Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Multi-Criteria Assessment for Hydrogen-Based Decarbonisation Towards Net-Zero Emission for Eco-Industrial Parks in Malaysia

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ARTICLE INFO

Article history:
Received 3 February 2025
Received in revised form 17 March 2025
Accepted 30 June 2025
Available online 20 July 2025

Keywords:
Analytic hierarchy process; eco-industrial park; industrial symbiosis; green hydrogen; sustainable energy planning; energy transition

ABSTRACT

This study employs the Analytic Hierarchy Process (AHP) methodology to conduct multi-criteria decision-making and determine the hydrogen-based energy transition model for the Eco-Industrial Park's decarbonization, based on the Malaysian industrial landscape. This research study is performed by incorporating the integration criteria of the industry supply chain and enabling parameters of funding, infrastructure, regulation, skills, and technology in the computational process of the AHP, and it is ranked accordingly. Two aspects are being considered for the hydrogen energy-based transition: the fuel switching option from the existing energy supply source at the industrial park comprising electricity and thermal, and the sustainable method for the hydrogen production source. The top three AHP results for the electricity and thermal energy indicated that the National Grid is ranked the highest at 0.87, followed by natural gas at 0.82 and biomass at 0.74 for the fuel switching into hydrogen for the energy transition. Meanwhile, the top three results for the hydrogen supply source indicated that the industrial park's best option for hydrogen production is the Green Hydrogen via electrolysis process from the Large-Scale Solar at 0.94. It is followed by Grey Hydrogen via Steam Methane Reforming from the natural gas source at 0.82 and Orange Hydrogen via biomass gasification at 0.82. The overall ranking process for the energy supply system at the industrial park provides a systematic priority and basis for the fuel switching strategy of the electricity and thermal energy and the best selection for hydrogen production towards the carbon emission reduction at the industrial park level. This method can assist the decision-makers in sustainability energy planning as part of the energy transition to transform the industrial park into an Eco-Industrial Park.

1. Introduction

The rise in global temperature or the global warming problem, is one of the most critical issues to address in this decade. The total greenhouse gas (GHG) emissions from industry, manufacturing and construction worldwide in 2020 reached 9.35 billion tons, making it one of the top sectors after

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https://doi.org/10.37934/ard.137.1.4767

electricity and heat in energy consumption [1]. This is further backed by the discovery that the industry sector consumed the most energy at 24.2%, primarily from iron, steel, chemical and petrochemical sources [2].

The primary energy supply in Malaysia is projected to increase by 60% (from 4.1 EJ in 2018 to 6.7 EJ in 2050). This is driven by the rise of the population and the growth of economic activities, mainly from the industry sector [3]. The statistics indicate that Malaysia's demand is closely correlated with its GDP growth. The national economy depends on energy-intensive industries, such as manufacturing [4]. According to the Malaysia Energy Commission, Malaysia's final energy demand (FED) for the industry sector in 2018 was 7.8 Mtoe, representing 12%, with a recorded compound annual growth rate (CAGR) of 4% from 2010 to 2018 [5]. The energy demand from the industry sector is expected to be increased annually. Therefore, transitioning towards a sustainable energy source is essential since Malaysia is committed to net-zero GHG aspiration by 2050 [6]. With this, while meeting the rising energy demand, Malaysia has strategized to embrace alternative energy supply and demand solutions by tapping into the significant potential of hydrogen energy sources, as outlined in several national strategic documents summarized in Table 1. More efforts are needed in various sectors [7] in Malaysia to ensure the achievement of our national commitment under the Paris Agreement.

Table 1
National strategic documents that advocate the hydrogen implementation

No.	Name of the Document	Description of the Document
1	The Blueprint for Fuel Cell Industries in Malaysia [8]	Identify the advantages and opportunities for Malaysia to embark on the fuel cell and hydrogen as an alternative energy.
2	National Energy Policy [9]	Outlined hydrogen as one of the action plans to unlock the opportunities for long-term competitive advantage in the emerging hydrogen economy under the Low Carbon Nation Aspiration.
3	National Energy Transition Roadmap [6]	The roadmap presents the role of hydrogen as one of the Energy Transition Levers and Flagship for Catalyst Projects towards decarbonization.
4	Hydrogen Economy & Technology Roadmap [10]	The roadmap enlightens Malaysia's blue and green hydrogen priority to achieve decarbonization targets.
5	New Industrial Master Plan published [11]	The hydrogen economy agenda is incorporated under the transition to a renewable and clean energy strategy to accelerate the development of the manufacturing industry.

Utilizing hydrogen for the energy transition process at the industrial park can support decarbonization efforts, as demonstrated by several successful case studies in South Africa and Egypt [12]. Additionally, this aligns with the requirements to elevate the industrial park to become an Eco-Industrial Park (EIP), as advocated by the United Nations Industrial Development Organization (UNIDO). This EIP guideline encompasses essential prerequisites and performance requirements across several pillars, including environmental, social, economic and park management, aiming to achieve low-carbon energy generation and resource-efficient production processes [13]. In Malaysia's context, the implementation of EIP is spearheaded by SIRIM Berhad under the supervision of the Ministry of International Trade and Industry (MITI), which focuses on technology-enabled support for the Development of Eco-Industrial Parks. Few industrial parks are moving significantly towards hydrogen-based as part of the fuel-switching strategy, such as Shanghai Chemical Industry Park, where the hydrogen is produced via Steam Methane Reforming (SMR) process and equipped with carbon capture technology to be supply to the industry [14]. Green hydrogen is produced via a Proton Exchange Membrane (PEM) and supplied to the industry, as seen in the present case at Hydrogen Park in South Australia [15].

Understanding the opportunities for hydrogen to drive decarbonisation at the industrial park, there is a need for a systematic methodology and tool to evaluate various factors of consideration for hydrogen utilisation at the industrial park in Malaysia. Multi-Criteria Decision Making (MCDM) is a system tool that performs a systematic decision-making process to find a solution based on complex problems with multiple judging criteria [16]. As such, the MCDM will consist of critical components, including the decision criteria (factors or attributes for the evaluation), alternatives (options for the decision to be made), the decision maker (responsible person or part in making the decision) and the weights (numerical value of each criterion which represents the relative importance on the decision-making process) [17].

Based on the search analysis from ScienceDirect from 2012 to 2022, the MCDM is widely adopted for studies in engineering, energy and environmental science. Among the MCDM methods, the Analytic Hierarchy Process (AHP) is the most cited method being applied in the studies, followed by Data Envelopment Analysis (DEA), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Goal Programming (GP) etc [16]. AHP is a structured technique for organizing and analysing complex decisions based on mathematics and psychology to comprehend sub-problems. The method works based on the pairwise comparison of hierarchical criteria, considering different information and decomposing the decision into a hierarchy [18,19]. The AHP method has been used in various applications, such as supplier selection [20].

Identifying the potential of a hydrogen energy-based transition for decarbonization at the industrial park, encompassing electricity, thermal energy and hydrogen production, is critical and requires a systematic decision-making process that considers various criteria. Many researchers apply MCDM methods in the context of hydrogen, typically for decision-making related to hydrogen production, transportation, storage and site selection. Zaidi *et al.,* [21] introduced the criteria and sub-criteria for the AHP analysis for the selection of fuel cell power generation in Malaysia, which include environmental, technological, social and economic factors. Ren *et al.,* [22] combined the extension theory and AHP methods to prioritize and classify the sustainability of the hydrogen supply chains in China. The framework developed by the researchers utilized the calculated weights of the AHP criteria to extend the ranking process theory. Ten scenarios are being introduced, demonstrating numerous types of hydrogen supply chains evaluated by stakeholders.

Acar *et al.,* [23] conducted a sustainability analysis using the hesitant fuzzy AHP for various hydrogen production mechanisms such as grid electrolysis, wind electrolysis, photovoltaic electrolysis, nuclear thermochemical water splitting cycles, solar thermochemical water splitting cycles and photoelectrochemical cells. The study evaluated a few sustainability criteria by considering technical performance, environmental, social and economic criteria based on the hydrogen production's availability and reliability. The results show that grid electrolysis is ranked as the most sustainable approach for hydrogen production among the six production methods.

Research work conducted by Seker *et al.,* [25] emphasised the production of green hydrogen in Iran due to its significant impact on reducing carbon footprint. It benchmarked the methodologies used by various countries in green hydrogen planning and policy, primarily focusing on China, Russia, South Korea, Malaysia and South America. The study conducted a SWOT analysis of Iran's green hydrogen technology development, examining several key factors. The proposed method is adopted as a decision matrix to hierarchize the experts' opinions, highlighting the importance of the green hydrogen energy program and pilot projects in enhancing public acceptance.

MCDM methods such as Weighted Aggregated Sum Product Assessment (WASPAS), weighted sum model and weighted product model (WSMWPM) and TOPSIS were applied by Olabi *et al.,* [24] to access the hydrogen production techniques based on economic, social and environmental impacts comprising 25 criteria. To enhance the reliability of the results, the research work introduces various weighting methods, including no priority, the consistency-based ranking index for decision making (CRITIC) and Entropy. In addition, the results are further examined to complement the SDGs requirement. With the specific limitations of the study highlighted, the production technology of hydrogen from the biomass gasification mechanism is ranked as the top option.

Seker *et al.,* [25] assessed the sustainability of hydrogen production in thermochemical, electrochemical, thermal, photochemical, plasma and thermal using the MCDM method. The proposed hybrid methods are combined to select the most sustainable production approach for hydrogen sulphide (H_2S), which is abundant in the Black Sea off the coast of Turkey. The study's outcome indicated that electrochemical methods are the most sustainable way for hydrogen production based on eight criteria: economic, ecological, efficiency, process simplicity, energy usage, safety, reliability, applicability, operational suitability and technical provenance. Abdel-Basset *et al.,* [26] also employed an advanced hybrid MCDM to evaluate sustainable hydrogen production options from various approaches under the Neutrosophic theory. As the study considers five main sustainability criteria and seventeen sub-indicators, it is found that wind electrolysis is the most sustainable compared to coal gasification, steam methane reforming, biomass gasification, biosynthesis, photovoltaic electrolysis and hydropower electrolysis methods. The sustainability criteria encompass technical, resource, economic, social and environmental aspects.

An Interval-Valued Intuitionistic Fuzzy Analytic Hierarchy Process method is implemented to determine the most sustainable of four identified hydrogen storage applications: Compressed Hydrogen Gas, Cryogenic Liquid Hydrogen, Metal Hydride and Underground Hydrogen [27]. The method assesses four perspectives of main criteria, comprising economic, environmental, social and technical performance, which contribute to achieving the sustainability goals. The proposed sub-criteria encompass cost aspects, GHG footprint, land use, water usage, waste and effluent management, safety, public acceptance, efficiency, energy and power density and cycle life. The method is introduced as this tool can provide solutions for conflict criteria as it involves qualitative and quantitative data and addresses uncertain and imprecise information. As such, the analysis revealed the CHG as the most sustainable choice for storage technologies, whereas the sensitivity analysis shows that the MH exhibits more environmentally friendly attributes than the others. Haktanır *et al.,* [28] presented a combination methodology using triangular intuitionistic Z-numbers to select hydrogen storage technologies. The principle of the method is to exhibit different degrees of precision of uncertain quantities by considering restriction and reliability functions. A sensitive analysis is also conducted to test the robustness by determining the alternative rankings, which will have particular implications for the weight of the criteria. The results show that chemical storage is the most effective storage technology compared to liquid storage, compressed storage, carbon nanostructure storage and metal-organic framework storage. Al Rizeiqi *et al.,* [29] studied the large-scale hydrogen storage option specifically for the application in Oman through the AHP method. The study found that compressed hydrogen gas was the most suitable option for large-scale hydrogen storage, followed by ammonia and liquefied hydrogen.

The other application that often involves MCDM is site location comparison. For example, Xuan *et al.,* [30] demonstrated the hybrid MCDM methods to determine the best site location for Uzbekistan's solar-powered hydrogen production plants. The study is conducted by integrating several MCDM methods to prioritize the best location for hydrogen production from solar power, based on key criteria such as solar radiation, hours of sunlight and wind speed. Based on the ranking of the site locations, the study also indicates the potential for solar power generation and hydrogen production. Mostafaeipour *et al.,* [31] analysed sixteen (16) sub-criteria from four (4) main categories such as technical, economic, social and environmental, for seventeen (17) potential regions were executed to determine the best location for hydrogen production from the wind energy power plant in Uzbekistan using the hybrid MCDM techniques. Thekkethil *et al.,* [32] developed a comprehensive AHP and GIS model to identify the optimal site location among thirteen states in India for establishing a green hydrogen hub. Considering the complex interplay parameters in the demand and supply connection, the critical criteria of proximity to refineries, fertiliser plants, substations, chlor-alkali units, steel manufacturing plants, water availability, gas pipeline access, access to railway infrastructure and distance to highways are evaluated. The ArcGIS is then used to locate the site, showcasing the scoring of each state and prioritizing the supply strategy based on national demand.

Various research studies on the MCDM method in hydrogen settings have yielded consistent results in determining the most sustainable approach for using hydrogen, based on specific industry segments from different countries. However, no specific study is currently being conducted to adopt the MCDM for hydrogen-based energy transition in multi-energy systems for eco-industrial parks, specifically in Malaysia. Therefore, this paper addresses the gap by performing an AHP to evaluate the identified criteria for the hydrogen-based energy transition. The AHP method is developed specifically for the industry park criteria in Malaysia and tailored for multi-energy systems through adaptation from the standard AHP approach. This will address the uncertainty of transitioning to a hydrogen-based energy system by considering the value chain and enablers for multi-energy systems. The novelty of this study is that it demonstrates the prioritization of the hydrogen energy transition for electricity, thermal energy and hydrogen towards decarbonization based on crucial criteria for the industrial park in Malaysia [33]. Secondly, the prospects of the criteria are developed by integrating the supply chain and enablers for electricity, thermal and hydrogen generation. The selected criteria for the supply chain incorporate the factors of generation, transmission, distribution, storage and utilization. Meanwhile, the assessment must consider five enablers' criteria, including the five perspectives of funding, infrastructure, regulation, skills and technology (F.I.R.S.T.). The Malaysian Industry-Government Group for High Technology (MIGHT), a Malaysian government's technology think tank, developed and used the FIRST framework to assess industrial landscapes, which is applied in various national strategic industry documents. In this study, the FIRST element is proposed as part of the criteria for the hydrogen industry landscape. Thirdly, the constructed criteria used in the AHP analysis represent the connection between supply and demand in the case of industrial parks.

2. Methodology

The methodology of this research work is divided into three steps: development of the criteria for the industrial park case study, pre-analysis of AHP to measure the weight of the criteria and finally, the ranking process using the AHP method. The overall flow of the research methodology is shown schematically in Figure 1. The sequence of steps in performing the research methodology is elaborated in this section.

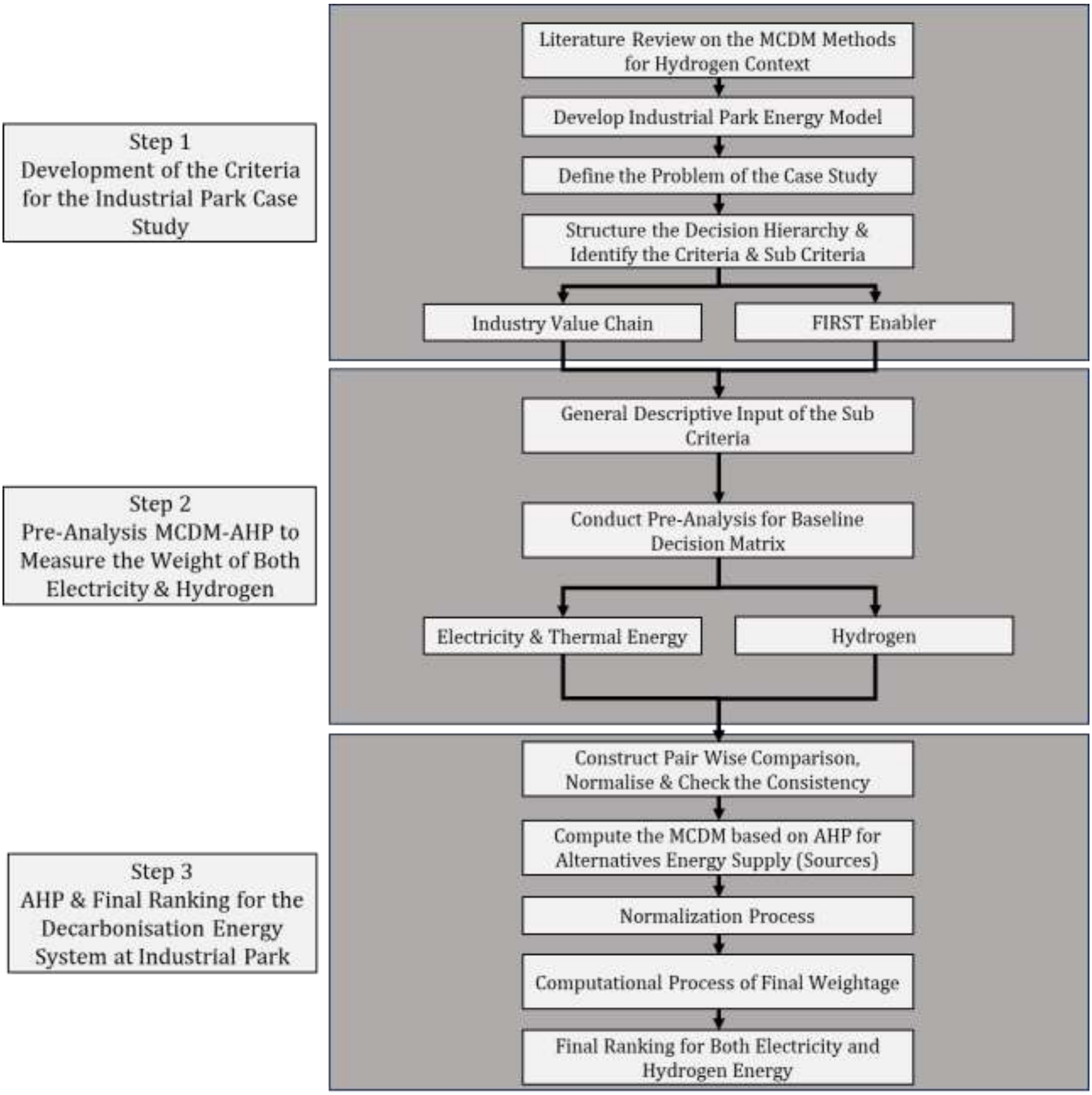

Fig. 1. Flow chart for the research methodology to study the AHP method for hydrogen energy transition at the industrial park towards decarbonization

2.1 Step 1: Development of the Criteria

i. The research works on the MCDM Method related to the hydrogen area are reviewed.
ii. The energy system for the industry park is developed based on the typical Malaysian industry landscape, comprising thermal, electricity and other energy source, as depicted in Figure 2.

However, the current national policy does not allow electricity trading between the industrial players. The external hydrogen supply is added to demonstrate a hydrogen-based energy transition.

On the supply side, the industry park depends on a few streams of energy sources such as from the national grid, renewable energy, i.e. large-scale solar photovoltaic systems, natural gas supply *via* transmission pipeline, biodiesel and biomass energy. The existing hydrogen supply to the industrial park from the external source is outlined first in the diagram to illustrate the current context in this case study. This energy supply from various sources will generate both thermal and electrical energy to support the industrial park's multi-purpose industrial activities, as shown in Figure 2.

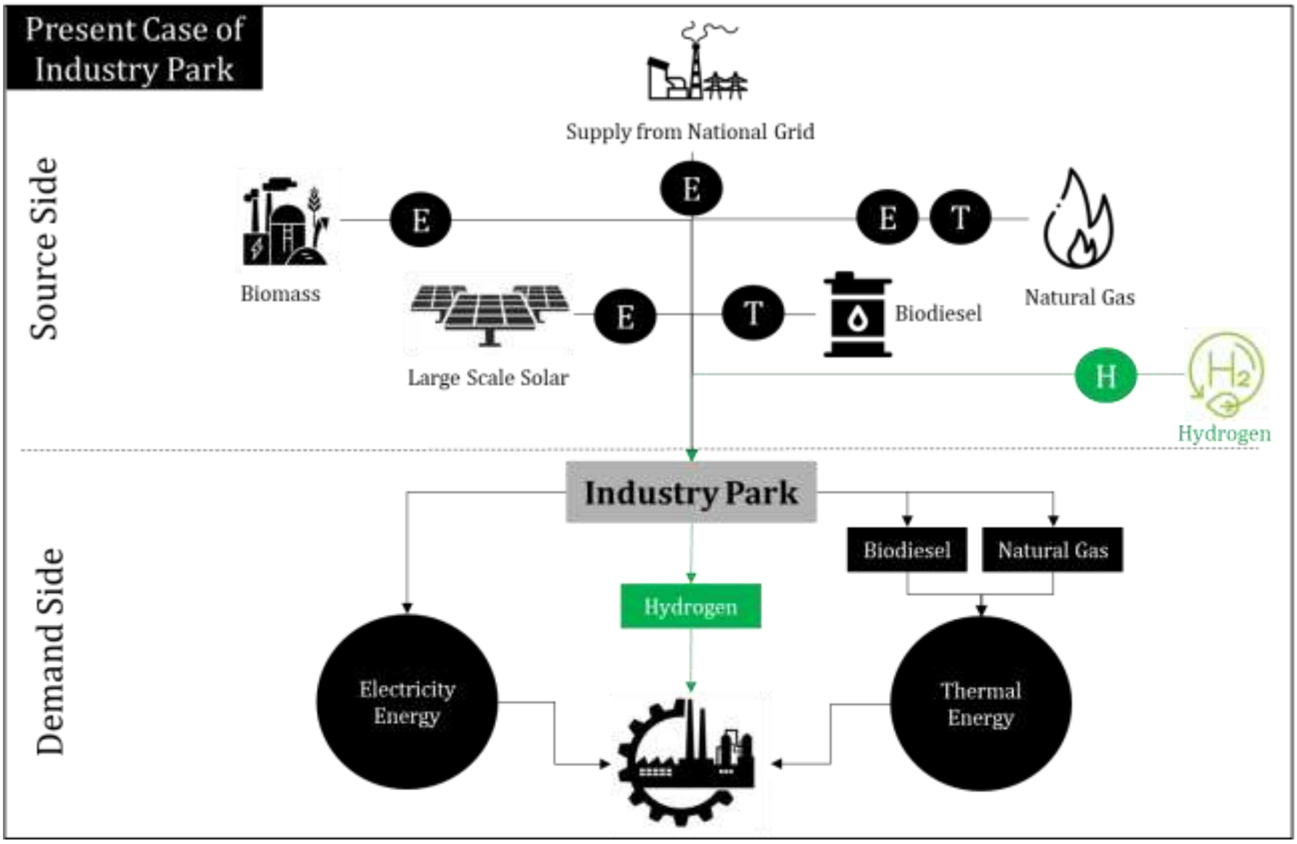

Fig. 2. Propose model of the energy system for industry park case study, note that (E) represents electricity, (H) represents hydrogen energy and (T) represents thermal energy

The variety of energy sources and their respective functionalities are shown in Table 2. Theoretically, the variety of the energy supply provides opportunities for hydrogen to be produced from various sources, utilizing different technologies, for further utilisation on the demand side. Setting up the industry park profile will provide a base case to evaluate the identified criteria for the energy transition process at the industry park, as part of the fuel switching into hydrogen and explore the best option for producing hydrogen within the industrial park. The primary motivation is to achieve decarbonization and transform the industrial park into an EIP by reducing carbon emissions from the supply side.

Table 2
Proposed variety of energy sources for different purposes

No.	Type of Energy Sources	Supply Requirements	
		Electricity Energy	Thermal
1	National Grid Plant	Yes	No
2	Large Scale Solar Plant	Yes	No
3	Biomass Plant	Yes	No
4	Natural Gas Co-Generation Plant	Yes	Yes
5	Biodiesel Plant	No	Yes

iii. Based on the developed case study, the problem statement is defined as elaborated in the introduction section. Due to the challenges of the industrial park's transition towards decarbonization and transformation into an eco-industrial park, the most sustainable way to transition to a hydrogen-based energy system, considering multiple energy sources, must be found.

iv. The aim is to identify the most sustainable fuel-switching strategy from multiple sources and the most sustainable method for producing hydrogen as part of the decarbonization efforts. As mentioned in the previous section, this study introduces the integration of two main criteria for the hydrogen energy-based transition at the industrial park: the industry value chain and the enabler known as FIRST. The sub-criteria for the energy industry value chain and FIRST as the enabling factors are further identified for electricity, thermal and hydrogen, respectively. The electricity and thermal value chain sub-criteria comprise feedstock, generation, transmission, distribution, storage and consumption. At the same time, the hydrogen supply chain encompasses feedstock, production, transportation, storage and end-use/demand. On the other hand, the sub-criteria for FIRST comprise the elements of funding, infrastructure, regulation, skills and technology, which apply to electricity, thermal and hydrogen. The list of the criteria and identified sub-criteria is shown in Table 4 and Table 5.

2.2 Step 2: Pre-Analysis of AHP

For the second step, a pre-analysis is performed for the AHP computational process, focusing on electricity, thermal and hydrogen energy, in accordance with the industry value chain and FIRST enabler criteria. The research supports the method of pre-analysis, which involves obtaining information on each criterion within the national context before evaluating the identified criteria.

i. The general description for the sub-criteria is predeveloped to indicate situational judgement in the AHP method, as shown in Table 3 and Table 4. This also serves as baseline information on the existing landscape and initiatives to assess the readiness and importance of the respective sub-criteria.

ii. The pre-analysis of the electricity, thermal and hydrogen criteria is also performed to identify concerns about hydrogen integration within the context of the industry supply chain and the FIRST, based on reports and literature information. The pre-analysis result will determine the importance of one criterion over another, thereby influencing the result of the criterion weights.

Table 3
Description of industry value chain and FIRST for electricity and thermal energy

No.	Criteria	Sub-Criteria	Description
1	Industry Value Chain	Feedstock	The feedstock for electricity and thermal generation is essential, as it determines the impact of GHG emissions and how they can contribute, either directly or indirectly, to hydrogen production for switching purposes.
2		Generation	Electricity and thermal energy will energize the industrial park and it needs to be environmentally friendly to promote eco-industrial park features at a viable cost of electricity generation.
3		Transmission	The generated electricity and thermal energy will be transmitted and distributed to the industrial park and beyond to any external regions for any excess generation. The electricity will be transmitted using the pylons, towers and high-voltage cables.

4		Distribution	The transmitted electricity and thermal will be distributed and supplied within the industrial park, leveraging the existing infrastructure and guided by the Distribution Code (for electricity).
5		Storage	Excess electricity and thermal generation from renewable sources, such as solar PV, will be stored in the energy storage system/ battery bank during peak times.
6		Consumption	The industry sectors will consume electricity and thermal energy for various applications, such as auxiliary heating, electrical furnaces and boilers, office operations and factory machinery equipment.
7	FIRST	Funding	Existing financial instruments that promote the development of the energy industry (conventional or renewable based) with a dedicated tariff.
8		Infrastructure	The infrastructure covers the transmission, distribution, substation, utilities pipeline, etc., which energise the entire operation in the industrial park.
9		Regulations	Electricity and thermal energy supply are guided by codes such as the Malaysian Grid Code, the Electricity Supply Act 1990, the Gas Supply Act 1993, etc. Any renewable energy integration needs to be followed with regulations, such as the (Grid-Connected Photovoltaic) GCPV system for solar.
10		Skills	Existing training programs for blue & white collars enhance the human capital in operating the electricity and thermal energy supply.
11		Technology	Technology for electricity and thermal generation, transmission, distribution, storage and at the application levels.

Table 4
Description of industry value chain and FIRST for hydrogen energy

No.	Criteria	Sub Criteria	Description
1	Industry Value Chain	Feedstock	Feedstock is a critical raw material for hydrogen production and it can be generated from various sources, including natural gas, biomass and biodiesel. The evaluation is based on each source's GHG emission factor and the industrial park's availability.
2		Production	The feedstock source and production method will determine the type of hydrogen colour, such as green or blue. Ideally, hydrogen production needs to be more environmentally friendly and economical. The evaluation is based on the economic cost of hydrogen production at the industrial park.
3		Storage	Hydrogen needs to be stored safely. Few methods are available to store it in liquid hydrogen, toluene-MCH, gaseous ammonia or solid-state (Magnesium Hydride) form. The evaluation is based on the challenges and advantages of the storage method.
4		Transport	Hydrogen can be transported in various ways, depending on the application segment. A few options for hydrogen transport include using the natural gas pipeline and tube trailers, among others. The evaluation is based on the readiness of the local infrastructure and safety factors, such as explosiveness and flammable gases, which must comply with the stipulated regulations and standards.
5		End-Use/ Demand	The industry park will utilize hydrogen for various potential applications, including supplementary electricity supply via fuel cells, power generation, heating purposes via boilers, combined heat and power, forklifts and fleet operations.
6	FIRST	Funding	The financial instruments and specific fiscal incentives are designed to promote the uptake of hydrogen utilisation. Currently, no subsidy is being applied for hydrogen utilisation. The cost aspect of hydrogen production must be considered.
7		Infrastructure	The infrastructure covers the distribution gas network and refuelling station. The evaluation is based on the availability of infrastructure for hydrogen supply, consumption and operation at the industrial park. This can be guided by the Gas Supply Regulation 1997 or the Gas Supply Act 1993. The gas industry players' existing commercial approach for hydrogen transportation utilizes tubes, trailers and storage vessels (both liquid and gaseous).

8	Regulations	Currently, there are the Gas Supply Act 1993, the Gas Supply Regulation 1997, the Industrial Coordination Act 1957 and the Occupational Safety and Health Act 1994. A few standards can be referred to, such as the National Fire Protection Agency (NFPA), the International Organization for Standardization (ISO) on the total value chain, the International Electrotechnical Commission (IEC) on the aspect of utilisation and the Society of Automotive Engineers (SAE), on the aspect of vehicle fuelling.
9	Skills	Existing training programs include hydrogen safety training provided by TUV SUD, etc. A few local institutions also offer short courses on hydrogen hazards, risks and safety. Some local research universities offer additional human capital development programs, including academic and research activities. The evaluation is based on the local talent's capability in operating the hydrogen system.
10	Technology	Technologies developed locally, such as the electrolyser and fuel cell or outsourced from foreign counterparts. The evaluation is based on technology readiness for specific hydrogen production methods, transportation, storage, etc.

2.3 Step 3: AHP and Final Ranking

In the third step, the AHP computational process is executed to prioritize and rank the hydrogen energy-based transition from multiple sources, including electricity and thermal energy. The steps of the AHP method are elaborated on in the following subsections.

2.3.1 Step 3a: Pairwise comparison

To perform the pairwise comparison, a scale of numbers is developed to indicate the relative importance or dominance of one sub-criterion over another as they are being compared. Table 5 exhibits the proposed scale adapted from Saaty [17].

Table 5
Propose scaling structure for pairwise comparison [19]

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgement slightly favour one activity over another
5	Strong Importance	Experience and judgement strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

Based on the scaling structure, two pairwise comparisons are performed for electricity and thermal energy, as well as hydrogen energy, according to the industry value chain and FIRST criteria. The judgement is performed based on the pre-analysis work as guidance and evaluated for the 11x11 matrix for electricity and thermal energy and the 10x10 matrix for hydrogen energy.

2.3.2 Step 3b: Normalisation

The sum value of the pairwise comparison matrix is calculated to normalise the figure by dividing the figures of all sub-criteria with the respective sum of the column. The normalised pairwise matrix is then obtained. The average value of all sub-criteria at the row level is calculated to determine the criteria weight.

2.3.3 Step 3c: Consistency check

The consistency value is validated to determine whether the calculated value is precise. This is performed by multiplying the value in each column and then normalising it with the respective criterion weight. The weighted sum value is determined by summing the values in each row and the ratio is calculated by dividing the weighted sum value by the corresponding criteria weight. The largest eigenvalue (λ_{max}) is then calculated based on the sum value of the ratio divided by the number of sub-criteria, as shown in Eq. (1). The consistency index (CI) is calculated using Eq. (2), where n refers to the number of compared sub-criteria. The consistency ratio (CR) is then calculated based on Eq. (3), where the RI value can be found in Table 6, corresponding to the number of sub-criteria. The indicative figure of CR, which is less than 0.1, indicates that the assumption made in the pairwise comparison is reasonably consistent and suitable for use in the next step of the calculation.

$$\lambda_{max} = \frac{1}{n} = \sum_{i=1}^{n} \frac{(Aw)i}{wi} \quad (1)$$

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

Table 6
Random Index (RI)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

2.3.4 Step 3d: Perform the MCDM calculation based on AHP

As shown in Table 7, a list of alternative energy supply approaches is identified for electricity, thermal and hydrogen. The multiple alternatives to energy supply are then evaluated based on criteria, including the industry value chain and FIRST, to determine the performance value.

Table 7
Alternatives for energy supply approach

Electricity & Thermal Energy	Hydrogen Energy
1. Natural Gas for Electricity Power Plant and Thermal Energy via Boiler	1. Green Hydrogen (renewable energy + electrolysis)
2. National Grid for Electricity	2. Grey Hydrogen (Natural gas + steam methane reforming)
3. Biodiesel for Thermal	3. Blue Hydrogen (Natural gas + Carbon Capture Utilization and Storage, CCUS)
4. Biomass for Electricity	4. Turquoise Hydrogen (Methane + pyrolysis)
5. Large Scale Solar for Electricity	5. Orange Hydrogen (Biomass Gasification)

2.3.5 Step 3e: Normalized performance score (NPS) determination

For the normalisation stage, the performance type of each sub-criterion is identified as beneficial or non-beneficial based on the scaling and justification. The maximum and minimum performance values are determined for each sub-criterion. The normalisation calculation is performed based on Eq. (4) to determine the normalised performance score (NPS), depending on the category of the sub-criteria and whether it is beneficial or non-beneficial.

$$NPS = \begin{cases} \mathrm{PV}/\ \mathrm{PV}_{\mathrm{max}} & (\mathrm{beneficial}) \\ \mathrm{PV}_{\mathrm{min}}/\mathrm{PV} & (\mathrm{non-beneficial}) \end{cases} \tag{4}$$

Where, PV is the performance value, PV_{min} is the minimum performance value in the non-beneficial category and PV_{max} is the maximum performance value in the beneficial category.

2.3.6 Step 3f: Weighted normalised decision matrix

The obtained figures of the criteria weights for the two sets of evaluation from Step 3a are used in the next step. The criteria weight of the respective sub-criteria is multiplied by the normalised performance score to obtain the weighted normalised decision matrix.

2.3.7 Step 3g: Final ranking

For the final step, the total sum of the weighted normalized decision matrix is calculated to get the total performance score. The total performance score of each alternative is ranked to determine the highest score, which indicates the best alternative for the hydrogen-based energy transition at the industrial park, aiming for decarbonization and reduced emission attributes.

3. Results and Discussion

This section presents the research study's results and deliberates on the findings in investigating the hydrogen-based energy transition model for the industrial park towards decarbonization. This study employed the AHP method, considering integrated criteria of the Industry Value Chain and FIRST for the multi-energy system at the industrial park, encompassing electricity, thermal and hydrogen sources. The methodology of this study is designed to determine how the fuel-switching strategy to hydrogen can be achieved from conventional sources of energy, such as electricity and thermal power, at the industrial park. Additionally, the existing supply of hydrogen sources is being evaluated to determine the most sustainable way to produce hydrogen within the industry park.

The pre-analysis work of the Industry Value Chain and FIRST for the hydrogen energy-based transition at the industrial park provides a clear picture of the features and profiles of each criterion based on the specific case. This also provides an adequate basis for the judgements and assumptions required to perform the pairwise comparison analysis in determining the criterion weights, as presented in Tables 8 and 9.

Table 8
Pairwise comparison and criteria weight for the electricity and thermal energy

	Electricity/Thermal Energy Supply Chain					
	Feedstock	Generation	Transmission	Distribution	Storage	Consumption
Feedstock	1.00	0.63	1.17	2.00	1.67	0.78
Generation	1.60	1.00	1.67	1.67	1.33	0.44
Transmission	0.86	0.60	1.00	1.50	1.50	0.57
Distribution	0.50	0.60	0.67	1.00	1.50	0.60
Storage	0.60	0.75	0.67	0.67	1.00	0.50
Consumption	1.29	2.25	1.75	1.67	2.00	1.00
Financial	1.60	0.75	0.63	0.75	0.88	0.63
Infrastructure	1.75	2.33	1.75	1.40	0.86	2.33
Regulation	1.60	0.38	0.57	0.71	0.86	0.71
Skills	1.60	0.63	1.33	1.14	0.22	4.00
Technology	1.67	0.40	2.50	1.67	0.67	2.00
SUM	14.06	10.31	13.70	14.17	12.48	13.57

	First Enabling Factors				
	Financial	Infrastructure	Regulation	Skills	Technology
Feedstock	0.63	0.57	0.63	0.63	0.60
Generation	1.33	0.43	2.67	1.60	2.50
Transmission	1.60	0.57	1.75	0.75	0.40
Distribution	1.33	0.71	1.40	0.88	0.60
Storage	1.14	1.17	1.17	4.50	1.50
Consumption	1.33	0.43	1.40	0.25	0.33
Financial	1.00	0.78	0.75	0.63	0.75
Infrastructure	1.29	1.00	1.75	0.63	1.50
Regulation	1.33	0.57	1.00	0.75	2.00
Skills	1.60	1.60	1.33	1.00	1.60
Technology	1.33	0.67	0.50	0.63	1.00
SUM	13.92	8.50	14.34	12.23	12.78

Table 9
Pairwise comparison and criteria weight for the hydrogen energy

	Hydrogen Supply Chain				
	Feedstock	Production	Storage	Transportation	End Use/ Demand
Feedstock	1.00	1.60	1.50	1.33	2.50
Production	0.63	1.00	2.00	1.60	0.40
Storage	0.67	0.50	1.00	1.50	0.67
Transport	0.75	0.63	0.67	1.00	0.60
End-Use/ Demand	0.40	2.50	1.50	1.67	1.00
Financial	0.60	0.75	0.80	0.75	1.33
Infrastructure	0.43	0.44	0.57	1.33	0.67
Regulation	1.67	0.57	0.57	0.63	0.60
Skills	2.00	0.63	1.67	2.00	2.50
Technology	2.00	0.60	0.67	0.56	0.50
SUM	10.14	9.22	10.94	12.36	10.77

	First Enabling Factors				
	Financial	Infrastructure	Regulation	Skills	Technology
Feedstock	1.67	2.33	0.60	0.50	0.50
Production	1.33	2.25	1.75	1.60	1.67
Storage	1.25	1.75	1.75	0.60	1.50
Transport	1.33	0.75	1.60	0.50	1.80
End-Use/ Demand	0.75	1.50	1.67	0.40	2.00

Financial	1.00	0.71	0.67	1.40	0.60
Infrastructure	1.40	1.00	1.40	1.33	2.00
Regulation	1.50	0.71	1.00	1.75	0.60
Skills	0.71	0.75	0.57	1.00	0.67
Technology	1.67	0.50	1.67	1.50	1.00
SUM	12.61	12.26	12.67	10.58	12.33

Based on the electricity and thermal energy analysis, the people's skills and infrastructure obtained the highest criteria value at 0.12, as shown in Table 10. This indicates that the capabilities of people in the industry and the availability of infrastructure provide more weight for switching the existing source supply to hydrogen-based.

Table 10
Criteria weights

Electricity & Thermal Energy		Hydrogen Energy	
Criteria	Criteria Weight	Criteria	Criteria Weight
Feedstock	0.07	Feedstock	0.12
Generation	0.11	Production	0.12
Transmission	0.08	Transport	0.10
Distribution	0.07		
Storage	0.10	Storage	0.08
Consumption	0.10	End Use/ Demand	0.12
Financial	0.07	Financial	0.08
Infrastructure	0.12	Infrastructure	0.09
Regulation	0.07	Regulation	0.09
Skills	0.12	Skills	0.11
Technology	0.09	Technology	0.09

Meanwhile, for hydrogen, three sub-criteria are recorded at the highest weightage value, namely feedstock, production and end-use demand, at 0.12, as presented in Table 11. The availability of feedstock to produce hydrogen will play a substantial role, as it will determine the type of hydrogen production. This is also related to the hydrogen production method, which depends on the type of source. The end-use demand for hydrogen also carries substantial weight, as it determines the need case from the supply side.

Table 11
Consistency ratio

	Electricity & Thermal Energy	Hydrogen Energy
Sum Value of Ratio	136.44	112.18
Value of λ_{max}	12.4034	11.2181
Consistency Index (CI)	0.1403	0.1353
n Random Index	11	10
Random Index (RI)	1.51	1.49
Consistency Ratio (CR)	0.0929	0.0908

The consistency of the calculated value is validated and the consistency value of the calculated criteria weight is calculated to determine the consistency ratio (CR), as presented in Table 11. The results indicate that the CR values for electricity and thermal energy are 0.0929 and 0.0908, respectively, for hydrogen. As both CR values are less than 0.10, the computed criteria weight is valid for decision-making regarding various energy supply sources in a multi-criteria situation.

Five types of energy supply are evaluated for electricity and thermal energy: natural gas, national grid, biodiesel, biomass and large-scale solar energy. Theoretically, based on this supply source, the

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industrial park can adopt fuel-switching strategies towards hydrogen to achieve the targeted supply capacity mix. Despite these opportunities, no specific evaluation study has been performed to make a systematic decision on the industrial park case in Malaysia. As such, this study analysed the best options for switching the multi-supply energy source to hydrogen, transforming the industrial park towards decarbonization, as shown in Table 12 and Table 13. The performance values (PV) are then normalized into the normalised performance score (NPS), as shown in Tables 14 and 15, based on the minimum and maximum performance values for each category.

Table 12
Performance value (PV) and normalised performance score (NPS) for different electricity and thermal supply

	Natural Gas		National Grid		Biodiesel		Biomass		Large Scale Solar	
	PV	NPS	PB	NPS	PB	NPS	PB	NPS	PB	NPS
Feedstock	155	0.94	165	1	150	0.91	130	0.79	60	0.36
Generation	2.5	0.8	2	1	3.5	0.57	3.5	0.57	3	0.67
Transmission	2	0.5	1	1	2.5	0.4	2.5	0.4	3.5	0.29
Distribution	2	0.5	1	1	2.5	0.4	2.5	0.4	3.5	0.29
Storage	2	0.67	2	0.67	2	0.67	2	0.67	3	1
Consumption	4.5	0.9	5	1	4	0.8	3.5	0.7	3	0.6
Financial	2.5	0.8	3	0.67	3	0.67	3	0.67	2	1
Infrastructure	3	0.86	3.5	1	3	0.86	3	0.86	2.5	0.71
Regulation	2.5	0.5	2	0.4	4	0.8	4.5	0.9	5	1
Skills	5	1	5	1	3.5	0.7	4	0.8	4	0.8
Technology	4	1	4	1	3.5	0.88	3.5	0.88	2	0.5

Table 13
Performance value (PV) and normalised performance score (NPS) for different types of hydrogen energy

	Green Hydrogen		Grey Hydrogen		Blue Hydrogen		Turquoise Hydrogen		Orange Hydrogen	
	PV	NPS	PB	NPS	PB	NPS	PB	NPS	PB	NPS
Feedstock	160	0.94	170	1	140	0.82	120	0.71	140	0.82
Production	4	0.75	3.5	0.86	5	0.6	3.5	0.86	3.5	0.86
Storage*	3	1	3	1	3	1	3	1	3	1
Transportation **	3	1	3	1	3	1	3	1	3	1
End-Use/ Demand	5	1	2.5	0.5	3	0.6	2	0.4	4	0.8
Financial	4	0.75	3	1	4.5	0.67	3.5	0.86	3.5	0.86
Infrastructure	5	1	3.5	0.7	3.5	0.7	3	0.6	3.5	0.7
Regulation	5	1	1	0.2	3	0.6	1	0.2	3.5	0.7
Skills	3.5	1	3.5	1	2	0.57	2	0.57	2.5	0.71
Technology	4.5	1	4.5	1	3	0.67	3	0.67	3.5	0.78

Note: * For storage, it is assumed to be a Liquid Hydrogen Storage type, ** For transportation, it is assumed to use a tanker

The computation process of weightage and the ranking results from Table 14 show that the National Grid is selected as the best option with a total performance score of 0.87 based on the evaluated criteria. This is followed by Natural Gas at 0.82, biomass at 0.74, Biodiesel at 0.72 and Large-Scale Solar at 0.70. In principle, the energy supply from the National Grid can be replaced with a hydrogen source and supplied to the industrial park. This will provide additional benefits for the industrial park in reducing GHG emissions. The GHG emission factor of the National Grid for Malaysia context is high at 10,345.63 tCO2eq/ktoe compared to the hydrogen GHG emission factor. The industrial park will be more independent if the facility can generate clean energy sources locally and outsource a small portion of its energy needs from outside sources. The ranking priorities also indicate that other energy sources, including natural gas, biomass and Biogas, will have the opportunity to be replaced with hydrogen-based sources, potentially transforming the industrial park into an eco-industrial park.

Table 14
Weighted normalised decision matrix and final ranking for electricity and thermal energy

	Criteria Weightage	Natural Gas	National Grid	Biodiesel	Biomass	Large Scale Solar
Feedstock	0.06	0.06	0.06	0.05	0.05	0.02
Generation	0.06	0.05	0.06	0.04	0.04	0.04
Transmission	0.06	0.03	0.06	0.02	0.02	0.02
Distribution	0.06	0.03	0.06	0.02	0.02	0.02
Storage	0.05	0.03	0.03	0.03	0.03	0.05
Consumption	0.07	0.06	0.07	0.06	0.05	0.04
Financial	0.11	0.09	0.07	0.07	0.07	0.11
Infrastructure	0.08	0.07	0.08	0.07	0.07	0.05
Regulation	0.11	0.06	0.04	0.09	0.1	0.11
Skills	0.22	0.22	0.22	0.16	0.18	0.18
Technology	0.12	0.12	0.12	0.11	0.11	0.06
TOTAL	1.00	0.82	0.87	0.72	0.74	0.7
Ranking		2	1	4	3	5

In the case of natural gas and biomass, various technological options can be employed to produce hydrogen from these existing sources. Although the GHG emission factor for Natural Gas is lower at 2337 $tCO_{2\text{-}eq}$/ktoe, compared to the biomass at 4605.42 $tCO_{2\text{-}eq}$/ktoe and biodiesel at 4396.08 $tCO_{2\text{-}eq}$ /ktoe, the natural gas source has more significant opportunity to be switched into hydrogen considering the existing low-cost technology such as steam methane reforming despite some issue on the environmental effect due to the emission factor for the conversion process is at 900 $gCO_{2\text{-}eq}$/kWh [34]. Additionally, the hydrogen produced can be utilized for both electricity and thermal purposes. As for biomass, which is ranked at the third level, it has a significant carbon footprint due to the conversion technology of the biomass gasification technique. Its carbon footprint is at 1200 $gCO_{2\text{-}eq}$/kWh. Therefore, this influences the decision to prioritise biomass as one of the top options.

Besides, the feedstock supply of the biomass source is still uncertain in most cases. Biodiesel is ranked at the fourth level, considering that the existing industrial landscape still relies on conventional technology to meet its thermal energy requirements, despite the emission factor for the conversion technology being 1100 $gCO_{2\text{-}eq}$/kWh. In this aspect, the research identified that biodiesel should be selected at the fourth level, considering the market uptake and abundant feedstock supply. The large-scale solar is ranked as the lowest since the emission factor is low at 640.99 $tCO_{2\text{-}eq}$/ktoe and the supply source is small as it depends on the sun irradiation. As such, replacing it with a hydrogen source is not required. However, there is an opportunity for the industrial park to leverage solar energy for green hydrogen production via electrolysis and various electrolyser technologies.

Meanwhile, five different types of hydrogen sources are being studied for hydrogen: Green Hydrogen, Grey Hydrogen, Blue Hydrogen, Turquoise and Orange Hydrogen. Using the criteria weight value, the performance value of the multi-options for hydrogen production is determined to make the decision based on inclusive criteria for the best hydrogen supply method to the industrial park. Table 15 shows that the best method for producing hydrogen in transforming the industrial park towards decarbonization is via green hydrogen using the electrolysis method, with a total performance score of 0.94. The ranking is followed by grey hydrogen at 0.83 *via* steam methane reforming from natural gas orange Hydrogen at 0.83 *via* biomass gasification, Blue Hydrogen at 0.70 *via* natural gas and carbon capture and utilization (CCUS) and Turquoise Hydrogen at 0.69 from a methane source *via* pyrolysis.

Table 15
Weighted normalised decision matrix and final ranking for hydrogen energy

	Criteria Weightage	Green Hydrogen	Grey Hydrogen	Blue Hydrogen	Turquoise Hydrogen	Orange Hydrogen
Feedstock	0.12	0.11	0.12	0.1	0.09	0.1
Production	0.12	0.09	0.11	0.07	0.11	0.11
Storage	0.1	0.1	0.1	0.1	0.1	0.1
Transportation	0.08	0.08	0.08	0.08	0.08	0.08
End Use/ Demand	0.12	0.12	0.06	0.07	0.05	0.1
Financial	0.08	0.06	0.08	0.05	0.07	0.07
Infrastructure	0.09	0.09	0.06	0.06	0.05	0.06
Regulation	0.09	0.09	0.02	0.05	0.02	0.06
Skills	0.11	0.11	0.11	0.06	0.06	0.08
Technology	0.09	0.09	0.09	0.06	0.06	0.07
TOTAL	1	0.94	0.83	0.70	0.69	0.82
Ranking		1	2	4	5	3

The existing solar PV system at the industrial park can be leveraged to produce green hydrogen from solar energy via the electrolysis process, as it demonstrates lower GHG emission attributes and is more environmentally friendly. Despite the high capital cost of the electrolysis system, the technology has proven to deliver the necessary capacity, particularly for electricity and thermal requirements and is subject to the selection of electrolyser technologies for large-scale production. Grey hydrogen, positioned at the second rank considering the existing production method via steam methane reforming of the natural gas source, is commercially available in the mainstream market. It has abundant sources within the Malaysian industrial park context, despite the existence of a carbon footprint from the production process. Orange hydrogen ranked as the third choice, considering the security of the biomass feedstock supply, which may pose some risks in delivering the demand capacity from the industrial park.

The blue hydrogen production from natural gas *via* steam methane reforming, integrated with CCUS, is ranked number four due to the high capital investment required to capture carbon from the process. Additionally, the regulatory aspect of CCUS implementation remains immature at this stage. The production of turquoise hydrogen from the biomethane source *via* pyrolysis is the least preferred option based on the AHP calculation. Although the turquoise hydrogen production process is less energy-intensive (10–30 kWh/kgH_2 < 50–60 kWh/kgH_2), the source of the production is still based on methane, which has some carbon emissions from the production source despite less than the grey hydrogen at 88.3% to 90.8% [35]. In addition, the technological readiness of methane pyrolysis via thermal plasma is still developing, especially for sizeable industrial-scale production [35]. It requires a comprehensive handling approach of the produced by-product of solid carbon as part of adopting the circular economy [36]. Other drawbacks include the high consumption of methane as the source of feedstock, which is higher than the requirement for blue hydrogen production [37], which will cause a high capital cost [38]. Nevertheless, it is worth noting that significant progress in research on the technological development of turquoise hydrogen production may be a significant game changer for the energy transition as it is claimed that the production method can achieve a negative carbon intensity [35].

The study's key findings successfully establish the transition to hydrogen-based energy at the industrial park, determine the optimal method for replacing the current energy source with hydrogen and identify a sustainable approach for hydrogen production throughout the value chain. This offers a greater level of competitiveness in decision-making compared to the majority of research that focuses on specific segments and is fragmented within the value chain.

4. Conclusions and Recommendations

Malaysia has set a long-term goal of achieving net-zero emissions by 2050. At the national level, various strategic documents outlined the strategies, action plans and initiatives to drive the country toward embracing the energy transition. For example, the Hydrogen Economy & Technology Roadmap (HETR) highlights the priority of hydrogen in achieving decarbonisation targets at the macro level, based on probable scenarios that may have a spillover impact on carbon emission reduction, revenue and job employment, among other factors. Despite the enormous opportunities for the country to utilize hydrogen for various applications, the industrial sector has remained primarily dependent on conventional energy sources. Therefore, this research study aimed to determine the hydrogen-based energy transition model at the industrial park using the AHP method. This study investigated the industry value chain relationship criteria and FIRST as part of the evaluation factors to determine and prioritise the fuel-switching strategy for electricity and thermal energy, as well as the sustainable approach for hydrogen production at the industrial park. As such, the following are the key results from this study:

i. The MCDM method, based on AHP, is designed to determine a hydrogen energy-based transition model that considers multiple criteria in a structured manner, facilitating a better decision-making process for decarbonization purposes. Eleven criteria are considered for electricity and thermal energy and ten criteria are identified for hydrogen.
ii. Alternatives for electricity and thermal energy are being evaluated: natural gas, national grid, biodiesel, biomass and large-scale solar. Based on the result, National Grid obtained the top score at 0.87, followed by Natural Gas at 0.82 and biomass at 0.74 for the fuel-switching strategy into hydrogen. The National Grid is selected as the main priority for the fuel switching option because it has a significant GHG emission factor and the industrial park can take this opportunity to self-generate hydrogen locally and become less dependent on external sources of supply.
iii. On the other hand, five alternatives are being assessed for hydrogen energy: green hydrogen, grey hydrogen, blue hydrogen, turquoise hydrogen and orange hydrogen. According to the AHP results, Green Hydrogen was ranked as the top priority, with a performance score of 0.94, followed by Grey Hydrogen at 0.83 and Orange Hydrogen at 0.83. Green hydrogen produced from large-scale solar power via the electrolysis process is selected as the primary priority for decarbonization compared to other options.
iv. Based on this result analysis, the industrial park can embrace a fuel-switching strategy by partially replacing the existing conventional source with hydrogen-based for different purposes such as electricity and thermal usage. On the other hand, the industrial park must also be supplied with green hydrogen generated via the electrolysis method from renewable solar energy sources to drive the industrial park towards decarbonization.

Therefore, it is recommended that policymakers and key stakeholders consider implementing the recommendations of this study and replicating the improved methodology for future evaluations.

However, there are some limitations in this research and suggestions for future research work, listed as follows:

i. It involves subjective judgments in assigning weights and evaluating alternatives from the authors' point of view.
ii. The criteria must consider additional factors that may suit the specific industrial park location.
iii. This work does not consider the fuel-switching initiative via co-firing, which could be the most immediate option for the industries.
iv. Requires comprehensive and accurate data for practical evaluation via engagement with stakeholders and subject matter experts for consensus decisions.
v. Potential to deep dive the investigation via the integration with other MCDM methods to amplify and validate the accuracy of the ranking result.
vi. Opportunity to leverage the AHP results as baseline data for future analysis work.

Acknowledgement
This research was funded by a Ministry of Higher Education of Malaysia grant under the Fundamental Research Grant Scheme (FRGS/1/2023/TK08/UTM/02/23).

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