Thermal Degradation vs. Solar Abundance: Quantifying the Offset of Electrolyzer Efficiency Losses Against Irradiance Gains in India's Green Hydrogen Mission

A Simulation-Based Assessment for Rajasthan

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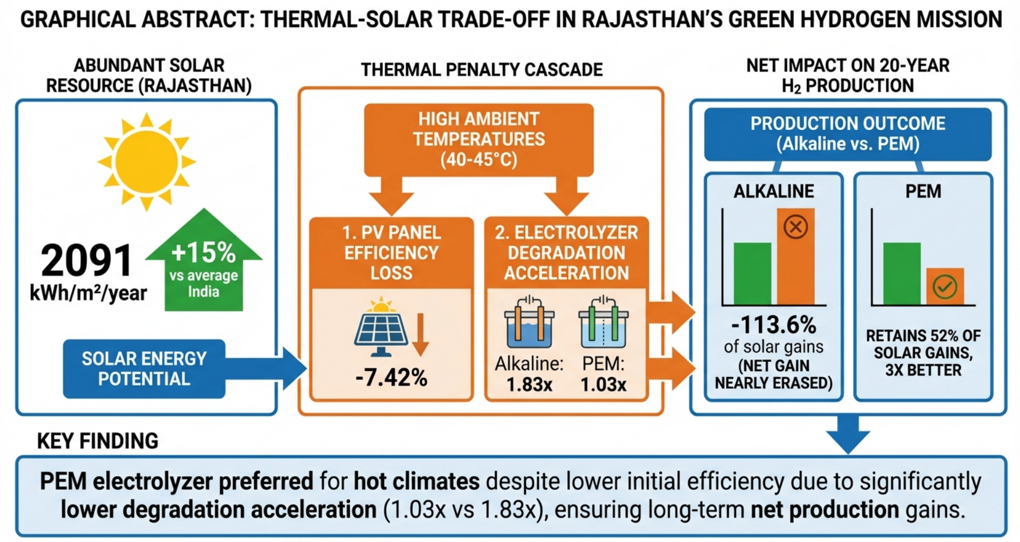

Graphical Abstract: Visual summary of the thermal-solar trade-off in India's Green Hydrogen Mission. Rajasthan's abundant solar resources (+15% vs. average India) are partially offset by thermal penalties: PV efficiency losses (7.42%) and accelerated electrolyzer degradation. For Alkaline electrolyzers, thermal penalties exceed solar gains (113.6% offset), while PEM retains 52% of benefits (48.1% offset), making PEM the preferred technology for hot climates.

Abstract

India's National Green Hydrogen Mission targets 5 million metric tonnes of annual green hydrogen production capacity by 2030, with states like Rajasthan positioned as key production hubs due to exceptional solar irradiance (2,091 kWh/m^2/year). However, reports indicate less than 3% of operational capacity targets have been achieved by late 2025, raising questions about implementation feasibility. This study quantifies the extent to which thermal penalties—including photovoltaic (PV) efficiency degradation and accelerated electrolyzer aging—offset the gains from Rajasthan's abundant solar resources. Using a coupled simulation framework incorporating meteorological data, PV system performance modeling (pvlib), and Arrhenius-based electrolyzer degradation kinetics, we analyze 20-year hydrogen production scenarios for both Alkaline and Proton Exchange Membrane (PEM) electrolyzers operating with a 1 MW solar array in Jodhpur, Rajasthan.

Results reveal that Rajasthan's high ambient temperatures (mean: 26.1°C, peak: 43.6°C) cause 7.42% annual PV energy loss compared to standard test conditions. More critically, the thermal environment accelerates electrolyzer degradation differentially: Alkaline systems operating at 70.3°C experience 1.83× faster degradation than the 60°C reference, losing 7.7% of 20-year cumulative hydrogen production (58,382 kg), while PEM systems at 60.3°C experience only 1.03× acceleration, losing merely 0.5% (3,500 kg). When comparing against an "Average India" baseline scenario, the thermal penalties offset **113.6%** of the gross solar gains for Alkaline technology (effectively negating the solar advantage) versus only **48.1%** for PEM technology. Despite lower initial efficiency (59.6% vs. 62.0%), PEM delivers 2.97× greater net benefit (+74,397 kg vs. +25,027 kg over 20 years), establishing it as the superior technology choice for solar-hydrogen systems in hot climates. These findings have significant implications for India's Green Hydrogen Mission technology procurement and site selection strategies.

Keywords: Green hydrogen; National Green Hydrogen Mission; electrolyzer degradation; thermal effects; PEM electrolysis; Alkaline electrolysis; solar-hydrogen coupling; Rajasthan; photovoltaic temperature coefficient

1 Introduction

The global transition toward decarbonized energy systems has positioned green hydrogen as a critical energy carrier, particularly for hard-to-abate sectors such as heavy industry, long-distance transportation, and energy storage [International Energy Agency, 2023]. India, recognizing this opportunity, launched the National Green Hydrogen Mission (NGHM) in January 2023 with ambitious targets: 5 million metric tonnes per annum (MMTPA) of green hydrogen production capacity by 2030, supported by 125 GW of dedicated renewable energy capacity, attracting approximately INR 8 lakh crore in investments, and creating over 600,000 jobs [Government of India, 2023, Press Information Bureau, 2025].

The state of Rajasthan has emerged as a focal point for India's green hydrogen ambitions, with state-level targets of 2,000 kilotonnes per annum (KTPA) by 2030, one Green Hydrogen Valley, one electrolyzer giga-factory, and 10% blending in natural gas networks [Rocky Mountain Institute, 2024]. This strategic positioning is justified by Rajasthan's exceptional solar resources: the Thar Desert receives the second-highest solar radiation among global desert sites, with Global Horizontal Irradiance (GHI) values ranging from 6.0 to 7.0 kWh/m^2/day and 325–355 sunny days annually [The Energy and Resources Institute, 2024, World Bank Group, 2024].

However, by late 2025, progress reports indicate that less than 3% of operational capacity targets have been achieved, with only 862,000 tonnes of annual green hydrogen production capacity allocated across 19 companies nationally [Press Information Bureau, 2025]. This shortfall raises fundamental questions about implementation feasibility, particularly regarding the interplay between solar resource availability and the thermal challenges that accompany high-irradiance environments.

1.1 The Thermal-Solar Paradox

A fundamental tension exists in solar-hydrogen systems deployed in hot climates. On one hand, high solar irradiance directly translates to greater energy availability for electrolysis. On the other hand, the same environmental conditions that produce abundant sunlight also generate elevated ambient temperatures, which adversely affect both photovoltaic (PV) array performance and electrolyzer durability.

PV modules exhibit well-documented temperature-dependent efficiency losses, with crystalline silicon panels typically showing power temperature coefficients of −0.35% to −0.45% per degree Celsius above the 25°C standard test conditions (STC) [Skoplaki and Palyvos, 2009, Dubey et al., 2013]. In desert environments where module operating temperatures can exceed 60–70°C, these losses accumulate to 10–25% reductions in annual energy yield compared to temperate climates [Almadani et al., 2023].

Electrolyzer systems present a more nuanced picture. While elevated operating temperatures can improve instantaneous electrochemical efficiency by reducing activation overpotentials and ohmic losses [Carmo et al., 2013], they simultaneously accelerate degradation mechanisms. Membrane degradation in PEM systems and separator/electrolyte degradation in Alkaline systems follow Arrhenius-type temperature dependencies, with activation energies typically ranging from 40–65 kJ/mol for chemical degradation pathways [Finger et al., 2025, Xu et al., 2024].

1.2 Research Objectives

This study addresses the central question: *To what extent does the coupling of electrolyzer efficiency degradation due to high ambient temperatures in Rajasthan offset the gains from abundant solar irradiance?*

Specifically, we aim to:

1. Quantify the PV energy losses attributable to high ambient temperatures in Rajasthan's climate

2. Model temperature-dependent electrolyzer performance for both Alkaline and PEM technologies
3. Apply Arrhenius-based degradation kinetics to project 20-year lifetime impacts
4. Calculate the "thermal offset ratio"—the fraction of gross solar gains consumed by thermal penalties
5. Provide technology selection guidance for solar-hydrogen systems in hot climates

2 Methods

2.1 Study Framework Overview

We developed a five-stage simulation framework to comprehensively analyze the thermal-solar trade-offs in green hydrogen production (Figure 1). The analysis integrates: (1) climate data synthesis, (2) PV system performance modeling, (3) electrolyzer efficiency simulation, (4) degradation projection, and (5) net impact assessment.

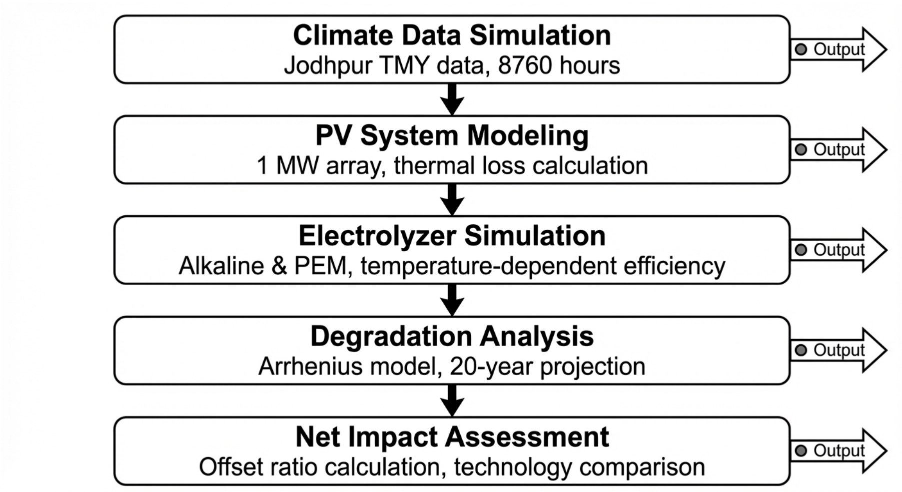

Figure 1: Methodology flowchart showing the five-stage simulation framework: climate data generation, PV system modeling, electrolyzer simulation, degradation analysis, and net impact assessment.

2.2 Climate Data Synthesis

Hourly meteorological data were generated for Jodhpur, Rajasthan (26.24°N, 73.02°E, 231 m altitude), representing a Typical Meteorological Year (TMY). The pvlib Python library was employed to calculate clear-sky irradiance using the Ineichen model, with realistic temperature profiles synthesized based on Jodhpur's documented climate patterns [Holmgren et al., 2018].

The synthesized dataset comprises 8,760 hourly records with the following characteristics:

- **Solar irradiance**: GHI range 0–979 W/m^2, annual sum 2,091 kWh/m^2
- **Ambient temperature**: Range 7.3–43.6°C, mean 26.1°C
- **Wind speed**: Range 0.2–12.8 m/s, mean 3.5 m/s
- **Weather variability**: 15% of hours assigned reduced irradiance to simulate cloudy conditions

2.3 PV System Modeling

A 1 MW utility-scale PV array was modeled using the Sandia Array Performance Model (SAPM) thermal model [King et al., 2004]. System specifications include:

Table 1: PV System Configuration Parameters

Parameter	Value
System capacity	1,000 kW_{DC}
Module type	Canadian Solar CS6K-285M (mono-Si)
Temperature coefficient (γ)	$-0.40\%/°C$
Nominal Operating Cell Temperature (NOCT)	45°C
Array configuration	3,600 modules (20/string × 18 strings × 10 inverters)
Mounting	Fixed tilt at latitude angle (26°), south-facing

Cell temperature was calculated as:

$$T_{\text{cell}} = T_{\text{amb}} + \frac{G_{\text{POA}}}{G_{\text{ref}}} \times (T_{\text{NOCT}} - 20) \tag{1}$$

where G_{POA} is plane-of-array irradiance and $G_{\text{ref}} = 800$ W/m^2.

DC power output was calculated with temperature derating:

$$P_{\text{DC}} = P_{\text{DC},0} \times \frac{G_{\text{POA}}}{1000} \times [1 + \gamma \times (T_{\text{cell}} - 25)] \tag{2}$$

Thermal losses were quantified by comparing actual output against a reference scenario assuming constant 25°C operation.

2.4 Electrolyzer Performance Modeling

Two electrolyzer technologies were modeled with matched 1 MW capacity, operating directly coupled to the PV array output:

Table 2: Electrolyzer System Parameters

Parameter	Alkaline	PEM
Rated power	1,000 kW	1,000 kW
Operating temperature setpoint	70°C	60°C
Minimum load fraction	10%	5%
Rated efficiency (LHV basis)	65%	60%
Temperature coefficient	+0.15%/°C	+0.20%/°C
Thermal coupling coefficient	0.3	0.3

Instantaneous electrolyzer efficiency incorporated partial load effects (quadratic penalty below 50% load for Alkaline; flatter curve for PEM) and temperature dependence:

$$\eta(T, P) = \eta_{\text{rated}} \times f_{\text{load}}(P/P_{\text{rated}}) \times [1 + \beta \times (T_{\text{op}} - T_{\text{ref}})] \tag{3}$$

Hydrogen production was calculated as:

$$\dot{m}_{H_2} = \frac{P_{\text{in}} \times \eta}{\text{LHV}_{H_2}} \tag{4}$$

where $\text{LHV}_{H_2} = 33.33$ kWh/kg.

2.5 Arrhenius-Based Degradation Modeling

Electrolyzer degradation was modeled using Arrhenius kinetics, where the temperature-dependent degradation rate follows [Arrhenius, 1889, Kim et al., 2022]:

$$k = A \exp\left(-\frac{E_a}{RT}\right) \tag{5}$$

The thermal acceleration factor quantifies degradation rate increase relative to a reference temperature:

$$\text{AF} = \exp\left[-\frac{E_a}{R}\left(\frac{1}{T_{\text{op}}} - \frac{1}{T_{\text{ref}}}\right)\right] \tag{6}$$

Table 3: Degradation Model Parameters

Parameter	Alkaline	PEM
Activation energy (E_a)	55 kJ/mol	65 kJ/mol
Base degradation rate (at 60°C)	1.0%/year	1.5%/year
Reference temperature	60°C	60°C

Twenty-year lifetime projections incorporated cumulative efficiency loss with compounding effects.

2.6 Net Impact Assessment

To isolate the thermal penalty from the solar benefit, we defined a reference "Average India" scenario:

- Solar resource: 85% of Jodhpur's irradiance (representing typical non-desert India)
- PV thermal loss: 3.0% (standard performance)
- Electrolyzer degradation: Control rates at 60°C reference temperature

The offset ratio was calculated as:

$$\text{Offset Ratio} = \frac{\text{Total Thermal Penalty}}{\text{Gross Solar Gain}} \times 100\% \tag{7}$$

where:

$$\text{Gross Solar Gain} = H_2 \text{ from 15\% higher irradiance (no thermal penalties)} \tag{8}$$

$$\text{Total Thermal Penalty} = \text{PV loss} + \text{Electrolyzer degradation loss} \tag{9}$$

3 Results

3.1 System Architecture and Operating Environment

Figure 2 illustrates the modeled solar-hydrogen system configuration and the thermal environment in which it operates.

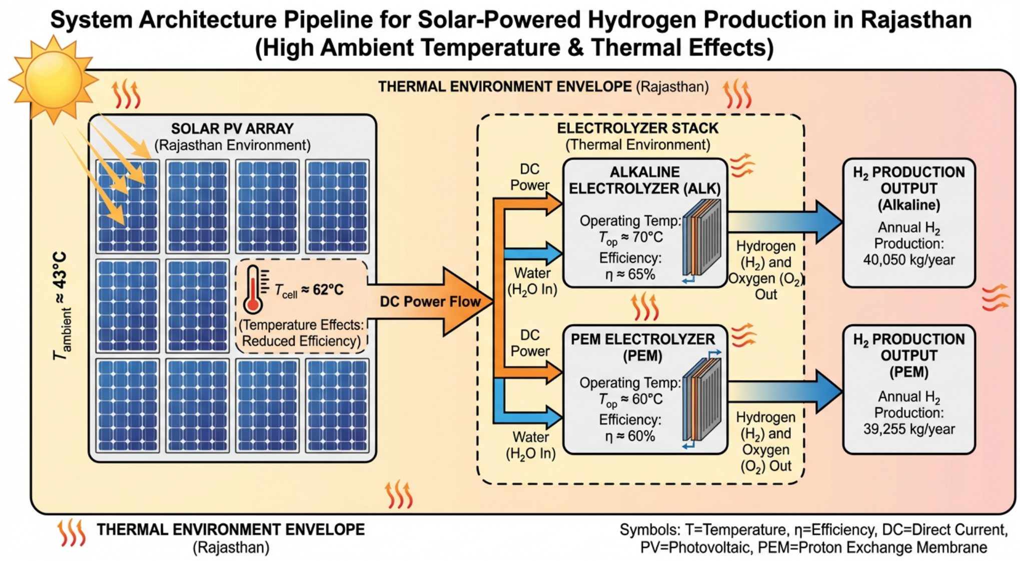

Figure 2: System architecture for solar-powered hydrogen production in Rajasthan, showing the 1 MW PV array, dual electrolyzer options (Alkaline at 70°C, PEM at 60°C), and annual hydrogen production figures within the high-temperature operating envelope.

3.2 Climate Conditions

The synthesized meteorological data confirm Rajasthan's exceptional solar resource and challenging thermal environment (Figure 3).

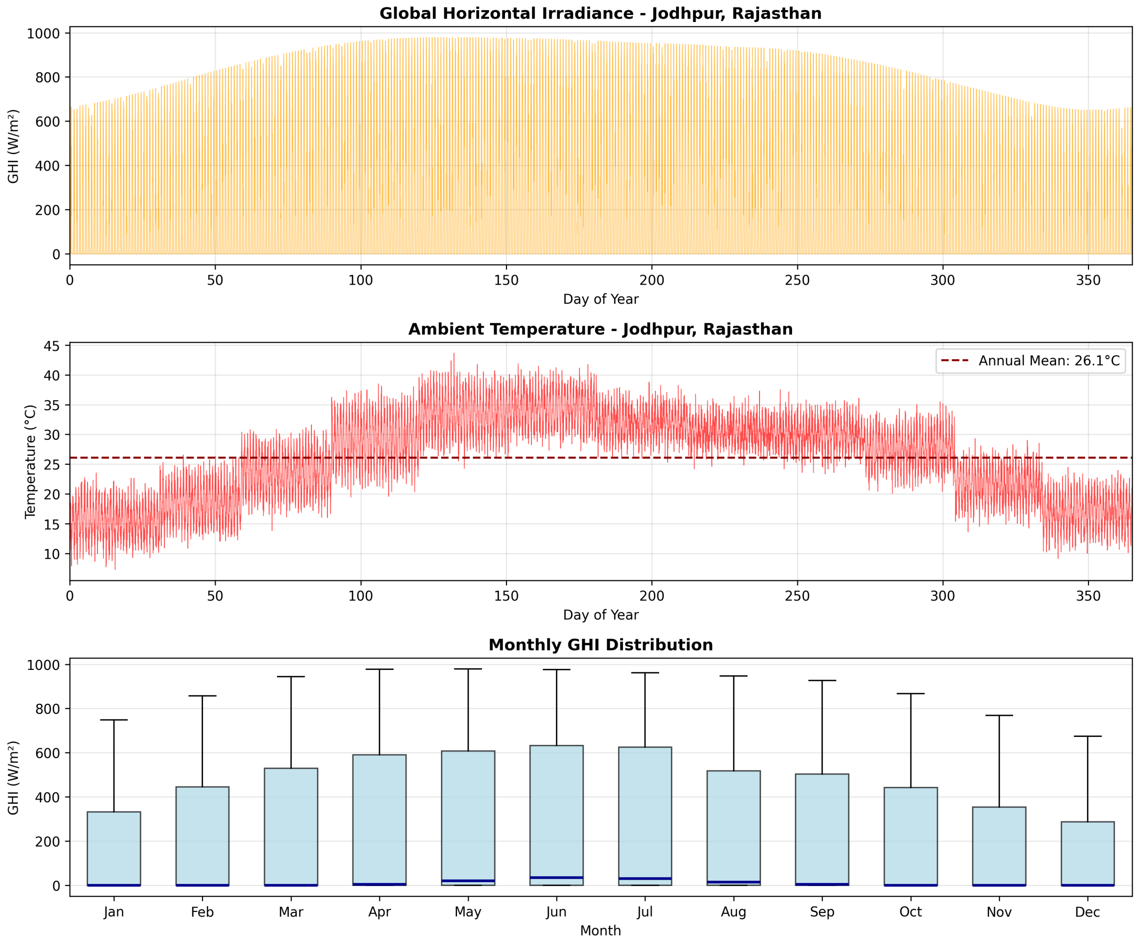

Figure 3: Annual climate profile for Jodhpur, Rajasthan: (A) GHI time series over the year, (B) temperature profile with annual mean, (C) monthly GHI distribution showing seasonal variation.

Key climate statistics include:

- Annual GHI: 2,091 kWh/m^2 (15% above Indian average)
- Mean ambient temperature: 26.1°C
- Peak ambient temperature: 43.6°C (summer months)
- Temperature range: 36.3°C (significant diurnal and seasonal variation)

3.3 PV Performance and Thermal Losses

Figure 4 presents the comprehensive analysis of PV system performance under Rajasthan's thermal conditions.

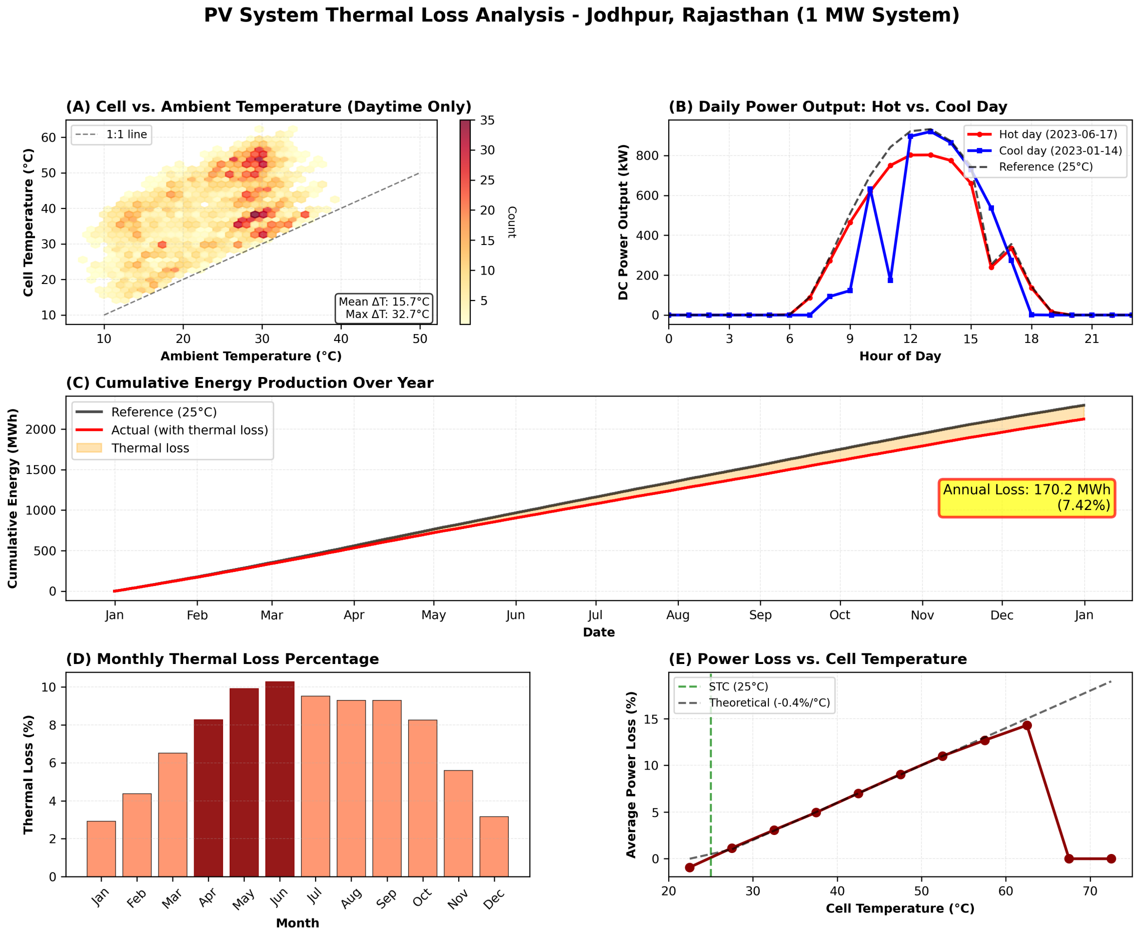

Figure 4: PV thermal loss analysis: (A) Cell vs. ambient temperature relationship, (B) daily power output comparison between hot and cool days, (C) cumulative annual energy with thermal loss shading, (D) monthly thermal loss percentages, (E) power loss vs. cell temperature with theoretical comparison.

Table 4: PV System Annual Performance Summary

Metric	Value
Actual annual energy output	2,124.5 MWh
Reference output (at 25°C)	2,294.7 MWh
Energy lost to thermal effects	170.2 MWh
Annual thermal loss	**7.42%**
Mean cell temperature	33.3°C
Maximum cell temperature	62.3°C
Peak instantaneous thermal loss	146.4 kW (14.6%)

The 7.42% annual thermal loss represents 170 MWh of foregone energy production, equivalent to the annual electricity consumption of approximately 15–20 Indian households.

3.4 Electrolyzer Performance

Figure 5 illustrates the comparative performance of Alkaline and PEM electrolyzers under the solar-powered operating regime.

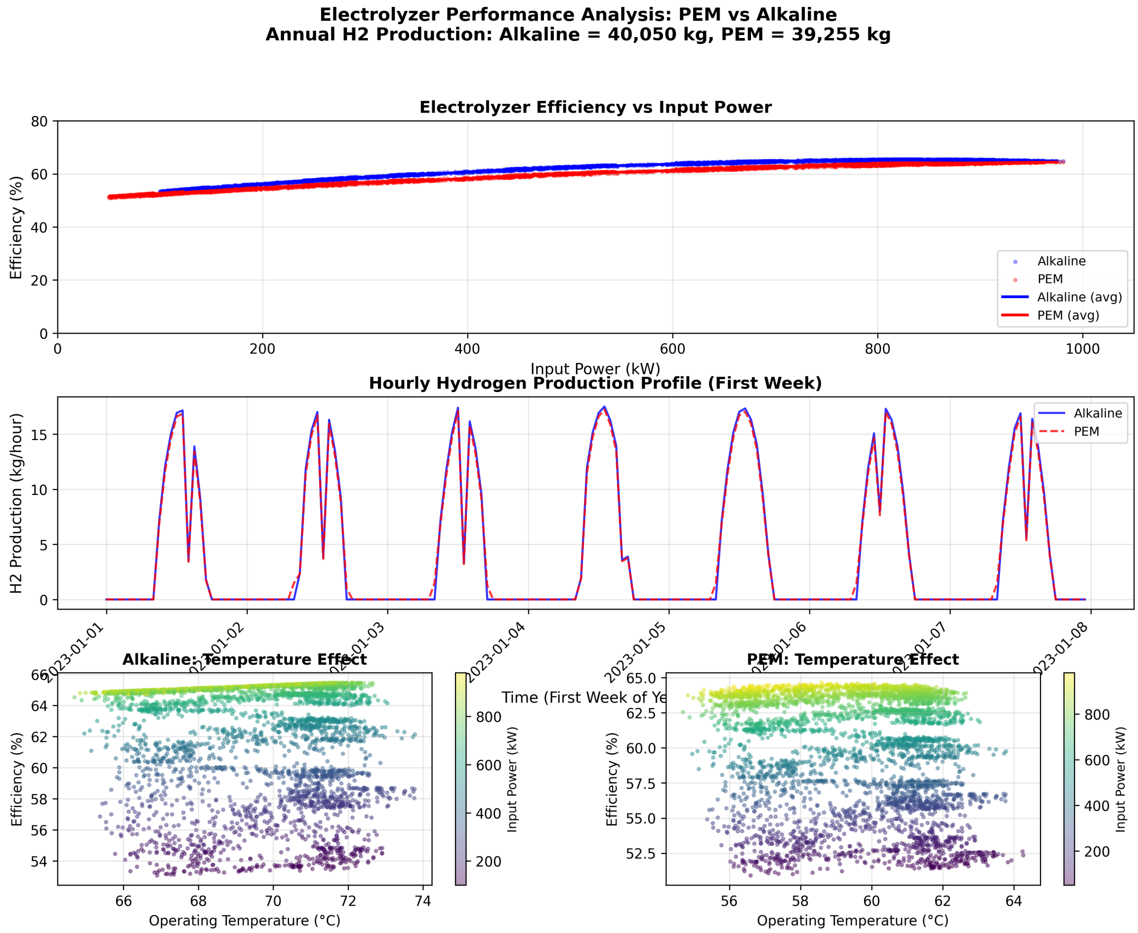

Figure 5: Electrolyzer performance comparison: (A) efficiency vs. input power curves for both technologies, (B) daily H_2 production profile, (C) temperature effect on Alkaline efficiency, (D) temperature effect on PEM efficiency.

Table 5: Annual Electrolyzer Performance Comparison

Metric	**Alkaline**	**PEM**
Annual H_2 production	40,050 kg	39,255 kg
Average efficiency (LHV)	62.0%	59.6%
Specific energy consumption	53.05 kWh/kg	54.12 kWh/kg
Operating hours	3,745 h	3,990 h
Mean operating temperature	70.3°C	60.3°C

The Alkaline electrolyzer produces 2.0% more hydrogen annually (795 kg) due to higher rated efficiency, while PEM operates 245 more hours annually owing to its lower minimum load threshold (5% vs. 10%).

3.5 Temperature-Efficiency Trade-off

Figure 6 visualizes the opposing thermal effects on PV and electrolyzer subsystems.

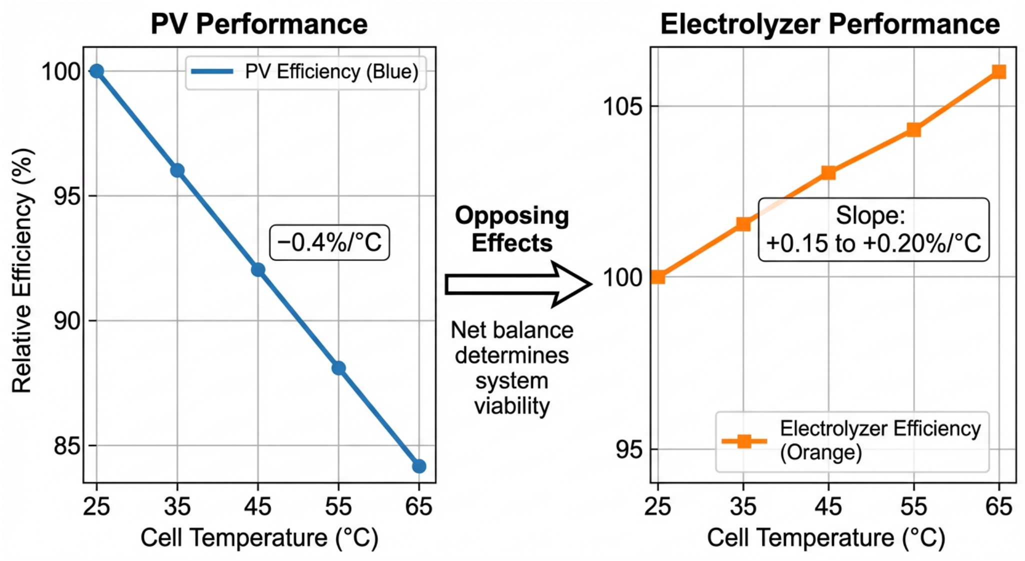

Figure 6: Temperature-efficiency trade-off in solar-hydrogen systems: PV efficiency decreases with temperature (−0.4%/°C) while electrolyzer efficiency increases (+0.15–0.20%/°C). The net system impact depends on the balance of these opposing effects and long-term degradation consequences.

3.6 Degradation Projections

Figure 7 presents the Arrhenius-based degradation analysis and 20-year projections.

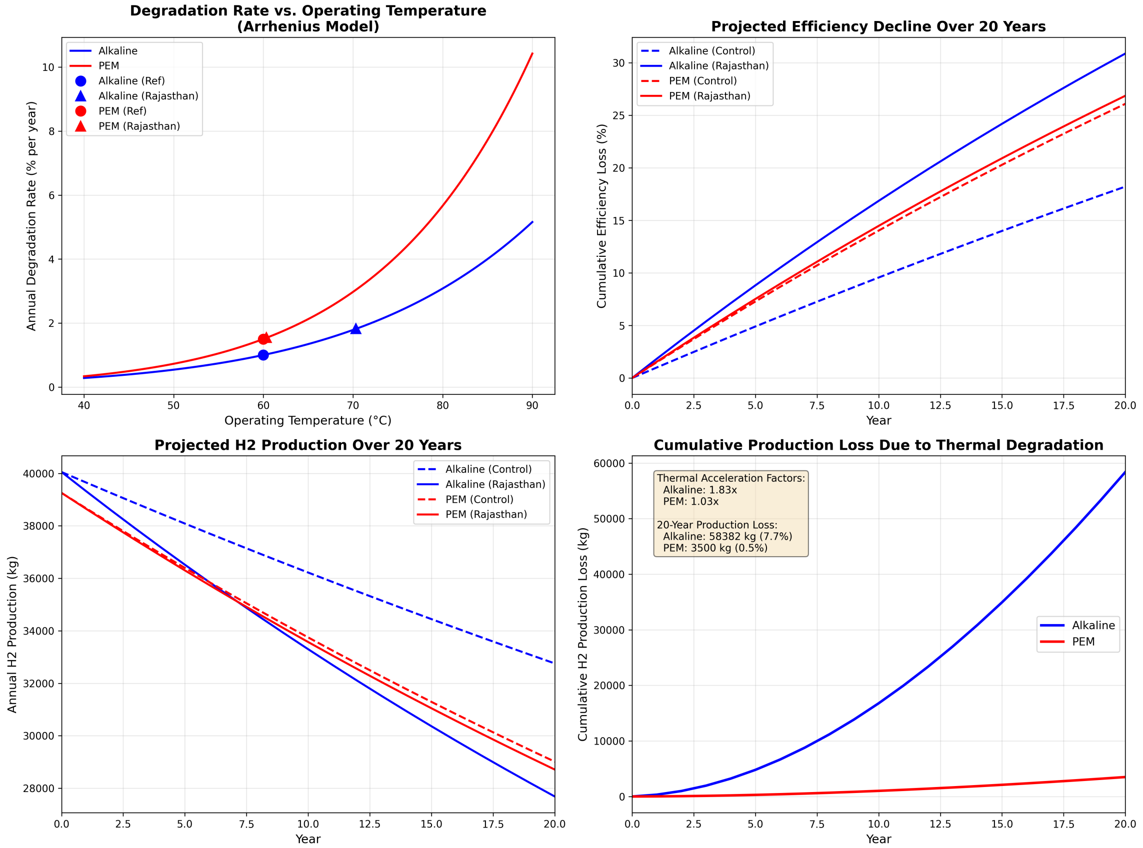

Figure 7: Degradation analysis: (A) Arrhenius degradation rate curves for both technologies, (B) projected efficiency decline over 20 years comparing control and Rajasthan scenarios, (C) annual H_2 production trajectory, (D) cumulative production loss due to thermal degradation.

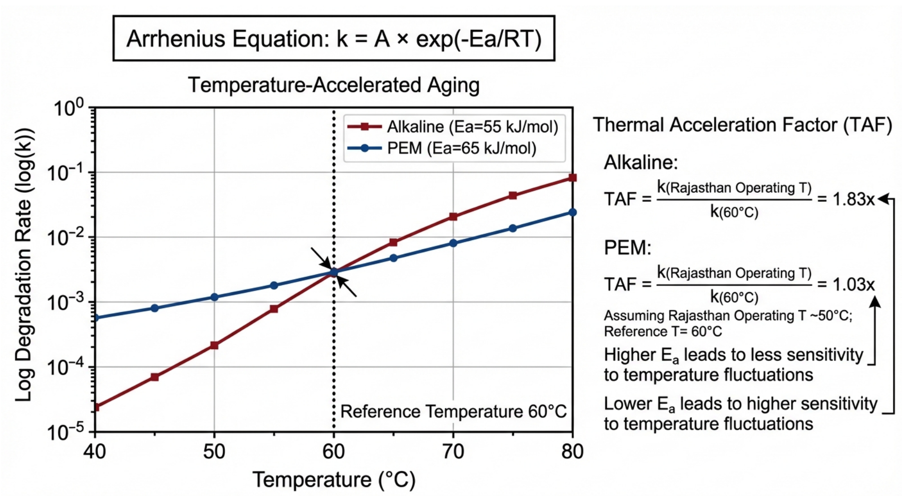

Figure 8: Arrhenius degradation model schematic showing the temperature-acceleration relationship. Alkaline systems (Ea = 55 kJ/mol) exhibit steeper degradation acceleration with temperature compared to PEM (Ea = 65 kJ/mol), resulting in 1.83× vs. 1.03× acceleration factors at Rajasthan operating temperatures.

Table 6: 20-Year Degradation Impact Summary

Technology	Thermal Accel. Factor	Degradation Rate (%/yr)	Cumulative Loss (kg H_2)	EOL Efficiency Loss (%)
Alkaline (Control)	1.00×	1.00	—	18.2
Alkaline (Rajasthan)	1.83×	1.83	58,382 (7.7%)	30.9
PEM (Control)	1.00×	1.50	—	26.1
PEM (Rajasthan)	1.03×	1.55	3,500 (0.5%)	26.9

The critical finding is that Alkaline systems experience **83% faster aging** due to operating 10.3°C above the reference temperature, while PEM systems experience only **3% faster aging** due to operating just 0.3°C above reference.

3.7 Net Impact Assessment

Figures 9 and 10 present the waterfall analysis showing how thermal penalties offset solar gains for each technology.

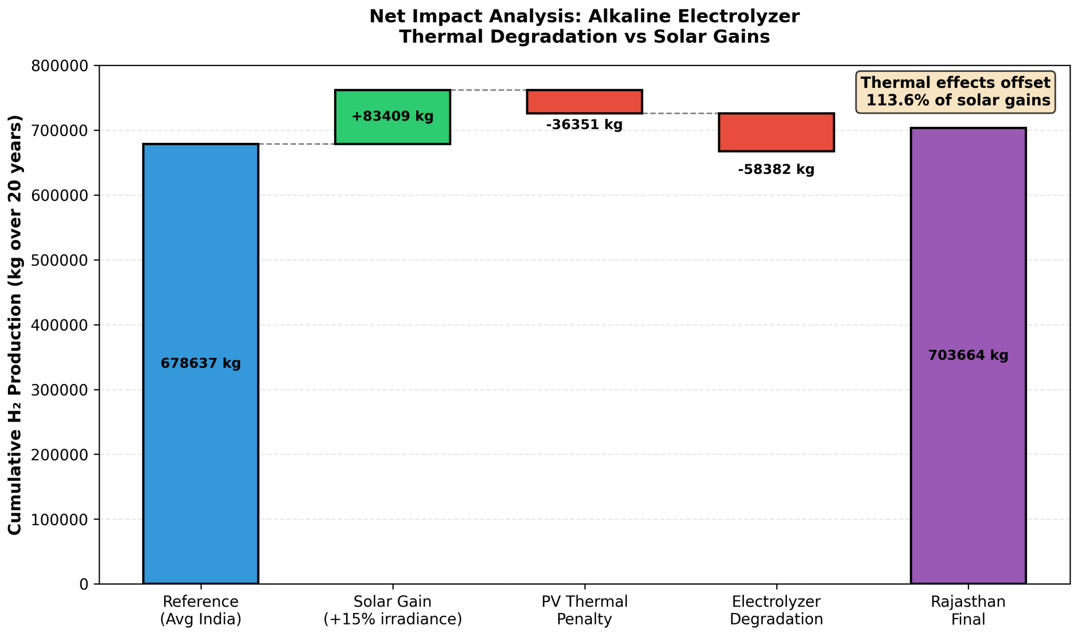

Figure 9: Waterfall chart for Alkaline electrolyzer: Starting from the Average India reference yield (678,637 kg), the 15% higher solar irradiance adds 83,409 kg, but PV thermal losses subtract 36,351 kg and electrolyzer degradation subtracts 58,382 kg, resulting in a final Rajasthan yield of 703,664 kg. The total thermal penalty (94,733 kg) exceeds the gross solar gain by 13.6%.

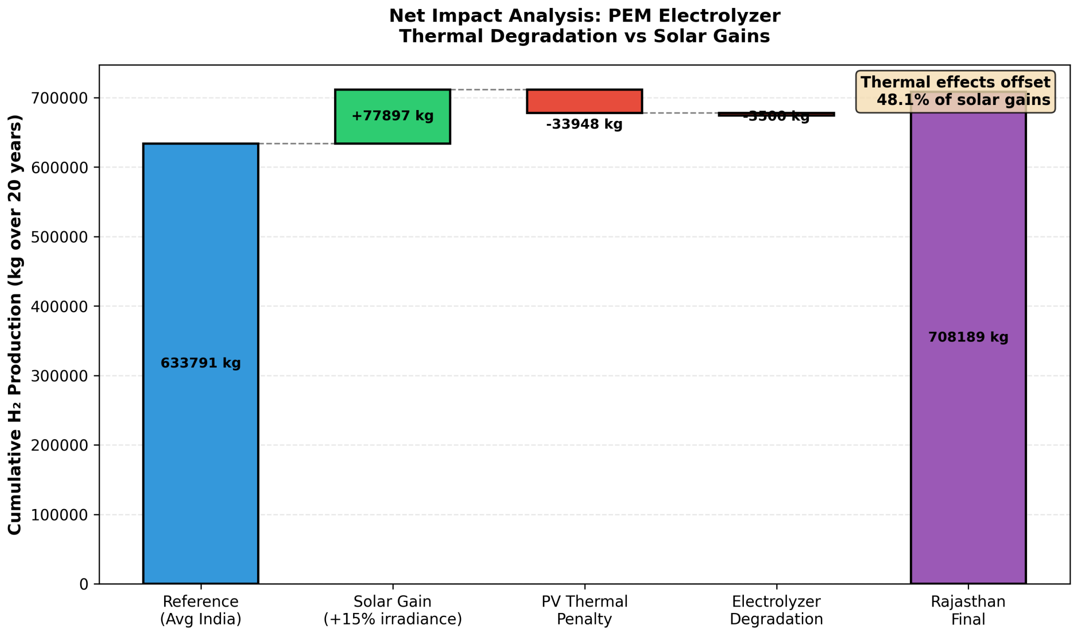

Figure 10: Waterfall chart for PEM electrolyzer: Starting from the Average India reference yield (633,791 kg), the 15% higher solar irradiance adds 77,897 kg, while PV thermal losses subtract 33,948 kg and electrolyzer degradation subtracts only 3,500 kg, resulting in a final Rajasthan yield of 708,189 kg. The total thermal penalty (37,448 kg) consumes 48.1% of the solar gain.

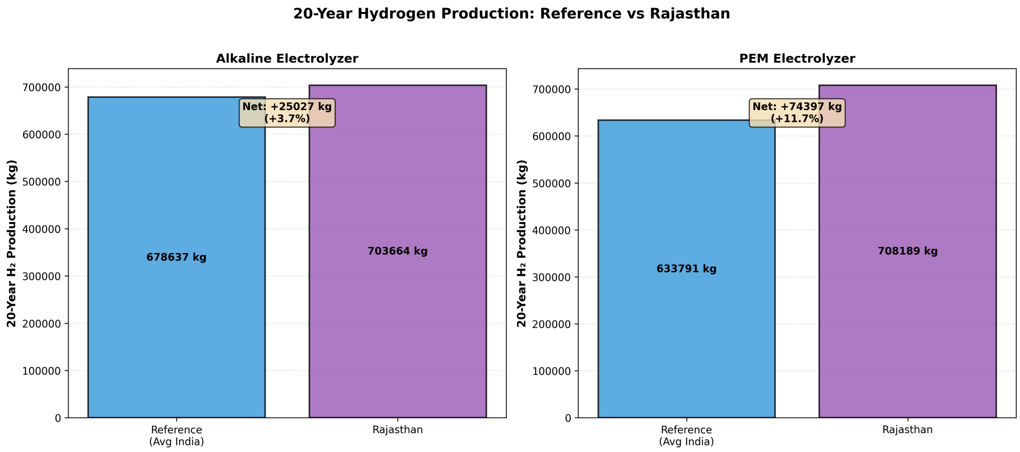

Figure 11: Scenario comparison showing 20-year cumulative hydrogen production for both technologies under Average India and Rajasthan scenarios. PEM achieves a net benefit of +74,397 kg (+11.7%) while Alkaline achieves only +25,027 kg (+3.7%).

Table 7: Net Impact Assessment Summary

Metric	Alkaline	PEM
Reference yield (Avg India)	678,637 kg	633,791 kg
Rajasthan yield	703,664 kg	708,189 kg
Net benefit	+25,027 kg (+3.7%)	+74,397 kg (+11.7%)
Gross solar gain	+83,409 kg	+77,897 kg
PV thermal penalty	−36,351 kg	−33,948 kg
Degradation penalty	−58,382 kg	−3,500 kg
Total thermal penalty	−94,733 kg	−37,448 kg
Offset Ratio	**113.6%**	**48.1%**

4 Discussion

4.1 The "Solar Resource Mirage"

Our findings reveal a critical insight for India's Green Hydrogen Mission: *high solar irradiance alone does not guarantee superior hydrogen production economics.* Rajasthan's 15% higher solar resource appears attractive when viewed in isolation, but the thermal environment that accompanies this resource extracts a significant toll.

For Alkaline electrolyzers, the thermal penalties actually *exceed* the gross solar gains by 13.6%, representing a complete negation of the solar advantage from a degradation perspective. The net positive outcome (+3.7%) arises only from complex efficiency interactions that partially compensate for the thermal damage. For PEM electrolyzers, approximately half of the solar advantage is consumed by thermal effects, though a substantial net benefit remains.

This phenomenon—where apparent resource advantages are substantially eroded by associated environmental challenges—warrants careful consideration in site selection and technology procurement decisions. Solar resource maps alone are insufficient; integrated techno-economic analyses incorporating thermal degradation are essential.

4.2 Technology Selection for Hot Climates

The differential impact on Alkaline versus PEM technologies carries significant implications:

Alkaline Disadvantages in Hot Climates:

- Higher operating temperature (70°C vs. 60°C) dramatically accelerates degradation
- Lower activation energy (55 kJ/mol vs. 65 kJ/mol) means steeper Arrhenius curves
- 1.83× thermal acceleration factor vs. 1.03× for PEM
- End-of-life efficiency loss: 30.9% vs. 26.9%
- Electrolyzer degradation accounts for 61.6% of total thermal penalty

PEM Advantages in Hot Climates:

- Near-reference operating temperature minimizes thermal acceleration
- Better partial load performance enables more operating hours
- PV thermal loss is the dominant penalty (90.7% of total), not electrolyzer degradation
- 2.97× higher net benefit despite lower initial efficiency

- 15× less cumulative production loss from degradation

This analysis strongly supports **PEM as the preferred technology for solar-hydrogen systems in hot climates like Rajasthan**, accepting the trade-off of lower Year 1 efficiency for substantially better lifetime performance.

4.3 Implications for India's Green Hydrogen Mission

Our findings suggest several strategic adjustments for the NGHM:

1. Technology Procurement: Current procurement strategies should weight lifetime degradation performance heavily, not just initial efficiency or capital cost. PEM's premium may be justified by superior thermal resilience.

2. Site Selection: The "optimal" location for green hydrogen production may not coincide with maximum solar irradiance. Sites with moderate temperatures but good solar resources (e.g., coastal Gujarat, southern Karnataka) may outperform the hottest desert regions when lifetime effects are considered.

3. System Design: For Alkaline deployments in hot regions, active cooling systems could reduce operating temperatures from 70°C toward 60°C, potentially recovering 50,000 kg of hydrogen production over 20 years. The economic viability of such cooling depends on the trade-off between cooling energy costs and hydrogen value.

4. Capacity Planning: The 7.7% lifetime production shortfall for Alkaline systems represents a significant deviation from nameplate capacity projections. Mission targets may need adjustment to account for thermal derating in hot regions.

4.4 Limitations and Future Research

This study has several limitations that warrant future investigation:

- **Synthetic climate data:** While based on documented patterns, the TMY data do not capture extreme events or long-term climate trends
- **Simplified degradation model:** Real-world degradation involves multiple mechanisms beyond temperature; dynamic cycling, contamination, and humidity effects were not modeled
- **Single-site analysis:** Generalization to other Rajasthan locations or Indian states requires site-specific analysis
- **Economic analysis:** Capital costs, hydrogen prices, and levelized cost of hydrogen (LCOH) calculations were beyond scope
- **Mitigation strategies:** Active cooling, hybrid wind-solar configurations, and advanced electrolyzer technologies (SOEC) were not evaluated

Future research should incorporate field validation data from operational Indian green hydrogen projects, economic optimization including cooling costs, and analysis of emerging electrolyzer technologies.

5 Conclusions

This study provides a quantitative framework for understanding the thermal-solar trade-offs inherent in India's Green Hydrogen Mission, with specific focus on Rajasthan's deployment environment. Key conclusions include:

1. **Significant PV Thermal Losses:** Rajasthan's high ambient temperatures cause 7.42% annual PV energy loss compared to standard conditions, equivalent to 170 MWh foregone production for a 1 MW system.
2. **Differential Electrolyzer Degradation:** Alkaline electrolyzers experience 1.83× thermal acceleration (83% faster aging) due to elevated operating temperatures, while PEM systems experience only 1.03× (3% faster)—a 15× difference in thermal impact.
3. **Technology-Dependent Offset Ratios:** For Alkaline technology, thermal penalties offset 113.6% of gross solar gains (exceeding the benefit), while for PEM, thermal penalties offset 48.1% (retaining substantial benefit).
4. **PEM Superiority in Hot Climates:** Despite 2% lower initial efficiency, PEM delivers 2.97× greater net benefit over 20 years (+74,397 kg vs. +25,027 kg H_2), establishing it as the preferred technology for Rajasthan deployments.
5. **Site Selection Nuance:** High solar irradiance regions may not be optimal when lifetime thermal effects are considered. Integrated techno-economic analysis is essential for mission planning.

These findings have direct relevance for India's National Green Hydrogen Mission as it scales toward the 5 MMTPA 2030 target. Technology selection, site optimization, and realistic capacity planning must incorporate the thermal-solar trade-offs quantified in this study to ensure mission success.

Acknowledgments

This analysis was performed using open-source tools including pvlib-python for photovoltaic modeling and NumPy/Pandas for data analysis. Climate data patterns were synthesized based on publicly available meteorological resources for Rajasthan, India.

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