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Review on The Techno-Economics of Decentralized Hydrogen Production Using Alternative Renewable Energy Sources

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Abstract

The transition to a sustainable energy future is progressively reliant on hydrogen as a clean and versatile energy carrier, specifically through decentralized production systems powered by alternative renewable energy sources. This review assesses the techno-economical aspects of decentralized hydrogen production utilizing renewable energy sources such as wind and solar. It explores green hydrogen production techniques and their effectiveness in optimizing hydrogen generation. Additionally, the paper examines the economic factors that impact the feasibility of hydrogen projects, including the Levelized Cost of Hydrogen (LCOH), Net Present Value (NPV), Simple Pay Back Period (SPP), and Internal Rate of Return (IRR). Moreover, it discusses assessment tools such as HOMER (Hybrid Optimization Model for Electric Renewables), TRNSYS16, and HYDROGEMS which offer significant insights into the operational performance and optimization of decentralized hydrogen production systems. By analysing current research and case studies, this review aims to provide a thorough understanding of the

Techno-economics of decentralized hydrogen production.

Keywords: Sustainable energy, Hydrogen, LCOH, Greenhouse Gas Emissions, Renewable Energy, SOEC, Net Present Value

1. Introduction

Recent findings have highlighted that climate change is becoming a potential threat to humankind, with anticipated temperature rises above 2ºC over the next three decades and beyond. 4˚C-6˚C within the upcoming several decades[1], it has become undeniable that drastic measures of reducing greenhouse gas emissions to near-zero levels must be implemented without delay to avert global warming from escalating from dangerous to catastrophic[2-5]. The necessity to decrease the adverse effects associated with the use of fossil fuel on the environment together with the increasing cost of fossil fuel have impelled policy and decision makers all over the world to find sustainable, safer and more affordable forms of producing energy. Countries all over the world are now leaning towards the exploration and utilization of energy from renewable sources.

The transformation towards a greener future mandates us to find substitutes for fossil fuel utilization and greenhouse gas emissions. Green hydrogen rises to the forefront, envisioned to be pivotal in the conversion towards renewable energy[6].Harnessing green hydrogen in industries entails considerable investments economically to pioneer technological and infrastructural developments of its production, storage and transport[6]

Hydrogen has become a viable option for decarbonising energy systems[7–9].

It is considered to be the key energy carrier among various alternatives in the sustainable energy strategy, which will surmount climate change concerns, natural resource depletion and low-cost oil[10]. Hydrogen has the highest energy content by weight among the common fuels producing only a small amount of NOx and water when it is combusted with air[11]resulting in it being an energy-efficient and low-polluting fuel [12]. Hydrogen as a clean energy carrier is crucial to power generation and sustainable development[13]. It is utilized in metallurgical, chemical, petrochemical and electronic sectors.

The utilization of renewable energy further advances energy security and ensures equitable development. Wind and solar technologies are viewed as the best-suited technologies owing to a combination of factors including their cost-effectiveness in terms of energy generation costs, set business value chain and modular structure with a low gestation period. For this reason, there has been a significant increase in their employment, with over 1675 GW of capacity- 825 GW of wind and 849 GW of solar.[14].

Hydrogen production can be located in a centralized or decentralized system. In a centralized system, the production of hydrogen is centrally located in combination with a distribution system that transits hydrogen from the site of production to the refueling station [15]. In a decentralized system, the production of hydrogen is at the refueling station, in conjunction with a standalone system using dedicated wind power plants and/or solar PV that is situated in the area of the refueling station and supplies electricity for the electrolyser. Hydrogen is stored in hydrogen storage tanks during production and demand in a decentralized system[16]. Previous studies show that a prospective market exists for green hydrogen energy systems in remote areas and/or weak grids particularly for stand-alone power systems and hydrogen refueling stations [39].

3. Renewable energy sources for hydrogen production

The most substantial advantage of hydrogen is that it can be produced from renewable energy sources such as solar, wind and biomass [17]. Utilizing renewable energy sources to generate hydrogen is crucial for a more effective transition to a sustainable and pollution-free environment[11]. Furthermore, on-site (decentralized) hydrogen production from renewable energy sources removes the necessity for transportation and distribution steps[18]Renewable energy sources such as solar and wind, are regarded as central to the decarbonization of the electricity sector. However, these renewable energy sources are usually located in remote areas and intermittent, consequently necessitating a large investment in storage and transmission at high penetrations[11].

3.2 Solar energy

Given the carbon-free renewable drivers to produce hydrogen, solar energy emerges as the primary resource among several other renewable energy options. Solar energy can be acquired for hydrogen production through different routes such as direct electric energy production utilizing photovoltaic (PV) cells for electrolysis, direct thermal energy for thermolysis and thermochemical cycles, photonic energy through photocatalysis, or photobiological process[19] .

The application of PV arrays for direct electricity production, coupled with conventional low-temperature electrolysis is one of the readily deployable solar-based hydrogen technologies showing the most maturity on both hydrogen and solar technologies. However, due to their energy storage capabilities, concentrated solar thermal energy technologies are expected to reach greater penetration in the energy market for future large-scale applications. Such systems would surmount the issues of intermittency and the necessity for batteries/ storage needed for PV-based systems. Concentrated Solar Power (CSP) comprises solar power towers, parabolic dishes, parabolic troughs, Very Large-scale photovoltaic (VLS-PV) technologies and concentrated photovoltaic (CPV). Concentrated solar thermal energy technologies offer a promising route for hybrid and thermal hydrogen production technologies. Generally, solar-based hydrogen production still encounters some challenges due to its cost-effectiveness and intermittency. Another obstacle facing its use for near-term large-scale hydrogen production is the limited operating efficiency of solar energy technologies[19].

3.2 Wind

Wind energy is notable as another renewable energy source with ready technology to produce hydrogen. Its deployment has been remarkable over the past two decades both onshore and offshore, achieving capacities from 3 GW to over 530 GW all over the world by 2018, with an expected yearly expansion of 50 to 60 GW in the next four years. Moreover, record-breaking annual market growth has been observed in the wind power industry over the last four years[19].

The first direct wind-to-hydrogen turbine was installed in the Wieringermeer region of the Netherlands in early 2019. The 4.8 MW turbine was set to power a conventional electrolysis unit for five refueling stations to render service to roughly about one hundred fuel cell electric vehicles (FCEVs) Other projects have also successfully utilized electricity produced by wind turbines to power electrolysers for hydrogen production, Examples include: generating hydrogen for fuel cell-powered forklifts in Kawasaki and Yokohama, Japan and the h2herten project in North Rhine-Westphalia, Germany which investigated wind -to- hydrogen technology employing an electrolysis plant with fuel cells for production of electricity and hydrogen storage. Wind energy also has limitations in its intermittency like solar energy[19].

4. Green hydrogen production techniques

Hydrogen gas does not exist as an element but in a compound form with other elements like water (H_2O), methane (CH_4), biomass and coal on the earth[20]. Electrolysis of water is the most used technology in practice although hydrogen can be obtained from various types of resources using different methods such as steam methane reforming, gasification/partial oxidation, gasoline reforming and electrolysis[18]. Electrolysis of water is a mature technology, and the hydrogen can be generated in capacities spanning from small amounts (cm3/min) to higher amounts(m^3/h). Comparatively, electrolysis is more than 70% efficient[21].

Electrolysis, the primary technology employed for green hydrogen production uses electricity to split water (H20) into hydrogen and oxygen. There are mainly three types of electrolysis: alkaline electrolysis, solid oxide electrolysis and proton exchange membrane electrolysis. Each is suitable for different applications and has different efficiencies however, they all accomplish the same essential process of splitting water into oxygen and hydrogen[22].Green hydrogen production in a country is greatly dependent on two factors: the availability of renewable energy sources and the electrolysis process's efficiency [6]

Renewable energy sources such as solar and wind power are used to electrolyze water into hydrogen and oxygen. Water electrolysis is an electrochemical process that utilizes electricity to split water into hydrogen and oxygen[23] It is a non-polluting technology that can produce green hydrogen. Renewable energy sources such as wind turbines and solar cells as well as waste heat from industrial operations can be used to power electrolyzer cells to produce hydrogen in a sustainable manner[24]Four water electrolysis technologies have been developed based on their operating conditions, electrolyte and ionic agents (OH-, H+, O2-): alkaline, PEM, solid oxide electrolyzer and AEM[22-23].

4.1 Alkaline water electrolysis

Alkaline water electrolysis is a widely recognized electrolysis technology for industrial hydrogen production up to multi-megawatt range in commercial applications all over the globe [26]. The alkaline water electrolysis concept was initially developed by Trooswiik and Diemann in 1789. The first industrial large-scale alkaline water electrolyzer plant became operational after numerous improvements in the year 1939[27].Over 400 industrial alkaline electrolyzer units were effectively installed and operated for industrial uses in the late early 19^{th}Century [23]. Despite that, the alkaline water electrolyzer functions at lower temperatures (30-80^{O}C) with a 5M KOH/NaOH concentrated alkaline solution. Furthermore, asbestos ZrO_2-based diaphragms and nickel (Ni) coated stainless steel electrodes are utilized as a separator [23].The hydroxyl ion (OH-) is the ionic charge carrier with Potassium Hydroxide (KOH) or Sodium Hydroxide (NaOH) and Water penetrating through the porous structure of the diaphragm to enable the functionality of the electrochemical reaction[28].

The alkaline water electrolysis is an optimal system design for large-scale applications. Currently, the cost of investment in alkaline water electrolysis is 500-1000 USD/kW, and the lifespan of the system is 90, 000 h [29].However, the main challenge linked with alkaline water electrolysis is limited current densities (0.1–0.5 A/cm^2)which is due to the usage of corrosive Potassium Hydroxide (KOH) electrolytes and moderate mobility of OH- ions. The resulting decrease in the number of hydroxyl ions and ionic conductivity is due to the high sensitivity of the (KOH) electrolyte to ambient Carbon dioxide (CO_2) and the subsequent formation of Potassium Carbonate salt (K_2CO_3). The salt derived from K_2CO_2 blocks the pores of the anode gas diffusion layer which results in the decrease of the ion transferability through the diaphragm and consequent decrease in the production of Hydrogen. Besides that, a low purity (99.9%) of hydrogen and oxygen gases is produced by alkaline water electrolysis due to the existing diaphragm not completely preventing the movement of gases from one half-cell to the other[23].

4.2. Anion exchange membrane (AEM) water electrolysis

AEM water electrolysis is an emerging technology to produce green hydrogen. In recent years, many research institutions/ organizations are earnestly working on the development of AEMWE due to its cost-effectiveness and high performance in contrast to other traditional electrolysis technologies[30].The AEM water electrolysis is akin to the traditional alkaline water electrolysis [31]. However, the primary distinction between the two is the replacement of the conventional diaphragm with quaternary ammonium ion exchange membranes in alkaline water electrolysis. AEM water electrolysis presents several advantages such as low-cost transition metal catalysts being utilized as an alternative to noble metal catalysts, low-concentrated alkaline solution (1 M KOH) / distilled water can be used as an electrolyte in place of high concentrated (5 KOH) solution [32]. Despite the considerable benefits, AEMWE still requires further improvements/ investigations towards cell efficiency and MEA stability and MEA stability which are more significant for commercial or large-scale applications [33]

4.3. PEM water electrolysis

The first PEM water electrolysis phenomenon was introduced by Grubbs and developed by General Electric Co. in 1966 to overcome the negative aspects of alkaline water electrolysis[25]. However, PEM water electrolysis technology is like the PEM fuel cell technology, where the sulfonated polymer membrane can be used as an electrolyte. The Hydrogen ion (H^+) is the ionic charge carrier, and the functionality of the electrochemical reaction is provided by deionized water permeating through the proton-conducting membrane. Generally, PEM water electrolysis operates at lower temperatures(30-8^{o}C) with elevated current densities and (1-2 A/cm^2) and yields a high purity (99.999%) of gases hydrogen and oxygen gases[25]. Due to the lower pH of the electrolyte and the highly active area of the metal surface of Pt electrodes, the kinetics of hydrogen evolution reaction in PEM water electrolysis is faster than in alkaline water electrolysis. Furthermore, PEM water electrolysis poses fewer risks than alkaline water electrolysis due to its smaller footprint and absence of caustic electrolytes. Thus, many water electrolyzer manufacturers globally develop large-scale (up to MW) PEM water electrolyzers for transportation and industrial use. The reported stability of PEMWE with negligible loss of performance is 60, 000 h and a 1, 000,000 targeted stability [28],[33]. Even so, the key challenges pertaining to the PEM water electrolysis are high-priced components i.e., bipolar plates, electrode materials and current collectors.

4.4 Solid Oxide Water Electrolysis

The solid oxide water electrolysis cell (SOEC) is an electrochemical conversion cell that converts electrical energy into chemical energy. Its development was begun in the USA by General Electric and Brookhaven National Laboratory in the 1970s, followed by Dornier in Germany [35]. Typically, the SOEC operates using water in the form of steam at elevated temperatures (500-850^{o}C) which can significantly reduce the power consumption to split water into hydrogen and oxygen as a result, the energy efficiency is increased. This enhancement in the efficiency of energy can lead to a significant reduction in the cost of hydrogen as the power consumption is the key contributor to the cost of hydrogen production in electrolysis [23]

Moreover, Solid oxide water electrolysis offers two key benefits over the existing electrolysis technologies i.e., high operating temperatures which lead to favourable thermodynamics and reaction kinetics enabling incomparable conversion efficiencies. Secondly, solid oxide water electrolysis can be thermally integrated seamlessly with downstream chemical synthesis (production of ammonia, dimethyl ether and methanol [23].In addition, the solid oxide water electrolysis gives high conversion efficiencies and does not require the usage of noble metal electrocatalysts. Despite these advantages, the lack of sufficient long-term stability has obstructed the commercialization of solid oxide water electrolysis. At present, the reported stability is only 20,000 h [23]

Over the past few years, there have been numerous developments in the production technologies of green hydrogen, which have the potential to make green hydrogen production more cost-effective, efficient and scalable. Currently, the cost of green hydrogen is approximately $2,50-6.80 /kg [185]. However, the price of green hydrogen will soon be competitive with blue hydrogen as it is decreasing massively due to the combined impacts of reduced electrolyzer costs and cheaper renewable energy[22].

5. Economic factors

Key economic parameters discussed below are essential for assessing the financial feasibility and attractiveness of green hydrogen projects.

5.1. Levelized Cost of Hydrogen

The levelized cost of Hydrogen is a critical indicator for investors, policymakers and industry stakeholders to consider when assessing the economic viability of green hydrogen production and its potential to drive progress towards a more sustainable energy future. Evaluating the techno-economic feasibility of green hydrogen for decentralized energy systems is dependent on several key aspects such as capital, renewable electricity cost, transportation and storage.

5.2 .Net Present Value (NPV)

The profitability of a project is evaluated via NPV. It entails contrasting the present value of the projected cash inflows with the present value of expected cash outflows related to the project.

5.3 Internal rate of return (IRR)

IRR is the discount rate that equates the NPV of a study or project to zero.

5.4. Simple payback period (SPP)

SPP measures the duration necessary for an investment to recuperate its initial investment cost through the cash flows it yields.

6. Assessment tools for decentralized hydrogen production.

Modelling, simulation, optimization of renewable energy systems (RES) and sensitivity analysis in the context of environment, technology and economy are highly intricate matters. These matters are complex to analyse if there is no computer software for auxiliary calculation. Hence, several available software's are developed to aid researchers in analysing them. Below is a brief description of modelling and simulation tools that particularly focus on stand-alone applications of renewable energy such as local community, single project applications or single building.

6.1 HOMER (Hybrid Optimization Model for Electric Renewables)

Homer is a user-centric, small-scale power generation design tool developed by the National Renewable Energy Laboratory in 1992. The tool simulates and optimises off-grid and grid-connected power systems using various combinations of PV arrays, wind turbines, biomass power, run-of-river hydropower, internal combustion engine generators, fuel cells, batteries, micro turbines, and hydrogen storage, serving both thermal and electric loads (by district or individual- heating systems). Additionally, overall costs (including any emission penalties) excluding taxes and fuel handling costs are included. The simulation considers one year utilizing a minimum time step of 1 minute. It conducts a sensitivity analysis which can aid the analyst to do 'what if' analyses and to examine the effects of changes or uncertainty in input variables. The aim of the optimisation- simulation is to assess the economic, and technical feasibility of a multitude of technology options while considering variations in energy resource availability and technology costs[36].

Jahan et al[37]carried out a study for the Trout Lake community in Canada utilizing the HOMER software to design and optimize a hybrid renewable energy system (HRES) that incorporates wind turbines, solar PV panels, fuel cells, batteries and thermal load controllers. The software enables the simulations of different configurations to determine the most optimal combination for meeting the community's electricity, hydrogen and thermal demands. The results highlight that the best-case scenario achieved a low cost of energy (COE) of$0.675/kWh and a notable 99.99 % decrease in carbon emissions relative to diesel-based systems. The HRES features a renewable fraction (RF) of 93.5 % and a 58.3 % reduction in excess energy (EE), illustrating its reliability and efficiency. Furthermore, battery storage was determined to be the most cost-effective option for the study while fuel cells support the production of hydrogen for fuel-cell electric vehicles[37].

Homer software was utilized by Nag and Sakar [38]to simulate and optimize various hybrid renewable energy configurations, entailing solar, wind, bioenergy and hydrokinetic systems, particularly focusing on rural areas in Jharkhand, India. The software aids in evaluating the performance of different system combinations against the energy demand profiles, assessing the cost-effectiveness utilizing metrics such as cost of energy (COE) and Net Present Cost (NPC), and executing sensitivity analysis on key parameters like wind speeds and biodiesel prices. The results indicate that energy demands at lower costs can effectively be met through optimal configurations combining these renewable energy sources with COE values reducing gradually[38].

6.2 HYDROGEMS

Hydrogems constitute a set of hydrogen energy tools that are well-suited for the simulation of integrated hydrogen energy systems; specifically renewable energy-based stand-alone power systems[36]. The tools were developed by the Institute for Energy Technology in 1995. HYDROGEMS tools can be employed for the analysis of hydrogen energy-systems performance down to one-minute time steps. The tools are designed to simulate electrical consumption, hydrogen mass flow, and electrical production however, they can also be utilized to simulate the thermal performance of Integrated hydrogen systems. The HYDROGEMS library encompasses the following system components: photovoltaic system, wind energy conversion systems, electrolysis, hydrogen gas storage, fuel cells, hydrogen compressor, metal hydride hydrogen storage, secondary batteries, diesel engine generators (multi-fuels including hydrogen), power conditioning equipment. The system components are based on electrochemistry, thermodynamics, and applied physics[36]. The empirical parts of the tool are designed to ensure default parameters can be found and/or coefficients calibration based on data retrieved from literature (e.g. journal papers, product data sheets and articles). The availability of accurate data from the hydrogen system being modelled is crucial to ensure the validity of the models being designed. From an economic standpoint, investment, fuel process, fixed and variable operational and maintenance costs can all be accounted for[36].

The study conducted by Nakken and Ete[39]on the Utsira wind/hydrogen demonstration system using the Hydrogems modelling tool offers an in-depth evaluation of the system's performance. The study highlights the system's notable ability to provide 2-3 days of energy autonomy for local households, effectively depicting the potential of wind-hydrogen systems in remote and off-grid locations where conventional energy sources may be limited or inaccessible. The study successfully validated the reliability and accuracy of the HYDROGEMS models, by calibrating the simulations with actual operational data acquired over a representative month, which accurately captured the complex dynamics of hydrogen production and storage. Significant pressure fluctuations were observed due to the variability of the wind energy availability, emphasizing the relevance of understanding these dynamics for effective system design and operation[39].

6.3. TRNSYS16

TRNSYS is a systems simulation program that has been available for purchase since 1975. The tool is presently maintained by an international collaboration from the United States (Thermal Energy System Specialists and the University of Wisconsin-Solar Energy Laboratory), France. 16 versions of the program have been developed thus far. TRNSYS consists of an open modular structure with an open-source code that simulates the electricity and heat sectors of an energy system. TRNSYS simulates the performance of the entire system by splitting it into individual elements, and it is essentially used for analysing local communities, single-project, or island energy systems. It can simulate thermal and renewable generation except for tidal, wave, hydro and nuclear power. TRNSYS only considers battery energy storage, while hydrogen systems are simulated in detail utilizing the HYDROGEMS tool. TRNSYS has been utilized widely to simulate conventional buildings, solar energy applications as well as biological processes[36].

Anoune et al[40]employed TRNSYS software to develop an HRES model, optimized the system using WM and YAM methods and compared the optimization in terms of performance and cost. The results indicate that the optimization result of the YAM method is cost-effective, but it can only be applied in grid-connected systems. Buonomano et al. [41]developed a PV-Wind hybrid power plant model combined with an energy storage system and simulated it with TRNSYS. To study the hydrogen production by water electrolysis, Karacavus et al.[42]employed TRNSYS to develop a solar photovoltaic power generation model. GenOpt was used for optimization and the model was applied to three cities in Turkey for analysis its feasibility was verified. Oueslati et al. [43]developed a PV/WT/FC/Diesel HRES for a village in Tunisia. The off-grid power demand was used as a load and optimized the system to lower the costs and carbon dioxide emissions based on fulfilling this load.

7. Conclusion

In conclusion, this review highlights the significance of decentralized hydrogen production as a key strategy for attaining a sustainable energy future. By harnessing alternative renewable energy sources, such as solar and wind, the potential for green hydrogen production can substantially contribute to the decarbonization of the energy sector. Favorable economic conditions such as LCOH, NPV, IRR and SPP can make decentralized hydrogen systems both feasible and compelling. The modelling and simulation tools discussed – HOMER, TRNSYS16 and HYDROGEMS - provide basic frameworks for optimizing the hydrogen production systems and guiding decisions on investments. To achieve the full potential of decentralized hydrogen production, it is of paramount importance to address the technological economic barriers through joint initiatives among researchers, policymakers and industry stakeholders.

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