Energy Reports 9 (2023) 5843–5856

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Hydrogen export competitiveness index for a sustainable hydrogen economy

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ARTICLE INFO

Article history:
Received 11 January 2023
Received in revised form 26 April 2023
Accepted 8 May 2023
Available online 22 May 2023

Keywords:
AHP
Expert interviews
Hydrogen production
Hydrogen policy
Natural gas
Renewable energy

ABSTRACT

The transition to cleaner energy sources, including renewables, introduces the need for versatile and transportable energy carriers such as hydrogen. This paper aims to quantify the hydrogen export competitiveness of all countries using a newly developed comprehensive index. The developed competitiveness index includes 21 indicators under four main categories: resource availability and potential, economic and financial potential, political and regulatory status, and industrial knowledge. Expert interviews and surveys are conducted to properly identify, choose and modify the categories and indicators, and to calculate the appropriate weight for each. Top-ranking countries include the United States, Australia, Canada, United Kingdom, China, Norway, India, Russia, Netherlands, and Germany, and they are poised to be significant players in the hydrogen market. Policy recommendations for growing the hydrogen production and export sector are given based on each category.

1. Introduction

The growth in global energy demand resulting from growing populations and developing economies has caused CO_2 emissions to increase constantly and rapidly. The COVID-19 pandemic caused a decrease in emissions in 2020, but the following year saw a rapid increase to previous levels, reaching 36.3 Gt in 2021 (IEA, 2021). Although renewable energy sources provide a carbon-free alternative, their adoption depends on various factors that reduce their reliability. The most significant of these challenges is their intermittent nature, which necessitates the integration of energy storage systems, which are costly as of today's technological development and capacity.

Hydrogen is an energy carrier that can be used to store energy and has gained significant attention and advocates in the past few years. The recent decrease in the cost of some renewable energy technologies has renewed interest in producing hydrogen through water splitting (Abdin et al., 2020). The resulting carbon footprint depends primarily on the production and transportation methods used. For example, hydrogen production leads to minimal emissions through water electrolysis using renewable energy sources (green) or conventional methods with carbon capture (blue). Once produced, hydrogen can be used as a fuel in several ways.

Hydrogen has a range of applications as a clean and efficient alternative to fossil fuels. It can be used in transportation as fuel for vehicles like cars, buses, and trains and the generation of electricity through fuel cells. Industrial processes such as refining, chemical processing, and steel production can also benefit from using hydrogen as a fuel, as it reduces greenhouse gas emissions and improves energy efficiency. Additionally, hydrogen can be used in residential and commercial heating systems such as boilers and furnaces and has even been used as a fuel in space exploration for rockets and spacecraft. While there are challenges to using hydrogen as a fuel, including the high cost of production and the need for infrastructure to store and transport it, it has the potential to play a significant role in the transition from fossil fuels towards a low-carbon future.

More than 20 countries have announced their hydrogen strategies since 2018, and more than 19 are preparing them. National hydrogen strategies indicate the willingness of countries to develop the global hydrogen market and their eagerness to participate in a hydrogen economy. These strategies signal an upcoming shift in the global energy market that can cause a decrease in CO_2 emissions if appropriately managed. The growing momentum for hydrogen can also be seen in the number and value of planned hydrogen projects. As of September 2022, more than 680 large-scale hydrogen projects have been announced globally, with investments of 240 bn USD until 2030 (Hydrogen Council and McKinsey & Company, 2022).

The global demand for hydrogen has been increasing steadily since the 1970s. If it is widely adopted as an energy carrier of

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https://doi.org/10.1016/j.egyr.2023.05.024

choice in the upcoming years, hydrogen demand is expected to grow much faster. Countries in the European Union and East Asia are expected to become major demand centers for hydrogen. Exporting the needed quantities of hydrogen to these regions requires conventional energy exporters and new market players to ramp up their hydrogen production capacities accordingly.

Hydrogen can be economically used for transporting renewable and fossil fuel energy in many domestic, regional, and international markets. Semeraro (2021) found that, for distances of 1000 miles with 2030 technology, a hydrogen pipeline can be a cost-competitive method for the transmission of variable renewable energy (VRE) compared to a high voltage direct current (HVDC) transmission line based on life-cycle costs normalized by energy flows. This article utilizes a high-level comparison model to evaluate the technical and economic feasibility. Its findings contribute to understanding hydrogen energy markets by highlighting the potential role of hydrogen pipelines in decarbonizing power transmission systems. However, it is not an exhaustive evaluation and does not consider alternative scenarios. Further research is needed to understand the feasibility and cost-effectiveness of VRE transmission and its impact on the energy market.

Al Ghafri et al. (2022) found that steam methane reforming (SMR) with carbon capture and storage (CCS) has the lowest total hydrogen supply cost and emissions intensity for the transport of liquefied natural gas (LNG) from Australia to Japan and can meet targeted hydrogen supply costs up to 2050. The authors analyzed the feasibility and efficiency of three distinct blue hydrogen production methods, namely SMR, ATR, and NGP, focusing on their application in a supply chain context and a hydrogen production rate of 100 tonnes per day. The study primarily focuses on the techno-economic and environmental aspects of the hydrogen supply chain, but policy and regulatory factors can also significantly impact the feasibility and implementation of such supply chains.

Hydrogen was also cheaper and more effective at reducing CO_2 emissions than biogas when injected into the existing natural gas pipeline network in the UK, with the most sustainable pathway being the injection of hydrogen generated from wind power (Ma and Spataru, 2015). The paper involves modeling the natural gas network from terminals to end-users, accounting for production, transmission, and distribution costs across four stages, and using daily gas flow data to calculate total costs via simulation. This provides insights into the economic feasibility of hydrogen integration into existing gas infrastructure and identifies key cost factors that influence the competitiveness of hydrogen compared to other energy sources.

Future hydrogen markets may resemble natural gas markets, and countries may assume specific roles in renewable hydrogen systems based on resources and infrastructure (Pflugmann and de Blasio, 2020). For example, countries with active hydrogen policies and high levels of research and development (R&D) may be well-suited to take on leadership roles in implementing an inter-state hydrogen energy system in the Asia-Pacific region (Aditiya and Aziz, 2021). In contrast, countries with strong primary energy supply capacity and economic advantages could contribute energy and commercial resources. This complements the hydrogen export competitiveness index by providing additional context on how countries can assume specific roles and offers further insights into potential collaborations and market dynamics among countries in the hydrogen sector.

A supportive policy framework, carbon pricing, and clean and green energy policies were recommended to improve the competitiveness of hydrogen energy and fuel cell electric vehicles in the Association of Southeast Asian Nations (ASEAN) member states (Li and Kimura, 2021). The authors apply a well-to-wheel (WTW) model and a total cost of ownership (TCO) model to compare the energy consumption, carbon emissions, and costs of FCEVs with alternative powertrains. The study's limitations include simplifying hydrogen infrastructure costs, omission of potential renewable energy technology improvements, and the availability of high-quality data on FCEVs' hydrogen production, transportation, storage, and fuel economy. This regional perspective enhances the understanding of hydrogen export competitiveness and contributes to developing more targeted policy recommendations for countries seeking to expand their hydrogen production and export sectors.

It is important to note that different pathways could majorly impact global energy trade, create new energy exporters, and alter geopolitical relations, while international governance and investments in hydrogen value chains could help to prevent some of the resulting risks (van de Graaf et al., 2020). The article provides valuable insight into the international governance and investments needed to scale up hydrogen value chains and reduce the risk of market fragmentation and intensified geo-economic rivalry. However, it may have limitations in considering various factors, regional contexts, and the roles of diverse stakeholders, as well as the impact of emerging technologies on hydrogen development and adoption.

Although various governments have set ambitious national goals for the use of hydrogen energy, the absence of clear policy guidelines at the national level is hindering significant cost reductions (Joy and Al-Zaili, 2021). The paper develops and employs a financial model for hypothetical H_2 projects in the UK and assigns price assumptions to a set of policies to assess whether current UK energy policies support an economic case for low-carbon and competitive H_2 production. However, the study is based on a financial model that may not fully capture real-world complexities, such as uncertainties in technological advancements, fuel prices, and government policies, and it focuses only on the UK's competitiveness in the hydrogen economy, so the findings may not be generalizable to other countries.

The future potential of hydrogen depends on policy frameworks, economies of scale, technological learning, and energy utilization rates (Ajanovic and Haas, 2018). The methodology used in the study includes economic analysis and modeling, but it does not incorporate empirical data. The authors analyze the economic prospects of hydrogen use in the energy system, focusing on integrating variable renewables in power systems and substituting fossil fuels in the transport sector. However, they only focus on passenger vehicles and do not cover other modes of transport, such as trains, trucks, and buses. Moreover, the study only considers the economic perspective and does not address the environmental impact of hydrogen use.

In addition, various measures, including industry standards, low-carbon vehicle policies, and carbon taxes, are needed to encourage the adoption of hydrogen energy systems (Parra et al., 2019). The paper provides a techno-economic review of hydrogen energy systems, focusing on their optimal operation as flexible assets and identifying three actions that can foster their uptake. It includes analyzing data from the largest abstract and citation databases of peer-reviewed research literature, but it may not capture all research and developments in the field. However, the authors do not focus on any specific location or country, and most examples and projects are observed in regions with fast diffusion of renewable energy technologies.

Evaluating the competitiveness of each market player to export hydrogen is essential for developing energy models and policy building. This paper proposes using a hydrogen export competitiveness index as a starting point for quantifying a country's potential for hydrogen export. The calculation of this index is based on several categories, including resource availability, economic and financial potential, geographic location, existing infrastructure, industry experience, and governmental regulations and policies. These categories are identified and then modified based on an extensive effort by conducting expert surveys and interviews.

The index score indicates a country's ability to participate in the global hydrogen market as an exporter and can be used as a condition for its inclusion in hydrogen energy models. The score also shows sensible hydrogen investment choices and market potential. It is also an excellent tool for comparing the strengths and weaknesses of different market players, therefore directing policymakers to better choices.

This study is part of a broader situation analysis of potential hydrogen exporters. A clear picture of the global market is obtained by analyzing the export potential of different players in the hydrogen sector. This work is expected to aid in developing a computational model for the global hydrogen energy market to simulate and investigate different scenarios and case studies. Optimization based on multiple scenarios can be developed based on the model results to guide decision-makers and policy efforts for different countries and players.

The rest of the paper is organized as follows: The methodology is presented in Section 2, which includes several subsections: preliminary index categories and indicators, expert interviews, expert surveys and the AHP methodology, and category and indicator scores. Section 3 presents the results and discussion, including expert interviews, category weights, and the hydrogen export competitiveness index scores. Policy recommendations are provided in Section 4, followed by the conclusions in Section 5.

2. Methodology

In this study, we have opted for a comprehensive methodology to evaluate export competitiveness in a hydrogen economy, which combines a range of factors, expert opinions, and the Analytic Hierarchy Process (AHP). The rationale for employing this method lies in its ability to offer a holistic perspective on a country's potential for hydrogen production and export, taking into account physical, economic, and political constraints. By involving energy experts in the selection and validation of categories and indicators, we ensure that our assessment is grounded in relevant and practical knowledge from the industry. Furthermore, the AHP technique allows for the structured incorporation of these subjective expert opinions, leading to a transparent and justifiable decision-making process. This method also provides scalability and flexibility, which are essential attributes for adapting to the dynamic nature of the hydrogen economy. As new data becomes available and indicators evolve, this methodology can be easily updated to maintain its relevance and accuracy in assessing countries' export competitiveness.

The proposed flowchart for evaluating export competitiveness in a hydrogen economy involves the following key steps:

1. Identify relevant categories and indicators: These are based on physical, economic, and political constraints limiting a country's ability to produce and export hydrogen commercially. These categories and indicators are refined based on the opinions of energy experts.
2. Survey energy experts: A group of energy experts is surveyed to evaluate the validity of the identified categories and indicators. The experts are asked open-ended questions about the importance of the categories and their relevance to hydrogen production and export.
3. Assign weights using AHP: The Analytic Hierarchy Process (AHP) assign weights to each category based on its importance in affecting a country's export competitiveness as a hydrogen producer and exporter. The AHP methodology allows for the integration of subjective expert opinions in a structured manner, making it easy to understand and justify the decision-making process.
4. Calculate sub-scores: Indicators within each category are scored on a 1–5 scale based on publicly available data or calculated from that data. These sub-scores are then multiplied by the weight of their respective category to calculate the category score.
5. Calculate overall index score: The category scores are then added to calculate each country's overall index score. This score allows for a direct comparison between the evaluated countries.

Table 1
Preliminary categories and indicators for the hydrogen export competitiveness index.

Category	Indicator
Resource availability	Gas reserves Water scarcity Renewable energy potential
Political status	Stability & transparency International relations Regulation and policies
Economic potential	Infrastructure Finances Geographical location
Knowledge	Research and development Experience Human Capital
Adaptability	Ease of doing business Governmental effectiveness

The comprehensive flowchart diagram illustrating the key steps involved in the proposed framework is shown in Fig. 1.

A more detailed chart is provided in Fig. 2. It shows how the framework is employed in each of the mentioned models using the corruption control score in the United Arab Emirates and the respective values for each step.

2.1. Preliminary index categories and indicators

Factors affecting a country's ability to produce and export hydrogen are multifaceted and multidisciplinary, spanning many fields. A country's hydrogen production may be limited by its petroleum resources, renewable energy potential, water resources, or land area. These factors are physical constraints that can be estimated for each country. On the other hand, a country might face problems producing or exporting hydrogen due to its infrastructure, financial capabilities, political atmosphere, and governmental policies. These factors are qualitative but can be assigned a value based on indices designed for other evaluation purposes. We adopt several well-established global indices in our evaluation as proxies for economic, financial, political, and governmental standing. As a starting point, we select the following categories: resource availability, political status, economic potential, knowledge, and adaptability. These categories and their sub-categories, referred to as indicators in this study are shown in Table 1.

Each indicator's minimum and maximum scores create a range of possible values converted to a 1–5 scale where 1 is the minimum value and 5 is the maximum value. This normalization allows us to calculate an overall index score of 1–5 by averaging all indicator scores or assigning an individual weight for each. This initial framework is described in our previous work (Hjeij et al., 2022) but is refined and developed based on expert

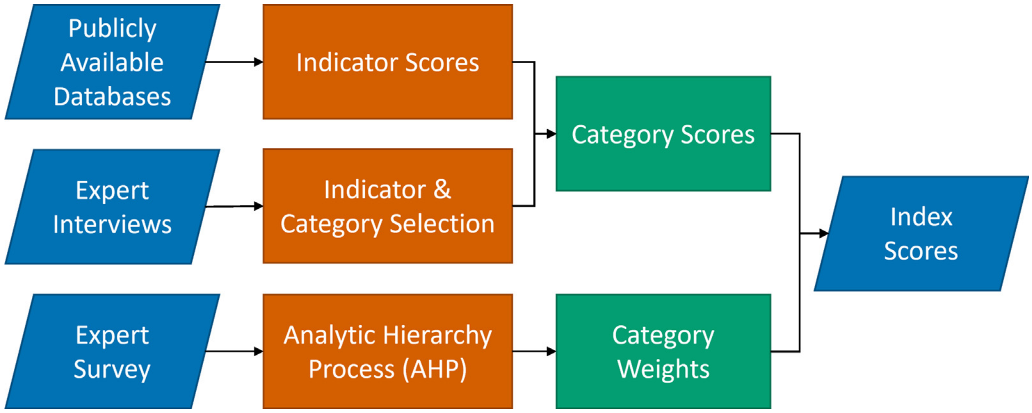

Fig. 1. Flowchart of adopted methodology for calculating hydrogen export competitiveness scores of all countries.

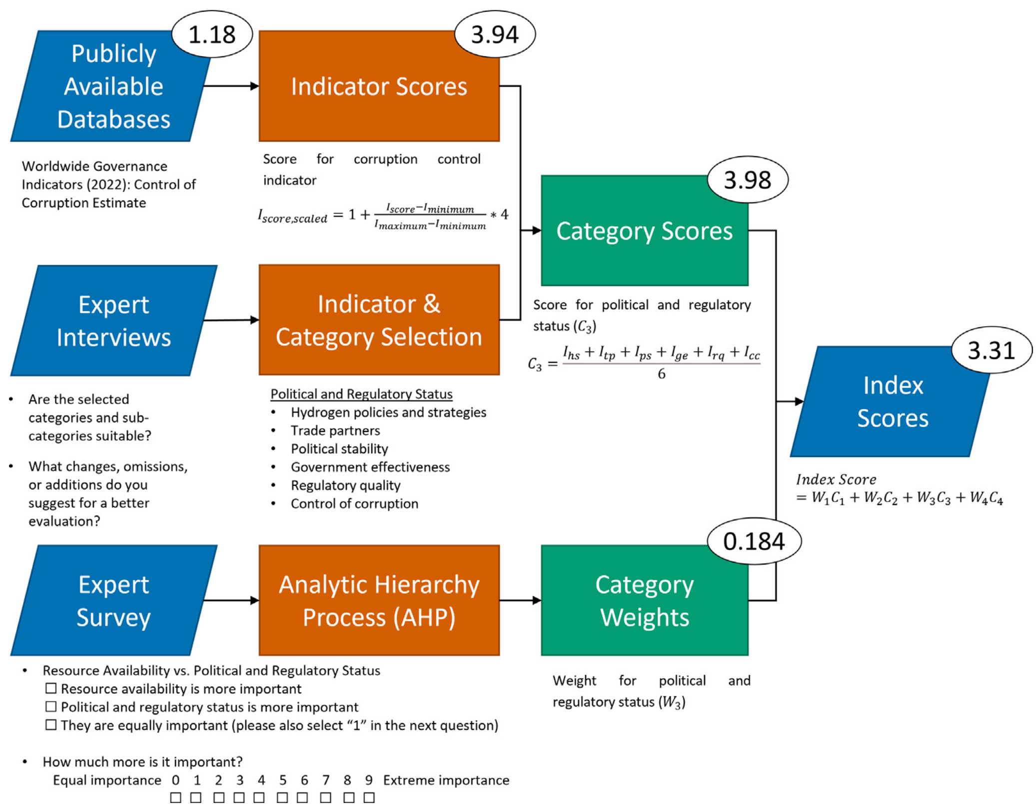

Fig. 2. An example of the framework implementation starting with the corruption control score for the United Arab Emirates.

opinions and surveys in this work. The scope is also modified to include all potential hydrogen-exporting countries instead of only gas exporters, as in the previous work. Subsequently, the name of the index is changed from hydrogen competitiveness to hydrogen export competitiveness.

The resource availability indicator uses gas reserves, water scarcity, and renewable energy potential to calculate a sub-score. Natural gas and water are used in steam methane reforming, the primary method for gray or blue hydrogen production, while water and renewable energy resources are required for green hydrogen production. Equal weights are assigned for each value within the resource availability indicator. Gas reserves and water scarcity are available from different sources, while renewable energy potential is calculated based on solar and wind potentials.

An aggregate of well-developed indices is used to calculate an average score for the remaining indicators. For example, the human capital index is used as a proxy for calculating the knowledge base of each country. In addition, several scores are assigned based on insight into the country's situation. For example, the status of hydrogen policies for a country is used to assign a score for its policies, and geographical location is assigned a score based on the advantage it provides for a country.

2.2. Expert interviews

A group of 12 energy experts working in different international energy-related organizations was interviewed to evaluate the validity of the used categories and indicators. The experts are kept anonymous since many are still working in the energy sector and do not wish to represent the opinions of their respective companies or organizations. All experts were sent a summary of the objectives, scope, and details of the developed index in advance so they would have ample time to prepare for the interviews.

Table 2
The scale used for pairwise comparisons (Saaty, 1987).

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one element over the other
5	Essential or strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	An element is strongly favored, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another of the highest possible order of affirmation

This summary is shown in Appendix A.1. Each interview included an introduction of the current work followed by open-ended questions about the importance of the used categories.

Although not specifically experienced in the hydrogen energy field, the experts have long working experience in petroleum markets and renewable energy. Their backgrounds include specializations in energy markets, finance, engineering, consulting, and research. Each interview was recorded, transcribed, and summarized to make decisions about the different categories used in the index. To conclude each interview, a description of the survey methodology was presented to ensure a uniform understanding of its requirements. Finally, all questions related to the study were answered, and any concerns were discussed and addressed appropriately.

2.3. Expert Survey — Analytic hierarchy process

A survey was sent out to all interviewed experts to quantify their opinions about each category's relevance and importance. The analytic hierarchy process (AHP) was selected to assign a weight for each category based on how much it affects the export competitiveness of each country as a hydrogen producer and exporter. The AHP methodology is useful for assigning the importance of categories based on expert opinions, particularly when multiple conflicting objectives or criteria need to be considered. It allows for the integration of subjective expert opinions in a structured manner, and its hierarchical structure makes it easy to understand and justify the decision-making process. This goal is achieved through pairwise comparisons leading to weight for every category, as shown in Appendix A.4.

Several other methods are similar to AHP and can be used for multi-criteria decision-making. These methods include Multi-Attribute Utility Theory (MAUT), Multi-Criteria Decision Analysis (MCDA), Decision tree analysis, Cost-benefit Analysis, and SWOT analysis. AHP is similar to MAUT in that both methods involve comparing and weighing the relative importance of different options or criteria. However, AHP uses pairwise comparisons to incorporate expert opinions, while MAUT relies on utility scores assigned to each option or criterion. AHP is different from decision tree analysis in that it uses a hierarchical structure to identify the criteria and sub-criteria used to make the decision and the relative importance of each criterion. Decision tree analysis, on the other hand, focuses on the expected values or outcomes of different options and does not involve the explicit comparison of criteria.

In the survey used for this study, experts were asked to select whether resource availability or political status is more important in the context of hydrogen export. Once a category is selected, the experts are asked to choose a number between 1 and 9, indicating the degree by which it is more important, where 1 is equal importance, and 9 is significantly more important. A matrix is then created to calculate the weight of each category relative to every other category in the index. Table 2 shows what each number indicates for the pairwise comparisons.

Table 3
Random consistency index values for different matrix sizes derived from a sample size of 500 (Saaty, 1987).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Saaty introduced a consistency index (CI) to define the inconsistency in a decision maker's comparisons (Saaty, 1987):

$$\mathit{Consistency\ Index}\ (CI) = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

where λ_{max} is the largest principal eigenvalue in the comparison matrix (A) of size (n). The consistency index is zero when the paired comparisons are perfectly consistent, while a larger consistency index indicates larger inconsistency. The CI is calculated by taking the difference between the largest principal eigenvalue (λ_{max}) of the comparison matrix (A) and the size of the matrix (n), and dividing it by ($n - 1$). A CI of zero indicates perfect consistency, whereas a larger CI indicates greater inconsistency.

In addition, a consistency ratio (CR) is calculated to measure the "degree of departure from pure inconsistency" (Wedley, 1993). CR is calculated by dividing the Consistency Index (CI) by the Random Consistency Index (RI):

$$\mathit{Consistency\ Ratio}\ \ (CR) = \frac{CI}{RI} \quad (2)$$

where RI is the average random consistency index of a randomly generated reciprocal matrix, as shown in Table 3. A consistency ratio that is 0.10 or less is usually tolerated. Since our survey initially included five categories, an RI value of 1.12 is used (Saaty, 1987).

The expert interviews and surveys were used to modify the existing categories and their indicators, as shown in the results section. The expert opinions indicated the need to reorganize, remove, and add some indicators. In addition, categories with very low scores were removed to focus on the essential ones that could be used to indicate the competitiveness for hydrogen production and export.

2.4. Category and indicator scores

The indicators within each category were changed and enhanced to reflect the experts' opinions, as shown in Table 4. The indicators within each category were either from publicly available data or calculated from that data. In both cases, the scores were changed to a 1–5 scale (1 being the lowest and 5 being the highest) using each indicator's minimum and maximum values. All indicator scores are scaled using the following formula:

$$I_{score,scaled} = 1 + \frac{I_{score} - I_{minimum}}{I_{maximum} - I_{minimum}} * 4 \quad (3)$$

Table 4
Modified and enhanced categories and indicators based on expert interviews and survey.

Category	Indicator
Resource availability and potential	Gas reserves Gas production Solar potential Wind potential Renewable energy generation (current)
Economic and financial potential	GDP per capita Credit rating score Hydrogen projects Distance to hydrogen demand centers Length of existing pipelines
Political and regulatory status	Hydrogen policies and strategies Trade partners Political stability Government effectiveness Regulatory quality Control of corruption
Industry knowledge	Research and development expenditure Researchers in R&D Labor force with advanced education LNG liquefaction capacity LNG exports

This equation scales the indicator scores to a 1–5 scale, where 1 is the lowest and 5 is the highest. A description for each indicator is shown in Table 5 with the source of the collected data.

The score for the resource availability and potential category (C_1) is calculated by averaging the scaled score of 5 indicators: Gas reserves (gr), gas production (gp), solar potential (sp), wind potential (wp), and renewable energy generation (rg).

$$C_1 = \frac{I_{gr} + I_{gp} + I_{sp} + I_{wp} + I_{rg}}{5} \tag{4}$$

The score for the economic and financial potential category (C_2) is calculated by averaging the scaled score of 5 indicators: GDP per capita (gc), credit rating (cr), hydrogen projects (hp), distance to hydrogen demand centers (dh), and length of existing pipelines (lp).

$$C_2 = \frac{I_{gc} + I_{cr} + I_{hp} + I_{dh} + I_{lp}}{5} \tag{5}$$

The score for the political and regulatory status category (C_3) is calculated by averaging the scaled score of 6 indicators: hydrogen policies and strategies (hs), trade partners (tp), political stability (ps), government effectiveness (ge), regulatory quality (rq), and control of corruption (cc).

$$C_3 = \frac{I_{hs} + I_{tp} + I_{ps} + I_{ge} + I_{rq} + I_{cc}}{6} \tag{6}$$

The score for the industry knowledge category (C_4) is calculated by averaging the scaled score of 5 indicators: research and development expenditure (re), researchers in R&D (rd), labor force with advanced education (la), LNG liquefaction capacity (lc), and LNG exports (le).

$$C_4 = \frac{I_{re} + I_{rd} + I_{la} + I_{lc} + I_{le}}{5} \tag{7}$$

These equations calculate the scores for each of the four categories (C1 to C4) by averaging the scaled scores of the indicators within each category. The categories are resource availability and potential (C1), economic and financial potential (C2), political and regulatory status (C3), and industry knowledge (C4).

Finally, the index score for each country is calculated using the weighted average of the four categories, where the weight is obtained from the expert survey results shown in Table 6.

$$\textit{Index Score} = W_1C_1 + W_2C_2 + W_3C_3 + W_4C_4 \tag{8}$$

This equation calculates the index score for each country by taking the weighted average of the four category scores (C1 to C4), where the weights (W1 to W4) are obtained from expert survey results. The index score is a comprehensive measure that incorporates multiple factors in evaluating a country's performance in a given context.

3. Results and discussion

3.1. Expert interviews

The expert interviews were scheduled and conducted over three weeks in March 2022. With a few exceptions, most interviews were conducted virtually. The interviews were transcribed and analyzed to extract the main points and repeated themes.

The experts generally agreed with the need for an index that evaluates countries' export competitiveness within an emerging global hydrogen energy market. The experts also expressed that most selected categories and indicators are suitable for the evaluation. However, it was suggested that some categories, mainly adaptability and knowledge, are not necessarily important for a country to become competitive. This suggestion stems from the argument that regulations and policies would drive adaptability and that technological and operational knowledge can be acquired with minimal cost. Therefore, indicators under adaptability were moved to other categories which are more relevant. As for the knowledge category, it was kept for a more quantitative result from the survey.

During the interviews, the experts raised several points about each category's relevance and applicability. In addition, the current state of the global hydrogen market was discussed with a focus on several potential exporters and their export potential. Important excerpts from the interviews are shown in Appendix A.2. These were selected based on the best judgment of the authors. The main conclusions from the interviews are as follows:

- Economic potential and resource availability are the two most important categories.
- Technology and knowledge can come with time or be imported, so they are not as important for evaluating future competitiveness.
- The adaptability category is confusing and not clear. The adaptability of a country can be difficult to evaluate and, therefore, should be removed.
- An overlap in categories should be avoided so that no double counting occurs.
- A small country area is detrimental to renewable energy and should be added when evaluating potential hydrogen production.
- Water requirement should not be an issue since desalination plants can be added whenever more water is needed.
- Access to international markets is very important and should be included as a criterion when evaluating the potential of different countries.
- Index ratings do not mean a country is locked; policies can change many aspects.

3.2. Category weights

The category weights used to calculate the index scores for different countries are a direct result of the expert survey. As discussed, the AHP methodology was used to calculate these weights. The surveys were sent two weeks after the interviews to allow experts additional time for research and analysis. Follow-up emails were also sent to serve as reminders later on. After the surveys were completed, the results were compiled and included in our index score computation.

Table 5
Description of collected data and source for each indicator score.

Indicator	Description	Data Source
Gas reserves	Total proven reserves of natural gas (2020)	(bp, 2022)
Gas production	Total annual natural gas production (2021)	(bp, 2022)
Solar potential	Average long-term theoretical solar PV potential using level 1 country area	(ESMAP, 2020)
Wind potential	Average mean power density at a hub height of 100 m for the 10% windiest areas in the country	(DTU, 2022)
Renewable energy generation	Total current power generation from renewable energy sources (2021)	(bp, 2022)
GDP per capita	Gross domestic product per capita (latest available data for each country)	(World Bank, 2022a)
Credit rating score	A forward-looking macroeconomic model based on the ratings of major credit agencies (2022)	(Trading Economics, 2022)
Hydrogen projects	The number of projects commissioned since 2000 to produce hydrogen for energy or climate change mitigation purposes (Oct 2022)	(IEA, 2022)
Distance to hydrogen demand centers	Average distance to hydrogen demand centers in 2050 weighted by volume of demand	(IRENA, 2022; Simone Bertoli et al., 2017)
Length of existing pipelines	Length of existing natural gas pipelines normalized by country area	(CIA, 2022)
Hydrogen policies and strategies	Status of hydrogen projects, policies, and strategies at the national level (Oct 2022)	(CSIRO HyResource, 2022; World Energy Council, 2021)
Trade partners	Number of countries that are trade partners for import or export (2017)	(WITS, 2017)
Political stability	Perceptions of the likelihood of political instability or politically motivated violence (2021)	(World Bank, 2022b)
Government effectiveness	Perceptions of the quality of public services, service, policy formulation, and implementation, and the commitment to such policies (2021)	(World Bank, 2022b)
Regulatory quality	Perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development (2021)	(World Bank, 2022b)
Control of corruption	Perceptions of the extent to which public power is exercised for private gain (2021)	(World Bank, 2022b)
Research and development expenditure	Percentage of gross domestic product used for research and development (latest available data for each country)	(World Bank, 2022a)
Researchers in R&D	Researchers in R&D per capita (latest available data for each country)	(World Bank, 2022a)
Labor force with advanced education	Percentage of the total working-age population with advanced education (latest available data for each country)	(World Bank, 2022a)
LNG liquefaction capacity	Operational liquefaction capacity by country (Apr 2022)	(IGU, 2022)
LNG exports	The volume of LNG exports and re-exports by country (2021)	(IGU, 2022)

Table 6
Category weights based on the AHP methodology.

Category	Weight
Resource availability and potential (W_1)	0.396
Economic and financial potential (W_2)	0.289
Political and regulatory status (W_3)	0.184
Industrial knowledge (W_4)	0.131

Table 7
Consistency ratio and AHP consensus for expert survey.

	Consistency Index (CI)	Consistency Ratio (CR)	AHP Consensus
Preliminary categories	0.025	0.027	0.642
Final categories	0.021	0.019	0.628

The results of the surveys are shown in Table 6. The adaptability category was removed due to its low score (∼8%) based on the expert surveys and the opinions expressed during the interviews. The AHP methodology allows for removing a category without affecting the scores obtained by all the other categories. This advantage is because the scores are based on a pairwise comparison of the importance of each category.

The weights assigned by the experts give importance to the resource and economic categories, followed by the political and knowledge categories. The resource category is given the highest weight since a country with no resources cannot produce or export hydrogen. Economic and financial capabilities are second since countries need to have the suitable infrastructure and the ability to invest in hydrogen production projects. The political and regulatory status is given a lower weight, but it is still important to have effective policymaking and a supporting political ecosystem. Finally, the industrial knowledge category is the least important to the experts as they do not consider technological know-how and experience a major barrier in today's global world.

The survey results allow us to calculate the consistency index and ratio for the answers provided by the experts, as shown in Table 7. The consistency ratio is well below the cutoff of 0.10, indicating a tolerated departure from pure inconsistency or randomly generated reciprocal matrices. In addition, an AHP consensus value is calculated and shown in the same table to show how close the expert opinions are to each other. The 0.63 value indicates that the experts mostly agree on how the weights for the different categories should be assigned. Therefore, these values show that the experts have a similar opinion on how important each category is when calculating the export competitiveness of the different countries.

3.3. Hydrogen export competitiveness index scores

3.3.1. Resource availability and potential

The availability of resources needed for producing hydrogen affects the competitiveness of exporting hydrogen from a country directly. Hydrogen is assumed to be produced from water using renewable energy (green) or natural gas using steam methane reforming with CCUS (blue) since these are the currently feasible methods for producing clean hydrogen. Therefore, the required resources are natural gas, water, and renewable energy sources. In order to assess both current production capabilities and future potential, both current production and potential values are used.

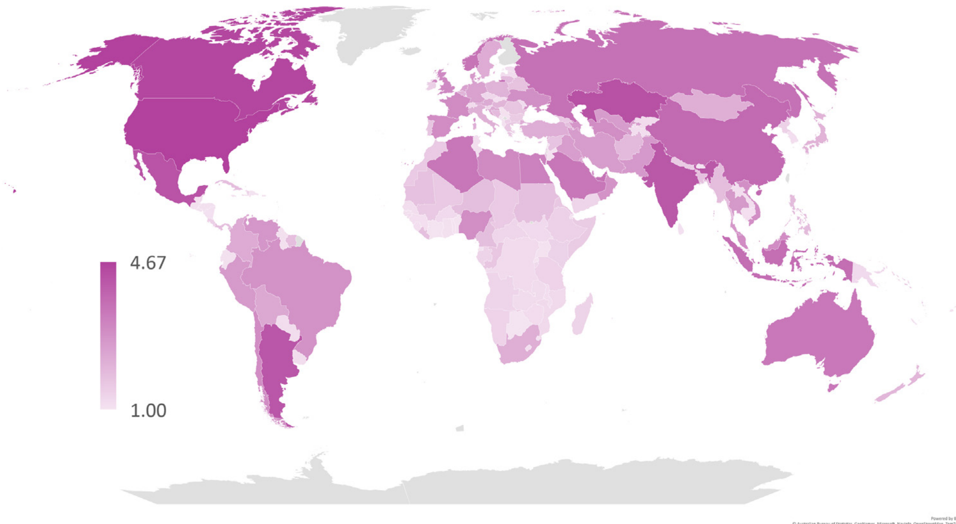

Fig. 3. Resource availability and potential scores for all evaluated countries (scale is 1–5, where 1 is the worst and 5 is the best).

The most recent estimates for natural gas production and reserves are used for natural gas. For renewable energy, the most recent values for renewable energy generation are used. Values for solar and wind potential are calculated using each country's available resources and land area to assess the future potential for renewables.

After calculating the overall score for the indicator, the scores for all countries are plotted on a world map, as seen in Fig. 3. Although large land areas, great renewable energy production, and significant natural gas production increase a country's score, the highest scoring countries have a combination of multiple factors. According to this evaluation, the top ten countries are the United States, India, Canada, China, Russia, Kazakhstan, Indonesia, Mexico, and Saudi Arabia. Evaluating the competitiveness of countries producing only blue hydrogen is important for understanding the export potential for this form of hydrogen on a large scale. The competitiveness of countries producing blue hydrogen depends on their access to natural gas reserves, the cost of producing hydrogen from natural gas, and their ability to capture and store the resulting carbon dioxide emissions. This information can be useful for governments, investors, and companies looking to establish or expand hydrogen production and distribution networks. It can also inform strategic decisions about where to locate hydrogen production facilities and how to position different countries in the global hydrogen market. The results are shown in Fig. 4. According to this separate ranking for resource availability, the top-scoring countries include Algeria, Australia, Canada, China, Egypt, Indonesia, Kazakhstan, Nigeria, Norway, Qatar, Russia, Saudi Arabia, Turkmenistan, United Arab Emirates, and the United States. It is important to note that the competitiveness of exporting blue hydrogen from a particular country may also depend on other factors, such as transportation costs and regulatory environments.

3.3.2. Economic and financial potential

A country's economic and financial potential affects its government's ability to invest in the required infrastructure and projects for developing an active hydrogen export sector. The indicators selected for this category give a general view of each country's economy. In addition, the length of existing natural gas pipelines indicates the potential for developing a domestic hydrogen market.

Another important indicator used is the weighted average distance to hydrogen markets. According to IRENA's simulation, the size of major hydrogen demand centers in the 2050s is shown in Table 8 (IRENA, 2022).

Table 8
Projected share of hydrogen demand in 2050 by country and region.

Country/Region	Share of hydrogen demand in 2050[a]
China	28.7%
India	10.1%
United States	9.3%
Russian Federation	7.8%
Japan	6.1%
Saudi Arabia	5.5%
Europe	3.7%
Iran	3.5%
Singapore	3.2%
Indonesia	2.6%
Canada	2.5%
Germany	2.2%
Trinidad and Tobago	1.8%
United Arab Emirates	1.8%
Brazil	1.7%
Egypt	1.7%
Republic of Korea	1.6%
Pakistan	1.4%
Qatar	1.4%
France	1.2%
South America	1.1%
United Kingdom	1.0%

[a]Shares were recalculated to exclude the "rest of the world".

These sizes are then used to assign a weight for the distances to them from all countries. This distance is obtained from the CERDI database, which gives the distances between all major ports and capitals by sea and road (when sea distance is longer than road distance) (Simone Bertoli et al., 2017).

Fig. 5 is obtained by plotting the weighted average distances to these demand centers from all countries. Larger values indicate that a country is far from demand centers, while smaller values indicate being closer to demand centers on average. Asian countries have the advantage of being closer to major demand centers (China, India, Russia, Japan, and Saudi Arabia), while South American countries are at a disadvantage due to being relatively far from both Asian and European markets.

These average distances are also converted to a 1–5 scale and combined with other indicators to calculate the overall economic and financial potential score. The scores for all countries are plotted on a world map, as seen in Fig. 6. Countries that score highest in this category have great finances, a well-developed natural

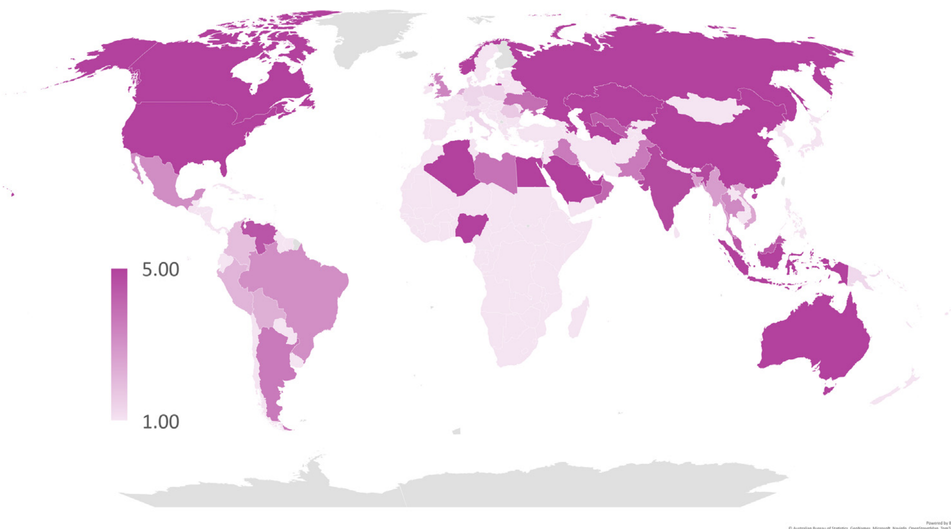

Fig. 4. Resource availability and potential scores for all evaluated countries based on blue hydrogen production (scale is 1–5, where 1 is the worst and 5 is the best).

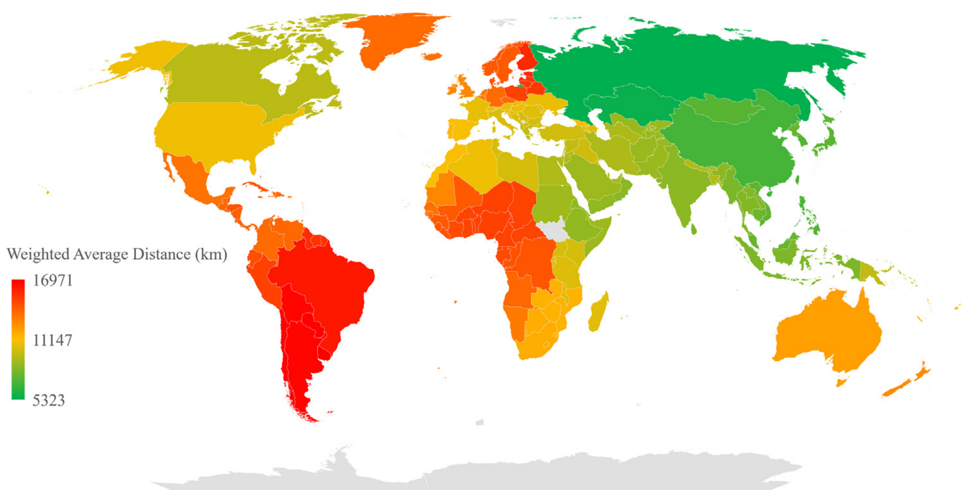

Fig. 5. Weighted average distance to hydrogen demand centers in 2050 (scale is 1–5, where 1 is the worst and 5 is the best).

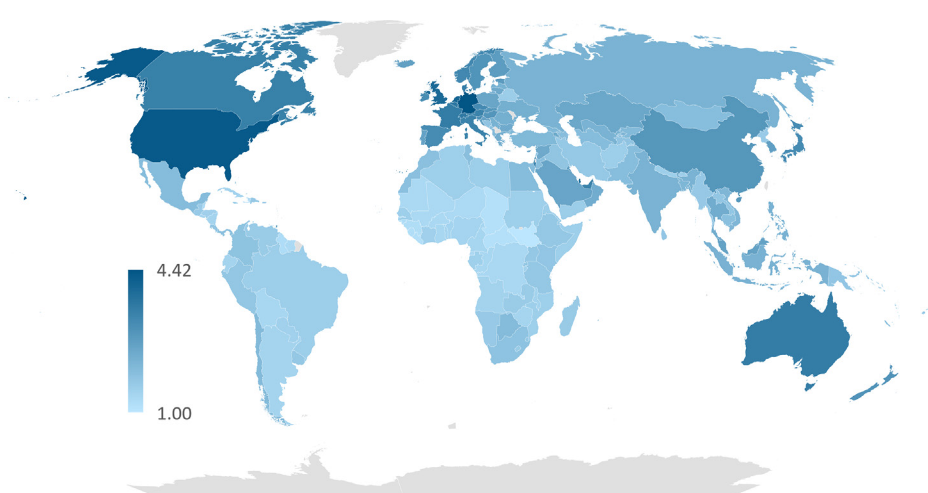

Fig. 6. Economic and financial potential scores for all evaluated countries (scale is 1–5, where 1 is the worst and 5 is the best).

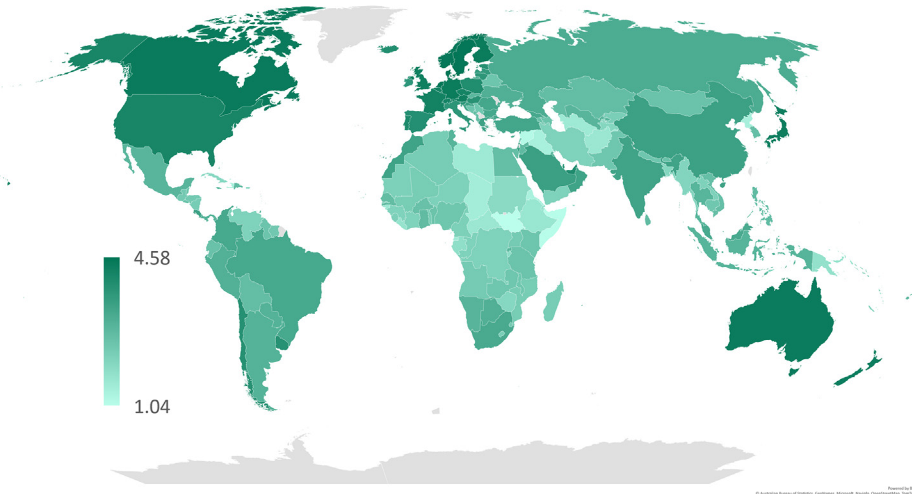

Fig. 7. Political and regulatory status scores for all evaluated countries (scale is 1–5, where 1 is the worst and 5 is the best).

gas network, and are closer to future major hydrogen demand centers on average. According to this evaluation, Germany, the United States, Singapore, the Netherlands, the United Kingdom, Liechtenstein, Qatar, Belgium, Switzerland, and France are the top ten countries.

Economic and financial potential is a critical factor, as it dictates a country's capacity to invest in infrastructure and projects necessary for developing a robust hydrogen export sector. Countries with strong finances and well-developed natural gas networks, such as Germany and the United States, are well-positioned to benefit from their proximity to future major hydrogen demand centers. However, the results also reveal that certain countries may face geographical disadvantages, such as South American countries being relatively far from both Asian and European markets.

3.3.3. Political and regulatory status

A country's political status affects its ability to import the technology necessary to develop hydrogen production and export hydrogen to global markets. Countries with good standing and no imposed sanctions are better positioned to take advantage of a future hydrogen market based on the free trade of clean energy.

On the other hand, the regulatory status affects a country's ability to develop a strong domestic sector for hydrogen production through effective policymaking and investments. An important aspect evaluated in this category is the status of existing hydrogen policies. Each country is given a score based on the most recent information for its hydrogen policies, as shown in Table 9. Another important indicator used in this category is the number of trade partners. This publicly available database can be easily integrated into any index as a proxy for international trade and political relationships.

Therefore, countries with high scores in this category have good international relations, nurturing local ecosystems, and effective policies and regulations. According to this evaluation, Denmark, Singapore, Sweden, Netherlands, Norway, Canada, Australia, Finland, and Germany are the top ten countries (see Fig. 7).

The political status and regulatory landscape play significant roles in a country's ability to import required technology and export hydrogen to global markets. Countries that foster strong international relations and comprehensive hydrogen policies, like Denmark and Singapore, are better positioned to capitalize on the emerging hydrogen market. These results highlight the importance of maintaining good diplomatic relations and enacting effective policies and regulations to support the development of the hydrogen sector.

Table 9
Indicator scores based on the status of hydrogen policies and strategies.

Indicator score (I_{hp})	Hydrogen policies and strategies
1	No hydrogen policies or projects
2	Hydrogen agreements or MoUs
3	Hydrogen policies/pilot projects
4	Hydrogen strategy in preparation/Hydrogen roadmap
5	Hydrogen strategy announced

3.3.4. Industry knowledge

The indicators used to evaluate the existing industry knowledge in the hydrogen sector are the volumes of LNG exports and re-exports, the expenditure on R&D, and the share of the labor force with advanced degrees. LNG is chosen due to its proximity to liquefied hydrogen and ammonia as potential energy carriers. The status of R&D is a good indicator of technological capabilities, while a well-educated labor force is more likely to succeed in newly created hydrogen markets.

Countries that have high scores in this category are major research hubs with significant experience in exporting and liquefying LNG and have a workforce that is highly educated. According to this evaluation, the top ten countries are the United States, Australia, Norway, United Arab Emirates, Malaysia, Russia, Qatar, Indonesia, and the Netherlands (see Fig. 8).

Existing industry knowledge, as demonstrated by experience in LNG exports, R&D expenditure, and the share of the labor force with advanced degrees, also contributes to a country's competitiveness in the hydrogen market. Countries with substantial expertise in exporting and liquefying LNG, strong R&D infrastructure, and a highly educated workforce, such as the United States and Australia, are well-equipped to succeed in the emerging hydrogen markets.

3.3.5. Weighted index scores

A country's overall index score is calculated using the weights for each category obtained from the expert survey results. A country scores higher with significant natural gas reserves, great renewable resources, and excellent economic and financial capabilities. To a lower extent, a country's political and regulatory status and its existing industry knowledge will affect the overall score. According to this evaluation, the top ten countries are the United States, Australia, Canada, United Kingdom, China, Norway, India, Russia, Netherlands, and Germany, as seen in Table 10.

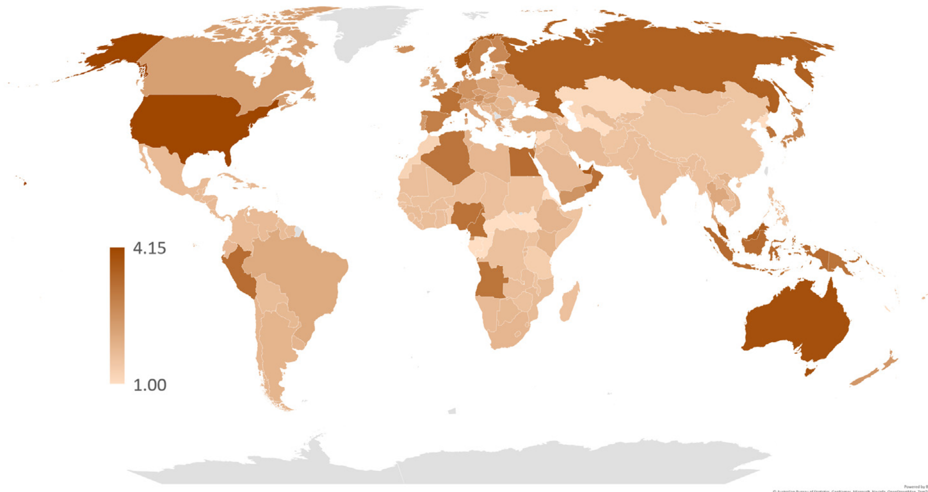

Fig. 8. Industry knowledge scores for all evaluated countries (scale is 1–5, where 1 is the worst and 5 is the best).

Table 10
Category and index scores for the ten countries with the highest overall indices.

Country	Resource availability and potential (C_1)	Economic and financial potential (C_2)	Political and regulatory status (C_3)	Industry knowledge (C_4)	HEC Index
United States	5.00	4.30	4.15	4.15	4.53
Australia	4.20	3.48	4.40	3.93	3.99
Canada	4.59	3.40	4.41	2.29	3.91
United Kingdom	3.14	3.93	4.32	2.40	3.49
China	4.55	2.87	3.46	1.50	3.47
Norway	3.07	3.22	4.48	3.77	3.46
India	4.91	2.21	3.36	1.64	3.42
Russian Federation	4.37	2.21	3.13	3.58	3.41
Netherlands	2.38	4.01	4.52	3.35	3.37
Germany	2.30	4.42	4.39	2.57	3.33

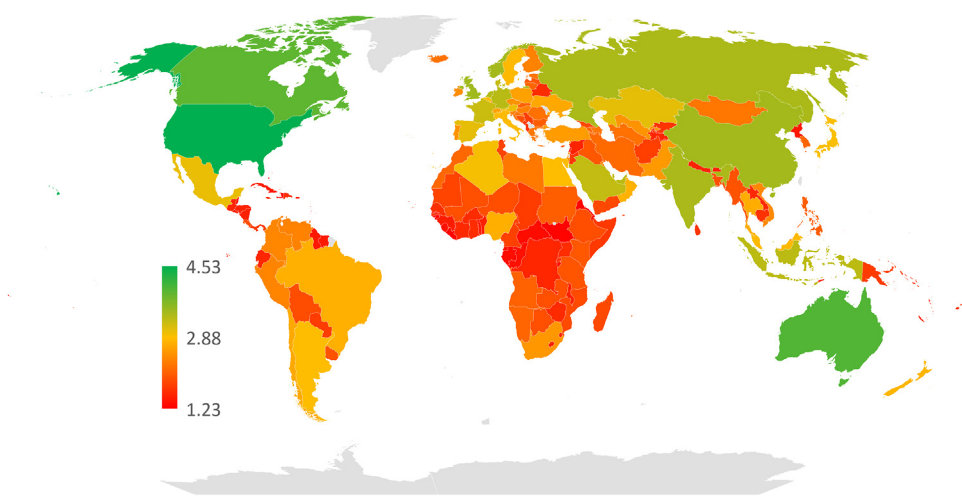

Fig. 9. Hydrogen export potential scores for all evaluated countries (scale is 1–5, where 1 is the worst and 5 is the best).

The overall scores for the hydrogen export competitiveness of all evaluated countries are shown in Fig. 9 and detailed in the Supplementary Data.

A separate index score was calculated for countries using the resources score that only evaluates blue hydrogen production. Fig. 10 shows the overall scores for the hydrogen export competitiveness of all evaluated countries. According to this evaluation, the top ten countries are the United States, Australia, Norway, Qatar, United Arab Emirates, Canada, Russia, China, Indonesia, and Saudi Arabia, as seen in Table 11.

Compared to similar indices in the literature, specifically the hydrogen investability index (H2i), we find some similarities and differences (Cranmore Partners and Energy Estate, 2021). The top ten countries for hydrogen investability are Germany, Spain, United States, Australia, France, Netherlands, Italy, United Kingdom, Canada, and China. The ranking is based on factors such as regulatory drivers, local demand, transportation & storage, renewable resources, and investability.

The United States, Australia, Canada, United Kingdom, China, and the Netherlands appear in the top ten for both H2i and

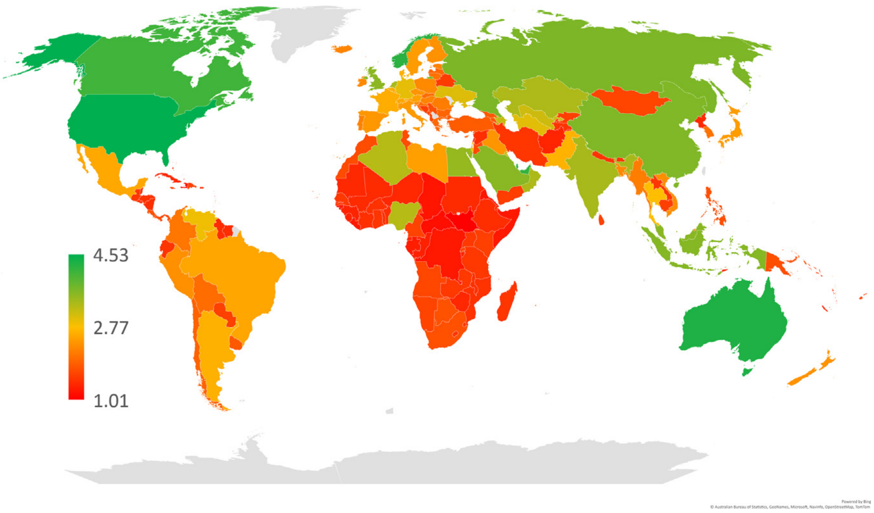

Fig. 10. Hydrogen export potential scores for all evaluated countries based on blue hydrogen production (scale is 1–5, where 1 is the worst and 5 is the best).

Table 11
Category and index scores for the ten countries with the highest overall indices based on blue hydrogen production only.

Country	Resource availability and potential (C_1)	HEC Index
United States	5.00	4.53
Australia	5.00	4.31
Norway	5.00	4.23
Qatar	5.00	4.19
United Arab Emirates	5.00	4.17
Canada	5.00	4.08
Russian Federation	5.00	3.66
China	5.00	3.64
Indonesia	5.00	3.60
Saudi Arabia	5.00	3.58

HEC indices. However, our results includes Norway, India, Russia, and Germany (for the first index), while the H2i includes Spain, France, and Italy in the top ten. Some differences can be attributed to the distinct methodologies and factors considered in the two analyses. Our research evaluates hydrogen export competitiveness, while the H2i focuses on hydrogen investability. The weights and indicators used in both studies also results in different rankings for the countries.

4. Policy recommendations

The development of policies to support the production and export of clean hydrogen depends on the strengths and weaknesses of each country. An optimal policy framework takes advantage of the existing strengths within a country and targets its weaknesses to improve the overall competitiveness of the country's domestic players within the hydrogen sector.

The developed index and its scores can help direct each country's policymakers to the strengths and weaknesses that exist in their respective country. These categories can then be targeted directly to improve the country's competitiveness. For example, a country with a low score in the industry knowledge category must direct its efforts toward research, education, and establishing a vibrant liquefaction and hydrogen transport ecosystem. The policy recommendations based on each category are shown in Table 12. These are the basic policies that would help policymakers in a country improve the overall conditions conducive to hydrogen production and export based on the specifically targeted sector. The recommendations are based on those implemented in high-scoring countries in each category and industry best practices.

However, it is important to distinguish between indicators that can be improved and those not under the control of policymakers. The average distance to hydrogen demand centers is an indicator that shows the proximity to demand and can be used as a proxy for transport costs. This indicator, for example, is out of the control of the countries aiming to benefit from the developing hydrogen economy. Unless demand centers shift drastically, Asian countries will always have an advantage over South American countries. Policymakers can and should reduce the transport cost using other instruments, such as directing public funds toward investments and incentives for infrastructure and developing transport technologies.

Another tool that can be used to improve policymaking is a direct comparison between countries. A country can be compared using the individual category scores with its neighbors or similar economic competitors to create a benchmark for its hydrogen sector. The gap between the two countries can then be targeted with policies and regulations in a well-structured manner.

Finally, it should be noted that the index is based on expert opinions, so it is subjective by design. The index only serves as a starting point for decision-makers interested in evaluating the status of their country's competitiveness and potential. Alternative indicators could have been used to show similar or slightly different results. Therefore, the indicators themselves should not be the target of policies; rather, the underlying ecosystem and the policy framework that led to low scores should be improved.

5. Conclusions

This study has developed a composite index to evaluate the competitiveness of countries in hydrogen production and export, with the United States, Australia, Canada, United Kingdom, China, Norway, India, Russia, Netherlands, and Germany emerging as the top contenders in the hydrogen market by 2050. When the index is calibrated to account solely for blue hydrogen production, the nations that stand out as the most competitive include the United States, Australia, Norway, Qatar, and the United Arab Emirates. These findings underscore the significant potential of these nations in spearheading the clean hydrogen industry, given their strategic resources and capacities, and underline the need for tailored policy interventions to optimize their competitive

Table 12
Policy recommendations for different categories.

Category	Policy recommendations
Resource availability and potential	• Establish a clear and fast process for constructing and operating renewable energy facilities and their connection to electric and gas grids. • Facilitate corporate power purchase agreements of renewable energy from small and medium enterprises. • Offer price-supporting mechanisms such as net metering, feed-in tariffs, real-time pricing, and capacity credits. • Launch a hydrogen accelerator program to build electrolyzers and supply the industry with clean fuel.
Economic and financial potential	• Deploy financial instruments such as subsidies, contracts-for-difference, and double auction models to support hydrogen projects. • Develop a domestic gas network to transport natural gas and hydrogen. • Secure public funding and private support investments in hydrogen energy pilot projects. • Identify the valuable areas for domestic hydrogen application and end uses (chemical synthesis, heating, transport, shipping, aviation) to guide policy priorities. • Introduce hydrogen offtake schemes through ammonia, mobility, and steel projects to encourage hydrogen investments.
Political and regulatory status	• Develop and announce a national hydrogen strategy that defines the country's ambition for hydrogen and outlines its vision. • Create a suitable regulatory ecosystem for hydrogen production, storage, transport, and use that meets local needs and international standards. • Improve the attractiveness of the hydrogen market through bilateral trade agreements with major customers.
Industry knowledge	• Define R&D priorities and allocate funds for developing hydrogen production and carbon capture technologies. • Increase the share of highly skilled labor in the manufacturing sector through targeted training programs. • Develop higher education programs for hydrogen energy and related technologies. • Establish a hydrogen hub that facilities research, education, and technology partnerships with local and international stakeholders.

advantage. The index considers resource availability and potential, economic and financial potential, political and regulatory status, and industrial knowledge, offering valuable insights for policymakers.

The significance of this study lies in its ability to inform strategic decision-making for countries looking to participate in and benefit from the growing hydrogen economy. The findings emphasize the importance of developing supportive policies and aligning national strategies with domestic capabilities and ambitions to foster a competitive and sustainable hydrogen industry.

The implications of these findings are far-reaching, as they not only highlight the potential of hydrogen as a clean energy source but also its role in combating climate change and promoting sustainable development. Countries can effectively address their energy and climate objectives by implementing the recommended policies and ensuring international collaboration, contributing to the United Nations Sustainable Development Goals.

Specifically, the growth of the hydrogen economy contributes to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), as it promotes using clean energy sources and reducing greenhouse gas emissions, helping countries reach their climate targets. International collaboration and sharing best practices are key to achieving the SDGs and fostering a competitive and sustainable hydrogen economy globally.

Overall, this research has successfully addressed the defined research question and objectives by providing a comprehensive framework for evaluating countries' competitiveness in the hydrogen market, offering valuable guidance for decision-makers navigating the complexities of the emerging hydrogen economy.

The recommended policies for countries aiming to have an active role in the growing hydrogen energy market include the following:

- Facilitate renewable energy and hydrogen production through better processes, power purchase agreements, and price-supporting mechanisms.
- Support investments in hydrogen projects through creative financial tools and defining priority sectors for the industry.
- Develop regulatory frameworks and national strategies for hydrogen energy that align with domestic capabilities and ambitions.
- Establish a knowledge-based industry for clean hydrogen with adequate R&D funding and dedicated educational programs.

The suggested framework for evaluating countries and their potential for competing in a hydrogen export market can also be used by policymakers to compare countries directly to target existing gaps. Future research should focus on improving the existing methodology by taking advantage of the growing data and indicators in the hydrogen sector. In addition, renewable energy sources for domestic electricity should be prioritized when estimating hydrogen production potential. By carefully considering these factors, policymakers can better understand the competitive landscape in the hydrogen energy market and take strategic actions to support the growth of the hydrogen economy.

Abbreviations

AHP	Analytic hierarchy process
ASEAN	Association of Southeast Asian Nations
CCUS	Carbon capture, utilization, and storage
GCC	Gulf Cooperation Council
GDP	Gross domestic product
HVDC	High voltage direct current
LNG	Liquified natural gas
LOHC	Liquid organic hydrogen carrier
MoU	Memorandum of Understanding
PV	Photovoltaic
R&D	Research and development
SMR	Steam methane reforming
VRE	Variable renewable energy
USD	United States Dollar

Nomenclature

A	Matrix
bn	Billion
CI	Consistency index
CR	Consistency ratio
mtpa	Million tons per annum
n	Matrix size
RI	Average random consistency index

CRediT authorship contribution statement

Dawood Hjeij: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Yusuf Bicer:** Conceptualization, Writing – review & editing, Supervision. **Mohammed bin Saleh Al-Sada:** Project administration, Supervision. **Muammer Koç:** Conceptualization, Writing – review & editing, Supervision.

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 work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The authors acknowledge the support provided by Hamad Bin Khalifa University, Qatar Foundation, Qatar (210005025).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2023.05.024.

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