

Article

Techno-Economic Environmental Risk Analysis (TERA) in Hydrogen Farms

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Abstract

This study presents a techno-economic environmental risk analysis (TERA) of large-scale green hydrogen production using Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) systems. The analysis integrates commercial data, market insights, and academic forecasts to capture variability in capital expenditure (CAPEX), efficiency, electricity cost, and capacity factor. Using Libya as a case study, 81 scenarios were modelled for each technology to assess financial and operational trade-offs. For AWE, CAPEX is projected between \$311 billion and \$905.6 billion for 519 GW (gigawatts) of installed capacity, equivalent to 600–1745 \$/kW. PEM systems show a wider range of \$612 billion to \$1020 billion for 510 GW, translating to 1200–2000 \$/kW. Results indicate that AWE, while requiring greater land use, provides significant cost advantages due to lower capital intensity and scalability. In contrast, PEM systems offer compact design and operational flexibility but at substantially higher costs. The five most economical scenarios for both technologies consistently feature low CAPEX and high efficiency, while sensitivity analyses confirm these two parameters as the dominant cost drivers. The findings emphasise that technology choice should reflect context-specific priorities such as land availability, budget, and performance needs. This study provides actionable guidance for policymakers and investors developing cost-effective hydrogen infrastructure in emerging green energy markets.



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Keywords: capital expenditure (CAPEX); efficiency; levelized electricity cost (LEC); capacity factor; green hydrogen; sensitivity analysis; environmental sustainability

1. Introduction

The accelerating global energy transition has brought renewed attention to hydrogen as a flexible and scalable energy carrier with the potential to enable deep decarbonisation across the power generation, industrial, and transport sectors [1]. Currently, conventional hydrogen production is largely reliant on natural gas reforming, a process that is highly carbon-intensive and misaligned with international net-zero climate objectives. In contrast, green hydrogen, produced via electrolysis powered by renewable energy sources, presents a promising pathway toward a low-carbon energy future. However, the widespread adoption of green hydrogen technologies is hindered by several challenges, including high upfront capital investment, uncertainties in technological performance, and complex environmental trade-offs. Overcoming these barriers demands more comprehensive evaluation tools. Specifically, there is a need for integrated analytical frameworks that extend beyond traditional techno-economic analyses by incorporating technical, environmental,

and risk-based dimensions. Such holistic approaches are essential for guiding informed policymaking, strategic investment, and long-term planning in the hydrogen sector [1].

Techno-Economic Environmental Risk Analysis (TERA) offers a comprehensive framework that integrates cost, efficiency, risk, and environmental impact into a unified methodology. Unlike conventional techno-economic assessments—which often consider economic or technical performance metrics in isolation [2], TERA facilitates a holistic evaluation of complex energy systems by capturing the interdependencies and trade-offs among multiple dimensions. Its adaptability has been demonstrated across various domains. For instance, Chen et al. [3] applied an energy–exergy approach to assess an Internal Rankine Turbine (IRT) engine, demonstrating enhanced exergy efficiency while also quantifying life-cycle environmental risks. Similarly, Mirzaei et al. [4] investigated the synergies between electricity generation and district heating systems, underscoring the value of integrated energy management frameworks for improved operational performance. In another example, a techno-economic study of a 1 MWth PR-SPT-IPH facility utilised a hybrid approach combining MATLAB R2022a simulations with the System Advisor Model (SAM) to estimate the levelized cost of heat (LCOH) alongside greenhouse gas (GHG) mitigation potential [5]. These applications illustrate TERA’s ability to support informed decision-making by offering a structured way to quantify both technical and environmental trade-offs in next-generation energy infrastructure.

Cicekalan et al. [6] evaluated the techno-economic and environmental feasibility of various municipal wastewater treatment technologies, considering capital investment, operational costs, and ecological implications. Taken together, these studies underscore the versatility of the TERA framework in capturing the interconnected economic and environmental dimensions of complex infrastructure systems.

Hydrogen production through electrolysis is currently dominated by two principal technologies: Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) systems. AWE is a commercially established, cost-effective solution for large-scale deployment; however, it demands significant land area and offers limited operational flexibility. In contrast, PEM electrolysis is characterised by a compact footprint and rapid response capabilities, making it well-suited for dynamic grid applications. Nevertheless, PEM systems entail substantially higher capital expenditure and are more sensitive to fluctuations in operational conditions. Although various techno-economic comparisons of these technologies have been conducted, most fail to explicitly incorporate scenario-based uncertainties or environmental risk factors—creating a gap in practical decision-support frameworks for policymakers, project developers, and investors.

Libya presents a compelling context for extending this line of inquiry. The country possesses substantial renewable energy resources, including high solar irradiance across its expansive desert regions and strong wind corridors along its 2000-kilometre Mediterranean coastline [7]. However, several sources of uncertainty remain. These include fluctuating electrolyser capital costs, the intermittent nature of renewable energy supply, balance-of-plant (BoP) energy consumption, and overall system efficiency at scale [7]. Together, these factors introduce significant techno-economic and environmental risks that must be properly evaluated. As such, there is a pressing need for a robust methodological framework capable of quantifying trade-offs, assessing system-level impacts, and capturing the probabilistic nature of future outcomes.

Against this background, this study develops and applies a TERA framework to assess the techno-economic, environmental, and risk dimensions of large-scale hydrogen farms in Libya. The analysis builds on earlier contributions, including the Hydrogen Farms Baseline Economic Model and prior studies on preliminary hydrogen farm assessments and hydrogen storage and pipeline evaluation [4,5]. By modelling 81 scenarios under

optimistic, baseline, and pessimistic assumptions for both AWE and PEM systems, the research identifies cost-effective configurations while quantifying the influence of key parameters such as capital expenditure (CAPEX), electrolyser efficiency, electricity price, and capacity factor.

In addition, the framework incorporates environmental dimensions, including land use, water consumption, lifecycle emissions, and CO₂ mitigation potential, thereby offering a holistic evaluation of the trade-offs inherent in scaling hydrogen infrastructure. In doing so, the study not only extends the application of TERA to the hydrogen sector but also delivers actionable insights to support policy development, investment strategies, and infrastructure planning aimed at advancing global decarbonisation objectives.

2. Identifying Ranges for Variables

2.1. Efficiency Range Determination for Alkaline Electrolysers

To account for the inherent uncertainty in the performance of alkaline electrolysers within the risk analysis framework, an efficiency range of 70% to 82% was adopted. This range is informed by current commercial benchmarks as well as anticipated advancements in electrolyser technology, based on both manufacturer specifications and recent literature. The lower bound of 70% represents a pessimistic scenario, capturing conditions such as suboptimal system operation, efficiency losses due to long-term degradation, or increased energy consumption from auxiliary balance-of-plant (BoP) components.

The baseline efficiency of 75% corresponds to the typical operational performance of commercial alkaline electrolyser units functioning at temperatures between 60 and 80 °C and pressures of 1–2 bar. This figure is well-supported by both industrial benchmarks and findings from academic literature. For the optimistic scenario, an upper bound of 82% efficiency has been adopted to reflect projected advancements in electrolyser design and system integration. This selection aligns with the projections of Reksten et al. [8], who forecast efficiency improvements ranging from 70% to 82% under conditions of large-scale deployment. Similar assumptions have been echoed in other decarbonisation-focused studies, which aim for efficiencies exceeding 80% in optimised system configurations. Therefore, this study adopts a three-point discrete range of 70% (pessimistic), 75% (baseline), and 82% (optimistic) to provide a realistic yet forward-looking representation of current performance levels and anticipated technological progress [9].

It is important to note that the reported gross efficiency values in this study inherently account for balance-of-plant (BoP) consumption, as the efficiency metrics adopted are based on net system output rather than isolated stack performance. This approach ensures that the efficiency assumptions used throughout the analysis are representative of realistic, full-system operation, rather than reflecting idealised electrochemical conditions. While this study does not explicitly separate stack and BoP efficiencies, it acknowledges the value of doing so in future research to allow for a more detailed assessment of internal energy losses and component-level optimisation [10].

Importantly, the efficiency values selected here are not exaggerated; they are grounded in commercially available data and aligned with current industry norms and future projections. By incorporating BoP effects, the model offers a more credible and engineering-relevant reflection of operational performance, rather than relying on overly optimistic theoretical values.

2.2. Efficiency Range Determination for PEM Electrolyser

To capture the uncertainties in Proton Exchange Membrane (PEM) electrolyser performance for risk assessment, this study defines an efficiency range based on current literature and technical forecasts. The pessimistic case (65%) reflects the lower end of operational

performance, accounting for system inefficiencies, variable loading, and long-term degradation. The baseline efficiency (77%) represents the typical performance of commercial PEM systems under standard operating conditions. The optimistic case (85%) corresponds to state-of-the-art performance achievable through advanced integration, thermal recovery, and improved stack design.

These assumptions are supported by the International Renewable Energy Agency (IRENA), which reports current PEM efficiencies of 60–70%, with future improvements expected to exceed 80% in optimised systems [11]. Similarly, Mohammed-Ibrahim and Moussab [12] document a range of 65–82%, influenced by factors such as electrolyser scale, membrane quality, and system integration. Together, these studies provide a strong basis for applying the selected range in both deterministic and probabilistic modelling.

Accordingly, the efficiency values used in this analysis are 65% (pessimistic), 77% (baseline), and 85% (optimistic), reflecting both present capabilities and anticipated advances in commercial-scale PEM systems.

2.3. Capital Expenditure Range Determination for AWE

To capture the commercial variability in capital expenditure (CAPEX) for large-scale alkaline electrolyser projects, this study adopts a range centred on a baseline of USD 752.55 billion, equivalent to about 1450 \$/kW for a 519 GW national-scale installation. The optimistic scenario assumes aggressive procurement from low-cost suppliers, particularly Chinese manufacturers, where total system costs are reported at around 600 \$/kW. For a 519 GW system, this equates to an overall CAPEX of approximately USD 311.4 billion. Bloomberg NEF data support this figure, noting a fourfold cost disparity between Chinese and Western electrolyser systems [13].

The pessimistic scenario reflects current Western market conditions, where installed costs for alkaline electrolysers are closer to 1745 \$/kW. According to S&P Global Commodity Insights, this revised estimate captures the effects of market stabilisation, supply chain improvements, and easing inflationary pressures [14]. At this rate, a nationwide 519 GW deployment would require an investment of about USD 905.6 billion.

The established range, \$311 billion to \$905.6 billion, therefore effectively encapsulates the variability of real-world project estimates and supply chain dynamics observed as of 2024, rendering it appropriate for immediate risk assessment concerning investments in hydrogen infrastructure.

2.4. Capital Expenditure Range Determination for PEM

To define the optimistic and pessimistic capital expenditure (CAPEX) parameters for Proton Exchange Membrane (PEM) electrolysers, this study relies on commercial data from 2020 to 2024, excluding future projections. The baseline CAPEX is estimated at USD 943.5 billion for a deployment of 510 GW, which equates to roughly 1850 \$/kW. This value lies within the mid-range of current market estimates. According to the U.S. Department of Energy (DOE), complete PEM systems presently cost between \$1400 and 2500 \$/kW, reflecting inflation and high balance-of-plant expenses in recent projects [15].

The optimistic case assumes favourable execution and procurement conditions, representing the lower end of commercial variability. Industry sources, such as Electric Hydrogen, report that large-scale PEM projects can achieve installed costs of around 1200 \$/kW, leading to a total CAPEX of about USD 612 billion for a 510 GW facility [16].

The pessimistic scenario is based on updated DOE evaluations, which estimate that fully integrated PEM electrolysers currently require approximately 2000 \$/kW in installed capital costs. This figure, informed by the H2NEW Consortium and corroborated by U.S. manufacturers, reflects prevailing commercial conditions in Western markets [17].

Applying this value to a 510 GW deployment produces a total investment of around USD 1020 billion, consistent with outcomes observed in smaller or pioneering projects.

The three estimates, \$612 billion (optimistic), \$943.5 billion (baseline), and \$1.020 trillion (pessimistic), capture the present-day global variability in PEM electrolyser costs and form a robust basis for risk analysis.

2.5. Levelized Electricity Cost Range Determination

Lazard's 2023 analysis shows that the unsubsidized Levelized Cost of Energy (LCOE) for onshore wind projects has declined significantly over time, reaching about 50 \$/MWh in 2023, where this decline reflects both technological improvements and economies of scale in wind energy deployment [18].

Similarly, the Institute for Energy Research (2019) estimates the LCOE for new Combined Cycle Gas Turbine (CCGT) plants at roughly 50 \$/MWh, a figure that highlights the efficiency and relatively low fuel costs of natural gas systems [19].

In project cost estimation, applying a fixed percentage range such as $\pm 20\%$ to a baseline value is a widely accepted method for defining optimistic and pessimistic scenarios. This approach provides a structured way to address uncertainty, particularly where detailed datasets are limited [20]. Based on this method, the present study adopts 40 \$/MWh for the optimistic case, 50 \$/MWh for the baseline, and 60 \$/MWh for the pessimistic case. These discrete values are applied consistently across both AWE and PEM electrolyser models to ensure comparability in risk analysis and to reflect realistic electricity pricing in emerging hydrogen markets such as North Africa.

2.6. Capacity Factor Range Determination

The International Energy Agency (IEA) identifies standard capacity factors for electrolyser facilities, including alkaline systems, and recommends a 20% capacity factor as a realistic reference point under current technological and market conditions [21]. This value is therefore used as the baseline in this study. The optimistic scenario (22%) reflects potential improvements from advanced operational strategies, such as optimised hybrid renewable systems that integrate solar and wind resources, or partial grid support. According to IEA (2023), co-location with baseload renewable sources like geothermal, or strategic curtailment of surplus renewable generation, can raise capacity factors to 22–25% even without dedicated storage [22].

By contrast, the pessimistic scenario (18%) accounts for suboptimal conditions, including reduced solar irradiance, grid limitations, or operational interruptions. Evidence from early hydrogen projects in Germany and Chile supports this assumption, with reported capacity factors as low as 15–19% under unfavourable weather or technical start-up challenges [23].

Accordingly, the final capacity factors applied to all electrolyser types are 18% (pessimistic), 20% (baseline), and 22% (optimistic). These values capture realistic performance ranges while considering variability in solar resource availability and grid reliability, particularly in North African contexts such as Libya, where intermittency remains a key constraint.

3. AWE Electrolyser Farms Risk Analysis

This section presents the risk analysis framework for large-scale hydrogen production using Alkaline Water Electrolysers (AWE). As one of the most mature electrolysis technologies, AWE provides a cost-effective pathway for hydrogen generation, particularly in regions with ample land and renewable resources. The analysis evaluates multiple operating scenarios to examine how changes in capital costs, system efficiency, electricity prices,

and capacity utilisation affect economic outcomes (Table 1). This approach highlights the cost dynamics and sensitivities that shape AWE-based hydrogen infrastructure planning.

Table 1. Scenario assumptions for the Alkaline Electrolyser farm.

Alkaline Electrolyser Farm			
Variable	Optimistic Scenario	Baseline Scenario	Pessimistic Scenario
Electrolyser CAPEX (Million USD)	311,400	752,550	905,600
Electrolyser Efficiency (%)	82	75	70
Levelized Electricity Cost (USD/MWh)	40	50	60
Capacity Factor (%)	22	20	18

The script in Figure 1 evaluates 81 distinct scenarios by varying four key input parameters: CAPEX, electrolyser efficiency, electricity cost, and capacity factor. For each scenario, a cost metric is computed to estimate the economic impact under different operating assumptions. The output is structured into a table and exported to Excel for further analysis.

```

% === Alkaline Electrolyser Risk Analysis (81 Scenarios) ===
% Step 1: Clear Environment
clear; clc.
% Step 2: Define Input Parameters Based on Your Table
capex_vals = [311400, 752550, 1297500]; % USD/kW
eff_vals = [82, 75, 70]; % Efficiency (%)
elec_vals = [40, 50, 60]; % Electricity cost ($/MWh)
cf_vals = [22, 20, 18]; % Capacity factor (%)

% Names and baseline values for labeling
param_names = {'CAPEX', 'Efficiency', 'ElectricityCost', 'CapacityFactor'};
baseline = [752550, 75, 50, 20]; % Baseline scenario

% Step 3: Generate All Combinations (3 x 3 x 3 x 3 = 81)
[CAPEX, EFF, ELEC, CF] = ndgrid(capex_vals, eff_vals, elec_vals, cf_vals);
all_combos = [CAPEX(:), EFF(:), ELEC(:), CF(:)];
n = size(all_combos, 1); % Total simulations

% Step 4: Initialize Results
results = zeros(n, 5); % Store inputs + cost
scenario_names = strings(n, 1); % Store descriptive names

% Step 5: Loop Over All Scenarios
for i = 1:n
    capex = all_combos(i, 1);
    eff = all_combos(i, 2);
    elec = all_combos(i, 3);
    cf = all_combos(i, 4);

    % === Cost Metric Calculation ===
    annual_energy = 8760 * cf;
    h2_kg = (annual_energy * eff) / 50; % 50 kWh per kg
    cost_metric = capex / h2_kg + elec;

    results(i, :) = [capex, eff, elec, cf, cost_metric];
    % === Scenario Naming Logic ===
    input_vals = [capex, eff, elec, cf];
    label = "";
    for j = 1:4
        if input_vals(j) == baseline(j)
            label = label + param_names{j} + "_Base_";
        elseif input_vals(j) < baseline(j)
            label = label + param_names{j} + "_Opt_";
        else
            label = label + param_names{j} + "_Pess_";
        end
    end
    scenario_names(i) = extractBefore(label, strlength(label)); % clean trailing
end

% Step 6: Create Table and Save to Excel
T = table(scenario_names, results(:,1), results(:,2), results(:,3), ...
    results(:,4), results(:,5), ...
    'VariableNames', {'Scenario', 'CAPEX', 'Efficiency', 'ElectricityCost',
    'CapacityFactor', 'CostMetric'});

writetable(T, 'alkaline_risk_analysis_81.xlsx');
disp("☑ Exported 81 alkaline scenarios to 'alkaline_risk_analysis_81.xlsx'");

```

Figure 1. MATLAB script for conducting risk-based techno-economic simulations of an alkaline electrolyser hydrogen farm.

Table 2 presents the most economically favourable configurations for hydrogen production using alkaline electrolyzers (Institute for Sustainable Process Technology, Amersfoort, the Netherlands). All five scenarios combine optimal capital expenditure with high electrolyser efficiency, confirming that minimising upfront investment and maximising conversion efficiency are the primary drivers of cost reduction. The resulting costs fall within a narrow range of 212.62 to 232.62 USD/MWh, with only minor variations arising from changes in electricity price and capacity factor. These results show that while electricity costs and system utilisation influence outcomes, their impact is far less significant than that of CAPEX and efficiency. Overall, the table demonstrates that carefully aligning design choices can unlock substantial cost savings in AWE-based systems.

Table 2. Most cost-effective scenarios for Alkaline Electrolyser hydrogen production.

Scenario	Cost Metric
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Opt_CapacityFactor_Opt	212.62
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Base_CapacityFactor_Opt	222.62
CAPEX_Opt_Efficiency_Base_ElectricityCost_Opt_CapacityFactor_Opt	228.73
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Opt_CapacityFactor_Base	229.88
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Pess_CapacityFactor_Opt	232.62

4. Alkaline Electrolyser Sensitivity Analysis

The sensitivity analysis for the Alkaline Electrolyser highlights how four key variables, Capital Expenditure (CAPEX), electrolyser efficiency, electricity cost, and capacity factor, affect overall costs across pessimistic, baseline, and optimistic scenarios. All trend lines converge at the same value under the baseline scenario, which serves as the reference point.

Among the variables, CAPEX (blue line) shows the largest variation, with costs dropping sharply from the pessimistic to the optimistic case, confirming its dominant role in cost variability. Electrolyser efficiency (red line) and capacity factor (orange line) both lead to moderate cost reductions as their values increase, showing their importance in improving economic performance. In contrast, electricity cost (green line) has a smaller but still noticeable effect, with a more gradual slope.

This visualisation corroborates the inference that reducing CAPEX constitutes the most effective strategy for minimising total costs in alkaline hydrogen production systems, followed by enhancements in efficiency and operational optimisation through improved capacity utilisation.

5. Frequency Plot of AWE

Figure 2 shows the frequency distribution for the Alkaline Electrolyser scenarios. The histogram reveals two distinct cost clusters: a lower band at 213–303 USD/MWh and a higher band at 528–618 USD/MWh. The *x*-axis represents cost ranges in USD/MWh, while the *y*-axis shows the frequency of occurrences. A notable feature is the absence of results in the intermediate band of 348–438 USD/MWh, suggesting that production costs tend to fall into either low-cost or high-cost extremes, with very few outcomes in between.

This gap is driven by non-linear interactions between the main cost drivers—particularly capital expenditure (CAPEX) and electrolyser efficiency—further shaped by electricity price and capacity factor (Figure 3). When CAPEX is low and efficiency is high, the Levelized Cost of Hydrogen (LCOH) falls sharply, producing the lower-cost cluster. By contrast, combinations of high CAPEX and low efficiency push costs disproportionately higher, forming the upper cluster. Because these drivers interact multiplicatively rather than additively, even small shifts in one or two parameters can significantly alter outcomes, making mid-range values inherently unstable.

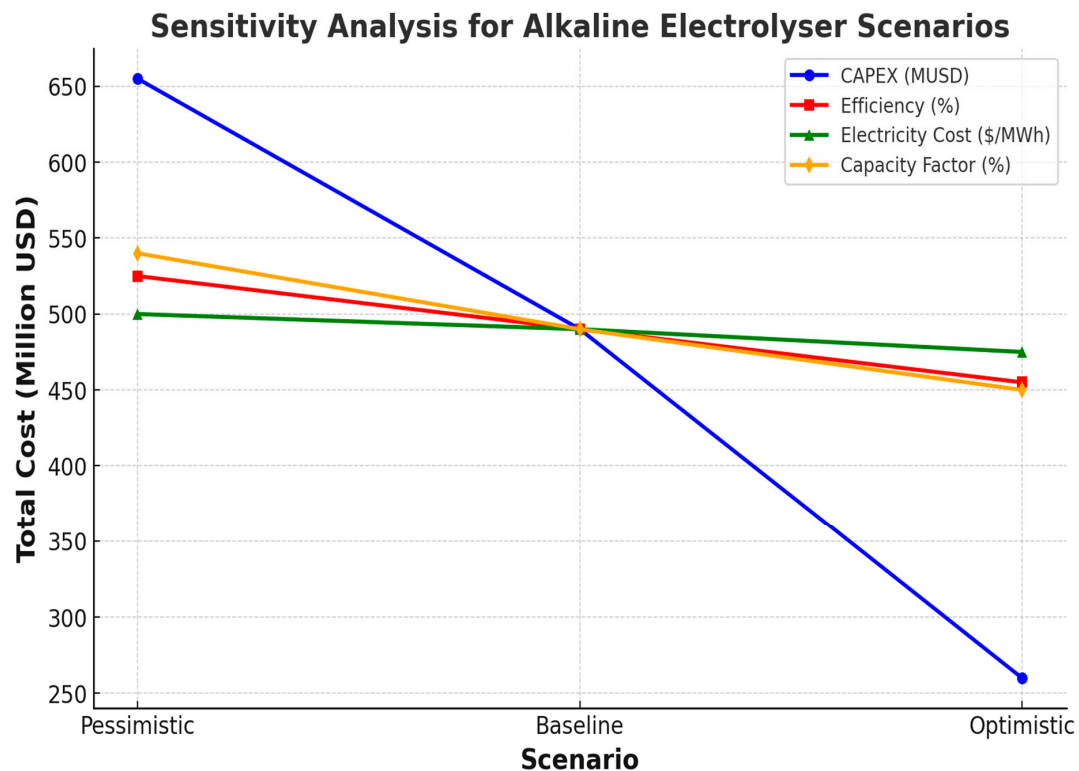


Figure 2. Sensitivity analysis of total costs for Alkaline Electrolyser scenarios across pessimistic, baseline, and optimistic conditions.

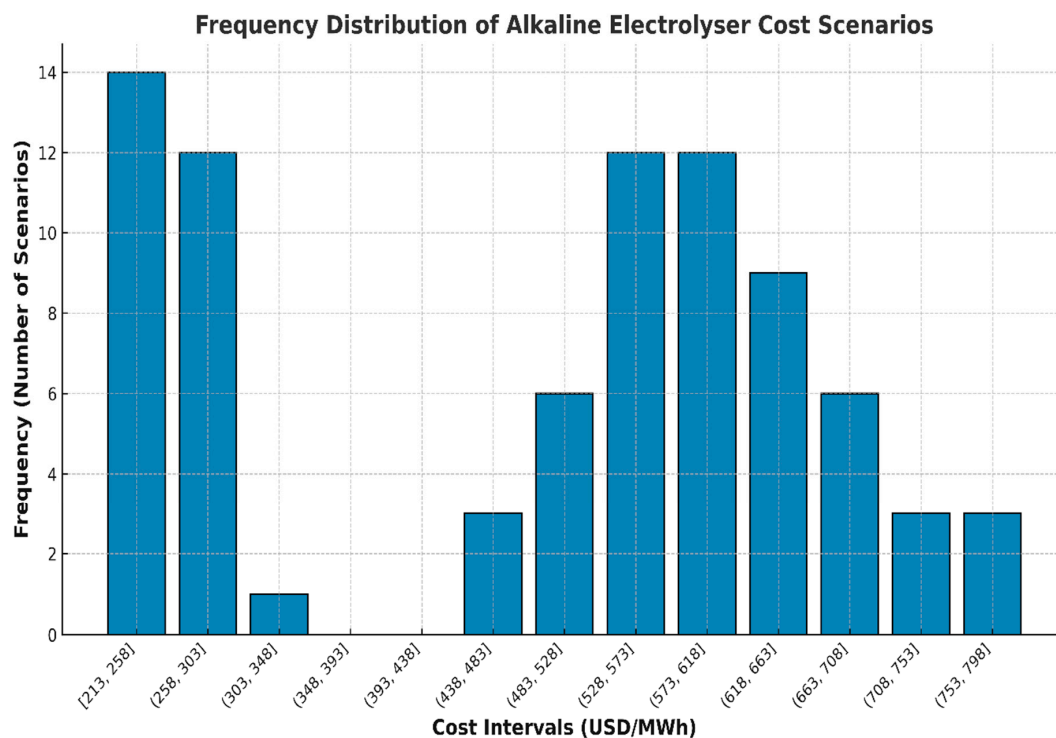


Figure 3. Frequency distribution of cost outcomes for Alkaline Electrolyser scenarios derived from the risk analysis.

The absence of intermediate results also reflects stepwise or threshold effects in how variables influence cost (Figure 3). For example, small increases in electricity price or slight reductions in capacity factor may move a scenario from near-optimal directly into a high-cost category, bypassing the middle range. Likewise, favourable conditions in one

variable may be offset by unfavourable changes in another, preventing stable mid-range outcomes. This behaviour underlines the complex interdependence of CAPEX, efficiency, electricity cost, and capacity factor, and highlights the importance of optimising all inputs to prevent cost escalation and achieve consistently competitive hydrogen production.

6. PEM Electrolyser Farms Risk Analysis

This section examines the risk analysis of Proton Exchange Membrane (PEM) electrolyser systems, which are valued for their high performance and compact design. However, their deployment is often constrained by higher capital costs and greater sensitivity to operating conditions. To address these challenges, a scenario-based approach is applied to evaluate how changes in key input variables influence the overall cost of hydrogen production. This analysis provides stakeholders with a clearer understanding of the trade-offs and uncertainties involved in scaling up PEM-based projects. The four scenarios considered in this study, along with their variables, are summarised in Table 3.

Table 3. Shows risk analysis variables in four scenarios for PEM.

Proton Exchange Membrane Electrolyser Farm			
Variable	Optimistic Scenario	Baseline Scenario	Pessimistic Scenario
Electrolyser CAPEX (Million USD)	612,000	943,500	1,020,000
Electrolyser Efficiency (%)	85	77	65
Levelized Electricity Cost (USD/MWh)	40	50	60
Capacity Factor (%)	22	20	18

The script in Figure 4 generates 81 simulations by varying four input parameters, CAPEX, electrolyser efficiency, electricity cost, and capacity factor—under optimistic, baseline, and pessimistic scenarios. For each configuration, a cost metric is calculated to assess the economic impact of different operational assumptions. Results are structured into a table and exported for further evaluation and comparison.

In MATLAB code, green text represents comments that are ignored during execution, while blue or purple text indicates MATLAB commands or built-in functions. Black text is used for variables and numbers, and light blue text denotes strings written within quotation marks. The symbol % marks the start of a comment, * is used for multiplication, and ... allows a command to continue onto the next line.

Table 4 highlights the five most cost-effective scenarios for hydrogen production using PEM electrolyser systems. In all cases, the top configurations combine optimal capital expenditure with maximum electrolyser efficiency, underscoring the decisive influence of these parameters in reducing overall costs. The resulting cost range, 367–401 USD/MWh, remains considerably higher than that of alkaline systems, reflecting the inherently higher baseline cost of PEM technology. Nevertheless, the repeated appearance of optimal parameters across all leading scenarios demonstrates the importance of precise system optimisation. These results provide valuable benchmarks for designing PEM-based projects, showing that even within a high-cost framework, strategic optimisation can substantially improve economic viability.

```

% == PEM Electrolyser Farm Risk Analysis (81 Scenarios) ==
% Step 1: Clear Environment
clear; clc;

% Step 2: Define Input Variables
capex_vals = [900,000, 1000,000, 1100,000]; % USD/kW
eff_vals   = [82, 78, 74]; % %
elec_vals  = [25, 35, 50]; % $/MWh
cf_vals    = [87, 47, 40]; % %

param_names = {'CAPEX', 'Efficiency', 'ElectricityCost', 'CapacityFactor'};
baseline    = [1000,000, 78, 35, 47];

% Step 3: Create All Combinations (3^4 = 81)
[CAPEX, EFF, ELEC, CF] = ndgrid(capex_vals, eff_vals, elec_vals, cf_vals);
all_combos = [CAPEX(:), EFF(:), ELEC(:), CF(:)];
n = size(all_combos, 1);

% Step 4: Initialize Outputs
results = zeros(n, 5); % 4 inputs + 1 cost
scenario_names = strings(n, 1);

% Step 5: Loop Through Scenarios
for i = 1:n
    capex = all_combos(i, 1);
    eff    = all_combos(i, 2);
    elec   = all_combos(i, 3);
    cf     = all_combos(i, 4);

    % Cost Metric Calculation
    annual_energy = 8760 * cf;
    h2_kg = annual_energy * eff / 50; % 50 kWh per kg
    cost_metric = capex / h2_kg + elec;

    results(i, :) = [capex, eff, elec, cf, cost_metric];

    % Build Scenario Name
    label = "";
    input_set = [capex, eff, elec, cf];
    for j = 1:4
        if input_set(j) == baseline(j)
            label = label + param_names{j} + "_Base_";
        elseif input_set(j) < baseline(j)
            label = label + param_names{j} + "_Opt_";
        else
            label = label + param_names{j} + "_Pess_";
        end
    end
    scenario_names(i) = erase(label, '_$'); % Clean up trailing _
end

% Step 6: Create Table
T = table(scenario_names, results(:,1), results(:,2), results(:,3), results(:,4),
    results(:,5), ...
    'VariableNames', {'Scenario', 'CAPEX', 'Efficiency', 'ElectricityCost',
    'CapacityFactor', 'CostMetric'});

% Step 7: Export to Excel
writetable(T, 'pem_risk_analysis_81.xlsx');
disp('Exported 81 PEM scenarios to 'pem_risk_analysis_81.xlsx');

```

Figure 4. MATLAB code used for scenario-based risk analysis of a Proton Exchange Membrane (PEM) electrolyser hydrogen farm.

Table 4. Most cost-effective scenarios for PEM electrolyser-based hydrogen production.

Scenario	Cost Metric
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Opt_CapacityFactor_Opt	367.27
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Base_CapacityFactor_Opt	377.27
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Pess_CapacityFactor_Opt	387.27
CAPEX_Opt_Efficiency_Opt_ElectricityCost_Opt_CapacityFactor_Base	400.0
CAPEX_Opt_Efficiency_Base_ElectricityCost_Opt_CapacityFactor_Opt	401.28

7. PEM Electrolyser Sensitivity Analysis

The sensitivity analysis of the PEM electrolyser scenarios (Figure 5) shows how variations in four key variables, capital expenditure (CAPEX), efficiency, electricity price, and capacity factor, affect hydrogen production costs under pessimistic, baseline, and optimistic conditions. All trend lines converge at the baseline scenario, which serves as the reference point. CAPEX (yellow line) has the largest impact, with costs dropping sharply under optimistic assumptions, confirming its dominant role in cost variability. Efficiency (orange line) is also highly influential, as lower values in pessimistic cases drive costs upward. By

comparison, electricity price (red line) and capacity factor (pink line) exert moderate but steady effects, each showing gradual cost reductions as conditions improve. Overall, the analysis highlights that lowering CAPEX and improving efficiency are the most effective strategies for reducing costs in PEM-based hydrogen production.

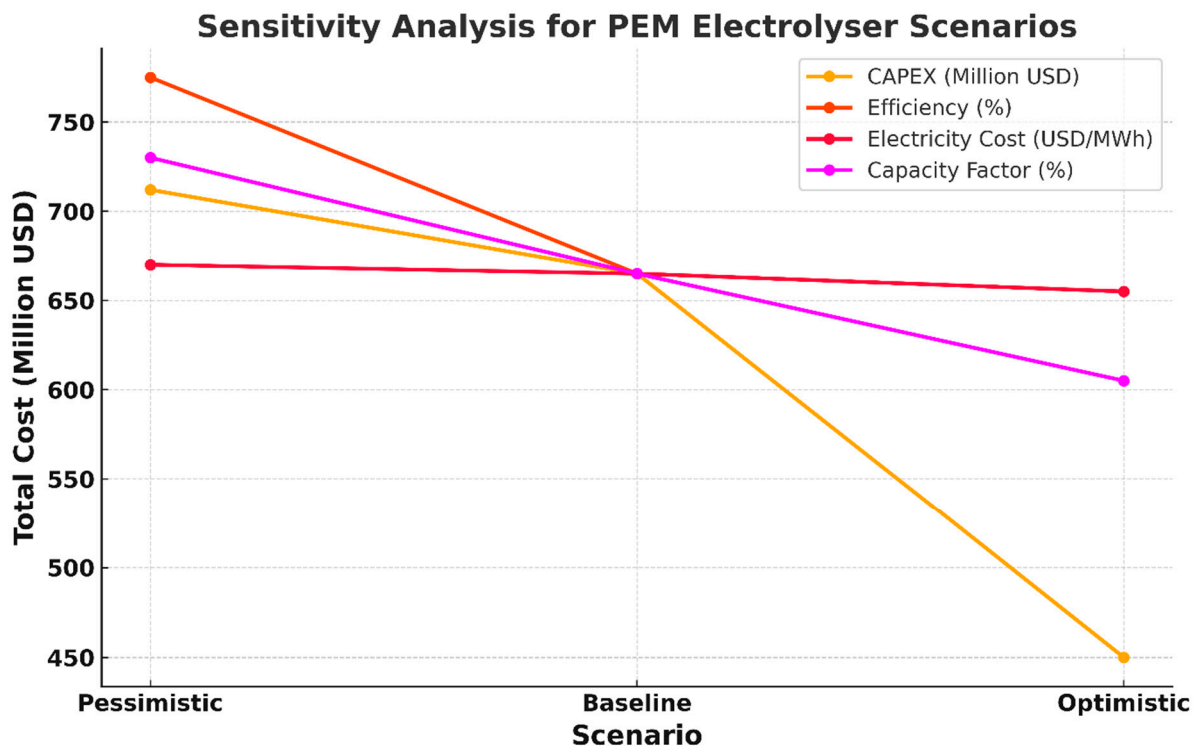


Figure 5. Sensitivity analysis of total costs for Proton Exchange Membrane (PEM) electrolyser scenarios across pessimistic, baseline, and optimistic conditions.

8. Frequency Plot of PEM

Figure 6 presents the histogram of PEM electrolyser scenarios, showing the frequency distribution of cost outcomes from the risk analysis. The horizontal axis indicates cost intervals in USD/MWh, while the vertical axis shows the number of scenarios. Results span a wide range, from 367 to 952 USD/MWh, highlighting the strong influence of capital expenditure (CAPEX), efficiency, electricity price, and capacity factor on economic performance. This broad spread underscores the sensitivity of PEM system costs to both technological and market factors, making their viability highly dependent on optimised operating conditions.

A clear feature of the distribution is the clustering between 592 and 682 USD/MWh, which emerges as the dominant cost band. This suggests that, in most configurations, PEM electrolyser operate in a moderately high-cost regime. The main drivers are the higher baseline CAPEX, and the efficiency constraints of PEM technology compared with alkaline systems. Even under favourable conditions, costs remain higher than those of other electrolyser types. By contrast, very low or very high outcomes appear rarely, occurring only under exceptional input combinations, such as unusually low CAPEX with high efficiency, or conversely, severe penalties from multiple unfavourable parameters.

The overall distribution shape reflects the role of non-linear interactions among variables. High CAPEX combined with low efficiency rapidly escalates costs into the upper range, while favourable conditions are required to shift results downward. This behaviour explains why intermediate outcomes are unstable: small changes in CAPEX, efficiency, electricity price, or capacity factor push results sharply toward one extreme. Consequently,

the performance of PEM systems depends not on improving a single parameter in isolation, but on optimising multiple cost drivers simultaneously to reduce instability and avoid persistently high costs.

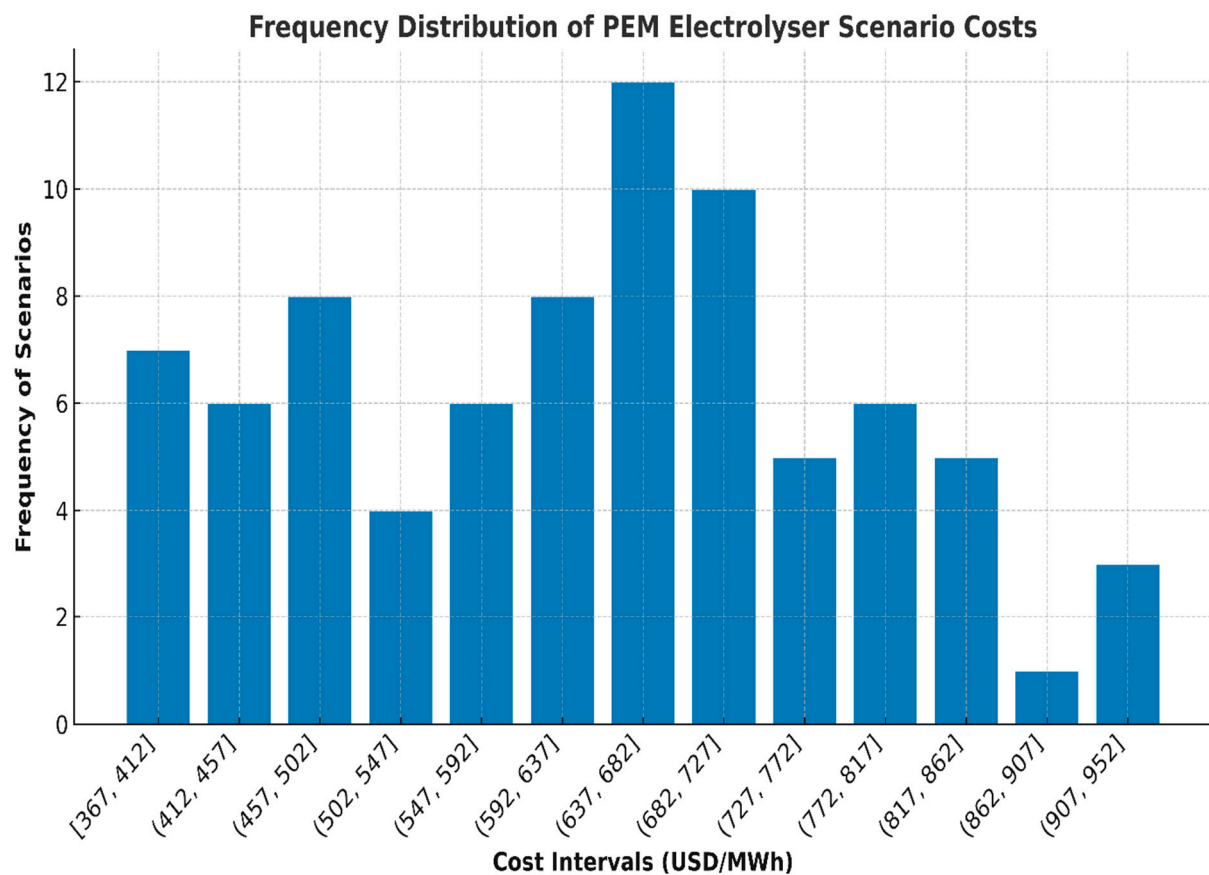


Figure 6. Frequency distribution of cost outcomes for Proton Exchange Membrane (PEM) electrolyser scenarios.

9. Comparative Analysis of AWE and PEM Electrolyser Risk Assessments

The techno-economic risk analysis of alkaline (AWE) and Proton Exchange Membrane (PEM) electrolyzers (Figure 7) highlights clear trade-offs between cost efficiency and technological performance. AWE systems have lower capital costs and simpler designs, making them well-suited for large-scale deployment in regions with abundant land and renewable resources, such as Libya. Their cost outcomes are most sensitive to CAPEX and efficiency, with the lowest-cost scenarios consistently linked to optimal investment and operating parameters. PEM electrolyzers, by contrast, are more compact and technologically advanced but require much higher upfront investment. They also show stronger sensitivity to efficiency and operational conditions, producing a wider range of economic outcomes and greater exposure to input uncertainties. Despite these drawbacks, PEM systems offer advantages in high-density or space-constrained environments. Overall, the choice between AWE and PEM depends on project priorities: AWE favours cost minimisation, while PEM supports performance optimisation. This distinction makes techno-economic risk analysis essential for guiding hydrogen infrastructure planning.

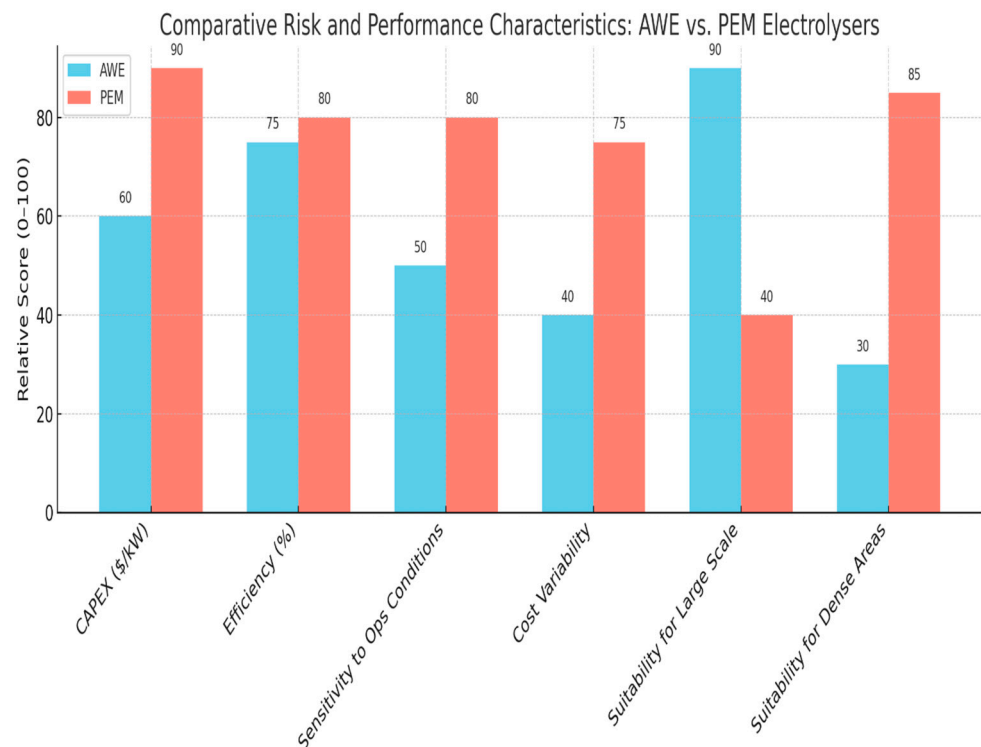


Figure 7. Comparative assessment of AWE and PEM electrolyzers across six key performance and risk dimensions.

10. Environmental Risk Quantification: Land Use, Water Consumption, and CO₂ Mitigation

A robust hydrogen deployment strategy must account for environmental factors as well as techno-economic ones. Key considerations include land footprint, water intensity, and emissions reductions per unit of output. In the case of Libya's large-scale hydrogen farms assessed through TERA, these parameters were quantified using contemporary modelling data and global benchmarks.

Land use differs between technologies. Alkaline Water Electrolysis (AWE) systems require more surface area because of their modular design and supporting infrastructure. Current estimates indicate 5–7 hectares per GW of installed capacity, compared to only 3–4 hectares/GW for Proton Exchange Membrane (PEM) systems [23]. While Libya's vast land availability makes this trade-off manageable, it would be a critical constraint in land-scarce regions.

In terms of water consumption, both electrolyser types use about 9 litres of deionised water per kilogram of hydrogen produced, although this value may increase slightly when considering system-level inefficiencies and purification stages. For example, producing 1 million tonnes of hydrogen annually would require approximately 9 million cubic metres of freshwater, a non-negligible volume in arid zones like North Africa [11].

Avoided CO₂ emissions are among the most compelling benefits. When replacing natural gas-derived hydrogen (grey hydrogen), each kilogram of green hydrogen avoids approximately 9–10 kg of CO₂ emissions. For the 519 GW AWE scenario modelled in this study, this equates to over 72 million tonnes of CO₂ avoided annually in the optimistic scenario, a significant contribution to global decarbonization efforts [24].

11. Lifecycle Emissions Comparison (AWE Vs. PEM)

A cradle-to-gate assessment distinguishes between embedded manufacturing emissions and use-phase impacts determined by the electricity mix. On the manufacturing side,

Proton Exchange Membrane (PEM) stacks carry a lower embedded carbon footprint (about 3.7 t CO₂ per unit) than Alkaline Water Electrolysis (AWE) units (>8.4 t CO₂), reflecting differences in stack design and material composition.

For equivalent installed capacity, AWE systems therefore begin with a higher carbon burden before operation. During operation, however, lifecycle emissions for both technologies are dominated by the carbon intensity of electricity supply. Reported life-cycle assessment (LCA) values range from 1.45 to 6.32 kg CO₂ per kilogram of hydrogen when powered by renewable sources, while displacing grey hydrogen avoids roughly 9–10 kg CO₂ per kilogram.

At the Libyan scale modelled, this translates to more than 72 million tonnes of CO₂ avoided annually under optimistic renewable supply conditions. In summary, AWE exhibits higher embedded emissions, whereas PEM starts with a lower footprint, but both technologies rely on renewable electricity to deliver substantial lifecycle emission reductions.

12. Materials and Recyclability Assessment

From a materials perspective, AWE systems rely mainly on recyclable ferrous metals and nickel-based components with a caustic KOH electrolyte. Steel and nickel have matured recycling routes, while the electrolyte can be neutralised and recovered, and nickel-rich elements safely separated before smelting. These features allow part of AWE's relatively high embedded carbon to be mitigated through high-yield metals recovery at end-of-life.

In contrast, PEM electrolyzers use platinum and iridium catalysts on polymer membranes within a compact balance-of-plant. The platinum-group metals are highly recoverable via hydrometallurgical processes, offering an economically attractive pathway that eases supply chain and embodied-carbon concerns. However, the perfluorinated ionomer membranes are far harder to recycle and require specialised handling, as current recovery methods remain underdeveloped. Other balance-of-plant metals such as stainless steel, aluminium, and copper follow conventional recycling streams.

Overall, AWE benefits from bulk-metal recyclability to offset embodied environmental impacts, while PEM relies heavily on efficient catalyst recovery to minimise lifecycle burdens.

13. Environmental Considerations Within the TERA Framework

While this study primarily focuses on the techno-economic and risk-based evaluation of hydrogen farms, environmental factors remain a core element of the Techno-Economic Environmental Risk Analysis (TERA) framework. Transitioning from fossil-fuel-based electricity to renewable-powered hydrogen production offers substantial benefits. Green hydrogen produced using solar or wind energy can cut lifecycle greenhouse gas (GHG) emissions by 60–90% compared to grey hydrogen from natural gas [25].

Life cycle assessment (LCA) studies further show that electrolysis-based hydrogen generates between 1.45 and 6.32 kg CO₂-equivalent per kilogram, depending on the energy source and system configuration [26].

For hydrogen-fuelled gas turbines, replacing natural gas with hydrogen virtually eliminates direct CO₂ emissions during combustion and reduces upstream emissions from fossil fuel extraction and transport. This supports decarbonisation targets and improves local air quality. Environmental impacts also vary by technology: Proton Exchange Membrane (PEM) electrolyzers have a lower embedded carbon footprint (about 3.7 t CO₂ per unit) compared to Alkaline Water Electrolyzers (AWE), which can exceed 8.4 t CO₂ [24].

AWE systems generally require larger land footprints because of their scale and configuration, but this is manageable in regions such as Libya where land is abundant and ecological pressures are limited. With careful siting and planning, disruption can

be minimised. Large-scale deployment of solar and wind infrastructure, however, may affect ecosystems through habitat loss, soil degradation, and visual impacts. Material sourcing also raises concerns, particularly for PEM systems that rely on platinum and iridium. Extraction and refining of these metals can create environmental harm and social conflict if not managed responsibly.

Furthermore, the large-scale installation of solar and wind infrastructure may disturb local ecosystems through habitat disruption, soil degradation, and visual impacts. Material sourcing is another concern, particularly for PEM systems, which rely on rare and costly materials like platinum and iridium. Their extraction and refinement can lead to environmental degradation and social conflicts if not ethically managed.

14. Influence of Environmental Factors on Risk Assessment

Within the Techno-Economic Environmental Risk Analysis (TERA) framework, environmental factors provide a vital dimension that extends the evaluation beyond cost-effectiveness. Two key metrics—water footprint and CO₂ abatement potential—were integrated to assess sustainability trade-offs across scenarios. Large-scale electrolysis requires significant water input, about 9 litres per kilogram of hydrogen. In arid regions such as North Africa, this creates reliance on desalination or recycling systems, which increase operational complexity and add environmental challenges, including brine disposal and higher energy demand.

Equally important is the CO₂ mitigation potential of green hydrogen. When powered by renewables, hydrogen production can displace grey hydrogen and avoid up to 10 kg of CO₂ per kilogram of output. In the modelled AWE deployment, this translates to more than 72 million tonnes of CO₂ avoided annually, representing a major climate benefit [23]. These factors were integrated into the TERA scoring system, shaping the risk profile of each scenario by embedding ecological feasibility and alignment with global decarbonisation targets.

15. Sensitivity Analysis of Environmental Trade-Offs

Within the TERA framework, environmental dimensions were assessed by examining how land use, water requirements, and CO₂ abatement potential influence the sustainability of large-scale hydrogen farms in Libya. The analysis shows that land requirements are relatively flexible given Libya's vast desert resources: AWE systems need 5–7 hectares per GW compared to 3–4 hectares per GW for PEM. This makes land a less restrictive factor in this case, though it would become a critical constraint in more densely populated or land-scarce regions.

Water consumption is a more sensitive parameter: both AWE and PEM require about 9 litres of purified water per kilogram of hydrogen, meaning that large-scale deployment could strain local water supplies without desalination or recycling systems.

Finally, CO₂ abatement provides the strongest positive environmental trade-off. Each kilogram of green hydrogen displaces roughly 9–10 kg of CO₂ from conventional grey hydrogen, with the modelled AWE deployment avoiding more than 72 million tonnes annually under optimistic scenarios. Taken together, the sensitivity analysis highlights that while land impacts are region-dependent, water availability poses a tangible operational risk, and CO₂ mitigation remains the most consistent environmental benefit.

16. Quantitative Comparison of AWE and PEM Electrolysers for Hydrogen Farms

Table 5 provides a quantitative comparison between Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) technologies across key performance and sustain-

ability indicators. In terms of capital expenditure (CAPEX), AWE systems are generally less expensive, with costs ranging from 600 to 1745 USD/kW, compared to the higher range of 1200 to 2500 USD/kW for PEM. Efficiency levels show some overlap, though PEM can achieve slightly higher upper limits (up to 85%) relative to AWE, which typically operates between 70% and 82%. Land use is another distinguishing factor: AWE installations require larger footprints (5–7 hectares per GW), while PEM offers a more compact design at 3–4 hectares per GW, making it more attractive for space-constrained locations.

Table 5. Quantitative comparison of Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) systems across key techno-economic and environmental indicators.

Indicator	AWE (Alkaline Water Electrolysis)	PEM (Proton Exchange Membrane)
CAPEX (USD/kW)	600–1745	1200–2500
Efficiency (%)	70–82%	65–85%
Land Use (hectares/GW)	5–7	3–4
Water Requirement	~9 L/kg H ₂	~9 L/kg H ₂
CO ₂ Emission Reduction	~9–10 kg CO ₂ avoided per kg H ₂	~9–10 kg CO ₂ avoided per kg H ₂
Embedded Carbon (t CO ₂ /unit)	>8.4	~3.7

Both technologies have similar water requirements, using approximately 9 litres per kilogram of hydrogen produced, which is significant in arid regions where water scarcity may pose a challenge. In terms of environmental performance, both systems deliver comparable CO₂ abatement potential, with each kilogram of hydrogen displacing around 9–10 kg of CO₂ when replacing grey hydrogen. However, their embedded carbon footprints differ: AWE carries a higher manufacturing impact (>8.4 t CO₂ per unit) due to heavier material use, whereas PEM systems exhibit a lower embedded carbon intensity (~3.7 t CO₂ per unit).

Overall, AWE offers clear cost advantages and established scalability, while PEM provides flexibility, higher efficiency potential, and reduced spatial and embedded carbon burdens. These distinctions highlight the trade-offs that must be considered when selecting electrolyser technologies for large-scale hydrogen deployment.

17. Conclusions

This study provides a comprehensive comparative assessment of large-scale hydrogen production using Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) technologies. By evaluating 81 scenarios for each system—varying capital expenditure (CAPEX), efficiency, electricity price, and capacity factor—the analysis identifies clear patterns in cost-effectiveness and operational trade-offs. The results show that AWE, though requiring more land, offers significant cost advantages, especially under conditions of lower CAPEX and higher efficiency. In contrast, PEM systems are more compact and technologically advanced but entail substantially higher financial costs.

The sensitivity analysis highlights CAPEX and efficiency as the most influential drivers of hydrogen production costs for both technologies. Electricity price and capacity factor exert more moderate effects but remain relevant to overall performance. For AWE, CAPEX is the dominant variable, followed by efficiency, while electricity price contributes to a smaller yet noticeable impact. Similarly, in PEM systems, cost outcomes are primarily governed by CAPEX and efficiency, reaffirming their critical role in determining economic feasibility.

Aligning these findings with scenario-based results demonstrates that optimal outcomes consistently emerge from configurations combining low CAPEX with high efficiency. These insights offer practical guidance for policymakers and investors, helping them maximise economic returns while addressing uncertainties in technology deployment and

energy pricing. Ultimately, the choice between AWE and PEM depends on project priorities: AWE favours cost minimisation, while PEM supports performance optimisation. Both approaches contribute to advancing the global transition toward green hydrogen.

Although, this study provides valuable insights into the techno-economic and environmental risks of large-scale hydrogen farms, but several limitations should be acknowledged. First, the modelling relies on scenario-based assumptions for CAPEX, efficiency, electricity cost, and capacity factor. While these values were drawn from the recent literature and market data, they remain sensitive to rapid technological and policy shifts, which may alter the results over time. Second, the analysis does not fully capture dynamic operational effects such as load-following behaviour, degradation profiles, or balance-of-plant efficiency losses, which could influence long-term performance and costs. Third, environmental impacts were considered primarily in terms of land use, water demand, and CO₂ abatement. Broader ecological effects, including biodiversity impacts, social acceptance, and supply chain sustainability, were beyond the scope of this work. Finally, the focus on Libya as a case study limits the generalisability of the results, as local conditions such as grid integration, financing structures, and regulatory frameworks vary significantly across regions.

Future research should address these gaps by integrating real-time operational data, exploring hybrid renewable–electrolyser configurations, and conducting detailed life-cycle assessments that include material sourcing and recycling. Comparative policy analysis across multiple geographies would also enhance the robustness of TERA as a decision-support tool for global hydrogen deployment.

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Nomenclature

TERA	Techno-Economic Risk Analysis
CAPEX	Capital Expenditure (USD/kW or million USD total)
LCOE	Levelized Electricity Cost (USD/MWh)
IEA	International Energy Agency
DOE	U.S. Department of Energy
\$/MWh	Dollars per megawatt-hour

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