's challenge is the lack of productive use of the wind energy generated for income generation within the community. A significant portion of the electricity generated is being wasted through dump load. The configuration is based on a 48 voltage direct current (V DC) system and the system's main components are as detailed below:

- Three 3.5 kW, e400nb, 3.5 kW, 110 V DC, PMSG-based Kestrel wind turbines
- Three Kestrel Voltage limiters, 3.5 kW, 110 V DC,
- Three Midnite Solar Classic 200 maximum power point trackers (MPPTs),
- Battery bank: 16 batteries, 12 V, 260 Ah @C10, Absorbent Glass Mat (AGM)
- A 48 V/10 kVA Victron inverter.

Figure 1. The Benguela Community Wind Energy System comprising the turbines, control room and sewing room

System configuration

The diagram presented in **Figure 2** outlines the current setup of the Benguela wind power demonstration project, along with the proposed integration of hydrogen production. To safeguard against high voltage, each turbine is linked to a voltage limiter, which protects the maximum power point trackers (MPPTs). The MPPTs are responsible for regulating the charging current needed to charge the battery bank, shielding it from overcharging and over-draining by the load. The battery bank is then connected to a 10 kW inverter that provides alternative current (AC) electricity to the load.

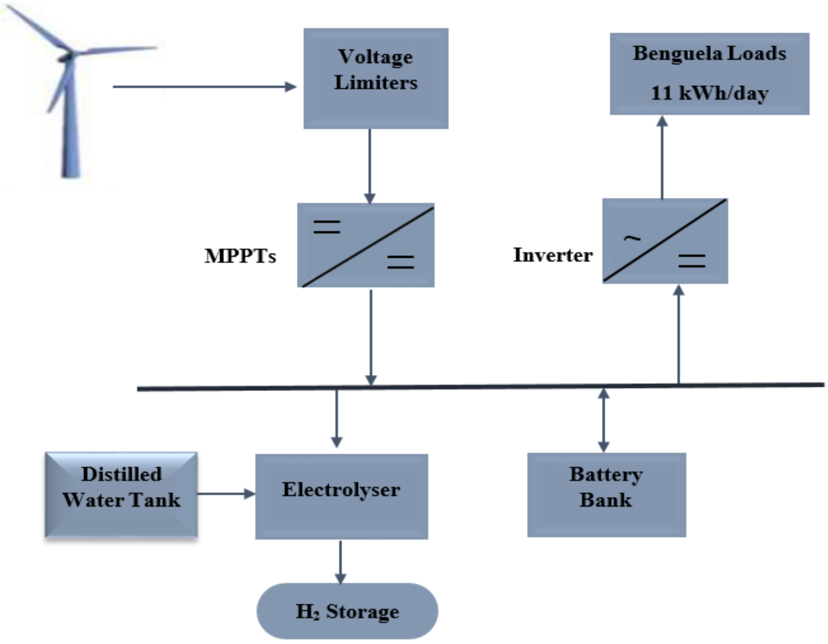

Figure 2. The Benguela wind demonstration project schematic diagram of the current system configuration plus the proposed hydrogen production to be integrated

Site wind speed characteristics

To ascertain the wind energy output profile generated by wind turbines, it is important to initially evaluate the wind characteristics present at the site. Wind data was collected from a nearby site in Lüderitz for resource assessment purposes from 2012 to 2018. Wind data covering a full year, from Sep 2017 to Aug 2018, based on a 10-min averaging time series was used for this study. There are several models for characterising site wind in literature [22], [23], for this analysis, the Weibull distribution model was used. Equation (1) below was used to calculate Weibull distribution $f(u)$ of the measured 10-min averaged data:

$$f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{1}$$

where k and c represent the Weibull shape and scale parameters in m/s, respectively, and u is the measured 10-minute wind speed in m/s.

Wind turbines' energy output

Wind turbines convert the kinetic energy in the wind into electrical energy. The power generated by wind turbines increases with the hub height of the turbine, as wind speed is directly proportional to hub height [24]. The power output of the wind energy system was estimated based on measured wind speed (u) at a hub height of 25 m, while the wind turbines are installed at 22m. To consider the actual hub height, researchers could use two well-known analytical models for wind speed data extrapolation, namely the power law and the logarithmic law [25]. However, both models require knowledge of the wind shear effect which is complex due to its dependence on various factors such as wind speed, site topography, surface roughness, atmospheric stability, and diurnal and seasonal variabilities [26]. As a result, the extrapolated wind speed data is prone to uncertainties, leading to larger errors in energy output estimations since it varies to the cube of the wind speed [26]. For this work, the potential impact of using the actual hub height in the simulation is deemed insignificant. In addition, the error that could be introduced by extrapolation may be larger compared to the impact of the 3 m height difference. **Table 1** lists the technical specifications of the site wind turbines which are crucial to accurately estimate the power generated by the turbines (P_{WT}) calculated using eq. (2) [27]. When the wind speed (u) is below the cut-in wind speed or above the cut-off wind speed, the wind turbine does not generate any power. However, if the wind speed (u) falls between the cut-in wind speed and the rated wind speed, the generated power can be calculated using eq. (2), which is further broken down in eqs. (3) and (4). When the wind speed (u) is at or above the rated wind speed but lower than the cut-off wind speed, the generated power equals the rated power of the wind turbines.

$$P_{\mathrm{WT}} = \begin{cases} 0, & \text{if } \ u_{\mathrm{f}} < \ u < u_{\mathrm{c}} \\ C_1 u^k + C_2, & \text{if } \ u_{\mathrm{c}} \leq u \leq u_{\mathrm{r}} \\ P_{\mathrm{r}}, & \text{if } \ u_{\mathrm{f}} \geq u \geq u_{\mathrm{r}} \end{cases} \tag{2}$$

P_{r} denotes the rated power of the wind turbine; k is the Weibull shape factor; u_{r} is the wind turbine rated speed, u_{c} is the cut-in wind speed, u_{f} is the cut-off wind speed. The constants C_1 and C_2 are defined as follows:

$$C_1 = \frac{P_{\mathrm{r}}}{{u_{\mathrm{r}}}^k - {u_{\mathrm{c}}}^k} \tag{3}$$

$$C_2 = \frac{P_\mathrm{r} \times {u_\mathrm{r}}^k}{{u_\mathrm{c}}^k - {u_\mathrm{r}}^k} \tag{4}$$

Table 1: Technical specifications of the system wind turbines

Parameter	**Value**
Rated power (kW)	3.5
Cut-in wind speed (m/s)	3
Rated wind speed (m/s)	11
Cut-off wind speed (m/s)	25
Hub height (m)	18 - 22

Proposed Polymer Electrolyte Membrane electrolyser model to produce green hydrogen

When the wind energy system generates more power than the load demands, the electrolyser splits water into hydrogen and oxygen using the excess energy. The amount of power ($P_{electrolyser}$) available for the electrolyser is computed following the schematic representation in **Figure 1** as:

$$P_\mathrm{electrolyser} = P_\mathrm{WT} \times \eta_\mathrm{mppt} - \left(\frac{P_\mathrm{load}}{\eta_\mathrm{inv} \times \eta_\mathrm{bat}}\right) \tag{5}$$

where η_mppt= 98 % is the MPPT power efficiency; P_load is the power required by the load; η_bat = 80% is the battery bank charge efficiency, and η_inv = 98% is the inverter efficiency.

During the night, all the power generated is available for the electrolyser and the chest freezer. The Kestrel voltage limiters use linear voltage regulation hence, they do not consume power during normal operation.

Respective, six PEM electrolysers with nominal power 3, 4, 5, 6, 7 and 8 kW were evaluated. The efficiency specifications utilised are in accordance with the recommendations provided by the manufacturers. The process of electrolysis involves a chemical reaction that requires a specific amount of energy to split water into oxygen and hydrogen. The electrolyser voltage ($V_\mathrm{cell\_elec}$) for splitting the reaction to occur can be expressed by eq. (6) [13]:

$$V_\mathrm{cell\_elec} = \frac{\Delta H}{2F} \times \eta_\mathrm{elec} \tag{6}$$

where ΔH = 285.85 kJ/mol, denotes the high heat value of hydrogen; F = 96485 C/mol is the Faradays constant and electrolyser efficiency is η_elec = 80%. 2 is the number of hydrogen electrons from its two atoms in the water molecule.

For water decomposition, 1.23 V is enough theoretically [28]. At this theoretical voltage, the electrolyser's operating was considered to have an efficiency, η_elec of 100%. However, in practical applications, it may vary depending on electrodes type. Applying the PEM electrolyser model in this study, a minimum voltage of $V_\mathrm{cell\_elec}$ = 1.48 V was considered, as per recommendation. The practical cell voltage is higher than the theoretical value to account for losses in the cell which are caused by internal resistance, Faradaic losses, and heat losses [6]. The electrolyser voltage efficiency used in this study is 80%.

The evaluation of electrolysers' nominal power, ranging from 3 kW to 8 kW, was conducted using an hourly hydrogen flow rate. Based on Faraday's law, the amount of hydrogen (M_{H_2}) produced by an electrolyser can subsequently be obtained by employing eq. (7):

$$M_{\mathrm{H}_2} = \frac{P_{\text{rated\_elec}}}{2 \times V_{\mathrm{cell}_{\mathrm{elec}}} \times F} \times 3600 \qquad (\mathrm{mol/h}) \tag{7}$$

where $P_{\text{rated\_elec}}$ is the rated power of the electrolyser. The operational constraint for the electrolysers was set according to minimum power requirement, normally referred to as low partial load range. Hence, a partial load range of 10% of electrolysers' rated power was considered in the analysis [29].

RESULTS AND DISCUSSION

This section presents the main outcomes of the project and discusses relevant and applicable findings.

Wind characteristics analysis

The data presented in **Figure 3** depicts the Weibull distribution wind speed collected during a 10-minute interval at a hub height of 25 m, spanning from September 2017 to August 2018. The Weibull distribution shape (k) and scale (c) parameters at 25 m were 1.626 and 6.961 m/s, respectively. **Figure 4** displays the monthly variation of wind speeds observed at heights of 11 m and 25 m, with the highest average wind speed recorded in January (7.83 m/s) and the lowest in April (4.17 m/s) at 25 m. The wind speed increases with height, indicating that more energy is generated as the hub height increases.

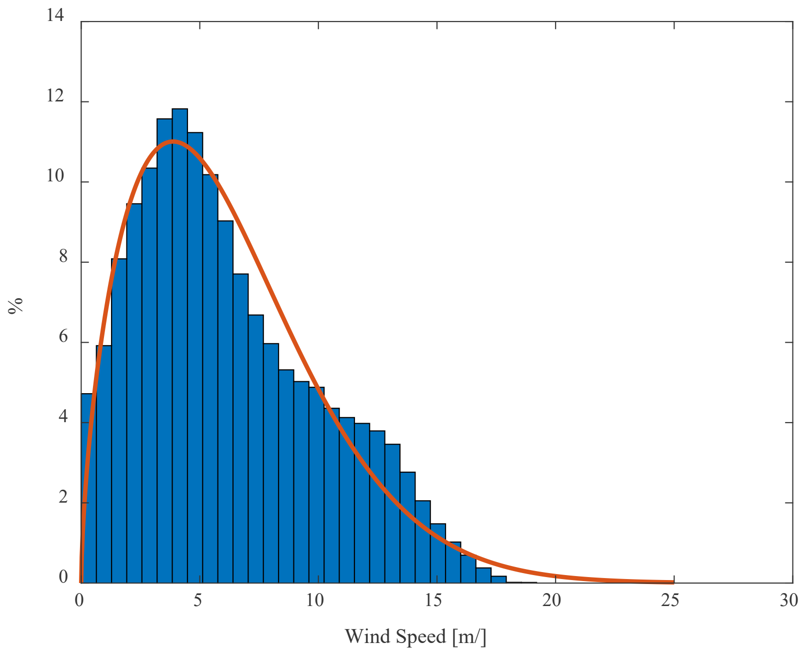

Figure 3. Weibull distribution based on site 10-minute measured wind speed values at 25 m height

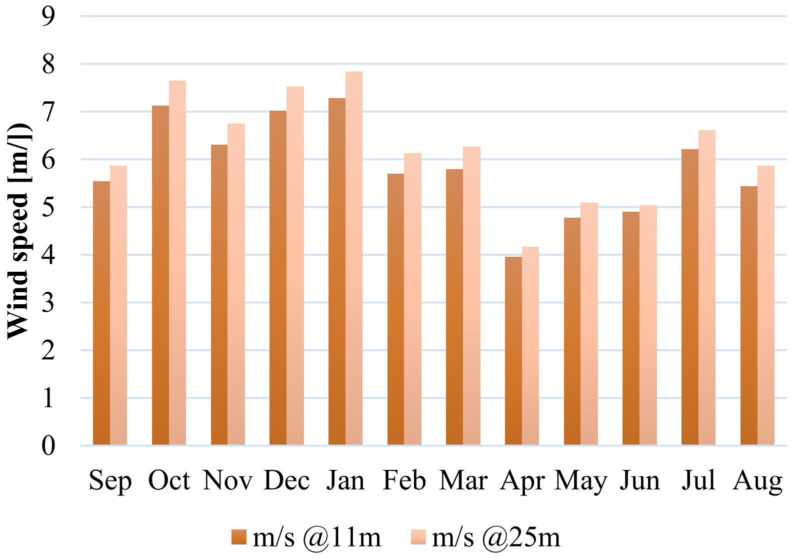

Figure 4. Monthly wind speed variations at 11 m and 25 m hub heights in Lüderitz, Sep 2017 –Aug 2018

Figure 5 shows the variation in wind speed throughout the day for January (high wind) and April (low wind). The graph illustrates that wind is calmer during night hours for both months, resulting in more energy generation during the day, which is beneficial for the system as community business activities require energy during the day, between 09:00 h and 18:00 h.

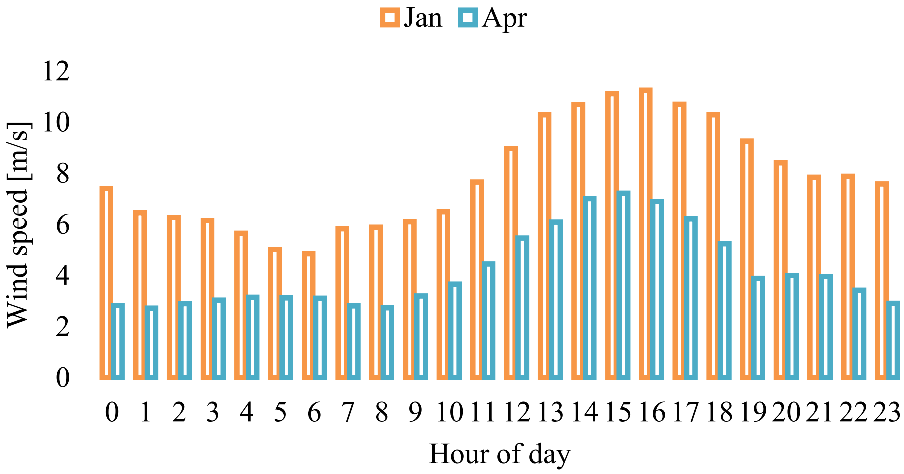

Figure 5. Average wind speed variation according to time of day

Wind turbines energy output

The turbine systems have been installed at a hub height of 22 m. The simulations, however, have been computed using hourly average of the wind speed data measured at 25m to estimate the generated power output of the turbines. The monthly variations of generated wind energy by wind turbines are shown in **Figure 6**. The wind system had an estimated annual energy generation of 33 MWh at 25m height and provided electricity for about 6850 hours annually. For over 2000 hours, the turbines were operating at their rated capacity, as the wind speeds surpassed the rated turbines' wind speed. Moreover, **Figure 6** shows the amount of excess generated energy by the system every month. The batteries can sustain the current load for up to nearly three days without needing a recharge, so it is assumed that a steady 100% state of charge, resulting in minimal energy needed for battery charging. All of these factors translate to an excess energy generation of nearly 28 MWh annually by the system with the current load.

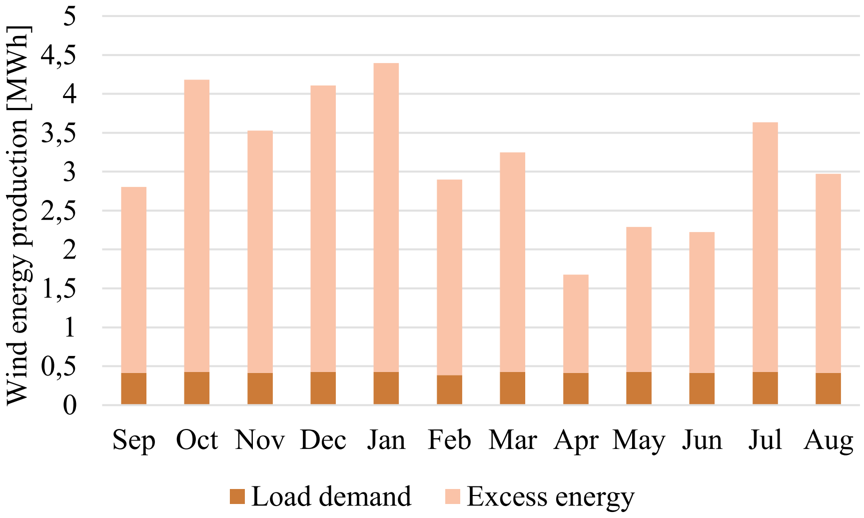

Figure 6. Monthly wind energy production indicating load demand and excess energy

Electrolyser selection and hydrogen production

In order to mitigate power wastage, as seen in Figure 6, it is advantageous to employ the surplus power generated by the wind system for the purpose of water electrolysis. Using the hourly hydrogen flow rate determined by eq. (7), electrolysers' nominal power ranging from 3 kW to 8 kW were evaluated. The monthly hydrogen production variations are given in **Figure 7**. Green hydrogen can be produced each month and with all electrolyser sizes. When using a 7 kW electrolyser, the production is at least 15 kg per month during high wind season and between 3 kg and 6 kg during low wind months. It's interesting to note that the 3 kW and 4 kW electrolyser sizes performed better during low wind season in terms of hydrogen production. However, in all other months, the system used significantly more energy to produce less hydrogen, suggesting that the electrolyser ratings may be too small for the wind system.

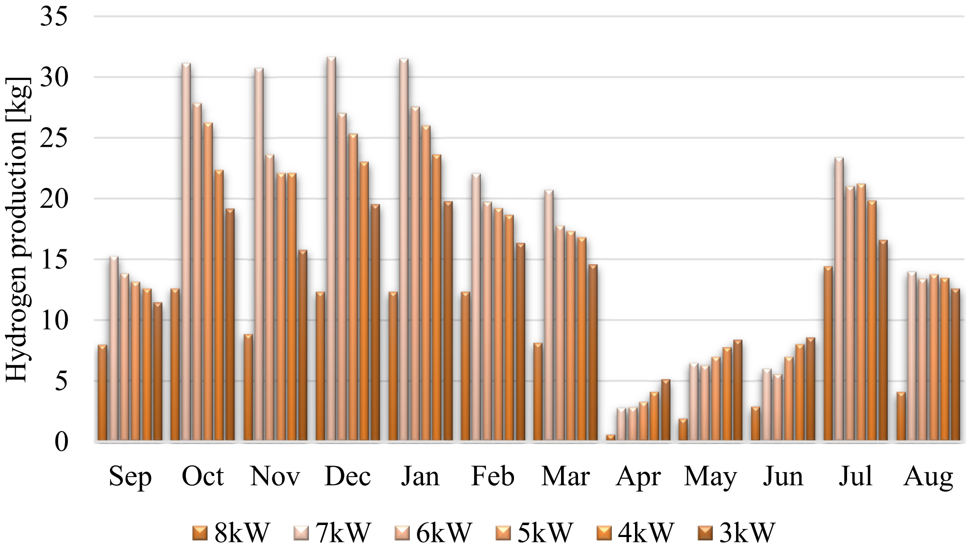

Figure 7. Monthly variation of hydrogen production at 25 m hub height

In **Figure 8**, the yearly totals for each electrolyser size are displayed. The 7kW electrolyser generated the highest amount of hydrogen production, producing 235 kg within 1562 hours of operation. This is in contrast to the 6kW electrolyser, which produced 206 kg but required 1862 hours of operation. The hours of operation are indicated above the respective bars. Additionally, having fewer hours of operation can extend the longevity of the electrolyser. The size of the electrolyser should not exceed 7 kW, as hydrogen production decreases significantly beyond that point. The 8 kW electrolyser can only generate hydrogen at night and reduces excess energy by only 19%, compared to the 6 kW and 7 kW sizes, which reduce excess energy by 40% and 39%, respectively. The green hydrogen gas produced can be stored in hydrogen tanks that can be located underground, to ensure both security and efficiency. This gas can undergo direct combustion or be transformed into electrical energy through the utilisation of fuel cells once more. The oxygen that will be produced can be used as an input gas in fuel cells. The inputs and outputs of this system can serve as a supplementary component of the system.

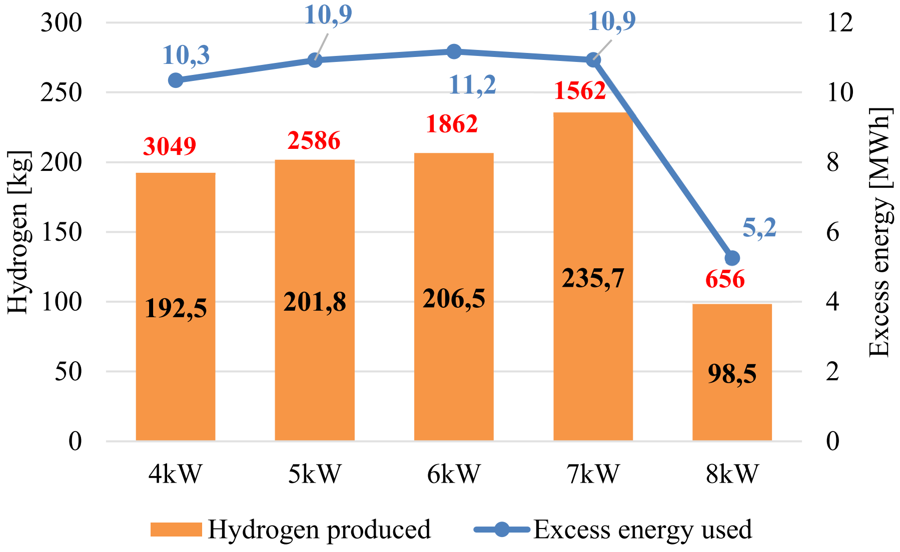

Figure 8. Annual hydrogen production and the excess energy used by each electrolyser size

As presented above, integrating an electrolyser can reduce excess energy generation by up to 40% with the current load demand, resulting in an annual dump load of approximately 17 MWh. Further analysis was conducted to determine how the size of the electrolysers would be affected by a potential increase in future load demands. With a 30% increase in load, the 7 kW electrolyser would only operate during the night and produce 103 kg of hydrogen annually. In this scenario, the 6 kW electrolyser produced the highest amount of hydrogen (194 kg) and reduced excess energy by 38%. If the load is adjusted with a 60% increase, the 6 kW electrolyser would only operate during the night and produce less hydrogen than the 5 kW electrolyser. If the load doubles in the future, the system may not be able to accommodate electrolyser sizes above 5 kW. In this case, the 5 kW electrolyser produced 172 kg of annual hydrogen, leaving a surplus of 12 MWh of excess energy and an operation time of 1899 hours.

The operational procedure of the wind energy- battery-based, and hydrogen-production unit control system is recommended as follows: upon detecting an average power demanded by the electrolyser, the control system transmits a command to initiate the activation of the electrolyser. On the contrary, in instances when the average power generation of the turbine falls below the minimum threshold of the electrolyser, it becomes necessary to deactivate the electrolyser. The electrolyser must also be deactivated once the hydrogen tank has reached its maximum capacity. A control system with a focus on robustness can be implemented to identify surplus wind energy and assess the capacity of the hydrogen storage tank to decide the optimal timing for activating the electrolyser.

Hydrogen has the potential to help achieve Sustainable Development Goal 7.1 (SDG 7.1), which aims to provide universal access to clean cooking by 2030. As a direct benefit to the community, the monthly hydrogen produced can be sold for clean cooking purposes. This can be achieved either by hydrogen cooking via direct combustion or using electric stoves powered by hydrogen. These clean cooking solutions may prove to be suitable for off-grid setups as they may only require minimal modifications for Liquid Petroleum Gas (LPG) cookstove users or enable the integration of high-load appliances like electric stoves onto off-grid systems, which are often limited by the battery bank. Therefore, the hydrogen production addition can act as a pilot to assess the impact of the two hydrogen cooking solutions, thus filling a research gap. In addition, hydrogen can also be used by the community for cooking and selling food, creating another business opportunity for the project.

CONCLUSION

The Benguela Community wind energy system, located in Lüderitz, Namibia, is a source of electricity that powers community business activities, ultimately promoting socio-economic development. This system is situated in the most optimal location for wind energy in Namibia, where wind speeds range from 4.17 m/s in April to 7.83 m/s in January, at a hub height of 25 m. The system's three 3.5 kW turbines generate around 33 MWh of wind energy annually. However, more business activities are needed to ensure the sustainability of the project. The surplus electricity that the system produces can be used to produce green hydrogen. To incorporate an electrolyser into the current system configuration, various sizes were examined. Electrolysers rated below 7 kW can be integrated with the current load. A 7 kW electrolyser can generate a significant annual amount of hydrogen, which is 235 kg, and reduce the amount of wasted electricity by 39% based on the current community load demand. In case the load increases in the future, a 5 kW electrolyser can be used with a 100% load increase and still generate 172 kg of hydrogen annually. This can help reduce excess energy by up to 45%. Hydrogen production can fuel direct combustion cookstoves or electric stoves via fuel cells, which may become a viable cooking solution in the future for off-grid set-ups.

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