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HYDROGEN FROM SEAWATER: AN ENVIRONMENTAL AND ECONOMIC EVALUATION OF AEM AND PEM ELECTROLYSIS COUPLED WITH ADVANCED DESALINATION SYSTEMS

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This research investigates the Global Warming Potential and the Levelized Cost of Hydrogen for Anion Exchange Membranes (AEM) and Proton Exchange Membranes (PEM) electrolysis plants fed by ultra-pure water produced from an innovative seawater purification system. The analyses are conducted by considering either the electricity supply from the Italian national grid or a 100% renewable energy mix. Values for Global Warming Potential (GWP) are equal to 22.3 kgCO2/kgH2 and 21.2 kgCO2/kgH2, respectively for PEM and AEM, when supplied with the Italian electrical grid, while a reduction of approximately 86% of impact is achievable in the case of renewable energy supply. The desalination unit contributes negligibly to the overall GWP. The Levelized Cost of Hydrogen (LCOH) was found to be equal to 6.33 €/kgH2 and 6.67 €/kgH2, respectively for PEM and AEM electrolysis. Most of the cost is associated to energy purchase during electrolysis, while water treatment accounts for only 0.20–0.65% of OPEX.

These findings highlight the importance of integrating desalination with green hydrogen production to mitigate pressure on freshwater resources and advance the transition toward more sustainable energy systems. The study underscores the necessity of redefining hydrogen production strategies by prioritizing seawater sources, enhancing process efficiencies, and leveraging renewable energy inputs.

* 1. Introduction

The transition towards a sustainable hydrogen economy imposes new challenges regarding the development of innovative production methods that can minimize overall environmental impacts through the reduction of the energy and resource consumption. One of the critical aspects related to hydrogen production with AEM and PEM electrolysis systems is the need for high-purity water (Becker et al., 2023). Moreover, the future demand for increased amounts of freshwater to guarantee hydrogen production, can create a competition with the human use, mostly nowadays when numerous countries face severe freshwater stress conditions (Kumar et al., 2024). Hydrogen can be produced from seawater either (i) directly, by feeding raw seawater to the electrolyser, or (ii) indirectly, via a desalination ‘pre-treatment’ that supplies ultrapure water to a conventional electrolyser. In this context, various studies have been published in recent years concerning direct seawater electrolysis, exploring experimental approaches. Liu et al. (2024) tested a floating electrolysis plant capable of operating for over 240 hours with a specific consumption of 55.63 kWh/kgH2, while Xie et al. (2022) proposed a novel membrane for direct seawater processing, achieving good stability for more than 3,000 working hours. However, while direct seawater electrolysis represents a promising long-term frontier, its current technology readiness level often limits immediate commercial application. Conversely, the adoption of purified seawater as inlet feed stream to the electrolysis unit is a practical solution that has gained increased attention during the last years, since it can operate with commercial technologies (Khan et al., 2021). Although the energy consumption and the environmental impact of desalination processes are minimal compared to that of hydrogen production, conventional desalination plants are energy-intensive and present potential for mitigation (Bamba et al 2024). As per the authors’ knowledge, the environmental and economical aspects of coupling seawater purification system and PEM or AEM electrodialysis has been studied by only a few authors in the recent literature. Khan et al., (2021) evaluated the emissions in terms of CO2eq/kgH2 and the levelized cost of hydrogen for a system composed of a seawater reverse osmosis plant and a PEM electrolyzer, with a production rate of 50 tons of hydrogen per day. Dokhani et al., (2023) proposed a techno-economic evaluation of PEM electrolyzer fed with seawater treated through a single or double-stage reverse osmosis process. The economic assessment also encompasses the recourse to different energy sources like grid electricity, photovoltaic (PV) or wind and a combination among them with or without the use of battery storage.

The present work, therefore, evaluates the GWP and the LCOH of a PEM and AEM electrolysis plant exclusively fed with ultra-pure water produced from a seawater treatment system. The aim is to assess the feasibility of employing purified seawater for hydrogen production by evaluating the impact of the water treatment system on the overall hydrogen generation.

* 1. Materials and methods
     1. Goal and scope

The functional unit is defined as the production of 1 kg of hydrogen, and the analysis adopts a cradle-to-gate system boundary. Environmental burdens are therefore accounted for from raw-material extraction and plant construction up to the point at which the hydrogen leaves the electrolysis facility. Electrolyzer size was set equal to 1 MW, while the water purification system can treat approximately 1,000 m3/h, since it was assumed that it can supply ultrapure water to other industrial activities. Two water-use scenarios are assessed for hydrogen production. (1) Stoichiometric water—the ultrapure water actually consumed in electrolysis—amounts to 10 L kg⁻¹ H₂. (2) Total water withdrawal comprises stoichiometric water plus cooling water. For this second scenario, IRENA (2023) reports 19.5 L kg⁻¹ H₂ of make-up water required by the evaporative cooling system (14.6 L evaporated, 4.9 L discharged). Thus, the total withdrawal reaches 29.5 L kg⁻¹ H₂.

* + 1. Life cycle inventory

2.2.1 Water purification system

An innovative desalination plant has been developed to produce ultra-pure water from seawater, specifically intended for hydrogen production. This process scheme stands out for the high quality of the produced water, combined with low specific costs and energy consumption. After developing simulation models for different system configurations in gPROMS®, a simulation campaign was conducted to identify the best configuration for the plant, analyzing the implementation of different technologies and operating conditions and their impact on the final water quality and production cost. The scheme in Figure 1 emerged as the most suitable solution, with the best water resistivity and specific production cost. The designed plant comprises the following processes: i) a pretreatment step for the removal of organic matter, ii) a SeaWater Reverse Osmosis (SWRO) step, iii) a Brackish Water Reverse Osmosis (BWRO) step, and iv) an electrodeionization step for further salt removal.



Figure 1 Conceptual scheme of the designed desalination plant for ultra-pure water production from seawater.

For the Reverse Osmosis (RO) technology, a lumped-parameters model was developed for a single module housed within a pressure vessel. The RO model validation was performed using the Wave database. Pretreatment and electrodeionization steps were modelled using black-box approaches, using empirical correlations from the literature for the pretreatment process and simulation data generated with the Winflows® software for electrodeionization.

The feed stream was assumed to be Mediterranean seawater, with a TDS of 35 g L-1. The productivity of the plant was fixed at 1,000 m3 h-1 of ultra-pure water with an electrical resistivity of 16 MΩ cm. Water recovery values were set at 89% for the pretreatment, and 50% and 82.5% for the SWRO and BWRO steps, respectively. The global water recovery of the chain was calculated as the ratio between the ultra-pure water produced and the seawater intake flowrate, resulting in 39.3%. The seawater intake was approximately 2,500 m3 h-1, while the produced waste brine had a flowrate of about 1,200 m3 h-1 with a concentration of 58 g L-1. The water production cost was calculated considering the annualized capital cost for equipment, including the intake structures and pumping systems, and the annual operational costs, divided by the total yearly production volume of ultra-pure water. The water production cost obtained was 1.43 € m-3, with a total specific energy consumption of 4.2 kWh m-3.

While data for the operational phase are taken from the model, published literature was used to account for the production step. As reported in different papers, the share of GWP associated to plant operation for the RO and the EDI unit account for more than 95%, while the construction phase is marginal, contributing in most of cases for less than 2%. Raluy et al., (2006) reported that the contribute of RO plant construction is between 0.95% and 2.4% of the overall GWP for the production of 1 m3 of potable water from seawater, while Shababi et al., (2014) reported emissions of 0.0754 kgCO2eq/m3 of desalinated seawater, corresponding to an overall impact of less than 2% on the global GWP. Goga et al. (2019) found that approximately 95% of the GWP is due electricity consumption, while less than 1% is attributable to plant construction. Similarly, Yuan et al., (2023) reported that more than 99% of the GWP associated to electro deionization process is associated to the operation phase. Here, impacts associated to plant construction were taken from Shahabi et al. (2014), while electrodeionization from Yuan et al., (2023).

2.2.2 Hydrogen production plant

A 1 MW electrolysis plant was proposed. Data for the PEM and AEM electrolyzers were taken from the work of Wei et al., (2024), which reports updated values for energy consumption and emissions for both plant production and operation. Impacts associated with plant construction account for less than 3% for both systems. Specific energy consumption was considered equal to 49.42 kWh/kgH2 and 53.45 kWh/kgH2, respectively for PEM and AEM electrolyzer. The contribution from plant construction was directly added on top of the GWP coming from the operational phase.

As introduced in paragraph 2.1, hydrogen electrolysis consumes 10 L kg⁻¹ H₂ of ultrapure (stoichiometric) water. In addition to the 10 L kg⁻¹ H₂ of stoichiometric ultrapure water consumed in electrolysis, the closed-loop evaporative cooler withdraws 19.5 L kg⁻¹ H₂ of make-up water to replace evaporative (14.6 L) and blow-down losses (4.9 L); the much larger volume that continuously circulates inside the cooling loop is reused and therefore is not counted as water withdrawa (IRENA 2023). If the entire water demand—including cooling make-up—comes from a seawater desalination plant, the total water withdrawal is 29.5 L kg⁻¹ H₂. However, in order to consider the possible recourse to tap water for the cooling step, the conditions with only stoichiometric water and total water withdrawal were considered. Although the water purification plant was designed for a significantly higher flow rate, the assumption is sound, as it could likewise provide ultra-pure feed water to local industry in water-stressed regions.

* + 1. Impact assessment and cost of hydrogen

The GWP and LCOH were calculated for four different scenarios. Scenarios 1 and 2 consider stoichiometric water consumption and the use of grid energy or a fully renewable supply comprising 50 % photovoltaic and 50 % wind energy. Scenarios 3 and 4 consider the consumption of the total withdrawn water, with the same energy conditions as before. The Global Warming Potential per kilogram of hydrogen is calculated as the sum of two contributions. (i) Operation covers the carbon intensity of the electricity consumed by electrolysis, pumping and desalination, as well as all minor operational inputs (chemicals for membrane cleaning, routine maintenance, component replacement, brine disposal). A screening analysis showed that these non-energy inputs account for < 1 % of the total impact and have therefore been aggregated into the operation contribution for brevity. (ii) Plant construction accounts for the materials and manufacturing of the electrolysers, desalination unit and auxiliaries, following the shares reported by Shahabi et al. (2014) and Yuan et al. (2023); this component represents ≈ 2 % of the overall GWP.

Electricity inventories for the Italian medium-voltage grid, photovoltaic (PV) and wind energy were taken from the Ecoinvent database (v3.x), and impact factors were calculated with the ReCiPe 2016 Midpoint (H) method.

The LCOH was calculated by using the following equation:

(1)

Where, CAPEX and OPEX are respectively the capital and operative costs of investment, PH2 is the amount of produced hydrogen, t is the number of years and r is the discount rate. The following table reports all the input data to define plant production, CAPEX and OPEX. Costs for stack, Balance of Plant (BoP), material and labour were taken from Kim et al., (2024), considering the equivalence of 1$ = 1€. The price of electricity was considered the same both for grid electricity and renewable electricity. The cost of ultra-pure water comes from the model introduced in paragraph 2.2.1. The calculation of the overall CAPEX (not reported in the table) includes the initial investment costs for the electrolyzer and balance of plant, as well as the annualized cost of all necessary stack replacements over the plant's operational lifetime, considering their respective lifespans.

|  |  |  |
| --- | --- | --- |
| Input data | | |
| Electrolyzer size | 1 | MW |
| Hourly production | 19 | kgH2/h |
| Daily working hours | 16 | h/d |
| Working days per year | 350 | d/y |
| Daily H2 production | 303 | kgH2/d |
| Daily water consumption (stechiom) | 3 | m3 H2O/d |
| Annual H2 production | 106,061 | kgH2/year |
| Stack lifetime\_PEM | 50,000 | h |
| Stack lifetime\_AEM | 30,000 | h |
| N. stack substitution in 20 years\_PEM | 2 |  |
| N. stack substitution in 20 years\_AEM | 4 |  |
| CAPEX | | |
| Stack | 210 | €/kWh |
| BoP | 258 | €/kWh |
| OPEX | | |
| Electric energy price | 0.10 | €/kWh |
| Ultra-pure water price | 1.4 | €/m3 |
| Materials | 2.5% of dcc | € |
| Labor | 5% of dcc | € |
| Discount rate | 10% |  |

Table 1. Input data for techno-economic evaluation

* 1. Results

Table 2 and Figure 2 report the results of the GWP analysis. Table 2 presents the absolute global warming potential values for each technology–scenario combination, whereas Figure 2 breaks down the contributions by process stage, from seawater purification through hydrogen production. From Table 2, it can be seen that the difference between the use of stoichiometric water and total water including the cooling purposes is minimal, accounting only for an increment of about 0.3% in the global value. Hydrogen produced through AEM systems presents approximately 5% lower impact than PEM, due to the reduced specific energy consumption. When energy is supplied by the national grid, the use phase with stoichiometric water for PEM and AEM presents, respectively, a global warming potential of 22.10 kgCO2eq/kgH2 and 21.04 kgCO2eq/kgH2. The use of renewable energy decrease the GWP to 2.85 kgCO2eq/kgH2 and 2.71 kgCO2eq/kgH2. From Figure 3, it can clearly be seen that the vast majority of the GWP is associated to the phase use of the electrolyzer, which range from 94.1% (PEM\_S4) to 99.2% (AEM\_S1), while the second highest contribution is associated to electrolyzer construction which account from 0.71% (AEM\_S3) to 5.71% (PEM\_S2). On average, the water purification system impact for less than 0.3%, ranging from 0.062% (1.69\*10-3 kgCO2eq/kgH2 for PEM\_S2) to 0.22% (4.3\*10-2 kgCO2eq/kgH2 for AEM\_S3).

Table 2: GWP of hydrogen production

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | S1 | S2 | S3 | S4 |
| PEM [kgCO2eq/kgH2] | 22.29 | 3.02 | 22.35 | 3.03 |
| AEM [kgCO2eq/kgH2] | 21.21 | 2.87 | 21.28 | 2.88 |

Figure 2. GWP impact share for the selected scenarios

Table 3 summarizes the levelized cost of hydrogen (LCOH) for AEM and PEM electrolysis under two water-use scenarios: (i) stoichiometric feedwater only and (ii) stoichiometric feedwater plus the extra water required for cooling. It also disaggregates the overall LCOH into capital expenditures (CAPEX), operating expenditures (OPEX), and the portion of OPEX attributable specifically to water production. As can be seen, AEM presents a 5.5% higher LCOH, which is primarily driven by its significantly larger CAPEX contribution, which accounts for approximately 20.78% of the total LCOH for AEM, versus 16.43% for PEM. This condition is a direct consequence of the lower expected lifetime of its stack, necessitating a doubled number of stack substitutions over the plant's operational lifetime compared to PEM. The aggregated cost of these initial and subsequent stack investments is incorporated within the CAPEX component in our LCOH calculation. The impact of water purification on the final hydrogen price ranges from approximately 0.2% (0.014 €/kgH2) to 0.65% (0.041 €/kgH2), when considering only stoichiometric water or also its use for the cooling system. For both technologies, the vast majority of the cost is associated to electricity consumption, which significantly impact on the final hydrogen price. A reduction in the price of energy to 0.05 €/kWh could result in a hydrogen price drop for PEM and AEM of 39% and 37%, respectively. An evaluation of hydrogen price according to different cost of electricity is reported in Table 4. The results of the obtained LCOH are in line with what is reported by BloomebergNEF, which defines the range of hydrogen cost between 4.5 $/kgH2 and 12 $/kgH2, with an average LCOH of 6.4 $/kgH2 (BloombergNEF, 2023).

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | PEM | AEM |
| Stochiometric water consumption | CAPEX | 16.40% | 20.74% |
| OPEX\_tot | 83.60% | 79.26% |
| OPEX\_only water | 0.22% | 0.21% |
| LCOH | 6.33 € | 6.67 € |
|  |  |  |  |
| Stochiometric + cooling water | CAPEX | 16.27% | 20.59% |
| OPEX\_tot | 83.73% | 79.41% |
| OPEX\_only water | 0.65% | 0.61% |
| LCOH | 6.38 € | 6.72 € |

Table 3. Share of CAPEX, OPEX and water production on the final LCOH

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Electricity price [€/kWh] | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.1 | 0.11 | 0.12 | 0.13 | 0.14 | 0.15 |
| LCOH\_PEM [€/kgH2] | 3.86 | 4.35 | 4.84 | 5.34 | 5.83 | 6.33 | 6.82 | 7.31 | 7.81 | 8.30 | 8.80 |
| LCOH\_AEM [€/kgH2] | 4.20 | 4.70 | 5.19 | 5.68 | 6.18 | 6.67 | 7.17 | 7.66 | 8.16 | 8.65 | 9.14 |

*Table 4. Trend in LCOH according to electric energy price*

* 1. Conclusions

This study quantifies the LCOH and GWP impact of integrating ultra-pure seawater purification with AEM/PEM hydrogen production, reducing the reliance on freshwater sources. The analysis confirms this coupling has a negligible effect on sustainability metrics: the treatment unit accounts for merely 0.06–0.20% of overall GWP and 0.20–0.65 % of LCOH, a marginal contribution maintained even when supplying the cooling water. While AEM further mitigates GWP, its LCOH is modestly higher due to increased stack replacement frequency, with associated investment costs included in CAPEX. Future research should assess on-site renewable power to reduce electricity costs and enhance competitiveness.

Market competitiveness of hydrogen from purified seawater, despite treatment, largely hinges on renewable electricity costs and policy. Key scale-up barriers include high electrolyzer CAPEX and ensuring robust, long-term desalination-electrolysis operation. Future improvements should focus on optimizing energy recovery, valorizing brine, and developing compact, modular designs for seamless water-power integration.

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