Environmental Sustainability Assessment of Green Hydrogen Production from Seawater Using Life Cycle Assessment

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Abstract: The electrolysis of water to produce green hydrogen fuel is pivotal for the transition to renewable energy sources. Predominantly, this process utilizes low-temperature alkaline or proton exchange membrane electrolysers, which require high-purity water, posing challenges for large-scale adoption due to freshwater scarcity. Seawater, comprising 96.5% of Earth's water reserves, presents an almost inexhaustible alternative. However, its complex composition, including various salts and organic compounds, complicates direct electrolysis. Specialized anodes and highly efficient electrocatalysts are essential to prevent corrosion and counteract undesirable chlorine evolution reactions. This study investigates the use of low-saline water from the Baltic Sea for hydrogen production via osmotic desalination and alkaline electrolysis using Life Cycle Assessment, focusing on economic, social, and environmental impacts. Findings indicate that electrodialysis is more energy-efficient compared to reverse osmosis, exhibiting lower environmental impacts across most categories, including global warming potential, ecotoxicity, and eutrophication. Reverse osmosis showed higher impacts, especially in fine particulate matter production and water-related parameters. Despite higher operational costs, integrating seawater desalination presents a promising method for renewable energy storage and hydrogen production. Optimizing electrodialysis could enhance its economic feasibility and performance, supporting sustainable green hydrogen production. Our research underscores the significant potential of seawater desalination coupled with electrolysis for sustainable energy transitions, particularly for regions with abundant seawater access but limited freshwater resources.

1 INTRODUCTION

The electrolysis of water to produce green hydrogen fuel is a cornerstone for the future of renewable energy. Currently, the most widespread technology of hydrogen production based on low-temperature alkaline electrolysers or proton exchange membrane electrolysers, primarily rely on high-purity water as feedstock [1]. However, if water electrolysis were to be adopted on a massive scale, as anticipated for the global energy landscape in the near future, issues related to water resource availability, particularly freshwater could emerge. This presents a significant challenge due to the exhaustive nature of freshwater sources. More than half of the world’s population faces water scarcity for at least one month a year. Only in last 60 years renewable internal freshwater resources in Germany decrease in around 15% [2].

Seawater, constituting 96.5% of the Earth's water reserves, offers nearly unlimited availability as a natural electrolyte feedstock. Despite this vast potential, direct seawater splitting for hydrogen production is still in its early stages due to the complex composition of natural seawater. Seawater contains various dissolved salts and organic compounds, posing significant challenges for electrolysis. Efficient seawater splitting needs highly Oxygen evolution reaction-selective anodes to counteract chlorine evolution reactions, alongside highly efficient electrocatalysts to protect the electrolysis cell, particularly the anode, from chloride-induced corrosion [3]. Nonetheless, seawater electrolysis may yield more hydrogen from the same volume of water compared to freshwater, thanks to its enhanced conductivity due to the presence of alkali and alkaline earth metal cations [3].

Some studies have suggested that coupling seawater reverse osmosis or forward osmosis systems with conventional electrolysers could be a feasible solution for seawater electrolysis [4]. However, this approach requires additional purification steps to bring the treated seawater to the necessary purity levels for current electrolysers, which increases the system's complexity and cost. This underscores the need for more efficient and direct methods of seawater electrolysis. On the other hand, some findings indicate that the increase in the levelized cost of hydrogen production is insignificant, as the capital and operating costs of seawater reverse osmosis are negligible [5]. Nonetheless, green hydrogen production from seawater has been largely overlooked, due to the belief that it is too expensive for industrial-scale implementation. To our knowledge, in Germany, there is currently only a pilot project, "OffsH2ore," which aims to produce green hydrogen in the North Sea.

To address these issues, the present study aimed to assess the economic, social, and environmental performance of producing green hydrogen through osmotic desalination and alkaline electrolysis of low-saline water from the Baltic Sea.

2 MATHERIALS AND METHODS

In this study, a comprehensive Life Cycle Assessment (LCA) using Open LCA software (https://www.openlca.org/) was performed to analyze green hydrogen production utilizing low-salt water from the Baltic Sea. This LCA study follows the four phases outlined in ISO 14040:2006 (ISO 2004). The first phase is the goal and scope definition. The second phase involves data collection and inventory analysis. The third phase focuses on assessing the life cycle impact of the two products. Finally, in the fourth phase, the results are interpreted, including a sensitivity analysis, and thoroughly discussed.

The system's scope incorporated set of input and output data, including resources, raw materials, machinery, power, the main and secondary products, waste, and contaminants. While key input parameters were adjusted for this study, majority of data have taken from Ecoinvent, needs_18 databases and references [6,7]. To evaluate the environmental impacts of H_2 production processes, the ReCiPe 2016 model as well as IMPACT 2002+ were employed [8]. ReCiPe 2016 model includes 22 midpoint impact categories related to global warming potential, ozone depletion, ionizing radiation, photochemical oxidant formation, human toxicity potential, ecotoxicity and eutrophication potentials and resource scarcity.

3 RESULTS AND DISCUSSION

In our study, we utilized life cycle inventory flows of each technology to compute life cycle midpoint impact category indicators for brackish water desalination might be used for green hydrogen production. This allowed us to shed light on the key midpoint environmental performance indicators and then identify the processes responsible for the potential impacts of the water desalination technologies required for subsequent green hydrogen production (Table 1).

Table 1: Life cycle environmental impacts of seawater desalination in terms of reverse osmosis and electrodialysis. The impacts are expressed per 1000 m^3 of potable water in ReCiPe 2016 model.

Name	RO	ED	Unit
Fine particulate matter	3.00E-5	1.27E-5	DALY
Fossil resource scarcity	3.11	1.33	USD2013
FW ecotoxicity	1.43E-11	5.87E-12	species.yr
FW eutrophication	1.47E-11	4.44E-12	species.yr
GW, FW ecosystems	3.54E-11	1.53E-11	species.yr
GW, Human health	6.49E-4	2.80E-4	DALY
GW, Terrestrial ecosystems	1.30E-6	5.60E-7	species.yr
Human carcinogenic toxicity	2.03E-6	3.79 E-7	DALY
Human non-carcinogenic toxicity	4.50E-5	1.88E-5	DALY
Ionizing radiation	1.68E-7	6.40E-8	DALY
Land use	1.11E-10	7.22E-8	species.yr
Marine ecotoxicity	2.51E-8	1.07E-8	species.yr
Marine eutrophication	1.91E-10	1.94E-13	species.yr
Mineral resource scarcity	0.002	0.010	USD2013
Ozone formation, Human health	1.14E-7	4.88E-8	DALY
Ozone formation, Terrestrial ecosystems	1.67E-8	7.15E-9	species.yr
Stratospheric ozone depletion	6.47E-8	3.08E-8	DALY
Terrestrial acidification	3.45E-8	1.48E-8	species.yr
Terrestrial ecotoxicity	1.46E-9	6.27E-10	species.yr
WC, Aquatic ecosystems	2.42E-15	3.41E-14	species.yr
WC, Human health	8.90E-9	1.25E-7	DALY
WC, Terrestrial ecosystem	5.41E-11	7.62E-10	species.yr

GW: Global warming, Freshwater: FW, Water consumption: WC

One significant finding was that the potential for fine particulate matter production, which serves as an indicator for NO_x and SO_x emissions, was markedly higher for Reverse Osmosis (RO) compared to Electrodialysis (ED). Similar trends were observed for other impact categories as well: the Global Warming Potential indicators, ecotoxicity-related indicators, and eutrophication indicators all demonstrated more intensive effects for RO than for ED.

Conversely, parameters associated with water consumption and related conjunction effects, as well as land occupation, were found to be higher for ED. However, these parameters contributed less than 5% across all impact categories for both RO and ED technologies.

Furthermore, both ED and RO processes contribute to the acidification of aquatic reservoirs, albeit to a marginal extent. Of the two, RO has a more significant potential to support water eutrophication (Table 2).

Table 2: Life cycle environmental impacts of seawater desalination in terms of reverse osmosis and electrodialysis. The impacts are expressed per 1000 m^3 of potable water in IMPACT2002+ model.

Name	RO	ED	Unit
Aquatic acidification	0.240	0.089	kg SO2 eq
Aquatic ecotoxicity	1783.3	509.8	kg TEG water
Aquatic eutrophication	0.336	0.0018	kg PO4 P-lim
Carcinogens	0.239	0.258	kg C2H3Cl eq
Global warming	52.59	22.73	kg CO2 eq
Ionizing radiation	476.08	160.64	Bq C-14 eq
Land occupation	0.013	8.576	m2org.arable
Mineral extraction	0.563	0.650	MJ surplus
Non-carcinogens	1.069	0.462	kg C2H3Cl eq
Non-renewable energy	566.59	253.15	MJ primary
Ozone layer depletion	1.86E-7	2.19E-7	kg CFC-11 eq
Respiratory inorganics	0.027	0.011	kg PM2.5 eq
Respiratory organics	0.025	0.011	kg C2H4 eq
Terrestrial acid/nutri	0.769	0.335	kg SO2 eq
Terrestrial ecotoxicity	235.71	99.2	kg TEG soil

The integration of data using a Sankey diagram highlights that the energy supply required for both ED and RO has the most significant impact (see Fig. 1).

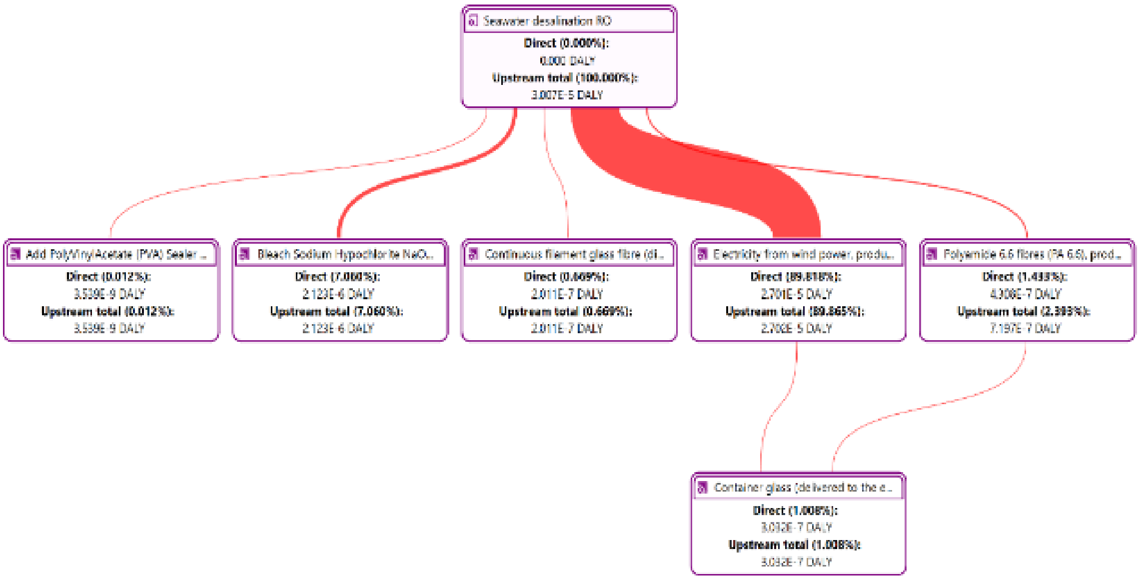
Our investigation into utilizing seawater at coastal locations highlights promising opportunities to harness sea water as abundant resource for storing surplus renewable electricity. While the cost of water from large-scale desalination plants is relatively minor compared to the overall expenses of producing green hydrogen through electrolysis, developing and maintaining desalination and deionization plants for water electrolysis demands significant capital investment and incurs ongoing operational and maintenance costs

Direct seawater use for water electrolysis without deionization presents several challenges that necessitate water desalination prior to hydrogen production. The most prevalent technique for this purpose is reverse osmosis [9]. However, only a limited number of studies explore alternative methods, such as electrodialysis or thin-film composite forward osmosis [10]. Some research indicates that electrodialysis may be a cost-effective alternative to reverse osmosis for low-salt desalination. If the costs of ion-exchange membranes are reduced and their performance is enhanced, electrodialysis could become economically preferable to reverse osmosis across the entire range of brackish water salinity [11].

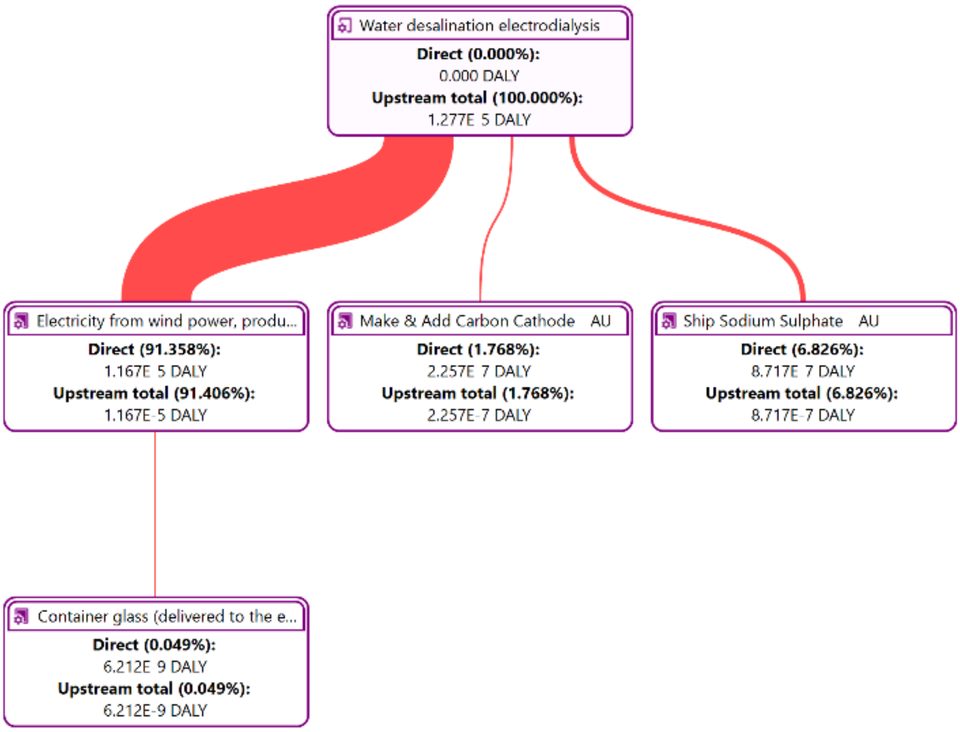
Germany, with access to the low-salinity Baltic Sea, has the potential to tap into an endless source of sustainable energy carriers. Proactive steps in this regard have already been made by research teams in Poland [12] who revealed that combining reverse osmosis with multiple-effect desalination systems can achieve water quality suitable for both alkaline and proton exchange membrane electrolytic cells. Our findings support that the electrodialysis treatment of brackish water from the Baltic Sea might reduce climate change potentials compared to reverse osmosis across nearly all considered scenarios. This advantage is largely attributed to lower energy requirements for desalination, measured at 2-3 kWh/m³ compared to 3-4 kWh/m³ for reverse osmosis [13].

Electrodialysis desalination showed to be more energy-effective related to non-renewables and therefore less carbon emission than reverse osmosis. This consumption is in good agreement with previous findings [11,14].

The IMPACT 2002+ model identifies water desalination as a key factor potentially contributing to aquatic ecotoxicity, particularly in the case of reverse osmosis due to brine discharge and associated salinity



a)



b)

Figure 1: Sankey diagram of environmental impacts of seawater desalination using reverse osmosis a) and electrodialysis b) technologies. The impacts are expressed per 1000 m^3 of potable water

changes. Increased salinity is known to induce more significant physiological and biochemical changes in marine organisms than chemical stressors [15]. Osmotic stress can lead to immune disorders, metabolic alterations, and increased oxidative stress [15, 16]. Nonetheless, the range of aquatic toxicity observed in our study is pretty low, favoring the use of brackish water for hydrogen production via potable water splitting.

Water consumption is critically important in our study, especially in regions with high potential for solar energy but limited water resources, such as desert areas. It is noteworthy that water consumption in our study is quite low, aligning well with previous findings [13]. As a cost-effective and environmentally friendly option, using seawater for hydrogen production offers a sustainable resource for renewable energy accumulation, thereby optimizing energy transition. This approach holds potential for further exploration and could support the economic and social development of low-income countries, such as those in Africa and South America, while also benefiting European nations.

Both studied methods for water desalination demonstrated a low impact on human health and may not induce carcinogenic pathologies, making them user-friendly options for producing potable water. These methods are suitable not only for green hydrogen production as a renewable energy carrier but also for supplying potable water in areas facing scarcity. Specifically, a photovoltaic-powered desalination system using time-variant electrodialysis reversal technology has been shown to provide brackish water desalination in India with a 22% cost reduction, making it competitive with fossil fuel-powered alternatives [14].

3 CONCLUSIONS

In conclusion, our study highlights the significant differences in environmental impacts between reverse osmosis and electrodialysis desalination technologies of brackish water for green hydrogen production. Integrating seawater desalination in coastal regions presents a viable pathway for renewable energy storage and hydrogen production. Electrodialysis pretends to be a more energy-efficient option, achieving lower environmental footprints in categories such as global warming potential, ecotoxicity, and eutrophication. Meanwhile, reverse osmosis exhibited higher impacts particularly in fine particulate matter production and water-related parameters. Using nanofiltration as pre-treatment for reverse osmosis might increase fresh-water output. Meantime forward osmosis and freeze desalination are expected to be promising for brine post-treatment, reducing environmental harm. Additionally, innovative nanomaterial membranes improve selectivity, reduce pressure, and lower costs [17]. These findings advocate for further exploration into optimizing electrodialysis, potentially reducing costs and enhancing performance, thereby supporting sustainable and economically feasible hydrogen production.

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