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Advancing nickel-based catalysts for enhanced hydrogen production: Innovations in electrolysis and catalyst design

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ABSTRACT

Nickel-based catalysts, recognized for their cost-efficiency and availability, play a critical role in advancing hydrogen production technologies. This study evaluates their optimization in water electrolysis to improve efficiency and system stability. Key findings highlight the enhancement of these catalysts with nickel-iron oxyhydroxide and nickel-molybdenum co-catalysts. Technological innovations, such as Perovskite Solar Cells integration for solar-to-hydrogen conversion, are explored. The use of nickel foam enhances electrode durability, offering valuable insights into designing sustainable and efficient hydrogen production systems.

1. Introduction

Investigating the role of nickel in renewable energy is profoundly important, especially considering Indonesia's ban on exporting raw nickel. This move is intricately linked to the worldwide effort to transition to eco-friendly energy solutions. By banning raw nickel exports, Indonesia's goal is to boost investments in local nickel processing industries. As a result, while production has seen a rise, investments in renewable energy ventures involving nickel remain stagnant.

Fig. 1 shows nickel ore production, as well as the value of investment in renewable energy in Indonesia from 2013 to 2022. Nickel ore production has increased significantly from year to year, peaking in 2022 with total production of 98.19 million metric tons. However, the value of investment in renewable energy is not comparable to the growth in nickel production, with investment remaining relatively stable or even declining in recent years. This disparity reflects the untapped potential of Indonesia's abundant nickel resources, as the utilization of nickel remains low due to the limited introduction of advanced technologies within the country. Given this context, this paper explores the potential of nickel for sustainable energy applications beyond traditional battery use, positioning it as a viable catalyst for hydrogen production to support Indonesia's renewable energy goals and sustainable development (see Fig. 2).

Building on the premise of Indonesia's abundant nickel resources and its potential for broader applications, research into nickel's role in renewable energy is essential to advance technologies that optimize its use, particularly as the demand for scalable, cost-effective hydrogen production increases. Fe/Ni nano-alloy catalyzes CO_2 reduction and could also be employed in hydrogen production systems (Lu et al., 2020). Nickel and its alloys, such as NiCo LDH, are known for their significant catalytic activity in HER (Yang et al., 2020), while Mladenova et al. (2023) highlight the use of Ni-based electrocatalysts in energy conversion reactions like oxygen reduction and oxygen evolution in zinc-air batteries, further emphasizing nickel's importance in energy systems. Additionally, Fikri et al. (2023) note that electrocoagulation processes, which share similarities with water electrolysis, could potentially use similar electrochemical setups for hydrogen production. The NiCu alloy, in particular, has demonstrated enhanced polarization resistance and higher current density in electrolysis, improving the efficiency of HER and reducing the energy required for water splitting, thus enhancing hydrogen production (Mert et al., 2024).

In water splitting, nickel is a critical component in electrocatalysts, such as NiFe-Layered Double Hydroxides (LDH), which are essential for efficient, cost-effective hydrogen production in electrolyzers (Aralekallu

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et al., 2024). Nickel's contribution extends to composite materials like MoNiSe@VNFL, where it enhances both the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) activity, improving overall water splitting efficiency (Zhou et al., 2024). Additionally, nickel's electrocatalytic properties are explored in the context of plasmonic nanostructures, where its integration could boost sensor performance for hydrogen production (Muldarisnur et al., 2023). In protonic ceramic fuel cells (PCFCs), nickel oxide (NiO) is used as an anode substrate, contributing to the performance of these systems (Li et al., 2023a). Nickel is also integral in CoFe-Layered Double Hydroxide (LDH) derivatives for photo-thermal hydrogen production, where its presence enhances reaction kinetics, potentially improving hydrogen production rates (Li et al., 2023b). Furthermore, in biomass gasification, nickel improves the catalytic efficiency of water gas shift (WGS) and steam methane reforming (SMR) reactions, important processes for hydrogen production from carbon sources (Zeng et al., 2023). Lastly, in photocatalytic hydrogen production, nickel in NiCo-Layered Double Hydroxide (LDH) enhances electron transfer, improving hydrogen evolution under visible light (Bai et al., 2023). By contrast, nickel-based catalysts can achieve hydrogen production at a more accessible cost, potentially below the target of €1.5 per kg, positioning them as viable alternatives, especially for large-scale applications [1].

In this study, we aim to shed light on the advantages of nickel in hydrogen production, emphasizing its cost-effectiveness and scalability. In resource-rich regions like Indonesia, nickel-based catalysts present significant economic and environmental benefits. By employing co-catalysts and advanced support materials such as nickel-iron oxyhydroxide and nickel foam, this research seeks to improve the catalytic efficiency and durability of nickel systems, positioning them as robust alternatives for sustainable hydrogen production. Given Indonesia's abundant sunlight, the integration of nickel-based technologies in both photovoltaic and hydrogen production could maximize solar energy utilization. Investment in these technologies offers dual benefits: reducing dependence on fossil fuels and greenhouse gas emissions, while simultaneously enhancing the nation's energy sovereignty.

1.1. Research question

Nickel-based catalysts play an important role in enhancing hydrogen production through water electrolysis. Thus, in this study, we evaluate aspects regarding the specific role, advantages, and efficiency improvements of nickel-based catalysts to provide a clearer picture of the potential of nickel. We also optimize the use of nickel for hydrogen storage, which requires a more detailed understanding based on research that has been published in reputable journals. Using previous research in reputable journals is very important to determine the most suitable option for the application of renewable energy. It is important to compare nickel-based technology with alternative materials in terms of cost, efficiency, and durability based on robust research results.

In relation to the effectiveness of renewable energy policies in Indonesia, we analyze how these policies facilitate the development and utilization of nickel for necessary improvements and strategic direction. In our analysis, we include the role of nickel in domestic processing, added value, and economic and environmental implications. In connection with the research problems that have been presented, we formulate research questions as follows:

Q_1: What are the specific roles and advantages of nickel-based catalysts in water electrolysis for hydrogen production and storage?
Q_2: How do nickel-based technologies compare to other materials in terms of cost, efficiency, and durability for hydrogen production and storage?
Q_3: How effective are Indonesia's renewable energy policies and technology recommendation in promoting the use of nickel in renewable energy technologies?

1.2. Research objectives

Furthermore, to conduct a comprehensive analysis of nickel-based catalysts' performance in water electrolysis and to enhance hydrogen production efficiency, we need to investigate the current advancements and challenges in using nickel for hydrogen storage to propose potential solutions for optimization. We also perform a comparative study of nickel-based technologies against other materials used in hydrogen production and storage. Subsequently, to assess how well Indonesia's National Energy, we identify areas for policy improvement and recommend strategies to enhance the effectiveness of these policies. Therefore, it is important to examine the effects of Indonesia's 2014 and 2020

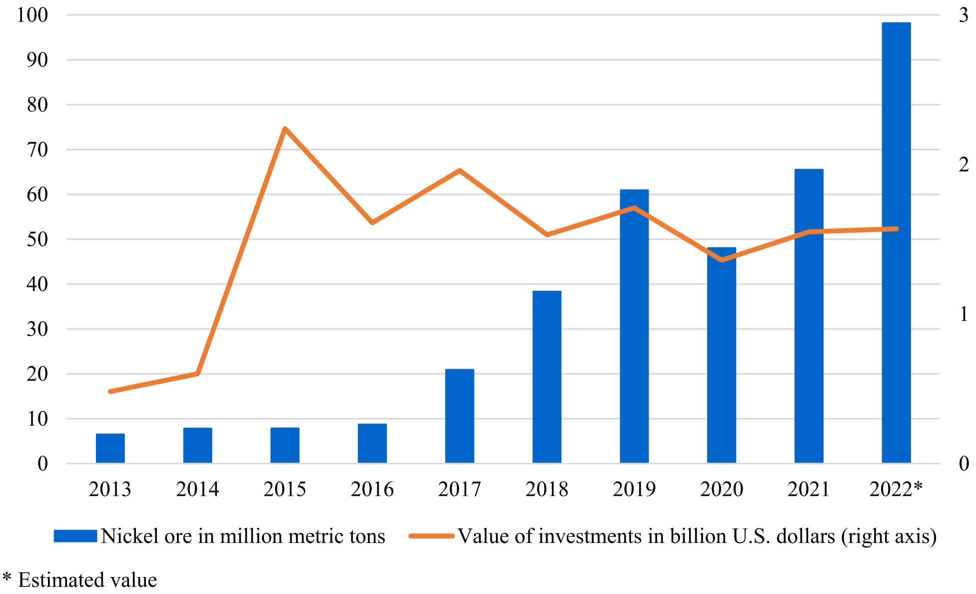

Fig. 1. Nickel Ore Production and Renewable Energy Investment Trends in Indonesia (2013–2022)
*Estimated value.
Source: Authors' composition based on Statista (2024a) [133] and Statista (2024b) [134].

nickel export bans on domestic processing, value addition, and broader economic and environmental outcomes. Thus, to answer the research questions, our research objectives as follows:

O$_1$: To Identify the Specific Roles and Advantages of Nickel-Based Catalysts.
O$_2$: To Compare Nickel-Based Technologies with Alternative Materials.
O$_3$: To Evaluate the Effectiveness of Indonesia's Renewable Energy Policies.

2. Methodology

2.1. Data collection procedure

In this subsection, we provide a detailed description of the processes involved in identifying, screening, and selecting relevant data. Our research focuses on nickel-based catalysts for hydrogen production and storage efficiency; thus, we need to outline the use of secondary statistical databases, and the keywords employed in our search strategy. The following is the figure how we obtain the necessary articles from high-reputable databases, such as Scopus and Web of Science (WoS):

The initial phase of our research methodology involves identifying relevant studies, reports, and data sources related to nickel-based catalysts for hydrogen production and storage efficiency. We conduct a comprehensive literature review using academic databases such as Scopus and WOS to gather peer-reviewed articles, conference papers, and dissertations. Our keyword search includes terms such as "Nickel-based catalysts," "hydrogen," "policy," and "Indonesia" to ensure a focused and relevant collection of data. Additionally, secondary statistic databases, including Statista and the Indonesian Statistic Database, will be utilized to obtain industry reports and governmental publications. From this phase, we found that the initial search yielded 385,179 documents. After excluding non-related documents, 1140 relevant documents were identified.

Following the identification phase, the screening process will narrow down the collected data to ensure relevance and quality. We apply inclusion and exclusion criteria to filter out studies that do not directly address the roles and efficiency of nickel-based catalysts in hydrogen production and storage and are not related to Indonesia's nickel policy. We use the methodological rigor criteria to focus more on the research published in the most pertinent and high-quality sources to ensure the subsequent analysis is grounded in credible and relevant data. Specifically, the screening process involved filtering documents based on type, language, and year of publication. We focused on articles, excluding other document types, and limited our selection to English-language articles published between 2014 and 2024. This thorough screening resulted in 616 articles after initial exclusions.

During the eligibility phase, we aligned the titles and abstracts with our research objectives, focusing on hydrogen, policy, and Indonesia. This phase will also involve checking for potential biases and ensuring that the selected studies represent a balanced perspective on the topic. This phase refined our selection to 262 articles that were deemed relevant and aligned with our goals.

The final inclusion phase will compile the eligible studies into a coherent dataset for qualitative and quantitative analysis. We assess all the necessary documents from the open access and the university, which are exclusively assets to the journal that published the articles. From this phase, we found that the 262 articles are accessible and can be processed for our further qualitative to quantitative analysis.

	Data bases selection	Included : Scopus and WOS Excluded : non-reputable databases.
Identification	Keyword and syntax search "photovoltaic" and "Nickel"	Included : 1,140 documents Excluded : non-related documents from a total of 385,179 documents
Screening	Document type: Articles	Included : 745 documents Excluded : other document type (395 documents)
	Language: English	Included : 735 articles Excluded : non-English articles (10 articles)
	Year of publication: 2014 - 2024	Included : 616 articles Excluded : articles before 2014 (119 articles)
Eligibility	Title and Abstract Alignment (TAA): Hydrogen, Policy, Indonesia	Included : 262 articles Excluded : articles do not align with our research objectives (354 articles)
Included	A total of 262 articles are included in the analysis.	

Fig. 2. Systematic Data Screening and Selection Process Source: Authors data analysis, 2024.
Source: Authors data analysis, 2024

2.2. Data analysis method

This research uses several text analysis tools or qualitative data analysis (QDA) software such as NVivo 12 plus, VOSviewer, and Voyant Tools. Our analysis begins with the simultaneous analysis utilizing clustering with co-occurrence network analysis of keywords. We argue that clustering provides a more detailed two-dimensional view of a network's structure compared to mapping, although it is limited in depicting multi-dimensional relationships. Clustering is not constrained by dimensional limits but operates on binary dimensions rather than continuous ones. The algorithm involves specific formulas for our calculations, which are as follows:

$$V(C_1, \ldots C_n) = \frac{1}{2m}\sum_{i\leq j}\delta(C_i, C_j)\omega_{ij}\left(C_{ij} - \gamma\frac{C_i, C_j}{2m}\right) \tag{1}$$

where C_i = element cluster i

γ = clustering resolution

m = total number of edges or sum of all edge weights.

$$\omega_{ij} = \frac{2m}{C_i}\,C_j$$

Source: Vysochan et al. [2]; Waltman et al. [3].

The most common tools for further analysis of the partial correlation and significance (p-value) from the text analysis are the person correlation and significance (p-value) based on a *t*-test. The correlation coefficient measures the strength and direction of a linear relationship between two variables in this research for term 1 and term 2. It is calculated using the Pearson correlation formula as follows:

$$r = \frac{\sum (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum (x_i - \overline{x})^2 (y_i - \overline{y})^2}} \tag{2}$$

Source: Hetenyi et al. [4]; Pearson [5]; Spaska et al. [6].where:

- x_i and y_i are the individual sample points of the two variables (in this case, keyword frequencies).
- $\overline{x}$ and $\overline{y}$ are the means of the variables/keyword frequencies.

Subsequently, to test the significance of the correlation coefficient whether the observed correlation is statistically significant, we use the *t*-test with the following formula for the test statistic:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{3}$$

Source: Hetenyi et al. [4]; Snedecor & Cochran [7]; Spaska et al. [6]. where:

- r^2 is the Pearson correlation coefficient.
- n is the number of paired observations.
- the p-value is then obtained from the t-distribution with $n-2$ degrees of freedom. This tests the null hypothesis that the true correlation is zero.

Interpretation:

- **Correlation (r):** Values range from -1 to 1, where values close to 1 or -1 indicate a strong relationship, and values close to 0 indicate a weak relationship.
- **Significance (p-value):** A low p-value (typically <0.05) indicates that the correlation is statistically significant.

2.3. Descriptive overview of the analyzed articles

In this section, we provide a bibliometric overview of the articles analyzed. This includes metrics such as the number of unique authors, journal sources, publishers, article origins, and keywords, as well as the count of single-author articles. The findings are detailed below:

Fig. 3 provides a comprehensive overview of the key descriptive metrics of our articles included in this study. A total of 262 articles were analyzed, featuring contributions from 1145 unique authors. Of these, only 4 articles were authored by a single individual. The articles span a wide range of topics; we counted 3779 distinct keywords that originated from 113 different countries. Additionally, we identified 42 funding sponsors, which means that research in nickel and renewable energy sources still gains attention for financial support. The articles were published across 154 different journals and by 63 unique publishers. The timespan of the articles ranges from 2014 to 2024, indicating a focus on recent and contemporary studies within the last decade.

3. Data analysis and result interpretation

3.1. Simultaneous test for comprehensive clustering and mapping

To perform the simultaneous keyword correlation and analyze the clustering, we use Equation (1) with the help of software analysis. We set the co-occurrence threshold at 5. Out of 3779 keywords, 3456 met this threshold, and 206 were used for further analysis. For the Cirrus data mining, we set the stopwords to automatic and added several abbreviation words such as AB, KW, TI, etc. The following figures present the results of the co-occurrence keyword analysis for the clustering analysis.

Fig. 4a illustrates the relationships and co-occurrences between keywords in the dataset. In this network, nodes represent keywords, while edges (lines) indicate the strength of co-occurrence relationships. Clusters of keywords are color-coded to represent distinct thematic groups. This clustering analysis offers a comprehensive view of nickel's potential across various applications, including:

- Red Cluster: Catalytic Processes for Hydrogen Production

The keywords in the red cluster revolve around hydrogen production through catalytic processes. Terms like “hydrogen production,” “catalyst supports,” “steam reforming,” and “catalytic reforming” indicate a focus on methods for producing hydrogen using various catalysts. “Ethanol” and “glycerol” suggest alternative feedstocks for hydrogen production, while “reaction temperature” and “oxygen vacancies” are critical parameters affecting catalyst performance. “Metal-support interactions” and “alumina” imply the use of support materials to enhance the stability and efficiency of catalysts. This cluster highlights the core elements of catalytic hydrogen production, where reaction conditions, feedstocks, and catalyst design play a central role in optimizing efficiency and yield.

- Blue Cluster: **Nickel**-Based Electrochemical Processes and Cost-Efficiency

The blue cluster focuses on nickel compounds and their electrochemical applications in hydrogen production, emphasizing cost-efficiency and advanced catalytic reactions. **“Nickel compounds,” “nickel-based catalyst,” and “nickel oxide”** underline the importance of nickel in catalyst formulation. Keywords like **“electrocatalysis,” “hydrogen evolution reactions,” and “water splitting”** reflect the electrochemical reactions essential for efficient hydrogen production. **“Electrolysis”** and **“hydrogen storage”** suggest the use of nickel in scalable energy storage solutions. Economic considerations are highlighted with terms like **“cost”** and **“alkalines”**, while **“ammonia”** and **“urea”** represent other pathways and feedstocks in hydrogen-related reactions. This cluster connects the electrochemical efficiency of nickel-based systems with their potential for cost-effective and sustainable hydrogen production.

- **Green Cluster: Nickel's Environmental and Geographic Context**

Fig. 3. Analyzed articles descriptive result.
Source: Authors data analysis, 2024

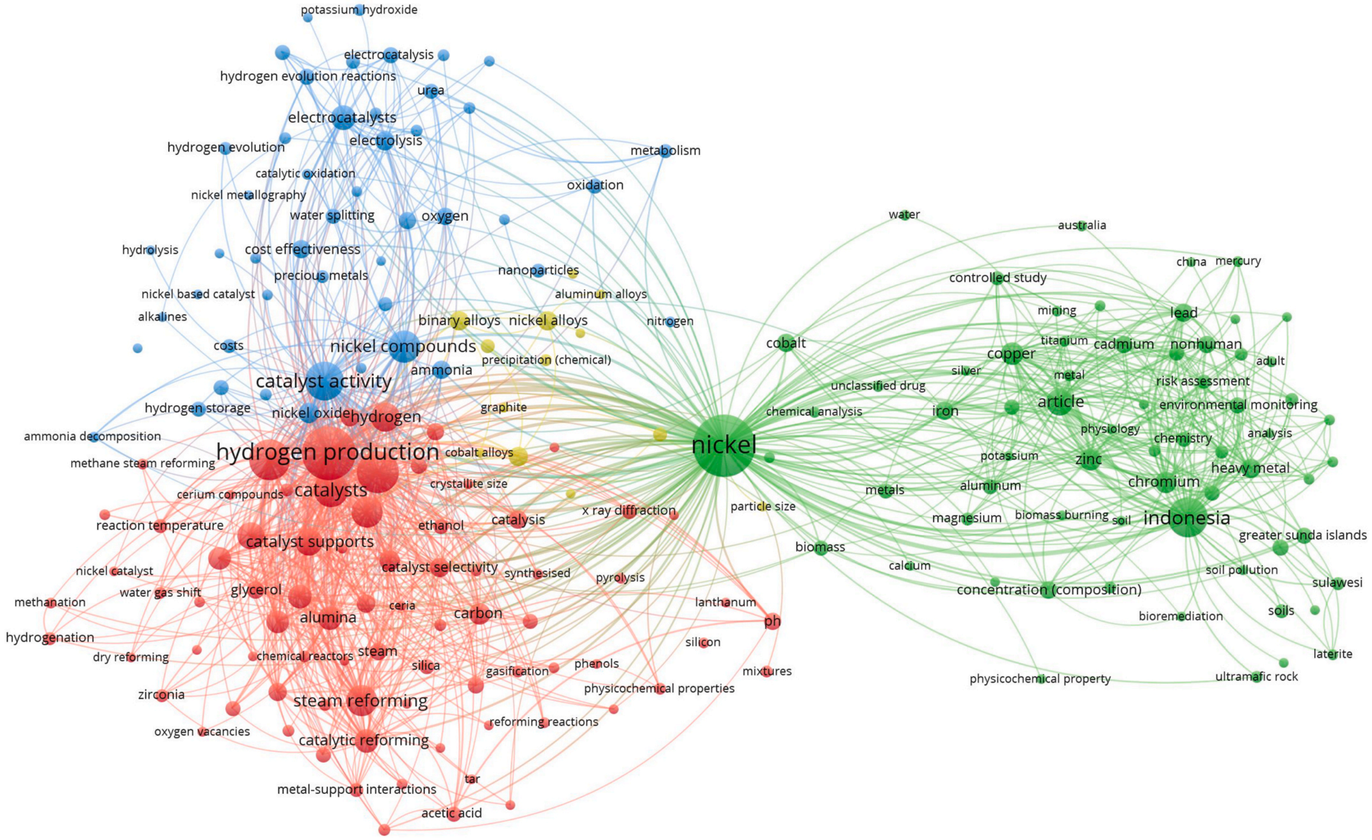

Fig. 4a. Keywords network visualization.

The green cluster centers on **"nickel"** within an environmental and geographical framework, particularly in the context of Indonesia and surrounding regions like China and Australia. Keywords like **"biomass," "bioremediation," and "soil pollution"** indicate nickel's role in environmental applications, including pollution remediation and biomass utilization. **"Chemical analysis," "risk assessment," and "environmental"** suggest a focus on assessing the impact of nickel on ecosystems and human health. **"Metal"** and **"aluminum"** denote the association of nickel with other metals in industrial and environmental contexts. This cluster connects nickel's industrial applications with environmental science, particularly in regions where nickel mining and processing are significant, highlighting both resource use and environmental concerns.

- **Yellow Cluster: Alloy Development and Temperature Effects**

The yellow cluster is focused on **"binary alloys," "nickel alloys," and "aluminum alloys,"** emphasizing the development and properties of nickel-based alloys. Keywords like **"graphite," "cobalt alloys,"** and **"temperature"** suggest studies related to the material properties and stability of these alloys under varying conditions. These alloys, which include nickel-cobalt and aluminum-nickel, are optimized for high-temperature applications and may be relevant to industries requiring durable materials for catalytic processes or energy storage. This cluster underscores the metallurgical research around nickel alloys, exploring their potential in high-temperature environments and industrial applications.

- Comparative Analysis of Clustering Results and Temporal Trends and Keyword Evolution

The clustering analysis reveals distinct thematic areas while also highlighting overlaps and interconnections among them. For instance, the interaction between the Red and Blue Clusters illustrates the integration of catalytic and electrochemical processes, such as the use of nickel-based catalysts in electrolysis for hydrogen production. Similarly, the environmental considerations in the Green Cluster align with the economic and scalability aspects in the Blue Cluster, underscoring the importance of sustainable and cost-effective technologies. Temporal analysis further enriches these insights by examining keyword frequency trends over time, revealing a consistent increase in terms related to nickel-based electrocatalysis and hydrogen production (Blue Cluster), which reflects the growing focus on scalable clean energy solutions. In contrast, keywords associated with environmental and geographical impacts (Green Cluster) have surged more recently, driven by policy changes in Indonesia, such as the 2020 nickel export ban, which highlight shifting research priorities influenced by technological advancements and geopolitical factors. These findings underscore the multifaceted role of nickel in advancing hydrogen production technologies and provide a roadmap for future research, which should prioritize enhancing catalytic processes, developing cost-effective electrochemical systems, and addressing environmental challenges. By integrating insights across these clusters, future efforts can develop holistic solutions that align with sustainability goals and meet global energy demands.

From this keyword clustering, we use text data mining using keyword cloud to collect more deeper understanding about the keyword combine with the title and abstract alignment (TAA). Fig. 4b is the keyword cloud that represents the most frequently occurring keywords within the dataset. Larger words indicate higher frequency and prominence in the analyzed texts. Prominent keywords such as "nickel," "hydrogen," "production," and "catalyst" suggest a significant focus on topics related to hydrogen production and catalysis involving nickel. The appearance of related terms like "catalysts," "reforming," and "energy" further highlights the central themes of the research corpus. Nevertheless, the author's keyword clustering is crucial as it provides a clear reference for grouping or clustering based on keywords. When performing text data mining with software, having a well-defined clustering reference is essential to avoid bias in the logical assessment of term relationships. Subsequently, the following is the table of statistical result from equation (1):

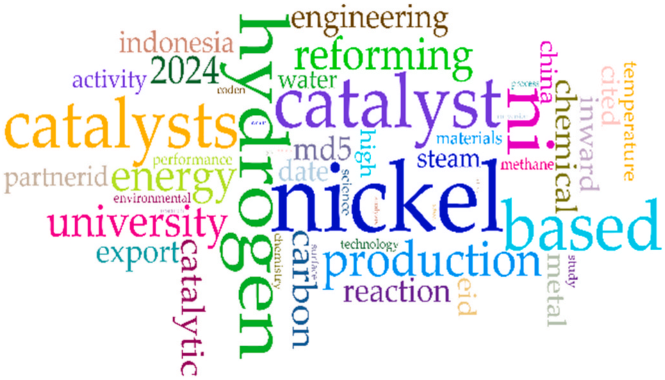

Fig. 4b. Keyword cloud.
Source: Author data analysis, 2024

This data is instrumental in creating a co-occurrence map, which aids in identifying clusters of related keywords within the dataset. The keyword "nickel" shows the highest occurrence (172) and total link strength (1,789), indicating its central role in the dataset. Similarly, "hydrogen production" is another significant term with 131 occurrences and a link strength of 1433. Several related keywords and clusters emerge from the data. Terms such as "nickel-based catalyst," "nickel-based catalysts," and "catalyst activity" exhibit substantial occurrences and link strengths. Additionally, the terms "steam reforming" and "catalytic reforming" indicate a focused interest in specific chemical processes involving catalysts, particularly in hydrogen production. The presence of the keyword "Indonesia" with a notable link strength (556) suggests a geographical context, possibly pointing to studies related to nickel production or mining in Indonesia. The following is the deeper analysis figure about the geographical context:

Fig. 5 illustrates the map depicting the density of country mentions in the 262 articles analyzed for this research, encompassing a total of 113 countries of origin. Indonesia is the most frequently mentioned country, appearing 34 times in the articles. China follows closely with 32 mentions, and the USA is mentioned 28 times. Germany has 20 mentions, while the United Kingdom is noted 15 times. France is mentioned 12 times, and Japan appears in 10 articles. Both Australia and Canada have 8 mentions each. South Korea is mentioned 7 times, and India's 6 mentions underscore its growing interest in nickel and energy policy. Brazil and the Netherlands each have 5 mentions. Italy appears in 4 articles, while Sweden and Spain are each mentioned 3 times. Russia also has 3 mentions. Finally, Switzerland is mentioned twice, with other countries appearing only once and zero in the articles.

3.2. Partial analysis for correlation and significance of keyword relationships

Based on Table 1, the proximity of co-occurrence between keywords is evident and is illustrated through the visualization in Fig. 4a. Furthermore, to ascertain the relationship between these keywords and other terms when combining keywords, titles, and abstracts, the keyword cloud depicted in Fig. 4b can be examined. These visualizations allow for the calculation of the correlation of keywords to terms in the titles and abstracts, as demonstrated in following figures:

Fig. 6a, b, 6c, and 6d illustrate the distribution of the frequency of each clustering across ten segments for temporal or sequential analysis, comparative analysis, and identifying focused intervention points within the articles. Each term is represented by a colored line, with the legend at the top of the tool specifying the colors assigned to each term. In Fig. 6a, the red cluster indicates that the most frequent terms are "reforming," "production," "nickel," "hydrogen," and "catalysts." The lowest frequency occurs around segments 4 and 5, while the peak frequency appears around segments 7 and 8, with the distribution clustering together in segment 10. Fig. 6b shows the most frequent terms in the blue cluster as "storage," "nickel," "cost," "compound," "catalyst," and "activity." While most terms are grouped together, "catalyst" and "nickel" display a significant increase, forming a higher group. This cluster, similar to the red cluster, exhibits peak frequency around segments 7 and 8. The green cluster in Fig. 6c highlights terms such as "metal," "Indonesia," "export," "environment," and "energy." Notably, the term "Indonesia" has the highest frequency in Segment 4, whereas "energy" peaks in frequency in Segment 10. Fig. 6d represents the frequency distribution of terms in the yellow cluster. Here, "nickel" shows a high-frequency distribution, while other terms remain in the low-frequency distribution. The term "alloy" has a similar frequency to "nickel" in segments 1 and 2 but then drops and aligns with the low-frequency distribution.

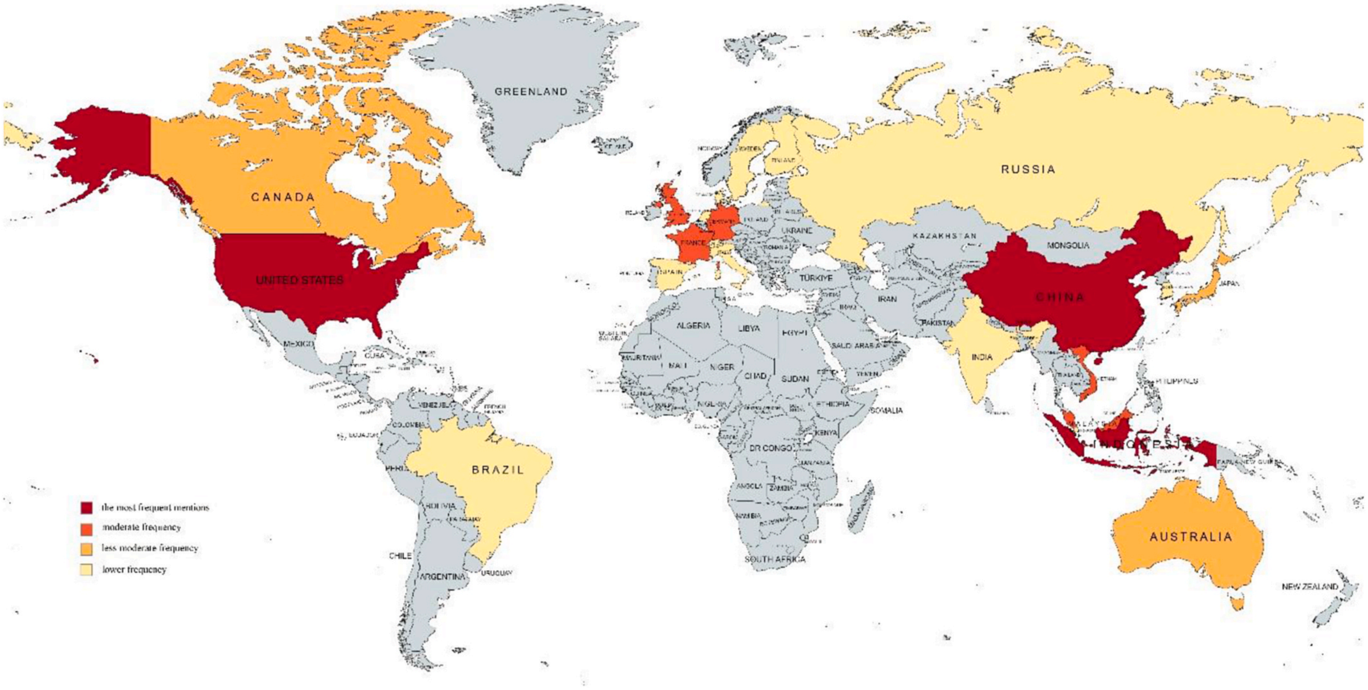

Fig. 5. Density of Country Mentions in Research Articles Source: Author data analysis modified from Voyant Tools and NVivo 12 Plus, 2024.

Table 1
Co-occurrence keywords analysis.

Keyword	Occurrences	Total Link Strength
nickel	172	1789
hydrogen production	131	1433
nickel-based catalyst	77	826
nickel-based catalysts	73	803
Indonesia	72	556
catalyst activity	68	762
catalysts	60	606
nickel compounds	47	471
steam reforming	44	535

Source: Author data analysis, 2024

From the frequency distribution, we also analyzed the correlation between the partial keywords and the term with the highest correlation. Furthermore, we tested the significance of this correlation. The following table explains the correlation and trend between the terms, the correlation value based on Equation (2), and the significance test based on Equation (3).

Table 2 represents a dataset consisting of term pairs and their corresponding Pearson correlation coefficients along with the significance levels, with the exception of the correlation between “hydrogen” and “storage.” This insignificant means that there is no significant correlation between hydrogen and storage across the articles used in this research. Most other correlation have significant meaning, for example, “hydrogen” demonstrates a strong correlation with “production” (0.9386627, $p = 0.000574$), underscoring its pivotal role in hydrogen production discussions. Notably, “Indonesia” shows significant

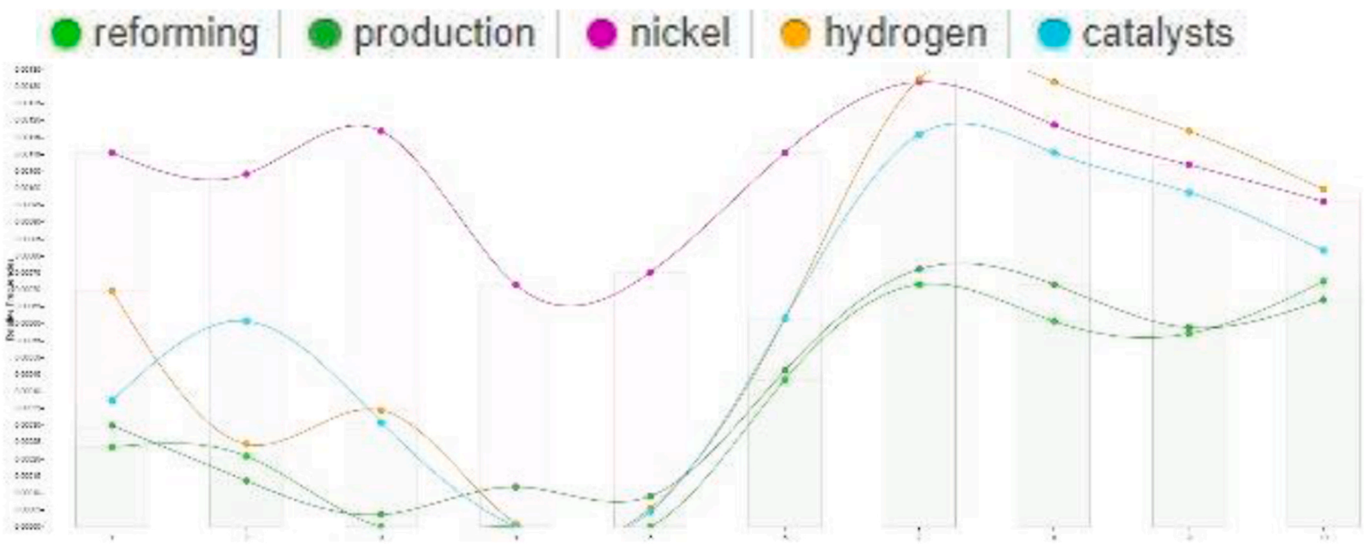

Fig. 6a. Term frequency trends red cluster

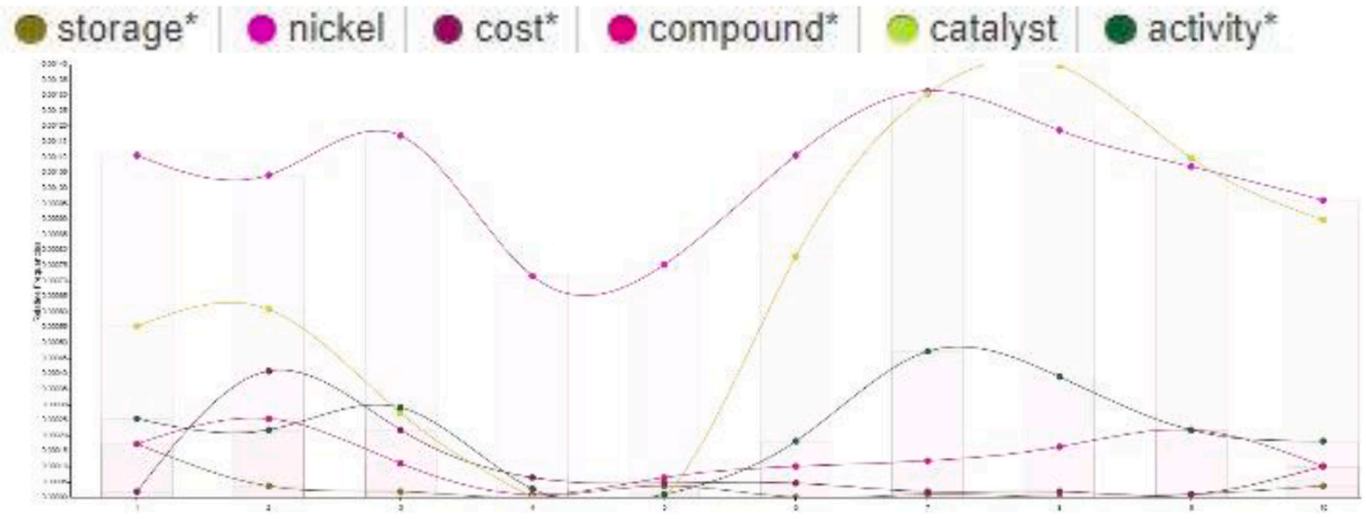

Fig. 6b. Term frequency trends blue cluster

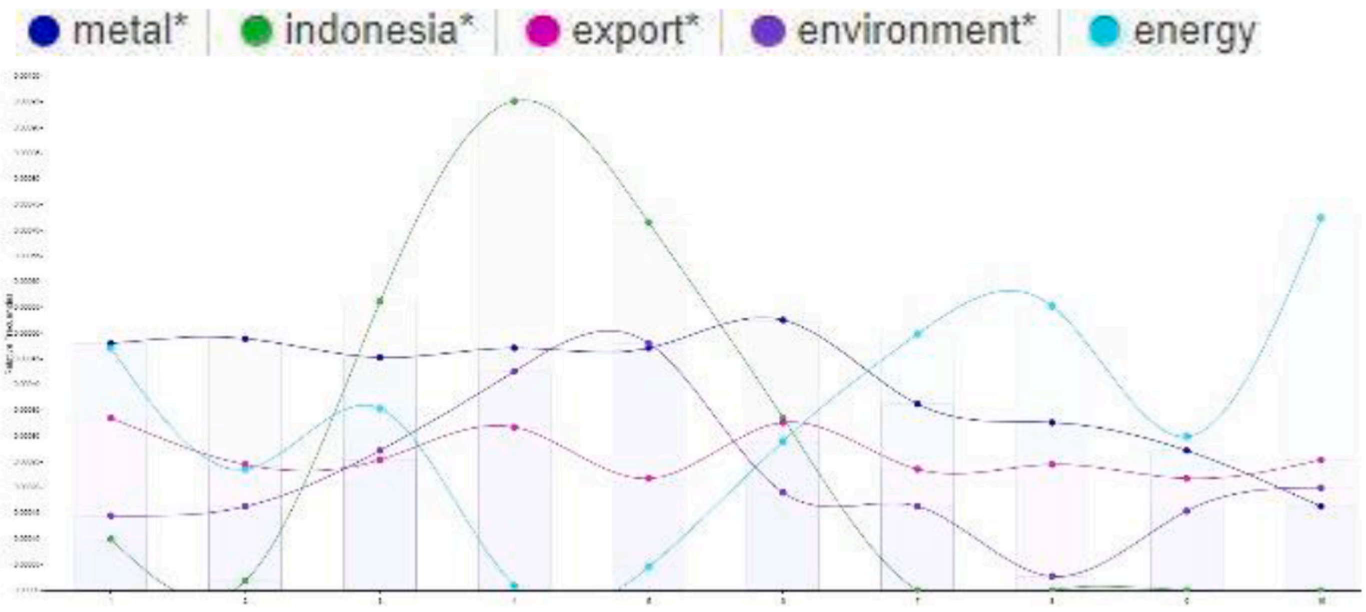

Fig. 6c. Term frequency trends green cluster

correlations with “energy” (0.7412545, p = 0.015565) and “export” (0.9585412, p = 0.000001), indicating a robust link between the country’s energy sector and export activities. Additionally, “PV” (photovoltaic) and “electrolysis” are strongly correlated (0.9845221, p = 0.000152), suggesting the integration of photovoltaic technology in hydrogen production in Indonesia, which aligns with the country’s energy and export dynamics. Thus, all correlations have significant values except the relationship between hydrogen and storage.

4. Discussion

4.1. Nickel-based catalysts: roles and benefits

Based on the data analysis, nickel-based catalysts are crucial for water electrolysis, a key process for sustainable hydrogen production [8,9]. Their multifaceted roles and advantages make them highly suitable for large-scale applications [10,11], especially in regions with abundant renewable energy resources like Indonesia [12,13].

In the clustering analysis derived from equation (1), we found that nickel plays a crucial role in hydrogen production and industrial applications [14–16]. In catalytic processes (Red Cluster), nickel is extensively used due to its high effectiveness and cost-efficiency [17–21]. The interaction between nickel and support materials, such as alumina, enhances the stability and dispersion of nickel particles [22–26], improving catalytic performance (Red Cluster). Additionally, synthesized catalysts involving ethanol reforming play a significant role in sustainable hydrogen production [27–30]. Reaction temperature and oxygen vacancies in catalyst support are critical parameters that affect catalyst performance [31–35], providing additional active sites for the reaction. Glycerol reforming using nickel catalysts [33,36–42], with glycerol being a byproduct of biodiesel production [41,43], represents another sustainable pathway for hydrogen production.

Nickel-based catalysts also excel in electrochemical applications for hydrogen production and storage (Blue Cluster), significantly enhancing efficiency in water splitting and hydrogen evolution reactions [11,44–46]. The affordability of nickel, compared to precious metals such as iridium [44,47] and platinum, makes it a favorable choice for large-scale hydrogen production [19,44,48–51]. Nickel catalysts are also involved

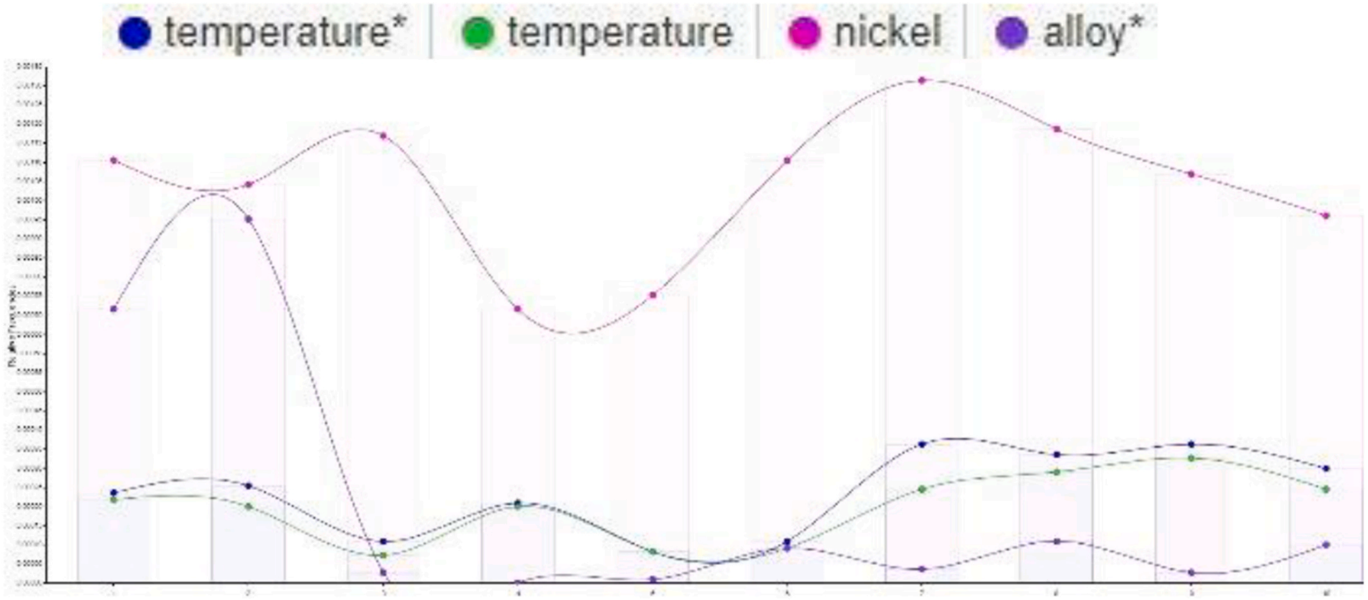

Fig. 6d. Term frequency trends yellow cluster
Source: Author data analysis modified from Voyant Tools and NVivo 12 Plus, 2024

in the decomposition of ammonia and urea, offering alternative pathways for hydrogen production and storage.

The scalability of technologies using nickel-based catalysts, such as integrated PV-electrolysis systems [10,52–55], is a major advantage, making them suitable for mass production and deployment in various capacities (Red and Blue Clusters). Nickel catalysts can be sourced from recycled materials [56], and their use in water electrolysis aligns with global sustainability goals (Green Cluster). Nickel-based electrolyzers can be seamlessly integrated with renewable energy systems, such as photovoltaic arrays, to harness solar energy for hydrogen production [17,54,57]. This synergy is particularly advantageous for Indonesia, which has abundant sunlight and can efficiently produce green hydrogen using nickel-based catalysts combined with solar power. This combination offers a sustainable and economically viable pathway for hydrogen production. Subsequently, nickel alloys, such as binary and nickel-cobalt alloys [58–62], exhibit unique properties that enhance their performance in hydrogen production and other industrial applications (Yellow Cluster).

4.2. Theoretical insights into active sites and reaction mechanisms in energy conversion

The performance of nickel-based catalysts in energy conversion processes, such as hydrogen production, is fundamentally governed by the characteristics of their active sites and the underlying reaction mechanisms. Active sites, often located on the surface of the catalyst, are regions where adsorption, activation, and conversion of reactants occur. For nickel-based systems, these active sites can include metallic nickel atoms, nickel oxide species, and metal-ligand interfaces, all of which play critical roles in enhancing catalytic activity.

4.2.1. Active sites in nickel-based catalysts

Metallic nickel atoms serve as primary active sites for hydrogen evolution reactions (HER), facilitating the adsorption of hydrogen ions (H^+) from the electrolyte and promoting subsequent electron transfer for hydrogen gas (H_2) generation. The catalytic activity of metallic nickel is largely attributed to its d-band structure, which provides an optimal balance between hydrogen adsorption and desorption energies, ensuring efficient reaction kinetics [63–65]. In oxygen evolution reactions (OER), oxidized nickel species, such as NiO and $Ni(OH)_2$, play a critical role by acting as active sites for water splitting [66,67]. These species facilitate the formation and stabilization of intermediate oxygen species, including OH* and OOH*, which are essential for driving the OER pathway [68]. Furthermore, the integration of co-catalysts, such as iron in NiFe-LDH or molybdenum, modifies the electronic structure of nickel, creating new active sites at the metal-ligand interface. These synergistic effects enhance the catalytic properties by improving charge transfer rates and lowering energy barriers for reaction intermediates, further optimizing the efficiency of nickel-based systems [69].

4.2.2. Reaction mechanisms in hydrogen evolution and oxygen evolution reactions

The reaction mechanisms of hydrogen evolution (HER) and oxygen evolution reactions (OER) on nickel-based catalysts involve distinct but interrelated pathways that determine their efficiency in electrochemical processes. In HER, the process typically follows a two-step mechanism: the Volmer step, where protons adsorb on the catalyst surface ($H^+ + e^- \rightarrow H^*$), and either the Heyrovsky or Tafel step, which leads to molecular hydrogen formation [50,70,71]. In the Heyrovsky step, an adsorbed hydrogen atom reacts with another proton and an electron ($H^* + H^+ + e^- \rightarrow H_2$), while the Tafel step involves the direct recombination of two adsorbed hydrogen atoms ($H^* + H^* \rightarrow H_2$). The rate-limiting step in HER is influenced by the hydrogen binding strength on nickel surfaces, which must achieve a delicate balance between adsorption and desorption to optimize efficiency [69,72]. For OER, the reaction proceeds through a multi-electron process, starting with the adsorption of water molecules on the active site ($H_2O \rightarrow OH^*$), followed by the oxidation of hydroxide to form intermediate oxygen species ($OH^* \rightarrow OOH^*$), and culminating in the release of oxygen gas and regeneration of the active site ($OOH^* \rightarrow O_2 + H^+$) [45,73,74]. Nickel-based catalysts excel in OER due to the presence of oxidized nickel species and metal-ligand interactions, which stabilize intermediates and reduce energy barriers, thus enhancing reaction kinetics and overall performance [26,55,68,75,76].

4.2.3. Theoretical models, computational, and implications for catalyst design

Theoretical models, particularly those based on density functional theory (DFT), have offered valuable insights into the electronic properties of nickel-based catalysts by predicting energy profiles for intermediate formation and reaction pathways [17,68,77,78]. These studies

Table 2
Correlation and significance of keyword relationships.

Term 1	←	→	Term 2	Correlation	Significance
hydrogen			nickel	0.7127797	0.020689
hydrogen			production	0.9386627	0.000574
hydrogen			storage	0.6355571	0.655421
nickel			catalyst	0.7500922	0.012460
nickel			electrolysis	0.7432995	0.013748
nickel			energy	0.6422161	0.045264
reforming			production	0.9773223	0.000001
reforming			hydrogen	0.9229349	0.000140
reforming			catalyst	0.9256113	0.000122
hydrogen			temperature	0.7110485	0.021144
indonesia			energy	0.7412545	0.015565
indonesia			export	0.9585412	0.000001
indonesia			china	0.7336954	0.013554
export			european	0.7177471	0.026654
cost			applying	0.9351364	0.000071
pv			electrolysis	0.9845221	0.000152
pec			pv	0.9254545	0.000131
pec			perovskite	0.7184555	0.025252

Source: Author data analysis modified from Voyant Tools and NVivo 12 Plus, 2024

highlight the importance of tuning the d-band center to optimize adsorption energies, demonstrating how alloying and the incorporation of co-catalysts can redistribute electronic density and enhance catalytic activity [79,80]. Additionally, surface morphology and defect engineering are identified as key factors in creating high-density active sites, which are crucial for improving overall catalytic performance. This theoretical understanding directly informs the design of advanced nickel-based catalysts by identifying optimal structural and electronic configurations for active site generation. It also underscores the significance of co-catalysts and support materials in stabilizing intermediates and accelerating reaction kinetics. Furthermore, such insights provide practical guidelines for tailoring catalyst properties through doping, alloying, and nanostructuring, enabling the development of more efficient and robust systems for hydrogen production.

4.3. *Electrochemical performance of catalysts*

To thoroughly examine the intrinsic properties of nickel-based catalysts toward hydrogen production, we analyzed key performance curves, including polarization curves, Tafel slopes, and overpotential plots (Fig. 7a, b, and 7c). These curves provide insights into catalytic efficiency, reaction kinetics, and energy requirements under various operational conditions.

Nickel-based and platinum catalysts exhibit distinct performance trends across polarization curves, Tafel slopes, and overpotential analysis. Platinum catalysts demonstrate lower overpotentials and steeper reaction kinetics, making them ideal for high-efficiency applications. However, their high-cost limits scalability, particularly for large-scale hydrogen production systems [19,44,49,51]. In contrast, nickel-based catalysts, while exhibiting higher overpotentials and slower kinetics, remain a cost-effective and scalable alternative. Innovations such as co-catalyst integration (e.g., NiFe-LDH, nickel-molybdenum) and hybrid materials like MOF/LDH composites significantly enhance nickel-based catalyst efficiency, stability, and reaction kinetics [81,81–88]. These advancements underscore the economic and environmental benefits of nickel-based systems, particularly in resource-abundant regions like Indonesia, and highlight the potential for further optimization to close the performance gap with platinum catalysts [89,90].

The electrochemical performance and stability of nickel-based catalysts were evaluated using polarization curves, Tafel slopes, and overpotential plots to understand their intrinsic properties and long-term viability for hydrogen production. The polarization curves highlight significant reductions in overpotential when nickel-based catalysts are modified with nickel-iron oxyhydroxide and nickel-molybdenum co-catalysts. These modifications enhance electron transfer kinetics and catalytic efficiency, making the catalysts highly suitable for scalable

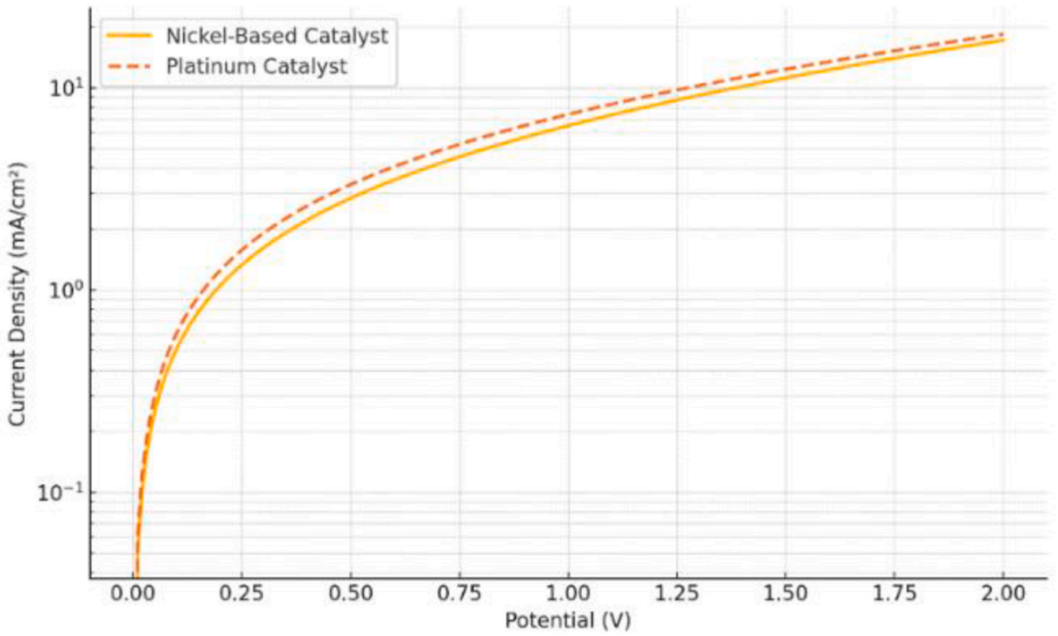

Fig. 7a. Polarization Curve – Current Density vs. Potential.

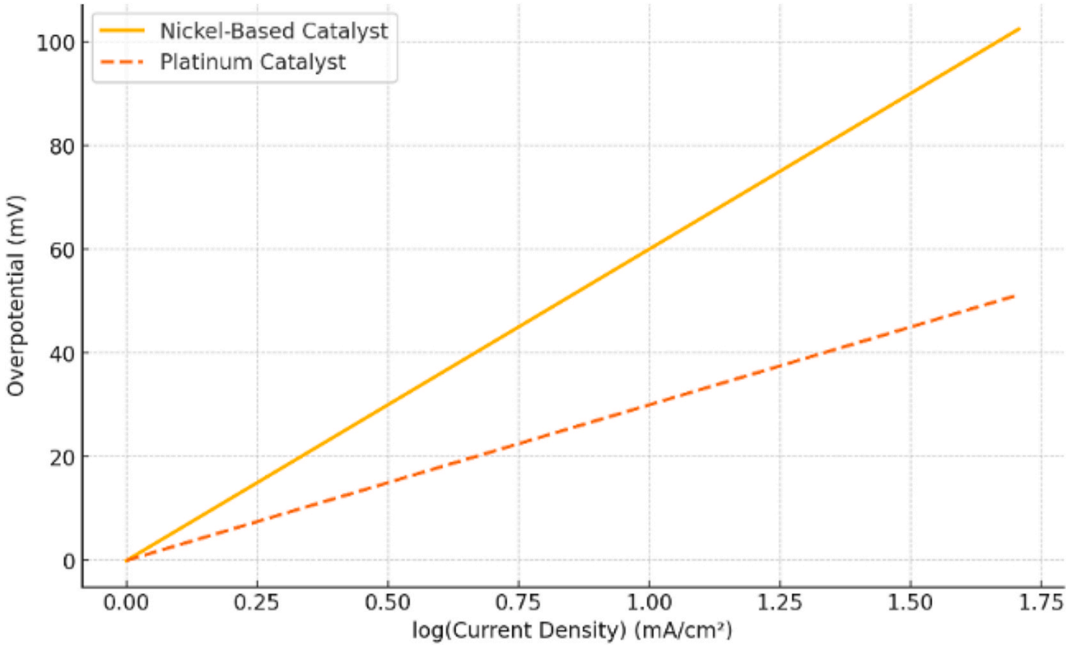

Fig. 7b. Tafel slope analysis.

hydrogen production. Notably, nickel foam-supported electrodes achieved significantly lower overpotentials at current densities, such as 10 mA/cm^2, compared to unmodified counterparts, reflecting improved reaction stability, durability, and energy efficiency. Tafel slope analysis revealed values ranging between 50 and 70 mV/decade, indicating favorable reaction kinetics and efficient proton-electron transfer mechanisms, comparable to more expensive catalysts like platinum.

Stability is a critical factor for the application of nickel-based catalysts in hydrogen production. These catalysts are prone to degradation mechanisms such as surface oxidation, catalyst sintering, and electrolyte corrosion, which can reduce their efficiency over time. However, the incorporation of co-catalysts and structural reinforcement with nickel foam mitigates these issues by providing protective layers, reducing overpotentials, and maintaining active surface sites. Additionally, alkaline environments were found to enhance stability by minimizing corrosion rates. Long-term performance tests show that nickel-based catalysts retain catalytic activity for extended hours or cycles under optimized conditions, rivaling or surpassing more expensive materials like iridium. Innovations such as composite materials like NiFe-LDH further improve resistance to mechanical and chemical wear, enhancing their suitability for industrial-scale applications.

These findings confirm that nickel-based catalysts offer a cost-effective, scalable, and efficient solution for sustainable hydrogen production. Their adaptability to diverse operational conditions, including varying pH levels and temperatures, underscores their broad applicability. In regions like Indonesia, where abundant nickel reserves and

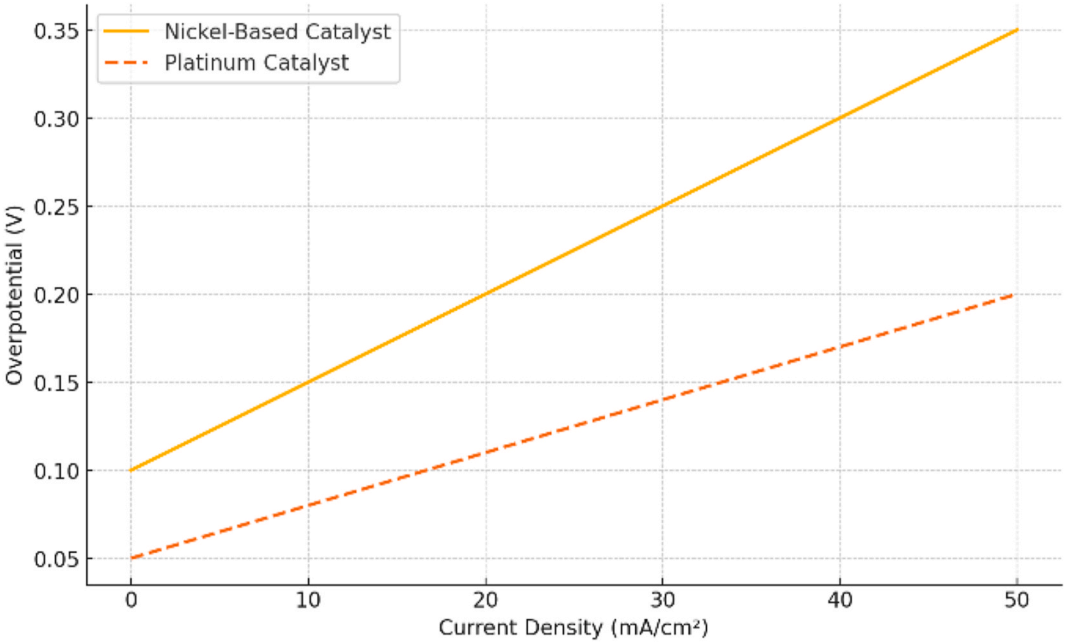

Fig. 7c. Overpotential vs. Current Density.

renewable energy resources are available, nickel-based systems hold significant potential to drive advancements in green hydrogen technologies. Future research should focus on advanced coatings and synergistic material combinations to further extend the operational lifespan of these catalysts.

Beyond their electrochemical performance, understanding the broader advantages, limitations, and structural optimization of nickel-based catalysts is crucial for their advancement in hydrogen production systems. The following section discusses these aspects in detail, highlighting the interplay between structural parameters and catalytic performance. Based on the clustering analysis, we found that Structural parameters play a pivotal role in determining the performance and stability of nickel-based catalysts for hydrogen production. These parameters include surface area, porosity, particle size, and morphology, all of which directly influence the number and accessibility of active sites, as well as mass and charge transfer rates.

1) **Surface Area and Porosity**:

High surface area and well-optimized porosity increase the exposure of active sites, enhancing catalytic activity. Nickel foam, for instance, provides a 3D porous structure that improves gas diffusion and electrolyte penetration, leading to lower overpotentials and higher current densities.

2) **Particle Size and Morphology**:

Smaller particle sizes enhance the dispersion of nickel particles, increasing the availability of active sites. Morphologies such as nanowires, nanosheets, or core-shell structures further enhance performance by reducing diffusion limitations and promoting charge transfer.

3) **Structural Stability**:

Catalyst structures that resist aggregation, sintering, and oxidation under operational conditions are crucial for maintaining long-term performance. For example, the integration of nickel with iron or molybdenum in layered double hydroxides improves structural robustness and prevents degradation during electrolysis.

4) **Support Materials**:

The choice of support materials, such as nickel foam or carbon-based scaffolds, significantly affects catalyst stability and efficiency. Support materials can prevent the detachment of nickel particles, reduce corrosion, and enhance conductivity.

5) **Electron Transport Pathways**:

Structural designs that facilitate efficient electron transport, such as conductive coatings or the inclusion of synergistic materials, reduce energy losses and improve catalytic efficiency.

4.4. *Temporal and segmental analysis of nickel - economic and policy implications of energy subsidies*

The environmental and geopolitical aspects of nickel production are significant, particularly Indonesia's ban on nickel ore exports [91–94], which affects global supply and market dynamics (Green Cluster). In Fig. 5 highlights Indonesia's pivotal role in the global nickel market, significantly impacting China and the United States. With abundant nickel reserves and strategic export policies, including a recent export ban, Indonesia influences global supply chains. Its strong relationship with China [95–97], a major consumer of nickel for stainless steel and battery industries, is bolstered by Chinese investments in Indonesian nickel mining and processing infrastructure [98]. China gains additional advantages by opening factories in Indonesia, such as building battery factory and automobile. The United States faces challenges as companies like Apple and Tesla must navigate Indonesian regulations and invest in domestic processing due to the export ban [99–101]. U.S. companies mainly aim to maintain their market share in Indonesia instead of setting up local production facilities. As a result, the significance of nickel and its added value in lithium batteries is called into question.

For temporal or sequential analysis, comparative analysis, and identifying focused intervention points within the articles, Fig. 6a shows nickel as a catalyst peak in segments 2, 3, 6, and 7, indicating focused discussions on catalytic materials at specific points [46,102–104]. Notably, the recognition of nickel as a catalyst for hydrogen production in the context of Indonesia [105] increases and reaches its peak at segments 7 and 8. The recognition of Indonesia's role in metal exports increases significantly in segment 4 [91–94,96], while discussions on the environment become prominent around segments 7 and 8. However, the recognition of nickel, in this case in the Indonesian context [105–107], as a part of renewable energy sources only starts to increase significantly in segment 10 (Fig. 6c).

Table 2 provides significant correlations between various terms, underscoring the potential for advanced hydrogen production technologies, particularly relevant for Indonesia's abundant sunlight. The Integrated PV-electrolysis system combines photovoltaic cells with electrolysis to produce hydrogen efficiently, using nickel-based catalysts [10,108,109]. Nickel foam electrodes coated with nickel iron oxyhydroxide (NiFeOx) enhance catalytic activity [108,110–113], making this technology well-suited for large-scale implementation in Indonesia, which has high solar irradiance. Similarly, the Tandem device combining PEC and PV for unassisted solar water splitting maximizes solar energy use, with nickel playing a crucial catalytic role. The combination of Cu(In,Ga)Se2-based photocathodes [114] and halide perovskite top cells further improves light absorption and conversion efficiency [53,115–117], again very ideal for Indonesia's solar-rich environment.

The insignificant correlation between hydrogen and storage (0.655571, p = 0.655421) means that there only views paper discusses about hydrogen storage in connection to the Indonesian context or otherwise that hydrogen storage is still not explore in Indonesian context because Indonesian renewable technology is very beginning level that might only focus on how to produce and less concern on how to storage the energy. This also because the demand of the energy in Indonesia is very high.

Indonesia's energy demand is driven by economic growth and industrialization. From Fig. 8, we analyze that the total energy consumption exhibits a consistent upward trend, increasing from 6.78 EJ in 2015 to 10.54 EJ in 2023. In contrast, renewable energy consumption remains relatively low but shows a gradual increase from 0.13 EJ in 2015 to 0.81 EJ in 2023. To further support this industrialization and to keep energy prices affordable for the middle and lower classes, the Indonesian government has implemented subsidies for energy. Energy subsidies, measured in trillion Indonesian Rupiah (IDR), exhibit significant fluctuations throughout the period. Starting at 117.40 trillion IDR in 2015, subsidies drop to their lowest point at 92.80 trillion IDR in 2017, before progressively rising to 209.90 trillion IDR by 2023. The sharp increase in subsidies from 2018 onwards may suggest a governmental push to stabilize energy prices or to encourage energy consumption amidst rising demands.

Reducing this disparity between total energy consumption and renewable energy consumption is crucial and can be achieved by implementing advanced technologies that produce renewable energy more efficiently and cost-effectively in connection with the use of nickel. One such promising technology is the Silicon microwires [118] with a radial junction for PEC hydrogen production [55] also highlight nickel's role as a co-catalyst, improving efficiency through enhanced light absorption and charge separation. The significant correlation between "PEC" and "perovskite" (0.7184555, p = 0.025252) further emphasizes the synergy between photoelectrochemical cells and perovskite materials in achieving efficient hydrogen production [115]. The significant correlation between "nickel" and "electrolysis" (0.7432995, p = 0.013748) further supports the use of nickel in enhancing electrolysis processes [10]. This finding highlights the need for research on upscaling and operational efficiency, reinforcing its feasibility for broader applications, underscoring the potential for mass production. The use of nickel foam as a support structure enhances efficiency and durability, further aligning with the significant correlation between "nickel" and "catalyst" (0.7500922, p = 0.012460) and reinforcing the strategic importance of integrating photovoltaic systems for hydrogen production in Indonesia [10,108,113,119].

5. Technology recommendation

Based on our analysis of the correlation and significance within the article, we propose that the conceptual schematic presented illustrates an advanced hydrogen production system. This system is optimized for both efficiency and scalability, building upon previous research in photovoltaic and electrochemical technologies. This system utilizes Triple Cation Mixed Halide Perovskite Solar Cells, known for their high efficiency and scalability. These cells are particularly suited for mass production and large-scale deployment, making them an ideal choice for Indonesia's solar-rich environment.

Fig. 9 shows the enhanced schematic diagram for the solar-driven hydrogen production system represents a sophisticated integration of photovoltaic and electrolysis technologies designed to harness solar energy efficiently for hydrogen production. At the heart of this system

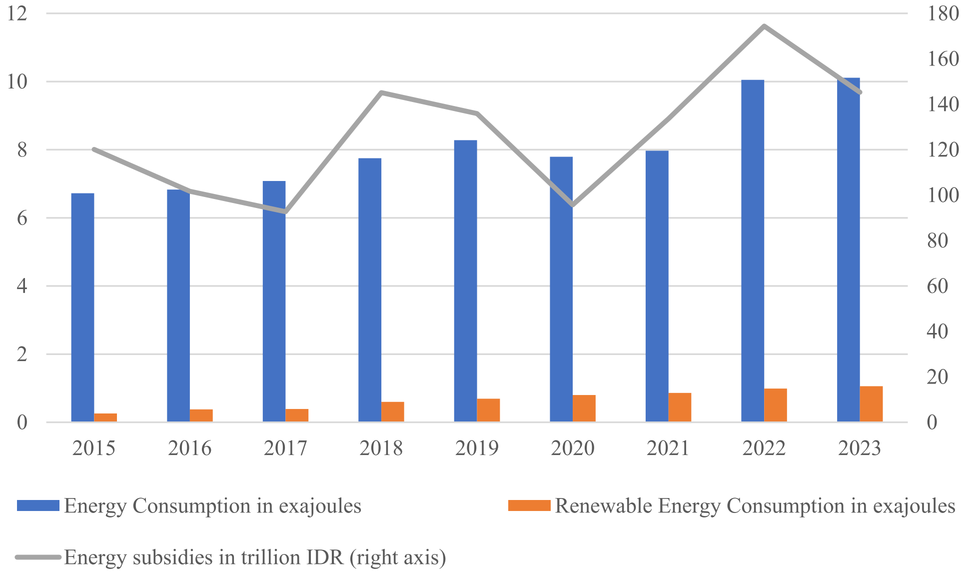

Fig. 8. Energy in Indonesia.
Sources: Authors' composition based on Statista (2024c) [135], Statista (2024d) [136] and Statista (2024e) [137].

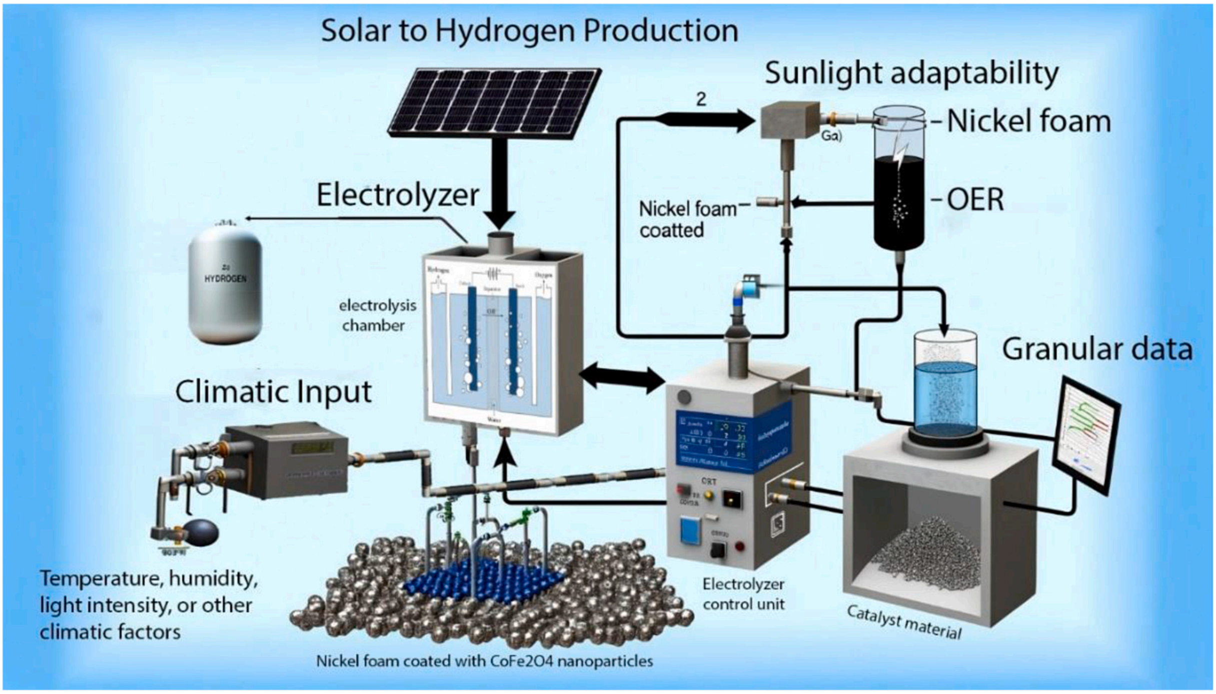

Fig. 9. Conceptual schematic of an advanced hydrogen production process.
Source: Author data analysis, 2024

are high-efficiency photovoltaic (PV) cells, such as silicon heterojunction (SHJ) cells [108,118,120] or tandem cells that combine Cu(In, Ga)Se_2-based photocathodes [76,114] with halide perovskite top cells [115,117], for advanced solar cells of converting a significant portion of solar energy into electrical energy, which is particularly beneficial in regions with high solar irradiance, such as Indonesia [121,122].

The process begins with these high-efficiency solar panels capturing sunlight and converting it into electrical energy. This electricity is then directed to an electrolysis chamber where water (H_2O) is split into its constituent gases, hydrogen (H_2) and oxygen (O_2). To ensure the efficiency of the electrolysis process, the system integrates a water purification unit that uses techniques like reverse osmosis [31,57,123,124]. This unit ensures that only high-purity water enters the electrolysis chamber, thus maintaining the electrolyzer's performance and longevity [125,126].

Inside the electrolysis chamber, nickel foam electrodes coated with nickel-iron oxyhydroxide (NiFeOx) [108,110–113] and amorphous molybdenum sulfide act as catalysts [68,69,72,119,121,127,128]. These advanced catalysts significantly enhance the catalytic activity, making the water-splitting process more efficient. The nickel-based catalysts facilitate the oxygen evolution reaction (OER) on the anode side and the hydrogen evolution reaction (HER) on the cathode side. The use of these catalysts ensures that the electrolysis process occurs at a lower energy input, increasing the overall efficiency of hydrogen production [68,122].

The electrolyzer control unit, a crucial component of the system, dynamically adjusts the electrolysis parameters based on real-time climatic data such as temperature, humidity, and light intensity [10], to ensures that the electrolysis process remains optimal under varying environmental conditions. Moreover, the system continuously collects granular data on its performance, which is then fed into an AI-based optimization algorithm [76,119,129]. This feedback loop allows for real-time adjustments and continuous improvement, ensuring that the system operates at peak efficiency [130,131].

As the electrolysis process proceeds, hydrogen gas is produced at the cathode, while oxygen gas is produced at the anode. The produced hydrogen gas is then collected and stored in a dedicated hydrogen tank. To ensure safety, the storage system is equipped with hydrogen sensors, automated shutoff valves, and pressure relief systems to mitigate any risks associated with hydrogen storage and handling [131,132].

Most of the prior literature used in our schematic diagram has an average of 20% efficiency. Assume an advanced solar-to-hydrogen system has an efficiency of approximately 20%. This means that 20% of the solar energy captured is converted into useable hydrogen energy. Based on the prior research, typical for sunny regions like Indonesia, the average solar irradiance is 5 $\text{kWh/m}^2\text{/day}$. Since nickel has high efficiency and is cheap, let us assume deploying 1 km^2 of high-efficiency solar panels. Then we can get the following results:

- Daily energy capture $= 5\ \text{kWh/m}^2\text{/day} \times 1,000,000\ \text{m}^2 = 5,000,000\ \text{kWh/day}$
- Annual energy captured $= 5{,}000{,}000\ \text{kWh/day} \times 365\ \text{days} = 1{,}852{,}000{,}000\ \text{kWh/year}$

Or equal to 1.825 TWh/year. Therefore, if we converted Hydrogen as an energy with 20% efficiency, the annual hydrogen energy produced = 1.825 TWh/year × 0.2 efficiency = 0.365 TWh/year. To meet with Fig. 8, we convert the energy to Exajoules $= 0.365 \times 10^{-3} EJ = 0.001314$ EJ/year. Therefore, to effectively boost renewable energy production, we assume to scale up deployment to cover roughly 100 km^2. This calculation shows that deploying the technology on 100 km^2 could contribute approximately 0.1314 EJ per year to the renewable energy consumption. Given the 2023 renewable energy consumption in Fig. 8 of 1.06 EJ, this technology could increase the total renewable energy consumption by 12.4%.

The cost for this technology for the combining SHJ and halide perovskite technology are more expensive than single-layer perovskite or silicon cells alone due to the complexity of integration. However, the increased efficiency can justify the higher costs, approximately $ 0.3/watt for the tandem cells. Thus for 100 km^2 with an efficiency of 300 W/m^2 (due to the higher efficiency of tandem cells), the total capacity would be 30 GW. The cost can be calculated as follows:

Cost for tandem solar panels:

$$Total\ capacity = 100,000,000\ m^2 \times 300\ W/m^2 = 30\ GW$$

Cost per Watt = $ 0.3/W

Cost for electrolyzers:

Assume the is $500/kW of capacity. Thus, for an annual hydrogen production capacity of 0.1314 EJ (assuming 20% efficiency, this is roughly 0.036 TWh of electrical energy):

- Daily energy requirement = 0.036 $TWh/year/365\ days$ = 100 MWh/day
- Required electrolyzer capacity (assuming 24-h operation) = 100 MWh/day/24 hours = 4.17 MW

Thus, the cost of electrolyzers = 4.17 MW × $500/kW = $2.085 million

Cost for Water Purification System:

We estimated the cost for purification system approximately $1 million for a system capable of supplying purified water for a large-scale electrolysis plant.

Cost for hydrogen storage and compression:

Since we have not identified any significant correlation between hydrogen and storage costs, and predicted the storage costs to be slightly higher, at around $ 1000 per kg of storage capacity. Thus, we convert the energy (in kWh) and mass (in kg) of hydrogen to measures of production, storage, and associated costs in the hydrogen production system. We found that the value of 33.33 kWh/kg represents the energy density of hydrogen. This means that 1 kg of hydrogen contains approximately 33.33 kW-hours (kWh) of energy. Therefore, for a daily production of 100 MWh of hydrogen, we calculate the cost as follows:

$$Daily\ hydrogen\ production = \frac{100,000\ kWh}{33.33\ kWh/kg} = 3,000\ kg \Big/ day$$

$$Storage\ for\ one\ day\ of\ production = 3,000 kg \times \$\ 1,000/kg = \$\ 3\ million$$

Cost for Auxiliary Systems, Infrastructure, Installation, and Maintenance:

The cost for auxiliary systems and infrastructure is estimated at $ 2 million. Installation and maintenance costs are projected to be around 10% of the total capital cost. Thus, the cost calculation as follows:

$$\begin{aligned} Installation\ and\ maintenance\ cost &= 0.10 \\ &\times (\$\ 9\ billion + \$\ 2.085\ million + \$\ 1\ million + \$\ 3\ million + \$\ 2\ million) \\ &= \$\ 900.81\ \text{million} \end{aligned}$$

Combining these expenses, the total cost estimate for the solar-driven hydrogen production system using SHJ and halide perovskite tandem cells includes $ 9 billion for tandem solar panels, $ 2.085 million for electrolyzers, $ 1 million for the water purification system, $ 3 million for hydrogen storage and compression, $2 million for auxiliary systems and infrastructure, and $ 900.81 million for installation and maintenance. Therefore, the total estimated cost is approximately $ 9.91 billion. Considering Indonesia's current GDP of $ 1.319 trillion (2022), this project represents a significant but manageable investment. Moreover, Indonesia is receiving substantial foreign investments, including from China, which is heavily investing in the development of Indonesia's new capital city. This influx of investment demonstrates a strong economic partnership and the potential for securing additional funding for innovative projects like the solar-driven hydrogen production system. Leveraging these economic strengths and investment flows, this renewable energy project can be realistically funded, supporting Indonesia's transition to sustainable energy and enhancing its energy security.

6. Policy implications

Indonesia's renewable energy policies, particularly the National Energy Policy and Presidential Regulation No. 22/2017, have shown mixed effectiveness in promoting the use of nickel. We found that the 2014 and 2020 nickel export bans profoundly affect domestic processing, value addition, and the broader economic and environmental landscape. These bans have spurred investments in domestic processing facilities, thereby increasing value addition within the country and fostering the development of local industries. Economically, the measures have boosted the domestic nickel industry, contributing to growth and job creation, although they have also led to trade disputes, such as the complaint lodged by the European Union at the WTO. However, environmentally, increased nickel mining and processing present challenges, including habitat destruction and pollution. Thus, we suggest stricter environmental regulations and sustainable mining practices be necessitated.

Revising the National Energy Policy and Presidential Regulation No. 22/2017 to explicitly support nickel-based hydrogen technologies is essential. This revision could include financial incentives, research grants, subsidies for domestic manufacturers, and the inclusion of universities. Implementing strict environmental regulations will ensure sustainable nickel mining and processing, thereby minimizing ecological damage. Additionally, developing trade strategies that balance domestic value addition with international trade obligations, potentially through negotiated agreements or adjustments in export policies, is crucial to enhance the nickel roles in hydrogen production in the Indonesian context.

7. Conclusion

This study makes significant theoretical contributions by demonstrating the pivotal role of nickel-based catalysts in hydrogen production technologies, particularly in enhancing hydrogen evolution reactions (HER) and oxygen evolution reactions (OER) during water electrolysis. Nickel's affordability, durability, and superior catalytic performance offer a cost-effective alternative to precious metals like platinum and iridium. Moreover, its integration into advanced catalytic systems, such as NiFe-LDH composites and nickel foam supports, exemplifies its versatility in improving efficiency, scalability, and sustainability. These findings enrich the theoretical framework of renewable energy technologies by elucidating nickel's role in bridging economic feasibility and high-performance catalytic processes.

While significant progress has been made in enhancing the electrochemical performance of nickel-based catalysts, their broader application in industrial settings presents unique challenges. One major limitation is their susceptibility to degradation mechanisms such as surface oxidation, sintering, and corrosion, particularly in acidic or high-temperature environments. These issues compromise the long-term stability and efficiency of nickel catalysts, necessitating frequent replacement or regeneration, which can increase operational costs in industrial-scale applications. Furthermore, the relatively higher overpotentials of nickel-based systems compared to platinum and iridium reduce their energy efficiency, posing challenges for cost-competitive hydrogen production at large scales.

The limited understanding of how structural parameters affect catalyst performance and stability under diverse operational conditions also hinders the full optimization of these systems for industrial use. Additionally, scaling the production and recycling of nickel-based catalysts in an environmentally sustainable manner remains a significant hurdle, especially given the potential environmental impacts of nickel mining and processing.

Future development should focus on addressing these challenges to ensure the industrial viability of nickel-based catalysts:

Enhancing Stability: Innovations such as advanced coatings, protective alloys, and the incorporation of synergistic materials (e.g., nickel foam with layered double hydroxides) can mitigate degradation and extend catalyst lifespans, improving reliability in continuous industrial operations.

Improving Efficiency: Further research into reducing overpotentials through the integration of novel co-catalysts and optimizing reaction environments (e.g., alkaline media) can enhance energy efficiency, making hydrogen production more cost-competitive.

Scaling Sustainability: Developing recycling and regeneration techniques for nickel catalysts will reduce material waste, mitigate environmental impacts, and ensure a sustainable supply chain for industrial applications.

Designing Advanced Architectures: Leveraging nanostructures, porous frameworks, and composite designs can increase active surface areas and improve mass transport properties, leading to higher catalytic performance at the scale required for industrial hydrogen production.

By addressing these challenges, nickel-based catalysts can evolve into a cornerstone technology for large-scale hydrogen production, bridging the gap between laboratory advancements and practical industrial implementation while supporting the transition to a sustainable hydrogen economy.

CRediT authorship contribution statement

Johan Reineer Tumiwa: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Tamás Mizik:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the results of this work.

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