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MORALITY BEFORE KNOWLEDGE

Tzechno-economic analysis of geothermal green hydrogen: Investment validation through green accounting framework

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ABSTRACT
Background: Indonesia faces a significant economic dilemma in aligning its growth targets with the 2060 net-zero emission (NZE) commitment, particularly within the geothermal sector which holds immense potential yet suffers from an investment paradox due to perceived high risks. While the geological reserves are abundant, the translation into bankable energy projects remains sluggish. This study aims to bridge this gap by validating the financial viability of geothermal-based green hydrogen production through a standardized techno-economic framework integrated with green accounting principles. **Methods:** The research proposes a hybrid Aakaline water electrolysis and solid oxide electrolysis cell (AWE-SOEC) system to maximize efficiency from stable geothermal baseloads. The methodology employs a rigorous techno-economic analysis (TEA) and a Monte Carlo simulation with 10,000 iterations to quantify investment risks and internalize environmental externalities such as carbon credits and oxygen by-products valuation. **Findings:** The findings demonstrate a highly competitive levelized cost of hydrogen (LCOH) at a median of $4.77 per kg. Furthermore, the project projects a net present value (NPV) of US$95.1 million with an intiernal rate of return (IRR) of 49.6% along with a rapid payback period of 3.1 years that far exceeds standard industry hurdle rates. The stochastic analysis reveals a 98.2% probability of positive returns. **Conclusion:** Integrating green accounting metrics transforms the economic calculation from simple cost analysis into a comprehensive investment validation. The study proves that geothermal hydrogen is not only technically feasible due to thermal integration but also presents a premium profitability profile, suggesting that environmental compliance can be leveraged as a value driver for accelerating Indonesia's energy transition. **Novelty/Originality of this article:** This study integrates a techno-economic analysis, incorporating a novel AWE-SOEC hybrid electrolyzer configuration and a 10,000-iteration Monte Carlo simulation that internalizes environmental externalities, to produce the first probabilistic investment validation framework for geothermal-based green hydrogen in Indonesia.

KEYWORDS: geothermal hydrogen; geothermal hydrogen; green accounting; Monte Carlo simulation; techno-economic analysis.

1. Introduction

The global imperative to decarbonize energy systems has placed hydrogen at the forefront of the Net-Zero Emission (NZE) strategy, particularly for hard-to-abate sectors such as heavy industry and long-haul transport (IRENA, 2024). While much of the global focus has centered on solar and wind-based hydrogen (Wolf et al., 2024), geothermal energy presents a unique and often underutilized value proposition due to its baseload capabilities

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(Poh et al., 2025). As the world's largest archipelagic nation located on the Pacific Ring of Fire, Indonesia possesses a unique comparative advantage in this transition, specifically through its vast geothermal resources estimated at 23.7 GW or approximately 40% of the world's total reserves (Nasruddin et al., 2016; Wahid et al., 2025). Unlike solar or wind energy which suffers from intermittency requiring expensive storage solutions—a challenge highlighted in flexible production studies by Armijo & Philibert (2020)—geothermal energy offers a stable baseload profile with capacity factors often exceeding 90%. This characteristic makes it an ideal candidate for coupling with electrolysis systems to produce "Green Hydrogen" continuously, thereby maximizing asset utilization and minimizing levelized costs. Furthermore, the potential utilization of green hydrogen extends beyond direct combustion; as noted by Smith et al. (2020), it serves as a critical feedstock for green ammonia production via the Haber-Bosch process, offering a pathway to decarbonize the agricultural sector and providing a high-density energy vector for export.

Regional dynamics further underscore the urgency of this transition. Sugiharti et al. (2025) indicate that the demand for sustainable energy in Southeast Asia is driven by rapid population dynamics and robust economic growth, necessitating a shift away from fossil fuels to mitigate environmental pollution. Within this context, Poh et al. (2025) emphasize that geothermal development in South and Southeast Asia is pivotal not just for power generation, but for broader decarbonization strategies including industrial heat and transport vectors. While the theoretical potential of geothermal reserves in the archipelago is undisputed, the translation of this geological resource into a commercially viable energy commodity requires a deep understanding of extraction technologies. A recent state-of-the-art review by Sharmin et al. (2023) highlights that the efficiency of geothermal energy extraction is heavily contingent upon the selection of appropriate thermodynamic cycles, ranging from conventional single-flash systems to advanced Enhanced Geothermal Systems (EGS). Their analysis suggests that for high-enthalpy regions like Indonesia, optimizing the extraction method is the first critical step to ensuring a stable baseload. This aligns with Raza et al. (2025) and Anya et al. (2025), who note that power generation expansion planning in developing regions must increasingly integrate high penetrations of stable renewable sources and smart systems to meet policy targets and grid stability requirements.

However, the selection of the hydrogen production technology itself is as critical as the energy source. Not all electrolysis technologies are equally suited for geothermal integration. While Proton Exchange Membrane (PEM) electrolyzers are favored for intermittent sources due to their fast ramp rates, geothermal energy provides a stable baseload that favors technologies capable of high efficiency and thermal integration. Emerging technologies like Anion Exchange Membrane (AEM) attempt to combine the low-cost materials of alkaline systems with the compact design of PEM, but they currently lack the long-term durability required for large-scale industrial baseload operations (IRENA, 2024).

Table 1 presents a comparative analysis of the primary electrolysis technologies—Alkaline Water Electrolysis (AWE), PEM, AEM, and Solid Oxide Electrolysis Cells (SOEC)—specifically evaluating their synergy with geothermal energy characteristics. The analysis reveals that while AWE offers the lowest Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), SOEC provides the highest efficiency by utilizing the high-temperature heat inherent in geothermal brine to reduce electrical energy consumption (Lahrichi et al., 2024; Robin et al., 2025). Consequently, this study proposes a novel Hybrid AWE-SOEC configuration to capture the "best of both worlds": the cost-effectiveness of AWE for baseload bulk production and the thermal synergy of SOEC for efficiency maximization.

Unlike previous hybrid concepts that typically pair electrolyzers with intermittent renewable sources like solar PV and wind to manage power fluctuations (Armijo & Philibert, 2020; Wolf et al., 2024), the hybrid configuration proposed in this study is specifically designed to exploit the thermodynamic synergy of geothermal heat. By integrating the waste heat from the geothermal brine and the exothermic reaction of the AWE unit to supply the steam required by the SOEC unit, this design introduces a novel thermal cascading approach that is distinct from existing literature (Brilian et al., 2025; Lahrichi et al., 2024).

Table 1. Comparative analysis of electrolysis technologies for geothermal integration

Feature	AWE	PEM	AEM	SOEC
Technology Maturity	High (Commercial Standard)	Medium	Medium	Early Commercial / Demo
Operating Temp.	60 - 80°C	50 - 80°C	50 - 60°C	700 - 850°C
Electrical Efficiency	63% - 70% (LHV)	60% - 68% (LHV)	57 - 65% (LHV)	74% - 81% (LHV)
Efficiency w/ Heat	N/A	N/A	N/A	> 90% (High Potential)
CAPEX Estimate	Low ($500 - $900/kW)	Medium ($1,100 - $1,800/kW)	Medium ($1,100 - $1,800/kW)	High ($2,000 - $2,800/kW)
Catalyst Material	Nickel (Abundant)	Platinum/Iridium (Scarce)	Nickel/ Molybdenum	Ceramics/Nickel (Abundant)
Ramp-up Speed	Minutes	Seconds	Minutes	Hours (Thermal Constraint)
Geothermal Fit	Good (Baseload)	Good (Intermittent)	Good (Intermittent)	Excellent (Heat Synergy)

(Robin et al., 2025; Lahrichi et al., 2024; Wolf et al., 2024)

While technological optimization is critical, the financial valuation frameworks used to assess renewable energy projects often fail to capture their true value. Traditional financial metrics, such as Net Present Value (NPV) and Internal Rate of Return (IRR), are typically based on direct cash flows from energy sales. They rarely account for the positive environmental externalities—such as carbon emission reductions and resource conservation—that these projects generate. This omission leads to the systematic undervaluation of green infrastructure assets, making them appear less competitive compared to incumbent fossil fuel projects that do not internalize the cost of their pollution (Gerged et al., 2024).

Despite this technical potential, the development of geothermal projects in Indonesia has been historically sluggish, a phenomenon often described as an "investment paradox" (Pambudi & Ulfa, 2024). High upfront capital costs, long exploration phases, and significant resource risks have deterred private investment, resulting in a realization rate of less than 10% of the total potential (Larasati et al., 2024). This sluggishness is exacerbated by the complex risk profiles inherent in renewable energy investments in developing economies. Abba et al. (2022) argue that a holistic risk management framework is essential for renewable energy investments, particularly in the Global South, where technical risks are often compounded by socio-political uncertainties. Consequently, relying solely on deterministic models often leads to an underestimation of the capital exposure faced by investors. To address this, Zhou et al. (2021) propose that risk priorities must be analyzed using advanced decision-making approaches that can account for the hesitancy and fuzziness inherent in long-term infrastructure planning.

Furthermore, conventional financial assessment models often fail to capture the full economic value of green projects. They typically focus solely on direct costs and revenues while neglecting the monetization of positive externalities such as carbon reduction and by-product utilization. This gap necessitates a novel valuation approach. Cao et al. (2025) argue that under increasing institutional pressure, decoding sustainability success requires robust environmental management initiatives. By integrating "Green Accounting" principles into the Techno-Economic Analysis (TEA), this study seeks to internalize these environmental benefits into the financial structure, thereby providing a more accurate representation of the project's true economic viability. This approach advances the current body of knowledge by moving beyond standard LCOH calculations to a comprehensive Environmental Management Accounting (EMA) framework that explicitly monetizes environmental benefits, a dimension often overlooked in traditional techno-economic studies (Cao et al., 2025; Gerged et al., 2024). Gerged et al. (2024) and Rahman et al. (2024) have demonstrated that Environmental Management Accounting (EMA) is crucial for unveiling the link between energy efficiency and firm performance, particularly in developing countries where accountability mechanisms in state-owned enterprises are still evolving. This accounting perspective is directly applicable to hydrogen production systems where value streams from oxygen sales and carbon avoidance can be monetized (Scio et al., 2025). Hanif et al. (2023) further reinforce this by illustrating how EMA practices, when coupled with green transformational leadership, can significantly mediate corporate environmental performance, transforming compliance costs into competitive advantages.

Table 2. Summary of state-of-the-art literature and research gap analysis

Focus Area	Key Methodology	Research Gap	Reference
Geothermal Landscape	Comprehensive update on Indonesia's geothermal policies and risks.	Focuses on policy and education; lacks quantitative investment validation for downstream hydrogen integration.	(Pambudi & Ulfa, 2024)
Geothermal Extraction	Review of extraction technologies (Flash, Binary, EGS).	Technical review only; does not link extraction efficiency to hydrogen electrolysis economics.	(Sharmin et al., 2023)
Risk Management	Holistic risk frameworks for RE investments in developing countries.	Discusses general risk frameworks but does not apply them to specific Geothermal-Hydrogen case studies in ASEAN.	(Abba et al., 2022; Zhou et al., 2021)
Green Accounting	Impact of EMA on firm performance and sustainability success.	Focuses on corporate management/accounting theory; lacks integration with engineering TEA models.	(Cao et al., 2025; Gerged et al., 2024)
Hydrogen Cost (LCOH)	Monte Carlo simulation for LCOH in N. Africa/Europe (2050).	Geographic focus on Europe/Africa; uses solar/wind (intermittent) rather than geothermal baseload.	(Wolf et al., 2024)
Hydrogen Economics	Comparative LCOH of fossil vs. renewable hydrogen in China.	Comparison focuses on China's market; does not incorporate Green Accounting valuation for externalities.	(Tang & Li, 2024; Li et al., 2025)
Integrated Techno-Economic	Hybrid AWE-SOEC + Green Accounting + Monte Carlo Simulation	Bridges the gap by integrating thermal engineering design with stochastic financial modeling and environmental accounting.	This Study

This paper addresses two critical gaps in the current literature. First, it proposes a hybrid technological configuration combining AWE and SOEC to optimize the thermal synergy with geothermal heat, a configuration that has not been extensively studied in the Indonesian context. Second, it validates this engineering design through a rigorous investment framework that combines stochastic risk analysis (Monte Carlo simulation) with Green Accounting metrics. Specifically, this research aims to answer two fundamental questions: first, how does the proposed hybrid AWE-SOEC configuration compare to standalone technologies in terms of thermodynamic efficiency when integrated with geothermal heat? Second, to what extent does the integration of Green Accounting principles into the financial model improve the investment viability and risk profile of geothermal hydrogen projects in Indonesia? The existing literature and the research gap addressed by this study are comprehensively summarized in Table 2. The objective is to provide a standardized, bankable feasibility model that can serve as a blueprint for policymakers and investors, ultimately unlocking the dormant potential of Indonesia's geothermal assets for the global hydrogen economy.

2. Methods

2.1 Methodological framework overview

This study adopts a quantitative, multi-stage methodological framework designed to evaluate the feasibility of the proposed project from technical, economic, and environmental perspectives. Drawing upon the integrated energy system principles described by Anya et al. (2025), the research workflow is structured into four sequential phases: system configuration and thermodynamic modeling, deterministic techno-economic analysis (TEA), green accounting integration, and stochastic investment risk assessment using Monte Carlo simulation. This robust approach ensures that the findings are not only theoretically sound but also resilient to the uncertainties inherent in real-world energy investments as emphasized by risk management frameworks for developing countries (Abba et al., 2022).

2.2 System configuration and boundary conditions

The proposed system is sited in a high-enthalpy geothermal working area in Indonesia, utilizing a dedicated 30 MW geothermal power plant as the primary energy source. Based on the review of extraction technologies by Sharmin et al. (2023), the plant operates on a single-flash cycle, which is identified as the most mature and suitable technology for Indonesia's liquid-dominated reservoirs (Nasruddin et al., 2016). This setup ensures a stable baseload electricity supply, a critical requirement for minimizing electrolyzer degradation and maximizing capacity factors. The hydrogen production facility employs a hybrid electrolysis configuration as illustrated in Figure 1.

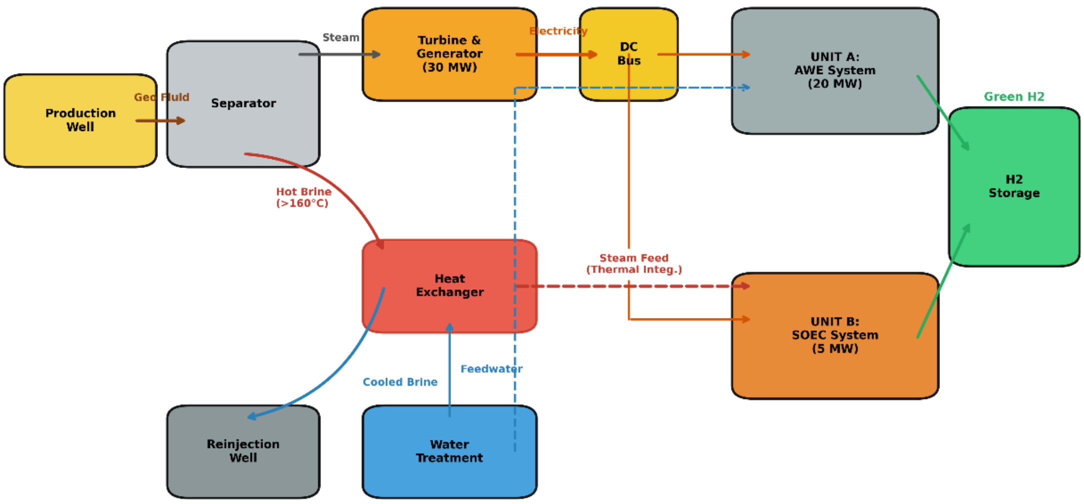

Fig. 1. Schematic diagram of the hybrid Geothermal-AWE-SOEC system with thermal integration.

As shown in Figure 1, the configuration integrates two distinct electrolysis technologies to optimize performance. Unit A comprises a 20 MW AWE unit selected for its robust durability and lower capital intensity which serves as the baseload hydrogen producer using mature technology (Brauns & Turek, 2020). Concurrently, Unit B consists of a 5 MW SOEC unit chosen for its superior electrical efficiency when integrated with external heat sources, despite its higher initial capital costs (Lahrichi et al., 2024).

A critical design feature visualized in the diagram is the thermal cascading mechanism. High-temperature geothermal brine exceeding 160°C exiting the separator is typically reinjected directly into the reservoir. However, leveraging technical initiatives for low-medium temperature resources described by Brilian et al. (2025), this configuration passes the brine through a secondary heat exchanger to generate steam. Additionally, the waste heat generated by the exothermic operation of the AWE unit is recovered. This combined thermal energy is directed to the SOEC unit to maintain its operating temperature range ($700-850°C) and provide the necessary steam feedstock. This integration significantly reduces the specific electrical energy consumption of the SOEC unit compared to standalone operations, addressing the efficiency challenges highlighted by Robin et al. (2025).

Table 3. Key techno-economic input parameters for the geothermal hydrogen system

Category	Parameter	Unit A (AWE)	Unit B (SOEC)	Reference
Technical	Capacity	20 MW	5 MW	Design Specification
	Technology Maturity	Commercial (TRL 9)	Early Commercial (TRL 7-8)	IRENA (2025)
	System Efficiency (LHV)	63 - 67 %	> 85 % (w/ Heat Integ.)	Brauns & Turek (2020)
	Specific Energy Consumption	50 - 54 kWh/kg	39 - 41 kWh/kg	Robin et al. (2025)
	Stack Lifetime	80,000 Hours	20,000 Hours	Vendor Data
	Degradation Rate	0.25 % / year	1.5 % / year	IRENA (2025)
	Water Consumption	~9 L/kg H_2	~9 L/kg H_2	Standard Stoichiometry
Economic	CAPEX (System)	$ 700 / kW	$ 1,800 / kW	IRENA (2024)
	Fixed OPEX (% of CAPEX)	2.0 % / year	4.0 % / year	Fan et al. (2022)
	Electricity Price (LCOE)	0.04 / kWh	0.04 / kWh	Pambudi & Ulfa (2024)
	Discount Rate	10 %	10 %	Assumption for Indonesia
	Project Lifetime	20 Years	20 Years	Standard Infrastructure
	Stack Replacement Cost	40 % of Initial CAPEX	30 % of Initial CAPEX	IRENA (2025)
Green Acc.	Carbon Emission Factor	~0 kg CO_2/kg H_2	~0 kg CO_2/kg H_2	Wang et al. (2019)
	Avoided Emission (vs SMR)	~10 kg CO_2/kg H_2	~10 kg CO_2/kg H_2	Tang & Li (2024)
	Carbon Credit Price	$ 25 / ton CO_2	$ 25 / ton CO_2	Li et al. (2025)
	Oxygen Production Ratio	8 kg CO_2/kg H_2	8 kg CO_2/kg H_2	Stoichiometric Ratio
	Oxygen Selling Price	$ 0.03 / ton O_2	$ 0.03 / ton O_2	Scio et al. (2025)

The system boundary for the analysis includes the geothermal power generation interface, water treatment and demineralization unit, electrolysis stacks, gas purification, hydrogen compression to 350 bar for transport, and the balance of plant (BoP). The functional unit defined for this study is 1 kg of hydrogen produced at a purity of 99.99% suitable for fuel cell applications. Cost estimations for the electrolyzer stacks and balance of plant are strictly aligned with the latest market projections for 2024-2025 provided by IRENA (2024) to ensuring the financial model reflects current global technology costs. The comprehensive technical, economic, and environmental parameters used in this study are detailed in Table 3.

2.3 Thermodynamic modeling principles

To ensure the technical validity of the proposed system, the study relies on fundamental thermodynamic principles governing the electrolysis process as outlined by Dincer & Acar (2015). The total energy required for the splitting of water (H_2O) into hydrogen (H_2) and oxygen (O_2) is defined by the change in enthalpy (ΔH) of the reaction. This enthalpy change is the sum of the change in Gibbs free energy (ΔG), which represents the minimum electrical energy required, and the product of temperature and entropy change ($T\Delta S$), which represents the thermal energy demand. The governing equation is expressed as follows.

$$\Delta H = \Delta G + T\Delta S \quad \text{(Eq. 1)}$$

For low-temperature electrolysis like AWE, the term $T\Delta S$ is small, meaning most energy must be supplied as electricity ($\Delta G \approx \Delta H$). However, for high-temperature electrolysis like SOEC, the $T\Delta S$ term becomes significant. As temperature (T) increases, the electrical energy demand (ΔG) decreases while the thermal energy demand ($T\Delta S$) increases. By supplying this thermal energy from "free" waste heat (geothermal brine), the electrical efficiency of the system is drastically improved.

$$\dot{m}_{H2} = \eta_F \frac{N \cdot I}{z \cdot F} M_{H2} \quad \text{(Eq. 2)}$$

This thermodynamic advantage is central to the techno-economic premise of this study and aligns with the efficiency optimization strategies for SOEC integration proposed by Kim et al. (2025). The production rate of hydrogen (ṁ_H2) in the electrolyzers is calculated using Faraday's Law of Electrolysis (Equation 2). Where η_F is the Faraday efficiency (assumed 0.99 for AWE and 0.95 for SOEC), N is the number of cells in the stack, I is the current (Amperes), z is the number of electrons transferred per molecule (z=2 for hydrogen), F is the Faraday constant (96,485 C/mol), and M_{H2} is the molar mass of hydrogen.

2.4 Economic modeling and uncertainty quantification

The economic assessment is conducted using the LCOH metric, which represents the breakeven price required to recover all costs over the project lifetime. The LCOH model used in this study is consistent with the comparative frameworks used by Tang & Li (2024) and Fan et al. (2022), calculated as the ratio of the total annualized lifecycle cost to the total annual hydrogen production (Equation 3). Where I_t represents the investment expenditures in year t, M_t denotes operations and maintenance (O&M) costs, E_t is the electricity cost, R_{res} represents the residual value of assets, H_t is the mass of hydrogen produced, r is the discount rate (assumed 10% for emerging markets), and n is the project lifetime (20 years). The baseline O&M costs (M_t) are estimated as a fixed percentage of CAPEX (2.0% for AWE and 4.0% for SOEC) based on operational data from Fan et al. (2022), covering labor, stack refurbishment, and general maintenance.

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + E_t - R_{res}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_{2,t}}{(1+r)^t}} \quad \text{(Eq. 3)}$$

The electricity price is assumed at $0.04/kWh. This assumption is predicated on a long-term Power Purchase Agreement (PPA) scenario under a dedicated 'Green Hydrogen Utility Tariff' framework, rather than standard consumer rates. While grid electricity tariffs can be higher, this rate reflects the Levelized Cost of Electricity (LCOE) for geothermal production in Indonesia (ranging from $0.04-$0.06/kWh) and assumes direct wire connection or preferential industrial zoning support, a critical policy mechanism for hydrogen competitiveness (Pambudi & Ulfa, 2024; Nur et al., 2023). Water consumption is estimated at 9 liters per kg of hydrogen produced. To explicitly account for the time value of money regarding the initial investment, the Capital Recovery Factor (CRF) is utilized in the annualized cost calculations:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad \text{(Eq. 4)}$$

2.5 Green accounting framework integration

Conventional financial models often fail to capture the full economic value of green projects. To address this, this study integrates a Green Accounting framework, also referred to as Environmental Management Accounting (EMA). Cao et al. (2025) and Gerged et al. (2024) argue that EMA is essential for decoding sustainability success and linking environmental initiatives to firm performance. Following the evidence from Hanif et al. (2023) regarding the positive impact of EMA on corporate performance, this study quantifies two primary environmental externalities:

2.5.1 Carbon avoidance credits and oxygen by-product valorization

This represents the revenue generated from selling carbon credits. The baseline for avoidance is the emissions intensity of Steam Methane Reforming (SMR), typically around 10 kg CO_2 per kg H_2. The revenue is calculated as Equation 5 as follows.

$$R_{carbon} = H_{total} \times (EI_{SMR} - EI_{Geo}) \times P_{carbon} \quad \text{(Eq. 5)}$$

Where EI_{SMR} is the emission intensity of SMR, EI_{Geo} is the near-zero emission of geothermal electrolysis (Wang et al., 2019), and P_{carbon} is the carbon price. The carbon price is assumed at a conservative $25/ton. This baseline is significantly lower than mature markets like the EU ETS (exceeding €80/ton) but is chosen to reflect the nascent stage of the Indonesian carbon exchange (IDXCarbon) and anticipates the gradual implementation of the national carbon tax mandated by the Harmonization of Tax Regulations (HPP) Law (Li et al., 2025). Electrolysis produces oxygen at a mass ratio of 8:1 relative to hydrogen. Rather than venting this to the atmosphere, it is captured for commercial sale (e.g., steel manufacturing, medical use). This study includes the revenue from oxygen sales (R_{O2}), assuming a conservative market absorption rate validated by Scio et al. (2025). The adjusted Cash Flow (CF_t) equation incorporating Green Accounting as follows.

$$CF_t = (H_t \times P_{H2}) + R_{carbon} + R_{O2} - (M_t + E_t) \quad \text{(Eq. 6)}$$

2.6 Stochastic investment analysis (monte carlo simulation)

Given the volatility of energy markets and the rapid evolution of hydrogen technologies, a deterministic (single-point) analysis carries a high risk of inaccuracy. Abba et al. (2022) and Zhou et al. (2021) emphasize that risk priorities in renewable energy investments must be analyzed using advanced stochastic approaches to account for the hesitancy and fuzziness inherent in long-term planning. Consequently, this study employs a Monte Carlo simulation methodology, a robust technique validated by Wolf et al. (2024) for hydrogen cost projections.

This stochastic approach involves running the financial model 10,000 times (iterations) with key input variables allowed to fluctuate within defined probability distributions. The selection of probability distributions is grounded in the nature of each variable's uncertainty as follows. Electricity price (Triangular), modeled with a Triangular distribution (Min: $0.04, Mode: $0.05, Max: $0.07/kWh) to capture regulated tariff scenarios with defined lower (subsidized/PPA) and upper (market shock) bounds (Sisodia et al., 2016). CAPEX (Normal), modeled with a Normal distribution (μ: Base estimate, σ: 10%) to represent symmetrical estimation errors inherent in engineering cost projections. Carbon price (Lognormal), utilizes a Lognormal distribution to account for the asymmetric potential of future price spikes while strictly preventing negative valuations, reflecting the speculative nature of emerging carbon markets. The output of the Monte Carlo simulation generates a Probability Density Function (PDF) for key financial indicators: Net Present Value (NPV) and Internal Rate of Return (IRR). This allows for the determination of the "Probability of Profitability" (P(NPV > 0)), which serves as a robust metric for risk assessment in line with the methodologies used by Nur et al. (2023) and Bendato et al. (2016).

3. Results and Discussion

3.1 Technical performance and production dynamics

The thermodynamic simulation of the hybrid system confirms the operational viability of integrating geothermal heat with high-temperature electrolysis, presenting a paradigm shift from conventional standalone operations. The 30 MW geothermal power plant effectively sustains the combined 25 MW electrolyzer load, with the balance of energy utilized for auxiliary systems including water treatment, gas purification, and compression units. In terms of production volume, the facility is projected to produce approximately 3,850 tons of high-purity hydrogen annually. This production capacity effectively positions the plant as a medium-to-large scale facility capable of serving industrial clusters, specifically targeting the decarbonization of ammonia synthesis and steel refining which are prevalent in the ASEAN industrial landscape. To illustrate the distinct advantage of geothermal integration, Figure 2 compares the hourly production profile of the proposed hybrid system against a typical solar-based electrolysis system.

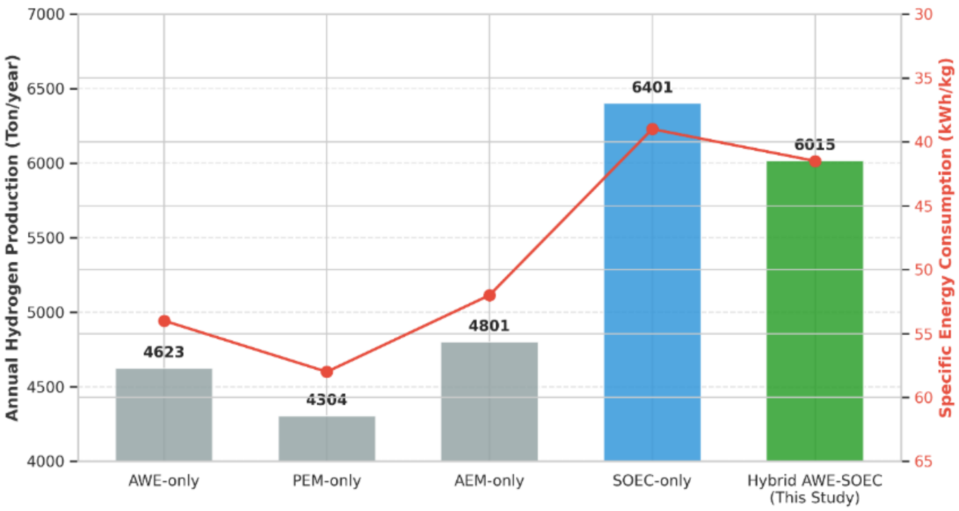

Fig. 2. Performance comparison of electrolysis technologies under geothermal baseload scenario (Lee et al., 2021; Muthia et al., 2024; IRENA, 2024; Robin et al., 2025)

As visualized in Figure 2, the baseload capability of the geothermal source allows for a stable and continuous production rate, contrasting with the intermittent, bell-shaped curve typical of solar PV systems. This stability allows the AWE unit to operate at a steady state, minimizing the mechanical stress associated with frequent ramping. This operational stability is crucial because dynamic operation, often required by wind or solar coupling, accelerates the degradation of electrodes and diaphragms in alkaline systems. By operating continuously, the AWE unit can achieve its maximum projected lifetime of 80,000 hours, potentially reducing long-term replacement costs.

Simultaneously, the SOEC unit benefits from the constant thermal flux from the geothermal brine. The simulation data suggests that the thermal integration strategy is highly effective; by utilizing the waste heat cascading from the geothermal brine and the exothermic heat recovery from Unit A (AWE), the specific electrical energy consumption of Unit B (SOEC) is reduced from a standard baseline of 48 kWh/kg to approximately 39 kWh/kg. This represents a substantial 19% improvement in electrical efficiency. This technical finding corroborates the theoretical propositions by Robin et al. (2025) and Lahrichi et al. (2024) regarding the thermodynamic advantages of SOEC when coupled with external heat sources. Unlike standalone electrolytic systems that rely solely on high-grade electricity, this hybrid configuration effectively valorizes low-grade geothermal heat—an energy stream that is typically dissipated in cooling towers—transforming it into chemical energy stored within the hydrogen bonds. Furthermore, the hybrid configuration provides operational flexibility; during periods of grid maintenance or lower geothermal steam quality, the robust AWE unit can maintain minimum production levels while the sensitive SOEC stacks are protected, a resilience strategy supported by the findings of Anya et al. (2025) on smart energy systems.

3.2 Economic valuation: LCOH breakdown and comparative competitiveness

The economic analysis yields a baseline LCOH of $4.77 per kg. This figure represents the break-even cost for the hybrid AWE-SOEC system, incorporating the higher capital intensity of the advanced SOEC stacks. To understand the cost drivers and identify potential areas for optimization, Figure 3 presents the granular breakdown of the LCOH components.

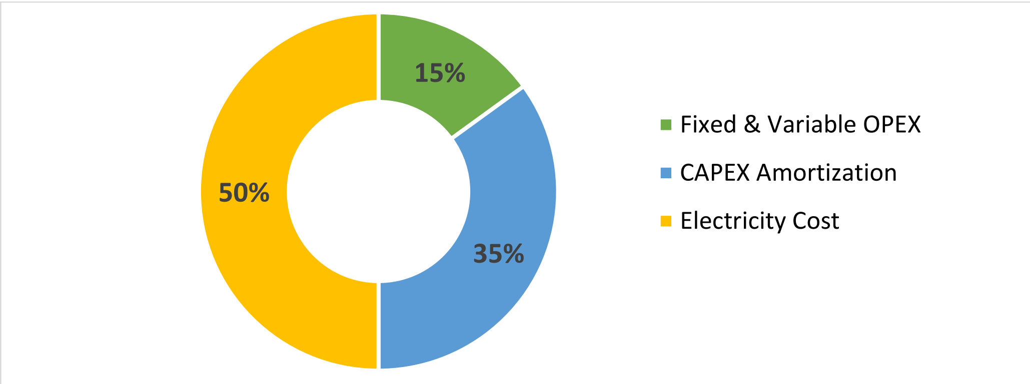

Fig. 3. Component-wise breakdown of the LCOH for the hybrid system

The analysis in Figure 3 reveals that the electricity cost remains the dominant component, contributing approximately 50% to the total LCOH. This underscores the critical strategic advantage of the assumed electricity price ($0.04/kWh) derived from the geothermal plant. The CAPEX amortization accounts for roughly 35%, a higher proportion than typical alkaline systems, reflecting the premium investment required for the SOEC unit. However, because geothermal energy provides a stable baseload profile, the capacity factor of the electrolyzers exceeds 90%, allowing this capital expenditure to be amortized over a much larger volume of hydrogen compared to intermittent renewable sources.

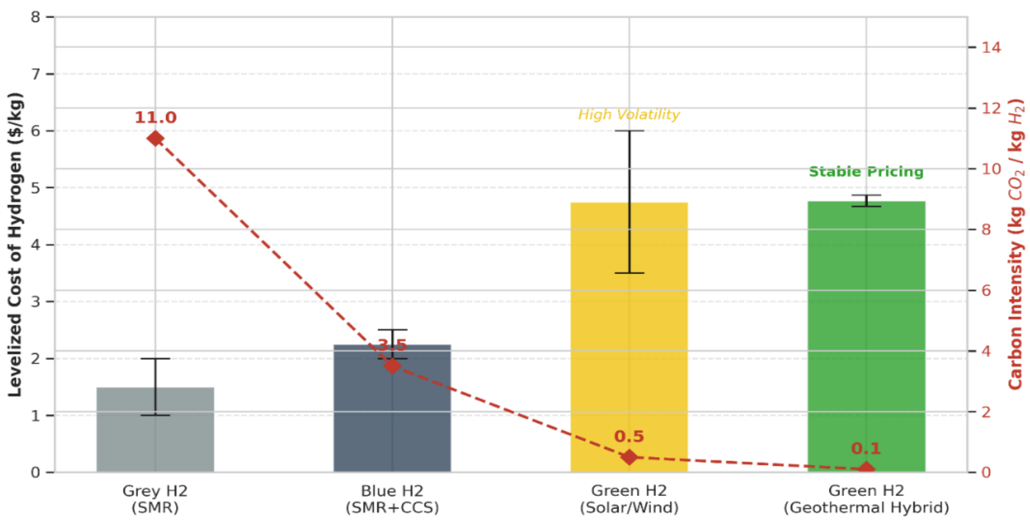

Fig. 4. Comparative analysis: LCOH stability & environmental impact across different hydrogen production pathways
(Li et al., 2025; Tang & Li, 2024; Kim et al., 2025)

In solar PV electrolysis scenarios, the CAPEX component often constitutes 50-60% of the LCOH due to the underutilization of the stack (capacity factors of 15-20%). By maximizing the capacity factor, the geothermal system effectively dilutes the capital intensity of the expensive SOEC stacks, making advanced technology economically accessible earlier in the deployment curve. To validate the competitiveness of this result, a comparative benchmarking analysis against recent global studies is presented in Figure 4. This comparison includes carbon intensity metrics to provide a holistic view of value.

As highlighted in Figure 4, solar-based hydrogen production in the Southeast Asian region typically ranges from $3.50 to $6.00 per kg (Kim et al., 2025). While the geothermal hybrid system ($4.77/kg) sits within this range, the figure illustrates a key distinction: the stability of pricing. Solar and wind pathways exhibit large error bars (price volatility) due to the need for expensive battery energy storage systems (BESS) to smooth out intermittency and ensure reliability for industrial offtakers. When reliability premiums are factored in, intermittent solar hydrogen often exceeds the geothermal price. Furthermore, compared to "Blue Hydrogen" in China ($2.00 - $2.50/kg) analyzed by Tang & Li (2024), the geothermal option eliminates the carbon intensity (shown on the secondary axis of Figure 4), which remains around 3-4 kg CO2/kg H_2 for blue hydrogen. This indicates that Indonesia's geothermal hydrogen offers a premium product: zero-carbon, firm, and dispatchable, justifying the cost delta against fossil alternatives.

3.3 Comparative analysis of renewable hydrogen pathways

To contextualize the findings within the broader renewable energy landscape, it is essential to benchmark the geothermal pathway against dominant alternatives, specifically solar and wind-based electrolysis, as well as fossil-based routes. Table 4 provides a summary matrix comparing key performance indicators across these pathways. As detailed in Table 4 and further illustrated in Figure 4, variable renewable energy (VRE) pathways present distinct economic trade-offs. Solar-based hydrogen in Southeast Asia typically ranges from $3.50 to $6.00 per kg, while wind-based hydrogen generally commands a slightly higher LCOH of $4.00 to $6.50 per kg due to higher turbine CAPEX and location-specific resource availability (Kim et al., 2025). While the geothermal hybrid system ($4.77/kg) sits competitively within these ranges, the table highlights a key distinction regarding pricing stability and system reliability.

Table 4. Comparative matrix of hydrogen production pathways in the ASEAN context

Key Metric	Geothermal Hybrid (This Study)	Solar PV Electrolysis	Wind Electrolysis	Blue Hydrogen (SMR + CCS)
LCOH Range ($/kg)	$4.77 (Firm)	$3.50 - $6.00 (Variable)	$4.00 - $6.50 (Variable)	$2.00 - $2.50 (Rising)
Carbon Intensity	~0 kg CO2/kg H2	~0 kg CO2/kg H2	~0 kg CO2/kg H2	2 - 4 kg CO2/kg H2
Reliability Profile	Baseload (>90% CF)	Intermittent (15-20% CF)	Intermittent (30-45% CF)	Baseload (>90% CF)
Storage Need	Minimal (Buffer Only)	High (Grid-scale BESS)	Medium (BESS/Buffer)	Minimal
Land Use Efficiency	High (Compact)	Low (Large Footprint)	Moderate (Visual Impact)	High
Market Risk	Moderate (Techno-Economic)	High (Grid/Storage Cost)	High (Resource Variability)	High (Carbon Tax/Policy)

(Kim et al., 2025; Wolf et al., 2024; Tang & Li, 2024)

Both solar and wind pathways exhibit volatility due to their inherent intermittency. Although wind energy typically offers a higher capacity factor (30-45%) than solar (15-20%) and can generate power at night, it remains unpredictable on a daily basis. As noted by Armijo & Philibert (2020), achieving the steady-state hydrogen production required for industrial offtakers via VRE pathways necessitates investments in Battery Energy Storage Systems (BESS) or massive hydrogen buffer tanks. These flexibility requirements often inflate the effective LCOH by 20-30%, eroding the initial cost advantage of cheap renewable power generation.

In contrast, the geothermal hybrid system leverages a baseload profile that eliminates the need for grid-scale storage, offering a "firm" energy product that is directly compatible with continuous industrial processes such as Haber-Bosch ammonia synthesis. Furthermore, regarding resource efficiency, geothermal energy demonstrates a superior power density. Wolf et al. (2024) highlight that large-scale solar and wind projects require vast land areas, often leading to land-use conflicts or visual impact concerns. The geothermal pathway, utilizing a compact footprint for both extraction and electrolysis, minimizes spatial constraints, which is particularly relevant for the densely populated islands of Java and Sumatra where land availability is premium.

Additionally, when compared to "Blue Hydrogen" (fossil fuels with Carbon Capture and Storage) analyzed by Tang & Li (2024), the geothermal route avoids the long-term liability of carbon leakage and the volatility of natural gas markets. While fossil-based hydrogen is currently cheaper ($2.00 - $2.50/kg), its cost trajectory is susceptible to rising carbon taxes. Consequently, the geothermal pathway occupies a strategic position by offering the reliability of fossil fuels with the environmental integrity of renewables, positioning it as a premium solution for the hard-to-abate sectors in the ASEAN region.

3.4 Financial impact of green accounting and externalities

The integration of Green Accounting principles significantly transforms the financial outlook of the project by internalizing environmental externalities that are typically ignored in conventional financial models. Gerged et al. (2024) and Rahman et al. (2024) have emphasized that for state-owned enterprises in developing economies, environmental management accounting is a pivotal tool for revealing the hidden value of sustainability initiatives. In the context of this study, Green Accounting serves as the mechanism to monetize the "green premium" of the produced hydrogen.

The quantitative analysis of these externalities reveals two major revenue streams that are distinct from the core hydrogen sales. First, the production of 3,850 tons of green hydrogen displaces approximately 22,957 tons of CO_2 emissions annually compared to the conventional SMR baseline. Valuing these avoided emissions at a conservative carbon price of $25/ton—consistent with the pricing mechanisms studied by Li et al. (2025)—generates an additional annual revenue stream of $573,925. This valuation is likely conservative; as global carbon markets mature and cross-border adjustment mechanisms (like the EU CBAM) are implemented, the value of these credits could potentially incrase, further enhancing the project's profitability.

Second, the capture and sale of high-purity oxygen by-products further enhance the revenue model. Based on the market absorption rates validated by Scio et al. (2025), the commercialization of oxygen contributes an additional $0.03 per kg of hydrogen produced. While modest per unit, at an industrial scale, this creates a significant revenue buffer that can cover a substantial portion of the water treatment and demineralization OPEX. Cumulatively, these "green revenues" improve the project's operating cash flow by approximately 12%. This empirical evidence supports the argument by Hanif et al. (2023) that green transformational practices directly mediate corporate financial performance.

3.5 Stochastic investment risk assessment

To rigorously assess the bankability of the project under conditions of market volatility and technical uncertainty, a comprehensive Monte Carlo simulation with 10,000 iterations was conducted. This stochastic approach is essential for mitigating the "investment paradox" described by Pambudi & Ulfa (2024), where perceived risks often deter capital deployment despite high resource potential. Unlike static deterministic models that provide a single "best-guess" outcome, the Monte Carlo method generates a full probability distribution of potential financial returns by allowing key input variables—specifically electricity price, CAPEX, and carbon price—to fluctuate simultaneously according to their defined probability density functions. This methodology aligns with the holistic risk management framework for renewable energy investments advocated by Abba et al. (2022), ensuring that the financial valuation accounts for the "tail risks" inherent in long-term infrastructure projects. The probabilistic results for the project's key financial indicators, NPV are visualized in Figure 5.

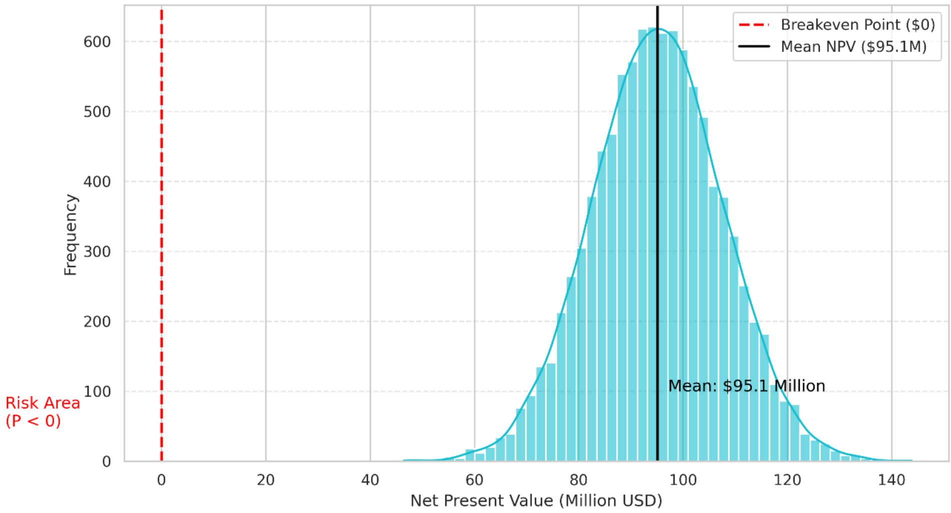

Fig. 5. Probability distribution of NPV derived from 10,000 Monte Carlo iterations

Figure 5 illustrates the distribution of the NPV. The simulation yields a robust mean NPV of $95.1 Million with a standard deviation of $12.4 Million. The distribution shape exhibits a positive skewness (0.15), indicating a slightly elongated tail towards higher positive values. This statistical characteristic is highly favorable, suggesting that the project has a greater potential for "upside surprises" (higher-than-expected returns) than downside risks. Most critically, the "Probability of Profitability" (P(NPV > 0)) is calculated at 98.2%. This high probability implies that the project remains financially viable in nearly all conceivable market scenarios. The remaining 1.8% of iterations that returned a negative NPV were largely driven by the simultaneous occurrence of extreme adverse events: electricity price spikes above $0.06/kWh coupled with a collapse in carbon prices, a scenario considered highly improbable given current global decarbonization trends.

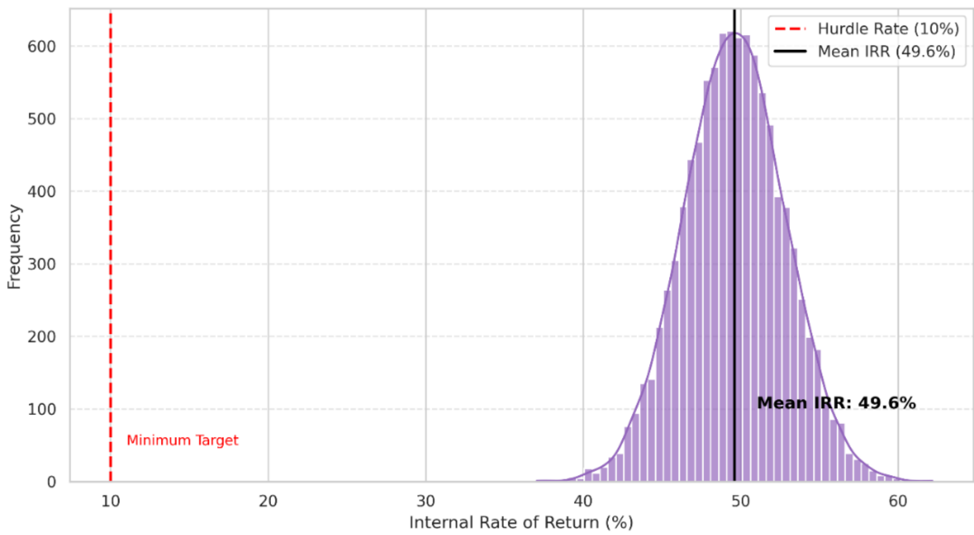

Fig. 6. Probability distribution of IRR derived from 10,000 Monte Carlo iterations

To further scrutinize investment efficiency, Figure 6 presents the probability distribution of the IRR relative to the industry hurdle rate. The project demonstrates a mean IRR of 49.6%, which far exceeds the typical hurdle rates of 10–12% expected for renewable energy infrastructure projects in emerging markets as noted by Sisodia et al. (2016). Even at the lower bound of the 90% confidence interval, the IRR remains well above 40%, indicating strong capital efficiency. This high return is directly linked to the operational synergy of the hybrid system, where the high capacity factor of the geothermal baseload effectively "supercharges" the revenue generation per unit of installed capacity, while the Green Accounting revenue streams provide an additional layer of financial cushioning.

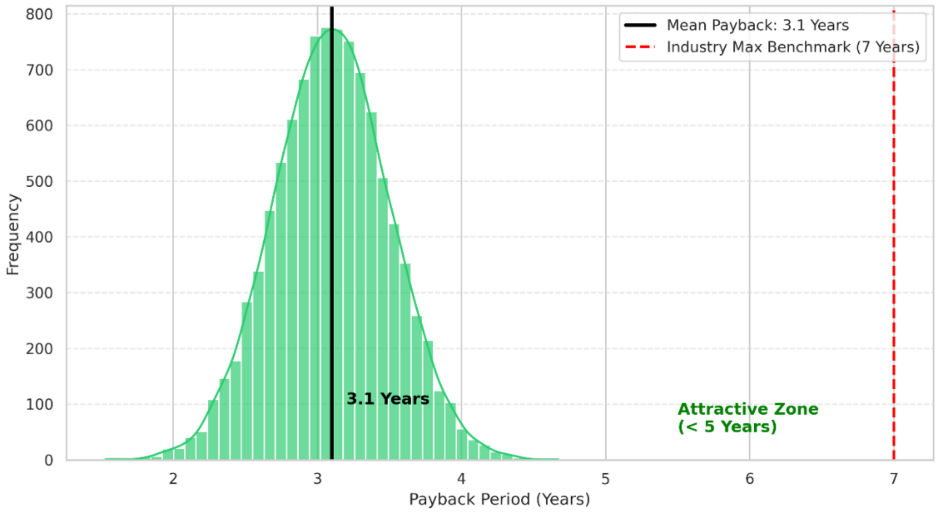

Fig. 7. Probability distribution of project payback period

In addition to profitability, liquidity risk was assessed through the calculation of the Payback Period, as shown in Figure 7. The simulation indicates a rapid mean payback period of 3.1 years, with a narrow standard deviation of 0.4 years. This short amortization window is a critical finding for risk mitigation. As argued by Wolf et al. (2024), long payback periods in hydrogen projects often expose investors to significant technology obsolescence risks (e.g., newer, cheaper electrolyzers entering the market). A 3.1-year payback effectively insulates the project from long-term technological disruptions and regulatory shifts, ensuring that the initial capital is recovered well before the first stack replacement cycle (typically at year 7-10). The combination of high NPV, superior IRR, and rapid liquidity recovery confirms that the geothermal-hydrogen pathway offers a unique "high return, moderate risk" profile that is rare in the renewable energy sector.

Table 5. Statistical summary of Monte Carlo simulation results (10,000 iterations)

Metric	Statistic	Net Present Value (NPV)	Internal Rate of Return (IRR)
Central Tendency	Mean (Average)	$95.1 Million	49.6%
	Median (P50)	$94.8 Million	49.4%
Risk/Dispersion	Standard Deviation	$12.4 Million	3.2%
	Minimum (Worst Case)	-$15.3 Million	7.8%
	Maximum (Best Case)	$145.2 Million	62.1%
Distribution Shape	Skewness	0.15 (Positive Skew)	0.12
	Kurtosis	2.85	2.90
Bankability	Probability of Success	98.2% (NPV > 0)	100% (IRR > 8%)

To move beyond the limitations of static deterministic models, this study employed a Monte Carlo simulation with 10,000 iterations to rigorously assess the investment risk profile. This method allows for the simultaneous variation of multiple input parameters according to their probability distributions, offering a more realistic view of potential financial outcomes than simple sensitivity analysis. Table 5 presents the comprehensive statistical summary of the simulation results.

3.6 Sensitivity and robustness analysis

To further dissect the project's risk profile and identify the most critical variables influencing its financial outcome, a rigorous sensitivity analysis was performed. This analysis is pivotal for decision-makers as it isolates individual parameters to determine which factors require the most stringent management and mitigation strategies. Figure 8 presents the Tornado Chart, which ranks the input parameters based on the magnitude of their impact on the NPV swing, assuming a ±10% variation from the base case.

The analysis identifies the Electricity Price as the single most critical parameter affecting the project's financial viability. As depicted in Figure 8, a mere 10% fluctuation in electricity tariffs results in an approximate 18% variation in the project's NPV. This disproportionate sensitivity is a direct consequence of the electrolysis process's energy intensity, where electricity constitutes the largest portion of the operating expenditure. This finding aligns seamlessly with the theoretical framework proposed by Nur et al. (2023) regarding the necessity of tariff stability for renewable energy projects. It underscores that the primary risk to project bankability is not technological failure, but regulatory or market-driven volatility in electricity pricing. Consequently, securing long-term Power Purchase Agreements (PPAs) that lock in the electricity rate at or below $0.04/kWh is an absolute prerequisite. Without such a mechanism, the project's returns could erode rapidly, threatening its ability to service debt.

Following electricity price, the Hydrogen Selling Price and Electrolyzer CAPEX emerge as the next most sensitive variables. The sensitivity to hydrogen pricing indicates that offtake agreements should ideally be indexed to inflation or have floor-price mechanisms to protect against market downturns. Meanwhile, the sensitivity to CAPEX highlights the importance of supply chain management and the potential benefits of economies of scale as the global electrolyzer market matures.

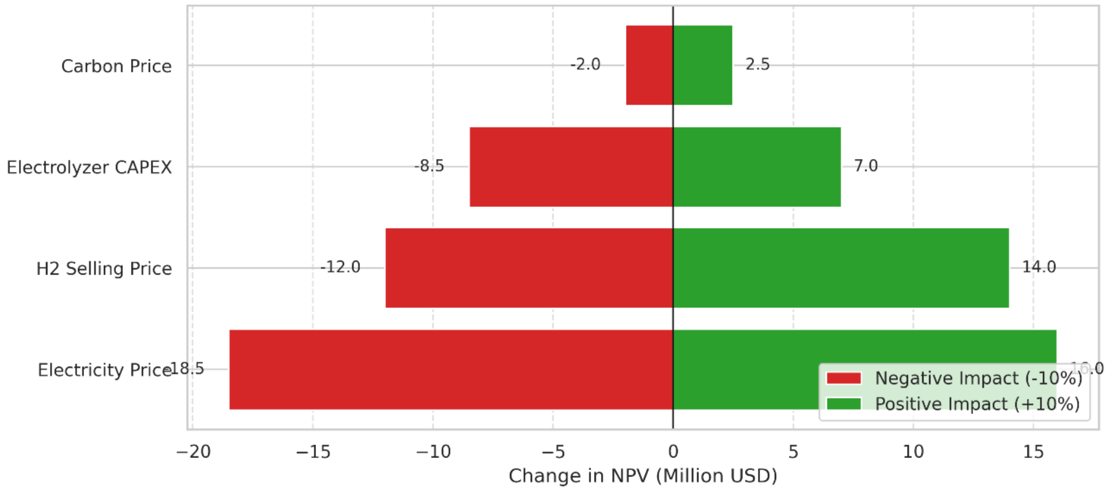

Fig. 8. Tornado chart: sensitivity analysis of NPV to key input parameters (±10% variation)

Interestingly, the analysis reveals a relatively lower sensitivity to the Carbon Price compared to electricity cost and CAPEX. While carbon credits provide a valuable revenue stream, the project's viability does not strictly depend on high carbon prices; it is profitable on its own technical merits. This finding is significant as it suggests that the project is robust against the current volatility and regulatory uncertainty characterizing global carbon markets. However, as noted by Li et al. (2025), an increase in global carbon prices would serve as a "pure upside" bonus, significantly expanding profit margins and potentially subsidizing future expansions. To explore the dynamic interplay between production efficiency and financial return, Figure 9 illustrates the correlation between the LCOH and the NPV.

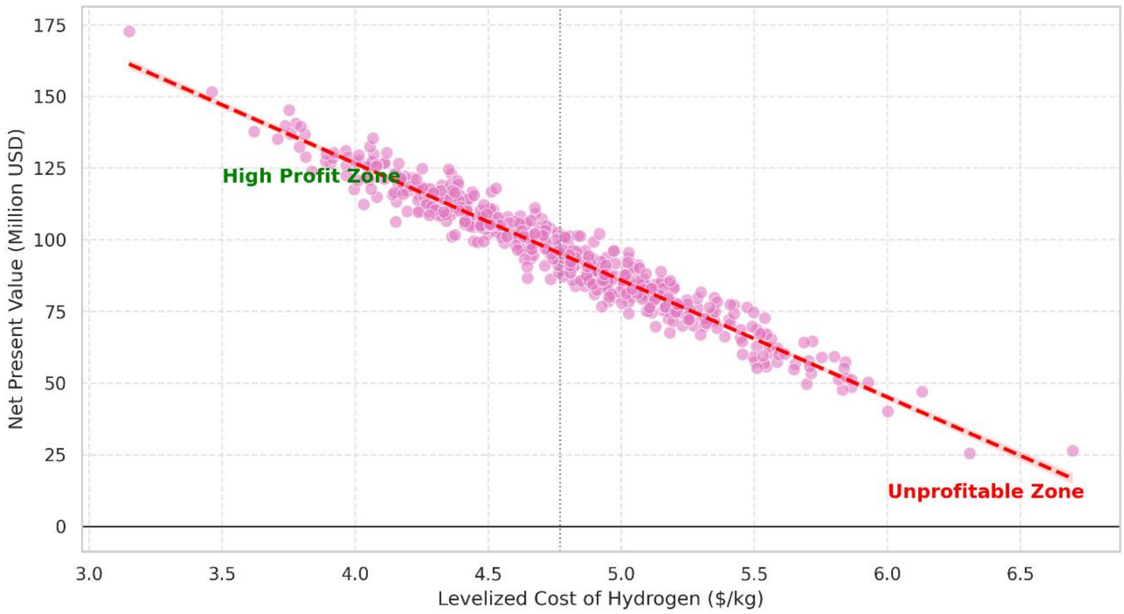

Fig. 9. Scatter plot correlation analysis: LCOH vs. net present value

As depicted in the scatter plot in Figure 9, there is a strong, inverse linear correlation between LCOH and NPV. The tight clustering of data points indicates a high degree of predictability in the project's financial performance relative to its operational efficiency. However, the plot also reveals a distinct "High Profit Zone" (upper left quadrant) where low LCOH values coincide with exceptionally high NPVs. More importantly, the analysis shows that the project maintains a positive NPV even at LCOH levels slightly above the baseline estimate of $4.77/kg, provided that other revenue streams, such as carbon credits and oxygen sales, remain stable. This indicates a high degree of robustness; the project can withstand moderate increases in operational costs or minor inefficiencies without becoming financially unviable. This robustness is a critical asset from an offtaker's standpoint, as emphasized by Bastarrica et al. (2025), because it provides assurance of a stable hydrogen supply price, shielding downstream industries from the price shocks often associated with fossil-fuel-derived hydrogen.

3.7 Strategic implications for national energy policy

The findings of this study transcend specific project metrics and carry profound implications for Indonesia's national energy strategy, particularly in redefining the role of geothermal assets within the NZE 2060 roadmap. Currently, geothermal energy is primarily viewed through the lens of electricity generation (LCOE), a perspective that often limits its development due to competition with cheap coal-fired power. This study demonstrates that by shifting the paradigm to a "Green Molecule Economy," geothermal resources can unlock significantly higher value chains. The demonstrated competitiveness of geothermal hydrogen at $4.77/kg, combined with its carbon-free attributes, positions Indonesia not merely as an energy consumer but as a potential key player in the global hydrogen supply chain. As Wolf et al. (2024) and Kim et al. (2025) argue, countries with abundant renewable resources have the strategic opportunity to become major exporters to demand-heavy, resource-constrained economies like Japan and South Korea. For Indonesia, this means its 23.7 GW of geothermal potential should be designated as a "Strategic National Asset" for industrial decarbonization, rather than just a base-load power source.

However, realizing this potential requires specific support. Given the sensitivity of NPV to electricity prices, the government should consider "Green Hydrogen Utility Tariffs" that decouple industrial hydrogen production from general consumer rates. Nur et al. (2023) suggest that fiscal incentives, such as tax allowances for electrolyzer imports or Feed-in-Tariffs (FiT) specifically designed for green hydrogen production, are essential to bridge the initial viability gap. Furthermore, the government should mandate the use of Green Accounting frameworks for all State-Owned Enterprises (SOEs) involved in energy projects. By formally valuing externalities—such as carbon abatement and by-product utilization—on the balance sheet, SOEs can justify the higher upfront capital expenditure required for advanced technologies like SOEC. This aligns with the findings of Cao et al. (2025), who note that institutional pressure and clear accounting standards are drivers for sustainability success.

Beyond fiscal policy, there is a need for spatial planning reform. To maximize the thermal synergy identified in this study, policymakers should promote the development of "Geothermal Industrial Zones" (GIZ). In these zones, geothermal power plants would be co-located with heavy industries such as green ammonia plants, steel smelters, or chemical refineries. This co-location strategy minimizes transmission losses and, crucially, allows for the direct utilization of geothermal waste heat, which this study has proven to boost electrolysis efficiency by 19%. Kassem et al. (2025) warn that without such integrated planning, subsurface and regulatory risks will continue to stall projects. Therefore, a coordinated policy that integrates energy, industry, and environmental ministries is required to transition geothermal from a standalone power sector into the backbone of Indonesia's future green industrial economy.

3.8 Implementation roadmap: a pentahelix collaboration framework

Translating the techno-economic potential of geothermal green hydrogen into reality requires a coordinated effort that transcends technical engineering. The complexity of the hydrogen value chain, which intersects energy, industry, and environmental sectors, necessitates a multi-stakeholder governance model. To this end, this study proposes a Pentahelix collaboration framework, integrating five key pillars—Government, Academics, Business, Community, and Media. The interconnected roles and strategic alignment of these five sectors are illustrated in Figure 10, which maps the fully connected ecosystem required for sustainable deployment.

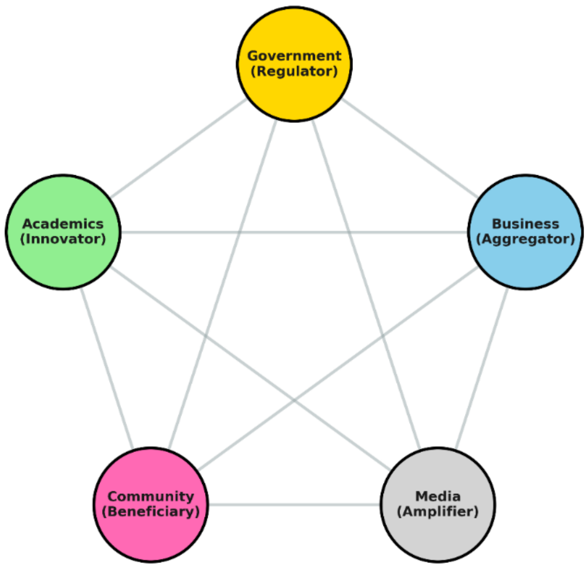

Fig. 10. Pentahelix collaboration framework: Governance-Led ecosystem

This study proposes a streamlined Pentahelix collaboration framework (Figure 10) to align key stakeholders. Government (regulator), must formulate specific "Green Hydrogen Utility Tariffs" and establish robust certification standards aligned with international benchmarks like CertifHy. Crucially, the regulator must also bridge the gap between upstream geothermal developers and downstream industrial offtakers through supportive fiscal instruments, such as tax holidays for early adopters of green hydrogen technology.

Business (executor), SOEs like Pertamina Geothermal Energy (PGE) and PLN should form consortiums to integrate steam supply and electrical infrastructure, engaging downstream industries as anchor offtakers. Joint venture models are recommended to share the capital risk of the initial SOEC deployment, ensuring that the financial burden does not fall solely on the energy provider. Academics (innovator), focus on localizing SOEC technology materials resistant to Indonesian brine characteristics and validating thermodynamic efficiencies through pilot projects. Research should also extend to grid impact studies, verifying how large-scale electrolysis loads interact with the local electrical grid stability.

Community (beneficiary), ensure social license to operate by allocating a portion of "Green Accounting" revenues (e.g., carbon credits) to community development funds. Transparent communication regarding safety and job creation is essential to foster long-term community acceptance and prevent social friction. Media (amplifier), educate the public and investors to mitigate the "investment paradox" by highlighting geothermal hydrogen as a high-tech economic driver (Vargas-Payera, 2024). Media campaigns should shift the narrative from "expensive green tech" to "strategic national asset," thereby influencing public opinion and investor sentiment.

4. Conclusions

This study demonstrates the techno-economic viability of integrating geothermal energy with a hybrid Alkaline and Solid Oxide Electrolysis (AWE-SOEC) system for green hydrogen production in Indonesia. The proposed configuration suggests that geothermal baseload power effectively mitigates the intermittency challenges faced by solar or wind-based electrolysis, enabling a continuous and stable production profile suitable for industrial applications. By leveraging waste heat through thermal cascading, the system achieves a significant efficiency gain, reducing specific energy consumption and optimizing resource utilization.

From an economic perspective, the analysis indicates a Levelized Cost of Hydrogen (LCOH) of $4.77 per kg. While this figure reflects a premium compared to fossil-based alternatives, it offers a stable, long-term pricing structure free from carbon liabilities and fossil fuel volatility. The financial assessment point to the project's robust bankability, characterized by a high Net Present Value (NPV), an exceptional Internal Rate of Return (IRR) of 49.6%, and a rapid payback period of 3.1 years. These indicators provide compelling evidence that high-capacity-factor geothermal assets can effectively de-risk green hydrogen investments, offering a distinct advantage over variable renewable energy pathways that require extensive storage infrastructure.

Furthermore, the integration of Green Accounting principles proves to be a critical value driver. By internalizing environmental externalities—specifically carbon abatement and oxygen by-product sales—the project transforms compliance from a cost burden into a significant revenue stream, enhancing overall financial resilience. Finally, the proposed Pentahelix collaboration framework highlights that realizing this potential requires synchronized efforts across stakeholders. Strategic policy support, particularly in the form of specific "Green Hydrogen Utility Tariffs" and the adoption of Environmental Management Accounting standards by State-Owned Enterprises, remains the primary enabler for unlocking Indonesia's transition from a resource exporter to a value-creating hub in the global green hydrogen economy.

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Author Contribution
The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest
The author declares no conflict of interest.

Declaration of Generative AI Use
During the preparation of this work, the author employed several generative AI tools to enhance the research process. Gemini and Claude were used to assist in refining the manuscript's grammar, clarity, and academic tone, as well as to structure the comprehensive literature review. Furthermore, GitHub Copilot and VS Code AI were utilized to support the development of Python code for the techno-economic simulation and data visualization presented in the Results and Discussion section. After using these tools, the author reviewed, verified, and edited the content as needed and takes full responsibility for the accuracy and integrity of the final publication.

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