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Green Hydrogen from Desert PV in North Africa: A Life Cycle and Water Footprint Perspective on Energy-Water Trade-Offs

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Abstract:

Green hydrogen production via photovoltaic (PV)-powered electrolysis is widely recognized as a key pathway for the global energy transition, particularly in solar-rich regions such as North Africa. A comprehensive Life Cycle Assessment and Water Footprint analysis was performed on a 13.5 MW PV park located in North Africa, designed to produce 488.7 tons of green hydrogen annually using alkaline electrolyzers. The system includes an on-site ultrapure water supply system (UPWS) to meet the stringent water quality requirements of electrolysis, ensuring operational self-sufficiency in a highly water-scarce desert environment. The assessment follows ISO 14040/44 standards and quantify cradle-to-grave impacts over a 30-year plant lifetime, considering a functional unit of 1 kg H_2 produced. Climate and water-related impacts are evaluated using IPCC GWP-20, ReCiPe 2016, and water scarcity indicators. Alternative scenarios investigate the use of the local Algerian electricity mix to power the UPWS and a geographically shifted configuration in Italy to explore the influence of regional water availability and characterization factors. Results identify the PV park as the dominant environmental hotspot, contributing 87% to Global Warming Potential (GWP) (3.05 kg CO2-eq/kg H2), mainly driven by upstream silicon production and land use. Electrolyzer systems account for about 11% of GWP, primarily due to the use of rare metals and plant components. While the UPWS contributes marginally to the GWP (2%), it plays a significant role in local water stress, posing additional pressure on already stressed freshwater resources. Supplying the UPWS with electricity from Algerian grid increases fossil-related impacts by a factor of 4.3 compared to the fully renewable baseline. In contrast, the Italy-based scenario highlights how regional context can lead to markedly different water footprint outcomes, resulting in a net water gain of 2.2 m^3/kg H_2 under the AWARE method. The study reveals critical trade-offs between climate mitigation benefits and water scarcity risks in desert-based green hydrogen projects. The findings provide decision-relevant insights for emerging North Africa–Europe hydrogen corridors, emphasizing the need to jointly consider water availability, regional sustainability and energy production methods.

Keywords:

Thermodynamics; Energy; ECOS Conference; Exergy; Sustainability.

1. Introduction

Hydrogen is increasingly recognized as a clean energy vector for CO_2 reduction in hard-to-electrify sectors **(1,2)**. The decarbonisation targets set by the Paris Agreement highlight the need for technological solutions to reduce emissions in fossil fuel-dependent industries. Growing investments by countries and companies are fostering cooperation and innovation in the hydrogen sector. The Hydrogen Council estimates that by 2050 hydrogen could account for 18% of final energy demand, with 16% of global electricity used for its production **(3)**. Hydrogen is therefore considered a key strategy for achieving decarbonisation, particularly in its green form. Although hydrogen itself is not environmentally harmful, its production pathways must be assessed to ensure overall sustainability. Moreover, hydrogen can facilitate the integration of renewable energy sources, representing one of the few viable options for long-duration energy storage over days, weeks and months **(4)**. Most power generation consumes water, whether to cool steam in thermoelectric plants or power turbines for hydropower, and the global demand for both water and electricity will continue to increase substantially in the coming decades **(5)**. Due to economic and population growth, as well as climate change, the water-energy nexus is becoming increasingly vulnerable. The thermoelectric sector relies heavily on water availability and requires significant water consumption for cooling processes. In 2010 the consumption of fresh water for power generation was 583 billion cubic meters. The highest water consumption is associated with nuclear and fossil fuel power plants. In contrast, combined cycle gas turbine (CCGT) plants have the lowest water use, as their lower heat rejection reduces the need for cooling water **(6)**. Also, climate change is making water scarcity worse and more unpredictable. Terrestrial water storage is declining, leading to increased water scarcity and disruptions to societal activities **(7)**. Renewable energy sources contribute to lowering water consumption, since solar photovoltaic systems and wind turbines require substantially less operational water than thermal power generation. Furthermore, wastewater treatment plants can alleviate pressure on freshwater resources, minimizing competition with other sectors, by enabling the reuse of treated and reclaimed water. In the case of hydrogen production, water use may appear significant and potentially impactful on freshwater resources. However, the production of green hydrogen needed for a 1.5°C-aligned future is expected to place only minimal additional demand on global water resources. To produce the same amount of energy, green hydrogen often requires less water than fossil fuel-based hydrogen and other water-intensive electricity generation technologies **(8)**. However, green hydrogen developers must prioritize efficient process design and account for local water availability in project planning.

1.1. State of the art

The water footprint of the energy sector, including hydrogen production, has received growing attention, with studies ranging from full life cycle assessments (LCA) to spatial, nexus-based, regional, and scarcity-weighted analyses. At the global scale, Tonelli et al. (9) evaluate the feasibility of large-scale electrolytic hydrogen production under country-specific land and water constraints in a 2050 net- zero scenario, combining spatially explicit renewable energy potential with land eligibility and water availability indicators to estimate land requirements and water withdrawals associated with both technology manufacturing and electrolysis. Although global water demand for hydrogen (3.2–95.6 billion m^3) (9) remains relatively limited, the results indicate that hydrogen production may exacerbate water scarcity in already stressed regions, particularly in Middle East and North Africa (MENA), with land availability emerging as a more critical constraint than water under specific conditions. The study highlights significant geographical disparities, pinpointing potential hydrogen exporters (e.g., Sub-Saharan Africa, South America, Canada, and Australia) and regions with structural resource constraints, underscoring the need to consider both land and water limits in planning the hydrogen transition(10). From a methodological perspective, a synthesis of LCA studies assessing hydrogen systems through a multi-indicator approach (11), shows that renewable-based electrolysis (wind and PV) generally exhibits low global warming potential (GWP) and good energy performance, while water footprint results vary significantly depending on system boundaries and electricity mix. Biomass-based pathways may achieve favorable carbon performance, particularly when credits for avoided emissions are included, yet often present higher water footprints due to irrigation and green water use. The study highlights clear trade-offs between carbon and water indicators and demonstrates that electrolytic hydrogen can have higher water impacts when powered by fossil-based electricity, thus emphasizing the need for harmonized, nexus-based LCA approaches. At the regional planning scale, a recent study (12) assesses the blue and green hydrogen pathways under future demand scenarios in Texas, explicitly distinguishing between water withdrawal and water consumption, and reports that wind-based PEM electrolysis may require up to 52.7 L/kg H_2 in water withdrawal, significantly higher than blue hydrogen pathways with carbon capture and storage (CCS). Under net-zero scenarios, hydrogen production could account for up to 6.8% of total statewide water demand by 2050; although this share appears moderate at the aggregate level, spatial analysis shows that planned hydrogen infrastructure overlaps with areas already expected to face water stress. This highlights the need to integrate hydrogen deployment into regional water resource planning frameworks, as large-scale expansion may create localized pressures even when overall impacts seem limited. Recent literature has also moved beyond purely volumetric water metrics toward scarcity-weighted indicators; in this context, a recent work (13) analyzes large-scale green hydrogen deployment in China, focusing on the substitution of coal-based hydrogen production, and, using a spatially differentiated LCA framework, demonstrating that the environmental relevance of water use depends more on regional scarcity conditions than on absolute withdrawal volumes. The substitution of coal-based hydrogen with renewable electrolytic hydrogen significantly reduces the water scarcity footprint (WSF), particularly in regions where conventional coal gasification is water-intensive and already located in stressed basins, highlighting the necessity of geographically explicit assessments in hydrogen transition strategies. Complementing scarcity-based approaches, a harmonized cradle-to-gate comparison of fossil based, blue, and electrolytic hydrogen pathways was provided, confirming that coal gasification exhibits the highest water footprint, followed by steam methane reforming (SMR) and blue hydrogen, while the water intensity of green hydrogen strongly depends on the electricity source (14). Notably, direct water use in electrolysis (approximately 9–10 L per kg H_2) represents only a minor share of total water consumption, with the dominant contribution arising from electricity generation; this finding underscores that the water performance of electrolytic hydrogen is structurally dependent on the upstream energy system and reinforces the need to account for energy mix characteristics when evaluating the sustainability of green hydrogen deployment. Overall, the current state of the art shows a clear evolution from simple volumetric assessments toward integrated land– water–energy and scarcity-based frameworks; however, significant heterogeneity persists in system boundaries, spatial resolution, and impact metrics, indicating the need for harmonized methodologies capable of capturing energy–water trade-offs across scales.

1.2. Aim of the study

Despite the growing body of literature on the water footprint of hydrogen production and the land–water–energy nexus, significant gaps remain, as most existing studies are conducted at global or national scales, relying on aggregated indicators of land availability and water scarcity, or providing technology-generic LCA comparisons without focusing on geographically specific installations. Consequently, these approaches fail to capture the environmental implications of deploying PV-powered electrolysis systems in hyper-arid desert regions, where water treatment requirements, local scarcity conditions, and infrastructure choices play a critical role. Furthermore, although several studies address climate–water trade-offs, these are often treated qualitatively or assessed using volumetric metrics rather than through fully integrated, scarcity-weighted cradle-to-grave analyses. This study aims to address these gaps by conducting a site-specific LCA of an existing desert-based PV hydrogen plant located in the South Saharan region of Algeria, integrating water footprint assessment with AWARE-based water scarcity indicators and explicitly quantifying energy–water trade-offs under alternative electricity supply configurations and geographical scenarios. In doing so, the research contributes to advancing methodological frameworks for evaluating hydrogen systems in water-stressed contexts and supports more robust decision-making for emerging hydrogen corridors. The study evaluates the environmental impacts associated with the production of 1 kg of hydrogen via electrolysis powered by a PV system, following a cradle-to-gate approach, meaning that hydrogen is considered at the stage where it is produced and ready for transport or storage. In addition, a comprehensive water footprint analysis is performed, taking into account water scarcity, water source depletion, and local water availability. Comparative analyses are included to evaluate water consumption under different electricity supply options, namely the local grid versus renewable energy sources, as well as to assess variations in water scarcity indices across locations with differing levels of water availability. The functional unit is defined as the production of 1 kg of hydrogen, providing a measurable reference against which all input and output flows are normalized, while the system boundaries encompass the extraction and processing of materials, component manufacturing, and energy use up to hydrogen production, excluding end-of-life stages such as waste management, recycling, and disposal. The operational lifetime of the plant is assumed to be 30 years, and containment buildings and auxiliary infrastructure for both the electrolyzer and water treatment systems are considered pre-existing and therefore excluded from the system boundaries. Due to data limitations, certain inventory parameters have been estimated or derived through scaling based on values reported in the literature.

2. Methods

2.1. Life Cycle Inventory

The inventory data were sourced from literature and complemented by adapting existing processes to meet the aim of the study. The background database adopted is Ecoinvent 3.9. The system is structured around three main components, with the PV park representing the core element, as it provides electricity to the downstream processes. The PV system is modelled distinguishing between construction (PV building) and operational (PV utilisation) phases. All material and energy flows are expressed with respect to the functional unit of 1 kWh of electricity generated over a 30-year lifetime. The total lifetime electricity production amounts to 785.1 GWh, as estimated using Global Solar Atlas, and all inventory flows were therefore calculated by dividing total life cycle inputs by the cumulative electricity generated over the system lifetime.

The construction phase of the PV system includes wafer production, ground mounting structures, electrical installation, and inverters. Multi-crystalline silicon modules and mounting structures were quantified based on a total module surface area of 135,276.84 m². Electrical installation and inverter datasets were scaled from a reference capacity of 570 kWp to the actual installed capacity of 13.5 MWp. Inverters, having a lifetime of 15 years, were doubled to match the overall system lifetime. The operational phase mainly accounts for module cleaning activities, which require water. The water supply was modelled as groundwater extraction in Algeria, including pumping, diesel consumption, electricity use, and infrastructure. For each kWh produced, the system includes the natural input of solar radiation, corresponding to a total of 10,303 GWh over the lifetime (ratio of approximately 13.12), a small amount of water for cleaning modelled as tap water available at the pump including supply chain impacts, and the contribution from the construction phase allocated per kWh (15) (16).

The alkaline electrolyser was modeled following literature sources (17), including both stack and balance of plant (BoP). The BoP inventory, originally scaled for a GW-scale plant, was adjusted by applying a scaling factor of 0.9 to account for economies of scale and subsequently rescaled to the system size. Since the original inventory referred to a different hydrogen production level, all values were first scaled to total hydrogen production, then converted to a 1 MW basis, multiplied to match the installed capacity of 9 MW, and finally normalized to the functional unit. Electricity required for plant construction was also included (18). Due to limited data availability, assumptions were introduced regarding materials, including copper for the cathode, chromium steel (18/8), polypropylene for plastics, electronics as control units, and process materials composed of 90% lubricant oil and 10% sodium hydroxide. Additional assumptions include Zirfon membranes composed of zirconium oxide and polysulfone, synthetic rubber gaskets, two types of nickel for coating and electrodes, and wrought aluminium. The stack lifetime of 8 years was addressed by tripling the stack material to approximate the required operating lifetime, while the BoP was only partially increased. The electricity demand is determined by the electrolyser efficiency of 50.93 kWh per kg of hydrogen and is supplied by the PV system.

The ultrapure water system (UPWS), including ultrafiltration, reverse osmosis, and electrodeionization, was adapted from processes available in the SimaPro database. Particular attention was given to water source modelling due to the application of the AWARE method. Since SimaPro applies characterization factors averaged over all regions and time periods, regional AWARE factors were manually implemented to ensure consistency. In the Algerian case, the water input was modelled as “water, well, in ground, non-agricultural, DZ,” while in the Italian case a correction was introduced as the dataset “water, unspecified natural origin” does not include characterization factors, which would otherwise result in zero water scarcity impact. Water feeding the UPWS is extracted from a well at 3 bar and includes pumping infrastructure. High-pressure pumps for reverse osmosis were approximated as standard 22 kW electric pumps, with electricity modeled independently from the PV system. The UPWS inventory was scaled to reflect the actual system requirements, increasing the feed-to-product water ratio from 1.5 to approximately 7 kg of water per kg of ultrapure water. Plant materials were multiplied by 3 to account for a 10-year lifetime. All infrastructure contributions, including reverse osmosis membranes, ultrafiltration units, electrodeionization modules, and nitrogen used for cleaning, were normalized over the total lifetime water production, which amounts to 186,498,000 kg. No replacement of components was assumed due to lack of detailed lifetime data, except for periodic nitrogen scouring in the ultrafiltration stage. The design of the water purification system is based on several simplifying assumptions, including a feed pressure of 3 bar, temperature requirements already satisfied, neglect of piping fluid dynamics, and approximation of total dissolved solids as NaCl. The system consists of a two-stage reverse osmosis process with recovery ratios of 30% and 40%, respectively, and recirculation of the second-stage concentrate. The resulting permeate flow is 1.56 m^3/h, with feed flows of 3.9 m^3/h and 10.66 m^3/h for the second and first stages, respectively, increasing to 13 m^3/h after recirculation. Operating pressures were calculated based on osmotic pressure using the van’t Hoff equation, resulting in 29.7 bar for the first stage and 26.4 bar for the second stage. Three membranes are required in the first stage, and a booster pump is installed between stages to restore pressure. The energy demand of the water purification system includes pumps and electrodeionization, amounting to 0.018 kWh per process unit and supplied by the PV system. Emissions were scaled consistently with system requirements, with wastewater representing the main emission. Of the total wastewater, 85% is discharged to water while 15% is assumed to evaporate. Wastewater treatment was not modelled in the technosphere, as it is considered an emission to the environment to avoid double counting.

2.2. Impact Assessment methods

Environmental impacts were assessed using three method libraries available in SimaPro: Global, Single-issue, and Water footprint methods. Single-issue indicators target specific mechanisms (e.g., climate change, water consumption), whereas global methods provide an integrated assessment across multiple impact categories. Water footprint methods focus on freshwater consumption and scarcity-related impacts.

The ReCiPe 2016 method (15) was applied as a global LCIA approach linking midpoint indicators to endpoint damage categories. Midpoint indicators quantify impacts such as climate change, toxicity, acidification, eutrophication, land use, water consumption, and resource depletion along the life cycle. These are aggregated into three endpoint categories:

- Human health, expressed in Disability Adjusted Life Years (DALYs).
- Ecosystems, expressed as species loss over time (years).
- Resource scarcity, expressed as surplus extraction costs (USD2013) using a 3% discount rate. Fossil resources are characterized individually per substance.

This framework enables a comprehensive evaluation from environmental pressures to final damages.

The IPCC 2021 method was used as a single-issue indicator to assess climate change impacts in kg CO_2-equivalents (16). The GWP20 time horizon was selected to capture short-term climate effects, increasing the contribution of short-lived gases such as methane.

2.3. Water Footprint

Water use is a critical environmental concern in LCA, particularly for energy systems like hydrogen production, which involve significant direct and indirect freshwater consumption. Conventional metrics based solely on water withdrawals fail to capture the broader implications along supply chains. The water footprint concept, introduced by Hoekstra (2003) (18), addresses this gap by accounting for both direct and embedded water use, providing a comprehensive measure of freshwater appropriation. The total water footprint is typically divided into blue, green, and grey components (17): blue water refers to surface and groundwater consumption, relevant for industrial processes; green water represents rainwater used in soils and vegetation, mainly for agriculture; grey water quantifies the freshwater required to assimilate pollutants, linking water use to potential quality impacts. While volumetric, these indicators do not reflect regional water scarcity. Integration into LCIA has led to characterization models translating water volumes into scarcity or deprivation indicators, varying in assumptions, spatial resolution, and impact pathways. Four LCIA water footprint methods were considered, (AWARE, Hoekstra, Boulay, and Berger) to evaluate hydrogen production in Algeria and Italy, countries with different water availability and dependency.

The Available WAter REmaining (AWARE) method quantifies water scarcity based on the Available Minus Demand (AMD), representing water remaining after human and ecosystem needs. This value is expressed relative to the watershed area and time period, with units of $m^3\ m^{-2}\ month^{-1}$. AMD is normalized to the global average and inverted to obtain characterization factors (0.1–100), where higher values indicate greater scarcity. The method is spatially explicit at sub-watershed and monthly levels and provides separate factors for agricultural, non-agricultural, and unspecified uses. Figure 1 shows the factors at annual level per watersheds (normal average over 12 months).

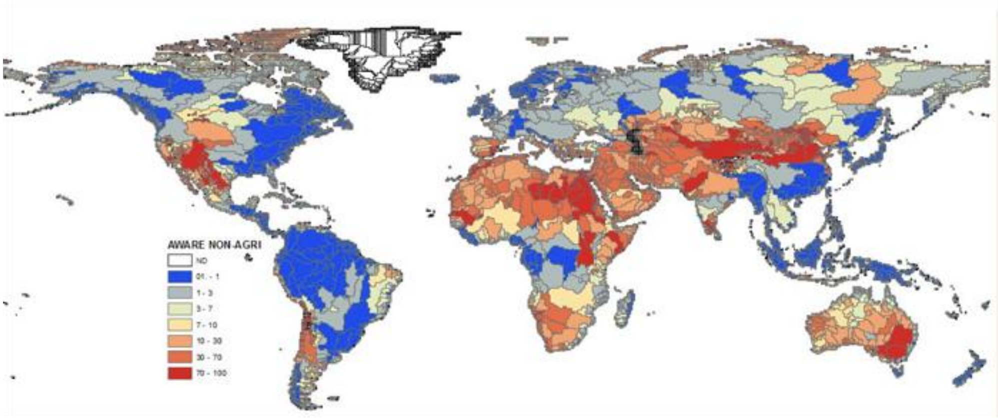

Figure 1: *Map of AWARE factors for non-agricultural activities (normal average over 12 months)* Interpretation – Spatio-temporal scale (19).

The Berger method (19) assesses the vulnerability of river basins to freshwater depletion by linking water consumption to local water availability. It evaluates water scarcity using the Water Depletion Index (WDI), relating consumption to renewable availability across over 11,000 basins worldwide. It includes surface water and groundwater and assigns high values to (semi-)arid regions, capturing both relative and absolute scarcity while avoiding zero-value artefacts.

The Boulay method (19) uses a consumption-to-availability (CTA) ratio, which represents the relationship between water consumed and the renewable freshwater resources available in a given region, modeled with a logistic function to derive a Water Scarcity Indicator (WSI) (0–1 m^3 deprived/m^3 consumed). It is calibrated using Organisation for Economic Co-operation and Development (OECD) thresholds, where 20% and 40% of water withdrawals correspond to moderate and severe water stress, respectively. The method also provides separate characterization factors for surface water and groundwater, applied only to consumptive water use.

The Hoekstra WSI (18) is based on a consumption-to-availability ratio using the blue water footprint. Water availability is derived from runoff, with 80% reserved for environmental flows. Datasets are derived from global hydrological assessments, with water runoff data obtained from Fekete et al. (2002) (20) and water consumption estimates from Mekonnen et al. The resulting characterization factors are provided for the major river basins worldwide and assesses consumptive water only.

2.4. Implementation of LCIA Methods in SimaPro – AWARE Factors

The selected LCIA methods were implemented in SimaPro. However, for the AWARE water scarcity method, adjustments were required to ensure consistency between characterization factors and the type of water consumption assessed. The default SimaPro implementation includes only generic factors for unspecified water use, which do not distinguish between agricultural and non-agricultural consumption. The AWARE methodology, developed by the WULCA working group, provides differentiated basin-level characterization factors allowing a more accurate representation of water scarcity impacts depending on the type of water use. The characterization factors are classified into three main categories:

- Agg_CF_irri: annual aggregated characterization factor for agricultural (irrigation) water consumption.
- Agg_CF_non_irri: annual aggregated characterization factor for non-agricultural water consumption sectors, including industrial and domestic water use.
- Agg_CF_unspecified: annual aggregated characterization factor for unspecified water consumption sectors, applied when the type of water use is not known.

Since these factors are not fully integrated into SimaPro datasets, manual implementation is necessary for refined assessments. In this study, water use is associated with industrial hydrogen production and therefore corresponds to non-agricultural consumption. The use of Agg_CF_non_irri factors ensures methodological consistency and avoids bias. Notably, the unspecified factors included by default in SimaPro can be significantly higher-up to twice those of non-irrigation factors in regions such as Algeria and Italy, potentially leading to overestimation of impacts. To address this, an updated AWARE method was developed in SimaPro by incorporating Agg_CF_non_irri factors from the WULCA database (2023) (21). This modification enables the water consumption associated with hydrogen production to be characterized using the most appropriate factors, thereby improving the accuracy and representativeness of the water footprint assessment.

2.5. Scenario Definition and Simulation Configurations

To evaluate the environmental and water-related impacts of hydrogen production, several scenarios were developed considering electricity supply, geographic context, and water treatment processes. All simulations are based on a functional unit of 1 kg of hydrogen. The first case study focuses on hydrogen production in Algeria, a region characterized by limited freshwater availability and high solar energy potential. Two configurations were analyzed to assess the influence of electricity supply:

- Scenario 1: PV-powered UPW plant

The UPW treatment plant required for electrolysis is powered by a PV park, representing a renewable-based hydrogen production pathway aimed at evaluating environmental performance using locally available renewable energy.

- Scenario 2: Grid-powered UPW plant

The UPW treatment plant is supplied by the Algerian electricity grid, reflecting current energy system conditions and allowing the evaluation of how electricity mix characteristics influence the overall environmental impacts of hydrogen production.

- Scenario 3: PV-powered UPW plant

The second case study examines hydrogen production in Italy under different energy and water availability conditions. It evaluates the production of 1 kg of hydrogen using PV-generated electricity for both water treatment and electrolysis, consistent with the renewable configuration in Algeria. This comparison enables the assessment of how geographical context influences water consumption and scarcity impacts.

Overall, the scenarios allow assessment of (i) electricity supply effects (PV vs. grid), (ii) and regional differences in water consumption and scarcity impacts between Algeria and Italy.

3. Results and Discussion

3.1. Algeria Case Study

The first group of simulations focuses on hydrogen production in Algeria, a region characterized by limited freshwater availability and high solar energy potential. Two configurations were analyzed to evaluate the effect of electricity supply on the environmental and water footprint results.

3.1.1. Scenario 1: PV-powered UPW plant

In this configuration, the ultrapure water (UPW) treatment plant required for electrolysis is powered entirely by electricity generated from a photovoltaic (PV) park. This scenario represents a renewable-based hydrogen production pathway, where solar energy meets the electricity demand of the water treatment process. The objective is to evaluate the environmental performance of hydrogen production when powered by locally available renewable energy resources. First, the environmental impacts associated with the reference scenario were assessed, in which a PV park located in southern Algeria fully supplies the electricity demand of both the electrolysis system and the UPW treatment plant, on a cradle-to-gate basis.

Scenario 1 exhibits a fossil carbon GWP of approximately 3.40 kg CO_2-eq/kg H_2 according to IPCC GWP20. The PV park is the dominant contributor, accounting for 86% of the total impact, while the PV-powered UPW plant and the electrolyzer contribute 2% and 12%, respectively. The ReCiPe 2016 Midpoint analysis confirms that the highest environmental pressures are concentrated in the upstream supply chain of the PV system, primarily silicon production, electronic components, and land use, which predominantly affect terrestrial ecotoxicity and human non-carcinogenic toxicity. The electrolyzer also contributes, albeit to a lesser extent, to terrestrial ecotoxicity due mainly to the extraction and processing of metallic components. Water consumption for electrolysis represents only a minor fraction of the total water footprint, which is largely dominated by indirect consumption associated with electricity generation from the PV park and, to a lesser extent, the operation of the UPW system. The application of the AWARE method, using basin-specific characterization factors for non-agricultural use, highlights a high-water scarcity footprint for Algeria, consistent with CF values greater than 1 in the desert and semi-arid basins considered.

3.1.2. Scenario 2: Grid-powered UPW plant

In the second configuration, the UPW treatment plant is supplied by the local Algerian electricity grid rather than by the PV park. This scenario reflects current energy infrastructure conditions and allows the assessment of how the electricity mix influences the overall environmental impacts of hydrogen production. The results indicate that ultrapure water production using the national grid is significantly more impactful in terms of greenhouse gas (GHG) emissions than in Scenario 1. This is confirmed by the IPCC GWP20 analysis, which shows that for every kilogram of H_2 produced under Scenario 2 (Grid-powered UPW plant), the UPW system generates an additional 0.144 kg CO_2-eq compared to Scenario 1. ReCiPe 2016 Midpoint (H) results further demonstrate that Scenario 1 is environmentally more sustainable across most impact categories, as reported in Figure 4. It is important to note, however, that for the Terrestrial Acidification category, the Grid-powered UPW plant exhibits a lower impact than the PV-powered UPW plant. This difference is primarily attributable to the significant contribution of PV panel components in the photovoltaic system, as highlighted in the previous section.

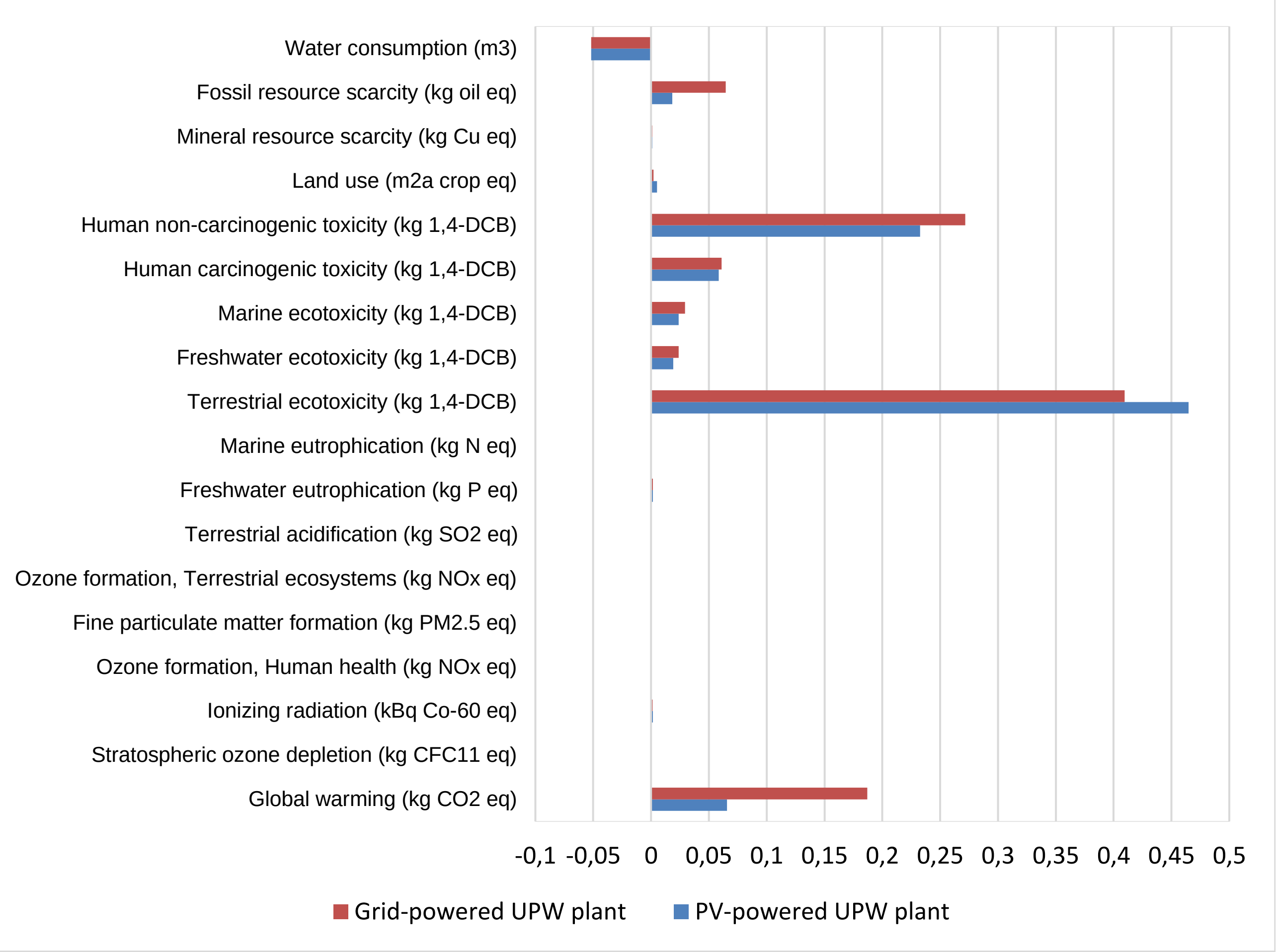

Figure 2. *Midpoint impacts of the UPW plant powered by the PV park (Scenario 1) and Algeria grid (Scenario 2) using ReCiPe 2016 Midpoint (H).*

3.2. Italy Case Study

An additional case study examines hydrogen production in Italy, where energy infrastructure and freshwater availability differ markedly from the conditions in Algeria. In this scenario, the environmental performance of producing 1 kg of hydrogen is evaluated using PV-generated electricity to power both the UPW treatment and electrolysis processes, mirroring the renewable configuration considered for Algeria.

Comparing the Algerian and Italian cases allows for an assessment of how geographical context influences water consumption and water scarcity impacts, particularly in light of the contrasting hydrological conditions of the two regions. In the Italian framework, the UPW system plays a critical role. The water footprint of the system in Italy is lower compared to Algeria. Although ultrapure water production exhibits net negative water balances at the inventory level for both countries, the application of AWARE characterization factors produces fundamentally different outcomes. In Italy, the low regional water stress allows returned water flows to offset consumptive use, resulting in a negative characterized water use for the UPW system of -1.18 m^3. By contrast, Algeria exhibits a positive water scarcity impact, as high regional characterization factors amplify even minor consumptive water use, leading to a UPW system water footprint of 0.053 m^3.

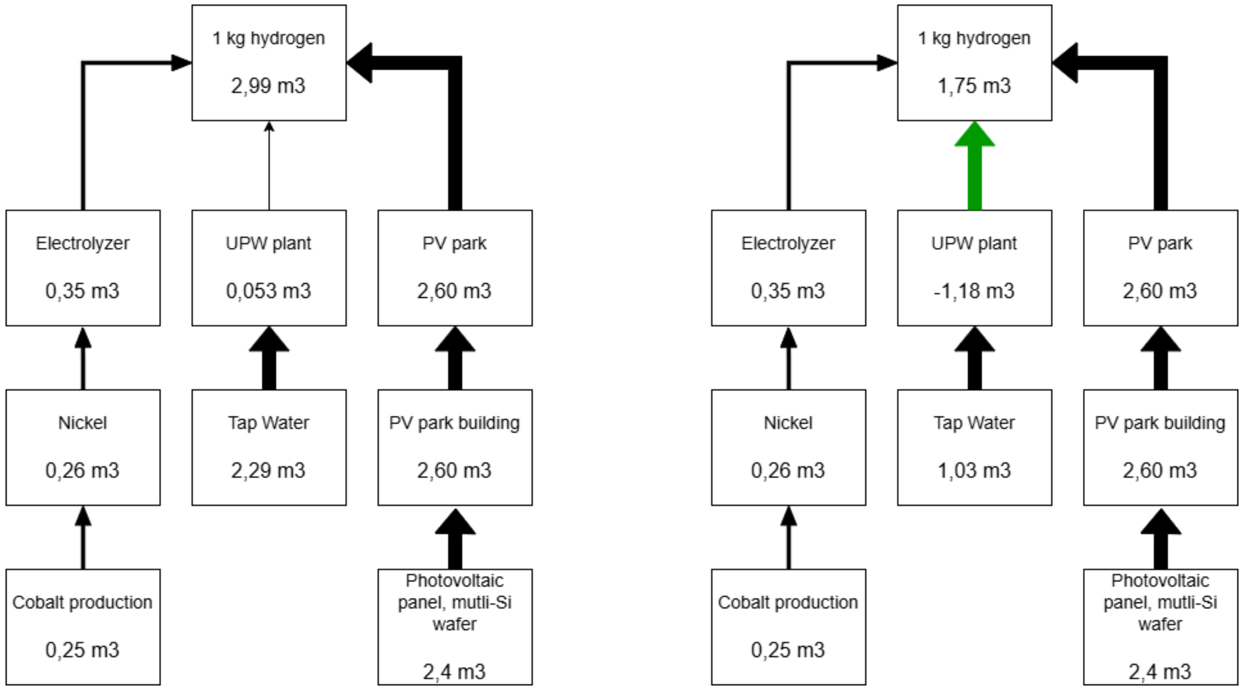

Figure 3. *Fluxes that contribute to the WF of hydrogen production from the Algeria Case Study (left) and the Italy Case Study (right).*

The study proposes an insight between climate mitigation and local water scarcity in desert-based green hydrogen projects. The PV-powered Algerian configuration substantially reduces fossil GWP compared to a grid-powered alternative, confirming that decarbonizing electricity supply is the main driver of climate benefits. However, when scarcity-weighted water indicators are considered, even modest consumptive uses in hyper-arid basins become environmentally significant, indicating that climate-only assessments would overlook critical risks for freshwater resources. Methodologically, combining a global LCIA method (ReCiPe 2016), a climate-specific indicator (IPCC GWP20), and multiple water scarcity models (AWARE, Hoekstra, Boulay, Berger) proves essential. ReCiPe shows that ecosystem and resource damages are dominated by the upstream PV supply chain, while operational stages play a secondary role. Climate results follow the same pattern, reinforcing the importance of PV manufacturing.

3.3. Comparative Analysis of Water Footprint Characterization Methods

The comparative assessment of the PV-based hydrogen production scenario in Algeria (Figure 4) reveals significant variation in magnitude and contribution patterns depending on the selected method, reflecting fundamental differences in impact modeling approaches. The AWARE method yields the highest total impact (2.987 m^3 eq.), nearly two orders of magnitude greater than the other indicators. This is attributed to its characterization factors (0.1–100), which strongly amplify water consumption in water-scarce regions. Consequently, the PV park dominates the results (2.588 m^3 eq.) due to its location in the arid, high-demand watersheds of Algeria where the Available Minus Demand (AMD) is critical. In contrast, the Berger (0.046 m^3) and Boulay (0.048 m^3) methods provide closely aligned results, as both are based on consumption-to-availability relationships. Interestingly, the Hoekstra WSI provides the most conservative total (0.025 m^3) and reports a negative value for the PV-powered UPWS (-0.072 m^3). This negative value functions as an environmental "credit," implying that the use of PV electricity for water purification avoids the significantly higher operational water consumption associated with the conventional thermal-heavy electricity grids in the study regions. These results underscore that while volumetric consumption remains constant, the choice of LCIA method significantly influences the interpretation of water-related impacts, depending on whether the emphasis is placed on water availability (AWARE), basin vulnerability (Berger), user deprivation (Boulay), or environmental flow requirements (Hoekstra). Therefore, water-related impacts are driven by geography and characterization choices: all four water methods, despite their different formulations, consistently identify Algerian basins as far more vulnerable than Italian ones. The comparison between Algeria and Italy illustrates how identical PV-electrolysis-UPW systems can have opposite implications for water scarcity. Inventory-level water balances for the ultrapure water system are net negative in both contexts, but characterization factors reverse the picture: in Italy, discharges to low-stress basins offset consumptive use and yield a net water gain, whereas in Algeria high stress levels translate into a positive water scarcity footprint. Thus, siting decisions become as important as technological choices for safeguarding water resources.

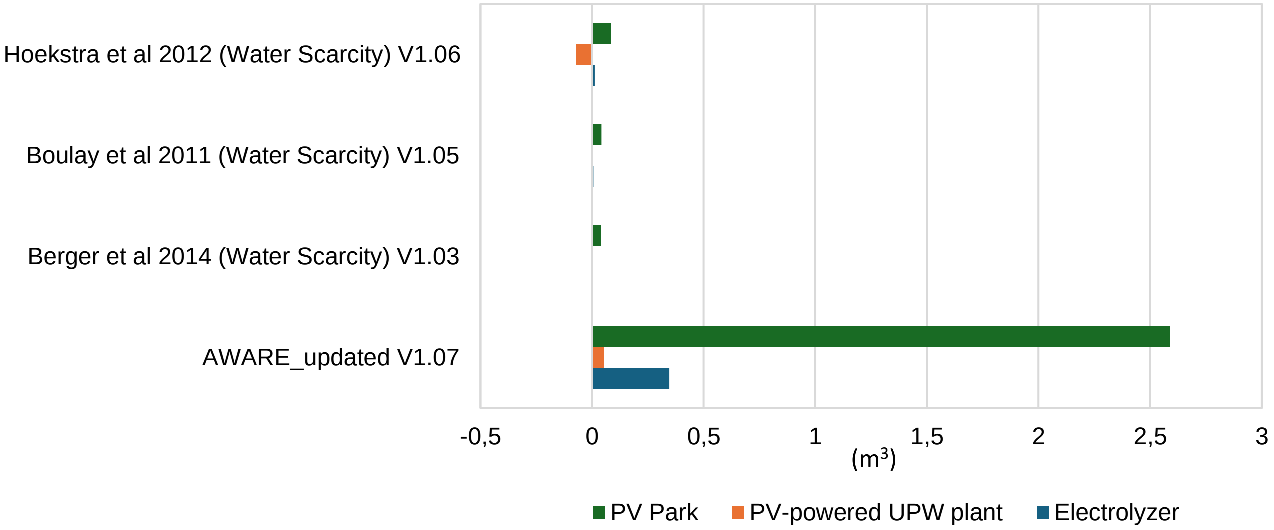

Figure 4: *Water footprint analyses of the PV-based hydrogen production scenario in Algeria (Scenario 1).*

3.4. Uncertainty analysis using Monte Carlo method

An uncertainty analysis was performed using the Monte Carlo simulation tool in SimaPro to evaluate the robustness of the LCA results. The method propagates inventory data uncertainty by repeatedly recalculating the model through random sampling of input parameter distributions. In this study, 1000 Monte Carlo iterations were carried out for the main 5 scenarios and impact categories in order to assess the statistical significance of the differences observed between the analyzed configurations.

For the Algerian case, PV-powered and grid-powered configurations were compared using the IPCC 2021 GWP20 indicator. The results show a mean difference of −0.144 kg CO_2-eq/kg H_2 between the two scenarios (PV − grid), with a standard deviation of 0.023 and a 95% confidence interval of −0.197 to −0.101 and no simulations where PV exceeds grid emissions. This confirms the statistical robustness of the climate benefit of PV electricity and ensures that the electricity source is the dominant contributor to the global warming impact of the system and that replacing grid electricity with renewable electricity significantly reduces the climate change footprint of hydrogen production. A second Monte Carlo comparison using the AWARE method between PV-based hydrogen production in Algeria (A) and Italy (B) indicates no statistically significant difference. As illustrated in the probability distribution (Figure 6), the histogram of the difference (A − B) spans both negative and positive values, indicating a substantial overlap between the results of the two scenarios, with Algeria showing higher impacts in 53.1% of simulations and Italy in 46.9%. This suggests that, despite differing regional water scarcity conditions, uncertainties in inventory data and relatively low water consumption led to inconclusive results regarding comparative water scarcity impacts. Therefore, the uncertainty analysis indicates that the climate advantage of PV over the Algerian grid mix is statistically robust, supporting strong recommendations in favour of renewable electricity. Conversely, AWARE-based differences between Algerian and Italian PV scenarios fall within inventory uncertainty, suggesting that fine-grained rankings of water scarcity impacts should be interpreted cautiously and always in conjunction with basin-level sustainability thresholds and local water management objectives.

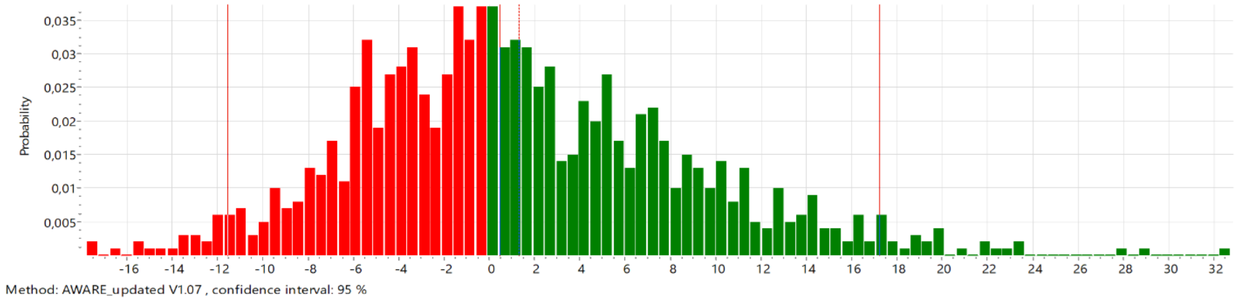

Figure 6: *Histogram of the difference (A-B) using the AWARE method, A: Algeria case, B: Italy case.*

4. Conclusions and Future Perspectives

In this study, a comprehensive life cycle and water footprint assessment of green hydrogen production via photovoltaic-powered electrolysis in a desert environment has been conducted, with a specific focus on the energy-water nexus. By integrating multiple LCIA methods, including climate change indicators (IPCC GWP20), a global environmental framework (ReCiPe 2016), and four water scarcity models (AWARE, Boulay, Berger, and Hoekstra), the analysis offers a multidimensional evaluation of environmental performance under different energy supply configurations and geographical contexts.

The results confirm that photovoltaic electricity is the primary driver of environmental impacts, particularly in terms of global warming potential. The manufacturing phase of the PV system dominates the life cycle emissions, accounting for the majority of GHG contributions, while the electrolyzer and ultrapure water system play a secondary role. Nonetheless, the choice of electricity source remains critical: replacing renewable electricity with the Algerian grid mix leads to a significant increase in climate impacts.

From a water perspective, the study highlights that direct water consumption for electrolysis is relatively limited, whereas indirect water use associated with electricity generation represents the dominant contribution. However, the application of scarcity-weighted indicators reveals that the environmental relevance of water consumption is highly dependent on geographical context. In water-scarce regions such as southern Algeria, even small volumes of water consumption translate into significant impacts due to high characterization factors, whereas in water-abundant regions such as Italy, similar systems may result in neutral or even beneficial outcomes when water return flows are considered.

The comparison among water footprint methodologies further emphasizes the importance of methodological choice. While volumetric consumption remains constant, the interpretation of impacts varies substantially depending on the underlying model assumptions. The AWARE method, in particular, amplifies the role of regional scarcity, identifying desert-based PV systems as critical hotspots, whereas other methods provide more conservative estimates. This variability underlines the necessity of adopting a multi-method approach when evaluating water-related impacts in energy systems.

Overall, the findings demonstrate that green hydrogen production in desert regions involves a fundamental trade-off between climate benefits and local water stress. While such systems are highly effective in reducing greenhouse gas emissions, they may exacerbate pressure on already vulnerable freshwater resources if not carefully managed. Therefore, technological optimization alone is not sufficient; spatial planning and resource availability must be explicitly integrated into project design and policy frameworks.

Future research should focus on improving the spatial and temporal resolution of water footprint assessments, particularly by incorporating dynamic hydrological data and seasonal variability. In addition, further work is needed to refine life cycle inventory data for key components such as electrolyzers and water treatment systems, reducing uncertainty and enhancing the robustness of results. The integration of water reuse strategies, desalination technologies, and circular water management approaches also represents a promising pathway to mitigate water scarcity impacts in arid regions.

Finally, the development of harmonized indicators capable of capturing energy-water trade-offs across different scales can offer a valuable step toward defining sustainability thresholds and operational limits for freshwater use in energy systems. Such tools, as the recently proposed Water Circularity Index (22), can support more informed decision-making and facilitate the deployment of green hydrogen in a way that is both climate-efficient and water-responsible.

Nomenclature:

AMD	Available Minus Demand	MENA	Middle East and North Africa
AWARE	The Available WAter REmaining	OECD	Organisation for Economic Co-operation and Development
BoP	Balance of Plant	PEM	Proton Exchange Membrane
CCGT	Combined gas turbine	PV	Photovoltaic panel
CCS	Carbon Capture and Storage	RO	Reverse Osmosis
CTA	consumption-to-availability	SMR	Steam Methane Reforming
DALYs	Disability Adjusted Life Years	TDS	Total Dissolved Solids
DZ	Algeria code	UF	Ultrafiltration
EDI	Electrodeionization	UPWS	Ultrapure water supply system
GHG	Greenhouse gases	WDI	Water Depletion Index

GWP	Global Warming Potential	WSF	Water Scarcity Footprint
LCA	Life Cycle Assessment	WSI	Water Scarcity Indicator
LCIA	Life Cycle Impact Assessment		

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