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Article

Techno-economic analysis of a green hydrogen-firing gas turbine in Malaysia via Monte Carlo simulations

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ABSTRACT

Based on Malaysia's National Energy Transition Roadmap, hydrogen is important to the country's energy transition. However, studies on potential green hydrogen applications in Peninsular Malaysia are scarce, particularly in gas turbine (GT) co-firing. This gap has shaped discussions around the economic and technological aspects of green hydrogen production and co-firing. Therefore, this paper focuses on the feasibility of green hydrogen co-firing in one of Malaysia's GTs, with a special emphasis on Peninsular Malaysia, the country's primary industrial hub, which houses most of the key GTs. The study uses a Monte Carlo model to evaluate the economic and technical factors affecting green hydrogen adoption, concentrating on three target years: 2023, 2030, and 2050, representing different stages of technological deployment and market adoption of electrolyzers. Actual GT data is used to calculate future green hydrogen demand based on the turbines' technology and the percentage of hydrogen co-firing they could accommodate. Scenario I for 2023 showed the widest Levelized Cost of Hydrogen (LCOH) distribution, ranging from \$3.54 to \$16.82 per kg, indicating a high level of uncertainty. By 2030, the outlook improves significantly, with the conceptual co-firing system potentially obtaining an LCOH of \$2.68 to \$9.43 per kg. Looking ahead to 2050, the study predicts a promising future for green hydrogen co-firing, with the LCOH potentially dropping to \$2.30 to \$8.54 per kg, and a mode of \$4.64 per kg. Sensitivity analysis also reveals shifting key cost drivers. In 2023, early-stage investments in electrolyzers are critical, while electricity prices become increasingly important in 2030 and 2050. Overall, three key cost drivers have been identified as having a significant effect on LCOH: electrolyzer power consumption, electricity price, and utilization rate, highlighting the need for industry and policymakers to concentrate on these factors when formulating new policy instruments for the green hydrogen co-firing initiative in Peninsular Malaysia's GTs.

1. Introduction

Malaysia, a Southeast Asian nation in the process of development, is situated along the South China Sea and includes parts of both the Malay Peninsula and the island of Borneo. It consists of 13 states, 11 of which are located on the peninsula, while the remaining two, Sabah and Sarawak, form East Malaysia on Borneo. The peninsula shares land borders with Thailand and maritime boundaries with Indonesia, Singapore, and Vietnam. In contrast, East Malaysia on Borneo borders Brunei and Indonesia by land and the Philippines and Vietnam by sea. The economic growth of Peninsular Malaysia has largely been driven by improvements in electrification, supported by various thermal power plants that aid in its socioeconomic progress. Recently, Peninsular Malaysia has made considerable strides toward establishing a hydrogen-based economy [1-16]. However, despite positive progress in decarbonization, the region faces distinct obstacles due to its historical reliance on traditional energy sources, which hinders long-term green growth. In 2020, about 85% of the country’s electricity was generated from fossil fuels, mainly from natural gas as well as sub-bituminous and bituminous coal [17, 18]. The rising request for low-cost electrical power is driving the expansion of Malaysia’s energy sector [19], which is heavily dependent on power plants, which form a considerable part of the power supply. At the same time, the Malaysian government has committed to achieving climate neutrality by 2050. This puts Peninsular Malaysia, the country's main economic center, at a pivotal point in deciding the tactical steps needed for a clean energy transition. To meet these challenges, the government introduced the National Energy Transition Roadmap (NETR), which sketches the country's plans for managing its energy needs, mitigating greenhouse gases (GHG), and advancing energy transition efforts. The NETR aims to cut GHGs in the energy sector by 32% by 2050, compared to 2019 levels, with per capita emissions expected to drop to 4.3 metric tons of CO_2 equivalent. These measures set the stage for Malaysia's energy shift, with hydrogen positioned as an essential energy carrier for the economy [17]. The country's goals to decrease carbon emissions through new technologies have sparked discussions regarding the adequacy of its goals for implementing electrolysis technologies to foster a domestic hydrogen production sector. This has led to widespread investigation into sustainable hydrogen and its wide uses in industrial processes, sustainable transportation, and balancing electricity supply [20, 21].

Malaysian researchers such as Zakaria et al. [20] and Rahman et al. [1] investigated Malaysia's renewable energy (RE) potential, focusing on green hydrogen. Their research covered a detailed review of the country's energy landscape and the practicality of integrating green hydrogen into the existing energy infrastructure. Their research explored the feasibility of using the country's natural gas pipeline for hydrogen transport, examined the possibility of integrating hydrogen into the country's gas turbine (GT) power plants, and considered key factors like energy demand, population data, energy policies, reliance on traditional energy resources, CO_2 emissions, and the overall adoption of RE in Malaysia. The research also explored hydrogen's role as a RE source, covering aspects like hydrogen production techniques, storage methods, and green hydrogen-based energy generation. While these investigations provided insights into hydrogen's potential in Malaysia's RE mix, they revealed a considerable gap in quantitative data and techno-economic analysis required to guide investments in green hydrogen.

Benalcazar et al. [22] studied the potential of green hydrogen in Poland. Employing a Monte Carlo simulation, they investigated the technical and economic elements that might affect the success of Poland's sustainable hydrogen policy. The investigation economically examined sustainable hydrogen production across various steps of technical progress and market growth. A significant result of their analysis was the prediction of optimal geographic locations for large-scale hydrogen production to minimize costs and improve efficiency. Their findings indicated that Poland's LCOH for a 20-MW Proton Exchange Membrane (PEM) electrolyzer could vary, with projections for 2050 showing a range between €1.95 and €2.03 per kg when using solar power and €1.23 to €1.50 per kg when using onshore wind power. Reference [23] investigated techno-economic aspects of three offshore wind power generation systems, each featuring a different hydrogen production method. The configurations included distributed, centralized, and onshore hydrogen production. The researchers applied different methods, such as net present value (NPV) assessments, sensitivity analyses, and Monte Carlo simulations to determine feasibility. Reference [24] developed a Monte Carlo model to assess sustainable geothermal-based hydrogen production in the Zilan area in Turkey's Van province, known for its rich geothermal and water resources.

The model was employed to evaluate the installed capacity of an Organic Rankine Cycle (ORC) geothermal power plant, identifying Lake Van as a desirable area for hydrogen production. Based on the model, the region could initially produce 18.6 kg of H_2/hr, with potential output rising to 28 kg by 2050, indicating strong prospects for sustainable hydrogen production. The study also estimated that in 2022, the cost to produce one kilogram of hydrogen would be €4.91, decreasing significantly to €1.21 per kg by 2050, suggesting the growing economic feasibility of geothermal-based hydrogen production in the Zilan region. Monte Carlo analysis is vital in assessing sustainable hydrogen production's economic viability and technical factors, offering crucial insights. These studies provide comprehensive information about cost efficiency and geographical differences related to renewable energy sources and technologies.

Rahman et al. [1, 25] conducted an in-depth assessment of Malaysia's renewable energy potential for green hydrogen. Building on this previous work, the present study focuses on quantitative data and performs technical and economic analysis of a potential hydrogen application in Malaysia. Specifically, this study examines green hydrogen co-firing in a gas turbine (GT) in Peninsular Malaysia, the country's main industrial hub, home to many significant GT plants. Prior research indicates the growing use of hydrogen in power generation through gas turbines [26-28]. Additionally, major original equipment manufacturers (OEMs) are increasingly entering the hydrogen GT market, signaling strong potential for the hydrogen economy, as gas turbines remain one of the most important power generation technologies globally.

Increasing gas turbine (GT) fuel flexibility to incorporate larger amounts of hydrogen is a critical advancement in driving the energy transition toward a hydrogen-centric future. For instance, blending 10% hydrogen into the fuel mix can decrease CO_2 emissions by 2.7%, equivalent to reducing 1.26 million metric tonnes of CO_2 for a 600 MW combined cycle gas turbine (CCGT) running at 60% efficiency for 6000 hours annually [1]. However, due to hydrogen's high reactivity, maintaining flame control to ensure the combustion system's durability while achieving required emission standards in GTs remains a major challenge [26-28]. It is known that co-firing GTs with unconventional fuels introduces risks concerning fuel quality, as GTs built and calibrated for specific fuel quality ranges tend to perform best within those limits, ensuring both reliability and optimal operational efficiency [29]. Despite these challenges, the EUTurbines industry group made a commitment in January 2019 to deploy GTs capable of operating entirely on hydrogen by 2030 [1], showing the sector's dedication to decarbonization and the potential for zero-carbon GT operations. While green hydrogen is widely seen as a promising option for reducing carbon emissions, its global expansion is slowed by high electrical power prices and capital costs related to electrolytic installations [30-32]. Although global research focuses on the economic perspective of hydrogen production and co-firing in GTs [33], there is a significant lack of studies addressing the future costs and feasibility of green hydrogen techniques and co-firing applications, specifically in Peninsular Malaysia. Furthermore, no research, to the author's knowledge, has yet examined the financial and technical uncertainties that influence the economics of sustainable hydrogen production and its co-firing in the region's GTs. This paper tries to bridge that gap by conducting an in-depth analysis of local technical, financial, and policy or regulatory factors associated with green hydrogen production and co-firing applications. Additionally, a Monte Carlo simulation analysis is introduced to assess the technical and economic feasibility of large-scale hydrogen production technologies designed to fulfill the hydrogen demand for a key GT in Peninsular Malaysia. The research focuses on the importance of solar photovoltaic (PV) technology as an essential RE source for sustainable hydrogen production in Peninsular Malaysia. Benefiting from its equatorial location, the country enjoys favorable solar conditions, with an average daily solar irradiance between 4.21 kWh/m^2 and 5.56 kWh/m^2 annually. The maximum solar energy is available in August and November, peaking at 6.8 kWh/m^2, while December experiences the minimum, down to 0.61 kWh/m^2 [34]. These factors position Malaysia as a desirable country for sustainable hydrogen production, which could be leveraged for hydrogen co-firing in GTs.

In this analysis, the LCOH is the key metric employed in the probabilistic evaluation of large-scale solar-powered electrolyzers and their integration into hydrogen co-firing at GT power plants. While interest in green hydrogen's role in Malaysia's energy sector is increasing [35], there is a lack of forward-looking investigations specifically focusing on Peninsular Malaysia. This limitation has shaped discussions on green hydrogen production's economic and technological prospects and its co-firing applications in the region. To address this gap, this research introduces a Monte Carlo-based model that estimates the LCOH for different green hydrogen co-firing scenarios in a major GT power plant in Peninsular Malaysia, considering different stages of market development and technological advancement for green hydrogen production. Additionally, a sensitivity analysis is employed to evaluate the most critical risk factors in large-scale hydrogen production and co-firing projects. The results offer valuable perspective on the projected costs of sustainable hydrogen co-firing in Peninsular Malaysia's GTs, further supporting the deployment of the regional hydrogen economy.

2. Materials and methods

This research presents a detailed model for determining the LCOH for on-site hydrogen production systems that utilize PEM electrolyzers despite the existence of multiple electrolyzer technologies. "In-situ" refers to the PEM electrolyzer plant's location within the GT power plant itself. This setup necessitates increased land use while eliminating transportation costs such as long-distance pipelines or trucks for green hydrogen delivery.

This arrangement can be considered an ideal case, and it has also been included in the Directive (EU) 2024/1788, which proposes that hydrogen production and consumption take place in the same location or as close as possible, ensuring stable hydrogen quality for end-use and minimizing costs, environmental impact, and hydrogen leaks related to transportation [36].

PEM electrolysis was chosen because of its benefits for distributed hydrogen production. These include a compact design, high efficiency, and flexibility, making it an ideal candidate for integration with existing power plants [37, 38]. In contrast to traditional studies that often depend on basic sensitivity assessment with single-point or anticipated values to forecast the LCOH for emerging or ongoing hydrogen technologies, this research adopts a probabilistic method to evaluate the influence of techno-economic uncertainties on the costs of hydrogen co-firing in Peninsular Malaysia's gas turbines. The technical and economic model incorporates a Monte Carlo assessment to address uncertainty across various input factors when calculating LCOH. The proposed methodology is illustrated in Figure 1.

The computer-based Monte Carlo modeling technique is based on selecting inputs randomly from random distributions to compute the projected value of a fixed model or output function [39, 40]. This method is applied when practical experiments are too costly or impractical. The Monte Carlo modeling process typically involves the following steps [22]:

- Statistical distributions are determined for model parameters influenced by uncertainty or risk factors.
- A set of N random samples is considered from each random distribution and employed as inputs in the deterministic model.
- The model's outcomes are evaluated according to the corresponding set of inputs.
- The outcomes are statistically evaluated, and the probability density function is estimated.

Although the Monte Carlo method has been previously applied successfully in research to assess risks in energy investments and project cost performance across different energy systems [41-44], it has not yet been methodically utilized to explore the economic feasibility of hydrogen co-firing in GTs in Peninsular Malaysia. Considering the ambiguities in long-term planning for hydrogen infrastructure, this paper introduces a static technical and economic model that generates potential outcomes employing random samples derived from probability density functions. These functions are made from anticipated and observed data, following standard practices. Additionally, the LCOH is a key metric to assess the economic viability of large-scale hydrogen co-firing projects in a significant GT power plant in Peninsular Malaysia. The LCOH ($/kg) is calculated as follows:

$$LCOH = \frac{I_o + \sum_{t=1}^{T} \frac{I_t + C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{H_t}{(1+r)^t}} \tag{1}$$

Where I represents the initial investment ($), T represents the project period (years)- 25 years, C stands for the operating costs ($), H indicates the hydrogen demand produced (kg), and r represents the discount rate (%).

The discount factor is assumed to be 8%. The same 8% rate is used to calculate the Net Present Value (NPV) of all costs, hydrogen produced, and energy generated. Using 10% for project evaluation is common practice as it represents a fair average of the cost of debt and equity. However, a lower rate is applied to projects that involve new and evolving technology, such as hydrogen technologies and new energy projects. Typically, this ranges from 5 to 10%. The initial investment I ($) can be calculated using Eq (2).

$$I = CP_{el} + LA_{el} + PP_{el} \tag{2}$$

where CP_{el} is the capital expenditure (CapEx) for the PEM electrolyzer ($), LA_{el} is the CapEx for the land acquisition investment cost of the electrolyzer ($/kW) and PP_{el} is the GT power plant upgrade cost for hydrogen co-firing ($). CP_{el} is calculated based on Eq (3).

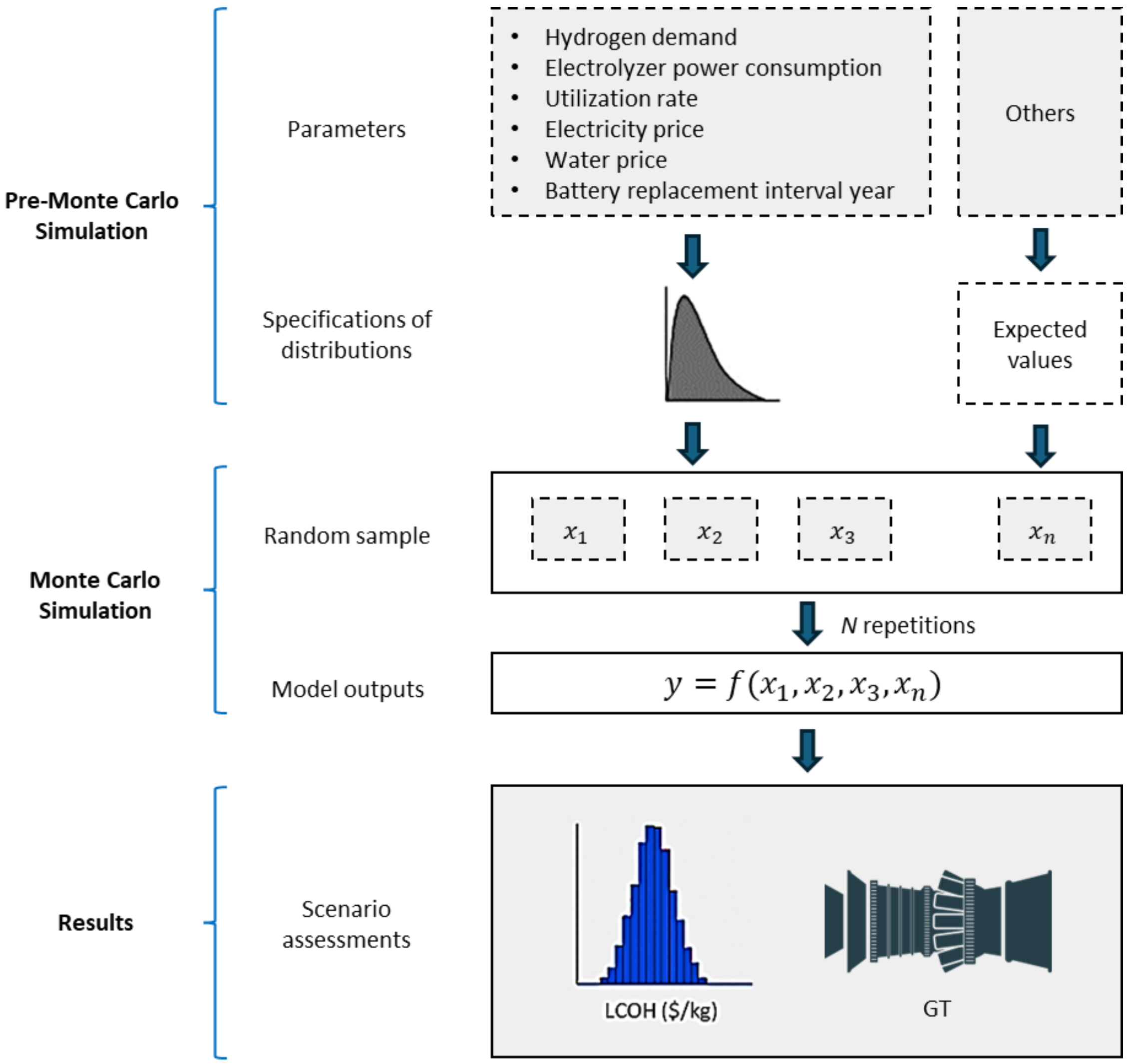


Figure 1. A summary of the Monte Carlo approach employed in this study

$$CP_{el} = P_{el} \times I_{el} \tag{3}$$

where P_{el} is the electrolyzer's rated power (kW) and I_{el} represents the specific investment cost of the electrolyzer ($/kW).

P_{el} is calculated based on the hydrogen demand (H) of the GT under study at varying co-firing ratios with natural gas. Table 1 displays the range of H based on data gathered from the power plant under study, indicating their GT's ability to accommodate hydrogen percentage co-firing. The hydrogen demand for co-firing is used to calculate the P_{el} using Eq (4).

$$P_{el} = \frac{H \times E_{el} \times CF}{u_{el}} \tag{4}$$

where E_{el} is the electrolyzer's power consumption in kWh/kg, CF is the assumed annual availability of the GT under study, and u_{el} represents the electrolyzer utilization rate expressed as a fraction of 1. The u_{el} value range is based on the previous study's estimated solar capacity factors in Peninsular Malaysia [25]. As stated before, it is considered that the PEM electrolyzer is operated by solar power plants.

Eq (5) shows how LA_{el} is calculated.

$$LA_{el} = L \times J \tag{5}$$

where L is the land size for the electrolyzer (m^2) and J is the specific land price in the region where the GT is located ($/m^2). L is calculated via Eq (6).

$$L = H \times L_s \tag{6}$$

where L_s is the specific land size for green hydrogen production (m^2/kg).

PP_{el} is calculated using Eq (7).

$$PP_{el} = P_{GT} \times P_{upg}$$

where P_{GT} is the estimated GT power plant price and P_{upg} is the cost of upgrading the GT to co-fire hydrogen, expressed as a percentage of P_{GT}.

The annual operating costs (OpEx) involve the cost of electricity, water, non-fuel variable operation and maintenance, and battery replacement.

$$C = (\tau \times P_{el} \times u_{el} \times C_e) + (\gamma \times H \times C_w) + (CP_{el} \times \vartheta) \tag{8}$$

where τ represents the total number of hours in a year (h), C_e denotes the electricity cost ($/kWh), γ indicates the water required to produce each kilogram of hydrogen (L/kg), and C_w signifies the water price ($/L). Maintenance expenses are considered constant over the system's lifespan [22] and are calculated as a fraction (ϑ) of the capital cost of the electrolyzer. Additionally, battery replacement costs are accounted for at regular intervals throughout the project's duration, with these replacement costs included in the operational expenditure (OpEx). The Monte Carlo-based model outlined in this section was implemented using Microsoft Excel. Simulations were conducted on a desktop computer equipped with a 4.7 GHz Intel Core i7-12700H processor, featuring six cores and 16 GB of RAM. The results generated by this computational tool were verified by comparing them with outputs from the H2A: Hydrogen Analysis Production Model, a well-regarded tool utilized in both academic and industrial settings [45, 46]. A sensitivity analysis was performed to improve the Monte Carlo approach and to pinpoint the uncertainties affecting the LCOH for the green hydrogen co-firing initiative. For this analysis, seven input parameters were chosen, corresponding to those represented in the probability distribution functions: hydrogen demand from the GT, electricity price, power consumption of the electrolyzer, utilization rate, water price, specific investment cost of the electrolyzer, and battery replacement interval. As detailed in Table 1, the sensitivity analysis involved systematically varying the values of a single parameter within the same ranges as the probability distributions. An interview with the original equipment manufacturer (OEM) of the GT power plant was conducted to ascertain the demand for hydrogen in the GT. This interview aimed to assess the GT's capability for hydrogen co-firing and to identify any necessary upgrades. The estimated percentage range for hydrogen co-firing can be utilized to determine the required mass flow range of hydrogen for the GT. According to the power plant staff, the GT's estimated annual availability is 42%. Scenario assessments were conducted for different ranges of specific investment costs associated with electrolyzers, as presented in Table 2, which reflects the anticipated future cost reductions and market maturity for Scenarios I through III. These scenarios projected specific investment costs for large-scale PEM electrolyzers across various years (2023, 2030, and 2050), utilizing data from previous research by Rahman et al. [25].

3. Case Study

3.1 Renewable energy in Malaysia

Malaysia possesses various resources that can be employed to produce RE. These resources include [82]:

- Solar irradiation: Malaysia enjoys abundant sunlight, making solar energy highly viable [83].
- Biomass: Biomass from agricultural, household, and industrial waste can be combusted or gasified to produce bioenergy [84].
- Small-size hydroelectric power: The nation's rivers offer opportunities for small-size hydroelectric power generation [85].

By 2020, Malaysia had deployed a considerable installed capacity in RE, totaling 8,450 MW, as demonstrated in Figure 2. The most important contributor among the different RE resources was large hydropower, with 5,692 MW, followed by solar PV and bioenergy, with 1,534 MW and 717 MW, respectively. The small-size hydropower capacity was 507 MW. In 2021, Malaysia substantially revised its RE targets to achieve 31% and 40% RE capacity by 2025 and 2035, respectively, a significant increase from the prior objective of 20% by 2025 [17].

The dedication of governmental bodies, including SEDA Malaysia and the Energy Commission (EC), operating under the Ministry of Natural Resources, Environment, and Climate Change (NRECC), is evident through various RE programs and initiatives. Examples of these initiatives include the Feed-in Tariff scheme (FiT), the Large Scale Solar auction (LSS), Net Energy Metering (NEM), and Self-Consumption (SELCO).

3.2 Important targets for Malaysia's hydrogen economy

Figure 3 illustrates that Malaysia initiated its hydrogen research and deployment attempts in the early 2000s, aligning with global advancements in hydrogen technologies [15].

Table 1. Distributional assumptions for key parameters

Operating Parameter	Unit	Distributional Value	Reference
Hydrogen demand from the GT	kg/hr	PERT (5,750; 8,662; 11,574)	OEM
Electrolyzer power consumption	kWh/kg	PERT (25.2; 49.2; 83.0)	[47-74]
Utilization rate		PERT (0.13; 0.20; 0.48)	[25]
Electricity price	$/kWh	PERT (0.045; 0.084; 0.098)	[75-76]
Water price	$/l	PERT (0.00016; 0.00032; 0.00070)	[77]
Battery replacement interval year		PERT (7; 10; 15)	[25]

Table 2. Scenario analysis assumptions

Operating Parameters	Unit	Scenario I (2023)	Scenario II (2030)	Scenario III (2050)	References
Electrolyzer cost	$/kW	PERT (500.0; 1164.8; 2097.6)	PERT (315.6; 362.0; 403.4)	PERT (138.6; 174.5; 210.5)	[22]

Table 3. Input parameters

Operating Parameters	Unit	Value	References
Specific land size for hydrogen production	m^2/ton H_2	51.0	Internal reference
GT power plant price	$	550,000,000	Internal reference
Upgrade cost	%	10	Internal reference
Lower heating value of hydrogen	kWh/kg	33.3	[78]
Replacement cost	% of electrolyzer cost	42.0	[79-81]
Maintenance cost	% of electrolyzer cost	5.0	[78]
Water requirement	L/kg H_2	9.0	[78]

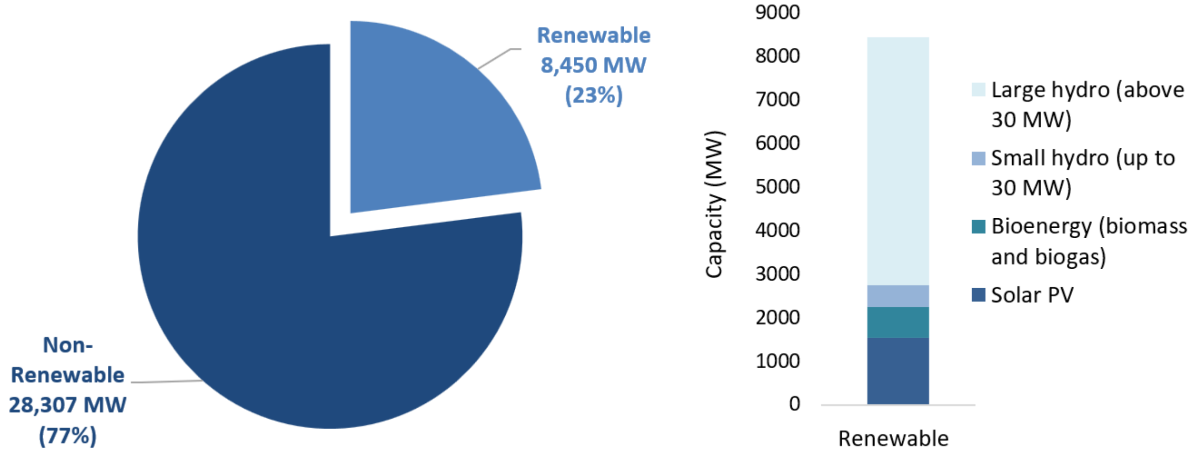


Figure 2. RE installed capacity as of 2020

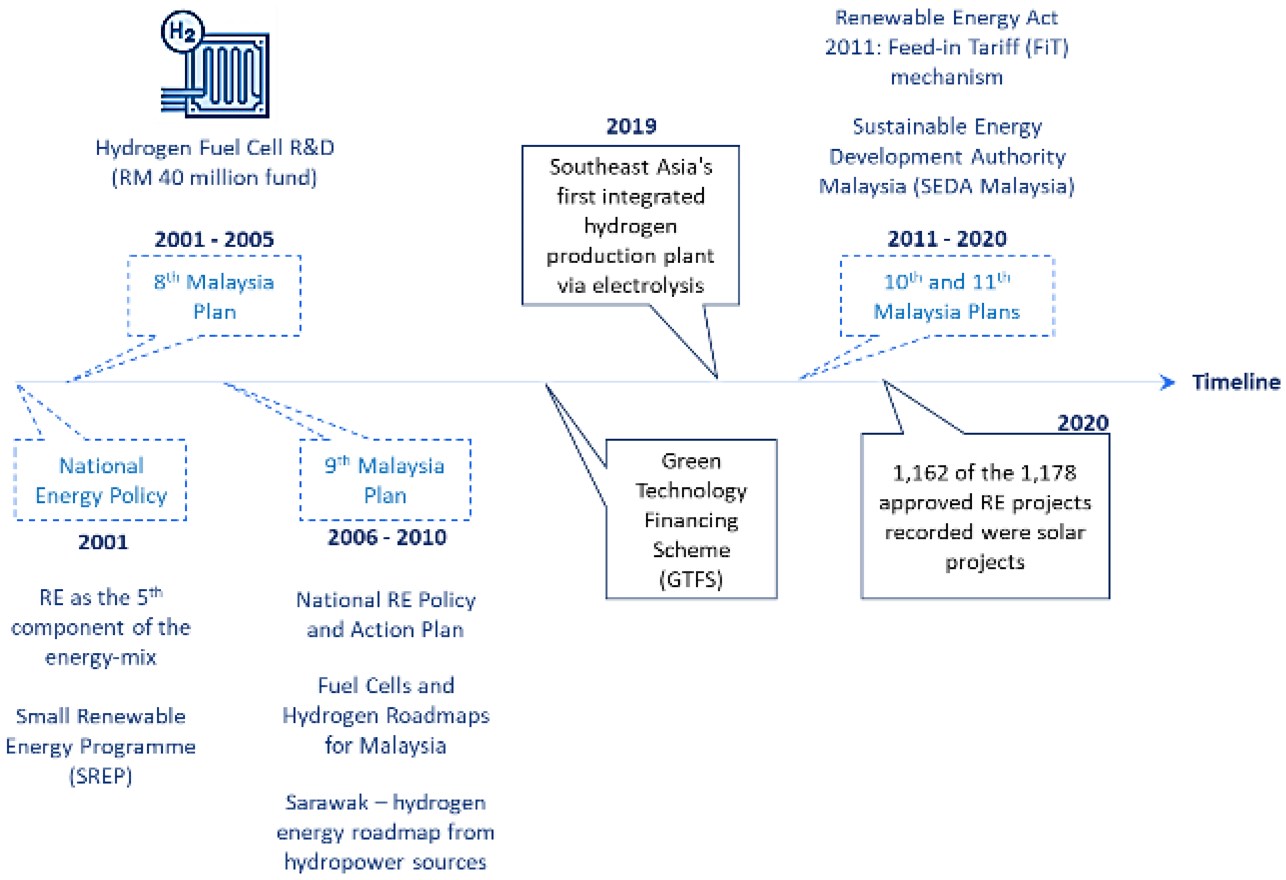


Figure 3. Key milestones toward Malaysia's hydrogen economy

Recognizing the potential of renewable energy (RE) sources like biomass, biogas, municipal waste, solar, and hydro, Malaysia integrated RE as the fifth element of its energy-mix strategy in 2001 under the National Energy Policy. This strategic initiative aimed to leverage Malaysia's rich RE resources, targeting a contribution of 5% and 10% to the energy mix by 2005 and 2010, respectively. To facilitate this transition, the Small Renewable Energy Programme (SREP) was established under the direction of the Special Committee on Renewable Energy (SCORE), reflecting the government's commitment to positioning RE as a key energy source [86]. During the 8th Malaysia Plan (2001-2005), the government acknowledged the significance of hydrogen fuel cells as a priority area for R&D, aligning this focus with its RE objectives [15]. From 1997 to 2013, the Ministry of Science, Technology, and Innovation (MOSTI) allocated RM 40 million for hydrogen fuel cell research.

In July 2006, the Fuel Cell Institute, later known as the Institute of Fuel Cell (IFC-UKM), was established at Universiti Kebangsaan Malaysia (UKM) [87]. This institute marked the commencement of Malaysia's exploration into fuel cells and hydrogen energy, beginning with the construction of the nation's first PEM fuel cell [16]. In 2009, the Institute of Hydrogen Economy (IHE) was established at Universiti Teknologi Malaysia (UTM) [88]. The Fuel Cell Research Group was created in 1996 with an RM 2 million grant, which was subsequently augmented by an RM 15 million grant from MOSTI's Intensification of Research in Priority Areas (IRPA) Programme. As Malaysia progressed, the 9th Malaysia Plan prioritized hydrogen development through various policies, initiatives, and strategic roadmaps. The National Renewable Energy (RE) Policy and Action Plan laid the groundwork for the Fuel Cells and Hydrogen Roadmaps (2005-2030), focusing on hydrogen production from renewable resources and establishing networks to support hydrogen fuel cell vehicles [15]. The hydropower-rich state of Sarawak also introduced its own hydrogen energy roadmap to utilize its hydropower potential [21]. During Phase 2, which covered the 10th and 11th Malaysia Plans, legislative and financial interventions were implemented to promote commercial-scale hydrogen projects [15]. In September 2011, the Sustainable Energy Development Authority Malaysia (SEDA Malaysia) was created to manage the Feed-in Tariff (FiT) system under the Renewable Energy Act of 2011 [89]. The FiT mechanism encouraged the public and industrial sectors to produce electricity from RE sources, such as solar and wind, and sell surplus energy to the National Grid [90]. The revised target under the RE Act aimed for 985 MW, or 5.5% of the energy mix, by 2015. By 2020, Malaysia sought to generate 11% of its electricity from renewable sources, amounting to 2,080 MW [15]. In 2010, the Green Technology Financing Scheme (GTFS) was launched to support green investments by making financing more accessible [91]. As of December 2017, GTFS had 28 Participating Financial Institutions (PFIs) funding 319 projects worth RM 3.638 billion. This initiative created 4,909 jobs and helped cut CO_2 emissions by 3,784 million tonnes annually. To further promote green technology, the Malaysian Green Technology and Climate Change Centre (MGTC) was tasked with managing Green Investment Tax Allowances (GITA) [92] and Green Income Tax Exemption (GITE) [93] to support the adoption of green technology.As Malaysia's hydrogen economy framework evolves, industry leaders are increasingly focusing on renewable energy commercialization. For instance, Sarawak Energy Berhad (SEB) set up Southeast Asia's first integrated hydrogen production facility using electrolysis, which includes a refueling station, and introduced hydrogen-powered vehicles as part of a demonstration project [1]. Meanwhile, NanoMalaysia Berhad (NMB) is advancing hydrogen production on-site and developing hydrogen hybrid energy storage systems within the Energy and Environment sector. By 2020, solar energy had gained significant traction, with 1,162 out of the 1,178 approved renewable energy projects in the government's database being solar-related, reflecting its affordability [15].

3.3 National Energy Transition Roadmap (NETR)

As of 2020, Malaysia's total primary energy supply (TPES) was largely driven by four main sources. Natural gas was the largest contributor at 42.4%, followed by crude oil and petroleum products at 27.3%, and coal at 26.4%. Renewable energy sources, mainly hydropower, solar, and biofuels, provided only 3.9% of the total [18]. Consequently, the government has set a more ambitious renewable energy (RE) target, raising the goal from 40% by 2035 to 70% by 2050. The Malaysian government recently unveiled the National Energy Transition Roadmap (NETR) to achieve the 70% RE capacity by 2050 [17]. The NETR outlines six key levers for the energy transition, with hydrogen being a critical focus. This lever aims to enhance hydrogen's viability and competitiveness through regulatory frameworks and innovation, alongside forging long-term agreements with importing nations. The main hydrogen-related initiatives under this plan include:

- Developing standards and regulations for low-carbon hydrogen.
- Expanding domestic green electrolyzer production capacity.
- Reducing the levelized cost of hydrogen (LCOH) to improve the economics of hydrogen hubs.
- Boosting demand for low-carbon hydrogen by pursuing bilateral agreements with key importing countries, promoting value chain development, and securing long-term green hydrogen commitments.

The NETR's focus on LCOH as a central program aligns with Malaysia's research into estimating LCOH for 2023, 2030, and 2050, supporting the country's net-zero carbon emission target.

3.4 Green hydrogen production from solar photovoltaic

As the energy sector is the largest contributor to greenhouse gas (GHG) emissions in Peninsular Malaysia [66], one potential solution for decarbonizing the region's energy systems is the implementation of power-to-gas-to-power technology, which can support long-term economic transformation [94]. This approach highlights two crucial areas in the hydrogen industry: the production of green hydrogen [95] and its application in power generation through hydrogen co-firing [96]. Malaysia's abundant solar resources, along with their substantial capacity, underscore the nation's significant potential for solar photovoltaic (PV) power generation. This favorable environment positions Malaysia to leverage its solar energy resources to further develop its renewable energy sector and achieve its ambitious RE targets. Figure 4 illustrates the potential of Malaysia's RE resources in terms of equivalent power generation capacity. The country has an impressive total RE potential of 288.9 GW, with solar PV making up 269 GW, or 93.1% of the total. Solar PV stands as the leading contributor to Malaysia's RE capacity, offering the greatest potential for power generation among all renewable sources in the country.

Peninsular Malaysia's proximity to the equator grants it abundant solar resources, as shown in Figure 5, making it an excellent location for utilizing solar energy in green hydrogen production. Solar installations are strategically dispersed throughout different regions of the country. This widespread adoption of solar power not only supports Malaysia's renewable energy (RE) objectives but also enhances its potential for sustained green hydrogen production, strengthening the nation's commitment to a cleaner and more sustainable energy future. Figure 4 outlines the solar photovoltaic (PV) potential across three key solar technologies: rooftop solar, floating solar, and ground-mounted solar [15].

- Ground-mounted solar on unused land: This category consists of installations on flat, unzoned land that excludes water bodies, forests, agricultural zones, and mountainous areas. With an estimated potential of 210 GW, ground-mounted solar installations on unused land represent

Malaysia's largest solar resource, driven by the availability of vast suitable land areas.

- Floating solar PV: Malaysia has an estimated potential of 16.6 GW for floating solar PV installations. These installations are located on water bodies at 17 major hydroelectric plants and 62 reservoir dams, covering a surface area of about 2,944 km^2 [15].
- Rooftop solar PV: Peninsular Malaysia leads in rooftop solar PV potential with 37.4 GW, largely due to its high level of urbanization. Sarawak and Sabah, in comparison, have rooftop solar PV potentials of 2.6 GW and 2.2 GW, respectively. These installations are located on residential, commercial, and industrial rooftops, taking advantage of existing infrastructure [97].

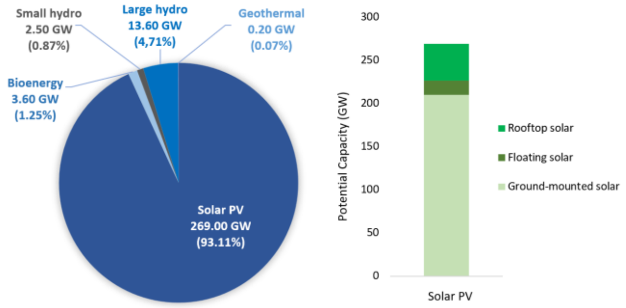


Figure 4. RE potential in Malaysia

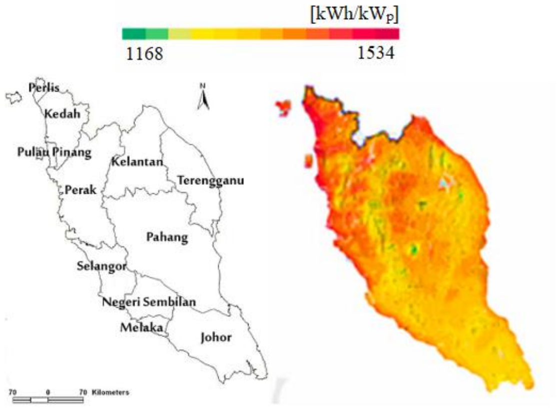


Figure 5. Solar irradiance level in Peninsular Malaysia [98]

Although Malaysia's energy system remains highly dependent on natural gas and coal, its renewable energy (RE) capacity has grown gradually in recent years. Nevertheless, the intermittent and non-dispatchable characteristics of renewables, particularly solar PV, which has lower capacity factors than thermal power plants, meant that renewable electricity generation (excluding hydropower) only reached 3,285 GWh in 2020, accounting for just 1.92% of the total electricity output [18]. Figure 6 shows the progress of electricity generation from different technologies in Malaysia since 2015. The Malaysian government's latest Hydrogen Economy and Technology Roadmap (HETR) demonstrates the country's commitment to achieving a 31% RE capacity share by 2025. To meet this goal, a plan was initiated in 2021 to develop 1,178 MW of new RE capacity in Peninsular Malaysia, with 1,098 MW coming from solar PV installations, reflecting a positive outlook for green hydrogen production via solar PV in the coming years [15]. For potential future hydrogen production incentives, such as tax credits, the production process itself is critical in reducing GHG emissions. While the combustion of hydrogen in GTs produces nearly zero GHG emissions (assuming 100% hydrogen firing), the emissions from hydrogen production vary greatly depending on the method used. Green hydrogen, which is produced using RE sources such as solar PV, has the lowest GHG emissions and thus is the most viable option for Malaysia's long-term hydrogen economy policies. Solar PV, given Malaysia's favorable solar conditions, has significant potential to support large-scale green hydrogen production, making it a critical enabler for the country's transition to a hydrogen economy. To deliver meaningful climate benefits and GHG reductions, hydrogen co-firing in GTs must maintain a low GHG profile throughout the production process. This ensures that the environmental benefits of hydrogen combustion are not offset by emissions during production, which aligns with broader climate goals and supports potential incentives for green hydrogen development.

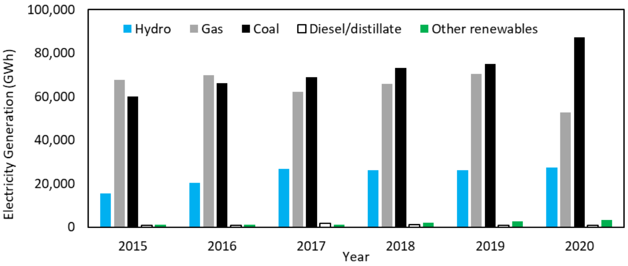


Figure 6. Electricity generation mix in Malaysia

3.5 Regulatory framework of hydrogen firing in GTs

The terms "regulation" and "policy" are frequently used synonymously, but they serve distinct functions. A policy is a set of guidelines or principles established by an organization or government to guide decisions and actions. For example, Malaysia's NETR is a key policy guiding the country's energy transition efforts, with hydrogen use in the energy sector identified as a potential catalyst for these efforts. Policies provide a broad framework for decision-making and outline the path to achieving specific objectives. They are typically aspirational and have no legal ramifications if not followed. In contrast, regulations are specific rules or laws enacted by governing bodies to ensure that policies or laws are followed. Regulations specify how broad policy principles should be implemented and are legally binding. Noncompliance with regulations may result in penalties or other legal consequences. For example, environmental regulations may limit factory emissions to protect air quality. At the time of writing, Malaysia did not have a regulatory framework in place for hydrogen-powered GTs. Thus, examining global regulatory frameworks can help outline potential regulatory scenarios for hydrogen-powered GTs in Malaysia, as well as provide insight into the technology's prospects.

In the United States, the Environmental Protection Agency (EPA) actively regulates GHG emissions from power plants, including those that use hydrogen-fired GTs. The EPA's regulatory efforts are part of a larger initiative under the Clean Air Act (CAA) to reduce the environmental impact of fossil fuel combustion and promote cleaner energy sources. The New Source Performance Standards (NSPS) for GHG emissions from new, modified, and reconstructed fossil fuel-fired electric generating units (EGUs) are an important benchmark. These standards aim to reduce CO_2 emissions. The updated NSPS for GHG emissions, which was finalized in April 2024, sets strict CO_2 limits for new gas-fired combustion turbines. However, the EPA declined to finalize its proposed plan to include low-GHG hydrogen co-firing as the "Best System of Emission Reduction" (BSER) for new and reconstructed base load and intermediate load turbines, citing uncertainties in the evaluation criteria. After reviewing public comments and conducting additional analysis, the EPA concluded that the uncertainties made it difficult to determine whether low-GHG hydrogen co-firing is the best system for reducing emissions at this time. Nonetheless, under CAA section 111, the EPA establishes performance standards without requiring the use of specific technologies, which means that sources may continue to co-fire hydrogen to meet the performance standards. Despite this, the Inflation Reduction Act (IRA) strongly encourages the use of low-GHG technologies in the power sector by providing tax credits, loan guarantees, and public investment programs [99]. The IRA includes provisions to promote Carbon Capture, Utilization, and Storage (CCUS) as well as clean hydrogen production, which can aid in the integration of coal and natural gas into a low-GHG electricity grid.

The European Union (EU) is implementing hydrogen-related regulations through key directives aimed at encouraging hydrogen production, distribution, and usage. One such directive, the Renewable Energy Directive (RED II), establishes binding targets for renewable energy and encourages the use of renewable hydrogen. RED II specifically establishes targets for renewable fuels of non-biological origin (RFNBOs), which are produced from renewable energy sources such as wind or solar but are not derived from biological materials. Hydrogen, for example, is produced through electrolysis using renewable electricity. By 2030, RFNBOs must account for at least 42% of all hydrogen used in industrial applications, whether for final energy consumption or non-energy purposes. By 2035, this target will have risen to 60%. The term "final energy purposes" refers to hydrogen's direct use as a fuel in energy production, such as power generation or industrial processes, which supports the future of hydrogen-powered GTs. Furthermore, the EU's Hydrogen and Decarbonized Gas Market Package seeks to establish a competitive, integrated hydrogen market [100]. This package includes measures to ensure non-discriminatory access to hydrogen infrastructure, cross-border trade, and common standards for hydrogen quality and safety. It also addresses issues like blending hydrogen with natural gas and building dedicated hydrogen pipelines. Although the regulatory framework related to hydrogen-fired GTs is still in its early stages and is not as stringent or comprehensive as for other technologies, the emerging trend emphasizes the importance of green/renewable hydrogen for clean energy production. This highlights the need for techno-economic studies on green hydrogen co-firing in Peninsular Malaysia's GTs to support future energy prospects.

3.6 Techno-economic evaluation of local green hydrogen production and co-firing

The study aims to analyze three distinct scenarios, each focusing on evaluating the economic feasibility of producing green hydrogen in Peninsular Malaysia at various stages of technological advancement and market acceptance. The hydrogen produced in these scenarios is then considered for use in co-firing at one of Peninsular Malaysia's gas turbines (GTs). Table 2 outlines the differing electrolyzer costs, highlighting anticipated cost reductions and market maturity for Scenarios I-III. As green hydrogen production in Peninsular Malaysia is still in its nascent phase, and with no commercial hydrogen co-firing GTs in operation, the levelized cost of hydrogen (LCOH) at both the national and local levels is subject to numerous independent variables, each with its own uncertainty. To address these uncertainties, the study employs a Monte Carlo simulation, using probability distributions—specifically beta-PERT distributions—due to their ability to be estimated with limited data and their inclusion of three key parameters: minimum value (lower bound), maximum value (upper bound), and most likely value (mode). Table 1 illustrates the types of distributions and parameters utilized in this study. Estimates were compiled from various public sources, including academic articles, government publications, and international organizations, alongside interactions with the gas turbine (GT) power plant being examined. For instance, information regarding electrolyzer technologies was sourced from IRENA, IEA, Bloomberg, Deloitte, and others, while data on ground-mounted solar PV technologies were obtained from multiple sources, such as IRENA, NREL, and Bloomberg NEF. Many of these data sources span the years 2017 to 2023, ensuring that the study reflects a contemporary perspective on the economics of green hydrogen production in Peninsular Malaysia. Additionally, water costs for hydrogen production were estimated using historical datasets, considering that each state in Peninsular Malaysia has its own water pricing system established by the state government. This thorough approach, incorporating probability distributions and information from a range of reliable sources, facilitates a comprehensive analysis of the economic factors surrounding green hydrogen production and co-firing in the region while addressing the uncertainties inherent in these early-stage endeavors.

4. Results and discussions

This section provides an overview of the findings and examines the levelized cost of hydrogen (LCOH) for green hydrogen co-firing in gas turbines (GT) across different stages of electrolyzer technological advancement, as reflected by anticipated cost reductions and market readiness in Scenarios I to III. Utilizing Monte Carlo Simulation, the model produces probability distributions for various LCOH results. Additionally, the outcomes of the sensitivity analysis are presented, emphasizing the major risk factors associated with green hydrogen co-firing initiatives in Peninsular Malaysia.

4.1 LCOH distributions

The LCOH formula in Eq (1) includes several input parameters that are subject to change and uncertainty. To address this uncertainty, the current study uses a Monte Carlo simulation approach that incorporates the variability of these inputs into the LCOH calculations. As described in the Materials and Methods section, this procedure entails determining the uncertain variables in the LCOH formula, also known as the "transfer equation." The probability distributions from Table 1 and Table 2 are then used to generate independent random values. The random value generation functions were integrated into Microsoft Excel to facilitate simulation. Unlike many studies that adhere to traditional replication rules, this study determined the number of replications using the methodology proposed by Benalcazar et al. [22]. This approach revealed that 300,000 replications provide an accurate representation of the LCOH while preserving computational efficiency. This thorough approach ensures that all potential outcomes and uncertainties regarding green hydrogen production and co-firing costs in Peninsular Malaysia are thoroughly investigated. The LCOH distributions for each scenario are shown in Figure 7. The y-axes of these distributions have been rescaled to a range of 0 to 1 to facilitate comparison, highlighting the impact of various parameters on the LCOH distributions. As shown in Figure 7, Scenario I has the widest distribution with longer tails than the other two scenarios, indicating the greatest level of uncertainty. The LCOH distributions narrow gradually from Scenario I to Scenario III, indicating a reduction in uncertainty as electrolyzer-specific costs fall from 2023 to 2050.

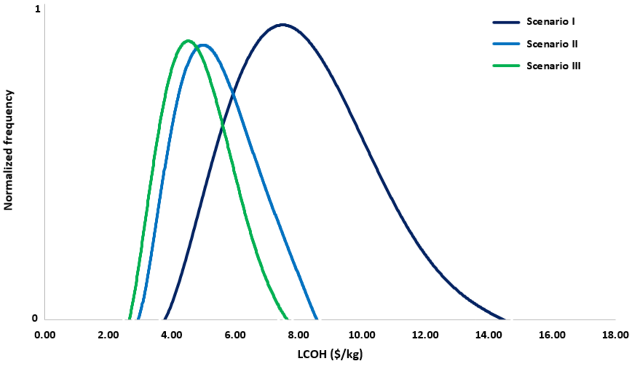


Figure 7. Uncertainty LCOH distributions

In Scenario I, LCOH values cluster around a mode value of $7.69 per kg, indicating that this is the most likely value based on 2023's electrolyzer-specific costs. Scenarios II and III exhibit LCOH mode values of $5.03 per kg and $4.64 per kg, respectively. This represents a reduction in LCOH mode values by 35% and 40% from the baseline of Scenario I for Scenario II and Scenario III, respectively. The greater shift in LCOH mode from Scenario I to Scenario II is primarily due to a greater reduction in electrolyzer-specific investment costs, emphasizing the rapid development expected by 2030. According to the most recent IEA report, the implementation of electrolyzer projects in the pipeline could result in an installed capacity of 170-365 GW by 2030 [101], driving further cost reductions. Table 4 provides additional information, such as the distributions' 5th, 50th, and 95th percentiles.

Table 4. 5th, 50th, and 95th percentiles of the LCOH distributions

LCOH ($/kg)	Percentiles		
	P5	P50	P95
Scenario I (2023)	4.98	8.07	12.53
Scenario II (2030)	3.60	5.39	7.75
Scenario III (2050)	3.15	4.73	6.89

4.2 Primary factors influencing the LCOH

The sensitivity analysis results for each scenario in the study are illustrated in Figures 8 (a) to 8 (c). Parameters with absolute values close to 1 have the greatest impact on the calculated LCOH. The horizontal bars are arranged in descending order of their influence on LCOH, from most to least significant. The relative importance of these parameters varies over the years studied. However, one consistent trend is that electrolyzer power consumption remains the most influential factor across all scenarios. Its influence is predicted to persist through the market maturity of electrolyzers. Specifically, in Scenarios II and III, representing the years 2030 and 2050, the influence of electrolyzer power consumption increases to 0.88, compared to 0.72 in Scenario I.Electrolyzer power consumption has been the main area of research related to green hydrogen production [47-100], and this study highlights the reasons why. Given its significant impact on the calculated LCOH, it is crucial to enhance research and development efforts to reduce electrolyzer power consumption. This will be essential for the future of widely commercially available green hydrogen in Peninsular Malaysia, aiming to lower the LCOH.

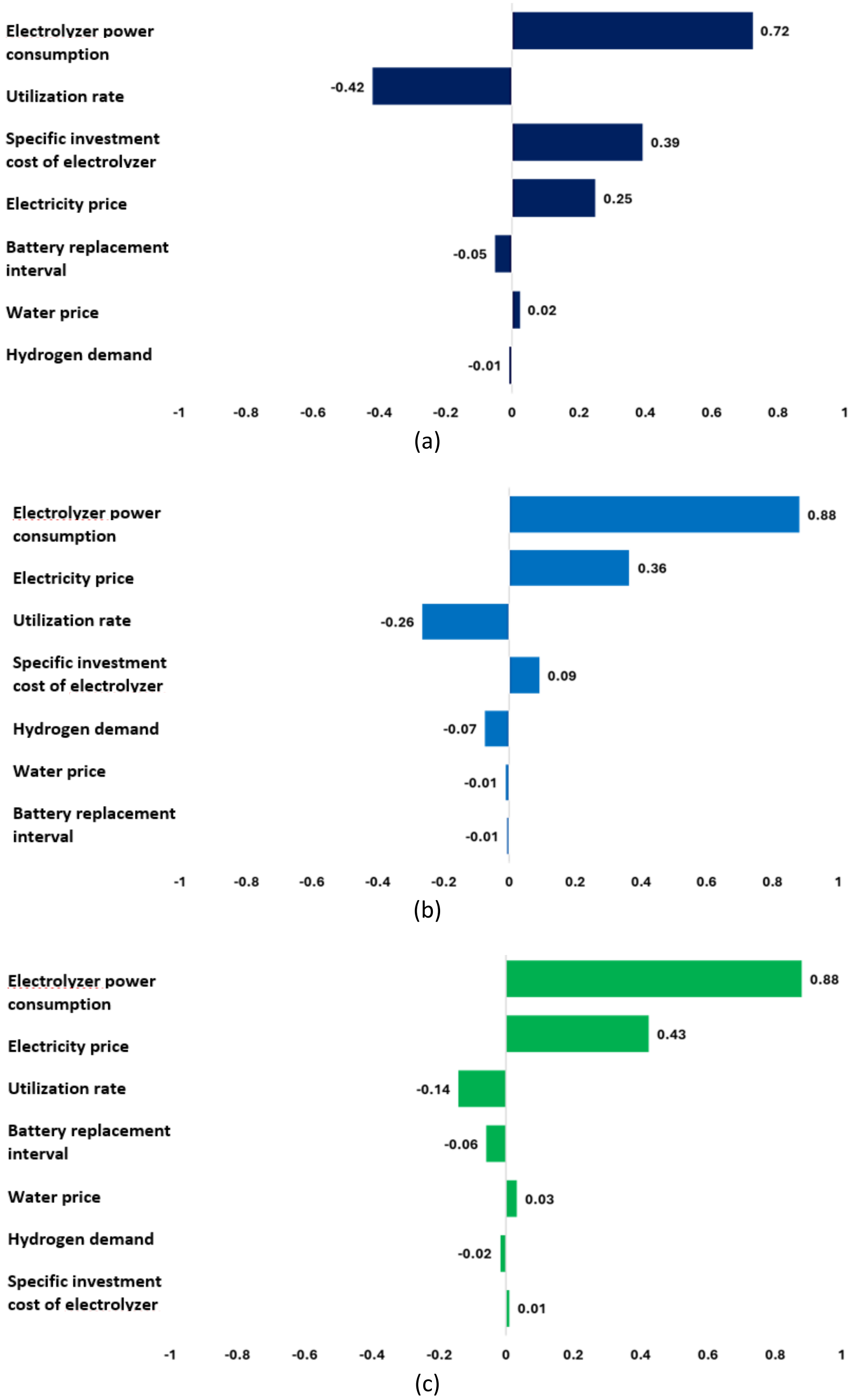
The utilization rate, based on the variability of the capacity factor of solar power plants in Malaysia (assumed to be the primary power source for electrolyzers), also significantly influences the LCOH. In Scenario I, it has an absolute value of 0.42, but this sensitivity drops to 0.26 and 0.14 in Scenarios II and III, respectively. This shift from second place behind electrolyzer power consumption in Scenario I to third place in Scenarios II and III indicates that the utilization rate's influence will diminish as electrolyzers mature in the market up to 2050.

It is important to note that the range of capacity factor for solar power plants in Peninsular Malaysia is assumed to remain constant in this study. Future developments in solar power plants, which may increase the capacity factor, and the integration with battery energy storage systems (BESS) are not considered here. These factors could further increase the capacity factor and, consequently, the utilization rate. Plus, the narrow range of capacity utilization employed in this study reflects that solar irradiance in Peninsular Malaysia is not highly impacted by future climate changes. The specific investment cost of electrolyzers, which varies from Scenario I to III, shows a significant drop of LCOH sensitivity from 0.39 in Scenario I to 0.09 and 0.01 in Scenarios II and III, respectively. This reduction moves it from third place in Scenario I to last place in Scenario III in terms of influencing factors. The decrease in specific investment costs from 2023 to 2050 is a key reason for this reduction in influence, as higher specific investment costs have a greater sensitivity to LCOH than lower specific investment costs. Therefore, it is important to reduce the specific investment cost of electrolyzers until the LCOH becomes less sensitive to this factor. The LCOH shows increasing sensitivity to changes in electricity prices in 2030 and 2050 (Scenarios II and III). In recent years, the correlation between electricity prices and LCOH has increased significantly, climbing to second place after the electrolyzer power consumption parameter. This indicates that LCOH has become increasingly sensitive to electricity prices over time. Hydrogen demand from GTs shows fluctuating sensitivity towards LCOH, with a very low correlation in Scenario I, a slight increase in Scenario II, and a drop again in Scenario III. On the other hand, the battery replacement interval year and water price have negligible sensitivity in all scenarios. This implies that changes in these variables have little effect on the economic performance of green hydrogen production and co-firing systems in Peninsular Malaysia's GT. Figure 9 illustrates the sensitivity dynamics of key parameters affecting the LCOH over the scenario years. The three primary factors significantly influencing LCOH are electrolyzer power consumption, electricity price, and utilization rate. These factors are crucial for green hydrogen production, highlighting the need for industry and policymakers to focus on these aspects for the green hydrogen co-firing concept in Peninsular Malaysia's GTs.

4.3 Implications for policies

While electrolyzer power consumption can be managed through advances in electrolyzer technology, electricity prices in Peninsular Malaysia are mainly determined by the government and Tenaga Nasional Berhad (TNB), Malaysia's largest power utility company. In future years, LCOH will be more sensitive to electricity prices, necessitating a specific tariff design to ensure a competitive LCOH as green hydrogen usage grows, particularly for potential co-firing in Peninsular Malaysia's GTs.

Despite the possibility of using green hydrogen for GT co-firing in this study, Malaysia's generation by source is expected to continue to consume a significant amount of natural gas in the future. In fact, the government's rationalized natural gas subsidy plan may result in significant increases in future electricity costs for consumers, particularly during economic downturns or geopolitical tensions, which have historically caused volatility in global gas prices. The Kumpulan Wang Industri Elektrik (KWIE) fund can help to reduce electricity tariff increases, but its limitations and potential depletion must be recognized [102].



(a)

(b)

(c)

Figure 8. Key LCOH cost drivers for (a) Scenario I (2023), (b) Scenario II (2030), and (c) Scenario III (2050)

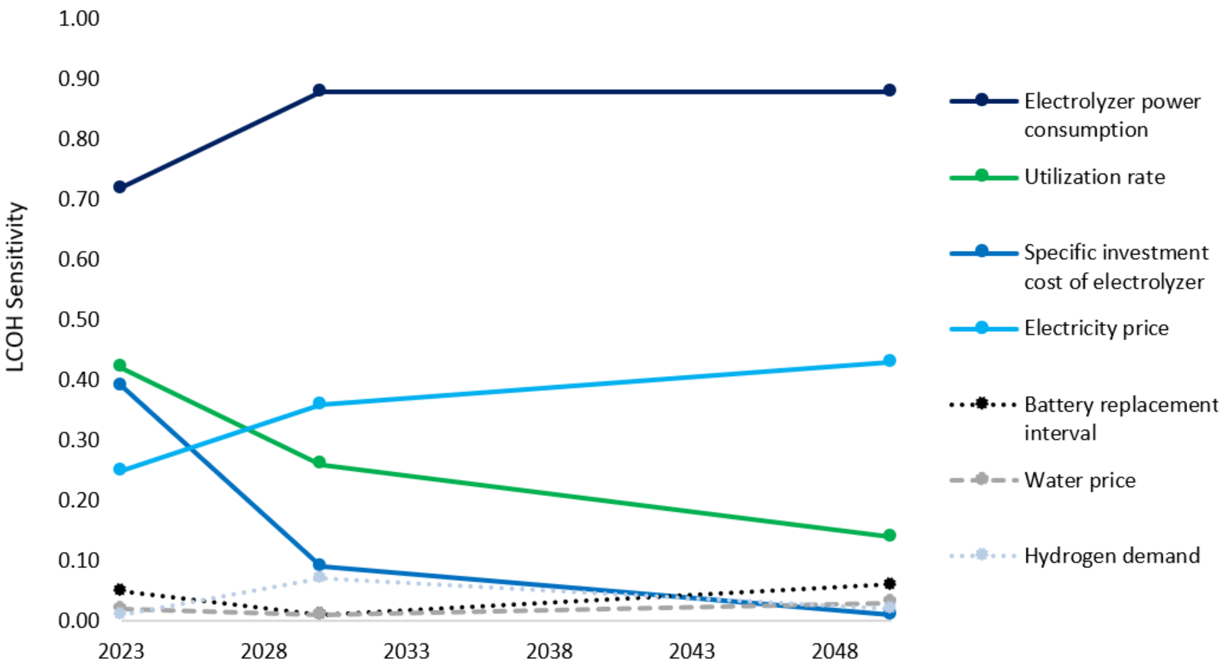


Figure 9. Dynamics of the studied key parameter sensitivity to LCOH

Subsidies could be provided, but they may have an impact on the government's fiscal performance. As a result, these factors may contribute to future LCOH price uncertainty, which is highly dependent on electricity prices. The study concludes that new policy instruments will be required to support green hydrogen production, particularly in Peninsular Malaysia, which faces high levels of uncertainty and risk in the coming decade. The effective implementation of such policies has the potential to lay a solid foundation for the decarbonization of the energy sector while also increasing the economic competitiveness of Peninsular Malaysia's GTs, which currently rely heavily on fossil fuels. Furthermore, these findings fuel the ongoing debate about the importance of policy interventions to promote hydrogen technologies and infrastructure in Peninsular Malaysia. As the LCOH in Peninsular Malaysia becomes more competitive, green hydrogen could emerge as a viable alternative to natural gas. As a result, policymakers must concentrate their efforts on creating strategic blueprints for establishing a hydrogen supply chain, considering the strategic location of production facilities and the availability of renewable resources. Furthermore, policies and strategies for expanding the hydrogen supply chain should be inextricably linked to public policies that increase RE capacity.

5. Conclusions

This study evaluates the economic performance of large-scale green hydrogen co-firing GT using PEM electrolyzers powered by solar energy in Peninsular Malaysia through a Monte Carlo approach. It focuses on three key years: 2023, 2030, and 2050, each representing different stages of market maturity for green hydrogen production, as indicated by the specific investment cost of electrolyzers. The findings highlight the evolving economics of green hydrogen in Peninsular Malaysia. In 2023, the LCOH ranged from \$3.54 to \$16.82 per kg, reflecting early-stage challenges and uncertainties. Scenario I in 2023 showed the widest distribution with longer tails, supporting the high level of uncertainty. By 2030, the outlook will improve significantly, with the conceptual co-firing system potentially achieving the LCOH of \$2.68 to \$9.43 per kg. Looking ahead to 2050, the study suggests a bright future for green hydrogen, with the LCOH potentially dropping to \$2.30 to \$8.54 per kg, and a mode of \$4.64 per kg. This research fills a significant knowledge gap by illuminating the long-term prospects for green hydrogen production and co-firing in Peninsular Malaysia’s GTs. While the uncertainty distributions of LCOH vary across the years, the study indicates that green hydrogen could become a competitive and economically viable fuel for Peninsular Malaysia’s GTs by 2050. The sensitivity analysis highlights the changing key cost drivers: early-stage investments in electrolyzers are crucial in 2023, while electricity prices become increasingly important in influencing LCOH in 2030 and 2050. This underscores the need for additional policy support mechanisms to mitigate risks associated with green hydrogen energy investments.

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Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements and states that the submitted work is original and has not been published elsewhere.

Data availability statement

The datasets analyzed during the current study are available and can be given upon reasonable request from the corresponding author.

Conflict of interest

The author declares no potential conflict of interest.

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