A Review on Electrolyser and Hydrogen production from wind Energy

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***Abstract* -In this paper, a brief review on technologies of electrolyser fed by renewable energy sources and specially by wind turbine to produce the hydrogen is presented. Indeed, one of the most developed technologies of renewable energy is wind energy to be integrated into power grids. However, wind power generation is highly dependent on weather conditions and so the intermittent production of electricity by wind turbines should be managed. Energy storage system may be a good solution in order to deal with their stochastic operation. Based on a brief review, this study reveals the potential role of hydrogen as a multifunctional storage application for wind energy among the different solutions. Clean hydrogen can be produced by a simple process of converting electricity into gas by water electrolyser, especially in regions which have potential in renewable energies. The capability of electrolysis could potentially answer the variable electrical load demand of the station by using of on-site hydrogen tanks because hydrogen can be stored and used when it is needed.**

***Keywords*-Hydrogen; Wind energy; Water electrolyser; Energy storage; Renewable energy**

I. INTRODUCTION

Primary energy consumption increases by about 2% per year and most energy is derived from fossil fuels, which has accelerated global warming as well as other elements of climate changes [1]. Multiple actions such as political decisions and technical solutions are needed to enable a rapid transition to a free CO2 production. According to the Paris Agreement adopted by consensus in 2015, a global transition to renewable and low-carbon energy technologies is mandatory [1]. Among renewable energy technologies, offshore wind turbine is the most cost-effective and one of the industrially mature renewable energy sources. This technology has undergone outstanding development in recent years, with wind farms rated up to 1000 MW [2]. Wind power generation is weather-dependent and so, there are a large quantitative and temporal gap between electricity supply and the energy demand. Thus, to optimize the use of wind energy, it may be necessary to use energy storage technologies with the wind energy conversion system [3]. More precisely, to achieve an optimize integration of wind energy, it is necessary to have the possibility to store excess energy. Figure 1 shows some technologies available for energy storage. While some technologies such as supercapacitors or flywheels are used to store a small amount of energy (up to 10 MW) for a short time (up to an hour) and release it quickly, it is necessary to use other technologies with the wind energy conversion system such as compressed air energy storage (CAES), pumped hydro energy storage (PHES) or hydrogen [3]. So far, the most common way to store large amounts of energy is PHES. The main disadvantage of this technology is that it requires specific geographical features for installation. Currently, hydrogen production is gaining prominence due to its energy density, high energy capacity and transportability [2]. In this paper, a brief review of hydrogen technology including the hydrogen production by electrolysers is presented and some research studied and industrial projected are mentioned.

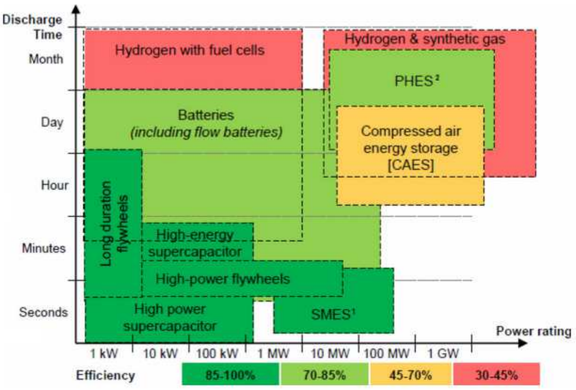

Figure 1. Current energy storage methods: SMES^1: Superconducting Magnetic Energy Storage, PHES^2: Pumped Hydro Energy Storage [3]

II. HYDROGEN PRODUCTION SYSTEMS

Hydrogen has the highest energy content of conventional fuels per unit weight, i.e. the energy content of hydrogen is about three times that of gasoline [4]. In recent years, interest in production of hydrogen has increased. That is expected to play a major role in the world's current transition to a cleaner and more environmentally friendly place. Hydrogen is not a primary energy source, but an energy carrier capable of storing energy and delivering it whenever needed. Green hydrogen (i.e. hydrogen produced from renewable energy sources) has a great potential as it connects renewable electricity to a wide range of applications where direct electrification is not needed [5]. Hydrogen has been produced by electrolysis of water since the 19th century. However, today the share of hydrogen produced by water electrolysis on a global scale is limited. If the electricity is produced from renewable sources, hydrogen can be produced with almost zero carbon emissions. The production of hydrogen by electrolysis of water is therefore called upon to play an important role in the process of energy transition [6].

A. Water electrolysis

Water electrolysis from renewable resources is currently the most practical process for the production of hydrogen in industrial scales [7]. It is the process in which an electrical voltage is applied into electrodes to break down water's molecule into its components [8]. The produced oxygen is transported and is eliminated from the cell. Indeed, protons produced from the oxidation reaction which occurs at the anode are transported through a membrane towards the cathode. Then, they are reduced to molecule of hydrogen according to the reduction reaction. The overall chemical reaction is given by equation 1 [9]:

$$H_2O \rightarrow \frac{1}{2}O_2 + H_2 \tag{1}$$

B. Electrolyser Technologies

There are different technologies for the electrolysis of water. In general, methods of producing hydrogen by electrolysis can be divided into three categories based on different electrolytes, including alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE) [10] which are explained and compared in follows.

- *Alkaline electrolyser*

Production of hydrogen by Alkaline Water Electrolysis (AWE) is now a well-established technology and electrolysis plants with electrical power up to one megawatt (MW) are commercially available [11,12]. Alkaline electrolyser operates at a current density of 0.2 to 0.4 A/cm2. The energy consumption is approximately 4.5 to 5.5 kWh/Nm3 of produced hydrogen. The efficiency of this process is 50% to 60% and the purity of the produced hydrogen is 99.5% to 99.9%. The main challenges of this process are the low load efficiency and the slow response time, so this technology does not easily adapt to renewable energy fluctuations [10,12,13]. The reversible cell voltage was expressed by equation (2).

$$V_{rev} = V_{rev}(T, P_0) + \frac{RT}{2F}\ln\left(\frac{(P_c - P_{V,KOH}).(P_a - P_{V,KOH})}{a_{H_2O.KOH}}\right) \tag{2}$$

Where F is the Faraday constant (equals to 96485C/mol), T (in Kelvin) is the operating temperature, R is the universal gas constant (equals to 8.314 J/mol.K), $P_{a/c}$ (in bar) is the anode/cathode operating pressure, $P_{V,KOH}$ (in bar) is the vapor pressure of the KOH solution and $a_{H2O.KOH}$ is the water activity of the KOH solution [14,15]. The term $V_{rev}(T, P_0)$ corresponds to the reversible voltage as a function of temperature in the standard reference pressure (1 bar) [14]. Figure 2 shows a typical voltage-current characteristic for a 5kW electrolyser [17].

The activation potentials at the anode and at the cathode were calculated from the Butler-Volmer method which is given in equation (3) [15]:

$$V_{act}^{a} = \frac{RT}{\alpha_a F}\left[\ln\left(\frac{i}{i_0^a}\right)\right]$$
$$V_{act}^{c} = \frac{RT}{\alpha_c F}\left[\ln\left(\frac{i}{i_0^c}\right)\right] \tag{3}$$

Where $\alpha_{a/c}$ is the charge transfer coefficient, i (in A/cm2) is the operating current density and i_0 (in A/cm2) is the exchange current density [16].

The Faraday's law which includes the Faraday's efficiency term may be used to assess the amount of hydrogen produced by the electrolyser [14].

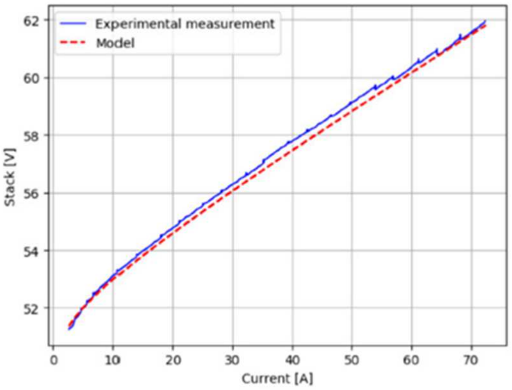

Figure 2. An example for voltage-current characteristics of a 5 kW, 33-cells PEMEL with an active area of 700 cm2 [17].

- *Electrolyser with proton exchange membrane (PEM)*

Proton exchange membrane electrolysis is a promising method for converting renewable energy sources into pure hydrogen. The main advantages of PEM electrolyser are flexible operation, high current density (0.5 to 2 A/cm2) and production of pure hydrogen [17,18]. They can operate with a greater flexibility and a quick respond, making them a suitable candidate for use in conjunction with renewables. The main bottlenecks of this technology are related to its cost, the complexity of the system and the high requirements for water purity [11,12,19].

The reversible cell voltage was expressed by equation (4).

$$V_{cell} = V_{0,el} + \frac{RT}{2F}\ln\left(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}}\right) + (R_{eq} + R_m)i + \frac{RT}{\alpha_a 2F}\ln\left(\frac{i}{i_0}\right) + \frac{RT}{\alpha_c 2F}\ln\left(1 + \frac{i}{i_{lim}}\right) \tag{4}$$

Where R_{eq} is the equivalent electrode and interface resistance, R_m is the membrane resistance and P is the pressure [17, 20, 21, 22].

The efficiency of a PEM water electrolysis cell can be expressed by equation (5):

$$\eta_{cell} = \eta_U \eta_F \tag{5}$$

With :

$$\eta_U = {V_{rev}}/{V_{cell}} \tag{6}$$

$$\eta_F = 1 - \frac{2F}{i}\left(\dot{N}_{H_{2,tot}} + 2\,\dot{N}_{O_{2,tot}}\right) \tag{7}$$

$\dot{N}_{H_{2,tot}}$ and $2\,\dot{N}_{O_{2,tot}}$ are the global rates of hydrogen and oxygen through the PEM membrane. In the above formula, it is assumed that all oxygen moving towards the cathode is electrochemically reduced with hydrogen generating water [14].

It is mentioned that the efficiency of a water electrolysis system can be represented by the equation 8 [17]:

$$\eta_{EL} = \frac{HHV\left(\frac{kWh}{kg}\right) \times produced\ hydrogen\ (kg)}{\left(\frac{Stack\ input\ energy\ (kWh)}{Power\ supply\ efficiency}\right) + Ancillary\ losses\ (kWh)} \tag{8}$$

In this equation, HHV is high heating value

- *Solid Oxide Electrolysis (SOE)*

It is also a relatively new technology and it is still used on a laboratory scale [12]. SOE works at temperatures between 700 and 1000◦C [11,24] which gives higher efficiencies (85% - 90%) than those of alkaline or PEM electrolyser due to better reaction kinetics. However, operation of the system at high temperature may lead to degradation of the materials [12,19].

Table 1 compares performance and maturity of the three hydrogen electrolysis technologies in terms of capacity, efficiency, cost and life of the electrolyser. From point of view of efficiency, SOE has the highest efficiency, followed by PEM, and alkaline electrolysis has the lowest efficiency [24]. However, alkaline electrolysis has the highest degree of industrialization than the other two electrolysis technologies [10].

Table 1. Performances and maturity of the three hydrogen electrolysis technologies [24]

Comparison Indexes	**Electrolysis Types**		
	Alkaline electrolysis	**PEM**	**SOE**
unit capacity (MW)	≤5	≤2	-
Electrolysis efficiency (%)	65-82	70-90	85-95
current density (A/cm2)	1~2	1~10	0.2~0.4
Electricity consumption (kWh/Nm3 H2)	4.5~5.5	~4.0	-
Operating temperature (°C)	70-90	55-80	700-900
hydrogen purity (%)	≥99.8	≥99.99	-
Cost (yuan/kW)	1500	＞4000	-
Life (h)	＞90000	＜50000	＜1500
degree of industrialization	Fully industrialized	Special applications, commercialization starts	still research on lab

C. Power Converters

Hydrogen can be produced by electrolysis of water, which is considered the cleanest production system, especially when the electrolyser is fed by renewable energy sources (RES) [25]. Unfortunately, the electrical energy produced by RES may not be used directly to produce hydrogen, because the voltage supplied by an RES system is not adapted compared to the supply voltage of electrolysers [26]. Power electronics is therefore a key interface whose size and performance can be optimized to maximize economic benefits as well as functionality and reliability between source and load [27]. Therefore, power electronics (converters and/or inverters) plays an important role to adjust the input voltage of the electrolyser and the output voltage of the electrical source [27]. Usually, a DC-DC converter is needed to couple the electrolyser to the system, especially in the hybrid system [25]. Among DC-DC converters, Buck converters may be used to feed electrolysers due to their simplicity and low cost. However, these topologies have several drawbacks, especially from the point of view of current ripple, availability and conversion ratio [28]. However, depending on the electrical network and the characteristics of the electrolyser, different topologies of DC-DC converters can be used [25]. For example a Buck converter including a second branch or compensation branch may be employed to minimize the output voltage ripple [26].

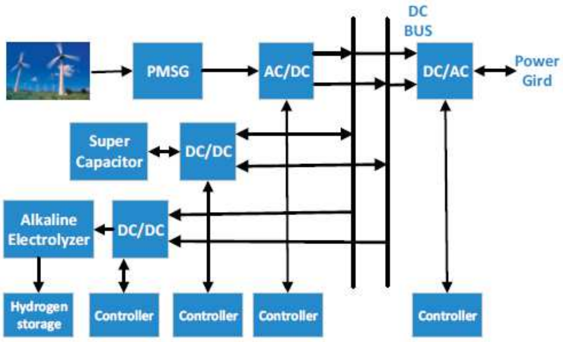

Figure 3. typical structure of a hydrogen production system with different types of power converters [30]

AC-DC power converters may be another choice for the flexible operation of electrolyser. However, if the electrolyser is coupled to the network through an AC-DC converter, special attention should be paid to the quality of the energy supplied to the cell in order to avoid additional losses [29].

Most of papers which deal with DC-DC converters and their controls for electrolysis applications only contain simulation results. Therefore, new contributions including experiments with electrolysers are needed to evaluate the real performance of the developed DC-DC converters and their control [26]. Figure 3 shows a typical structure of a distributed hydrogen energy system with energy conversion which uses the different types of power converters according to the energy supply nature [30].

III. STUDY OF AGING MECHANISMS OF ELECTROLYSERS

To use clean energy sources in the electrolysis of water, behavior of electrolysers should be evaluated. More precisely, fluctuations of the renewable source effect on the life time of electrolysers. In [31], authors have studied how the residual ripples of thyristor-based power supplies influence the operation load of the system, and how these ripples effect on the efficiency of alkaline electrolyser. For this purpose, they developed a simulation model and then, a model which is able to minimize the effect of ripple on the hydrogen production of alkaline electrolyser was proposed.

Paper [32] looked at the effects of ripples on the energy efficiency of the PEM electrolyser cell. The published results show that in the case of a sinusoidal current ripple and a thyristor bridge power supply, the average or RMS values of the voltage do not give a reliable estimation for the power quality. It is better that the waveform of voltage be monitored.

Reference [33] has investigated the effect of power supply converters on the specific power consumption of a MW-scale alkaline electrolyser and has compared it to an ideal DC power supply. The simulated modifications in power consumption of the alkaline electrolyser stack outweigh the losses that occur in the rectifiers. In addition, AC voltage level may have a more negative effect on power consumption with thyristor-based rectifier than with transistor-based rectifier.

Several studies have been carried out within the framework of the behavioral model of the electrolyser; however, the field

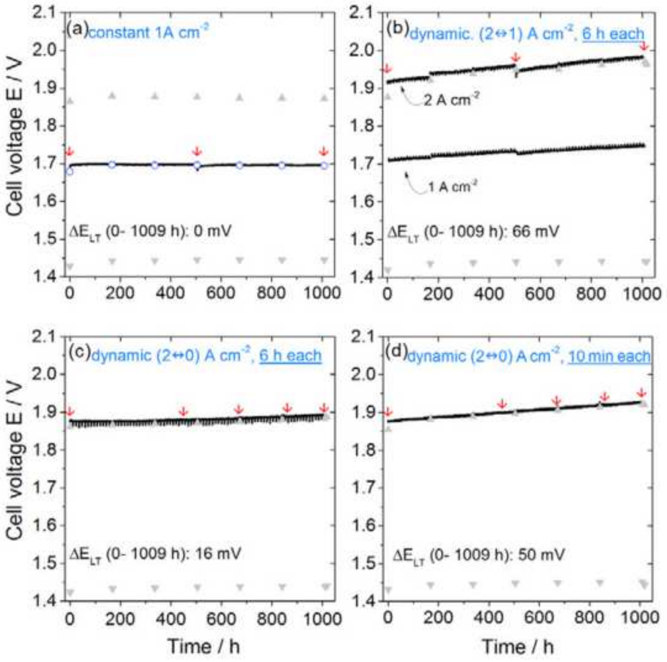

Figure 4. cell voltage under different operating modes: (a) constant current at 1 A/cm2, (b) current variations from 2 to 1 A/cm2 each 6 h, (c) current variations from 2 to 0 A/ cm2 each 6 h, (d) current variations from 2 to 0 A/cm2 each 10 min. [34].

remains open for the improvement of the production of energy through renewable sources. For PEM electrolysis, similar results can be concluded. This means that efficiency of the PEM electrolysers decrease at low load if thyristor-based rectifiers are used. This point is important since PEM electrolysis is often presented as the electrolysis technology which is well adapted into flexible operation [31].

Reference [34] summarizes fluctuating power characteristics for operation and system restrictions, for efficient operating methods and for configurations of water electrolysers, system requirements, lifetime, catalyst degradation and universal electrolyser performance. More precisely, it describes current achievements and challenges related to water electrolysers to promote the realization of a hydrogen-based society.

It should be mentioned that researches on start-stop operations of a single cell PEM water electrolyser has been clearly shown significant degradation on life-time. Figure 4 shows some test results with fluctuating power. In this figure, current variations from 1 to 2 A/cm2 each 6 hours or current variations from 0 to 2 A/cm2 each 10 minutes are presented. It is shown in this paper that the degradation could be occurred by an increase in titanium porous transport layer (PTL) contact resistance and by catalyst degradation in cathode (e.g., increased particle size and agglomeration). Conversely, no performance degradation was observed under a constant current of 1 A/cm2 (i.e. steady mains supply) or during the switching between constant currents from 0 to 2 A/cm2 each 6 hours. These results indicate that the PEM electrolyser can operate stably using constant power supply.

IV. Some Scientific and Industrial Projects in the World

As it is mentioned in above, utilization of wind energy which is essential for the development of a green energy system, may cause critical issues for the electricity grid. Indeed, the questions due to intermittency, fluctuation and variability of this resource should be answered [1]. To improve the flexibility of systems, production and storage of hydrogen is a good choice [1]. Recent researches have highlighted the importance of integrating hydrogen into power systems. For example, Mazloomi et al. discussed the prospects and challenges of hydrogen as an energy vector by explaining current hydrogen generation technologies and cost potentials [11]. Strachan et al have evaluated the role of hydrogen in the UK energy system with a focus on infrastructure [4]. Endo et al, Dodds et al, Ball et al, and Contreras et al have studied the decarbonization of the transport sector (especially road transport) in Japan, in the UK, in Germany and in Spain, respectively [4]. Abdin and M'erida carried out a technical and economic feasibility study for a hydrogen production plant for nine system configurations which use different renewable energy sources and storage technologies. The analysis was carried out using the HOMER software, for five different sites spread all over the world: United States of America (USA), Canada and Australia, with the aim of studying the minimum cost of the energy in the considered sites and systems [10]. Apostolou and Enevoldsen have reviewed several systems based on wind energy coupled with the production of hydrogen by electrolysis of water. The authors identified three wind/hydrogen applications, namely grid-connected systems, stand-alone applications, and transportation support systems. For these applications, the level cost of hydrogen varies from 0.3 to almost 27 € per kg of produced hydrogen [6].

There are also the important projects which go in the same direction as the studies carried out in the scientific world. Some of them are listed in below:

INGRID Project (Italy) is started in 2014. This industrial demonstration project includes the hydrogen production by electrolysis of water and renewable electricity. The hydrogen is then store in the solid form for the two mentioned applications: Converting to the electricity via a fuel cell or supplying to the hydrogen market. This project has a nominal capacity of 39MWh including a 1.2 MW hydrogen generator and solid hydrogen storage of more than 1 ton of hydrogen [35].

H2BER project (Germany) is proposed to smooth the fluctuations and surplus of the Enertrag wind farm, an electrolyzer for hydrogen production dedicated to the fuel cells buses and cars running. In addition, solid hydrogen storage will provide the demand of electricity or heating [36].

JUPITER 1000 project (France) is a 1MW installation composed of two electrolyzers (PEM and Alkaline) which will be fed by renewable energy to produce hydrogen. It will be injected directly into the gas network and/or used to capture CO2 gas in industrial chimneys to form methane. Methane will then be injected into the natural gas network according to the defined standards [37].

The objective of GRHYD project (France) is to evaluate and validate the injection of hydrogen into the natural gas networks of a new district and Hythane into a bus station (CNG) in the Urban Community of Dunkerque [38].

The AUDI E-GAS plant: Located in Werlte (Germany) since 2013. An offshore wind farm in the North Sea of 4x3.6 MW turbines feeds 3x2 MW alkaline electrolyzers to produce hydrogen. The required carbon dioxide is separated from the raw biogas of a biomethane plant [39].

These projects show that researchers and governments are interested in issues of hydrogen energy. They also allow to see the big guidelines that are advanced.

V. CONCLUSIONS

Hydrogen can play an important role in reducing greenhouse gas emissions. Efforts have been made to accelerate the process of turning this potential into the real projects. This document reviews the key technologies that facilitate hydrogen production. The potential of hydrogen for energy storage in scientific researches and industrial projects is reviewed specially in the case in which electrolysers are fed by wind turbine. The improvement in the technology makes installations of green hydrogen electrolysers more interesting in future. However, cost of hydrogen production system is still not competitive. In addition, the efficiency and life time of electrolyser systems should be improved.

REFERENCES

[1] Soonho Hwangboa, KiJeon Namb, SungKu Heob and ChangKyoo Yoob ‟Hydrogen-based self-sustaining integrated renewable electricity network (HySIREN) using a supply-demand forecasting model and deep-learning algorithms” Energy Conversion and Management, vol. 185 , pp 353-367 February 2019

[2] Aitor Saenz-Aguirre, Jon Saenz , Alain Ulazia and Gabriel Ibarra-Berastegui ‟ Optimal strategies of deployment of far offshore co-located wind-wave energy farms”, ScienceDirect , Energy Conversion and Management, vol. 251, November 2021.

[3] Martín Davida, Carlos Ocampo-Martínez and Ricardo Sánchez-Peña, ‟Advances in alkaline water electrolyzers: A review”, ScienceDirect, Journal of Energy Storage, vol. 23, pp 392-403, January 2019.

[4] Lukas Weimann, Paolo Gabrielli, Annika Boldrini, Gert Jan Kramer and Matteo Gazzani ‟Optimal hydrogen production in a wind-dominated zero-emission energy system”, ScienceDirect, Advances in Applied Energy, vol. 3, May 2021.

[5] Dimitrios Apostolou and Peter Enevoldsen ‟The past, present and potential of hydrogen as a multifunctional storage application for wind power” ScienceDirect , Renewable and Sustainable Energy Reviews, vol. 112, pp 917-929, June 2019.

[6] Petronilla Fragiacomo, Matteo Genovese ‟Technical-economic analysis of a hydrogen production facility for power-to-gas and hydrogen mobility under different renewable sources in Southern Italy”, ScienceDirect, Energy Conversion and Management, vol. 223 , August 2020 .

[7] Z. Abdin and W. Mérida, ‟Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis”, ScienceDirect, Energy Conversion and Management, vol. 196, pp 1068-1079, June 2019

[8] Roxanne Pinsky , Piyush Sabharwall, Jeremy Hartvigsen and James O'Brien, ‟Comparative review of hydrogen production technologies for nuclear hybrid energy systems”, ScienceDirect, Progress in Nuclear Energy, vol. 123, February 2020

[9] M_onica S_anchez, Ernesto Amores, David Abad, Lourdes Rodrı´guez and Carmen Clemente-Jul, ‟Aspen Plus model of an alkaline electrolysis system for hydrogen production”, ScienceDirect, international journal of hydrogen energy, vol. 45, pp 3916-3929, December 2019

[10] Christian Schnuelle , Timo Wassermann , David Fuhrlaender and Edwin Zondervan ‟Dynamic hydrogen production from PV & wind direct electricity supply e Modeling and techno-economic assessment” sciencedirect, international journal of hydrogen energy, vol. 45, pp 29938-29952, November 2020 .

[11] S.A. Grigoriev, V.N. Fateev , D.G. Bessarabov and P. Millet ‟Current status, research trends, and challenges in water electrolysis science and technology”, ScienceDirect, international journal of hydrogen energy, vol. 45, pp 26036-26058, March 2020 .

[12] Ramchandra Bhandari and Ronak Rakesh Shah, ‟Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany”, ScienceDirect, Renewable Energy, vol. 177, pp 915-931, June 2021.

[13] Roxanne Pinsky, Piyush Sabharwall, Jeremy Hartvigsen and James O'Brien, ‟Comparative review of hydrogen production technologies for nuclear hybrid energy systems”, ScienceDirect, Progress in Nuclear Energy, vol. 123, March 2020.

[14] Paolo Marocco , Domenico Ferrero , Andrea Lanzini and Massimo Santarelli, ‟Optimal design of stand-alone solutions based on RES + hydrogen storage feeding off-grid communities ”, ScienceDirect, Energy Conversion and Management, vol. 238, April 2021

[15]] Chunjun Huang, Yi Zong, Shi You and Chresten Træholt, ‟Economic model predictive control for multi-energy system considering hydrogen-thermal-electric dynamics and waste heat recovery of MW-level alkaline electrolyzer ”, ScienceDirect, Energy Conversion and Management, vol. 265, May 2022.

[16] Tohid Adibi , Atta Sojoudi and Suvash C. Saha, ‟Modeling of thermal performance of a commercial alkaline electrolyzer supplied with various electrical currents ”, ScienceDirect, International Journal of Thermofluids, vol. 13, November 2021

[17] Meiling Yue , Hugo Lambert , Elodie Pahon , Robin Roche , Samir Jemei and Daniel Hissel ‟ Hydrogen energy systems: A critical review of technologies, applications, trends and challenges” ScienceDirect, Renewable and Sustainable Energy Reviews, vol. 146, May 2021

[18] Alexander Buttlera and Hartmut Spliethoff , ‟Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review”, ScienceDirect, Renewable and Sustainable Energy Reviews, vol. 82, pp 2440-2454, September 2017

[19] Shams Anwar, Faisal Khan, Yahui Zhang and Abdoulaye Djire, ‟Recent development in electrocatalysts for hydrogen production through water electrolysis”, ScienceDirect, international journal of hydrogen energy, vol. 46, pp 32284-32317, July 2021.

[20] Maja Persson, Dimitri Mignard and David Hogg, ‟Insights on performance and an improved model for full scale electrolysers based on plant data for design and operation of hydrogen production”, ScienceDirect, international journal of hydrogen energy, vol. 46, pp 31396-31409, August 2020.

[21] Joonas Koponen, Vesa Ruuskanen, Michael Hehemann, Edward Rauls, Antti Kosonen , Jero Ahola and Detlef Stolten, ‟Effect of power quality on the design of proton exchange membrane water electrolysis systems”, ScienceDirect, Applied Energy, vol. 279, September 2020.

[22] Gaoqiang Yang, Jingke Mo, Zhenye Kang, Yeshi Dohrmann, Frederick A. List III, Johney B. Green Jr., Sudarsanam S. Babu and Feng-Yuan Zhang, ‟Fully printed and integrated electrolyzer cells with additive manufacturing for high-efficiency water splitting”, Science Direct, vol. 215, pp 202-210, February 2018.

[23] Ali Bidadfar , Oscar Saborío-Romano , Nicolaos A. Cutululis and Poul E. Sørensen, ‟Control of Offshore Wind Turbines Connected to Diode-Rectifier-Based HVdc Systems”, IEEE on trans Sustainable Energy, vol. 12, pp 514 – 523, January 2021.

[24] Wenjia Chu and Yajie Zhang, ‟The Efficiency and Economic Feasibility Study on Wind-Hydrogen System” IEEE on trans Sustainable Power and Energy Conference (iSPEC), Chengdu, China, February 2021.

[25] Rebah Maamouri , Damien Guilbert, Michel Zasadzinski and Hugues Rafaralahy, ‟Proton exchange membrane water electrolysis: Modeling for hydrogen flow rate control”, ScienceDirect, international journal of hydrogen energy, vol. 46, pp 7676-7700, January 2021

[26] Damien Guilbert , Dario Sorbera and Gianpaolo Vitale, ‟A stacked interleaved DC-DC buck converter for proton exchange membrane electrolyzer applications: Design and experimental validation”, ScienceDirect, international journal of hydrogen energy, vol. 45, pp 64-79, October 2019

[27] David Parra, Luis Valverde, F. Javier Pino andMartin K. Patel, ‟A review on the role, cost and value of hydrogen energy systems for deep decarbonisation”, ScienceDirect, Renewable and Sustainable Energy Reviews, vol. 101, pp 279-294, November 2018

[28] Vittorio Guida, Damien Guilbert and Bruno Douine, ‟ Candidate Interleaved DC-DC Buck Converters for Electrolyzers: State-of-the-Art and Perspectives”, IEEE on trans International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Palermo, Italy, October 2018.

[29] Simone Mucci , Alexander Mitsos and Dominik Bongartz, ‟Power-to-X processes based on PEM water electrolyzers: A review of process integration and flexible operation”, ScienceDirect , Computers and Chemical Engineering, vol. 175, April 2023.

[30] Ruiming Fang and Yin Liang, ‟Control strategy of electrolyzer in a wind-hydrogen system considering the constraints of switching times”, ScienceDirect, international journal of hydrogen energy, vol. 44, pp 25104-25111, March 2019.

[31] Senan F. Amireh, Niels N. Heineman, Paul Vermeulen, Rodrigo Lira Garcia Barros, Dongsheng Yang, John van der Schaaf and Matheus T. de Groot, ‟Impact of power supply fluctuation and part load operation on the

efficiency of alkaline water electrolysis ", ScienceDirect, Journal of Power Sources, vol. 560, January 2023

[32] Matheus T. de Groot a, Joost Kraakman and Rodrigo Lira Garcia Barros, "Optimal operating parameters for advanced alkaline water electrolysis", ScienceDirect, international journal of hydrogen energy, vol. 47, pp 34773-34783, September 2022

[33] Joonas Koponen, Vesa Ruuskanen, Antti Kosonen, Markku Niemel¨a, and Jero Ahola, "Effect of Converter Topology on the Specific Energy Consumption of Alkaline Water Electrolyzers", IEEE on trans Power Electronics, vol. 34, pp 6171 – 6182, July 2019

[34] Hirokazu Kojima , Kensaku Nagasawa , Naoto Todoroki ,Yoshikazu Ito , Toshiaki Matsui and Ryo Nakajima"Influence of renewable energy power fluctuations on water electrolysis for green hydrogen production", ScienceDirect, international of hydrogen energy, vol. 48, pp 4572-4593, November 2022.

[35] INGRID PROJECT: High-capacity hydrogen-based green-energy storage solutions for grid", https://innsight.eu/?page_id=41

[36] H2BER PROJECT: Applying hydrogen as an energy source produced from wind power and solar energy" http://erh2-bretagne.over-blog.com/2014/06/10-06-2014-projet-h2ber-station-service-hydrogene-de-berlin-schoenefeld.html

[37] JUPITER 1000: Innovative Power-to-Gas Industrial Demonstrator Project" https://www.jupiter1000.eu/projet

[38] GRHYD PROJECT: Gestion des Réseaux par l'injection d'Hydrogène pour Décarboner les énergies", http://grhyd.fr/presentation/

[39] ETOGAS GmbH: Audi E-gas description", chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://gronamobilister.se/wp-content/uploads/2019/09/Audi_e-gas_Project_LCA_English.pdf