

Case Report

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Case Report

Green Hydrogen Production with 25 kW Alkaline Electrolyzer Pilot Plant Shows Hydrogen Flow Rate Exponential Behavior with the Stack Current

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Abstract

Green H₂ production using electrolyzer technology is an emerging method in the current mandate, utilizing renewable-based power sources integrated with electrolyzer technology. Elaborate research has been conducted to understand the effects of intermittent power sources on the hydrogen production output. However, in this context, the characteristics of the working electrolyzer behave differently under system-level operation. In this current study, we have investigated a 25 KW alkaline electrolyzer for its stack performance in terms of stack efficiency; stack current vs stack voltage followed by the understanding of H₂ flow rate with stack current. It was found that 52 A is the best current to have the best system efficiency of 64% under full load operation for 1 hour. The H₂ flow rate behaves in an exponential pattern, and it is also found that the ramp-up time for hydrogen generation by the electrolyzer is significantly low, thus marking it as an efficient option for producing green hydrogen with the input of a hybrid grid and renewable PV-based power sources. Hydrogen production techno-economic analysis has been conducted, and the LCOH is found to be on the higher side, considering the current electrolyzer under investigation.

Keywords: Green Hydrogen; Electrolyzers; System Efficiency; LCOH

Introduction

Green hydrogen is a promising renewable energy vector for various industrial and mobility sectors decarbonization. The technology for making green hydrogen is known as electrolysis and is a mature technology; however, the electrolyzer needed for this purpose has faced the integration problems associated with various power sectors such as PV-arrays and grid-based electricity due to intermittent nature of both. The integration of renewable energy into existing grid systems also faced inherent challenges in terms of wind and solar variability in different geographic locations. The grid stability is further affected in terms of power imbalances by the changes in wind / sun / weather patterns or fluctuations in daily / seasonal patterns. In the case of solar insolation and wind speed, it causes inconsistencies in voltage and frequencies parameters, which in future needs AI powered central systems to supply stable grid powers and thus enhancing the efficiency of electrolyzer technologies to produce green hydrogen and to fulfill the required demand. Followed by this, further optimization is needed to integrate the electrolyzer directly with PV-array with definite sizing. In the case of wind-based sources, BESS systems could be the best option.

Electrolyzer technologies are currently running with several types, and each has its own efficiency and cost analysis have been done. For instance, PEM electrolyzer BOSCH 1.25MW system shows the highest efficiency of 80% with ramping rate <1s but its cost is affected by the use of scarce materials such as IrO₂ / Pt and upfront cost comes at (700-1400 \$/Kg)[1] while alkaline electrolyzer is more mature technology and cheaper (500-1000 \$/Kg) but its slow ramping (min) and lower efficiency

(~ 65 -70%) makes it less suitable for intermittent renewables. The highest efficiency obtained is for SOEC (solid oxide electrolyzer) but it's not suitable under dynamic grid conditions. The current cost of green H₂ comes at 3.75 – 6 \$/kg when compared to fossil fuel alternatives (1.5 -2 \$ / kg). The 2040 vision for green H₂ cost would be around 2 \$ with the scale up in production and cheaper renewable power availability [1]. This can be cut short with the help of recent advances in automotive manufacturing and new materials innovation to achieve the DOE target of 1 \$ / kg of hydrogen production by 2031.

More studies have recently been conducted with respect to the integration of renewable energy with electrolyzer. For instance, Su et. Al [2] studied the optimization and analysis of a PV-coupled electrolyzer direct coupling system. Here, focus was put forward to effectively design and sizing the system to enhance hydrogen production from solar energy. The main goal of the work was to improve PV modules and electrolyzer to achieve high efficiency and reduced cost. The PV source operating point matching with that of an electrolyzer is found to be an important parameter to achieve a best performance. It is found that a well-designed direct coupling system can significantly increase energy transfer efficiency thereby offering deep insights into the efficiency challenges associated with power electronics. Next, Khalilnejad and Riahy studied [3] the effect of hybrid wind – PV based system embedded with an alkaline electrolyzer. The goal of studying this is to obtain stable hydrogen output throughout the year by the integration of wind turbines, PV- arrays and energy storage solutions. The study also emphasizes the way to reduce the effect of intermittent renewable energy supply by BESS based system to make a coordinated effort to make hydrogen in synergy with energy supply. When renewable energy generation is insufficient, the operational mode involves the combined input powers from both batteries and grid. This hybrid approach not only enhances hydrogen production but also decreases carbon emission reductions. Another PV coupled with alkaline electrolyzer system discussed the performance of commercial alkaline electrolyzer of 1 nm³ / hr. capacity using actual weather data for irradiance, temperature, and wind speed [4]. The capacity of both PV and wind turbines are 6.8 kW and 6 kW, respectively. The main finding of the work is related to the application of two strategies for proper integration. They are viz. operation between smallest limit for brief period and addition of extra battery bank. The overall service life and performance of the electrolyzer increased by 63.1% in number of operational steps and increases in energy efficiency by 7.6%. Followed by this, another study [5] assessed the technical and economic viability of using photovoltaic -fuel cell battery hybrid system in Amazon region of Brazil. HOMER software was used to make comparative cost analysis, and it was found that the first cost was around \$87138 and electricity cost 351\$ / kWh. Besides onshore renewable energy sources, offshore wind farms are coupled to electrolyzer in Germany [6]. The idea is to check the economic viability in ancillary service markets. The best bidding approach for ancillary services and best sizing power to hydrogen facilities are developed as strategies and it is found that the offshore wind based H₂ production is more sustainable. It is suggested that providing subsidies like those for conventional offshore windfarm could reduce further costs.

The volatile power sources significantly hamper hydrogen production. Various advanced control systems such as battery-hysteresis cycle, model-based scheduling and frequency response were developed by Alsagher and Wilcken et. Al [7] to mitigate this effect. A model predictive control [MPC] algorithm is developed by researchers which dynamically adjust electrolyzer load to support a breakdown energy balance on the DC bus bar linking generation and demand. The system is assessed for 5 kW PEM electrolyzer and it achieves automated energy balancing for both grid connected and standalone systems. Key outcomes of this study are 6.3 – 7.6% improved energy efficiency and enhanced H₂ yield under variable renewable inputs. Besides these, a few studies associated with the successful coupling of electrolyzer with renewable energy sources have been conducted in recent past [8 - 16]. Next, a bilevel optimization model is proposed by Li et. Al [17] for the wind-photovoltaic electrolyzer system sizing embedded with hydrogen energy storage [HESS] and economic performance. The volatility is addressed via source load interaction at the interface between wind solar as well as demand responds thus reducing cost and improving output matching. Followed upon this; a total annual cost (TAC) model is developed by integrating levelized cost of storage (LCOS) for HESS, which shows a 7.3% reduction in TAC and LCOS value drop by 10.3%. A

scale up project was recently developed by Sonya et. Al. [18] using an area over 10 m² by exploring various PV-electrolysis combinations, which includes thermally integrated PV electrolyzer and direct coupling of PV modules to PEM electrolyzer. The main outcome of the so-called PECSYS project is to increase the solar to H₂ efficiencies ranging from 4% to 13% by using bifacial PV modules which exceed 10% over extended periods. Similarly, a kilowatt scale solar H₂ production system using an integrated photoelectrochemical device is recently developed by Holmes- gentle et. Al. [19]. The thermally integrated PEC device able to achieve solar-to hydrogen efficiency at 20% and the system efficiency at 5%. This makes it to further scale up lab scale to kW scale pilot facility. The research applies novel strategies such as managing solar irradiation, thermal integration, and electrolysis process to find major energy losses as well as increasing the system level efficiency.

The operational experience, performance testing and system integration of alkaline and PEM electrolyzer in coupled with PV and wind based renewable sources recently discussed in NREL case study report [20]. The project wind-2- H₂, which is a collaboration between XCel Energy and NREL, is a pioneering demonstration facility at NREL, specifically focused on production of hydrogen from renewable energy sources. The project shows the production and storage of H₂ and converting it into electricity by the integration of wind turbines and photovoltaic arrays with electrolyzer. The key aim of the project was to reduce H₂ costs to 2 – 3 \$/kg to match the DOE target and to improve the system efficiency with the inclusion of power electronics. The project further employs H₂ storage as an effective solution to meet challenges of variable renewable energy sources aiming to enhance further system performance and reduce the cost of renewable H₂ production. The grid integration advancement has been incorporated in another case study [21] as it needed for balancing renewable energy variability and enhance grid stability. Under this study, which involves a 1.25 MW PEM electrolyzer project predictive modelling tools are developed which focus on performance characterization under diverse grid scenarios. The future direction in this case is to mitigate the associated challenges in communication protocols, safety compliance and grid dynamics management and to scale up both centralized and decentralized systems and the integration of technology synergies like offshore H₂ island and digital twins for the hardware in the loop testing. A further study has been conducted for the optimization of integrated renewable energy – electrolysis system [22]. In this case, the main priority was to refine constructive interaction between renewable energy and that of grid with a balanced approach to absorb the excess energy for H₂ production with electrolyzer. However, in this case, the cost is still highest at 5-6 \$ / kg which is mostly driven by electrolyzer expenses and renewable energy variability. U.S. DOE H₂shot program was launched recently to get the desired 1\$/kg of H₂ by 2031 to address the cost issue.

With reference to cost analysis, a recent report published by IRENA [23] stressed the scale up of electrolyzer to meet the 1.5°C goal. The study mentioned that the cost of H₂ production is controlled by key components such as electricity supply, electrolyzer CAPEX and use rates. In this case, electricity cost ranges from 20 – 65\$/ MWh depends on location and then next electrolyzer costs accounted for 25 – 40% upfront cost with current costing of 700-1400 \$/ kWh and it is projected that the cost significantly reduced by 2030 through scaled manufacturing. Strategic optimization of approaches such as electrolyzer innovation, policy support (carbon pricing and mandates) and inclusion of leverageable low-cost renewables in ideal locations. Islanded H₂ production with huge renewable energy potential serves as H₂ export hubs. The cost and environmental impact of such systems is recently studied by Mazzoti M *et. al.* [24]. The researcher proposed that using hybrid systems combining different electricity sources offer the best economic and environmental performance. The main challenges met here are the associated catalysts for electrolyzer scale up due to materials scarcity (IrO₂ and Pt used for PEM electrolyzer) and the required land for installation of renewable energy infrastructure. With reference to export hub, a case study was recently proposed by Mio et. Al [25] by considering the Trieste port with the application of different hydrogen production pathways to make grey, blue, green and grid based H₂. The study finds that the LCOH for grey H₂ is comparable to green and grid H₂ and Green H₂ has competitive disadvantage in terms of total cost ownership for H₂ vehicle is more than the diesel equivalents.

So far, we have discussed various integrated system and related technoeconomic associated to production of green H₂. Now we will focus on recent progress in electrolyzer research and gap behind

their performance integration with both renewable and grid based on electrical power followed by establishing objectives of the current experimental and performance study of a 25-kW alkaline commercial electrolyzer integrated with hybrid power supply from PV and grid.

Electrolyzer are the primary support mechanism for grid-based electricity power management combined with renewable energy. The idea here is that the electrolyzer can consume the surplus power by converting it into hydrogen and electricity in the form of hydrogen storage. A recent review [26] discussed the electrolyzer based system for providing ancillary services. Electrolyzer supports functions like voltage and frequency control, grid balancing by using excess electricity and converting it into H₂. One of the recent challenges faced by alkaline electrolyzer is its system efficiency when running under low loads < 30% capacity due to the electrical limitations imposed by fluctuating renewable energy sources (RES). To address this Xia *et. al.* [27] developed a multi-mode self-optimization electrolysis strategy which adjusted dynamically voltage/current based on real time RES inputs and AWE operating states enhancing adaptability to variable power conditions. The approach improves efficiency from 30% - 53.21% under 15% load and expands operational range from 30 -100% of rated capacity confirmed for both lab scale and commercial systems. The method also stabilizes H₂ output by improving thermal management and electrical response without required hardware modifications. Such approaches are important to reduce energy consumption to 51-57 kWh/kg H₂ and to achieve a stack lifetime of 7-10 years. Besides dynamical adjustment, alkaline electrolyzer also suffers from H₂ cross overs, which is a major challenge for renewable energy integration. The current zero gap designs show high H₂ cross over (supersaturation level: 8 – 80 at the diaphragm electrolyte interface) due to imperfect electrode – diaphragm contact, which causes unstable performance under dynamic loads. A finite-gap configuration [500 μm] has been designed by Lua Garcia Boras *et. Al.* [28] to mitigate this. Innovation reduces cross-over dramatically to a supersaturation level (2 - 4). Here, cathodes gaps proving particularly effective at lowering gas impurities compared to anode gaps. It enables AWE to run safely across a broad range without compromising efficiency. Next, the effect of operating temperature on the electrolyzer at low current density limitations has been reviewed by Lohman- Richters *et. Al.* [29]. Higher operating temperature [70 - 200°C] reduces cell voltage requirements thus improving energy efficiency and allowing thermal integration with industrial processes. It is found that material stability is still a challenge for components like catalysts, diaphragm, and electrode. They must be stable under corrosive molten hydroxides and elevated temperature.

Recent advances show stable operation upto 150°C with experimental systems achieving 200°C as operating temperature using robust materials like porous metal oxide matrices and PTFE based components. However, the technology is not yet conducted for higher TRL and to be scale up it requires addressing the capital costs, durability (which target 7-10 years for stacks) and infrastructure gaps.

From the above critical analysis of the current state of the art, the electrolyzer parameter study is still lacking in terms of a pilot level system integrated with grid-based electricity and PV for green hydrogen production. The main goal of the current work is to analyze various aspects of electrolyzer parameters such as stack efficiency, stack current and voltage behavior with respect to electrolyte temperature and balance of plant discussion in a real case scenario. Here, we have adapted protocols from NREL case study wind 2H₂ project. But the main novelty here is to understand how hydrogen flow rate behaves with stack current at various time of day with integration of PV and grid-based hybrid power sources. We also made a correlation between stack power and hydrogen output in (Kg) following system efficiency, which has not been done for a commercial pilot system of KW capacity to the best of our knowledge. Followed by this, our next goal is to calculate the LCOH by applying the AGORA tools to get a rough estimate of cost of green hydrogen production and build strategy to further improve the condition in a reverse engineering scale from pilot scale to lab level.

Methods

After the generation step, the H₂ generated is passed via dioxo unit and finally via a gas drying system fitted with heat exchanger to remove the moisture content from hydrogen gas as condensates which are collected later, and the output gas is 99.9% purity. The condensates mixed with generated

H₂ and O₂ gases from untreated water molecules from the electrolyte during the electrocatalytic water splitting process. Note that condensate removal is necessary to support the purity of product H₂ as its application, for instance in fuel cell needs 99.999% pure form. After passing through the drying process, the hydrogen produced is not stored and passed via the water reservoir and to air. The aim of this step is to mitigate any explosion-related incidents safety scenario.

As the above demonstration step has been conducted and it was found that electrolyzer continuously is able to generate H₂ at the desired rate and we set up the operational protocol. Here, the electrolyzer is coupled with a grid-based power source provided electricity by PV array of 200 KW capacity. It is found that during the peak solar insolation, a capacity of 200 kw has been obtained. Note that electrolyzer energy input is 25 KW and more power load of 10 kw needed to run different components of the electrolyzer such as lye fan for cooling purposes and heat exchanger to support the output temperature and a dryer with vacuum pump installation. The electrolyzer is constituted of two alkaline stacks of 10 KW capacity and is connected to the gas collection chamber and with more cylinder to collect the unreacted electrolyte. The collected gas is further transferred to the dryer to remove the condensate as described above. The oxygen gas is collected and directly vented out to the environment. The power electronics and associated reaction engineering balance of plant (BOP) is controlled by unironic based PLC system as shown in Figure 1. The electrolyzer shows a maximum hydrogen production rate is 4.1 nm³/hr. which is equivalent output pressure of 0.80 Barr under full load operation. The electrolyzer operation mode is – pressurization – generation. First the electrolyzer oxygen valve is open to build up the necessary pressure with the closure of hydrogen vent valve. Once the hydrogen generation steps into the initiation, the hydrogen valve is open and gas flows towards the drying chamber.

The drying chamber was installed with more valves, which is open slowly until the gas passed via the various stages of drying and finally passed via distilled water and then into the air. The gas is not stored as the desired pressure of 3 bar is not achievable, However, the gas generated will be used in further power- to -X application. After each operation, O₂ gases are vented out and condensate are drained from the drying chamber. The condensate has been drained, or it can be used as a recycled electrolyte. The electrolyte needed to produce 1 Kg of H₂ is around nine liters of 8M KOH. Following this calculation, the water consumption for one ton of H₂ plant would be nine thousand liters.

Results and Discussion

Here we will describe the commissioning and testing of an alkaline electrolyzer. The 25 KW alkaline electrolyzer (Piel M, McPhy Italia) was installed and commissioned in 2023. It is an integrated electrolyzer with inbuilt power electronics controller by Unitronics systems (PLC = programmable logic controller). The electrolyzer operation is performed by supporting the ATAC safety standard.

The goal of the work is to understand the effect of grid-based power on its operational characteristics. The electrolyzer input power is provided by both PV and grid-based electricity. The PV array is connected to a DC-AC inverter, which supplies electricity to it in parallel to the grid load. The ramp-up time of the electrolyzer until the hydrogen production or generation step is around 5-10 min. If the pressure build-up is not adequate, the electrolyzer is not in operation mode.

Balance of Plant of the Electrolyzer and Its Reaction Engineering Discussion

The BOP consists of electrolyzer stacks, where liquid electrolyte is fed with the help of centrifugal pump premixed with water with other pump, which is called as electrolyte circulation pump. The electrolyte temperature is kept with the help of heat exchanger and another fan as shown in Figure 2. The minimum voltage requirement for electrolyzer is 200 V and 17 A current from one stack. As the electrolyzer investigated here has two stacks so, total voltage and current requirements will be 400 V and 34 A. As hydrogen generation steps reach, the gas will be collected in respective electrolyte -gas separation Tanks. From here, it is collected into catch pots for both H₂ and O₂. After this step, it will be passed to the dioxo step, where condensates associated with both oxygen and hydrogen gases will be collected. The oxygen generated is vented out into air and condensates associated with it will be directly collected from the output valve from the rear of the electrolyzer. H₂

generated is passed via the same step and finally collected in the drying chamber for removing the residual water molecule as well as condensate collection. After the drying step, the output H_2 pressure is around $4.2 \text{ nm}^3/\text{hr}$. giving a total of 400 g/hr ., which will result in 9.6 Kg/day of the electrolyzer operation. After the shutdown of the electrolyzer and production target reached, the dryer is working by condensation using heat exchanger plates with recovery and condensate drain devices. The temperature is controlled by refrigerant chiller. Hydrogen constant dew point is obtained by these types of dryers.

After an operational and construction overview of the electrolyzer, we will now discuss the various results obtained regarding electrolyzer reaction engineering perspective such as stack current resistance, stack efficiency and system efficiency. Also, we will study the effect of electrolyte temperature on the performance of the electrolyzer. We have seen and compared this result with well-established cases studied performed at NREL. The NREL studies focus more on total system installation and various outcomes of associated H_2 production in both wind and solar energy scenarios followed by the development of advanced power electronics. The novelty of study in our case lies in the direct correlation of system efficiency with that of stack efficiency and maximum gas output volume or production rates and, we used an innovative methodology to understand the correlation while the NREL studies did not directly compare it with an alkaline electrolyzer.

Following the understanding of various parameters, we have applied AGORA LCOH calculation tool to understand the cost of H_2 produce under current operational scenario. Then we discussed various electrolyzer parameters along with the outlook for further improvement in electrolyzer performance.

Coupling of PV Array and Grid-Based Electricity with Electrolyzer and the Effect of Proximity of Electrolyzer to the Power Sources

Next, to see the effect of input power supplied from both PV-Array and grid-based powers, we studied the electrolyzer characteristics about its proximity to the power sources. We have seen that electrolyzer functions normally in terms of its stack current and the associated H_2 production. We believe that there are no transmission losses as electrolyzer shows stable voltage operation and stack current. However, during cloudy conditions, when PV-array output power is limited, it has been observed that the stack current decreases, but the desired input power is automatically adjusted by the in-built power electronics of the electrolyzer with added load provided by the grid. The electrolyzer stable operation is made possible by the combined power input of both grid and PV powered electricity.

Effect of Shut Down Action on the Operational Performance of the Electrolyzer:

We have performed experiments related to the effect of shut down operation on the performance of the electrolyzer. It is worthwhile to mention that the electrolyzer shut down action causes the stack degradation, resulting in the decrease in stack current and thus finally affects the associated power needed to run the electrolyzer to achieve the desired H_2 flow rate output. The shut down action leaves the electrolyzer both anodes and cathodes undergo spontaneous self-discharge process due to bipolar plates acting as a galvanic cell and thereby generating an electromotive force. This in turn generates a reverse current which flows in the opposite direction of electrolysis current between anode and cathode until an equilibrium is reached. This condition creates a reverse redox current and thereby anode get reduced, and cathode gets oxidized [30 – 32]. In this case, the alkaline electrolyzer cathode is made of Nickel which on oxidation produces a $\beta\text{-Ni}(\text{OH})_2$ according to a recent in-situ study with X ray spectroscopy [33]. In this case we have not noticed any observational change in current density on the next day of operation within one month of running the electrolyzer by following the on-off strategy, so degradation mechanism is momentarily ruled out. The shut-down action of the electrolyzer usually brings it back to the equilibrium state and on the next day also, it has been seen that ramp up time to the hydrogen generation step remains same as compared to the very first day of operation and before each consecutive shutdown along with same magnitude of stack current.

There is no loss of either potential or current in this case and hence the effect of shutdown on the operational performance is confirmed.

Effect of intermittency on the PV – coupled electrolyzer: Intermittency of PV- supplied electricity is not seen here as electrolyzer is indirectly coupled to the PV-Array. However, during the end of the day, when PV-panels are not producing electricity anymore, voltage step down has been observed during the operation of the electrolyzer. Due to reduction in stack voltage stack current also decreases along with output pressure.

Stack efficiency

Next, to understand the correlation of stack voltage [V] against stack current [I], we have plotted them in figure 3. From the results obtained, the trend is a linear pattern with stack voltage stays same with the increase in stack current in the range of 35 -55 A. It is due to the function of the Ohmic losses concerning the ionic resistance by the electrolyte. A similar type of observation had been Made by NREL study involving alkaline electrolyzer equipped with power electronics [20]. The electrolyte temperature does play a role in the performance of stack current as the electrolyte temperature influences it and that’s why it is cooled down with the help of lye fan and heat exchanger as described in the balance of plant. Besides electrolyte temperature overall electrolyzer system temperature increases from 37.8°C to 51°C. Above 37°C; stack voltage decreases further and ultimately reaction engineering parameters such as output hydrogen pressure and gas flow gets affected.

Here, temperature and pressure remain constant. The cathode and anode pressure are respectively 0.86 and 0.80 Barr. This value is used further to calculate the ideal stack voltage needed to calculate the stack efficiency according to the following equations [20]

$$v_n = 1 \cdot 48 + \frac{RT}{z \cdot F} \ln \left[\frac{P_{O_2} \cdot P_{H_2}}{P_{H_2O}} \right];$$

where V_n stands for Nernst potential including the toral potential of 1.48 V at HHV. R is the Universal gas constant (8.341 J/ mol-K), T is the operating temperature in Kelvin, Z stands for the number of electrons taking part in the overall reaction. F is the Faraday constant (96485 C/mol) P_{H2} is the pressure of the cathode and P_{O2} is the pressure of the anode, and P_{H2O} is the pressure of the anode feed water. The Nernst potential (V_n) is added here as an extra term to account for the electrochemical compression energy which is used to generate the cathode pressure (Hydrogen) of the cell within stacks.

$$\text{Stack voltage Efficiency} = \frac{\text{Ideal Stack Potential}}{\text{Actual Stack potential}}$$

Stack efficiency is defined as the voltage efficiency figured out by comparing the ideal stack potential with the actual stack potential. The measured operating voltage is always compared to this ideal voltage to calculate stack efficiency, as shown in Figure 4. Stack efficiency (%) is plotted against the stack current (A) as shown in the figure. Hereby, it is seen that stack efficiency is still at maximum ability when the stack is working at low current. Next, it decreases with the increase in stack current. It is also clear from the figure that a stack current of 50 A results in a stable stack voltage. The stack current also increases because of the rise in electrolyte temperature. A stack current operating in the range of 36-50 A results in good stack efficiency; so, it is recommended that the best stack current is 52 A with the largest stack efficiency of 99%. Also, it is clear from the figure that 52 A gives maximum hydrogen output [figure 6, as discussed below], and with a voltage of 490 V; the output power is 25 kW, which is equivalent to the electrolyzer maximum capacity in terms of power output. Also, stack resistance decreases with the rise in stack current [Figure 5]. It points to the fact that the electrolyzer beast operatable current is 52A.

Correlation of Hydrogen Flow Rate [nm³/hr.] with Stack Current [A]

Hydrogen flow rate follows an exponential growth pattern with respect to the stack current and time stamp for a day of operation as shown in Figure 6. Here, generation Starts at 10.00 am and from generations step till the hydrogen flow rate saturation, it takes around 20 min from the startup of the hydrogen production by the electrolyzer. As can be seen from the result obtained, after 20 min till 1 hr. period of operation, electrolyzer hydrogen flow rate stays stable. The graph obtained on fitting with an exponential function clearly shows an exponential growth for hydrogen flow rate with

respect to the stack current. This finding is novel in terms of hydrogen flow rate with respect to the stack current in case of an industrial pilot alkaline electrolyzer.

We also came across other research dealing with MATLAB simulation of parameter adjustable dynamic mass and energy balance model of a large-scale industrial plant of 3 MW capacity [34]. The study also stimulates the experimental data of working electrolyzer in terms of hydrogen production vs. DC current but the ramp up time in this case is 7 hr. and hydrogen production rate is stable with respect to DC current. In this case both measured and modeled H₂ production shows a linear pattern while in our case; it shows an exponential growth in H₂ flow rate during the electrolyzer ramp up time.

Correlation of Stack Power (Kw) with That of System Efficiency (%)

System efficiency is defined as the amount of energy needed to produce 1 Kg of H₂. For a system to be 100% efficient, an output power of 39.4 kWh/ Kg is needed [20]. Based on this, we have calculated the system efficiency, and it is plotted against the stack power, stack current and amount of H₂ generates in Kg. The result obtained is shown in Figure 7. From here, it is found that the system efficiency is maximum when stack current is highest and here, we have seen highest hydrogen production capacity of 0.42kg. The system efficiency is calculated and is found to be 65%. System efficiency, stack power (kW) and hydrogen output (Kg) all match the same stack current, which is 52 A, where stack resistance is still at minimum. So, we finally conclude here that 52 A is the ideal current to have maximum hydrogen output as well as to support the capacity of the electrolyzer which is 25 kW.

Technoeconomic investigation: Three key components decide the cost of green hydrogen production. They are viz. electricity supply, electrolyzer capex and use rates. Here, 60 -70% of the total production cost accounts for electricity costs, and the price is declining due to falling renewable energy prices related to regions with abundant solar and wind resources. Electrolyzer costs, which are currently at 700-1400 \$/ KW, are expected to decrease by 40 - 80% in 2030 if scaled manufacturing and technological improvements are made currently. Further cost reduction of electrolyzer is possible by increasing the system efficiency, hybrid systems integration and by induction of carbon pricing and supportive policies. The production cost of green hydrogen is 2-3 times more than that of blue H₂, it is mostly due to renewable electricity price fluctuation and CAPEX of the electrolyzer. The research gap in cost minimization balancing is mostly driven by location specific factors. Production cost optimization and environmental sustainability need favorable locations with high renewable energy ability. The current production cost of islanded green H₂ production via electrolysis from solar and wind energy is at 3.7 – 5€/ Kg and is competitive with reference to grey H₂ when natural gas prices are high. The current cost can be reduced further to 2\$ in 2040 by adoption of renewable deployment scaled up and hybrid system. This can be conducted by use of cost drivers such as infrastructure, where “offshore island” can reduce grid cost and intermittency can be managed well with the integration of both wind and solar renewables. But the desalination cost can affect the price due to limited availability of fresh water. The final scale up of such islanded green hydrogen production can be conducted by the development of strategic infrastructure hybrid renewable system and policy support.

AGORA data analysis: The levelized cost of H₂ production (LCOH) in the current study is calculated using LCOH tools developed by Agora industry by using parameters as shown in Figures 8. The LCOH is found to be at the high-end side because the system under investigation is a pilot plant with only 25 KW capacity alkaline electrolyzer. As described above and discussed in various scenarios, the scaling up of the plant will further reduce the cost. Hence, electrolyzer scale up by more installation will provide higher hydrogen output and along with a reduced cost by consideration of the same parameters as listed in Table 1.

Conclusions

In this study, we have conducted a detailed understanding of 25 kW alkaline electrolyzer in terms of its integration with a hybrid PV-Array and grid-based hybrid power sources. The balance of plant understanding in terms of electrochemical reaction engineering is thoroughly understood along

with the role of power electronics. It is found that due to the intermittent voltage fluctuations, electrolyzer able to run in stable conditions and output hydrogen gas flow rate is well supported. Next, we have analyzed the various parameters of the electrolyzer such as stack voltage and stack current with respect to increase in overall temperature of the electrolyzer. It was found that stack voltage is stable at 37.8°C with a stack current of 52 A.

The largest Stack efficiency (65%) is obtained at 52A current, and it is correlated with particularly good hydrogen production as well with increased output pressure. Further optimization is needed to tune the electrolyzer parameters under full access control by the supplier. The electrolyzer performance enhancement is not hindered by any kind of shut down step as it needs a long-term study. It is also found that the LCOH for hydrogen production using this electrolyzer comes around at 21.73 \$ /kg calculated using the AGORA tools. The outlook of green hydrogen cost reduction involves consideration key aspects of cost reduction such as combinations of BESS (Battery energy storage systems) and electrolyzer, PEM technologies development responsive to grid-based power and infrastructure development to prevent transmission losses. About the infrastructure, distributed power generation (e.g., rooftop solar) and policy framework for grid expansions need to be implemented. The next outlook will be to implement coordinated efforts in advanced controls system development, material research for better prospects of cheap and highly efficient electrocatalysts and scalable electrolyzer plant installation to match with the renewable energy demand in sustainable manner.

Data Availability Statement: Data are available on request.

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