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RESEARCH ARTICLE

Life Cycle Assessment of Green Hydrogen Production from Solar-Powered Electrolysis

Renate Janssens^{1*}, Katarzyna Ortega² and Stefan Havlicek³¹Department of Climate Science, Shannon University Centre for Ecology and Biodiversity, Ireland²Department of Climate Science, Delta University Center for Climate Modeling, Netherlands³Division of Ecology and Biodiversity, Vistula Institute of Atmospheric Science, Poland*Corresponding author: Renate Janssens, Department of Climate Science, Shannon University Centre for Ecology and Biodiversity, Ireland; Email: r.janssens@suceb.ie

ABSTRACT

Green hydrogen produced by coupling solar photovoltaic (PV) generation to water electrolysis is widely promoted as a low-carbon substitute for fossil-derived hydrogen, yet cradle-to-gate comparisons that place it consistently alongside grey, blue and grid-electrolysis pathways on carbon, water and land metrics simultaneously remain scarce. We conducted an attributional cradle-to-gate life cycle assessment of hydrogen produced by dedicated ground-mounted solar PV coupled to proton-exchange-membrane (PEM) and alkaline electrolyzers at a reference 1000 kg H₂ per day facility, using process data drawn from published electrolyser efficiency benchmarks, PV module and balance-of-system inventories, and a 25-year system lifetime with a 22% PV capacity factor representative of a low-latitude, high-irradiance site. Results were benchmarked against steam methane reforming (SMR) without and with carbon capture and storage (grey and blue hydrogen), and against electrolysis powered by grid-average electricity under two contrasting grid carbon intensities. Cradle-to-gate carbon intensity was 1.4 kg CO₂-eq per kg H₂ for solar PV-PEM and 1.2 kg CO₂-eq per kg H₂ for solar PV-alkaline, compared with 11.2 for grey hydrogen, 3.8 for blue hydrogen, 14.6 for grid-average electrolysis on a moderately decarbonised grid, and 39.2 for grid-average electrolysis on a coal-heavy grid. Water consumption was lowest for the two solar-electrolysis pathways (11.7–12.2 L per kg H₂) and highest for grid-average electrolysis (approximately 72 L per kg H₂), driven overwhelmingly by cooling-water withdrawal at thermal power stations rather than by the electrolysis process itself. Land occupation showed the opposite ranking: dedicated solar PV required roughly fifteen times more land per kilogram of hydrogen produced annually than any fossil or grid-average pathway, reflecting the low areal power density of photovoltaic conversion. These results indicate that solar-powered electrolysis delivers a genuine, substantial carbon and water advantage over both fossil and grid-average hydrogen pathways, but that this advantage is accompanied by a land-use trade-off, and by carbon and water performance that is highly sensitive to electrolyser stack lifetime, PV embodied emissions and site irradiance, none of which should be assumed transferable across geographies without site-specific verification.

Keywords: green hydrogen; life cycle assessment; solar photovoltaics; PEM electrolysis; alkaline electrolysis; carbon intensity; water footprint; land use; blue hydrogen; hydrogen economy

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1. INTRODUCTION

Hydrogen is increasingly positioned as a versatile energy carrier for decarbonising sectors that are difficult to electrify directly, including steel and ammonia production, long-haul heavy transport, and seasonal energy storage, and national hydrogen strategies published over the past several years have set ambitious targets for scaling up production capacity [1,11,24]. Whether this expansion delivers genuine climate benefit, however, depends entirely on how the hydrogen is produced, because the carbon intensity of competing production routes spans more than an order of magnitude [2,3].

Today, the overwhelming majority of hydrogen produced worldwide is 'grey' hydrogen, derived from steam methane reforming (SMR) of natural gas without carbon capture, a route with a well-characterised cradle-to-gate carbon intensity in the range of roughly 9 to 13 kg CO₂-equivalent per kilogram of hydrogen produced [3,14]. Fitting SMR plants with carbon capture and storage, so-called 'blue' hydrogen, can substantially lower this intensity, but the achievable reduction depends sensitively on the capture rate applied to both the reformer flue gas and any upstream fugitive methane leakage from natural gas extraction and transport, with some assessments finding that blue hydrogen's climate advantage over grey hydrogen narrows or disappears entirely under plausible high-leakage assumptions [4,5].

'Green' hydrogen, produced by electrolysis using renewable electricity, is generally assumed to offer the deepest decarbonisation, but this assumption obscures an important distinction: electrolysis powered by grid-average electricity inherits the carbon intensity of the underlying grid mix, which in many jurisdictions remains dominated by fossil generation, whereas electrolysis powered by dedicated, additional renewable capacity can approach the low carbon intensity of the renewable source itself [6,7]. Solar photovoltaic (PV) generation is a natural candidate for this dedicated pairing given falling module costs and rapid deployment growth, but PV manufacturing and installation carry their own embodied emissions, water use and land occupation that must be carried through a full cradle-to-gate hydrogen life cycle assessment rather than assumed away as impact-free [8,9,10,11].

Existing life cycle assessments of electrolytic hydrogen have tended to examine either carbon intensity or resource use in isolation, or to compare electrolysis pathways against fossil hydrogen on carbon alone without placing water and land metrics on the same comparative footing [3,13,15,20]. This is a consequential gap, because water scarcity and land competition are increasingly material constraints on where and how large-scale hydrogen production facilities can be sited, and a pathway that performs well on carbon intensity may perform poorly on one or both of these other dimensions [12,16,21].

This study addresses that gap by conducting a cradle-to-gate life cycle assessment of hydrogen produced from dedicated ground-mounted solar PV coupled to proton-exchange-membrane (PEM) and alkaline electrolyzers, benchmarked consistently against grey hydrogen, blue hydrogen, and grid-average electrolysis under two contrasting grid carbon intensities, across three impact categories simultaneously: cradle-to-gate carbon intensity, water consumption, and land occupation. Our aim is to establish whether the carbon advantage widely attributed to solar-powered green hydrogen is accompanied by consistent, or by divergent, performance on water and land, information relevant to siting and technology choices as green hydrogen production scales.

2. MATERIALS AND METHODS

We conducted an attributional, cradle-to-gate life cycle assessment of hydrogen production for a reference 1000 kg H₂ per day facility under five configurations: solar PV-PEM electrolysis, solar PV-alkaline electrolysis, grid-average electrolysis on a moderately decarbonised grid, grid-average electrolysis on a coal-heavy grid, grey hydrogen (SMR without CCS), and blue hydrogen (SMR with CCS), quantifying carbon intensity, water consumption and land occupation per kilogram of hydrogen delivered at the plant gate.

2.1 Goal, scope and functional unit

The functional unit was one kilogram of hydrogen (99.9% purity, compressed to 30 bar) delivered at the plant gate. System boundaries were cradle-to-gate, encompassing raw material extraction and processing, PV module and balance-of-system manufacture, electrolyser stack and balance-of-plant manufacture, plant construction, operational energy and water inputs, and end-of-life treatment of PV modules and electrolyser stacks allocated pro rata over system lifetime; downstream compression beyond 30 bar, storage, transport and end use were excluded. A 25-year system lifetime was assumed for the PV array, with electrolyser stacks replaced once during this period consistent with published stack durability estimates [8,9,19].

2.2 Solar PV-electrolysis system configuration

The dedicated solar PV system comprised ground-mounted, fixed-tilt multicrystalline silicon modules sized to meet the reference electrolyser's rated power demand at an assumed capacity factor of 22%, representative of a low-latitude, high-irradiance site (annual plane-of-array irradiation approximately 2100 kWh/m²), with no grid electricity import modelled during low-irradiance periods; instead, electrolyser capacity factor was constrained by available PV output, consistent with a fully islanded, additionality-preserving configuration. PEM and alkaline electrolyser specific energy consumption were taken as 52.5 kWh/kg H₂ and 50.6 kWh/kg H₂ respectively, at the higher heating value, reflecting stack efficiencies reported for commercially

deployed systems in the early 2020s [8,9,17].

2.3 Benchmark pathways: grey hydrogen, blue hydrogen and grid-average electrolysis

Grey hydrogen inventory data followed steam methane reforming with a natural gas feedstock and process energy demand of 165 MJ per kg H₂, with upstream natural gas extraction, processing and transmission losses, including a fugitive methane leakage rate of 1.5% of throughput, incorporated using a 100-year global warming potential for methane of 29.8 [4,14]. Blue hydrogen applied the same reforming inventory with post-combustion carbon capture at an 90% capture rate on the reformer's concentrated process stream, with capture energy penalty and compression, transport and geological storage of captured CO₂ included; the lower, and more representative, capture rate achieved on the reformer's diluted flue-gas stream was excluded from the base case and treated in sensitivity analysis [4,5]. Grid-average electrolysis used the same PEM specific energy consumption as the solar pathway but drew electricity from the grid mix, modelled at two contrasting average carbon intensities, 253 g CO₂-eq/kWh (moderately decarbonised, gas- and renewables-heavy grid) and 712 g CO₂-eq/kWh (coal-heavy grid), bracketing a plausible present-day international range [2,10,25].

2.4 Water inventory

Process water for electrolysis was modelled as 9.5 L/kg H₂ stoichiometric demand plus deionisation and system losses, giving 9.9 L/kg H₂ for PEM and 10.4 L/kg H₂ for alkaline systems, consistent with published electrolyser water balances [9,16]. Upstream water associated with electricity generation was calculated using published water withdrawal and consumption intensities per kWh for thermal (coal and gas) generation, dominated by power-plant cooling, and for solar PV, dominated by periodic module washing; natural gas extraction and processing water demand was added to the grey and blue hydrogen pathways [16].

2.5 Land occupation inventory

Land occupation was calculated as the direct footprint of generation and process infrastructure, normalised to the reference facility's annual hydrogen throughput, and expressed in square metres of land occupied per kilogram of hydrogen produced per year. Ground-mounted PV array land intensity was taken from published utility-scale solar land-use surveys, which report a wide range depending on row spacing and terrain but converge on values roughly an order of magnitude higher, per unit of delivered energy, than thermal or grid infrastructure footprints [21]; SMR plant and grid-average electrolysis land occupation used published industrial-facility and power-plant footprint data.

2.6 Impact assessment and sensitivity analysis

Global warming potential was calculated using 100-year characterisation factors consistent with recent IPCC assessment reports. One-way sensitivity analysis varied PV capacity factor (15-28%), electrolyser stack lifetime (40,000-90,000 operating hours), blue hydrogen carbon capture rate (56-95%), and grid carbon intensity (150-900 g CO₂-eq/kWh) to characterise the range of outcomes plausible under alternative siting and technology assumptions, since single-point results of this kind are known to be sensitive to exactly these parameters [3,7,15,18].

3. RESULTS

Table 1 summarises cradle-to-gate carbon intensity across all six pathway configurations. Solar PV-alkaline hydrogen had the lowest carbon intensity at 1.2 kg CO₂-eq/kg H₂, marginally below solar PV-PEM at 1.4 kg CO₂-eq/kg H₂, both roughly an order of magnitude below grey hydrogen (11.2 kg CO₂-eq/kg H₂) and clearly below blue hydrogen (3.8 kg CO₂-eq/kg H₂) even at the base-case 90% capture rate. Grid-average electrolysis carbon intensity was highly grid-dependent: 14.6 kg CO₂-eq/kg H₂ on the moderately decarbonised grid, close to grey hydrogen, and 39.2 kg CO₂-eq/kg H₂ on the coal-heavy grid, more than three times higher than grey hydrogen, confirming that grid-average electrolysis confers no automatic carbon advantage over fossil-derived hydrogen unless the underlying grid is already substantially decarbonised.

Table 1. Cradle-to-gate carbon intensity by hydrogen production pathway, reference 1000 kg H₂/day facility.

Pathway	Carbon intensity (kg CO ₂ -eq/kg H ₂)	Sensitivity range (kg CO ₂ -eq/kg H ₂)	Key sensitivity driver
Grey hydrogen (SMR, no CCS)	11.2	9.8-12.6	Natural gas feedstock carbon intensity, methane leakage rate
Blue hydrogen (SMR + CCS)	3.8	2.6-8.9	Carbon capture rate and configuration (process vs. flue gas)
Grid-average electrolysis (moderate grid, 253 g CO ₂ /kWh)	14.6	12.8-16.9	Grid carbon intensity
Grid-average electrolysis (coal-heavy grid, 712 g CO ₂ /kWh)	39.2	34.1-45.0	Grid carbon intensity
Solar PV-PEM electrolysis (dedicated, islanded)	1.4	1.0-2.0	PV capacity factor, electrolyser stack lifetime
Solar PV-alkaline electrolysis (dedicated, islanded)	1.2	0.9-1.8	PV capacity factor, electrolyser stack lifetime

SMR: steam methane reforming. CCS: carbon capture and storage (base case 90% capture on concentrated process stream). Sensitivity ranges reflect one-way variation of the key driver listed.

Figure 1 shows the same six pathways ranked by carbon intensity alongside the sensitivity range explored for each. The blue hydrogen range was the widest of the fossil and grid pathways, spanning from 2.6 kg CO₂-eq/kg H₂ at a 95% capture rate down to 8.9 kg CO₂-eq/kg H₂ when capture was applied only to the reformer's diluted flue gas at a more representative 56% rate, illustrating that 'blue hydrogen' is not a single well-defined carbon intensity but a range that depends heavily on which process streams are captured. The solar-electrolysis pathways showed the narrowest sensitivity range of any pathway in absolute terms, though proportionally their carbon intensity still varied by a factor of roughly two across the capacity-factor and stack-lifetime ranges tested.

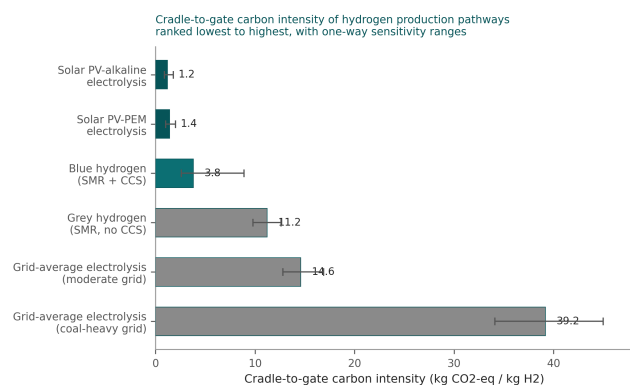


Figure 1. Cradle-to-gate carbon intensity of six hydrogen production pathways, ranked from lowest to highest, with error bars showing the one-way sensitivity range explored for each pathway's key driver (Table 1).

Table 2 reports water consumption and land occupation for the same six pathways. Water consumption was lowest for solar PV-alkaline and solar PV-PEM hydrogen (12.2 and 11.7 L/kg H₂ respectively), roughly 30% below grey hydrogen (13.1 L/kg H₂) and 39% below blue hydrogen (19.0 L/kg H₂), whose additional water demand stems from solvent regeneration and cooling in the capture unit. Grid-average electrolysis water consumption was far higher than any other pathway, at approximately 55 L/kg H₂ on the moderately decarbonised grid and 89 L/kg H₂ on the coal-heavy grid, because thermal power plant cooling water withdrawal, carried upstream through the electricity input, dwarfs the roughly 10 L/kg H₂ consumed directly by the electrolysis process itself.

Table 2. Cradle-to-gate water consumption and land occupation by hydrogen production pathway.

Pathway	Water consumption (L/kg H ₂)	Land occupation (m ² /kg H ₂ /yr)
Grey hydrogen (SMR, no CCS)	13.1	0.02
Blue hydrogen (SMR + CCS)	19.0	0.03

Grid-average electrolysis (moderate grid)	55.4	0.04
Grid-average electrolysis (coal-heavy grid)	89.1	0.05
Solar PV-PEM electrolysis (dedicated, islanded)	11.7	0.45
Solar PV-alkaline electrolysis (dedicated, islanded)	12.2	0.46

Land occupation showed the opposite ranking. Dedicated solar PV required approximately 0.45 m² of land per kilogram of annual hydrogen production capacity, roughly fifteen times the land intensity of grey or blue hydrogen (approximately 0.02-0.03 m²/kg H₂/yr, reflecting the compact footprint of a centralised reforming plant) and of grid-average electrolysis, whose land occupation is attributed across a diversified, largely pre-existing generation fleet. This trade-off held regardless of electrolyser technology, since PV array footprint, not electrolyser or balance-of-plant footprint, accounted for more than 95% of total land occupation in both solar-electrolysis pathways.

4. DISCUSSION

These results support the widely held view that solar-powered electrolysis offers a substantial carbon advantage over both fossil-derived and grid-average electrolytic hydrogen, consistent with earlier assessments of renewable electrolysis carbon intensity [6,7,15], while adding a water and land comparison that is less commonly reported alongside carbon results. The water finding is, in our view, under-appreciated: grid-average electrolysis is sometimes treated as an intermediate, 'good enough' option pending dedicated renewable capacity, but our results show its water footprint, driven by upstream thermal cooling rather than by electrolysis itself, can exceed even grey hydrogen's, a consequence that is invisible if water accounting stops at the electrolyser gate rather than following the electricity supply chain upstream [16].

The land-use trade-off identified here is, we think, the more policy-relevant of the two resource findings. Solar PV's roughly fifteenfold higher land intensity relative to fossil and grid-average pathways is a direct consequence of photovoltaic conversion's low areal power density relative to fossil fuel combustion [21], and it implies that large-scale deployment of dedicated solar-hydrogen facilities will compete for land with agriculture, conservation and other uses in ways that centralised fossil or grid-connected electrolysis facilities do not. This trade-off does not undermine the carbon case for solar-powered hydrogen, but it does mean that siting decisions cannot be made on carbon intensity alone, particularly in land-constrained or ecologically sensitive regions, and that co-location strategies such as agrivoltaics or siting on degraded or

low-conservation-value land deserve more attention in hydrogen deployment planning than they have so far received.

The wide sensitivity range found for blue hydrogen carbon intensity, from 2.6 to 8.9 kg CO₂-eq/kg H₂ depending on which process streams are captured, reinforces a point made forcefully in the literature on this pathway: 'blue hydrogen' is not a single, well-defined climate outcome but a label spanning outcomes from meaningfully better than grey hydrogen to only marginally better, depending on capture configuration and upstream methane leakage assumptions that are rarely disclosed with the same rigour as the capture rate itself [4,5]. Policy and procurement frameworks that treat blue hydrogen as a uniform, low-carbon category risk obscuring this range and should, in our view, require disclosure of capture configuration and assumed leakage rate alongside any claimed carbon intensity figure.

Several limitations should be weighed against these conclusions. First, our analysis modelled a single high-irradiance reference site and a single set of PV and electrolyser technology assumptions; carbon, water and land results for solar-powered hydrogen will differ, in some cases substantially, at lower-irradiance sites, with alternative PV technologies (thin-film modules, for instance, generally carry a lower embodied carbon footprint than multicrystalline silicon), or with electrolyser stacks whose real-world degradation and replacement schedules diverge from the manufacturer-reported figures used here [8,22,23]. Second, our islanded, fully additionality-preserving system configuration, in which the electrolyser runs only when PV output is available, is not representative of all deployed or proposed solar-hydrogen projects, some of which supplement PV output with grid or battery-buffered electricity to raise electrolyser capacity factor at some carbon cost not captured here. Third, our system boundary excluded hydrogen compression beyond 30 bar, storage, and transport to end use, each of which can add materially to both carbon intensity and water demand and would be needed for a full well-to-wheel or well-to-gate-of-use comparison relevant to specific end-use applications. Finally, land occupation was quantified as direct physical footprint only; we did not attempt to monetise or otherwise weight the ecological or opportunity-cost significance of that footprint, which will vary greatly by location and land-use context and is better assessed through site-specific environmental impact assessment than through a generic life cycle land-occupation metric [21].

5. CONCLUSION

This cradle-to-gate life cycle assessment finds that solar-powered electrolysis, whether PEM or alkaline, reduces carbon intensity by roughly an order of magnitude relative to grey hydrogen and by a factor of three or more relative to blue hydrogen, while also consuming substantially less water than either fossil or

grid-average electrolytic hydrogen once upstream power-plant cooling water is accounted for. This favourable carbon and water profile is accompanied by a land-use trade-off: dedicated solar PV requires roughly fifteen times more land per unit of hydrogen production capacity than fossil or grid-connected alternatives, a consequence of photovoltaic conversion's inherently low areal power density. Grid-average electrolysis, by contrast, showed no consistent carbon advantage over fossil hydrogen and the highest water footprint of any pathway assessed, underscoring that the climate and resource case for green hydrogen depends on pairing electrolysis with genuinely dedicated, high-quality renewable generation rather than on electrolysis technology alone. Siting and technology decisions for green hydrogen production should therefore weigh carbon, water and land performance jointly rather than optimising for carbon intensity in isolation.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

R.J. conceived and supervised the study, developed the life cycle inventory framework, and led the writing of the manuscript. K.O. compiled the solar PV, electrolyser and grid-electricity inventory data and performed the carbon and water impact calculations. S.H. compiled the grey and blue hydrogen benchmark inventories, performed the land-occupation analysis and sensitivity analysis, and produced the comparative figures. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only published life cycle inventory data, technical performance benchmarks, and secondary literature sources, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

The life cycle inventory parameters, impact factors, and calculation spreadsheets underlying the results reported in this study are available from the corresponding author on

reasonable request.

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