Life Cycle Assessment of Hydrogen Production via Electrolysis Technologies: Insights from India for a Sustainable Energy Transition

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Overview

The transition to sustainable energy systems depend on hydrogen as a vital energy carrier, crucial for decarbonizing hard-to-abate sectors. Life cycle assessments (LCA) are required to comprehensively examine the environmental implications of green hydrogen production and to find the most sustainable pathways. However, limited research has been conducted on the LCA of hydrogen generation via electrolysis and its comparative analysis, particularly in the Global South. This study conducts a comprehensive LCA of hydrogen production through four electrolysis technologies: Proton Exchange Membrane (PEM), Alkaline Water Electrolysis (AWE), Alkaline Anion Exchange Membrane (AEM), and Solid Oxide Electrolysis (SOE) using grid electricity, Solar Powered Battery Energy Storage System (BESS) (Li-Ion and Lead Acid), stand alone solar photovoltaics and stand alone wind power as Source of electricity.

Methods

A cradle-to-gate approach is adopted using the software OpenLCA 2.3 with the ecoinvent database and the ReCiPe Midpoint (H) and Endpoint (H/A) methods, analyzing 18 midpoint and 3 endpoint environmental impact categories. The findings provide novel insights into hydrogen production technologies in the Indian context, offering scalable implications for the Global South and contributing to global efforts towards sustainable energy transitions.

Results

Results from the midpoint analysis reveal that SOE exhibits the highest climate (5.46, 2.8 kg CO2-Eq) and water depletion (34,17 Liters) impacts when powered by solar and wind but has the lowest impacts (57.28 kg CO_2-Eq, 290 Liters) when powered by grid-mix electricity. In comparision PEM has second lowest climate (4.67, 1.13 kg CO_2-Eq) and water depletion (31, 15 Liters) impacts for solar and wind but highest (74.85 kg CO2-Eq, 385 Liters) for grid supplied electricity. Figure 1 and 2 below shows the CO_2 emissions and water depletion per kg of hydrogen production for the four electrolysis technologies using different sources of electricity.

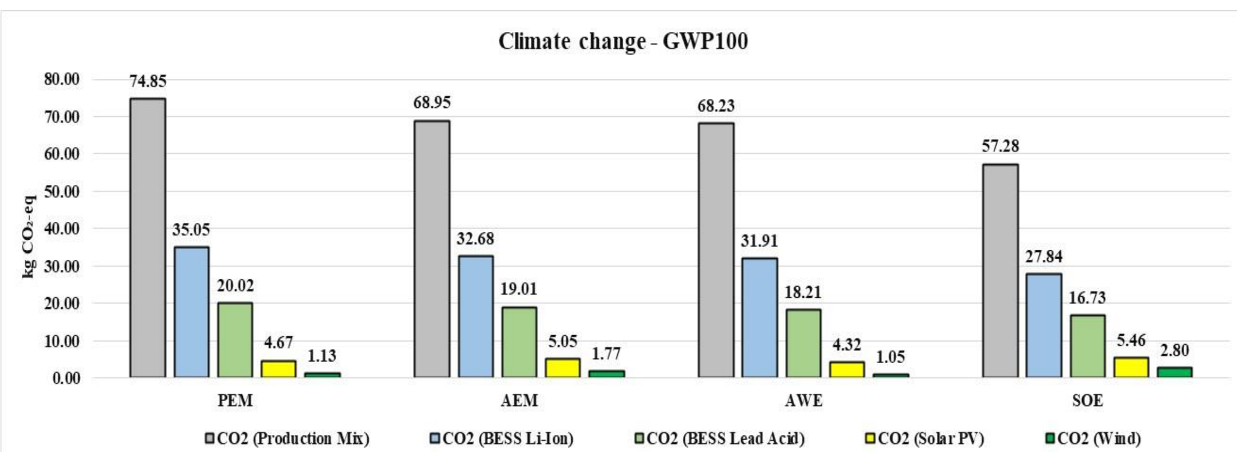

Figure 1 *CO2 emissions per kg of hydrogen production*

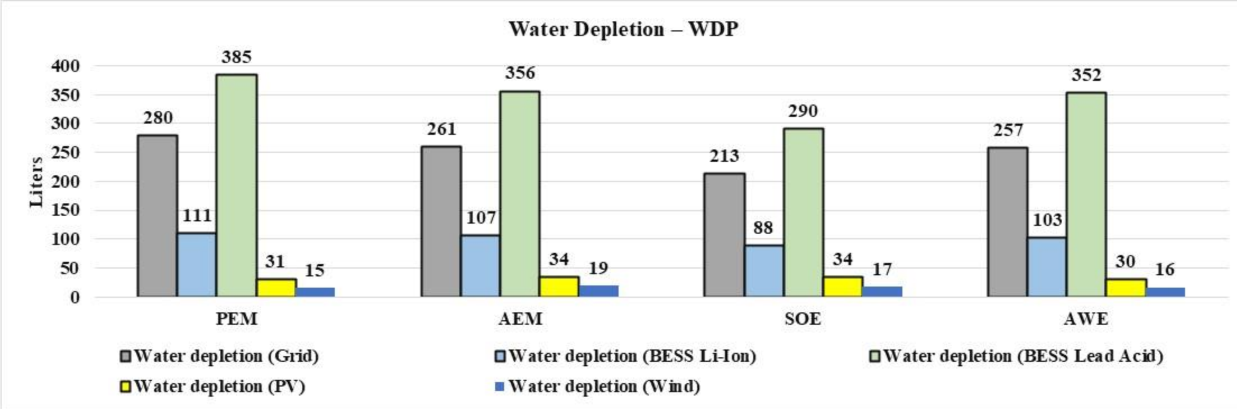

Figure 2 *Water Depletion per kg of hydrogen production*

The endpoint analysis shows BESS Li-Ion powered hydrogen production has higher overall impact compared to Grid, BESS Lead Acid, solar and wind. This impact is most pronounced on human health followed by resource depletion and ecosystem quality. Figure 3 shows the end point impact per kg of hydrogen production for the four electrolysis technologies using different sources of electricity.

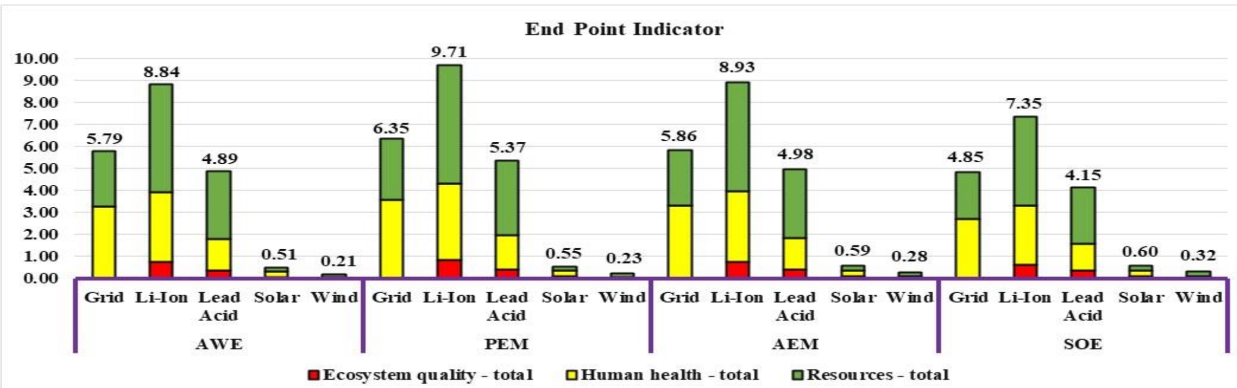

Figure 3 *End point impact per kg of hydrogen production*

Comparative analysis reveals that electricity generated from hydrogen achieves significantly lower CO_2 emissions and water depletion when renewable energy is used but performs worse than coal, oil, and natural gas under grid-powered scenarios per MWh of electricity produced underscoring the critical role of energy source selection in determining the environmental impacts of hydrogen production.

Conclusions

This study emphasizes the relevance of LCA in assessing the environmental implications of hydrogen generation using electrolysis technologies, as well as the crucial role of energy source selection in determining sustainability. The findings show that SOE has the highest global warming potential and water depletion implications when fueled by renewables, but it performs better in grid-mix scenarios. Endpoint analysis reveals that grid-powered hydrogen generation has a substantial influence on human health, resource depletion, and ecosystem quality, whereas BESS-solar PV powered hydrogen is extremely resource-intensive. Renewable energy-powered hydrogen reduces CO_2 emissions and water depletion compared to fossil fuels. However, it performs poorly in grid-powered settings, highlighting the need for cleaner grid electricity. The findings underscore the necessity for policy interventions to promote renewable energy integration and cleaner grid infrastructure to align with decarbonization goals and achieve Net Zero commitments. By addressing the limited research on the LCA of hydrogen production in the Global South, this study provides actionable insights into the Indian context and scalable implications for similar regions. The findings contribute to the global discourse on sustainable hydrogen production, supporting decarbonization efforts and the transition to clean energy systems.