AN OVERVIEW OF GREEN HYDROGEN PRODUCTION SYSTEM THROUGH LOW TEMPERATURE WATER ELECTROLYSIS USING SOLAR ENERGY

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Climate change and the increasing demand for energy become major issues in public discussions today. The Paris Agreement is one of the results of such public discussions that focuses on achieving the 2050 Net Zero Emission target. Many energy agencies have created scenarios to achieve this target. In this regard, green hydrogen is expected to have a significant role in energy transition plan. For this reason, in recent years, research related to green hydrogen production using the water electrolysis method continues to develop. The paper aimed primarily to conduct an overview of alternative technologies that can be used in producing green hydrogen with the solar energy based low temperature water electrolysis method. Secondarily, it would present information about several solar energy-based electrolysis project plans and a summary of challenges and opportunities in the development of solar energy based low temperature water electrolyzers in the future. Furthermore, to achieve commercially viable green hydrogen production, it is important to find new ideas, potential solutions, and constructive recommendations as soon as possible for further development research. This paper expectedly would be able to help initiate the development of green hydrogen production research through water electrolysis technology that is efficient, cost effective economically, and environmentally friendly.

Key words*: low temperature water electrolysis, green hydrogen, solar energy, AWE, PEM, AEM.*

1. Introduction

The world is currently facing two major issues: climate change due to carbon gas emissions and increased demand for energy due to urbanization and increasing population growth rates [1][2]. Based on estimates, the world's human population will reach around 10 billion in 2050 and will cause energy needs to increase sharply [3]. If the world's population continues to use fossil fuels as the main energy source without trying to reduce this dependency, according to International Energy Agency (IEA), the increase in world temperature could reach 2.7°C in 2100, which could cause serious damage to the environment [4]. For this reason, currently, various parties are working together and making various efforts to investigate new energy sources that are friendly to the environment [3][5].

In 2016, countries in the world agreed to sign the Paris Agreement, which stated a commitment to restrain the rate of increase in global average temperatures below 2°C and continue efforts to limit the temperature rise to 1.5°C [6] and achieve the 2050 Net Zero Emission (NZE) target. Data provided by International Renewable Energy Agency (IRENA) show that as of April 2022, 131 countries had announced commitments to achieve the NZE target (representing 88% of global greenhouse gas emissions). Associations and researchers that focus on the energy sector have made various scenarios. Tab. 1 below provides a summary of the energy scenarios for 2050.

Table 1. Kinds of Projection Scenario Parameters in 2050

Source		Annual Energy Projections in 2050	GDP growth rate	Population (billion)
IEA [4]	Net zero by 2050. A roadmap for the global energy sector (3rd revision). 2021	TFEC (300-550 EJ)	3%	9.7
EIA [7]	International Energy Outlook 2021	World energy consumption (886.3 Quad Btu = 935.046 EJ)	2.8%	9.655
IRENA & OECD/IEA [8]	Perspectives for the energy transition-investment needs for a low carbon system. Chapter 4. 2017	TPES (635 EJ) TFEC (380 EJ)	2.8%	9.7
IRENA [9][10]	Global Renewables Outlook: Energy transformation 2050 (Edition: 2020)	TPES (538 EJ)	> 2.4%	-
	World Energy Transitions Outlook 2022: 1.5°C Pathway	TPES (614 EJ) TFEC (348 EJ)	-	-
Teske [11]	Achieving the Paris Climate Agreement Goals. 2019	TPES (439 EJ) TFEC (310 EJ)	3.2 %	9.8
Grubler et al. [12]	A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies.2018	245 EJ	-	9.166
Scott et al. [13]	Demand vs supply-side approaches to mitigation: What final energy demand assumptions are made to meet 1.5 and 2° C targets? 2022	Primary Energy (628 EJ) Final Energy (442 EJ)	-	-

Tab. 1 shows that the scenarios regarding the world's demand for energy have a wide range, namely 310-935 EJ, because each scenario has different methods, assumptions, conversion rates, and targets regarding the composition of the energy mix. Several other references state that Total Primary Energy Supply (TPES) ranges from 439-635 EJ and Total Final Energy Consumption (TFEC) ranges from 310-408 EJ [14]. IEA set a target that in 2050, the world will achieve NZE with a TFEC of 340 EJ and a maximum global temperature rise of 1.5°C [4]. The term NZE here does not refer to 'not producing carbon emissions at all' but to a condition where the amount of carbon emissions released into the atmosphere does not exceed that absorbable by the earth [15].

Until 2050, the TFEC value, based on the NZE scenario by IEA is around ± 344 EJ, in which fuels and others reach 175 EJ (50.87%) and electricity use reaches 169 EJ (49.13%). Hydrogen has a composition of about 9.92% (8.74% from fuels and others and 1.18% from electricity use). The total energy derived from hydrogen in 2050 is around 34,128 EJ [4]. Meanwhile, according to the projection results by IRENA, hydrogen has a composition of 12% (41.76 EJ) of the total final world energy consumption (348 EJ) [10]. These data reveal that in the future, hydrogen will have an important role in the energy transition plan in the NZE program [16] [17].

Hydrogen is a chemical element with a high energy density value [18]. Its LHV is around 119.9 $MJkg^{-1}$, almost 3 times that of diesel fuel [19] [20]. Apart from having a high calorific value, hydrogen is the most abundant element in the universe and is included in the 10 most abundant elements on the earth's surface [21]. Hydrogen can produce energy in two ways, namely combustion (for example an engine or turbine) and the use of fuel cells to generate electricity. In the process of converting hydrogen into other forms of energy, no carbon emissions are produced at all (only water vapor and heat) [22]. For these reasons, hydrogen is a very promising clean and renewable energy.

Currently, hydrogen has been widely applied in various sectors. In the transportation sector, for example, it can be used as fuel for fuel cells and internal combustion engine vehicles. It can also be useful in the refinery process and the ammonia fertilizer, pharmaceutical, steel production, and other industries. In the field of power and heat, it can be used for energy storage and electricity/heat power generation [3][23][24]. The following fig. 1 presents information regarding the use of hydrogen in various sectors.

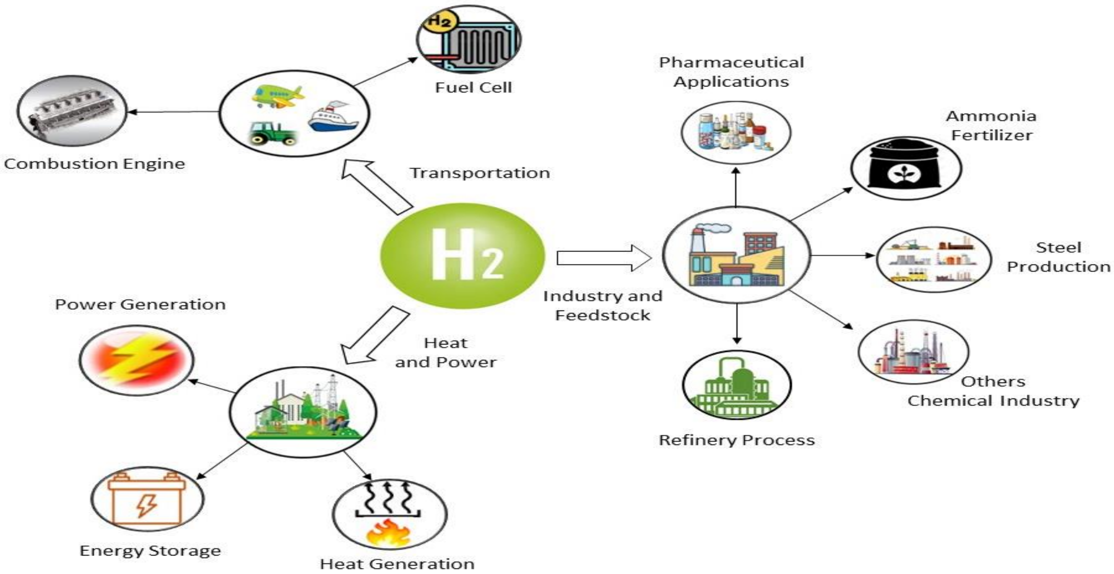

Figure 1. Hydrogen applications

The extensive use of hydrogen is directly proportional to the demand for it in the future. Regulators and producers play a very important role in ensuring the supply. In general, hydrogen comes from two kinds of resources: fossil fuels and renewable resources. Hydrogen produced from fossil fuels is further divided into blue and grey hydrogen [5], while that from renewable resources is called green hydrogen. The definition of green hydrogen in general refers to hydrogen produced from renewable resources where the driving energy for the production process also comes from renewable energy [25][26]. In fig. 2, a comparison of the types of hydrogen is presented.

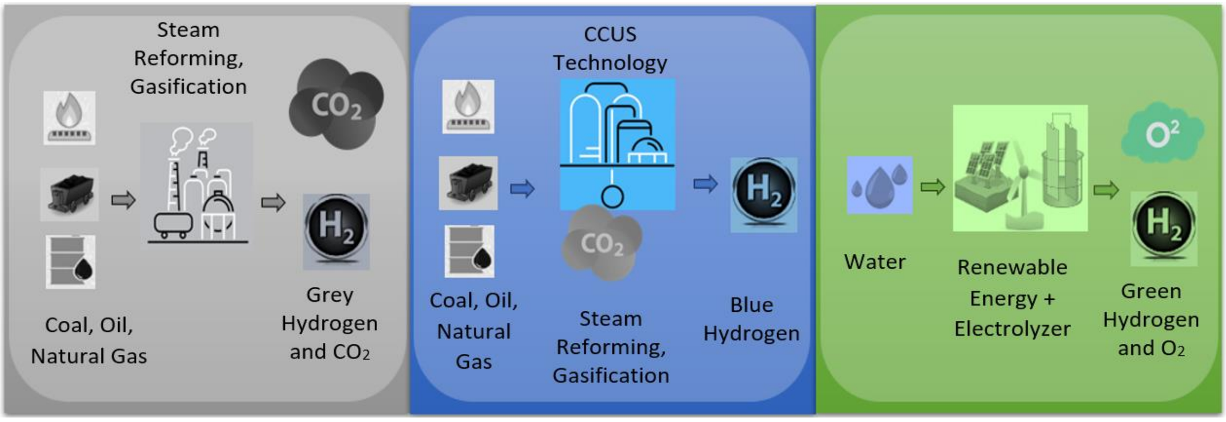

Figure 2. Difference between types of hydrogen

Hydrogen is currently mostly produced from fossil fuels [27]. The results of studies by IEA show that 76%, 22%, and 2% of the hydrogen produced today comes from natural gas, coal, and water electrolysis, respectively [5][28]. Meanwhile, IRENA stated that of the 120 MT of hydrogen produced in 2018, 95% came from natural gas and coal, and only 5% came from the electrolysis process [29]. These data explain that currently the production of hydrogen from renewable resources is still very limited and is one of the tough challenges that must be faced together to achieve the 2050 NZE target. According to the Hydrogen Council, by 2050, the world should use only green and blue hydrogen, the ratio of which must be 2:1, respectively [9], and, by 2030, 30% of grey hydrogen must be replaced with green and blue hydrogen. For this aim, it is important to immediately increase the quantity and quality of green hydrogen production. Fig. 3 below presents a hydrogen transition scheme according to the Hydrogen Council.

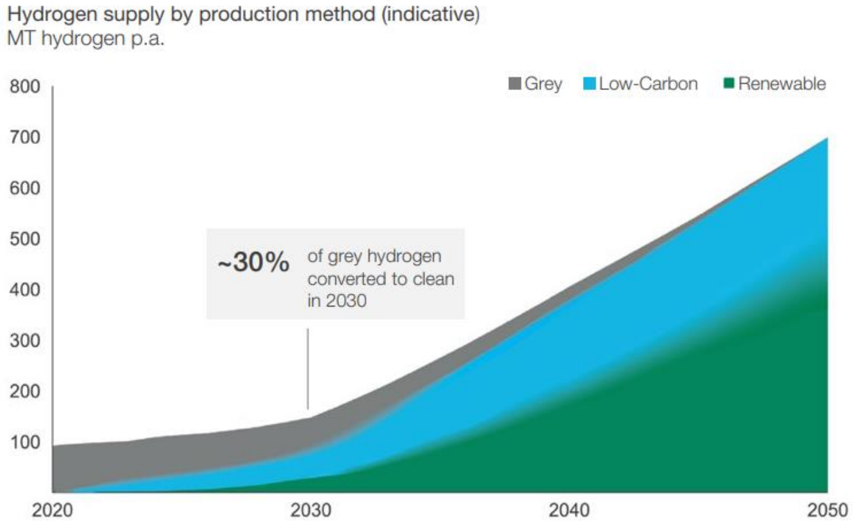

Figure 3 Hydrogen Transition [30]

Green hydrogen is hydrogen produced using driving energy and raw materials which both come from renewable resources [25][26]. Among the various green hydrogen production process schemes that exist, currently, water electrolysis is the most widely used production process. In fact, based on the results of a comparative analysis of 16 methods of hydrogen production (fossil and non-fossil) using the parameters energy efficiency, exergy efficiency, production cost, cost of carbon, global warming potential, acidification potential, and technology maturity level, large-scale electrolysis is overall is considered the most sustainable method [31].

Water electrolysis is a water splitting method that uses electrical energy as its driving energy. The electrical energy used is a form of carrier energy that can be produced from a variety of renewable resources [32]. Of the various types of available renewable resources, by the composition of the TFEC for the 2050 NZE scenario, the most dominant electrical energy comes from solar and wind energy [4], which, as a study stated, the solar energy is superior in providing energy for the hydrogen production process than the wind energy [33]. This means that the production of hydrogen from water raw materials and electricity from solar energy is a combination that is expected to be the biggest contributor to meeting green hydrogen needs in the future.

Due to the important role of green hydrogen in the 2050 NZE scenario, it is necessary for researchers to immediately participate and take part in the development of green hydrogen production. This paper is expected to be a reference for researchers who are interested in this field and become a means of gaining an understanding of matters related to the green hydrogen production process. The main objective of this review paper is to present an explanation of several alternative technologies for producing green hydrogen using the low-temperature water electrolysis method, combined with solar energy as the driving energy, and will also present several examples of projects planned to be carried out. Another objective of this paper is to provide a summary of the challenges and opportunities for green hydrogen production systems via solar energy-based low-temperature water electrolyzers (AWE, PEM, and AEM) in the future.

2. Utilizing Solar Energy for Hydrogen Production

Driving energy in the green hydrogen production process can be obtained directly from the main energy source or can also be produced from the conversion of other energy sources. One of the most dominant renewable energies used today is solar energy, which has the highest capability to meet global demand for clean energy in the future [16]. Economically, solar energy is also a renewable energy with low-cost electrical power generation compared to other sources such as solar thermal, geothermal, wind, and biomass [34]. Fig. 4 below presents information on the use of solar energy in producing hydrogen via a water splitting process.

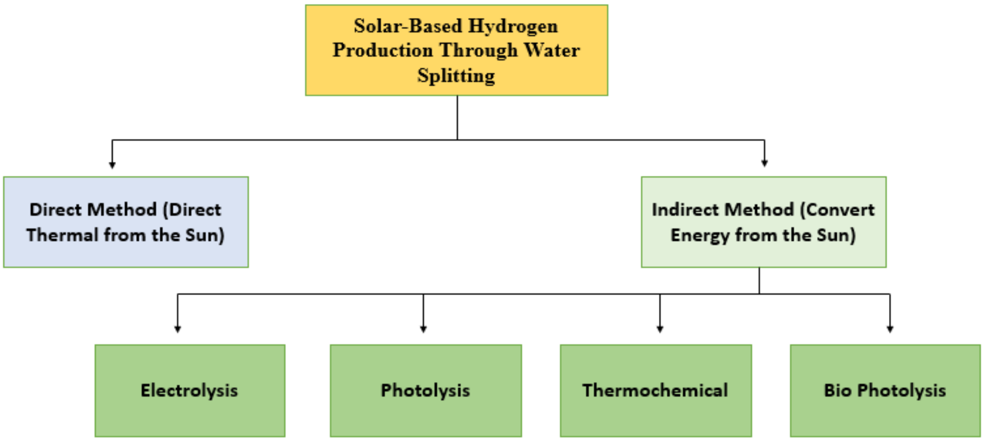

Figure 4. Water splitting process using solar energy

The utilization of solar energy in the green hydrogen production process using the water splitting method can be divided into 2 categories, namely the direct and indirect methods. The direct method splits water compounds by using heat from solar energy; and the water splitting process is carried out in one step. This method, however, is considered not feasible because the gas produced as an end-product is very difficult to separate; it requires very high energy to run the process. Besides, it is very difficult to find a reactor capable of operating at normal pressure and very high temperature. So, this method is rarely used in the water splitting process [35].

The indirect method is a water splitting method that uses solar energy in another form of energy as driving energy for the process of separating water compounds. This method can be divided into 4 categories, namely electrolysis, photolysis, thermolysis, and bio-photolysis [35]. Electrolysis has become the most feasible method of producing green hydrogen to date. Solar energy in electrolysis functions as a driving energy, thus requiring conversion first into electrical energy. Currently, there are two main methods for producing electricity from solar energy, namely PV and CSP. The following is an explanation of how to use solar energy to produce hydrogen via electrolysis.

2.1. Photovoltaic (PV)-electrolysis system

A PV works by converting direct sunlight energy into direct current based on the photoelectric effect, in which the semiconductor material in PV solar cells generates an electric current when exposed to sunlight. The electricity generated by PV is then used as driving energy for the electrolysis process [36] [37]. Solar energy development and utilization involve a significant application domain centered around photovoltaic power generation technology, where photovoltaic cells play a central role [38]. The following fig. 5 presents a schematic diagram of a PV power plant-Electrolysis.

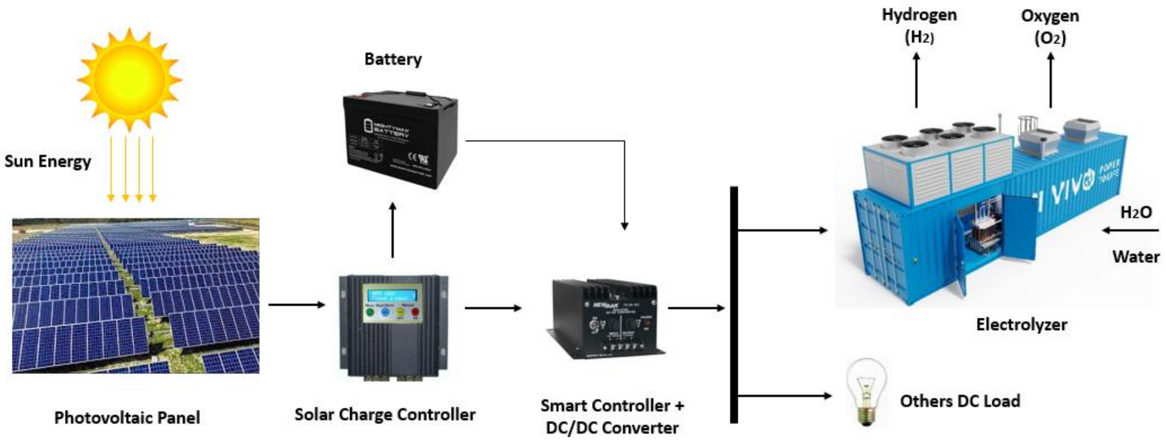

Figure 5. Schematic diagram of PV- electrolysis

In Fig. 5, information about the constituents of a PV-electrolysis scheme that generally include a solar panel, controller, energy storage (battery), and electrolyzer is presented. PV and battery function as the main driving energy for the electrolysis process. This PV-electrolysis scheme has several advantages, including those related to scale flexibility (small-large scale) and the location of its application. However, this scheme also has a weakness that is common in the use of solar energy, namely its dependence on weather conditions (intermittent).

2.2. Concentrated solar power (CSP)-electrolysis system

One of the most widely developed and used solar power generation technologies is CSP, whose basic principle is to convert heat from the sun into electricity using a thermal fluid. The concentrated sunlight is directed at the receiver located at the point-focusing collector (can be a tower or a horizontal pipe on a parabolic mirror). The heat received by the receiver can increase the temperature of the thermal fluid therein. Furthermore, the heat will be stored in a thermal tank storage and channeled to the boiler steam generator. The hot steam produced is used to rotate a turbine which is coupled to a generator to generate electricity. The electricity generated can later be used as driving energy for the electrolysis process [39][40]. Fig. 6 presents a schematic diagram of a CSP plant-Electrolysis.

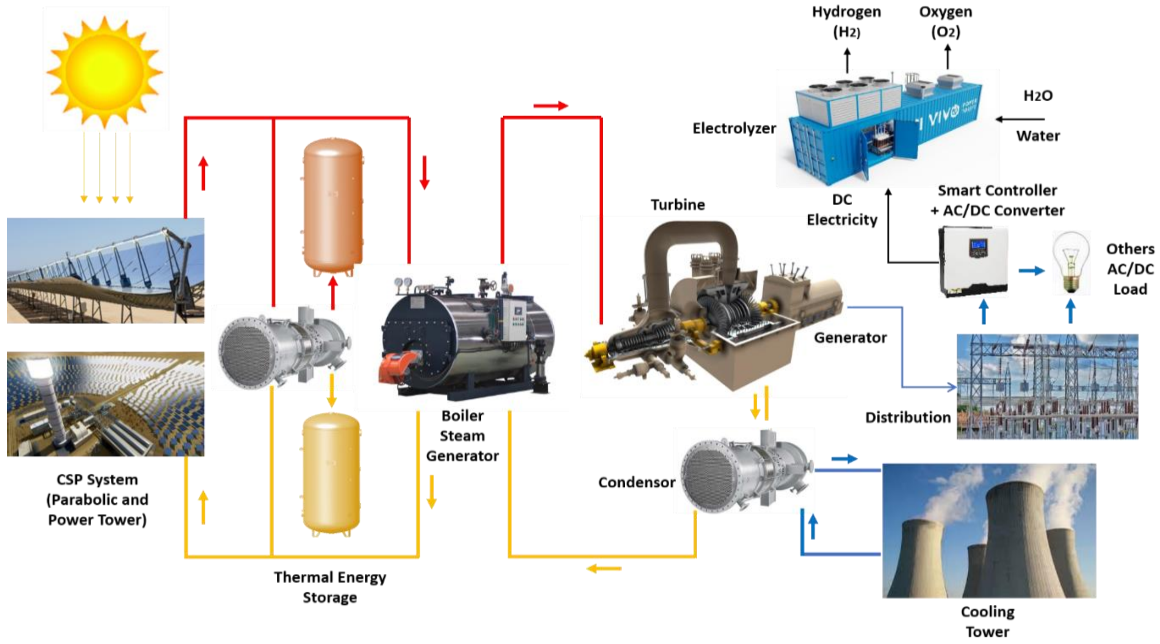

Figure 6. Schematic Diagram of CSP-Electrolysis

Fig. 6 depicts the CSP-electrolysis scheme which generally consist of a solar collector and receiver, a thermal storage system, and a thermal power generation system. In this scheme, the electricity generated comes from a thermal power generation system (generator). The heat used to produce steam to drive the turbine coupled with the generator comes from heated water in the solar collector and receiver. This CSP-electrolysis scheme has several advantages, such as the efficiency of solar energy conversion and energy storage technology (thermal energy storage). However, this scheme also has weaknesses. Apart from its dependence on the weather, it, in terms of scale, is not flexible because it is only suitable for large scale production.

3. Low Temperature Water Electrolysis overview

Optimization of green hydrogen production is of course not only focusing on driving energy. The electrolyzer must also be developed optimally for its most important role in the green hydrogen production process, which functions to break down water compounds (H_2O) into Hydrogen (H_2) and Oxygen (O_2). The better the quality of the electrolyzer used, the more optimal the green hydrogen production. Currently, based on the parameter operating temperature, water electrolyzer technologies can be divided into two categories, namely low and high temperature water electrolyzers [41]. Low temperature electrolyzers include Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), and Anion Exchange Membrane (AEM)water electrolyzer, while high temperature ones include Solid Oxide Electrolyzer Cells (SOEC) [42]. However, until now, only the low temperature electrolyzers have entered the commercial stage, while SOEC is still in the research and development stage [43].

There are several water splitting methods that can be used to produce green hydrogen by using solar energy as driving energy. Until now and for the future, according to projections, water electrolysis has been and will be dominating in green hydrogen production for its several advantages, especially in terms of efficiency and technological maturity. In tab. 2, a summary comparison of several water splitting methods is presented [19][24].

Table 2. Hydrogen Process with various feedstock, maturity level and energy efficiency

Production Process	Feedstock	Maturity Level	Efficiency Energy (%)	Ref.
Electrolysis (alkaline electrolysis)	H_2O+ electricity	9–10	62–82	[24][44]
Electrolysis (PEM electrolysis)	H_2O+ electricity	8-9	65-82	[45]
High Temperature Electrolysis (HTE electrolysis)	H_2O+ electricity +heat	5	81-86	[20][24]
photo electrolysis (photo-electrochemical)	H_2O + light	1-2	0.06-14	[24][46]
Bio photolysis (photosynthesis) with microalgae	H_2O + organism + light	1-3	0.02-2	[24][47]
Bio photolysis (photo fermentation) with cyanobacteria	H_2O + organism + light	-	16.3	[48]
Thermolysis (water thermolysis)	H_2O + heat	2–5	20–55	[24]

Tab. 2 provides information on various methods that can be used for green hydrogen production using solar energy. Of the several existing production methods, electrolysis gives the highest maturity level and energy efficiency. Specifically, high-temperature electrolysis has the highest level of conversion efficiency but needs high temperatures, thus requiring a large amount of thermal energy. In addition, its maturity level is still below that of the low-temperature electrolysis method. Therefore, despite having low energy efficiency, low-temperature electrolysis technology is preferred for use in producing green hydrogen.

3.1. Alkaline Water Electrolysis

AWE is a water splitting method that has been used for a long time. It was discovered in 1789 by Troostwijk and Diemann. Currently, it is a method with the best technological maturity level. It operates at a temperature range of 30-80°C, an alkaline concentration of 5M KOH/NaOH, a current density of 0.2-0.4 A/cm^2, and an efficiency of around 63-71% of the value of LHV hydrogen [29]. Alkaline water electrolysis is the splitting of electrochemical water compounds into oxygen and hydrogen using direct current. The direct current flows through the solution via the cathode (negative electrode), at which a reduction reaction occurs. As a result, two water molecules react by capturing two electrons, thus reduced to be H_2 gas and hydroxide ion (OH^-). This reaction is called the hydrogen evolution reaction. Meanwhile, on the anode (positive electrode), hydroxide ion (OH^-) splits and forms O_2 gas, water molecules (H_2O), and releases 2 electrons which will flow towards the cathode. This reaction is called oxygen evolution reaction [49][50][51]. The following is a chemical reaction that occurs in the alkaline water electrolysis process:

Cathode: $2H_2O(l) + 2e^- \rightarrow 2OH^- (aq) + H_2(g)$ (1)

Anode: $2OH^-(aq) \rightarrow H_2O(l) + ½ O_2(g) + 2e^-$ (2)

Total reaction: $2H_2O(l) \rightarrow 2 H_2(g) + O_2(g)$ (3)

In theory, for the process of splitting of H_2O into H_2 and O_2 (Eq. (1-3)) to take place under conditions of a standard pressure of 1 bar and a room temperature of 25°C, a minimum voltage of 1.23 V is required. However, in practice, the voltage needed is greater because of the additional kinetics and ohmic resistance of the electrolyte and other components in the electrolyzer cell. Meanwhile, based on thermodynamic calculations, the amount of energy required for the splitting process to take place is 285.8 kJ mol−1 from electricity and heat of 237.2 kJ mol^{-1} and 48.6 kJ mol^{-1}, respectively [5][21][50]. Tab. 3 presents information about several alkaline water electrolyzer products available on the market.

Table 3. List of alkaline water electrolyzer commercial products [52]

Producer	Series and Operating Pressure (bar)	Hydrogen Flow Rate ($Nm^3.h^{-1}$)	Energy Consumption ($kWh·Nm^{-3}$ H_2)	Power
Hydrogenics	HYSTAT/10–25 bar	10–60 max. 15/stack	4.9–5.4	100–515 kVA
McPhy	McLyzer/10–30 bar	10–800	4.43–5.25 DC	57 kW–4 MW
Teledyne Energy Systems	TITAN HMXT 10 bar	2.8–11.2	-	-
Wasserelektro-lyse Hydrotechnik	EV 50–EV 150 Atmospheric 4 bar	75–220	5.28	-
NEL	A Series 1–200 bar	50–3880	3.8–4.4	up to 2.2 MW
Nuberg PERIC	ZDQ 5–600 15 bar to 20 bar	5–600	4.6 DC system	23.7 kW–2.74 MW
Sagim S. A	M–series 7 bar	1.5–5	5	14–42 kVA
Green Hydrogen	A-Series 35 bar	2.7–8.1	4.63–4.81	125–390 kW

Along with scientific developments and increased understanding of green hydrogen production, alkaline water electrolyzer technology has also undergone many changes. Supports by various companies have given rise to many product variations of this technology. Tab. 3 presents a compilation of data that provides insight into various manufacturers of AWE technologies and technical details regarding their product series. Important information that must be considered regarding electrolyzer product specifications includes operating pressure, hydrogen production flow rate, energy consumption, and power requirements.

3.2. Proton Exchange Membrane Water Electrolysis

PEM water electrolyzer is currently one of the most widely used water splitting technologies for producing green hydrogen. PEM water electrolyzers have been developed over 60 years by General Electric. This technology is also known as polymer electrolyte membrane electrolysis. In the proton exchange membrane, the feedwater used is deionized water without electrolytic additives. The advantages of the PEM water electrolyzer include its high density, greater energy efficiency, lower gas permeability, wider operating temperature, and relatively easier handling and maintenance [53]. The working principles of electrochemically water splitting is slightly different from those of other low temperature water electrolysis technologies because in this process water molecules are split into oxygen (O2), protons (H+), and electrons (e) at the anode of the PEM water electrolyzer. The oxygen gas will then go to the surface side of the anode, while the protons will go to the cathode through the proton exchange membrane, and the electrons will go to the cathode through the external DC power source circuit. On the cathode side, protons (H+) will capture electrons and form H2 gas, which will then go to the cathode surface [5][21][54]. The following is a chemical reaction that occurs in the PEM water electrolysis process [55]:

Cathode: $2H^+ (aq) + 2e^- \rightarrow H_2 (g)$ (4)

Anode: $2H_2O (l) \rightarrow 4H^+ (aq) + 4 e^- + O_2 (g)$ (5)

Total reaction: $2H_2O (l) \rightarrow 2 H_2 (g) + O_2 (g)$ (6)

Tab. 4 presents information about several PEM water electrolyzer products available on the market.

Table 4. List of PEM electrolyzer commercial products [52]

Producer	Series and Operating Pressure (bar)	Hydrogen Flow Rate ($Nm^3.h^{-1}$)	Energy Consumption ($kWh \cdot Nm^{-3}$ H_2)	Power
Proton Onsite	S Series 13.8 bar	0.265–1.05	6.7	-
Proton Onsite	H Series 15–30 bar	2–6	6.8–7.3	-
H-TEC Systems	ME unpressurised 30 bar	13–210	4.9	225 kW–1 MW
Hydrogenics	HyLYZER 0–7.9 bar	1–2	6.7	-
ITM Power	HPac, HCore, HBox, HFuel 15 bar	0.6–35	4.8–5.0 (system)	2 MW
Siemens	SILYZER 200 35 bar	225	-	1.25 MW
Green Hydrogen	P–series/15–50 bar	1	-	4.95 kW
NEL	M Series 30 bar	103–413	4.53	0.5–2 MW

Currently, the PEM water electrolyzer is a product with technology that has entered the commercial stage and is quite widely used in various green hydrogen demonstration projects. Several companies engaged in the energy sector have also started producing PEM electrolyzers with various capacities. In tab. 4, a data compilation is presented that provides insight into the various PEM technology manufacturers and the technical details regarding their product series.

3.3. Anion Exchange Membrane Water Electrolysis

AEM water electrolysis is a fairly new electrochemical water splitting method. It can be defined as a combination of AWE and PEM electrolyzers, which complement each other [56]. Basically, AEM water electrolysis technology is the same as AWE in terms of working principle. Their difference takes place in their separators: AWE has a diaphragm, while AEM has anion exchange membrane. The electrochemical reactions consist of two half-cell reactions, namely the hydrogen evolution reaction and the oxygen evolution reaction. On the cathode, H_2O molecules are reduced to H2 and hydroxyl ions (OH^-) due to the addition of 2 electrons. Furthermore, H_2 in gaseous form goes to the cathode surface, while hydroxyl ions (OH^-) go to the anode (positive side) through the anion exchange membrane. Because the separator used is an anion exchange membrane, only negative ions can pass. On the other hand, the DC forces electrons to move towards the cathode (negative side) through the external circuit, so that the anode loses electrons and causes hydroxyl ions to form water molecules (H_2O) and oxygen gas. The oxygen gas produced then goes to the anode surface [21][52]. The following is a chemical reaction that occurs in the AEM water electrolysis process [57] :

Cathode: $2H_2O(l) + 2e^- \rightarrow 2OH^- (aq) + H_2(g)$ (7)

Anode: $2OH^-(aq) \rightarrow H_2O(l) + \frac{1}{2} O_2(g) + 2e^-$ (8)

Total reaction: $2H_2O(l) \rightarrow 2 H_2(g) + O_2(g)$ (9)

In Tab. 5, information regarding several AEM water electrolyzer products is presented.

Table 5. List of AEM electrolyzer commercial products [58]

Producer	Series and Operating Pressure (bar)	Hydrogen Flow Rate ($Nm^3.h^{-1}$)	Energy Consumption ($kWh.Nm^{-3}$ H_2)	Power (kW)
Enapter	AEM Multicore 35 bar	210	4.8	1.008
	AEM EL 2.1 35 bar	0.5	4.8	2.4
	AEM EL 4.0 35 bar	0.5	4.8	2.4

Currently, there are only a few manufacturers that produce AEM water electrolyzer products. Based on the literature study conducted, only the Enapter company has produced AEM water electrolyzers for sale in the market. The limited number of AEM water electrolyzer products has resulted in this technology not being widely used in various green hydrogen pilot projects. However, despite the current limited production of AEM water electrolyzers, the role companies like Enapter have invested in this technology is an important first step in developing sustainable solutions for green hydrogen production.

4. Comparison Between Low Temperature Water Electrolysis Technologies

The following tab. 6 is designed to make it simpler to identify and understand the differences between the 3 low temperature water electrolysis technologies. Indeed, each electrolyzer technology has its own set of advantages and disadvantages. By using Table 6 for comparison, it's easier to assess the strengths and weaknesses of each technology. This allows for a more comprehensive evaluation of which technology might be the most suitable for a specific application or situation.

Table 6. Comparison of low temp. water electrolysis technologies [21][26][31][33][59][60]

	AWE	PEM	AEM
Operational Parameters			
Temperature (°C)	70–90	50–80	40–60
Cell Pressure (bar)	<30	<70	<35
Current density (A/cm^2)	0.2–0.8	1–2	0.2–2
H_2 purity (%)	99.5–99.9998	99.9–99.9999	99.9–99.9999
Voltage (V)	1.4–3	1.4–2.5	1.4–2.0
System Parameters			
Lifetime (stack) (hour)	60 000	50 000–80 000	>30 000
Technology status	Mature/Industrialized	Commercialized	R & D – limited Commercialized
Efficiency (%)	50–78	50–83	57–59
Electrode area (cm^2)	10 000–30 000	1500	<300
Energy consumption (kWh/Nm^3)	4.5-7	4.5-7.5	~ 4.8
Feedwater types	High concentration solution	Distilled water	Distilled water or Low concentration solution
Production yield (Nm^3/h)	100–760	~30	2.05–1
Economic Parameters			
Capital cost min. 1 MW	\$270/kW	\$400/kW	-
Capital cost min. 10 MW	\$500-1000/kW	\$700-1400/kW	-
Others Parameters			
Separator	Asbestos/Zirfon/Ni	Nafion®	Fumatech
Electrolyte	KOH/NaOH (5M)	Solid polymer electrolyte (PFSA)	DVB polymer support with 1 M KOH/NaOH
Electrode catalyst (H_2)	Nickel coated perforated stainless steel	Iridium oxide	Nickel
Electrode catalyst (O_2)	Nickel coated perforated stainless steel	Platinum carbon	Nickel or NiFeCo alloys
Bipolar Plates	Stainless steel/Nickel coated stainless steel	Platinum/Gold-coated Titanium or Titanium	Stainless steel/Nickel coated stainless steel
Gas Diffusion layer	Nickel mesh	Titanium mesh/carbon cloth	Nickel foam/carbon cloth
Charge carrier	OH^-	H^+	OH^-
Advantages			
	Noble metal-free electrocatalysts	Operates higher current densities	Noble metal-free electrocatalysts
	Low-cost investment	High purity of hydrogen	Low concentrated (1M KOH) liquid electrolyte
	Long-term stability (established)	Quick response (Start up and operational)	Load fluctuation suitable
Disadvantages			

	Limited current densities	Cost of the cell components	Limited stability
	Crossover of the gasses	Noble metal electrocatalysts	Under development
	High concentrated (5M KOH) liquid electrolyte	Acidic electrolyte	

The Tab. 6 provides information about the operational, system, and economic parameters, the advantages, and the disadvantages of three types of water electrolysis technologies. AWE is good at cost and technological stability but not at current density and quality of hydrogen. PEM has the potential for higher current densities, pure hydrogen generation, and good responsiveness, but the high costs for its cell components remain a challenge. Meanwhile, AEM, although commercially still in the development stage (only 1 producer), shows potential for the use of electrocatalysts without precious metals and the use of low concentration electrolyte solutions.

5. Project of Green Hydrogen Production by Water Electrolysis Using Solar Energy

Tab. 7 below presents information about several solar energy-based electrolysis projects and summary or collection of data about these specific projects, including key information and perhaps performance metrics for each project. It serves as a reference or resource for understanding the various initiatives related to green hydrogen production through solar-powered water electrolysis.

Table 7. List of green hydrogen project solar water electrolysis

Project and Location	Specification	Power Capacity	Cost	Ref.
Fukushima Hydrogen Energy Research Field (FH2R), Japan	• 1200 Nm^3 of H_2/hour • Electrolyzer capacity stands at a rated power of 6 MW (max. 10 MW)	• 20 MW of solar PV Plant	$189 million	[61]
YURI Project, Australia	• 10 MW alkaline or PEM electrolyzer (by Peric) • Up to 640t of H_2/ year	• 18 MW Solar PV Plant • 8 MWh lithium-ion Battery Storage	$58.46 million	[62]
The Centrale Electrique de l'Ouest Guyanais (CEOG) project, French Guiana	• 16 MW Alkaline Electrolyser • ± 860t of H_2/year.	• 55 MW Solar PV Plant • 128 MWh hydrogen- energy storage system	$200 million	[63]
Iberdrola Puertollano Green Hydrogen Plant, Spain	• 20 MW PEM (MC250 1.25MW 246 Nm^3/h and MC500 2.5 MW 492 Nm^3/h) • ±3.000t H_2 /year	• 100 MW Solar PV Plant • Storage capacity of 20MWh lithium-ion	$160.02 million	[64]
Alliander Oosterwolde - solar park of Groen Leven, Dutch	• GHS HyProvide™ A90 alkaline electrolyzer 1.4 MW • ±100,000 kg of H_2 annually	• 50 MW solar PV Plant	-	[65]
Ecopetrol, Colombia	• 50-kW PEM electrolyzer • 20 kg H_2/day	• 270 solar panels 137-kW PV plant	-	[66]
Green hydrogen pilot Project, Mohammad Bin Rashid Solar Park, part of DEWA project, UAE	• PEM electrolyzer at 1.25 MWe of peak power • ± 20.5 kg/h of H_2	• 1.25 MWe of peak power solar panel	$14 million	[67]

Solar-powered green hydrogen Riau archipelago, Indonesia	• 10 MW electrolyzer • ±1,650-ton hydrogen per year	• 100 MW PV Plant	-	[68]
Sinopec Photovoltaic Green Hydrogen Production Project in Kuqa, Xinjiang, China	• 52 PEM electrolyzer sets, each capacity 1000 m^3 of H_2 per hour. • Annual output reaching 20,000 tons	• 300 MW PV Plant	$470.77 million	[69]
Greece large scale solar-battery-hydrogen project, Greece	• 50 MW electrolyzer • 16 tons H_2 per day	• 200 MW PV Plant	$224.4 million	[70]

Tab. 7 which presents information on green hydrogen projects shows a comprehensive picture of the increasing development of clean energy in various parts of the world. This investigation reveals several important aspects in the development of green hydrogen that deserve attention: first, the various electrolysis technologies used in these projects, such as alkaline and PEM; secondly, the diversification of project locations that reflects a strong global interest in green hydrogen development; thirdly, varying power capacities that reflect the elasticity of green hydrogen technology at various scales; fourthly, the use of renewable energy sources as the main power source for the electrolysis process that underscores the importance of integration with renewable energy in the production of green hydrogen; and, fifthly, variations in project costs that indicate the complexity of factors influencing green hydrogen development, including scale, technology, and supporting infrastructure.

6. Challenges in Solar- Low Temperature Water Electrolysis for Green Hydrogen Production

Green hydrogen is an energy source that has an important function in the energy transition process to achieve the 2050 NZE target, and solar energy-based low temperature water electrolysis is one of the most potential methods to meet this green hydrogen demand. However, currently, there are still many obstacles to reach the optimal points. Innovations by researchers in this field are expected to be able to answer existing challenges and in the future green hydrogen is expected to be able to compete with other energy sources both in terms of quality and quantity. In the following, a more specific explanation of the technical challenges in the development of a solar energy-based low temperature water electrolyzer will be presented. Some of the key technical challenges in green hydrogen production via electrolysis include:

- AWE Crossover of the gases Diaphragms: During the electrochemical process, there is a possibility of mixing gas products from each side of the electrode than can reduce the purity of the gas produced. This usually occurs due to problems with the diaphragm. To reduce crossover, a diaphragm with materials suitable for alkaline water electrolysis operating conditions is needed, like materials capable of operating in high concentration electrolyte solutions (5M KOH). In addition to the materials, the use of a diaphragm with a thick size as a separator can also increase the possibility of gas mixing not occurring but can increase the overall resistance value of the electrolyzer cell.
- AWE-Current density: Currently, the average operating current density of the electrolyzer cell is at a value of 0.8 A/cm^2. This is of course a big obstacle in the water electrolysis process because, in principle, the greater the current density value, the better the efficiency of the electrolyzer cell. To get to the optimal point, the current density in the electrolyzer cell must reach a value of 2-3

A/cm^2. One effort to increase the current density is to use a thinnest diaphragm, to reduce the system resistance, and electrode materials with high surface area.

- PEM-Membrane: Membrane is the main component of PEM, and is the most significant component to reduce electrolyzer production costs. Research on inexpensive and effective membrane materials has become the main topic for the development of PEM.
- PEM-Electrocatalyst Materials: Besides the membrane, the electrocatalyst is the other most expensive component of a PEM. Currently, the material used as an electrocatalyst is precious materials (Pt/IrO_2). The high costs for these components are the main obstacle to the PEM electrolyzer scale-up process. Therefore, the most significant solution is to look for alternative materials that are cheaper, while still having the same advantages.
- PEM-Stack ability (Electrolyzer cell stack): The membrane and electrocatalyst are the components that most influence the efficiency of the PEM electrolyzer cell, and are also the most expensive components. Therefore, the PEM electrolyzer cell stack requires effective design and manufacturing. This aims to reduce production costs.
- AEM-Membranes and Ionomers: the durability of membranes is the main challenge of this technology scale-up process. Currently, the lifetime of the membrane used is only around 30,000 h. If the operation exceeds the available lifetime value, degradation of the polymer membrane chain will occur (chemically unstable). Therefore, the main focus of the development of the AEM electrolyzer is to increase the durability and chemical stability of the polymer membrane used.

Solar Energy Technical Challenges in Green Hydrogen Production Harnessing solar energy for green hydrogen production is an environmentally friendly approach, but it also presents several technical challenges. Some of the key technical challenges in using solar energy for green hydrogen production include:

- Solar energy conversion efficiency: the development of materials used to convert solar energy into electricity is one of the keys to increasing conversion efficiency, especially for the PV-electrolysis production method. Besides, conversion efficiency can also be increased through collector designs, solar energy tracking, and other components.
- Intermittency of solar energy: Because solar energy is only available when the sun is shining, hydrogen production must be stopped in periods of low sunshine. This can cause fluctuations in the green hydrogen production system. Therefore, efforts are needed to overcome this problem, such as a combination with energy storage such as fuel cells, batteries, or others.
- Durability and reliability: Solar panels are exposed to various environmental factors like fluctuations in temperature, humidity, and dust, which can affect their performance over time. Ensuring the long-term durability and reliability of solar panels is critical to maximize their service life and keep the energy produced optimum.

7. Conclusions

Utilizing green hydrogen is one of the promising pathways to achieve the NZE target in 2050 and in the future will have an important role in meeting the demand for clean energy in the future. The utilization of solar energy in the green hydrogen production process under the water splitting method can be divided into two categories, namely the direct method (thermolysis) and the indirect methods (electrolysis, photolysis, thermolysis, and bio-photolysis). When viewed from two parameters efficiency and technological maturity level, PV electrolysis is the method that has the most dominant opportunities in the green hydrogen production process in the future. Specifically, the electrolyzer technology that also has the biggest opportunities is the low temperature water electrolyzer type; water splitting technology is the best in producing green hydrogen. There are two kinds of water electrolyzer technologies that have reached the commercial stage and have been widely used in green hydrogen pilot projects, namely AWE and PEM. However, currently, there are still quite a lot of challenges that must be faced to reach the optimal point of the solar PV-water electrolyzer. These challenges include component efficiency, production costs that are still high, and energy source intermittency. For this reason, new ideas, potential solutions, and constructive recommendations are needed to perform research on solar energy-based water electrolyzer technology development to reach the stage of commercially viable green hydrogen production as soon as possible. It is hoped that this study can eventually help initiate the development of solar energy-based water electrolysis technology that is efficient, cost-effective economically, and safe for the environment.

Nomenclature

Acronyms
TFEC – total final energy consumption, [exajoule]
TPES – total primary energy supply, [exajoule]
LHV – low heating value, [$MJkg^{-1}$]

Subscripts
l – liquid
aq – aqueous
g – gas

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Submitted: 20.11.2023
Revised: 1.3.2024.
Accepted: 8.3.2024.