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Article

# Green hydrogen prospects in Peninsular Malaysia: a techno-economic analysis via Monte Carlo simulations

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**ABSTRACT**

According to Malaysia's National Energy Transition Roadmap, hydrogen is a critical component of the country's energy transition. However, there is a scarcity of hydrogen studies for Peninsular Malaysian states, which limits discussions on green hydrogen production. This study employs a Monte Carlo model to assess the economic and technical factors influencing the success of green hydrogen in Peninsular Malaysia. The study focuses on three target years: 2023, 2030, and 2050, representing various stages of technological development and market adoption. The levelized cost of hydrogen (LCOH) of a 1-MW Proton Exchange Membrane (PEM) electrolyzer system ranges from $5.39 to $10.97 per kg in 2023, highlighting early-stage challenges and uncertainties. A 6-MW PEM electrolyzer system could achieve an LCOH of $3.50 to $4.72 per kg by 2030, indicating better prospects. Because of technological advancements and cost reductions, a 20-MW PEM electrolyzer system could achieve an LCOH of $3.12 to $3.64 per kg in 2050. The findings indicate that the northern regions of Peninsular Malaysia have consistently low LCOH values due to favorable geographical conditions. Due to minor variations in solar capacity factors, uncertainty distributions in LCOH remain stable across different regions. Some states may face increased uncertainty, emphasizing the need for additional policy support mechanisms to mitigate risks associated with green hydrogen investments. The sensitivity analysis shows that key cost drivers are shifting, with early-stage electrolyzer investments dominating in 2023 and electricity prices becoming more important in 2030 and 2050. Future research could focus on optimizing green hydrogen systems for areas with underdeveloped green hydrogen industries. This study contributes to informed discussions about green hydrogen production by emphasizing the importance of tailored strategies that consider local conditions and highlighting the role of Peninsular Malaysia in the energy transition.

## 1. Introduction

Malaysia, a developing Southeast Asian country, is located along the South China Sea, encompassing parts of the Malay Peninsula and the island of Borneo. The country is divided into 13 states, 11 of which are in Peninsular Malaysia, while Sabah and Sarawak on Borneo are known collectively as East Malaysia [1]. Peninsular Malaysia has land borders with Thailand as well as maritime borders with Singapore, Vietnam, and Indonesia, whereas East Malaysia on Borneo has land borders with Brunei and Indonesia as well as maritime borders with the Philippines and Vietnam. Peninsular Malaysia has primarily benefited from electrification improvements, serving as the focal point of the nation's significant economic advancements, which are supported by a number of thermal power plants that facilitate its socioeconomic endeavors [1-14]. In recent years, significant efforts have been made in Peninsular Malaysia to realize the vision of a hydrogen-based economy [1, 15-16]. Despite the encouraging momentum towards decarbonization, Peninsular Malaysia faces unique challenges, primarily due to its historical energy trajectory, which impedes its prospects for long-term green economic growth. Notably, nearly 85% of Malaysia's electricity generation in 2020 originated from fossil fuels, primarily sub-bituminous and bituminous coal, as well as natural gas [17-18]. The growing demand for affordable electricity, driving Malaysia's power generation expansion [19], has resulted in a heavy reliance on thermal power plants, which account for a significant portion of the energy mix [17-18]. Concurrently, Malaysia has pledged to achieve climate neutrality by 2050. As a result, Peninsular Malaysia, the nation's economic hub, is at a crossroads in determining the strategic choices required for a sustainable and successful energy transition. In order to address some of the aforementioned challenges, the Malaysian government recently adopted the National Energy Transition Roadmap (NETR), which aims to chart the course for the country's energy mix, greenhouse gas (GHG) emission reduction, and energy transition initiatives [17].

The NETR initiatives are expected to result in a 32% reduction in GHG emissions in the energy sector by 2050 compared to the 2019 baseline, with GHG emissions per capita reaching 4.3 Mt of carbon dioxide ($CO_2$) equivalent. These documents lay the groundwork for the country's energy transition, positioning hydrogen as a critical energy vector for the economy and various end-use sectors [17]. Furthermore, Malaysia's strategy to decarbonize its economy through innovative energy carriers has raised concerns about whether national targets for developing electrolysis technologies are sufficiently ambitious to foster a domestic hydrogen production industry. This has resulted in extensive research into green hydrogen and its diverse range of applications, including industrial processes, sustainable and intelligent mobility, and electricity balancing [1, 16, 20, 21].

Rahman et al. [1] and Zakaria et al. [20] conducted in-depth assessments of the potential of renewable energy (RE) based on green hydrogen in Malaysia. Their investigation included a thorough examination of Malaysia's energy landscape, as well as an assessment of the feasibility of incorporating green hydrogen into the country's energy infrastructure. Exploring the viability of leveraging Malaysia's natural gas network for hydrogen transportation, assessing the integration of hydrogen in Malaysia's existing gas turbine (GT) plants, and examining critical factors such as energy demand, current population figures, energy policy summaries, the use of conventional energy sources, carbon emissions, and the overall trajectory of RE adoption in Malaysia were all important aspects of their analysis. Furthermore, these studies addressed the conceptual framework for hydrogen as one of the RE sources, delving into various aspects of the hydrogen economy, production technologies, storage solutions, and energy generation using green hydrogen. This comprehensive investigation provided a comprehensive view of hydrogen's potential as one of the RE sources in Malaysia. Nonetheless, it is worth noting that a critical gap exists in these studies, particularly in the realm of quantitative data and techno-economic assessment necessary for formulating investment guidelines for green hydrogen.

Benalcazar et al. [22] conducted a study that provides valuable insights into the potential of green hydrogen in Poland. Their study used a Monte Carlo approach to thoroughly analyze the complex economic and technical factors that could affect Poland's success in its green hydrogen strategy. The research also investigated the economics of green hydrogen production at different stages of technological development and market adoption. One noteworthy aspect of their approach was their ability to predict the best geographic locations for large-scale hydrogen production facilities at a low cost. This is an important factor to consider when strategically locating such facilities to maximize efficiency and minimize costs. According to their findings, the levelized cost of hydrogen (LCOH) produced by a 20-MW Proton Exchange Membrane (PEM) electrolyzer system in Poland could vary within a range. They estimated that by 2050, the LCOH could be between €1.95 and €2.03 per kg when powered by solar energy and between €1.23 and €1.50 per kg when powered by onshore wind. Jang et al. [23] conducted a comprehensive techno-economic analysis of three different offshore wind power plant configurations, each with its own hydrogen production strategy. There were three configurations: distributed hydrogen production, centralized hydrogen production, and onshore hydrogen production. To provide a thorough assessment of feasibility, the researchers used various methods, including net present value (NPV) calculations, sensitivity analysis, and Monte Carlo simulations. Their analysis yielded the following estimated hydrogen production costs for three scenarios:

- Distributed Hydrogen Production: \$13.81 per kg of hydrogen (kg$H_2$)
- Centralized Hydrogen Production: \$13.85 per kg$H_2$
- Onshore Hydrogen Production: \$14.58 per kg$H_2$

Akdağ et al. [24] presented a Monte Carlo model for extracting green hydrogen from geothermal resources, with a specific case study focusing on the Zilan region in Turkey's Van province. This region is well-known for its abundant geothermal and water resources. The researchers used their developed Monte Carlo model to calculate the installed capacity of an Organic Rankine Cycle (ORC) geothermal power plant. Lake Van was identified as an efficient location for hydrogen production by the model's results. Their estimates indicated an hourly hydrogen production potential of 18.6 kg, with a projected increase to 28 kg by 2050. This suggests that the region has a lot of potential for green hydrogen production. Furthermore, the study calculated the cost of producing one kg of hydrogen, revealing that it would be €4.91 per kg in 2022. However, by 2050, this cost is expected to drop significantly to €1.21 per kg. This decrease in production costs over time highlights the potential economic feasibility of utilizing geothermal resources for green hydrogen production in the Zilan region. All these studies highlight the critical role that Monte Carlo analysis plays in evaluating green hydrogen production, shedding light on its economic and technical aspects. They offer a wealth of information on the viability, cost-effectiveness, and geographical nuances associated with various RE sources and technologies. The current study places a strong emphasis on solar photovoltaic (PV), a prominent RE source for green hydrogen production in Peninsular Malaysia. Malaysia's geographical location, which is entirely within the equatorial region, results in a tropical climate characterized by heavy rainfall on a regular basis, consistently high temperatures, and relative humidity levels. Malaysia's annual average daily solar irradiance typically ranges from 4.21 kWh/m$^2$ to 5.56 kWh/m$^2$. Notably, the highest levels of solar radiation are observed in August and November, with peaks estimated at 6.8 kWh/m$^2$, while the lowest levels are observed in December, with levels as low as 0.61 kWh/m$^2$ [25]. These favorable solar conditions highlight Malaysia's significant solar PV energy generation potential, positioning the country as a prime candidate for a green hydrogen production hub. While it is widely acknowledged that green hydrogen is an effective solution for reducing carbon emissions, global advancement of electrolytic installations is hampered by high electricity prices and capital costs [26-28]. Despite numerous international research efforts focusing on the economic viability of individual hydrogen production and storage facilities, studies exploring the future costs associated with green hydrogen production systems in Peninsular Malaysia are noticeably lacking. Furthermore, to the best of the author's knowledge, no research has yet been conducted to investigate the technical and financial uncertainties that may impact the economics of green hydrogen production in Peninsular Malaysian coal-dependent states. As a result, the driving force behind this research is to provide timely and well-founded insights to both researchers and decision-makers regarding the economic aspects of green hydrogen production in Peninsular Malaysia, spanning from the national to regional levels. To achieve these goals, this study will play three major roles: (1) the characterization of local RE resources suitable for hydrogen production via water electrolysis; (2) the execution of a quantitative analysis aimed at evaluating the technical and economic viability of hydrogen production via solar PV potential; and (3) the use of a Monte Carlo approach to delve into the fundamental economic and technical factors that may influence the outcomes of Peninsular Malaysia's green hydrogen strategy.

To achieve these research goals, an extensive analysis of local technical, financial, and policy-related aspects of green hydrogen production is conducted. In addition, a Monte Carlo simulation framework for the techno-economic evaluation of large-scale hydrogen production systems in Peninsular Malaysia is developed. It is critical to emphasize that this study is the first to use a Monte Carlo approach to investigate the economic prospects of green hydrogen production in Peninsular Malaysian states. Furthermore, the LCOH is the primary metric used in this probabilistic approach to assess the economic performance of large-scale electrolyzers powered by solar energy. While there is a growing body of literature investigating the future role of green hydrogen in Malaysia's energy systems [1, 16, 20, 21, 29], a lack of prospective studies tailored to Peninsular Malaysia limits the scope for informed discussions about the technological alternatives available for clean energy production. As a result, this study aims to fill this gap and make contributions in four critical areas. For starters, it presents a Monte Carlo-based model for calculating the LCOH in large-scale production systems powered by ground solar PV. Second, it examines the economics of green hydrogen in Peninsular Malaysia at various stages of technological advancement and market adoption. The LCOH for large-scale PEM electrolyzers in various years (2023, 2030, and 2050) is used to accomplish this. Third, a sensitivity analysis identifies the key risk factors in large-scale green hydrogen projects. Finally, the findings provide researchers and policymakers with invaluable insights into the future costs of green hydrogen production in Peninsular Malaysia, ultimately contributing to the regional advancement of a green hydrogen economy. The rest of this paper is organized as follows: Section Materials and Methods describes the quantitative approach used in this study and elaborates on the model used to assess the economic performance of green hydrogen production systems in Peninsular Malaysia. Section Case Study describes the case study in detail, including research scenarios, core assumptions, capacity factor determination (solar PV), and data sources. Section Results and Discussions presents and compares the outcomes of various scenarios, as well as the sensitivity analysis findings. Finally, Section Conclusions provides final thoughts on the methodology and the prospects for large-scale green hydrogen production in Peninsular Malaysia.

## 2. Materials and methods

This section provides an overview of the methodology used to address the complex challenges and uncertainties associated with large-scale green hydrogen production in Peninsular Malaysia. As previously stated, the focus of this research is on the generation of hydrogen via water electrolysis, specifically using solar PV resources. Despite the availability of various electrolyzer technologies, this study provides a comprehensive model for calculating the LCOH in the context of off-grid, standalone hydrogen production systems powered by PEM electrolyzers. PEM electrolysis was chosen because of the advantageous features that make it a good choice for decentralized hydrogen production, such as high flexibility, efficiency, and a compact design [1, 22, 30, 31]. Unlike many conventional studies that rely on simplistic sensitivity analyses using single-point or expected values to predict the LCOH for upcoming or in-progress hydrogen production systems, this study takes a probabilistic approach to assess the impact of technical and economic uncertainties on hydrogen production costs in Peninsular Malaysia. In the techno-economic model, a Monte Carlo approach is used to account for the uncertainty associated with multiple input factors in the calculation of LCOH. Figure 1 depicts the approach proposed in this study.

Monte Carlo modeling is a computer-based technique that uses random sampling of inputs from probability distributions to estimate the expected value of a deterministic model or an output function [22, 32, 33]. This methodological approach is commonly used in systems or processes where conducting real-world experiments would be prohibitively expensive or impractical. The following steps are typically involved in the Monte Carlo modeling process, as summarized below [22]:

- Statistical distributions for model parameters affected by risk or uncertainty are identified.
- N random samples are generated from each probability distribution and used as input parameters for the deterministic model.
- Model outputs are computed based on each set of input parameters.

- Model outputs are statistically analyzed, and the probability density function is approximated.

The Monte Carlo method, which has been used successfully in previous studies for risk-based analyses of energy investments and project cost performance in various energy technologies [22, 34-36], has not yet been used systematically to investigate the economic viability of green hydrogen production in Peninsular Malaysian states. Given the inherent uncertainties in long-term strategic planning for green hydrogen production facilities, this study proposes a static techno-economic model that estimates potential output values using randomly generated samples from probability density functions. These probability density functions are built using subsets of observed and projected data, as is standard practice. Furthermore, the LCOH is used as a metric in the study to assess the economic feasibility of large-scale PEM electrolyzers powered by solar in various Peninsular Malaysian states. The LCOH ($/kg) is calculated as follows [22]:

$$LCOH = \frac{(C_{cc} \times CRF) + C_{O\&M} + C_{REP}}{M_{H_2}} \tag{1}$$

Where $C_{cc}$ represents the total capital cost of the electrolyzer ($), $CRF$ represents the capital recovery factor, $C_{O\&M}$ stands for the annual operation and maintenance costs ($), $C_{REP}$ indicates the annual replacement costs ($), and $M_{H_2}$ represents the total hydrogen produced by the electrolyzer in one year (kg).

The capital recovery factor, abbreviated $CRF$, converts the capital cost into a series of equivalent annual payments over the system lifetime $N$, assuming an interest rate $i$. Eq (2) is used to define it [22]:

$$CRF = \frac{i \times (1+i)^N}{(1+i)^N - 1} \tag{2}$$

The capital costs of the electrolyzer $C_{cc}$ ($) can be calculated using Eq (3) [22].

$$C_{cc} = P_{el} \times I_{el} \tag{3}$$

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

The annual operation and maintenance costs, $C_{O\&M}$ ($), consist of the costs of water, electricity, non-fuel variable operation, and maintenance [22].

$$C_{O\&M} = (\tau \times P_{el} \times u_{el} \times C_e) + (\gamma \times M_{H_2} \times C_w) + (C_{cc} \times \vartheta) \tag{4}$$

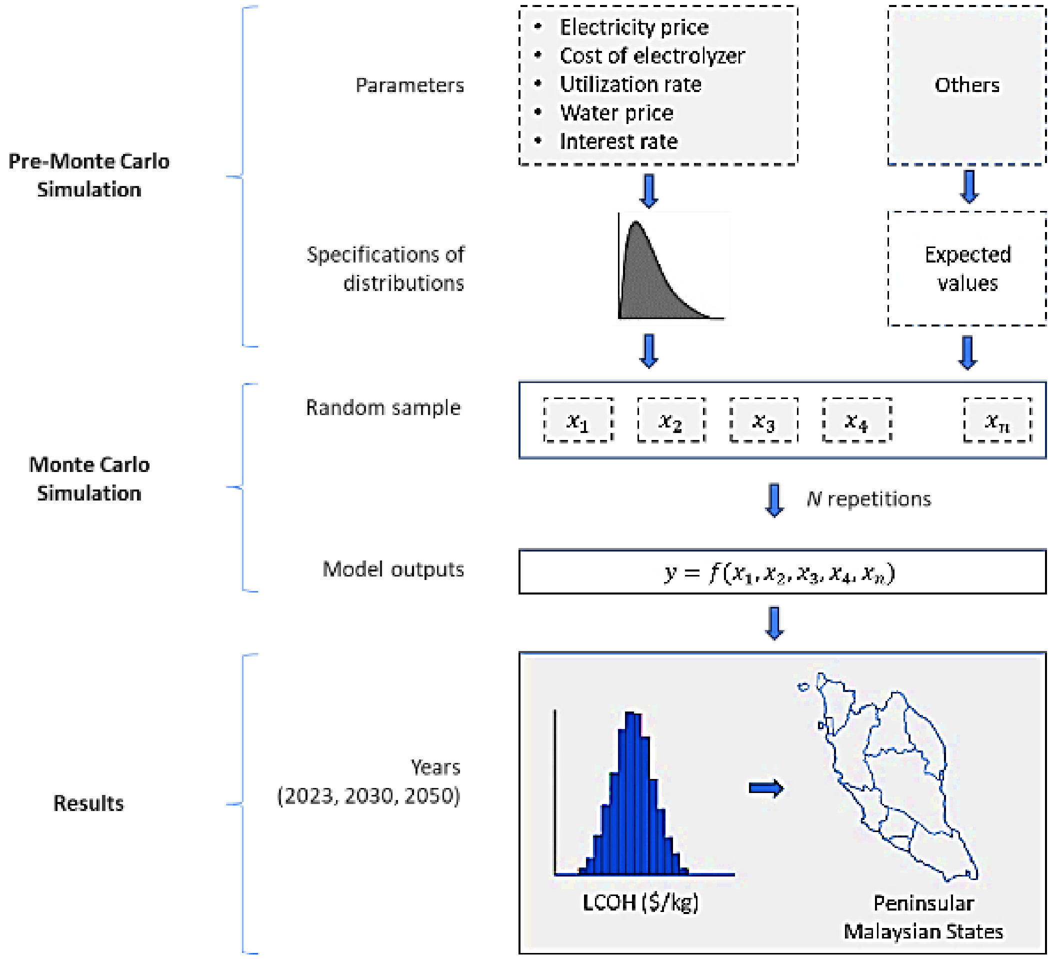



**Figure 1.** Overview of the Monte Carlo approach applied in the current study

where $\tau$ is the total number of hours in the year (h), $P_{el}$ is the rated power of the electrolyzer (kW), $u_{el}$ is the electrolyzer utilization rate expressed as a fraction of 1, $C_e$ is the electricity price ($/kWh), $\gamma$ is the water needed to generate each kg of hydrogen (L/kg), $M_{H_2}$ indicates the hydrogen generated by the installation in 1 year (kg), and $C_w$ represents the water price ($/L). Maintenance costs are assumed to be constant throughout the system's lifetime and are estimated as a fraction ($\vartheta$) of the electrolyzer capital cost.

The annual production of hydrogen using the PEM electrolyzer can be calculated by employing Eq (5) [22]:

$$M_{H_2} = \frac{\tau \times P_{el} \times u_{el}}{E_{el}} \tag{5}$$

In the equation earlier, $E_{el}$ represents the electrolyzer's power consumption in kWh/kg.

The capital recovery factor can be used to convert the replacement costs $C_{REP}$ in year $t$ into annual costs, as is shown in Eq (6):

$$C_{REP} = \frac{i \times (1+i)^N}{(1+i)^N - 1} \times \frac{C_{TotalRep}}{(1+i)^t} \tag{6}$$

where $C_{TotalRep}$ denotes the system's total replacement cost ($).

Microsoft Excel was used to implement the Monte Carlo-based model described in this section. The simulations were run on a desktop computer with a 4.7 GHz Intel Core i7-12700H processor, six cores, and 16 GB of RAM. The results of the computational tool were validated by comparing them to those produced by the H2A: Hydrogen Analysis Production Model, a well-established tool widely used in academia and industry [22, 37, 38].

A sensitivity analysis was performed to enhance the Monte Carlo approach and identify the sources of uncertainty affecting the LCOH in Peninsular Malaysian green hydrogen projects. For this analysis, five input parameters were chosen that correspond to those used for probability distribution functions: electricity price, electrolyzer cost, utilization rate, water price, and interest rate. As shown in Table 1 and Table 2, the sensitivity analysis involved systematically varying the values of a single parameter within the same ranges defined for the probability distributions. The interest rate distributional assumptions were developed using historical data from the Bank Negara Malaysia (BNM) spanning the years 2014 to 2023 [39]. Tenaga National Berhad (TNB), Peninsular Malaysia's primary electric utility provider, provided information for the distributional assumption for the electricity rate [40, 41]. Regarding the distributional assumption of water prices in Table 2, it should be noted that each Peninsular Malaysian state has its own water pricing, which is regulated by the state government [42].

In all scenarios, water prices in each state remain unchanged, assuming that water prices will remain stable until 2050 due to government subsidies, making water prices highly affordable. Table 3 also includes constant parameter values from Equations (1) to (6). It is worth noting that the majority of data sources considered in this study span 2017-2023, providing an up-to-date view of the economics of green hydrogen production in Peninsular Malaysia. The annual average capacity factor for solar ground PV was used to calculate the utilization rate ranges. The following section (Case Study) discusses how to calculate the annual average capacity factor for each state.

## 3. Case study

The methodology outlined in the Materials and Methods section was used to address the complexities and uncertainties associated with large-scale green hydrogen production in Peninsular Malaysia.

### 3.1 RE in Malaysia

Malaysia has an abundance of resources that can be used to generate RE. Among these resources are [15, 17, 54]:

- Solar irradiation for solar generation: Malaysia receives a lot of sunlight, which makes it ideal for solar power generation [55].
- Biomass from agricultural, domestic, and industrial waste for bioenergy: Biomass from agricultural, domestic, and industrial waste can be effectively burned or gasified to generate bioenergy [56].
- Rivers for small hydroelectric power: The country's rivers provide opportunities for small-scale hydroelectric power generation [57].

Malaysia had already established a significant installed capacity in RE by 2020, totaling 8,450 MW, as seen in Figure 2. The largest contributor among the various RE sources was large hydropower, with 5,692 MW, followed by solar PV, and bioenergy, with 1,534 MW and 717 MW, respectively. The small hydro capacity was 507 MW. The Malaysian government significantly increased its RE targets in 2021, aiming for 31% RE capacity by 2025 and 40% by 2035, a significant increase from the previous goal of 20% by 2025. The Malaysia Renewable Energy Roadmap, developed by the Sustainable Energy Development Authority (SEDA) Malaysia, outlines this transition plan [17]. Various RE programs and initiatives demonstrate the commitment of government agencies such as SEDA Malaysia and the Energy Commission (EC), both under the Ministry of Natural Resources, Environment, and Climate Change (NRECC). The Feed-in Tariff scheme (FiT), Large Scale Solar auction (LSS), Net Energy Metering (NEM), and Self-Consumption (SELCO) are examples of these.

**Table 1.** Distributional assumptions for the electrolyzer cost, the interest rate, and the electricity price

| 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] |
| Interest rate | % | PERT (1.69; 3.02; 3.26) | PERT (1.69; 3.02; 3.26) | PERT (1.69; 3.02; 3.26) | [39] |
| Electricity price | $/kWh | PERT (0.0404; 0.06675; 0.1142) | PERT (0.0404; 0.06675; 0.1142) | PERT (0.0404; 0.06675; 0.1142) | [40-41] |

**Table 2.** Distributional assumptions for the water price [42]

| Peninsular Malaysian states | Unit | Scenario I (2023) | Scenario II (2030) | Scenario III (2050) |
|---|---|---|---|---|
| Perlis | $/L | PERT (0.000080; 0.000158; 0.000340) | PERT (0.000080; 0.000158; 0.000340) | PERT (0.000080; 0.000158; 0.000340) |
| Kedah | $/L | PERT (0.000100; 0.000193; 0.000410) | PERT (0.000100; 0.000193; 0.000410)) | PERT (0.000100; 0.000193; 0.000410) |
| Pulau Pinang | $/L | PERT (0.000044; 0.000115; 0.000420) | PERT (0.000044; 0.000115; 0.000420) | PERT (0.000044; 0.000115; 0.000420) |
| Perak | $/L | PERT (0.000060; 0.000077; 0.000330) | PERT (0.000060; 0.000077; 0.000330) | PERT (0.000060; 0.000077; 0.000330) |
| Kelantan | $/L | PERT (0.000090; 0.000156; 0.000440) | PERT (0.000090; 0.000156; 0.000440) | PERT (0.000090; 0.000156; 0.000440) |
| Terengganu | $/L | PERT (0.000084; 0.000121; 0.000280) | PERT (0.000084; 0.000121; 0.000280) | PERT (0.000084; 0.000121; 0.000280) |
| Pahang | $/L | PERT (0.000074; 0.000126; 0.000420) | PERT (0.000074; 0.000126; 0.000420) | PERT (0.000074; 0.000126; 0.000420) |
| Selangor | $/L | PERT (0.000074; 0.000167; 0.000572) | PERT (0.000074; 0.000167; 0.000572) | PERT (0.000074; 0.000167; 0.000572) |
| Negeri Sembilan | $/L | PERT (0.000100; 0.000144; 0.000540) | PERT (0.000100; 0.000144; 0.000540) | PERT (0.000100; 0.000144; 0.000540) |
| Melaka | $/L | PERT (0.000140; 0.000473; 0.000490) | PERT (0.000140; 0.000473; 0.000490) | PERT (0.000140; 0.000473; 0.000490) |
| Johor | $/L | PERT (0.000160; 0.000318; 0.000700) | PERT (0.000160; 0.000318; 0.000700) | PERT (0.000160; 0.000318; 0.000700) |

**Table 3.** Input parameters

| Operating Parameters | Unit | Scenario I (2023) | Scenario II (2030) | Scenario III (2050) | References |
|---|---|---|---|---|---|
| Stack efficiency | % | 59.0 | 63.0 | 71.0 | [43] |
| Lifetime | Years | 20 | 20 | 30 | [44-48] |
| Power consumption | kWh/kg | 51.0 | 46.0 | 44.0 | [43] |
| Rated power of electrolyzer | kW | 1000 | 6000 | 20000 | [49] |
| Lower heating value of hydrogen ($H_2$) | kWh/kg | 33.3 | 33.3 | 33.3 | [48] |
| Replacement cost | % of electrolyzer cost | 42.0 | 42.0 | 42.0 | [50-52] |
| Maintenance cost | % of electrolyzer cost | 5.0 | 2.2 | 1.85 | [48] |
| Replacement year | Years | 7.0 | 10.0 | 15.0 | [53] |
| Water requirement | L/kg $H_2$ | 9.0 | 9.0 | 9.0 | [51] |

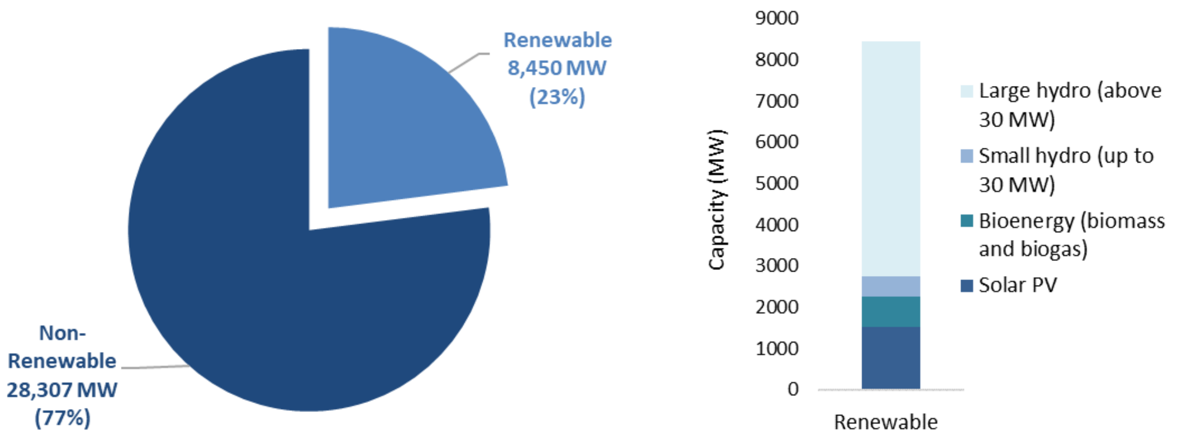



**Figure 2.** RE installed capacity as of 2020, adapted from [15, 18]

### 3.2 Key Milestones Toward Malaysia's Hydrogen Economy

As seen in Figure 3, Malaysia began its journey in hydrogen-related research and development (R&D) in the early 2000s, in line with global advances in hydrogen technology [15]. Recognizing the potential of RE resources such as biomass, biogas, municipal waste, solar, and hydro, Malaysia implemented RE as the 5th component of its energy-mix strategy in 2001 under the National Energy Policy. This strategic move aimed to capitalize on Malaysia's abundant RE resources, with the goal of contributing 5% and 10% of Malaysia's energy mix by 2005 and 2010, respectively. The Small Renewable Energy Program (SREP) was launched under the guidance of the Special Committee on Renewable Energy (SCORE) to facilitate this transition, aligning with the government's commitment to promote RE as a prominent energy source [58].

As early as the 8th Malaysia Plan (2001-2005), the Malaysian government recognized the potential of hydrogen fuel cells as a priority area for R&D, aligning this focus with its RE targets [15]. Between 1997 and 2013, the Ministry of Science, Technology, and Innovation (MOSTI) allocated RM 40 million in R&D funds for hydrogen fuel cell research. The Fuel Cell Institute, later renamed the Institute of Fuel Cell (IFC-UKM), was founded at Universiti Kebangsaan Malaysia (UKM) in July 2006 [59]. This institute marked the beginning of Malaysian research into fuel cells and hydrogen energy, beginning with constructing the country's first PEM fuel cell [16].

In 2009, the Institute of Hydrogen Economy (IHE) was founded at Universiti Teknologi Malaysia (UTM) [60]. The Fuel Cell Research Group was founded in 1996 with an RM 2 million grant, and it later received an RM 15 million grant from MOSTI's Intensification of Research in Priority Areas (IRPA) Program. As Malaysia advanced, the 9th Malaysia Plan emphasized hydrogen development through policies, programs, and roadmaps. The National RE Policy and Action Plan paved the way for the Fuel Cells and Hydrogen Roadmaps for Malaysia (2005-2030), with a focus on hydrogen generation using RE resources and the establishment of hydrogen networks to support hydrogen fuel cell vehicles [15]. Notably, the hydropower-rich state of Sarawak implemented its own hydrogen energy roadmap to harness energy from hydropower sources [21].

Phase 2, which spanned the 10th to 11th Malaysia Plans, introduced interventions in the form of legislative and financial assistance, facilitating the development of commercial-scale projects [15]. In September 2011, the Sustainable Energy Development Authority Malaysia (SEDA Malaysia) was established to administer the Feed-in Tariff (FiT) mechanism mandated by the Renewable Energy Act 2011 [61]. The FiT mechanism encouraged the industrial and public sectors to generate electricity from RE sources such as solar panels and wind turbines and to sell excess energy to the National Grid [62]. The revised target under the RE Act of 2011 was set at 985 MW, representing 5.5% of the energy mix by 2015 [15].

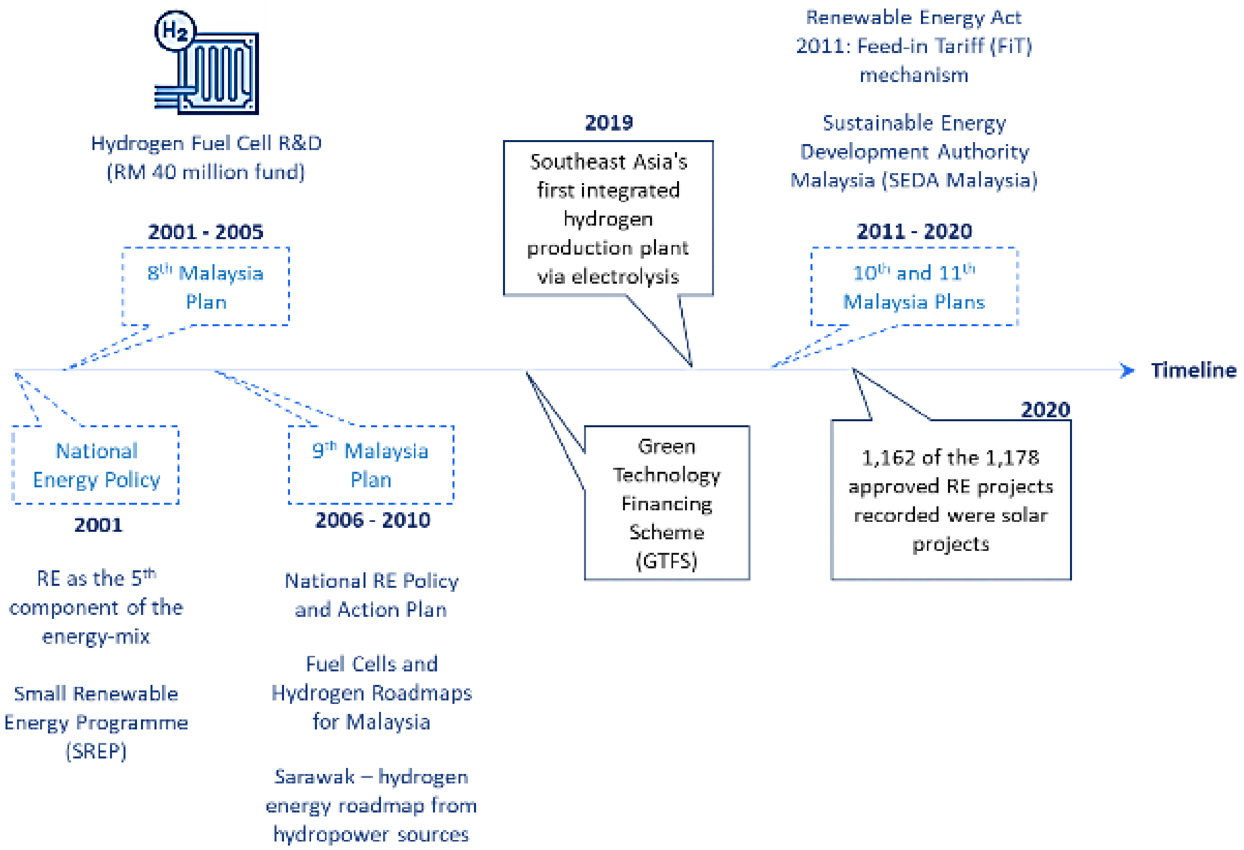



**Figure 3.** Key milestones toward Malaysia's hydrogen economy, adapted from [1, 15, 18]

Malaysia aimed for RE to account for 11% of total electricity generation, or 2,080 MW, by 2020 [15]. The Green Technology Financing Scheme (GTFS) was introduced in 2010 to encourage green investments by making financing more accessible and affordable [63]. GTFS had 28 Participating Financial Institutes (PFIs) for 319 projects totaling RM 3.638 billion as of December 2017. This scheme created 4,909 job opportunities and contributed to a reduction in $CO_2$ emissions of 3,784 million tons per year. In line with the Malaysian government's green economy agenda, the Malaysian Green Technology and Climate Change Centre (MGTC) was tasked with overseeing Green Investment Tax Allowances (GITA) [64] and Green Income Tax Exemption (GITE) to promote green technology adoption [65].

Industry players are increasingly venturing into RE commercialization as Malaysia's hydrogen economy framework takes shape. Sarawak Energy Berhad (SEB), for example, established Southeast Asia's first integrated hydrogen production plant via electrolysis, complete with a refueling station and the introduction of the state's first hydrogen-powered vehicles as a demonstration project [1]. NanoMalaysia Berhad (NMB) is developing in-situ hydrogen production and hydrogen hybrid energy storage systems in the Energy and Environment domain. In 2020, 1,162 of the 1,178 approved RE projects recorded in the government's database were solar projects, reflecting the widespread adoption of solar energy due to its low cost [15].

### *3.3* National energy transition roadmap (NETR)

The national total primary energy supply (TPES) was primarily driven by four sources as of 2020. Natural gas had the highest contribution, accounting for 42.4%, followed by crude oil and petroleum products at 27.3% and coal at 26.4%. Renewables, primarily hydropower, solar, and biofuels, supplied only 3.9% of the total [18]. As a result, the government has increased its RE capacity goal from 40% in 2035 to an ambitious 70% by 2050.

The Malaysian government has recently announced the NETR, which is a comprehensive guide to achieving 70% RE capacity by 2050 [17]. The NETR introduces six critical energy transition levers, one focused on hydrogen. This lever attempts to improve hydrogen's viability and competitiveness through regulatory initiatives and innovation while negotiating long-term agreements with importing countries. The following are the primary hydrogen initiatives within this framework:

- Establishing low-carbon hydrogen standards and regulations.
- Increasing domestic production capacity for green electrolyzers.
- Improving the economics of hydrogen hubs by lowering the LCOH for low-carbon hydrogen.
- Increasing demand for low-carbon hydrogen through exploring bilateral agreements with important importing nations, promoting the development of the low-carbon hydrogen value chain, and ensuring long-term green hydrogen commitments.

The inclusion of LCOH as a key program in Malaysia's NETR emphasizes the importance of the current research, which is the estimation of LCOH for the years 2023, 2030, and 2050, aligning with the nation's goal of net-zero carbon emissions.

### 3.4 Green hydrogen production from solar PV

Since the energy industry has been the primary source of GHG emissions in Peninsular Malaysia [66], the use of power-to-gas-to-power technology is one possible method for decarbonizing Peninsular Malaysia's energy systems and allowing long-term economic change [1, 67]. This strategy emphasizes the significance of both key aspects of the hydrogen sector, such as green hydrogen production [1, 68] and green hydrogen for power generation (hydrogen co-firing) [1, 69-70]. Malaysia's diverse range of solar resources, combined with their significant capacity, highlight the country's enormous potential for solar PV power generation. This favorable scenario positions Malaysia to capitalize on these resources to expand its RE sector and meet its ambitious RE targets.

Figure 4 depicts Malaysia's RE resource potential, as measured in equivalent power generation capacity [15]. Malaysia has a remarkable total RE supply potential of 288.9 GW, with solar PV accounting for 269 GW, or 93.1%. Solar PV is the primary contributor to the country's RE resource potential, with the highest power generation capacity potential of any RE source in Malaysia.

Peninsular Malaysia has a wealth of solar resources due to its proximity to the equator, as seen in Figure 5, making it an ideal candidate for leveraging solar energy in green hydrogen production. Solar installations are strategically distributed across the country in various geographical areas. This widespread adoption of solar power generation not only contributes to Malaysia's RE goals but also positions the country favorably for the long-term production of green hydrogen, bolstering Malaysia's commitment to a cleaner and more sustainable energy landscape. As illustrated in Figure 4, Malaysia's solar PV potential is divided into three types of solar technology: rooftop solar, floating solar, and ground-mounted solar [15].

- Ground-mounted solar installation on unused land: This category includes installations on flat land that is not zoned for any particular use and excludes water bodies, forests, agricultural land, and mountainous areas [15, 71]. Ground-mounted solar installations on such land have the greatest solar potential in Malaysia, with an estimated 210 GW [15]. The availability of ample unused suitable land drives this potential.
- Floating solar PV resource: Malaysia has an estimated 16.6 GW of floating solar PV installation potential. This includes floating installations on bodies of water at 17 large hydroelectric power plants and 62 reservoir dams, totaling approximately 2,944 $km^2$ in surface area.
- Rooftop solar PV resource: Peninsular Malaysia has the most rooftop solar PV potential, with 37.4 GW. This is primarily due to the region's high level of urbanization. Sarawak and Sabah, on the other hand, have rooftop solar PV potentials of 2.6 GW and 2.2 GW, respectively [15]. Installations on residential, commercial, industrial, and building rooftops harness these resources [15, 72].

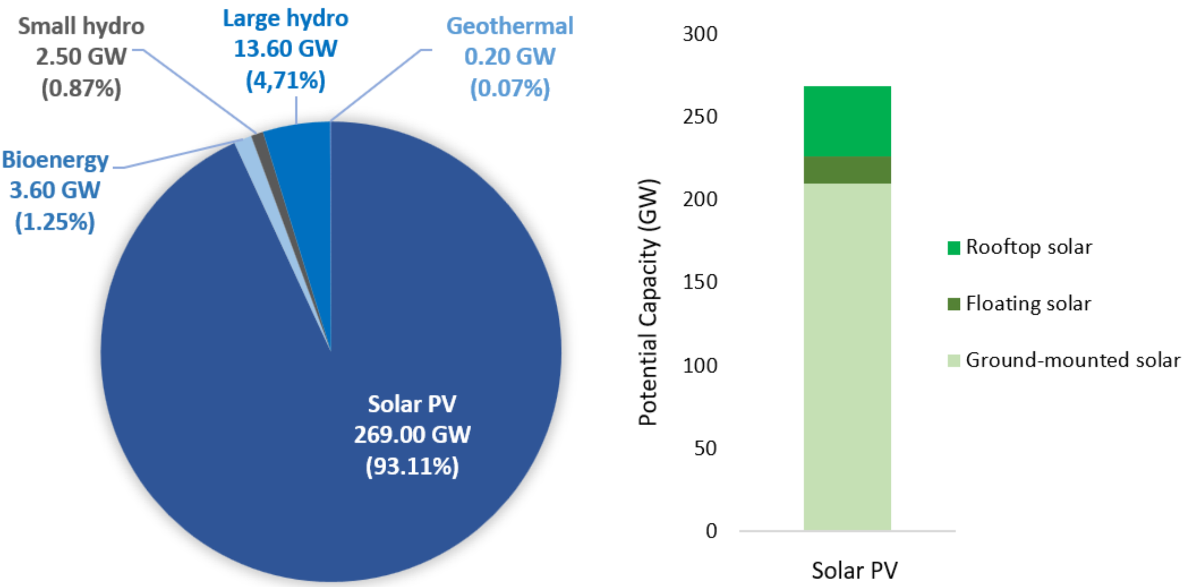



**Figure 4.** RE potential in Malaysia, adapted from [15]

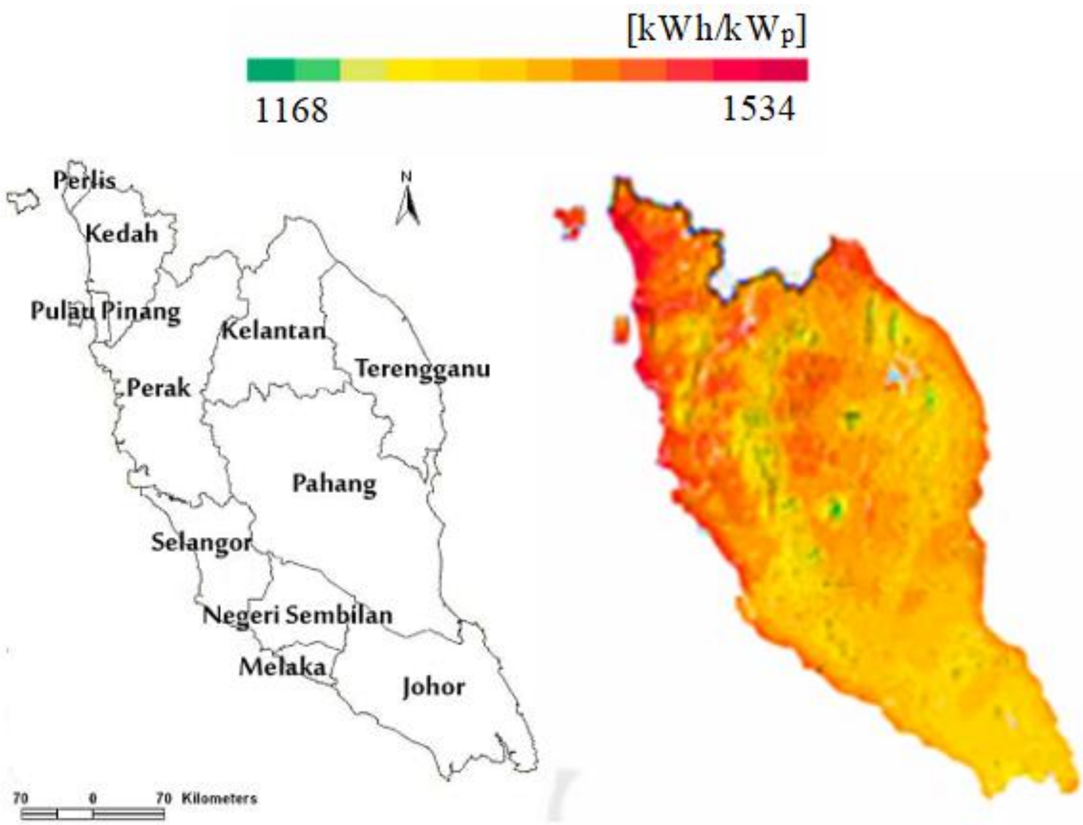



**Figure 5.** Solar irradiance level in Peninsular Malaysia, adapted from [73]

While Malaysia's power system remains heavily reliant on natural gas and coal, RE capacity has steadily increased in recent years. However, due to the intermittent and non-dispatchable nature of renewable sources, particularly solar PV with lower capacity factors when compared to thermal power plants, renewable electricity generation (excluding hydropower) contributed only 3,285 GWh in 2020, accounting for 1.92% of total electricity production [18]. Figure 6 depicts the evolution of electricity generation for various technologies in Malaysia since 2015.

According to the most recent update of the Malaysian government's Hydrogen Economy and Technology Roadmap (HETR), Malaysia is making a concerted effort to achieve its target of a 31% RE capacity mix by 2025. To achieve this goal, plans have been put in place to develop 1,178 MW of new RE capacity in Peninsular Malaysia, beginning in 2021. This addition includes 1,098 MW of solar PV capacity, signaling a promising trajectory for green hydrogen production through solar PV in the near future [15]. However, despite these significant developments, there has yet to be a comprehensive regional-level study that systematically examines the economic competitiveness of future green hydrogen production through solar PV in Peninsular Malaysia. As a result, this study encompasses all states in Peninsular Malaysia and employs the Monte Carlo simulation method to thoroughly evaluate the economic feasibility of large-scale hydrogen production in off-grid standalone facilities. This research aims to shed light on the viability and potential of green hydrogen production in the region, ultimately contributing to the nation's sustainable energy goals. In accordance with the primary objectives outlined in the proposed Hydrogen Strategy, as detailed in the NETR, the study conducts a comprehensive economic analysis of a 1-MW PEM electrolyzer system powered entirely by solar energy across all Peninsular Malaysian states. This analysis is critical regarding the development of the domestic hydrogen industry.

It acknowledges that the potential of RE, particularly solar power, varies greatly depending on the unique geographical conditions found throughout Peninsular Malaysia. Furthermore, this study expands its analysis to include the economic performance of 6-MW and 20-MW PEM electrolyzers to provide a more comprehensive overview of the trajectory of green hydrogen production in Peninsular Malaysia. Based on global strategies and trends [22], this study assumes that 6-MW capacity electrolyzers will be available by 2030, followed by the availability of 20-MW capacity electrolyzers in 2050.

### 3.5 Techno-economic considerations of local green hydrogen generation

The study has been designed to investigate three distinct research scenarios, each of which is intended to examine the economic viability of green hydrogen production in Peninsular Malaysia at various stages of technological development and market adoption. It is important to note that the costs of hydrogen storage and transportation were not considered in this study. The three scenarios are as follows:

**Scenario I**: Scenario I revolves around a 1-MW PEM electrolyzer system that will be deployed in 2023. The system operates independently of the transmission grid and is entirely powered by ground solar PV. In this scenario, data from a typical solar PV capacity factor from each state is used to evaluate the effect of different utilization rates on the LCOH.

**Scenario II**: A 6-MW stand-alone green hydrogen production system is investigated in this scenario. It is assumed that by 2030, water electrolysis technologies will have advanced to the point of being ready for large-scale deployment in Peninsular Malaysia.

**Scenario III**: In the year 2050, this scenario investigates the economic performance of a 20-MW PEM electrolyzer powered by ground solar PV. It anticipates that as technology advances, RE capacity factors will increase.

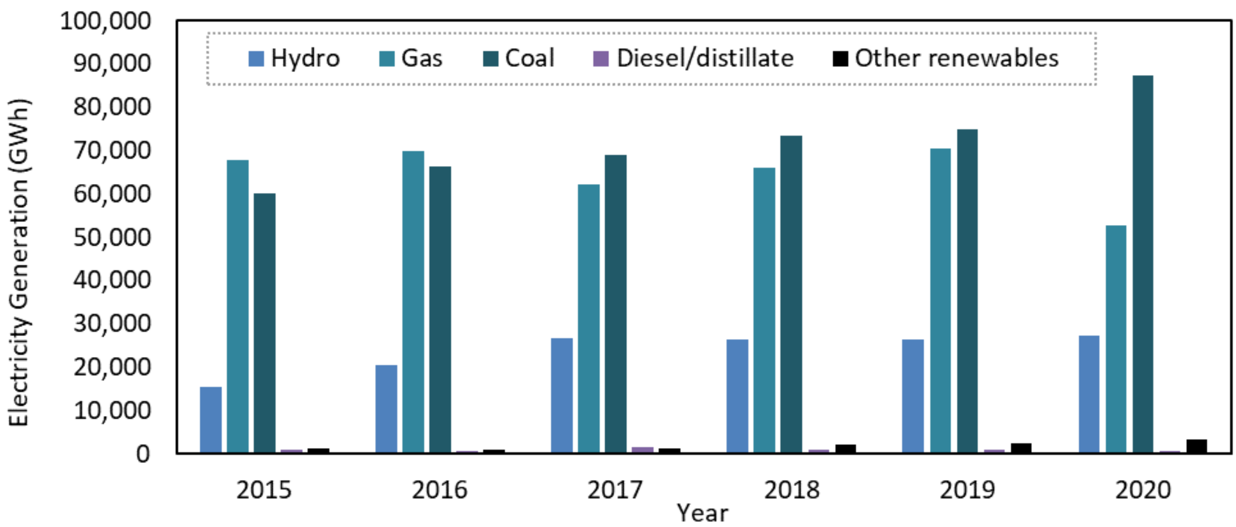



**Figure 6.** Electricity generation mix in Malaysia (adapted from [18])

It also assumes that learning curves and economies of scale will result in significant cost reductions in PEM and solar technologies. It is critical to understand that each scenario is calculated using specific economic and technical assumptions. Levelized costs of renewable electricity for ground solar PV, investment costs for electrolyzers, efficiencies, lifetimes, maintenance costs, replacement costs, and replacement years are among these. Future changes in the capital costs of renewable technologies are also considered within the scenarios. The scenarios also assume the installation of new ground solar PV systems in 2030 and 2050 to tap into the RE potential for powering the electrolyzers.

A variety of technical and economic parameters define the electrolyzers studied in this research, including:

- **Rated power**: The electrolyzer's nominal power capacity.
- **1 kg of hydrogen energy consumption**: The amount of energy required to produce one kilogram of hydrogen.
- **Utilization rate throughout the year**: The percentage of time the electrolyzer runs in a given year.
- **Maximum hydrogen production in a year**: The most hydrogen that the system can produce in a given year.
- **PEM electrolysis efficiency (including losses coefficient)**: The overall efficiency of the PEM electrolysis process, taking losses into account.
- **Lifetime**: The electrolyzer's expected operational lifespan.
- **Replacement intervals**: The time periods between which the electrolyzer components may need to be replaced.
- **Capital expenditures**: The initial costs of establishing the electrolyzer system.
- **Maintenance costs**: Ongoing expenses associated with the system's maintenance and upkeep.
- **Replacement costs**: The costs of replacing components or the entire system during the system's operational life.

Given the fact that green hydrogen production in Peninsular Malaysia is still in its early stages, the LCOH at both the national and local levels is influenced by a plethora of independent parameters, each with a degree of uncertainty. The study employs a Monte Carlo approach to account for this uncertainty. The uncertainties associated with the input parameters are expressed using probability distributions, specifically beta-PERT distributions. These distributions were chosen because they can be estimated using a small sample size and have three key parameters: lower bound (minimum value), upper bound (maximum value), and most likely value (mode).

Table 1 shows the distribution types and parameters used in this study. Data for these estimates were gathered from various public sources, including academic publications, government reports, and international organizations. Data on electrolyzer technologies, for example, was obtained from IRENA, IEA, Bloomberg, Deloitte, and others. Data on ground solar PV technologies were gathered from various sources, including IRENA, NREL, Bloomberg NEF, and others.

It is worth noting that many of these data sources span 2017-2023, ensuring that the study provides an up-to-date view of the economics of green hydrogen production in Peninsular Malaysia. Furthermore, water prices for hydrogen production were estimated using historical data sets, considering that each Peninsular Malaysian state has its own water pricing structure set by the state government.

Table 3 shows the constant parameters used in the Equations (1) to (6). This comprehensive approach, which incorporates probability distributions and data from various credible sources, enables a robust analysis of the economic aspects of green hydrogen production in the region while addressing the inherent uncertainties in such endeavors in the early stages.

### 3.6 Annual average capacity factor (solar PV) for Peninsular Malaysian states

The capacity factor is a metric used to evaluate the efficiency and utilization of solar PV generating units in Peninsular Malaysia. It is defined as the ratio of the electricity actually produced by the generating unit over a given time period to the electrical energy that could have been produced if the unit had operated at its maximum continuous full power capacity for the entire time period [74].

Based on the annual average capacity factors of solar PV in each state, the parameters for the PERT distributions of the PEM electrolyzer utilization rates in each Peninsular Malaysian state were determined. The Grid System Operator (GSO) website was used to access the real-time solar generation profiles in Peninsular Malaysia, which covered data from September 2022 to September 2023 [75], as seen in Figure 7. The average annual capacity factors for solar PV in each state were calculated using these profiles.

Statistical analyses were performed on hourly datasets to estimate the yearly average capacity factors for ground solar PV (Table 4). The upper, lower, and most likely values of the PERT distributions were calculated using monthly average capacity factors for each Peninsular Malaysian state. The PERT probability distribution's upper limit was set at the highest monthly average capacity factor observed throughout the year. Similarly, the lowest and mean values of the monthly average capacity factors were chosen as the distribution's lower limit and most likely value.

## 4. Results and discussions

This section provides a summary of the results and explores the future developments in the LCOH in Peninsular Malaysia. It presents the LCOH values for the years 2023, 2030, and 2050 for large-scale PEM electrolyzer systems powered by local solar PV energy sources. Since the model relies on the Monte Carlo Simulation approach, it generates probability distributions for multiple LCOH outcomes. Additionally, this section compares the LCOH distributions across three selected regions: favorable, unfavorable, and average capacity factor (CF) locations. Finally, the results of the sensitivity analysis are discussed, highlighting the key factors influencing risk in Peninsular Malaysian green hydrogen projects.

### 4.1 LCOH in Peninsular Malaysian states

The LCOH distributions in the target years (2023, 2030, and 2050) for the eleven Peninsular Malaysian states were calculated using the simulation model described in the Materials and Methods section. The median values were chosen in this study to represent the central tendency of the probability distributions. As a result, the maps in Figure 8 depict the median LCOH values for each state, with all monetary amounts given in real terms ($2023).

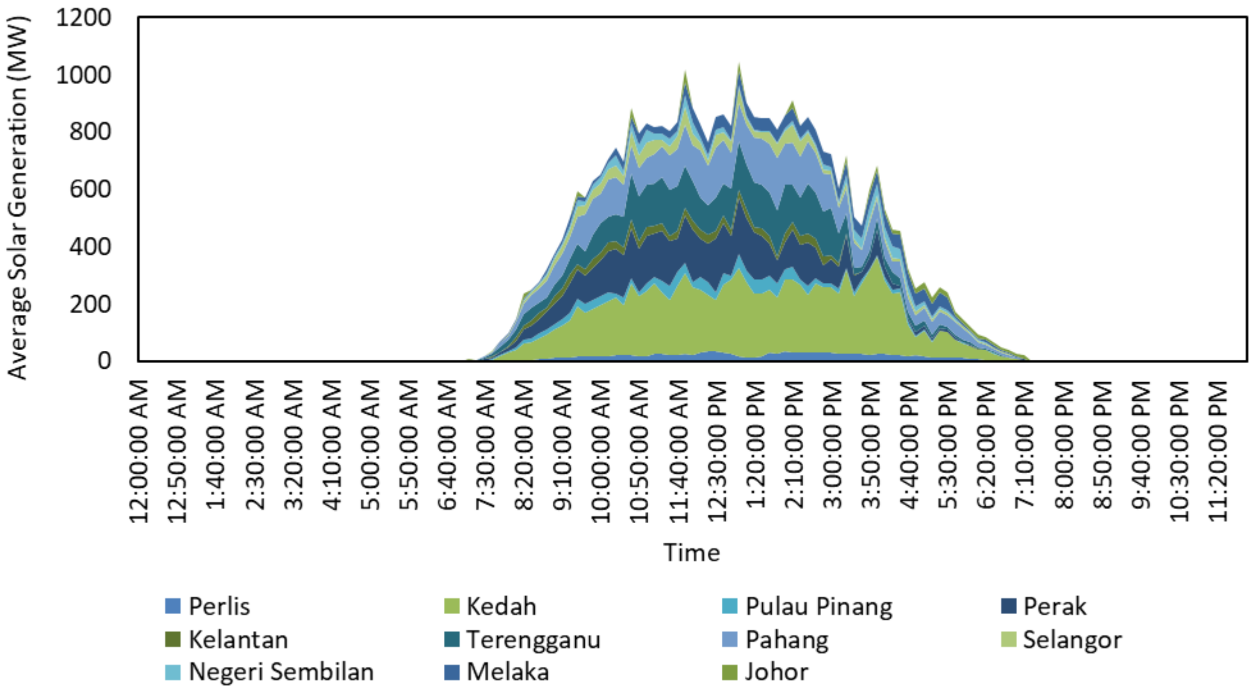



**Figure 7.** Daily average solar generation profile in Peninsular Malaysia (September 2022 to September 2023), adapted from [75]

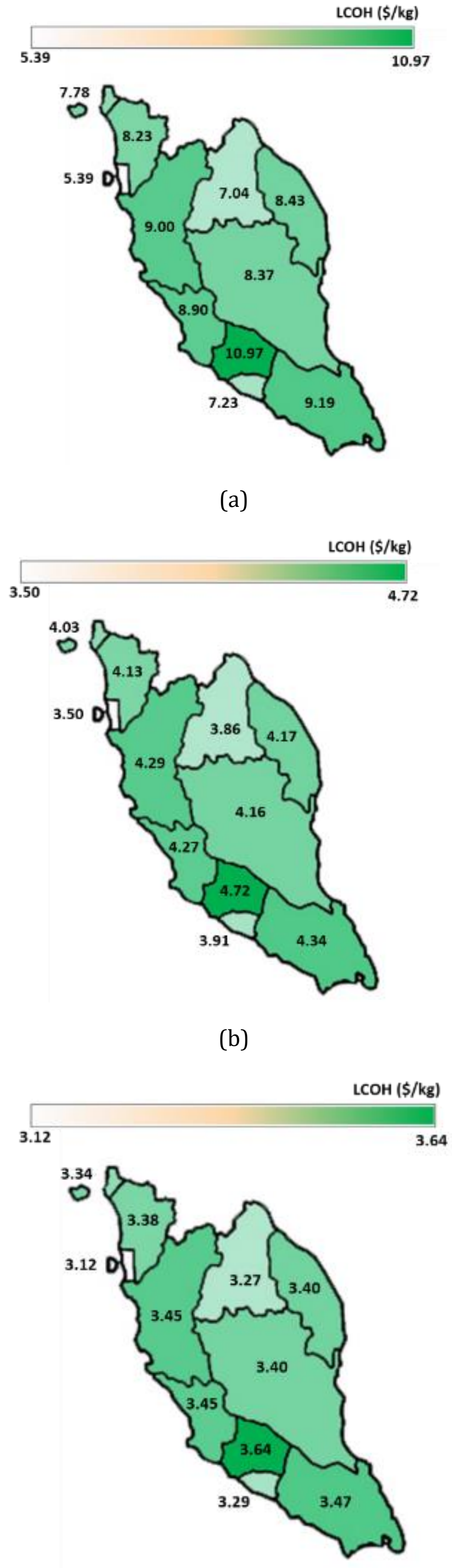
**Table 4.** Annual average capacity factor (solar PV) for each Peninsular Malaysian state

| Peninsular Malaysian states | Annual average capacity factor (CF) |
|---|---|
| Perlis | 0.2177 |
| Kedah | 0.1972 |
| Pulau Pinang | 0.4792 |
| Perak | 0.1701 |
| Kelantan | 0.2621 |
| Terengganu | 0.1894 |
| Pahang | 0.1916 |
| Selangor | 0.1731 |
| Negeri Sembilan | 0.1258 |
| Melaka | 0.2489 |
| Johor | 0.1645 |

Figure 8(a) depicts the median LCOH values for Scenario I, which involves the deployment of a 1-MW PEM water electrolyzer system powered by ground solar PV in 2023. These prices range from $5.39 to $10.97 per kg, depending on the Peninsular Malaysian states' geographical location. The northern parts of Peninsular Malaysia have the lowest LCOH values. This observation is consistent with previous studies that have mapped solar radiation in the region [73, 76, 77]. Due to the influence of monsoon seasons, the northern part of Peninsular Malaysia receives more solar radiation than the southern part. The northeast and southwest monsoons, which alternate throughout the year, have an impact on Malaysia's climate [76, 77]. The northeast monsoon lasts from October to March, while the southwest monsoon lasts from May to September [76].

Heavy rain marks the transition between these two monsoons. The northern part of the Peninsula, which is shielded by Sumatra's landmass, experiences a drier period during the southwest monsoon [76]. Furthermore, Malaysia's maritime scenario results in abundant rainfall, which, as previous studies have shown, can affect solar radiation levels [77]. This explains the differences in solar potential and, as a result, LCOH values between Peninsular Malaysia's northern and southern regions. Figure 8(b) in Scenario II (2030) depicts the LCOH values generated by ground solar PV in Peninsular Malaysia. In this scenario, the LCOH values range from $3.50 to $4.72 per kg. Because the land available for solar PV projects is assumed to be constant in all three scenarios, changes in technical and economic factors have the greatest influence on the spatial distribution of LCOH estimates. These changes include lower PEM electrolyzer capital costs and lower generation costs from ground solar PV systems. As a result, Figure 8(b) shows that LCOH production decreased by 35% to 57% in all Peninsular Malaysian states over a 7-year period when compared to Scenario I (2023). The decrease in LCOH values is a positive development that reflects cost-effectiveness improvements driven by technological advancements and reductions in capital and operational expenses.

The LCOH produced by ground solar PV in 2050 (Scenario III) is depicted in Figure 8(c). While the spatial distribution of LCOH is similar to the previous two scenarios, the LCOH values have dropped to a range of $3.12 to $3.64 per kg. This decrease represents a drop of nearly 11% to 22% when compared to Scenario II (2030) and a significant drop of 42% to 67% when compared to Scenario I (2023). These significant LCOH reductions show the long-term impact of technological advancements and cost reductions in both PEM electrolyzers and ground solar PV systems, making green hydrogen production even more economically competitive.




(c)

**Figure 8.** LCOH at the Peninsular Malaysia states for: (a) Scenario I (2023), (b) Scenario II (2030), and (c) Scenario III (2050)

## 4.2 LCOH distributions

The LCOH formula in Eq (1) takes into account a variety of input parameters that are subject to change and uncertainty. The current study uses a Monte Carlo approach to incorporate the variability of these inputs into the LCOH calculation to address this uncertainty. This procedure, as described in Section Materials and Methods, entails selecting the variables in the LCOH formula that are uncertain, also known as the "transfer equation". The probability distributions specified in Table 1 and Table 2 are then used to generate independent random values.

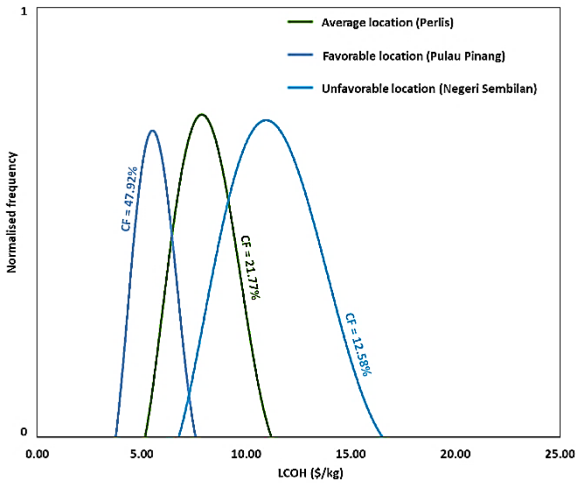
To facilitate the simulation process, these random value generation functions were implemented in Microsoft Excel. It is worth noting that while many studies follow conventional rules or use a standard number of replications, the number of replications in this study was determined using the methodology proposed by Geissmann et al. [78]. Using this method, it was discovered that $3x10^5$ replications provide a precise representation of the LCOH without compromising computational efficiency. This rigorous approach ensures that the potential outcomes and uncertainties associated with green hydrogen production costs in Peninsular Malaysia are thoroughly examined.

The LCOH distributions for Peninsular Malaysian states with varying electrolyzer utilization rates are depicted in Figures 9(a) to 9(c). These states include those with the highest and lowest utilization rates, as well as one with a rate close to the national average. It is worth noting that the y-axes of these distributions have been rescaled to fall between 0 and 1, allowing for easier visual comparison and emphasizing the effect of location on the LCOH distributions.

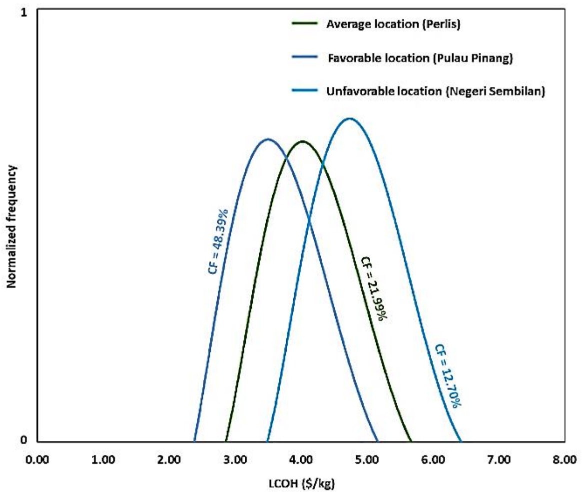
Under Scenario I, as seen in Figure 9(a), the most favorable location for green hydrogen production is Pulau Pinang, which is located in the western part of Peninsular Malaysia. The LCOH values in this region generate a relatively narrow distribution, indicating lower uncertainties and risks when compared to other assessed states. Negeri Sembilan (an unfavorable location) and Perlis (an average capacity factor location) have wider distributions with longer tails, indicating higher levels of uncertainty. Pulau Pinang's LCOH values cluster more closely around the mode value of $5.39 per kg, indicating that this value is the most likely to be observed. Table 5 contains additional information, such as the $5^{th}$, $50^{th}$, and $95^{th}$ percentiles of these distributions. Scenarios II (2030) and III (2050) are depicted in Figures 9(b) and 9(c), respectively. These scenarios involve varying economic and technical assumptions. Despite these distinctions, the uncertainty distributions for states with favorable, unfavorable, or average capacity factor locations are strikingly similar. This resemblance can be attributed to minor variations in ground solar PV capacity factors across the country, indicating consistent results across these scenarios.

## 4.3 Primary factors influencing the LCOH

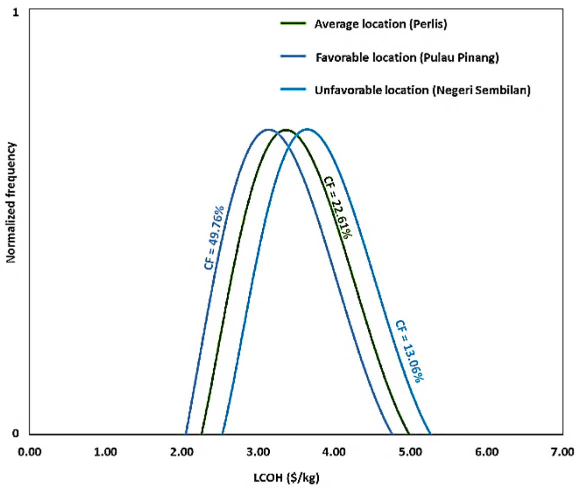
The results of the sensitivity analysis for each scenario considered in the study are depicted in Figures 10(a) to 10(c). The parameters with values close to 1 have the greatest influence on the calculated LCOH. The horizontal bars are sorted in descending order based on their impact on LCOH, from the most significant to the least significant.




(a)

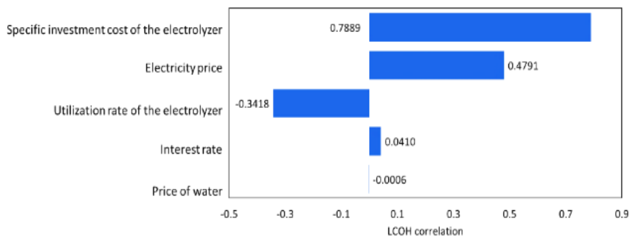



(b)

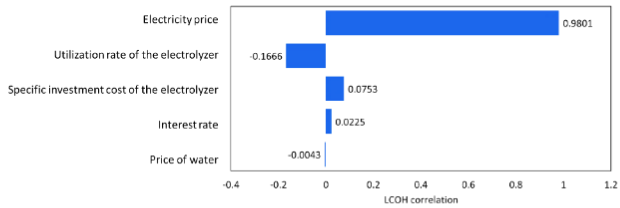



(c)

**Figure 9.** Uncertainty LCOH distributions for the Peninsular Malaysian states with the highest and lowest electrolyzer utilization rates, and the region with the utilization rate closest to the national average: (a) Scenario I (2023), (b) Scenario II (2030), and (c) Scenario III (2050)




(a)

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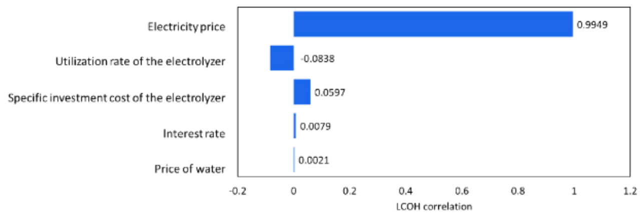


(c)

**Figure 10.** Key LCOH cost drivers for (a) Scenario I (2023), (b) Scenario II (2030), and (c) Scenario III (2050)

The relative importance of the parameters varies with the year studied. Changes in electrolyzer investment costs have the greatest impact on the LCOH in 2023 (Scenario I), with a correlation value of 0.7889, as seen in Figure 10(a). The LCOH is most sensitive to changes in electricity prices in 2030 and 2050 (Scenarios II and III). In these years, the correlation between electricity prices and LCOH exceeds 0.9, indicating that LCOH has become increasingly sensitive to electricity prices over time.

It is worth noting that in Scenario I (2023), three parameters significantly correlate with LCOH: electrolyzer specific investment cost, electricity price, and electrolyzer utilization rate, with absolute correlation values ranging from 0.3418 to 0.7859. The utilization rate of the electrolyzer and the specific investment cost of the electrolyzer have a lower absolute correlation with LCOH in 2030 and 2050, ranging from 0.0753 to 0.1666 for 2030 and 0.0597 to 0.0838 for 2050. The interest rate and the price of water, on the other hand, have negligible sensitivity in all scenarios due to minor changes in the values of these parameters. This implies that changes in these two variables have little effect on the economic performance of green hydrogen production systems in Peninsular Malaysia.

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

| **Scenario I (2023)** | | | |
|---|---|---|---|
| LCOH ($/kg) | Percentiles | | |
| | P5 | P50 | P95 |
| Favorable location (Pulau Pinang) | 4.22 | 5.60 | 7.14 |
| Average CF location (Perlis) | 5.88 | 8.03 | 10.52 |
| Unfavorable location (Negeri Sembilan) | 7.89 | 11.25 | 15.22 |
| **Scenario II (2030)** | | | |
| LCOH ($/kg) | Percentiles | | |
| | P5 | P50 | P95 |
| Favorable location (Pulau Pinang) | 2.69 | 3.62 | 4.76 |
| Average CF location (Perlis) | 3.20 | 4.14 | 5.28 |
| Unfavorable location (Negeri Sembilan) | 3.84 | 4.83 | 6.00 |
| **Scenario III (2050)** | | | |
| LCOH ($/kg) | Percentiles | | |
| | P5 | P50 | P95 |
| Favorable location (Pulau Pinang) | 2.35 | 3.24 | 4.32 |
| Average CF location (Perlis) | 2.56 | 3.46 | 4.55 |
| Unfavorable location (Negeri Sembilan) | 2.84 | 3.75 | 4.85 |

## 5. Conclusions

The economic performance of large-scale PEM electrolyzers powered by solar energy in various states of Peninsular Malaysia was evaluated using a Monte Carlo approach in this study. The study looked at three key years: 2023, 2030, and 2050, each representing a different stage in the development and adoption of green hydrogen production. This study's findings highlight the shifting landscape of green hydrogen economics in Peninsular Malaysia. The LCOH for a 1-MW PEM electrolyzer system in 2023 ranged from $5.39 to $10.97 per kg, highlighting early-stage challenges and uncertainties. Fast forward to 2030, and the outlook improves significantly, with a 6-MW PEM electrolyzer system potentially achieving the LCOH of $3.50 to $4.72 per kg. According to the study, green hydrogen will have a bright future in 2050, with the LCOH for a 20-MW PEM electrolyzer system in Peninsular Malaysia potentially falling to $3.12 to $3.64 per kg. This significant reduction can be attributed to the advancement of solar technologies as well as significant cost reductions in PEM technologies. Interestingly, regardless of the year or electrolyzer capacity, Peninsular Malaysia's northern regions consistently had the lowest LCOH values for solar-based hydrogen production, owing to the favorable geographical conditions in these areas. This study closes a significant knowledge gap by shedding light on the long-term prospects for green hydrogen production in Peninsular Malaysia. Green hydrogen may become a competitive and economically viable alternative to other green energy sources by 2050, according to the findings. Furthermore, the study reveals that the uncertainty distributions of LCOH for ground solar PV are stable across diverse regions, owing to marginal variations in annual average capacity factors of solar resources. Certain regions in Peninsular Malaysia may face increased uncertainties in the years ahead, highlighting the need for additional policy support mechanisms to mitigate risks associated with green hydrogen energy investments. The sensitivity analysis highlights the changing key cost drivers, with early-stage investments in electrolyzers playing a key role in 2023, while electricity prices gain prominence in influencing LCOH as the years progress, particularly in 2030 and 2050.

### 5.1 Implications for policies

The study's findings provide critical insights into the transformative shifts expected in Peninsular Malaysia's energy sector over the next few decades. The findings highlight two critical aspects: first, the geographic areas where large-scale PEM hydrogen production facilities will be most economically viable, and second, the regions that will require additional policy instruments to mitigate the risks associated with hydrogen investments. As a result, these findings promote informed debates about the available technological alternatives for clean energy production and provide timely, evidence-based information on the economic dynamics of green hydrogen in Peninsular Malaysia. The study emphasizes the importance of policymakers and regulators developing strategies that are tailored to the specific conditions of each region. It is clear that new policy instruments will be required to support green hydrogen production, particularly in Peninsular Malaysian states that facing 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 and boost the economic competitiveness of Peninsular Malaysia's industrial sector, which currently relies heavily on fossil fuels. Furthermore, these findings add momentum to the ongoing debate about the importance of policy interventions to foster hydrogen technologies and infrastructure in Peninsular Malaysia. The findings highlight the need for specific states to develop a hydrogen grid and supply chain in the coming decades. As the LCOH in Peninsular Malaysia becomes more competitive, green hydrogen may emerge as a viable alternative to natural gas. As a result, policymakers must focus their efforts on developing strategic blueprints for establishing a hydrogen supply chain, taking into account the strategic placement of production facilities and the availability of renewable resources. Moreover, policies and strategies for advancing the hydrogen supply chain should be intricately intertwined with public policies that strengthen RE capacity. Given Peninsular Malaysia's continued need to generate energy from coal, addressing the multifaceted challenges of decarbonization necessitates a comprehensive assessment of various solutions. Access to information about renewable potential and the long-term viability of green hydrogen production in these states can provide novel and valuable insights into the future paths of hydrogen storage and solar energy applications. As a result, these findings have the potential to shape strategies and initiatives aimed at promoting sustainable energy transitions in coal-dependent states.

## 6. Study limitations and future research

While the approach developed here can be used to assess LCOH in other countries and regions, more research is needed to fully explore the opportunities associated with green hydrogen production. Future research could include expanding and refining the Monte Carlo approach to account for the effect of storage and transportation on LCOH for green hydrogen. Furthermore, combining the proposed methodology with mathematical programming may be a promising avenue for optimization, providing intricate insights into the dynamic behavior of energy systems for green hydrogen production, particularly in areas with relatively underdeveloped green hydrogen industries and infrastructure, such as Peninsular Malaysia. Such research tools could shed light on whether Peninsular Malaysia is poised to play an important role in ASEAN, either as a green hydrogen importer or exporter, and provide valuable guidance to policymakers seeking to accelerate the decarbonization of coal-dependent economies. A critical area that requires additional research is the exploration of optimal system configurations, including the capacity of electrolyzers and renewable technologies in relation to their geographic location. Although the capacity of the renewable power system was directly linked to the capacity of the electrolyzer in this study, recent research findings suggest that location-specific characteristics have a significant impact on the optimal configuration of hydrogen production systems. As a result, our future work will concentrate on optimizing hybrid installations while taking into account the unique characteristics of various Peninsular Malaysian states. Furthermore, the method described in this study will be expanded to include indirect costs associated with the construction, installation, and operation of green hydrogen systems, as these cost components have a significant impact on the economics of electrolyzers and the LCOH.

## Ethical issue

The authors are aware of and comply 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 authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

## Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

## Conflict of interest

The authors declare no potential conflict of interest.

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