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Comprehensive Analysis of Design Trends in Scattered Power Systems Utilizing Hydrogen as the Power Carrier

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Abstract: In this paper, the technological applications of hydrogen in the distributed energy systems are explored and various technological solutions such as gasification units, fuel cells, electrolyzers, hydrogen storage methods and methanation reforming reactors are analyzed. The study shows that electrolysis and fuel cells are widely recognized as the preferred technologies for incorporating hydrogen into energy systems, with alkaline electrolyzers in particular being favored for their greater capacity and technological advantages. Besides, research on hydrogen storage has focused on gas storage methods, as liquefied hydrogen requires great economic and energy inputs at low temperatures and high pressures. End uses of hydrogen include hybrid fuels, storage media and industrial raw materials. The results show that the widespread use of hydrogen energy storage is a direct result of the integration of renewable resources and indicate the potential of distributed energy systems for the sustainable provision of transportation fuels and raw materials. In addition, it analyzes a systematic assessment of hydrogen as an energy source, focusing on economic, technological, and environmental issues, noting that about 80% of the studies focus on economic factors, and emphasizes the importance of establishing an integrated framework to facilitate the application of hydrogen technology.

Keywords: Distributed Energy System (DES), Carbon Neutralization, Hydrogen Conversion, Renewable Energy Sources

1. Introduction

In 2017, global energy demand grew by 2.1%, and is projected to increase by 30% by 2041 compared to current consumption levels, equivalent to the additional demand of India and China. Although this growth rate has slowed down from 40% between 2010 and 2020, the continued expansion of the global population and economy, as well as growing concerns about climate change, continue to pose new challenges for the energy sector. Energy use is now a major source of CO2 emissions, and future trends suggest a significant increase in the share of electricity in final energy consumption, further driving the rapid development of renewable energy sources, especially before 2018, despite its share being only 30%. In addition, energy security is threatened by the limited availability of conventional energy sources, and there is an urgent need to provide sustainable electricity to the 1.19 billion people worldwide without access to electricity, mainly in developing countries and rural areas. The advent of distributed energy systems (DES) and the continued rise in the share of renewable energy sources

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are reshaping the way energy systems are planned and operated . The study aims to provide an insight into the application of hydrogen in distributed energy systems, focusing on the key criteria that should be considered in the design, planning and operation of these systems. The study covers technologies such as electrolysis, reforming and gasification, as well as the end uses of these technologies in storage, fuel and raw materials. Through a review of the relevant literature, this paper analyzes the technological, economic, and environmental related objectives that can set the stage for future research priorities, especially in integrating hydrogen-based distributed energy systems, to address the paradox between the rising global energy consumption and the transition to sustainable energy.

2. Multiple Roles and Advantages of Hydrogen in Distributed Energy Systems

Hydrogen, as an energy carrier in distributed energy systems, has a high energy density, enabling it to store and transport large amounts of energy in a lightweight form. Hydrogen can be generated from a wide range of renewable energy sources, such as water electrolysis via solar or wind power, making it a sustainable solution for energy storage and distribution. Its adaptability allows it to be utilized for power generation fuel cells, heating and industrial feedstock. And hydrogen combustion produces only water vapor as a by-product, helping to reduce greenhouse gas emissions. However, challenges remain, including efficient production, storage and distribution infrastructure, as well as economically viable technical solutions to facilitate its widespread use in the energy sector. Hydrogen plays a key role in enhancing the efficiency and sustainability of energy transmission [1]. A major advantage of hydrogen is its ability to store excess energy generated from renewable energy sources such as solar and wind, mitigating the intermittency of these sources. Hydrogen can provide a stable and reliable flow of energy when demand exceeds supply. It can also be converted to electricity through fuel cells, which are suitable as a clean energy source for transportation and grid support, emitting water vapour and greatly reducing greenhouse gas emissions. Meanwhile, it can be integrated with natural gas into existing infrastructure, facilitating a smooth transition to a clean energy system [2]. The introduction of hydrogen enhances energy independence in distributed energy systems, especially in remote or off-grid areas, where localized generation and use can boost energy security. Its versatility, ecological advantages, and fit with renewable energy sources make hydrogen an important component in driving the transition to a sustainable energy system.

DES is decentralized energy systems designed to generate, store, and disseminate electricity at or near the point of use. These systems enhance the resilience, stability, and efficiency of energy distribution by integrating multiple renewable energy sources (e.g., solar, wind, and biomass) with traditional energy production methods [3].The goals of DES include reducing transmission losses, lowering greenhouse gas emissions, and enhancing energy security through local energy production and consumption. Its technological architecture covers several important components, including renewable energy generation (e.g., solar photovoltaic systems for on-site power generation, wind turbines, biomass generators, and hydropower systems) as well as standby generators and cogeneration systems that work in concert with renewable sources [4]. For energy storage systems, lithium-ion, lead-acid, and flow batteries are used to store excess energy generated from renewable sources, while thermal storage systems store heat for subsequent utilization and integration with renewable heat sources [5]. In smart grid technologies, Advanced Metering Infrastructure (AMI) provides real-time data on energy use and production, while demand response technologies help balance supply and demand by enabling users to adjust their energy consumption to grid demand. In addition, energy management systems (EMS) enhance generation, storage, and consumption efficiency through software and algorithms, and distributed control systems facilitate decentralized decision-making and management of energy generation and transmission. Microgrid technologies enhance resilience and provide localized energy support by providing solutions that operate independently or in concert with the main grid through local energy grids [6]. Integration of electric vehicles enables vehicles to return energy to the grid, enhancing storage and balancing functions. Finally, interconnection standards and regulatory frameworks ensure that distributed energy resources (DERs) are safely and reliably integrated into the existing energy grid. The integration of these components enables DES to construct a more flexible, sustainable, and efficient energy ecosystem that is capable of meeting local energy demands and advancing overall energy goals.

DES provides a paradigm shift in the energy framework by strategically placing smaller units near energy customers to replace or complement large conventional centralized power plants. This concept aims to address long-standing issues in the energy industry, such as the challenge of supplying power to remote areas, and thus provide a reliable pathway for the energy transition [7,8]. Hydrogen has been recognized as an important sustainable energy carrier to combat air pollution, climate change and energy security [9]. Although hydrogen is the most abundant element on earth, it does not naturally occur in pure form. However, this fact does not constitute an obstacle, but rather creates a wealth of opportunities, as hydrogen can be accessed through a variety of sources, including biomass, fossil fuels, nuclear energy, and renewable energy [10]. The use of hydrogen for energy storage has the potential to act as an intermediary between chemical, electrical, and thermal networks through the process of energy transgasification [11].

Above mentioned papers provide a comprehensive overview of key principles concerning distributed power systems, including intrinsic structures, features, as well as small-scale utilization [12]. The work [13] provides a comprehensive analysis aimed at identifying the many models put up for energy applications. A study on the future prospects of hydrogen in energy systems at regional and national levels, together with its factors and obstacles, is examined [14]. Several researchers have focused on hydrogen-related generation techniques, storage devices and safety concernment. Additionally, numerous perspectives of hydrogen regarded as power transporters could be addressed in references. Also, researcher [15] introduces a study on the notion of totally renewable power, also emphasises the significance of fuel cells in the changing power landscape of deposit and transportation industries. This paper illustrated a comprehensive analysis of hydrogen alternatives in energy systems, focussing on their smartness. The analysis is based on a sustainable-based portfolio that encompasses several concepts such as greenization, exergization, hydrogenization, renewabilization, multigeneration, storagization, integration, as well as intelligence. A comprehensive analysis of analyzing tools for hydrogen-related renewable power organization, including the constraints and capabilities, is conducted within reference [16]. The research provides a comprehensive categorisation of agent-based modelling approaches used in the context of energy grids, and their significance in facilitating the alignment of stakeholders. [17] Fathima et al. [18] provide a comprehensive overview of the current cutting-edge utilization and optimisation techniques inside microgrids that incorporate greensnf extendable energy sources. The focus is on optimisation targets and methodologies. A comprehensive analysis of energy-to-gasification pilot factories is available [19], encompassing both the currently operational plants and the ones now under planning globally. Additionally, this paper provides details on components, capabilities, and acquired expertise during the operation of the systems. It emphasises the impact of the designation, dimensions, and operational methodologies on the effectiveness and dependability of these schemes.

Moreover, numerous publications have been released on the subject of hydro-energy generation and storage. Regarding production stage, the analyzing of the present energy landscape is presented, focussing on the key features, advantages, and disadvantages of the hydrogen manufacturing process. Similarly, in reference [20], 19 methods of hydrogen production are examined and contrasted within the framework of sustainability. This evaluation includes the assessment of exergy and energy efficiency, global tendency of warming, and social/political cost of carbon emission. Regarding hydrogen storage, a comprehensive review of technologies is provided in reference [21], including their latest advancements and insights from industry. A process-oriented analysis of storage requirements and performance is conducted [22], specifically focussing on long-term conservation. The difficulity of the hydro gas provision chain has been examined in references [23, 24], with the aim of comprehending the mechanisms for including the hydrogen supply routes into models of bottom-up energy systems. Furthermore, Demir et al. [25] presents an analysis of the environmental and economic-relevant evaluation of three distinct hydro gas transfer scenarios, encompassing conservation, transfer, as well as distribution conditions. Several publications have been published on the evaluation of the economical-social-technical advancement of Distributed Energy Systems in urban designing and regulations. The novelty of the current study resides in its universal approach to analyse DES, particularly in the context of hydrogen integration.

3. Hydrogen Energy and Deionized Energy Storage in Renewable Energy Systems

The increasing interest in DES has led the scientific community to put forth a multitude of aggregation concepts and methodologies. Microgrids enhance resilience through decentralized generation from local resources and facilitate the integration of renewable energy sources. Multi-energy systems aim to transform sector-oriented energy systems (e.g., electricity and heating) into interconnected networks that capitalize on the synergies of different energy sources. Multi-generation involves the production of multiple energy carriers through a single operation, such as combining a fuel cell with a combined heat and power (CHP) plant. Hybrid energy systems use multiple conversion devices to meet energy demand, such as power plants that utilize both wind and solar energy. Integrating diverse energy transmissions is a key challenge when transforming power systems, and hydropower is an attractive alternative due to its ability to connect various energy networks. Hydrogen is seen as a versatile energy carrier that can be used as a fuel and feedstock and as an interface between chemical and electrical energy in electrification gasification processes. Specifically, hydrogen can be used as a storage material to balance fluctuations in renewable energy sources or as a feedstock for the generation of syngas through methanation reactions. In addition, its ability to contribute to the reduction of carbon emissions in certain chemical-physical processes and in the transportation industry makes hydrogen an important energy carrier to address environmental and energy issues [26]. Although hydrogen is the most abundant element, it is mainly combined with oxygen and carbon rather than alone.

Table 1: Features and Obstacles in Hydrogen Manufacturing Technology

Technology	Advantage	Disadvantage	Challenges
Steam reforming	Well-established and thoroughly developed technology Optimal thermal efficiency Most cost-effective manufacturing technique (now)	Substantial energy use and high operational expenses Carbon dioxide emissions Deactivation of catalysts	Optimise production purification Enhanced proceure intensification using membranes
Gasification	Surplus and inexpensive raw material (biomass) Eco-friendly Well-suited for extensive manufacturing	Soaring capital expenditure Expensive heat exchanger Efficiency of the system Emissions of greenhouse gases	Purification of products Management of feedstock variability Analysis of process cost and efficiency

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Table 1: (continued).

Electrolysis	Emission-free - decarbonized route Absolute purity of hydrogen Integral relationship between electrical and chemical energy	Excessive power usage Suboptimal system efficiency High initial investment cost	Optimise productivity Renewable energy sources incorporation Robust and cost-effective materials
Fermentation	Fundamental reactor technology Independence from light and oxygen Extensive range of carbon sources can be utilized	Suboptimal hydrogen production Substantial amounts of secondary products are generated. Variability between reactors	Analysis of process efficiency and cost Studies in metabolic-related engineering Significant advancement in materials engineering Enhance the selectivity for hydrogen

Thermal reforming of natural gasification is regraded as the most advanced and widely used technology for hydrogen production globally. This process involves the correlation between steam and methane to generate possible syngas, as shown in Eq.1 where a combination of carbon monoxide as well as hydrogen. Typically, this reaction is conducted with a catalyst on nickel, at temperatures and pressures of 700 to 900 ℃ with pressure being from 3 to 25 bar. In addition, in order to increase the hydrogen content, the resulting syngas must undergo a gas-water conversion equation, as in equation 2, which ultimately produces carbon dioxide and hydrogen. Ultimately, the gas vapour consisting mostly of H2 is separated and purified using the pressure swing adsorption method for achieving the specific level of hydro-gas purity needed for its intended application.

$$\mathrm{H_2O + CH_4 \ = 3H_2 + CO} \tag{1}$$

$$\mathrm{H_2O + CO \ = H_2 + CO_2} \tag{2}$$

Typically, reformers are partially designed as large infrastructures (150-300 MW) and are mainly used to meet the needs of the refining and chemical production sectors. These units utilize proven technologies and can achieve efficiencies of 70 to 85 percent. In keeping with the current trend towards decentralized systems for energy and the expected use of water gas as a power source for transportation, the reforming technology is being adapted to small-scale hydrogen processing. The electrochemical process of electrolysis involves the separation of water into hydrogen and oxygen by means of an electric current, as in Eq. (3). During this process, electrons are transferred through ionic species and a circuit is formed.

$$\mathrm{2H_2O \ \rightarrow 2H_2 \ + O_2} \tag{3}$$

Alkaline electrolyzers now represent advanced and established technology, employing a sodium or potassium hydroxide solution (23-40% wt.) as the electrolyte and function, with an efficiency up to 70-80% [27]. The efficiency of the electrolyzer ranges from 65% to 80%, and operate at temperatures ranging from 25 to 80 ℃ [28]. PEM technology has several benefits, including its hydrogen purity and superior power density, rapid response time, and ability to function throughout a broader load range and at higher pressures compared to alkaline systems. Yet, their performance is constrained by the membrane's lifespan and the catalyst's cost. Currently, although the electrolysis alternative offers great potential, Solid Oxide Electrolysis Cell (SOEC) is the least developed technology and its progress is limited to laboratory-scale operations. In contrast, alkaline and Proton Exchange Membrane (PEM) electrolyzer systems are now available at megawatt scales. Their costs are typically two to more times lower than electrolysis [29]. However, due to ongoing technological and research advancements within electrolyzers and implementation of larger plants, a substantial reduction in the operating expenses and investment is anticipated within the following years [30]. Nevertheless, the production of CH, H_2S, CO_2, and NH_3 can also occur, contingent upon the feedstock and experimental parameters. The process of gasification includes several sequential stages. The initial step entails the extraction of drying, followed by a physical/chemical breakdown with heating in oxygen-free atmosphere (pyrolysis) to liberate volatile chemicals (mostly CH, Co, H_2). In the subsequent stage, the system is provided with an oxygen-controlled sphere to promote volatile matter combustion. Under temperatures ranging from 800 to 1300 ℃, the gasification process concludes, as shown in reactions between the coal and a syngas mostly consisting of O_2, H_2 and CO_2 as in Eq.4-Eq.7. Depending on the intended application of the syngas, it undergoes additional water-gasification transition reaction with purifying procedures to be utilized as power or as a original sources for synthetic natural gas and methanol synthesis (methanation) respectively.

$$\mathrm{C(s)} + \mathrm{O_2} \rightarrow \mathrm{CO_2} \tag{4}$$

$$\mathrm{O_2} + 2\mathrm{C(s)} \rightarrow 2\mathrm{CO} \tag{5}$$

$$\mathrm{H_2O} + \ \mathrm{Cs)} \rightarrow \mathrm{H_2} + \mathrm{CO} \tag{6}$$

$$2\mathrm{H_2O} + \mathrm{C(s)} \ \rightarrow 2\mathrm{H_2} + \mathrm{CO_2} \tag{7}$$

Dark fermentation is the metabolic process carried out by an anaerobic bacteria that interacts with organic material to generate a gas stream consisting from H_2 and CO_2. This method has two primary benefits: the ability to utilize a diverse range of waste as raw material and its straightforward reactor technology, which allows for the acceptance of even nonsterile conditions and contaminants without compromising the process performance. Nevertheless, the limitations arising from the buildup of by-products within the equipment and challenges associated with hydrogen purification process are process constraints that require additional investigation. Conversely, anaerobic digestion is a biological process in which various microorganisms break down the large molecules within biomass for generating biological-gas (a combination containing methane and carbon dioxide), subsequently undergoing a reforming process to make hydrogen. Apart from synthesis options, the dependable use of hydrogen serving as an energy container is closely linked to the efficiency of the storage. Specifically, hydrogen can be held either as the compressed vapour or in liquid cryogenic form, and in solid state with metal hydrides. This method has great potential since it offers increased volume densities under operating conditions not involving the safety risks associated with pressured and cryogenic processes [31]. Nevertheless, this techique is still in its former stages of development and faces several unresolved challenges, including the expansion of material volume caused by the stress generated by the desorption/adsorption cycles [32].

4. Analysis and Evaluation of Technological Applications of Hydrogas

4.1. Application Analysis

This paper provides an analysis of several technological solutions, including gasification units, fuel cells (FC), electrolyzers (EL), hydrogen storage methods as well as methanation reforming reactors.

Figure 1 illustrates electrolysis and fuel cell are acknowledged as the more favored technologies for incorporating hydrogen into energy systems. It is widely acknowledged that the greater capacity and technological advancement of Alkaline electrolyzers were superior than other methods, while SOEC and PEM alternatives are selected for their optimal responsiveness to actual arrangement or energy efficiencies. Figure 1 displays the distribution of FC and EL technologies, with PEM type being the predominant technology for both electric and fuel cell applications.

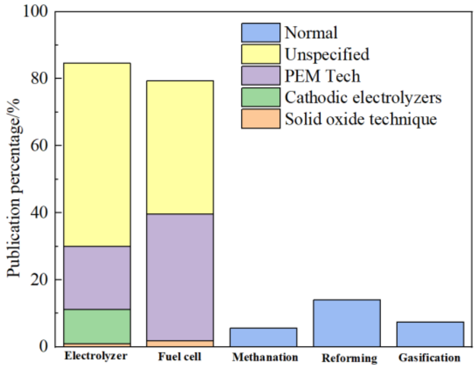

Figure 1: Publication Analysis in Terms of Hydrogas Generation Technologies

The data in Figure 2 depicts the analysis of FC and ELof the examined power systems. Most studies focus on utilization of electricity demands (less than 200 kW). The majority of case studies used to assess Domestic Energy Systems with hydro-gas as the power source are small villages or households. The finding presents a potential avenue for expanding research, backed by technology advancements, towards the implementation of such systems in broader applications. It is noteworthy to mention that no research on hydrogen storage options including liquid storage of hydrogen were identified. The major reason for this is the significant economic and energetic expenses involved in liquefying and maintaining it as a liquid phase under conditions of low temperature and high pressure . Among these articles discussing a particular type of hydro-gas conservation, the most desired one is gas stored in pressure tanks, accounting for 58% of the reports. Natural gas pipelines, metal hydride adsorption, and subterranean sea caverns are employed as alternate methods.

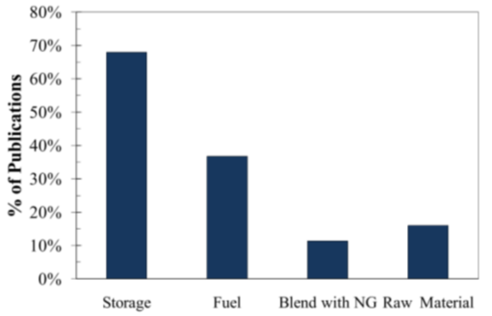

Figure 2: Distribution of Hydrogen Applications of Distributed Energy Systems within Publications

With respect to end-uses, the identified applications of hydrogen include mixed fuel containing natural gas, as fuel, as a storage medium, and as a original resources for industry. The conservation choice pertains to situations when the sole goal is to effectively address the excess renewable production by means of an electrolyzer-storage cell system. This includes use in transportation (e.g., buses and automobiles), integrated heat and power systems, and gas turbines, including fuel-related uses. This raw material group encompasses the utilizationutilization of syngas in the methanation procedure and the sale of hydro-gasgen for chemical sectors. It should be emphasized that hydrogen

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uses are not mutually exclusive. Consequently, research studies exploring more than one or even the complete range of potential applications were identified. As shown in Figure 2, the results indicate that the widespread use of hydrogen for energy storage is a direct response to the significant integration of intermittent renewable resources in DES. Based on the above findings, it's noteworthy that DES embrace the potential to offer a sustainable fuel for transportation and to provide the compound sector with extendable-derived original resources. This reality gives a considerable prospect for the social and economic advancement of organizations, as they may not only meet their energy requirements but also contribute as hydrogen providers, utilizing their local resources.

4.2. Performance Evaluation

The research to assess energy systems utilizing hydrogen serving as an energy sections focuses on economic, technological, and environmental concerns. The analysis of research works based on their evaluated objective was shown in Figure 3. This underscores the widespread occurrence of economic concerns, which are implicated in about 80% of research. Significantly, roughly 45% of articles use multi-objective analysis. Among these, 9 research works tackle economic, environmental and technical objectives concurrently, and one of the three also considers the health effect expense resulting from contamination (social element).

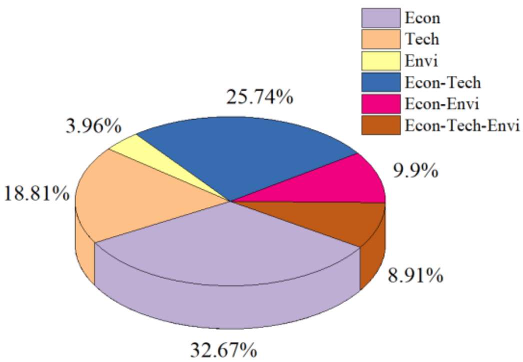

Figure 3: Analysis of the Performance Distribution Targets Assessed in DES from Publications. (Environmental, Technical, Economic).

Summarily, the findings of this study could be categorised into two primary topic groups: one pertaining to technique matters, while the other addressing methodologies and study goals. According to the first section, which pertains to hydrogen-related conversion and generation technologies, the findings provide fundamental data (such as technology types and equipment dimension) which would be useful for the first phases of research planning of DES (Deep Energy Storage) systems utilizing hydrogen.

5. Conclusion

This extensive literature review of dispersed power systems employing hydro-gas as an energy transport produces several notable conclusions: The research delineated several areas for the application of hydro-gas systems, encompassing buildings, communities, households, existing power plants, and universities. This diversity highlights the adaptability of hydro-gas applications across various contexts, enhancing energy resilience and sustainability. The analysis indicated a significant incorporation of renewable energy sources, including solar and wind, with hydro-gas systems. This underscores the capacity of hydro-gas to augment renewable power, mitigating issues associated with energy intermittency and reliability. The emphasis on hydrogen technology offers significant opportunities for persons pursuing careers in hydrogen-related domains, highlighting the demand for proficient professionals in this burgeoning sector.

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