Water for Green Hydrogen Production

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***Abstract*—Hydrogen is considered a powerful fuel for the future. Hydrogen production technologies vary widely. Green hydrogen is generated by electrolyzing water with electricity produced from renewable energy sources. According to the stoichiometry reaction, 9 kg of water is consumed to produce 1 kg of hydrogen. The water to be electrolysed has to meet stringent requirements and its preparation generates large quantities of wastewater, which should be managed appropriately. The objective of this research is to examine the methods by which water is prepared depending on its source and to determine the level of wastewater generated by its treatment. The results of the analyses carried out indicate that the water abstraction associated with green hydrogen production is significantly higher than the 9 kg per 1 kg of hydrogen value reported in numerous studies.**

Keywords*—green hydrogen*, *water quality, water treatment, water-energy nexus*

I. Introduction

Concerns regarding the negative impact of fossil fuels on the environment, but also the war in Ukraine and therefore the problem to fossil fuels access, have led to a change in thinking shift towards sustainable energy systems. Numerous nations are prioritizing the implementation of eco-friendly energy strategies to foster sustainability and reduce carbon emissions [1], [2]. Among the primary objectives set by these nations for 2050 is the reduction of reliance on fossil fuels to combat climate change effects [3]. Hydrogen, considered a powerful fuel for the future, seems to be the way to go, if these goals are to be met. Hydrogen serves as a portable energy carrier capable of powering electricity generation, industrial processes, and transportation. In contrast to fossil fuels, its combustion results solely in the production of water, eliminating harmful greenhouse gas emissions. Leveraging renewable energy in water electrolysis to generate green hydrogen holds considerable potential for decarbonization across various sectors [4]–[7]. Yet, for hydrogen to substantially impact clean energy transitions, its adoption must extend into sectors where its presence is currently minimal, including transportation, construction, and electricity generation. As of January 31, 2023, Europe accounted for 36 percent of the investments in announced hydrogen projects worldwide, representing a value of 117 billion U.S. dollars by 2030. Asia Pacific followed, with hydrogen investments of 69 billion U.S. dollars required to develop the projects that have been announced there through 2030 [8]. The ways of producing hydrogen are very different and unfortunately, comparing actual hydrogen production (data from 2020), he majority of hydrogen (95%) was derived from non-renewable fossil fuels, primarily through steam reforming of natural gas, while only a small portion (5%) originated from renewable sources, notably water electrolysis [9]. Meanwhile, it is hydrogen produced by electrolysis that is the so-called clean/blue energy source. Referring to how the hydrogen is produced, there are many “colours” of hydrogen. Classification of hydrogen by production method, together with an indication of CO_2 emissions, is shown in Table I.

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TABLE I. Classification of Hydrogen According to its Production Method

Raw material/ Technology	Products/ Level of CO_2 emissions	Hydrogen
Water+Energy/ Electrolysis	$H_2 + O_2$	**Green**
Natural gas/ Gasification +carbon capture	$H_2 + CO_2$ CO_2 emission	**Blue**
Natural gas/ Reforming	$H_2 + CO_2$ Medium CO_2 emission	**Grey**
Black coal / Gasification	$H_2 + CO_2$ High CO_2 emission	**Black**
Brown coal/ Gasification	$H_2 + CO_2$ High CO_2 emission	**Brown**

As evident, green hydrogen, generated through water electrolysis, emerges as a crucial solution for addressing global decarbonization due to its CO2 neutrality [10]. According to projections outlined in the Accelerated Energy Decarbonization Scenario, it is estimated that green hydrogen technology will account for a 48 percent share of global hydrogen production by 2050 [11].

Electrolysis of water is an electrochemical procedure that divides water into hydrogen and oxygen, employing electricity generated from renewable sources. Primarily, there exist three distinct types of water electrolysis technologies:

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Alkaline Water Electrolysis (AEC): This technology stands out as the most developed, having been implemented commercially owing to its exceptional energy conversion efficiency and consistent performance.

Polymer Electrolyte Membrane Water Electrolysis (PEM): This can be integrated into a compact system and operate at higher current densities, exhibiting rapid responsiveness to renewable electricity.

Solid Oxide Electrolysis (SOES): This operates at high temperature with less electrical energy consumption.

In most countries, announced projects with AEC technology currently exceed PEM. In United State, PEM electrolysers account for 45% of installed and announced electrolyser projects. In contrast, Australia relies more on PEM electrolysers. A comparison of the most important performance parameters of electrolysers is presented in Table II.

TABLE II. PERFORMANCE PARAMETERS OF ELECTROLYSERS (OWN COMPILATION, BASED ON [9])

Electrolyser type/ Operating parameters	Unit	AEC	PEM	SOES
Hydrogen production capacity	Nm^3H_2/h	1÷500	0.01÷250	n.d.
Energy consumption	kWh/Nm^3H_2	4÷5	4÷5	2.5÷3.5
Operating temperature	°C	25÷100	20÷80	850÷1200
Operating pressure	bar	1÷30	1÷80	1÷30
Efficiency	%	50÷82	60÷82	81÷86
Lifetime	h	<100K	10÷50K	10÷30K

Water is indispensable for the production of green hydrogen. As the green hydrogen production grow, crucial questions about the quantity and quality of water are starting to arise the process. In the production of green hydrogen, it is necessary to ensure the supply of ultra-pure water to electrolysis process [18]. Depending on the type of electrolysis, electrode material or system design, the specific quality of so-called 'ultrapure water' may vary marginally. Each ion and molecule contained within water will exert distinct effects on the electrolyzer. Certain ingredients present in the water can increase operation costs because of increased need for cleaning, Meanwhile, some may diminish the efficiency of the electrolyzer or cause irreversible damage and degradation to it. It should be noted that it is difficult to apply uniform standards when designing water treatment systems for electrolysers, because both the variable quality of the raw water (water before treatment) and the variable standards for ultrapure water quality mean that water treatment must be tailored individually for each project [13]. While a hydrogen economy has been advocated as a pioneering element of a low-carbon future [14], assessing the influence of a green hydrogen system on local water systems requires attention not only to the consumption of ultrapure water but also to the quantity of water extracted from the raw water source to produce ultrapure water.

II. AVAILABLE WATER SOURCES

The aim of this article is to compare water purification methods for green hydrogen production depending on the water source. Three different sources were selected for analysis: surface water, groundwater and water from dewatering of mine galleries. The surface water selected to these analyses comes from an intake on the Mała Panew River. After treatment, the water is used in the power industry for the Opole Power Plant. The groundwater is water abstracted from quaternary deposits, which are characterized by elevated concentrations of iron and manganese. The water came from the Zawada water intake and was a mixture of water from several wells. The third source of water is water from mine drainage, the water selected for analysis was low in salinity and came from the drainage of the disused mine. The results of the raw water quality analyses from these three sources are presented in Table III. It should be noted that raw water is water taken directly from the source, which has not yet undergone any treatment process.

TABLE III. PHYSICAL AND CHEMICAL PARAMETERS OF THE WATER FROM THREE DIFFERENT SOURCES

Contamination indicator	Unit	Type of water source		
		Surface	Under ground	Mine[1]
Conductivity	µS/cm	300÷445	380	793÷908
pH	-	6.8 ÷10.1	7.4	6.7÷7.7
Silica	mg/L	20÷24	n.d	n.d.
Total suspended solids	mg/L	1÷30	n.d	556÷664
Chlorides Cl^-	mg/L	20 ÷27	12	54÷63
Sulphates SO_4	mg/L	47÷80	65	88÷187
Total iron Fe	mg/L	0.04÷2.01	6.5	4÷12
Manganese	mg/L	0.196-0.82	0.043	0.15÷3.7
Total alkalinity	mval/L	5÷1.79	2.0	3.6÷4.09
Magnesium	mg/L	0.22÷1	0.05	n.d
Total hardness	mval/L	1.64÷3.19	3.2	6.6÷7.4
Calcium	mg/L	82÷129	2.7	n.d.
Nitrates NO_3	mg/L	0.2÷12	1.6	1÷2.9

(1) *mine water from dewatering of non-working galleries*

Water holds exceptional significance in regions vulnerable to water scarcity or quality degradation, such as Northern China, the Middle East, North Africa, and India. These challenges present a possible limitation on the extensive deployment of green hydrogen installations [4]. Therefore, at the investment planning stage, it is necessary to identify the water source, its capacity and to determine the demand for water from the source, which significantly exceeds the demand for ultrapure water used in the electrolyser.

III. Water Treatment Technology

The location of green hydrogen production facilities is closely linked to the location of sites where renewable energy is available (wind or solar farms) [15]–[18]. Establishing a solar or wind farm adjacent to an electrolyzer offers reduced power loss and lower initial system costs compared to transmitting power over long distances [15]. In such places, tap water is not always available [20]–[22], and investors often have to use a locally available water source, which it could be e.g. a river, well, or industrial or sea water. Each source provides water (raw water) whose quality requires correction [23], [24]. Because of the characteristics of untreated water, it necessitates treatment before being utilized to supply green hydrogen facilities. The water treatment plant for such facilities should be designed to produce ultrapure water of the, independently of the water quality of the source. Each of the raw waters requires different treatment processes. The technological schemes of the treatment processes for the previously presented water sources, are presented in Tables IV–VI. Tab. IV presents the technological scheme of surface water treatment; Tab. V - the groundwater treatment scheme and Tab. VI - the mine water treatment scheme.

When it comes to water quality requirements, one of the main parameters used for defining quality of water for green hydrogen production is the electrical conductivity. Electrical conductivity quantifies water's capacity to conduct an electrical current due to dissolved salts and inorganic chemicals. In terms of conductivity, values below 0.1 µS/cm are frequently specified for some of the more stringent electrolysers. It should be noted, however, that due to the relatively low additional investment required to achieve conductivity below 0.1 µS/cm, this is often preferred, as the water is rarely considered ‘too pure’ for the electrolyser [28].

Therefore, the available water should be prepared in such a way that it meets the above requirements after the entire treatment process. The presented analysis focused on three selected water sources, however in scientific publications it can be also find the information about the use of wastewater for the production of green hydrogen [4], [28], [29]. Some authors recommend the use of seawater for this purpose [30]–[32]. Despite the promising potential of direct seawater electrolysis for large-scale green hydrogen production (without dependence on limited freshwater), it is significantly hindered by excessive energy consumption (> 4.3–5.73 kWh m−3 H2) and detrimental chlorine corrosion [31].

TABLE IV. Technological Scheme of Surface Water Treatment

Water purification on grids
Pre-filtration on slit filters;
Pre-oxidation with ClO_2
Aluminum sulphate coagulation, flocculation, flotation
Filtration on rapid filters and adsorption on activated carbon
Ultrafiltration process itself is based on the molecular sieve effect with a pore diameter of 0.01–0.1 µm
Reverse osmosis module
Membrane degassing units (MDU)
Electrodeionization (EDI) / Ion Exchange
The point-of-use ion exchange polishing

TABLE V. Technological Scheme of Ground Water Treatment

Aeration
Sedimentation
Filtration on rapid filters
Ultrafiltration process itself is based on the molecular sieve effect with a pore diameter of 0.01–0.1 µm
Reverse osmosis modules
Membrane degassing units (MDU)
Electrodeionization (EDI) / Ion Exchange
The point-of-use ion exchange polishing

As can be seen from the examples presented below, the technological scheme differs only in the pre-treatment steps. Treatment directly for the electrolyse process includes the same unit processes: ultrafiltration, reverse osmosis; degasification, ion exchange and polishing (the ultra-pure water production system for the electrolyser is marked in blue in Tables IV–VI).

TABLE VI. TECHNOLOGICAL SCHEME OF MINE WATER TREATMENT

Aeration
Coagulation (aluminum sulphate coagulation, flocculation)
Sedimentation
Filtration on rapid filters
Ultrafiltration process itself is based on the molecular sieve effect with a pore diameter of 0.01–0.1 µm
Reverse osmosis modules
Membrane degassing units (MDU)
Electrodeionization (EDI) / Ion Exchange
The point-of-use ion exchange polishing

When comparing the presented treatment schemes, it should be noted that most pollution will be generated by surface water treatment processes (Tab. IV) and the greater the pollution, the higher the amount of wastewater generated during the treatment process. Based on the process analysis, it can be estimated that wastewater will account for approximately 50% of the volume of water produced. For groundwater, this value will represent approximately 30% of the volume of water produced. For mine water this will depend on its composition but will often be close to what is produced from underground water. It should be noted that the use of such mine water for hydrogen production appears to be a very good solution, as it is rarely used (especially in Poland). The use of mine water in the production of green hydrogen is a method to reduce the consumption of water resources. In order to maintain the mining infrastructure, this water is pumped to the surface and immediately lost.

When analyzing individual water treatment unit processes, special attention should be paid to electro deionization process (EDI), which is undoubtedly a modern alternative to traditional ion exchange processes. EDI combines the two technologies of ion exchange and electrodialysis. It is a desalination technology developed based on electrodialysis, and it is a water treatment technology that is increasingly widely used and has achieved better results after ion exchange resin. During operation, a transverse DC electrical field is applied to the electrodes. Ions entering the dilute cell in the feedwater stream, under the influence of this electric field, migrate from the dilute cell towards their respective electrode and become trapped in the concentrate cells [25]–[27]. The EDI operation diagram is presented in Fig. 1.

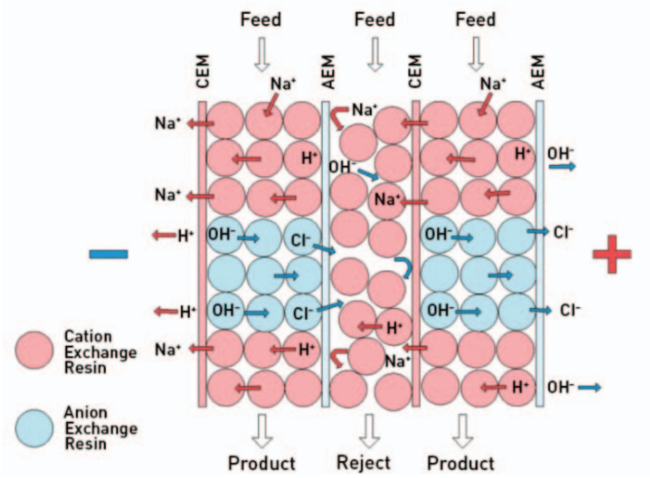

Fig. 1. EDI operation diagram [26]

It seems that using the above solution can significantly reduce the amount of wastewater. Of course, the application of this process need to control the inlet water:

* conductivity (the EDI inlet water conductivity need to be less than 40us/cm, these ensure outlet water conductivity). is qualified as well as the removal of weak electrolytes;

* hardness (if the residual hardness of the feed water in the EDI is too high, it will lead to membrane surface scaling in the concentrated water channel);

* iron, manganese and silica (metal ions will cause resin "poisoning", resin metal "poisoning" will cause rapid deterioration of EDI water quality);

* turbidity (too high turbidity will make the channel clogging, resulting in system differential pressure rise, water production decreased);

* Total Organic Carbon (if the organic content in the feed water is too high, it will cause organic contamination of the resin);

IV. CONCLUSIONS

With the decline in renewable electricity costs and advancements in electrolyzer efficiency, certain critics have started to raise concerns regarding water availability [33].

Considering the impact of hydrogen production on global water reserves, it is imperative to account not only for water directly used in water electrolysis but also for the total water extracted from its source. Furthermore, hydrogen production via electrolysis consumes water not only directly (as a feedstock for hydrogen) but also indirectly, as a cooling fluid for thermoelectric power generation. On average, thermoelectric power generation will withdraw approximately 4.2 m^3 of cooling water per kilogram of hydrogen produced for an electrolyzer operating at 75% efficiency [34].

When comparing these values, we must be aware that in extreme cases the amount of water taken from the source may be several dozen times greater as the amount of water needed to produce hydrogen.

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