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Green hydrogen supply chain risk analysis: A european hard-to-abate sectors perspective

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ABSTRACT

Green hydrogen is a tentative solution for the decarbonisation of hard-to-abate sectors such as steel, chemical, cement, and refinery industries. Green hydrogen is a form of hydrogen gas that is produced using renewable energy sources, such as wind or solar power, through a process called electrolysis. The green hydrogen supply chain includes several interconnected entities such as renewable energy providers, electrolysers, distribution facilities, and consumers. Although there have been many studies about green hydrogen, little attention has been devoted to green hydrogen supply chain risk identification and analysis, especially for hard-to-abate sectors in Europe. This research contributes to existing knowledge by identifying and analysing the European region's green hydrogen supply chain risk factors. Using a Delphi method 7 categories and 43 risk factors are identified based on the green hydrogen supply chain experts' opinions. The best-worst method is utilised to determine the importance weights of the risk categories and risk factors. High investment of capital for hydrogen production and delivery technology was the highest-ranked risk factor followed by the lack of enough capacity for electrolyser, and policy & regulation development. Several mitigation strategies and policy recommendations are proposed for high-importance risk factors. This study provides novelty in the form of an integrated approach resulting in a scientific ranking of the risk factors for the green hydrogen supply chain. The results of this study provide empirical evidence which corroborates with previous studies that European countries should endeavour to create comprehensive and supportive standards and regulations for green hydrogen supply chain implementation.

1. Introduction

Accelerating the transition towards decarbonising the economy has become an integral component of European Union (EU) strategies in response to climate change concerns [1,2]. To achieve a fully decarbonised economy, the emissions from hard-to-abate sectors in heavy industries such as steel, cement, and chemicals needs to be reduced [3,4]. Hard-to-abate sectors have relatively higher abatement costs for decarbonisation than the rest of the economy due to several factors such as lack of technology and financial feasibility. The production processes of these industries need high temperatures which are primarily supplied by fossil fuels. Therefore, these sectors are considered carbon-intensive as they mostly rely on fossil fuels [2,3] and together produce 10 gigatonnes (30%) of total global CO_2 emissions [5,6].

One of the tentative solutions for decarbonising the hard-to-abate sectors is green hydrogen. Green hydrogen is a specific type of hydrogen that is produced through water electrolysis fueled by renewable-based electricity [7,8]. Green hydrogen is not only capable of being used as a source of renewable energy (RE) but it can also be consumed as a raw material for the production of chemicals and feedstocks in hard-to-abate sectors. The burning of hydrogen has zero carbon emission and based on its production procedure, the amount of CO_2 which is emitted into the atmosphere can be lowered remarkably [9–11]. Therefore, the global hydrogen market is predicted to rise from 70 million tonnes in 2019 to 120 Mt in 2024. The EU currently uses

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Nomenclature

Abbreviations

EU	European Union
RE	renewable energy
CO2	carbon dioxide
UN	United Nations
BWM	best-worst method
H2	hydrogen
GHG	greenhouse gas
IRENA	International Renewable Energy Agency
AHP	analytical hierarchy process
MCDM	multi-criteria decision-making
ECHA	European Hydrogen Alliance
DM	decision-maker
O/M	operations and maintenance

Notations/Symbols

C_i	i^{th} category, $i = 1,2, \ldots,$ m
N_i	Number of sub-criteria in the i^{th} category
N_{max}	Maximum number of sub-criteria among all the categories
W_i	Weight of the i^{th} category
W_{ij}	Weight of the j^{th} sub-criteria and the i^{th} category
C_i^{AF}	Adjustment factor of the i^{th} category
W_{ij}^{Adj}	Adjusted local weight of the i^{th} sub-criteria in the j^{th} category
W_{ij}^{G}	Adjusted global weight of the i^{th} sub-criteria in the j^{th} category
a_{Bj}	preference of the best criterion/category over j^{th} criterion/category
a_{jW}	represents the preference of j^{th} criterion/category criterion over the worst
W_{avg}^{*}	the average weight of a criterion

approximately 9.7 million tonnes of hydrogen per year and has the largest market for green hydrogen [12,13] and has been at the forefront of global RE deployment for the past several years. The long-term target acceptance and supportive policy events have resulted in solid growth in green hydrogen demand within the EU [12,14]. There are several stages in the typical green hydrogen supply chain. Firstly, electricity is generated from RE sources such as wind, solar, and hydro [15]. Then, the electricity from the RE source is used for hydrogen production using electrolysers. Afterwards, the produced hydrogen can be transported and delivered to customers using various transportation modes.

Hydrogen can be transported using several modes of transportation, including pipeline, road, rail, and maritime transport using special tanks or cylinders [16]Hydrogen can be transported via pipelines, similar to natural gas. However, hydrogen requires pipelines made of special materials due to its high reactivity, which can make pipeline transportation more expensive than other modes of transportation. Hydrogen can also be compressed and transported in high-pressure tanks or cylinders. This is a common method for transporting small amounts of hydrogen, such as for fuel cell vehicles. In the liquid hydrogen mode of transport, hydrogen can be cooled to a very low temperature (−253 °C) and liquified. Liquid hydrogen takes up less space than compressed gas and can be transported in specialised cryogenic tanks via trucks, ships, or railcars. However, liquifying hydrogen requires a significant amount of energy, and the tanks used to transport liquid hydrogen are expensive. Ammonia transportation is another mode of transport. Hydrogen can be combined with nitrogen to produce ammonia, which can be transported more easily than hydrogen gas or liquid. Ammonia is a common industrial chemical and can be used as fuel for power generation or transportation. Each mode of transportation has advantages and disadvantages depending on the distance, quantity, and destination of the hydrogen. The choice of transportation mode depends on the specific application and local infrastructure [16].

As green hydrogen production is in an early stage, there are certain risk factors that could impact the supply chain. Identifying and assessing risk factors associated with the green hydrogen supply chain is crucial for successful implementation. Therefore, it is essential to conduct a thorough risk assessment for the green hydrogen supply chain, taking into account stages such as transportation, storage, and production, to identify the potential risk factors and their impacts on the environment and society [5]. By ranking and prioritising the most important risk factors, policymakers and practitioners can allocate resources efficiently to mitigate the risks with the highest potential for negative impact. Developing effective mitigation strategies based on this analysis is key to reducing the likelihood of costly project failures. Overall, proper risk management in the green hydrogen supply chain is essential to facilitating the growth of the green hydrogen industry and achieving a sustainable, low-carbon future based on RE sources [2]. Ultimately, this will help the EU move towards achieving its climate targets by promoting the use of Renewable energy and supporting the (United NationsUN) sustainable development goals, particularly for climate action [2].

Several studies investigate and assess supply chain risk in various industries such as telecommunications [17], manufacturing [18], leather [19], and automotive [20], while it is evident that less attention has been given to the RE sector [21,22]. In addition, limited attention has been devoted to developing an integrated approach that identifies and assesses a comprehensive list of risk factors associated with the green hydrogen supply chain, especially in the European region and for hard-to-abate sectors. This study employed a multi-method approach to collect data on supply chain risk factors and mitigation strategies. Firstly, the authors conducted a review of the relevant studies to identify an initial pool of risk factors. Secondly, the authors utilised the Delphi method to gather expert opinions and achieve consensus on the most important risk factors. Lastly, the authors conducted semi-structured interviews using the BWM to compare the risk factors in pairwise comparisons and gather participants' thoughts and opinions on risk mitigation strategies [23].

In Section 2, we provide a review of the existing studies on supply chain risk management, which served as the foundation for this research. Section 3 describes the methodology and implementation of this study, including the data collection methods, participant selection, and data analysis techniques. In Section 4, we present and discuss the findings on the most important risk factors associated with the green hydrogen supply chain and propose various risk mitigation strategies that can be implemented by policymakers and practitioners. We also discuss the implications of this study's findings for the development of appropriate standards, rules, and regulations to support the transition to green hydrogen. In Section 5, we provide a summary of the main findings, draw conclusions from this research, and discuss the limitations of this study. We also outline potential areas for future research and offer recommendations for policymakers and practitioners seeking to effectively manage risks in the green hydrogen supply chain.

2. Green hydrogen supply chain risk analysis

2.1. Green hydrogen supply chain: towards a decarbonisation economy

A large amount of the world's greenhouse gas (GHG) emissions is produced from hard-to-abate sectors such as refinery, steel, iron, and chemical products as they are energy-intensive industries. For example, the chemical, iron, and steel sectors alone were responsible for around 13% of the global energy consumption (International Renewable Energy Agency, 2020b). Therefore, there is an urgent need for alternative clean sources of energy and raw materials that help to decarbonise these hard-to-abate sectors. Hydrogen is one of the most promising alternative energy carriers, which is not available freely in nature. Hydrogen can deliver low emission energy to all shares of the economy and across the whole energy system comprising of mobility and stationary applications such as heating, chemical feedstocks, large-scale industrial processes, and power generation. These multiple applications for hydrogen can be classified into two large groups [3,24].

1. Hydrogen as an industrial feedstock: The application of hydrogen in a wide range of industrial processes will remain progressive and grow, as climate change requirements are prioritised by policymakers.
2. Hydrogen as an energy carrier empowering the energy transition: The adaptability of hydrogen to be used in a variety of applications together with production and consumption with zero emissions reflects the crucial role of hydrogen in the economy's decarbonisation targets.

Even though hydrogen has great potential to be used for clean energy generation, only a small amount of the produced hydrogen is currently used as an energy carrier. The remainder of the produced hydrogen is used as a raw material and chemical feedstock for different industries such as refinery, chemical, and steel production [3,25]. Hydrogen can be produced, stored, and converted through a variety of procedures, which have been classified and symbolised in simple colour-coding terms such as green, blue, grey, and brown hydrogen. These colours are frequently used to represent the changing levels of carbon concentration from their various types of production.

Among all the classifications of hydrogen, green hydrogen has become one of the promising solutions for decarbonising the hard-to-abate sectors [9,26]. Since in the production of green hydrogen fossil fuels are not used it produces very low or zero CO_2. Green hydrogen is produced by water electrolysis (i.e., splitting water) using electricity produced from RE sources such as hydro, wind, solar, or geothermal. Since there are zero CO_2 emissions associated with hydrogen production and consumption with, it is classified as green.

One way green hydrogen can contribute to decarbonisation is by replacing the fossil fuels currently used to produce high-temperature heat. Green hydrogen can be used as a feedstock for industrial processes, such as steel, pulp, paper, ceramics, and glass, to contribute to the decarbonisation of these sectors. These sectors are often difficult to decarbonise as they require enormous amounts of high-temperature heat, which is typically produced using fossil fuels like coal, oil, or natural gas. When green hydrogen is used in these processes, it can reduce or eliminate the carbon emissions associated with these industries [27] In the steel industry, for example, green hydrogen can be used as a reducing agent in blast furnaces to convert iron ore into steel. This process, known as direct reduced iron, can significantly reduce CO2 emissions compared to traditional methods. Similarly, in the pulp and paper industries, green hydrogen can be used to power the production of hydrogen peroxide, a key bleaching agent. This can replace the traditional use of chlorine, which produces harmful pollutants and greenhouse gases. In the ceramics and glass industries, green hydrogen can be used as a fuel for high-temperature kilns. These kilns are used to produce ceramics, glass, and other materials and require temperatures of up to 1500 °C. By using green hydrogen instead of natural gas, these industries can significantly reduce their carbon emissions. The use of green hydrogen has the potential to reduce emissions in these hard-to-abate sectors and support the transition to a low-carbon economy. However, the adoption of green hydrogen will require significant investments in production, infrastructure, and technology, as well as policy support to create a level playing field with traditional fossil fuels [28]. In general, the production of green hydrogen is more expensive than other types of hydrogen, although prices are becoming more economical [29,30].

The typical green hydrogen supply chain that is taken under consideration for this study has several interconnected nodes including electricity production from RE sources, hydrogen production, transportation, and end-user consumption. Fig. 1 illustrates a typical green hydrogen supply chain. As it was mentioned earlier, for the first stage of the green hydrogen supply chain, electricity is produced from RE sources. Then, this electricity is used in electrolyser for hydrogen production. Afterwards, the produced hydrogen is transported through different modes including truck, shipping, and pipeline. Using the pipeline, the green hydrogen can also be stored. Then, depending on the final usage of the green hydrogen, it can be directly and indirectly used in hard-to abate sectors.

Although green hydrogen supply chains can play key roles in moving towards a low-carbon economy, their economic viability should be considered. There are several factors that impact the economic viability of green hydrogen supply chains including the RE sources cost, availability, production cost, demand in the market, bargaining power of customers, and logistics & transportation costs. At the moment, the cost of green hydrogen is higher than the other types of hydrogen which are dependent on fossil fuels [66]. However, it is expected to have cheaper green hydrogen in the coming years as the price of RE such as solar and wind are declining. In addition, governments are interested in green hydrogen as a clean fuel, consequently, they are investing in the green hydrogen supply chain by supporting research and development projects, and providing incentive plans for private sectors [66]. Therefore, this could lead to growth in the green hydrogen market in the coming years. As a result of the higher demand for green hydrogen, the economies of scale will take place which would lead to a lower cost of production. The green hydrogen sector is in its infancy stage and requires further development as the global green hydrogen market size is expected to exceed US$ 89.18 billion by 2030 [1,12].

2.2. Green hydrogen supply chain risk categories and factors

Like every supply chain, green hydrogen supply chains have their risk factors. These risk factors would cause the risk of green hydrogen supply chain disruptions. In this research, risk factors are considered as threats, forces, and barriers preventing the successful implementation of green hydrogen supply chains. According to the business continuity management systems standard developed by the International Organization for Standardization (ISO 22301, 2019), a risk analysis examines the threats to the critical business processes.

Therefore, these risk factors should be identified and analysed to help the successful implementation of green hydrogen supply chains. As shown in Table 1, during the past decade, several studies have been accomplished to deal with supply chain risk management for different industries/sectors. That includes telecommunication, automotive, oil, RE, manufacturing, and blockchain technology industries. However, there is still a lack of a comprehensive study that identifies and analyses the risk factors associated with the green hydrogen supply chain, especially for the hard-to-abate sector in the EU.

From conducting a review of previous studies in the area of supply chain risk management, categories of risk factors were extracted such as economic, supply chain & operations, governance, technological & infrastructure, environmental, market & social, and policy & regulation. Further to this, individual risk factors were extracted from the relevant studies prior to classification using previously identified categories. Then, the identified categories and risk factors are defined and tailored to the context of a green hydrogen supply chain. Table 2 provides details on each of the risk factors under their respective category along with a definition and the source of the risk.

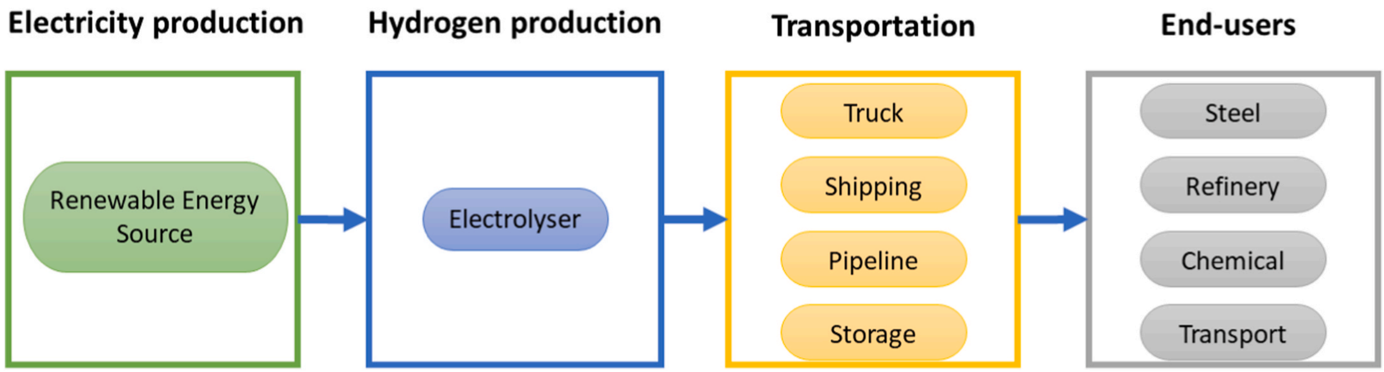

Fig. 1. Green hydrogen supply chain.

Table 1
Previous studies on supply chain risk management.

Author	Ranking Method (If non-applicable N/A)	Region	Industry/Sector
Abdel-Basset and Mohamed [17]	Plithogenic TOPSIS-CRITIC Model	China	Telecommunications Equipment
Azevedo, Santos [31]	N/A		Renewable Energy (Specify energy)
Ciotola, Fuss [21]	Holistic Risk Analysis and Modelling (HoRAM) method	Germany	Renewable Energy (Vanadium)
Etemadi, Borbon-Galvez [32]	N/A		Blockchain Technology
Jelti, Allouhi [33]	N/A		Renewable Energy
Jianying, Bianyu [34]	Single BP and optimised BP Neural Networks	China	Fresh grape
Kim [35]	N/A	Korea	Renewable Energy
Lahane and Kant [18]	Pythagorean fuzzy AHP and Pythagorean fuzzy VIKOR	India	Manufacturing
Moktadir, Dwivedi [19]	Pareto analysis and BWM	Bangladesh	Leather
de Oliveira, Marins [20]	Analytical Hierarchy Process (AHP)	Brazil	Automotive
Pathak, Sharma [22]	Modified Delphi & AHP method	India	Renewable Energy
Rangel, de Oliveira [36]	N/A		
Rostamzadeh, Ghorabaee [37]	Fuzzy TOPSIS-CRITIC approach	Iran	Oil
Shahbaz, Sohu [38]	N/A		
Song, Ming [39]	Rough weighted DEMATEL	China	Telecommunications Equipment
Wee, Yang [40]	N/A		Renewable Energy
This study	Delphi-BWM	Europe	Green hydrogen for hard-to-abate sectors

3. Methodology and implementation

This research follows the proposed methodology illustrated in Fig. 2. The methodology contains four steps to identify and rank the risks for the RE supply chain of green hydrogen. Step 1 begins by identifying the risk factors for the hydrogen supply chain based on extracting the risks from previous studies and expert's opinion using the Delphi method. Step 2 aims to identify the multi-criteria decision-making (MCDM) methods available for ranking the risks before selecting the most appropriate method. Then in step 3, the selected MCDM method is used to assign a weight of importance to each of the risk factors, in this case, the BWM. Finally, step 4 comprises ranking and classifying the risk factors based on their scores from the previous step. As a conclusion to the research study, risk mitigation strategies for the high-ranked risk factors are developed and discussed.

3.1. *Identifying the risk factors for hydrogen supply chain*

In the first stage of the process for this study, the most relevant risk factors for the green hydrogen supply chain were identified. The initial step was to extract the risk factors from previous studies as explained in section 2 which resulted in the comprehensive list of risks portrayed in Table 2. Initially, 46 risk factors in 6 categories were identified. Then, these risk factors were put through an evaluation and validation process using a Delphi panel. The panel members were selected for this stage based on their expertise in RE supply chain management, and green hydrogen production. Based on these input criteria, 20 experts were identified and involved in the research process. Table 3 shows the experts' profiles. The experts were presented with a Yes/No based questionnaire and were asked to determine the relevance of each identified risk factor in the context of the green hydrogen supply chain. To do this, a questionnaire containing the risk factors extracted from previous studies was presented to 20 experts. At this stage the experts were also requested to add any risk factors they believed were relevant that were not already mentioned in the list of risks. The data from the first round of questionnaires was then analysed and any risk factors that did not receive a 50% yes indication were removed from the list. Then the list was updated to consider the omissions and include the new risk factors recommended by the experts. This resulted in several changes in the list including adding/omitting some risk factors and small changes in risk categories. For example, it was suggested by the experts to divide "market & social" category into separate "market" and "social" categories. The second round of questionnaires was then distributed and when the results were again analysed in the same manner a final list of risk factors was validated. The result of this process was the identification and validation of 43 risk factors which were classified into 7 categories. Fig. 3 shows the main categories of the green hydrogen supply chain risks. The finalised set of risk factors and their respective categories are presented in Fig. 4.

3.2. *Identifying the multi-criteria decision-making method for ranking the risks*

One of the main objectives of this research study is to assign weights and rank the risk factors for the green hydrogen supply chain. This requires the use of a MCDM method [53] of which there are many used in previous studies including; TOPSIS (technique for order of preference by similarity to ideal solution) [17], AHP (analytic hierarchy process) [22],

Table 2
Green hydrogen supply chain risk factors.

Category	NO.	Risk Factors	Definition	Source
Economic	1	High investment of capital for hydrogen production and delivery technology compared to other sources of energy	Hydrogen production projects require a higher initial investment of capital cost. In addition, storing produced hydrogen is a relatively expensive process. That needs highly complex systems. Thus, this increases the overall costs.	[5,41,42]
	2	Fluctuation in unit costs of electricity	Green Hydrogen production involves a process known as electrolysis, which requires electricity from a renewable source, which means it is directly impacted by the unit cost.	[35,33,34]
	3	High operation and maintenance (O/M) costs	The cost of operating and maintaining sophisticated technical equipment required to produce RE is high.	[43,44,45]
	4	Access to funding and financial constraints	The difficulty and uncertainty in obtaining credit from financial institutions could pose a risk for green hydrogen project development.	[31,33,46]
	5	Inflation rate	The risk of an unexpected increase in inflation or interest rates.	[17,18,39]
	6	Currency Exchange rates	The risk of volatile currency exchange rates can affect organisational and international trade.	[17,18,39]
	7	Economic Recession	An economic crisis poses a risk to RE organisations' ability to operate profitably.	[17,47]
	8	Taxes & Tariffs	The risk of an increase in taxes and tariffs on RE production or trade.	[18,19,41]
	9	Long term financial viability and profit	Uncertainty about the financial feasibility of production of green hydrogen in the long-term considering green H2 production cost and market demand	[41,43,48]
Supply chain processes & governance	10	Improper location of facilities	Green H2 supply chain facilities should be placed in locations that ensure the provision of a sufficient and continuous resource supply	[40]
	11	Information flow	The risk of distorted reverse information flows within the network can lead to difficulties in demand estimation and cause a bullwhip effect in the H2 supply chain.	[18,36]
	12	Power Grid power disruption	The intermittency of power generation from RE can disrupt the operation of a power grid. This requires grid companies to adjust and offset the variations in energy production through increased planning activities.	[33,49]
	13	Supplier failure	Failure of any key supplier (raw material and electrolysers) will result in the delayed delivery of critical materials and equipment for H2 production and disrupt the entire SC	[17,19,47]
	14	Collaboration and Transparency	This risk is associated with a lack of collaboration or transparency leading to distrust and conflict among SC partners.	[47,49]
	15	Inventory management and forecasting	Inadequate forecasting and proper inventory management policies can lead to shortages and failure to meet customer demand	[34,49]
	16	Bargaining power of RE supplier	Bargaining power of RE supplier over H2 manufacturer. This can cause a lack of RE to manufacture green H2.	[47]
	17	Disruption or failure to deliver electricity from renewable sources	Failure to deliver electricity from renewable sources to the electrolyser	[5,43,42]
Technological & Infrastructure	18	Lack of enough capacity for Electrolyser	The current electrolyser capacity is far less than the future consumption forecasting of green H2. It has been promised that there would be a great number of instalments in Europe. But still, there will be uncertainty regarding the delay from the electrolyser manufacturer	[5,41,48]
	19	Lack of storage, transportation, and delivery capacity	Uncertainty regarding the storing and converting H2 along with the capacity for H″ transportation.	[5,43,50]

(continued on next page)

Table 2 (*continued*)

Category	NO.	Risk Factors	Definition	Source
			Although there are ongoing projects for the H2 pipeline, there still will be uncertainty about the availability of an effective pipeline in the EU.	
	20	Smart Grid malfunction or scarcity	This risk points to the lack of a 'smart grid' that can regionally store and distribute RE.	[33,40,49]
	21	Lack/failure of energy storage system	An effective energy storage system is required for RE to ensure energy availability and low cost-efficient conversion devices.	[5,48,50]
	22	Conversion devices	The current inefficiency of conversion devices poses a risk as there is high variability between the input level of RE sources and the output level of electricity.	[33,40]
	23	Quality issues with H2 production	The risk is associated with unexpected errors or deviations from what is needed as a result of the lack of proper implementation of H2 production standards.	[48,51,52]
	24	Integration risks for RE	This risk is linked to the different design features of integrating RE into an already existing supply chain network such as pipelines.	[5,18,43]
	25	Rapid technological development and uncertainty in H2 production	The risk associated with rapid changes in H2 production can be costly and confusing for the H2 manufacturers that need new settings, integration, and arrangement.	[48,51,50],
	26	Information and communication technology	The success of RE production largely depends on the ICT tools that are used in planning, decision making and tracking throughout the SC. This risk is linked to a failure in any of these technologies.	[17] [47,46],
	27	Machine & equipment failure	The failure in machines or equipment will decrease the effectiveness of RE operations and production.	[18,19,49]
Environmental	28	Natural disasters and disease outbreaks	Heavy rain, thunderstorms, snow, earthquakes, and even tsunamis can damage equipment and disrupt the RE supply chain. This includes outbreaks of diseases or viruses such as Covid-19 which can also cause major delays and disruption to supply chains.	[17,38,39]
	29	Land, water, and air pollution	Installation of RE equipment can cause damage to the environment. Wind Turbines alter airflow and cause change to the physical landscape, hydro dams impact aquatic life, and solar panels attract increased heat from the sun to nearby areas. Also converting and transporting hydrogen can create additional CO2 emissions.	[2,17,19]
	30	Climate change & availability of RE sources	The effects of climate change mean the atmosphere and biosphere are continually changing, which means the resources needed for RE are subject to a certain level of uncertainty. (Wind, Tidal)	[21,22,34]
	31	Terrorism and War	Acts of terrorism and war are known to shut down entire countries and halt business operations causing major disruptions within supply chains	[47]
	32	Cleaner Technology	The inability of any supply chain actor to implement cleaner technology for their processes will undermine the whole supply chain's efforts in RE production.	[18]
Market & Social	33	Fluctuating Demand	The energy demand is not at a constant and instead, is known to fluctuate with little notice. There is uncertainty regarding the demand for green H2 because of the cost issues.	[38,39,47]
	34	Customer failure	This risk is associated with the failure of a key customer which will impact the demand for RE in the form of a shock.	[18,20,21]

(*continued on next page*)

Table 2 (*continued*)

Category	NO.	Risk Factors	Definition	Source
	35	Substitute product	The risk is associated with the threat of substitute products being available instead of H2 such as fossil fuels, other renewable energies, or even Blue/Grey Hydrogen.	[43,50]
	36	Bargaining power of customers	Bargaining power of customer over H2 manufacturer. This can diminish the profitability of H2 manufacturers and lowers the attractiveness of the industry.	[47]
	37	Skilled Human resources	Green H2 supply chain requires a skilled workforce. The lack of skilled human resources poses a risk to the development of RE production.	[35,22,33]
	38	Acceptance of H2 from consumers	The risk that green H2 will not be accepted by consumers due to the mentioned problems of land/air pollution and temporary energy price increase.	[42,51,53]
	39	Lack of community pressure and concern	The increase in pressure from communities and concerns over sustainability poses a risk for the green H2 supply chain.	[18,36]
	40	Health and safety	RE production involves several risk factors for workers such as exposure to chemicals, loud noise, and hazardous operating equipment which can be detrimental to their health. Also, the transportation of Hydrogen is hazardous to the population as it is explosive and corrosive.	[5,43,51]
	41	Consumer awareness	Low levels of consumer awareness of sustainability pose a risk for RE as it influences demand.	[41,43,54]
	42	Labour strike	Unfair working conditions often lead to labour strikes which will impact operational output and RE production.	[47]
Policy and Regulation	43	Government incentives	Inadequate government incentives pose a risk as they are necessary to encourage RE production and consumption initially.	[5,41,48]
	44	Policy & regulation development	Lack of coordination among government entities failing to improve policies that supports the development of green H2 can cause conflicts among the operations involved in the RE supply chain. Adverse changes to industry regulations are a risk for the RE sector.	[5,22,54]
	45	Technical standards	Non-compliance with technical standards could harm RE production in the case of unclear government procedures for supplying an electricity grid.	[33,55]
	46	Political instability	The instability of a government can hinder the transition to RE as rules and regulations are under constant review and change	[21,37,47]

and BWM [56] among others which merge fuzzy logic with the MCDM technique such as fuzzy analytic hierarchy process (FAHP) and fuzzy TOPSIS [53]. The review of previous studies identified both the AHP and BWM techniques as the most appropriate for ranking the risk factors in this study. The BWM is a relatively recent development in MCDM techniques and differs from AHP in a few ways [23]. First, the BWM was developed to reduce the number of pairwise comparisons a decision-maker would have to make. In comparison to AHP, the BWM requires much fewer comparisons as it takes a vector-based approach rather than the typical matrix approach used in AHP. Second, the BWM uses a scale between 1 and 9 for comparisons and does not require the use of fractions (1/9) unlike the AHP method. Finally, the BWM is considered more reliable in terms of the consistency ratio derived from comparisons. This is likely due to the fewer number of comparisons needed to weight the criteria and sub-criteria [23]. Having considered the clear advantages of the BWM over AHP, the BWM is used to rank the risk factors in this study, the steps of which are outlined in step 3.

3.3. Weighting the risk factors using the BWM

In this step, the risk factors are each assigned a weight using the BWM by conducting pairwise comparisons using a group of experts. Table 3 provides details on the profile of these experts. The steps of the BWM proposed by Rezaei [23] include:

Step 1: Determine a set of decision criteria.

The decision-making criteria are defined as $\{C = C_1, C_2, \ldots, C_n\}$ are identified by the decision-maker.

Step 2: Determine the best and the worst criteria.

The DM is then asked to determine the best (most desirable or important) and the worst (least desirable or important) criteria from the set C from step 1. No comparisons between the criteria are made at this stage.

Step 3: Determine the preference of the best criterion over all the other criteria using a number between 1 and 9.

The DM performs a pairwise comparison between the best criterion

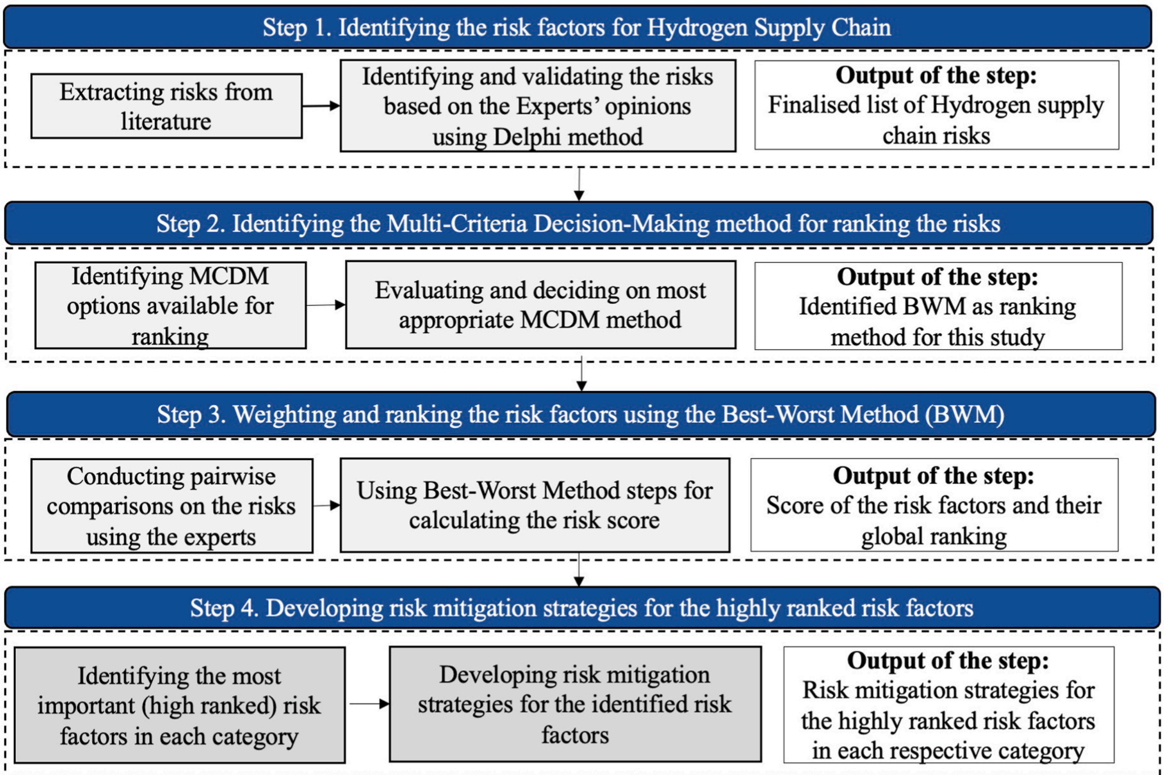

Fig. 2. The proposed methodology steps used for this study.

Table 3
Experts' profile.

Type of Experts	Experience (years)	
	5–10	*> 10*
Academia	3	5
Experts from industry	6	6
Sum	9	11

and all other criteria. The DM states their preference for the best criterion over the others by assigning a number between 1 and 9. The value of 1 means the best and other criteria are of equal importance and a value of 9 means the best criterion is absolutely more important than the other criterion being considered. This will form the Best-to-Others (B2O) vector A_B, where:

$$A_B = (a_{B1}, a_{B2}, \ldots., a_{Bn})$$

where a_{Bj} represents the preference of the best criterion over the other criterion and $a_{BB} = 1$.

Step 4. Determine the preference of all the other criteria over the worst criteria using a number between 1 and 9 in a similar fashion to step 3. This will form the Others-to-Worst (O2W) vector

$$A_W = (a_{1W}, a_{2W}, \ldots., a_{nW})$$

Where a_{jW} represents the preference of the other criterion over the worst and $a_{WW} = 1$.

Step 5: Find the optimum weights of the criterion ($W^* = W_1^*, W_2^*, \ldots.,$ W_n^*).

Several different methods can be used to assign the optimum weights to the criteria. One of which is to linearize the BWM as follows (Rezaei, 2016).

$$min\ max_j \left\{ \left| \frac{W_B}{W_j} - a_{Bj} \right|, \left| \frac{W_j}{W_w} - a_{jW} \right| \right\} \tag{1}$$

Such that;

$$\sum_j w_j = 1 \tag{2}$$

$$w_j \geq 0, \text{for all } j \tag{3}$$

The problem can then be programmed linearly and is equivalent to:

$$\min \xi \tag{4}$$

Such that;

$$\left| \frac{W_B}{W_j} - a_{Bj} \right| \leq \xi, for\ all\ j \tag{5}$$

$$\left| \frac{W_j}{W_w} - a_{jW} \right| \leq \xi, for\ all\ j \tag{6}$$

$$\sum_j w_j = 1 \tag{7}$$

$$w_j \geq 0, \text{for all j} \tag{8}$$

By solving the problem, the optimal weights $(w_1^*, w_2^*, \ldots, w_3^*)$ and ξ^* can be found. ξ^* can then be used as a direct indicator of the consistency of the comparisons. The responses of the experts are amalgamated using the arithmetic mean calculated by equation (9):

$$W_{avg}^* = \frac{1}{n} \sum_{j=1}^{n} W_j^* \tag{9}$$

Once the necessary calculations and linearisation have been done the output will be the weight of each risk factor along with the weight of the category they are in. This study then utilises the global adjustment

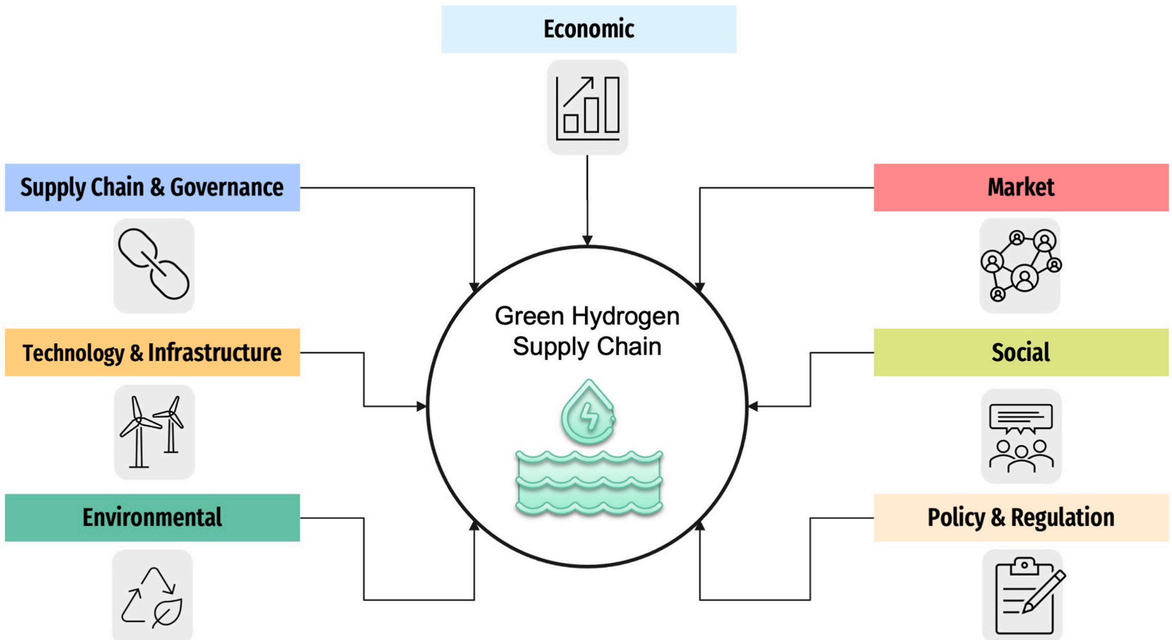

Fig. 3. Green hydrogen supply chain risk categories.

mechanism proposed in Ghadimi, Donnelly [56] to adjust the values of the weights of each risk factor in accordance with the risk factor's position in the final global ranking. This is necessary as an issue arises from the risk factors being split into unequal categories. This results in risk factors from categories with a higher number of risk factors receiving lower weights as $\sum Wij = 1$, which means risk factors in smaller categories have and advantage over risk factors in larger categories. To solve this problem the following adjustment factor was utilised to make the comparison more reliable. The steps involved are noted and Table 7 provides the adjustment factors that were used.

Notation:

C_i: i^{th} category, $i = 1,2, \ldots,$m

N_i: Number of sub-criteria in the i^{th} category

N_{max}: Maximum number of sub-criteria among all the categories

W_i: Weight of the i^{th} category

W_{ij}: Weight of the j^{th} sub-criteria and the i^{th} category

C_i^{AF}: Adjustment factor of the i^{th} category

W_{ij}^{Adj}: Adjusted local weight of the j^{th} sub-criteria in the i^{th} category

W_{ij}^{G}: Adjusted global weight of the j^{th} sub-criteria in the i^{th} category

First, find the maximum number of sub-criteria among all the categories (N_i). The sub-criterion in the largest category is given an adjustment factor of 1 which means they do not change their weights. To find the adjustment factor of the other smaller categories, the size ratio is calculated by dividing the number of sub-criteria of the smaller category by the number of sub-criteria in the largest category. This can be calculated using equation (10):

$$C_i^{AF} = \frac{N_i}{N_{max}}, i = 1, 2, \ldots, m \tag{10}$$

The adjustment factor can then be applied to the sub-criteria weight within the group by taking the product of the weight of the sub-criteria with the adjustment factor of the group. The local adjusted weight of the sub-criteria is calculated using equation (11):

$$W_{ij}^{Adj} = C_i^{AF} \ x \ W_{ij}, for \ all \ i \ and \ j \tag{11}$$

Finally, the adjusted global weights of the sub-criteria can be calculated then using equation (12):

$$W_{ij}^{G} = W_{ij}^{Adj} \ x \ \ W_i \tag{12}$$

To facilitate the process of utilising the BWM, structured interviews were conducted with all the experts rather than simply distributing questionnaires to them. The reason for this is that experts can find it difficult and confusing to answer the pairwise comparison questionnaires without guidance. Also, supervising the experts during the interview would help to achieve a better consistency ratio. To conduct the structured interview, BWM questionnaires were designed based on the identified risk categories and factors. Then we held interviews with each expert and asked them separately about their opinion based on the designed questionnaires. The structured interviews were used to conduct the BWM in order to find the relevant weights of the risk factors. Therefore, the same set of questions was designed to do pairwise comparisons. The experts were asked to.

- Determine the most important and the least important risk factor in each category based on their opinion.
- Express the preference of the decision-maker on "the most important risk factor over all the other risk factors", and the preference of "all the other risk factors over the least important risk factor" by selecting a number between 1 and 9. They were given an excel file in which they could select the number from the drop-down menu while they could see the meaning of the number.

Once the experts had made their pairwise comparisons via the 'best-to-others' and 'worst-to-others' vectors respectively, the data was analysed, and a numerical weight value was assigned to each risk factor and the categories. To analyse the data gathered through the interviews, a BWM excel spreadsheet template was utilised to complete the calculations necessary to derive the weights of the risk factors along with their categories. The consistency ratio (Ksi*) was also calculated after each comparison to ensure the experts were not contradicting themselves and to ensure the reliability of their judgements. Then, the average weights of the risk categories and factors were calculated. The average weights of the categories are depicted in Table 4 while the average local weight of the individual risk factors is presented in Table 5. Then, the adjustment factor for each category was calculated using Eq. (10). Table 6 shows the adjustment factors. The global weights of the risk factors were

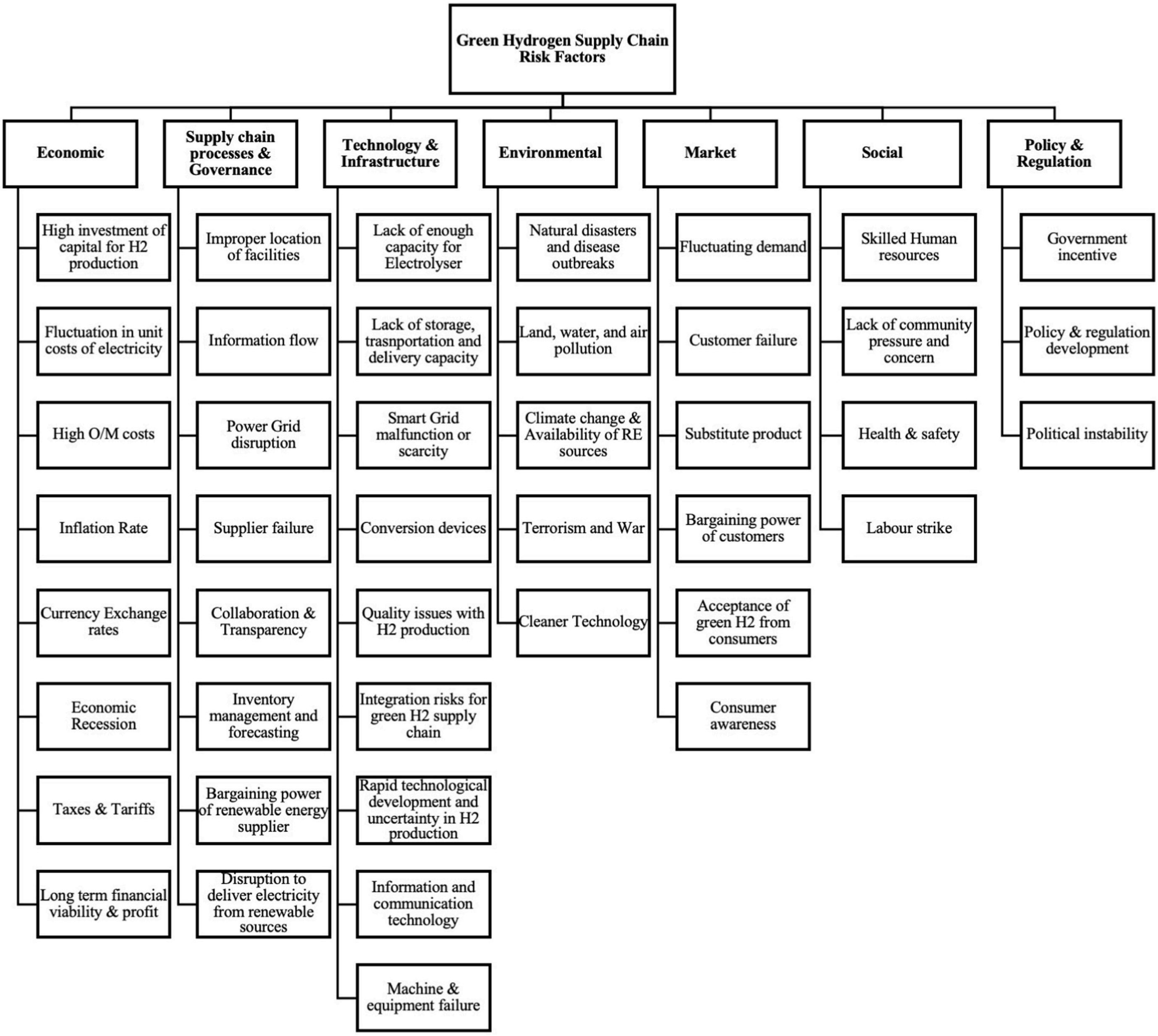

Fig. 4. Finalised list of risk factors for green hydrogen supply chain.

Table 4
Risk categories weights.

Category	Economic	Supply chain processes & Governance	Technological & Infrastructure	Environmental	Market	Social	Policy & Regulation
Local Weight	0.17813	0.1344	0.183	0.0725	0.1194	0.1144	0.1981

calculated using Eq. (12). Table 7 shows the 43 risk factors, their ranks, and global adjusted weights.

As shown in Table 4, policy & regulation, technological & infrastructure, and economic risk categories recieved the highest importance weight followed by supply chain processes & governance, market, social, and environmental respectively. A detailed discussion of the risk categories with their relevant risk factors along with mitigation strategies for the high importance risk factors are provided in section 4.

4. Discussion, risk mitigation strategies & implications

In this section, the results of this empirical study are discussed, and relevant policy and managerial implications are provided. The initial pool of risk factors was classified into six categories; economic, supply chain processes and governance, technological and infrastructure, environmental, market and social, and policy and regulation. After applying the Delphi method, the initial 46 risk factors were reduced to 43. The Delphi method allowed for a more comprehensive and accurate identification of the most critical risk factors in the green hydrogen supply chain, which is essential in devising effective mitigation strategies and policies. The Delphi experts also recommended changes to the categorisation in the form of splitting 'market and social' into separate 'market' and 'social' categories respectively along with adjusting the name of 'supply chain, processes and governance' to 'supply chain and

Table 5
Average local weights for the risk factors.

Category	Risk factor	Local Weight
Economic	High investment of capital for H2 production and delivery technology	0.40706641
	Fluctuation in unit costs of electricity	0.06619456
	High O/M costs	0.1647179
	Inflation rate	0.06616804
	Currency Exchange rates	0.06616804
	Economic Recession	0.07059339
	Taxes & Tariffs	0.03555324
	Long term financial viability and profit	0.12353843
Supply Chain & Governance	Improper location of facilities	0.14018466
	Information flow	0.05256925
	Power Grid power disruption	0.09433973
	Supplier failure	0.21027699
	Collaboration and Transparency	0.02961105
	Inventory management and forecasting	0.06007914
	Bargaining power of RE supplier	0.07691162
	Disruption or failure to deliver electricity from renewable sources	0.33602756
Technology & Infrastructure	Lack of enough capacity for Electrolyser,	0.32721135
	Lack of storage, transportation, and delivery capacity	0.16448432
	Smart Grid malfunction or scarcity	0.06639071
	Conversion devices	0.06186172
	Quality issues with H2 production	0.11543751
	Integration risks for green H2 supply chain	0.07966885
	Rapid technological development and uncertainty in H2 production	0.05690632
	Information and communication technology	0.02845316
	Machine & equipment failure	0.09958606
Environmental	Natural disasters and disease outbreaks	0.16144796
	Land, water, and air pollution	0.42600302
	Climate change & availability of RE sources	0.24217195
	Terrorism and War	0.12108597
	Cleaner Technology	0.0492911
Market	Fluctuating Demand	0.06331454
	Customer failure	0.09249166
	Substitute product	0.13718149
	Bargaining power of customers	0.13718149
	Acceptance of H2 from consumers	0.36405858
	Consumer awareness	0.20577224
Social	Health and safety	0.43396226
	Lack of community pressure and concern	0.24528302
	Skilled Human Resources	0.24528302
	Labour strike	0.0754717
Policy & Regulation	Government incentives	0.225
	Policy & regulation development	0.65
	Political instability	0.125

governance'. Three risk factors 'access to funding and financial constraints', 'lack/failure of energy storage system' and 'technical standards' were removed from the final list of risk factors as the Delphi experts recommended, they were not relevant.

The experts ranked the risk factors using the BWM, a technique that allowed for the determination of the importance weights of the risk categories and factors. The results showed that the highest-ranked risk factor was the high investment of capital for hydrogen production and delivery technology. This was followed by the lack of enough capacity for electrolyser, and policy & regulation development. Interestingly, the 'threat of a substitute product' did not rank within the top 20 risk factors and was placed at number 24. This is interesting as there are many available substitute products in the market such as fossil fuels, and even other types of hydrogen such as blue, grey, and brown which could pose a significant threat to green hydrogens success. Regarding the categorisation of the risk factors, the experts were also asked to provide their comments. There are a couple of risk factors in the list that could belong to more than one category. For example, government incentives can belong to both economic and policy and regulation categories based on the previous studies around supply chain risk management. However, the risk factors remained in the policy and regulation category based on the expert opinion. In addition, there would be interrelations between some of the risk factors. For example, supportive policy and regulation and government incentives can directly influence the risk factors in the "economic" and "policy and regulation" categories. At the moment, there is no tailored and dedicated supportive policy and regulations for green hydrogen. Most of the supportive policies and regulations are around renewable energy and green hydrogen would struggle to get this supportive plan due to the difficulties with the guarantee of origin. The guarantee of origin ensures green hydrogen is produced from RE such as wind, hydro, and solar. Therefore, green hydrogen does not have a great share of current subsidies for the development of renewable energy.

One of the risk factors that could be on the list is hydrogen leakage. Hydrogen leakage can pose a safety risk as hydrogen is highly flammable and can ignite or explode in the presence of air or other oxidizers. However, the risk of hydrogen leakage depends on the specific circumstances and the measures in place to prevent and mitigate leaks. One risk of hydrogen leakage is the potential for a fire or explosion if the hydrogen mixes with air in the presence of an ignition source. This risk can be reduced through proper storage and handling procedures, such as using leak detection systems and ensuring that hydrogen storage tanks and pipelines are properly maintained. Another risk of hydrogen leakage is that hydrogen is an asphyxiant gas, which means that it can displace oxygen in an enclosed space and cause suffocation. This risk can be mitigated by ensuring that enclosed spaces where hydrogen is used or stored are properly ventilated and monitored for hydrogen levels. Hydrogen leakage can also contribute to GHG emissions if it escapes into the atmosphere. This is because hydrogen is a very light gas and can escape from containers and pipelines more easily than other gases like natural gas. To minimize this risk, proper measures should be taken to prevent leaks and capture any escaped hydrogen for reuse or safe disposal. The risks associated with hydrogen leakage can be managed through proper safety protocols, equipment maintenance, and monitoring. As with any industrial process, the safe handling and use of hydrogen require appropriate training, procedures, and controls to ensure that the risks are minimized {Salehmin, 2022 #76}.

After, identifying and quantifying the risk factors, proper mitigation strategies need to be developed in order to minimize the negative impacts of the risks on the green hydrogen supply chain, especially for the risks with high importance weights. The authors responded to prioritised risk factors within the top 20 in the global ranking or among the three highest in their relevant categories. In order to develop the mitigation strategies, the relevant studies were revisited which included journal publications on hydrogen production, risk management, and policy documents. Of these, a few documents were of particular importance to developing risk mitigation strategies in this study including; Green hydrogen: a guide to policy making [43], European Clean Hydrogen Alliance: reports of the alliance roundtables on barriers and mitigation measures [5], EU hydrogen vision: regulatory opportunities and challenges [41], Green hydrogen: the holy grail of decarbonisation [48], and Mainstreaming green hydrogen in Europe [42]. The experts were also consulted to help with risk mitigation strategy

Table 6
Adjustment factors used for each category.

Category	Economic	Supply chain processes & Governance	Technological & Infrastructure	Environmental	Market	Social	Policy & Regulation
Mechanism	8/9	8/9	9/9	5/9	6/9	4/9	3/9
Adjustment factor	0.89	0.89	1	0.56	0.67	0.44	0.33

Table 7
The final ranking of the risk factors with the adjusted mechanism for global weights.

Rank	Risk Factor	Adjusted Global Weight
1	High investment of capital for H2 production and delivery technology	0.064452182
2	Lack of enough capacity for Electrolyser	0.059920578
3	Policy & regulation development	0.042927083
4	Disruption or failure to deliver electricity from renewable sources	0.040136626
5	Lack of storage, transportation, and delivery capacity	0.03012119
6	Acceptance of H2 from consumers	0.028972995
7	High O/M costs	0.026080334
8	Supplier failure	0.025116418
9	Health and safety	0.022059748
10	Quality issues with H2 production	0.021139494
11	Long term financial viability and profit	0.019560251
12	Machine & equipment failure	0.018236698
13	Land, water, and air pollution	0.017158455
14	Improper location of facilities	0.016744279
15	Consumer awareness	0.016376041
16	Government incentives	0.014859375
17	Integration risks for green H2 supply chain	0.014589358
18	Skilled Human Resources	0.012468553
19	Lack of community pressure and concern	0.012468553
20	Smart Grid malfunction or scarcity	0.012157798
21	Conversion devices	0.011328428
22	Power Grid power disruption	0.011268357
23	Economic Recession	0.011177286
24	Substitute product	0.01091736
24	Bargaining power of customers	0.01091736
26	Fluctuation in unit costs of electricity	0.010480805
27	Inflation rate	0.010476606
27	Currency Exchange rates	0.010476606
29	Rapid technological development and uncertainty in H2 production	0.01042097
30	Climate change & availability of RE sources	0.009754148
31	Bargaining power of RE supplier	0.009186666
32	Political instability	0.008255208
33	Customer failure	0.007360795
34	Inventory management and forecasting	0.00717612
35	Natural disasters and disease outbreaks	0.006502765
36	Information flow	0.006279105
37	Taxes & Tariffs	0.005629262
38	Information and communication technology	0.005210485
39	Fluctuating Demand	0.005038782
40	Terrorism and War	0.004877074
41	Labour strike	0.003836478
42	Collaboration and Transparency	0.003536875
43	Cleaner Technology	0.001985336

development and verification. The developed risk mitigation strategies for the most important risk factors are now presented in each category according to their global ranking. In addition, relevant managerial and practical implications are discussed along with the mitigation strategies for each risk factor.

4.1. Economic

The economic category groups together the various economic and financial risk factors for green hydrogen supply chain that have been identified. The economic category ranks as the third most important in terms of the weightings. Three of the economic risk factors are regarded as highly important in the ranking namely, high investment of capital for green hydrogen production and delivery technology, high O/M costs, and long-term financial viability & profit. The following proposes and discusses mitigation strategies for each.

4.1.1. High investment of capital for H2 production and delivery technology (1)

This risk factor is considered the most important both at a local and overall global ranking. It is widely accepted that at this moment in time green hydrogen production projects require a considerably high initial investment of capital cost [51]. Several infrastructural elements drive the implementation of green hydrogen such as high amount of capital for developing electrolyser plants, prohibitive cost of developing new storage and transportation system or retrofitting existing transportation modes for delivering green hydrogen, higher cost of renewable energy compared to fossil fuel for running electrolysers, and lack of economies of scale for the infrastructure as green hydrogen production is on its early stage. For example, the initial cost of investment in an alkaline electrolyser was around $750–800 per kilowatt in 2020 and the high sensitivity to capacity means this cost could double [43]. Also, storing, and transporting hydrogen either in gaseous or liquid form is relatively expensive, especially in liquid hydrogen which requires a mechanical plant with complex functioning systems to operate which increases overall costs [48,51]. The European Hydrogen Alliance (ECHA) has a crucial role to play in this area by facilitating the implementation of the hydrogen strategy that leads to a scale-up in production and demand for green hydrogen [41]. The ECHA will determine viable projects to invest, which enhances the coordination of investments along the green hydrogen supply chain, improves cooperation between public and private stakeholders, and provides public support for attracting greater investment [42]. Policymakers have the opportunity to mitigate this risk by allocating funding in the form of research and development grants and offering low-interest fixed-term loans to support organisations in their efforts to invest in RE projects [5]. Examples of financing facilities the EU may be eligible to offer green hydrogen projects include; the Invest EU programme, European regional revelopment fund, the cohesion fund, the just transition mechanism, connecting Europe facility and connecting European facility transport [41]. In addition, alternative financing schemes such as build-operate-transfer, build-lease-transfer, and build-lease-operate-transfer can be taken into account to attract investment from private sectors or countries outside the EU.

4.1.2. High O/M costs (7)

The current cost of operating and maintaining the sophisticated technical equipment required for green hydrogen production is high [48]. The production cost of green hydrogen is around 2.5–5.5 €/kg compared to fossil fuel hydrogen which is approximately €1.5/kg to produce [41]. Green hydrogen production is also comparatively much more expensive (€74.9-€164.7/MWh) than natural gas production (€11/MWh) although the EU expects green hydrogen to become cost-competitive by 2030 [41,44]. Connecting electrolysers to the grid is an option to reduce cost and better utilisation of electrolysers throughout the year would subsequently improve the financial viability of green hydrogen production. The hybrid model appears to be the optimal solution to mitigating this risk and in addition to reliable supply, excess electricity can be sold to the grid if the RE producers exceed the demand from the electrolyser [5,43]. According to Mayyas, Ruth [45] increasing the manufacturing scale from 10 to 1000 units per year could decrease the cost of the stack which is one of the main components in an electrolyser by almost 60%. A further 60% cost reduction could be achieved by increasing the module size from 1 MW to 100 MW [43]. Also, the processes involved in green hydrogen production requires a large volume of manual labour which contributes to the high O/M costs, however, as the volume of electrolysers increases and technological advances are made, many of these processes could be increasingly automated [5,43]. Furthermore, governments and policymakers can assign more budgets to research and development in green hydrogen operations, maintenance, and automation. This could increase the level of engagement from the private sector by providing incentive schemes. There also could be a significant opportunity to assign budgets to knowledge and technology transfer schemes from outside of the EU.

4.1.3. Long term financial viability and profit (11)

There is a considerable amount of uncertainty around the financial feasibility of green hydrogen production in the long term which is mainly due to the two contributing factors; market demand and the previously mentioned high costs of producing green hydrogen [41,43]. At present green hydrogen cannot be classed as cost-competitive with substitute products. However, there are positive indications that the production costs of green hydrogen will decline mainly due to lowering costs of RE, lower cost of electrolysers as they become readily available, and new technological developments [48]. In the short term, manufacturers believe that a 50–75% cost reduction is achievable which is driven by upscaling in electrolyser manufacturing capacity shortly [44,54]. Green hydrogen production requires electricity which comes from renewable sources and in order to compete with the carbon-intensive grey, blue or brown hydrogen, this electricity must be affordable [50]. Electrolysers connected to the grid currently may be subject to the same taxes and tariffs as other large industrial consumers amounting to a total cost which can be up to $200/MWh [43]. Also, taxes and tariffs make up a considerable proportion of the final price of electricity and this results in a much higher operational cost being added to the final cost of green hydrogen [54]. For example, Germany can produce hydrogen for $7/kg at an average electricity price of $24/MWh. However, Germany has realised that exempting the electrolysers from all the taxes and fees such as electricity tax and the RE surcharge means they can produce hydrogen at a cost of $2.5/kg. Electrolysers are also exempt from electricity tax in Norway, France and the Netherlands, and other European countries should follow suit [43]. In the long term, the global cost of green hydrogen production is predicted to decrease from 1 to 2.2/kg in 2030 to 0.8–1.6/kg in 2050 which supports a positive outlook on the future financial feasibility of a global hydrogen market and associated projects [42,48]. Based on the meeting with the experts, it was also mentioned that there could be significant opportunities for doing a comprehensive feasibility study on the green hydrogen supply chain and production to verify the financial feasibility.

4.2. Supply chain & governance

This category contains the risk factors that affect the supply chain and the governance of green hydrogen production. This group ranked fourth in terms of importance overall, however, there are two risk factors within that rank highly in the global weighting which should be investigated. Mitigation strategies and recommendations have been developed for the risk factors “supplier failure” and “disruption or failure to deliver electricity from RE sources”.

4.2.1. Supplier failure (8)

Abdel-Basset and Mohamed [17] claim the failure of any key supplier will result in the delayed delivery of critical materials. In the case of green hydrogen production, the electrolysers which are used to produce hydrogen are considered key components that should be manufactured and delivered by suppliers. It is predicted that 400 million tonnes of green hydrogen will be consumed by 2050 and this will need to be produced by an installed capacity of electrolyser amounting to 5 TW [43]. Currently, the global manufacturing capacity of electrolysers is expected to be around 3.1 GW/year. However, this will need to be increased significantly in order to meet the capacity targets on time [41]. A manufacturing capacity of between 130 and 160 GW/year will be required to achieve the 5 TW target for installed electrolysers and any delays in increasing manufacturing capacity will hinder the production of hydrogen alongside the need to heighten the rate of manufacturing capacity more steeply at a later stage [43,48]. Policymakers, therefore, need to ensure they support the expansion of electrolyser manufacturing in the private sector. There are several supplier relationship management strategies to deal with supplier failure. Policymakers and governments can create a long-term relationship with the suppliers rather than a contractual structure. Therefore, there could be a robust supplier selection process put in place to select and manage a few qualified suppliers for the critical materials and components.

4.2.2. Disruption or failure to deliver electricity from renewable sources (4)

The production of green hydrogen requires electricity for the electrolysers which comes from RE sources with the main two being wind and solar, among others such as biofuels [42]. Failure to deliver electricity from renewable sources to the electrolyser compromises the sustainability of the entire green hydrogen supply chain as it will then be classed as either blue, grey, or brown hydrogen [54]. Guarantees of Origin are a method of ensuring the renewable source of the electricity consumed during green hydrogen production [57]. A guarantee of origin certifies the emissions associated with the production and delivery of hydrogen and it should account for the impact on the overall grid mix [43,57]. The best example of this is provided by the EU RE Directive II. This directive states the electricity used for green hydrogen production can only be considered renewable if the electrolysis process utilises an on-site production model or if the manufacturer can provide evidence that the hydrogen fuel has been produced using only RE sources [5,43]. Also, the hybrid model of hydrogen production could help increase dependability. In the hybrid model, the electrolyser is connected to RE plants as well as the electricity grid which allows production to continue when power plants are not available and excess generated electricity to be sold back into the grid [43].

4.3. Technological & infrastructure

These risk factors relate to the development of infrastructure necessary for green hydrogen production, storage and transportation along with the implementation of technologies to support manufacturers in their capacity building projects for electrolysers. The Technological & Infrastructure category received a ranking of 2nd which highlights the importance of all the risk factors in this group. However, five of the most important have been selected here for mitigation strategy development; lack of enough capacity for electrolyser, lack of storage, transportation, and delivery capacity, Quality issues with hydrogen production, integration risks for green hydrogen supply chain, and machine & equipment failure.

4.3.1. Lack of enough capacity for electrolyser (2)

The current installed electrolyser capacity is estimated to be around 200 MW which is simply not enough in terms of capacity for the future consumption of green hydrogen as projected by the EU [43]. There is reason to be optimistic about a sharp increase in capacity with the growing number of newly announced large electrolyser projects [43]. Policymakers can utilise the target setting strategy to encourage the development of electrolyser capacity [5]. Targets demonstrate a commitment from government and policymakers to green hydrogen transition and they take the form of public plans or even a national hydrogen strategy. The EU has set a target of 6 GW of electrolysers in their hydrogen strategy by 2024 and 40 GW by 2030 [41]. While several member states have developed national strategies, vision documents, and roadmaps, there is a need for all EU member states to develop plans to meet these targets [43]. Policymakers and government can develop a comprehensive strategic plan for the development of electrolysers capacity followed by tactical and operational planning. The output of the operation plan can lead to several projects for electorlyser capacity expansion.

4.3.2. Lack of storage, transportation, and delivery capacity (5)

The physical properties of hydrogen mean that there are certain challenges associated when it comes to transportation. Hydrogen has a high density of energy by weight (33.3 kW h per kg) but a relatively low density of energy by volume (3 kW h per cubic metre). This means larger volumes of hydrogen are required to be transported to deliver the same amount of energy when compared to other fuels such as methane gas [2,43]. As such, most hydrogen produced today is also consumed on-site, and in order to change this, a large infrastructure establishment needs to take place, which will also require cross-border cooperation in the EU

[48]. Hydrogen can be treated to reduce its volume for transportation and options include compression, liquification, a liquid organic hydrogen collider and conversion to other synthetic fuels. Compressed hydrogen can be transported via haulage vehicles for short distances as a viable option in low volumes [5] When hydrogen needs to be transported for longer distances, liquification is often used to transport up to 3500 kg by truck. However, the most promising transportation mode for green hydrogen is via pipelines which carry compressed hydrogen. Currently, there is only 5000 km of hydrogen purpose pipeline which is minuscule compared to the 3 million km of fossil gas pipeline. There is an opportunity to repurpose these pipelines dedicated to fossil gas for the transportation of green hydrogen [43]. There is a potential issue with converting gas pipelines to hydrogen pipelines in that it essentially locks the end-use of the pipeline. This can be mitigated with careful planning and assessment of each application to determine its suitability for green hydrogen which also avoids unnecessary spending [43]. The establishment of hydrogen infrastructure for transportation can be expensive and energy-intensive even when up and running thus there is an opportunity here to repurpose these pipelines dedicated to fossil gas for the transportation of green hydrogen [43]. Building a global hydrogen market will therefore require significant investment in pipeline development alongside a range of technologies that will enable a well-functioning value chain capable of storing and transporting hydrogen in an effective and cost-friendly manner [48,50].

4.3.3. Quality issues with H2 production (10)

There is a need for developing and implementing international standards and policies on hydrogen production if policymakers are to be successful in developing a hydrogen market [51,50]. The risk that there could be unexpected errors or deviations from what is needed is a common supply chain risk and it is true for green hydrogen production also. The absence of contaminants in the hydrogen is critical to ensure the life of fuel cells in electric vehicles and so green hydrogen producers need to ensure this is a priority. Since green hydrogen is an emerging market there is a limited amount of international standards on the production and consumption end [48], as the quality of hydrogen must be guaranteed based on only two international standards; ISO 14687–2:2012 and ISO/DIS 19880–8 respectively [52]. This lack of common regulations can lead to single countries developing internal standards which limits the potential of hydrogen and results in countries having a flexible approach to environmental issues such as CO2 emissions threshold for hydrogen to be considered green [48]. A common international framework would avoid unfair competition and enhance cross-border cooperation by agreeing on operational rules and safety standards [48,50].

4.3.4. Integration risks for green H2 supply chain (17)

This risk is concerned with the various design aspects of integrating any RE into an already existing supply chain network [18]. In the case of hydrogen production, there is a risk associated with integrating electrolysers and the grid as this connection could use up RE at the cost of other electricity uses due to an increase in demand [5]. When there is excess demand, it will usually be covered by a "marginal plant". Hence, the problem is here as these marginal plants are often fossil fuel plants. Therefore, integrating the electrolyser with the grid electricity poses a risk that it could lead to an increase in fossil fuel use and subsequently this could increase the CO2 emissions for electricity which would have been used elsewhere had it not been for green hydrogen production. Policymakers need to prioritise developing electrolysers in areas with high grid congestion which would reduce the curtailment of RE. Another option is to increase the RE quotas to account for the electrolyser needs or exclude electricity used by electrolysers from capacity target accounting [2,43].

4.3.5. Machine & equipment failure (12)

A failure in machines or equipment is a risk as it will decrease the effectiveness of hydrogen operations and consequently production [35]. Proper maintenance, the development of standards and the fact that much of the equipment required to produce RE or green hydrogen is relatively new means that the manufacturers need to use modern techniques to ensure the quality of their machines. The development and enforcement of EU legislation regarding quality standards for equipment are important to ensure the machines and equipment are of a high standard and will operate as expected for an acceptable period [5]. Also, based on the experts' opinion, reliability-based maintenance and preventive maintenance over the supply chain would avoid unexpected machine and equipment failure.

4.4. Environmental

The Environmental category is concerned with those risk factors that potentially impact the environment in which green hydrogen is produced. The category itself received the lowest ranking of all the categories however, there is one important risk factor that warranted discussion; land, water, and sir pollution.

4.4.1. Land, water, and air pollution (13)

Installation of RE equipment can cause damage to the environment. Wind turbines alter airflow and cause change to the physical landscape, hydro dams impact aquatic life, and solar panels attract increased heat from the sun to nearby areas [34]. A reduction in CO2 emissions is the main advantage of green hydrogen, however, if the source of electricity is not RE, there could be displaced CO2 emissions. In addition, green hydrogen conversion and transportation can create additional CO2 emissions [2,43]. More accurate and comprehensive methods to calculate these emissions need to be developed and adopted to mitigate the risk of unsustainable fossil fuel-based hydrogen being produced and greenwashed as an alternative to carbon fuels without effective emission reduction [50]. Policymakers also need to enforce certification requirements from green hydrogen producers which is discussed further in 4.7.

4.5. Market

The Market category groups together risk factors that pose a threat to the development of a global green hydrogen market for both producers and consumers. The category ranks fifth in terms of importance and two risk factors rank highly in the global ranking; acceptance of green hydrogen from consumers and consumer awareness.

4.5.1. Acceptance of H2 from consumers (6)

The risk that green hydrogen will not be accepted by consumers due to the mentioned problems of land/air pollution and temporary energy price increase has been identified in previous studies [5,42]. The absence of incentives for customers to switch to green hydrogen is an obstacle to its acceptance among consumers [5,51]. Customers may not see the immediate benefits of switching to a new fuel source and may perceive it as an inconvenience. Furthermore, compared to other conventional and renewable fuels, green hydrogen may not be as competitively priced, adding to customer reluctance to adopt it [50].

To address this issue, policies and market mechanisms can be implemented to incentivise consumers to switch to green hydrogen. For instance, governments can offer tax incentives or subsidies to companies that use green hydrogen in their operations, which would in turn reduce the costs of green hydrogen and encourage its adoption. In addition, green procurement policies can be implemented to promote the use of green hydrogen in public sector operations, further boosting demand and reducing costs [5].

However, increasing customer awareness and education about the benefits of green hydrogen is also crucial in driving its acceptance. Consumers need to understand the environmental benefits of green hydrogen and how it contributes to meeting the sustainable development goals and reducing the impacts of climate change [51]. This can be achieved through strategic green marketing by the EU and private organisations seeking to build their customer base. With more knowledge about green hydrogen, customers may be more likely to switch to companies producing their products with green fuels such as green hydrogen. By addressing the price and awareness issues, policymakers can encourage the acceptance of green hydrogen among consumers and support the transition to a more sustainable energy future [41]. The EU strategy for increasing demand for green hydrogen also includes incentives and allowances for green hydrogen use in certain sectors [50]. Additionally, the sustainable and smart mobility strategy mentions increasing hydrogen fuel cell trains, heavy goods vehicles, marine uses and commercial uses such as taxis as a means of boosting hydrogen acceptance among consumers [41].

4.5.2. Consumer awareness (15)

This risk is associated with the threat of substitute products being available instead of green hydrogen such as fossil fuels, other RE, and even blue and grey hydrogen. A low level of consumer awareness of sustainability poses a risk for green hydrogen as it influences demand [54]. 120 million tonnes of hydrogen are produced each year from fossil fuels also known as grey hydrogen, which accounts for almost 95% of hydrogen production. In addition, almost 75% of hydrogen consumption is used for the refinery of crude oil and ammonia/methanol synthesis [43]. Also, many national and regional hydrogen strategies include blue hydrogen production as part of their solutions. While blue hydrogen does offer some decarbonisation impacts through carbon capture the presence of competitors to green hydrogen reduces opportunities for green hydrogen production and respective manufacturers [41]. At present, there are low levels of value recognition being placed on green hydrogen as there is little demand for green products made with green hydrogen such as green steel or green ammonia [2]. The demand for these types of products is still detached from the origin of their feedstocks i. e green, blue, or grey hydrogen and this needs to be mitigated by increased mandates, public procurement requirements and enhanced green marketing efforts by the EU [5,43].

4.6. Social

Social risk factors mainly concern any risk to society or the social sustainability of green hydrogen production and the activities associated with such. The main risk factor from this category is health and safety while the overall category ranking is sixth.

4.6.1. Health and safety (9)

Green hydrogen production involves several risk factors for workers such as exposure to chemicals, loud noise, and hazardous operating equipment which can be detrimental to their health. Also, the transportation of green hydrogen is hazardous to the wider population in society as it is explosive and corrosive [5,43]. It is hopeful that the prominent levels of manual labour required at present to produce green hydrogen will reduce over time as rapid technological advancements are made and much of the processes which take place involving electrolysers at dedicated plants will become automated and carried out by robotics, thus reducing the risks posed to workers [52]. Also, in terms of safety when transporting and storing hydrogen, the upgrading of pipelines and other necessary infrastructure should ensure these methods are fit for purpose and do not pose a danger to the population in any given area [51,50]. Although health and safety issues were considered under social aspects based on the previous studies and the experts' opinion, there is a relation between safety problem and machine and equipment failure too. Therefore, there is an interrelation between safety risk factors and machine and equipment failure which can be considered by policymakers and practitioners when they develop safety policies.

4.7. Policy & regulation

Finally, the policy & regulation category groups together the risk factors mainly concerning the government which are responsible for policy & regulation development. This category ranks first overall and this highlights the importance of mitigating these risk factors in order to progress the green hydrogen production, consumption and acceptance. The two main risk factors discussed for mitigation strategies here are government incentives and policy & regulation development.

4.7.1. Government incentives (16)

Inadequate government incentives pose a risk as they are necessary to encourage green hydrogen production and consumption initially. Policymakers could provide financial incentives for both manufacturers, and industrial customers of green hydrogen [5]. There is a high level of uncertainty associated with the supply and demand of hydrogen in the future and this will make it difficult for both consumers and producers to commit to hydrogen in the long term [41]. The cost gap between different types of hydrogen adds to this uncertainty as the production costs of green hydrogen are around 2.5–5.5 €/kg compared to fossil fuel hydrogen which is approximately €1.5/kg to produce, and it is this cost gap that makes consumers unwilling to accept green hydrogen or for producers to produce it without the presence of financial incentives, legislative requirements or both [41,50]. It is likely these support schemes and incentives will need to remain in place for a significant transition period to allow the scale-up of green hydrogen production and a boost in demand [48]. Direct support schemes could be made available for green hydrogen production and the allocation of such would be through competitive tender offers which are in line with a transparent, efficient and competitive hydrogen market [41]. This would also provide price signals which reward electrolysers for their services provided to the energy systems such as more flexibility or by reducing the burden endured on renewable incentives [41]. In addition, the development of policies that help the financial cost reduction involved with electrolyser investment could also decrease the burden and strengthen the business case in terms of the cost of green hydrogen for more industries. Another government action that could incentivise green hydrogen production is the exemption of electrolysers which produce green hydrogen from taxes and other fees [50]. Although the government incentives risk factor is categorised under policy and regulation, it has direct impacts on the economic risk factors as it could provide better financial schemes for the industry, especially the private sector. Therefore, developing supportive incentive policies can help reduce the negative impact of economic risk factors.

4.7.2. Policy & regulation development (3)

There are a number of mitigation strategies that could be deployed for the risk of poor policy & regulation development which could hinder the expansion of the green hydrogen supply chain. Several market mechanisms could be used such as cap-and-trade systems, carbon taxes and carbon contracts for difference. For example, a CO2 price of at least between €55-€90 per tonne is required to make green hydrogen competitive with other fossil fuel-based substitute products [41]. The current EU emissions trading scheme price falls well short of this at €25 per tonne. Therefore, carbon contracts for difference offers an alternative long-term compensation contract for investors that fill the gap between the prices [41]. Applying taxes to grey or blue hydrogen alongside support for green hydrogen will help make green hydrogen cost-competitive with grey hydrogen over the medium and long term [42,54]. France has already made grey hydrogen subject to the carbon tax which is due to increase from €44.6 per tonne to €100 per tonne in 2030, further reducing the competitiveness of grey hydrogen [43]. Policy developments which offer tariffs or premiums for producing green rather than grey hydrogen could also close the cost gap. In an equivalent manner offering production subsidies for each unit of green hydrogen produced is an attractive policy development that would increase the economic attractiveness of new electrolyser projects and should be considered by the EU [43]. The earlier mentioned targets and support for scale-up and efficiency of green hydrogen manufacturers will also help attract investment from the private sector entities which are essential to develop a green hydrogen market with adequate supply and demand levels [2,5].

4.8. The importance of the adjustment mechanism for ranking

This section presents a comparison between the ranking of the risk factors prior to the adjustment mechanism technique and after it had been applied. Table 8 shows the ranks of the risk factors. It can be observed that the adjustment mechanism has a significant impact on the ranking of risk factors with the economic, policy & regulation, and technological & infrastructure risk factors witnessing a particularly significant rise or fall in positions in the final adjusted global ranking. In order to validate the results of the study were shown to the experts and they preferred the results of the ranking from the adjusted method.

Table 8
The impact of the adjustment mechanism on the ranking of risk factors.

Risk Factor	Global Rank (Adjusted)	Global ranking
High investment of capital for H2 production and delivery technology	1	4
Lack of enough capacity for Electrolyser,	2	7
Policy & regulation development	3	1
Disruption or failure to deliver electricity from renewable sources	4	6
Lack of storage, transportation, and delivery capacity	5	15
Acceptance of H2 from consumers	6	5
High O/M costs	7	14
Supplier failure	8	12
Health and safety	9	2
Quality issues with H2 production	10	23
Long term financial viability and profit	11	21
Machine & equipment failure	12	24
Land, water, and air pollution	13	3
Improper location of facilities	14	17
Consumer awareness	15	13
Government incentives	16	11
Integration risks for green H2 supply chain	17	27
Skilled Human resources	18	8
Lack of community pressure and concern	19	9
Smart Grid malfunction or scarcity	20	31
Conversion devices	21	36
Power Grid power disruption	22	25
Economic Recession	23	30
Substitute product	24	18
Bargaining power of customers	24	18
Fluctuation in unit costs of electricity	26	32
Inflation rate	27	33
Currency Exchange rates	27	33
Rapid technological development and uncertainty in H2 production	29	38
Climate change & availability of RE sources	30	10
Bargaining power of RE supplier	31	28
Political instability	32	20
Customer failure	33	26
Inventory management and forecasting	34	37
Natural disasters and disease outbreaks	35	16
Information flow	36	39
Taxes & Tariffs	37	41
Information and communication technology	38	43
Fluctuating Demand	39	35
Terrorism and War	40	22
Labour strike	41	29
Collaboration and Transparency	42	42
Cleaner Technology	43	40

5. Conclusion

Green hydrogen has recently received significant attention among academia, practitioners, and policymakers as it can be utilised for the decarbonisation of hard-to-abate sectors in Europe. However, the green hydrogen supply chain has not been properly developed and is currently in an infancy stage. The supply chain of the green hydrogen for hard-to-abate sectors has several members from RE providers to the final industries that use the green hydrogen. There are many risks associated with the activity of the green hydrogen supply chain members which have rarely been investigated. To fill this gap, this research used an integrated approach of the Delphi method and BWM to identify and analyse the green hydrogen supply chain risk factors in Europe. This research has three main contributions. First, green hydrogen supply chain risk factors for hard-to-abate sectors from a European perspective were identified using a Delphi method. 43 risk factors were identified and categorised into 7 main categories for the first time in the green hydrogen research. Second, a structured approach using Delphi and an adjusted BWM was used to find the importance weights of the risk categories and factors. Third, relevant mitigation strategies for the most important risks were developed. Using the proposed approach, the green hydrogen supply chain risk factors were ranked. Afterwards, risk recommendations for mitigating the high-ranked risk factors were presented. As there is only a limited number of studies around the green hydrogen supply chain, the results of this study can help EU governments, policymakers, and practitioners to effectively implement green hydrogen supply chain initiatives and projects. The results of the study equip them with great insight into the existing green hydrogen supply chain risk factors, their importance, and potential mitigation strategies within the EU. Consequently, this leads to a better implementation of green hydrogen supply chains which help the EU to move towards its climate target plan. In addition, the results of the study can be useful for policymakers and practitioners in developing relevant standards for green hydrogen production.

The results of the empirical study highlight that high investment of capital for green hydrogen production and delivery technology was the highest-ranked risk factor followed by the lack of enough capacity for electrolysers, policy & regulation development, disruption or failure to deliver electricity from renewable sources, lack of storage, transportation, and delivery capacity, and acceptance of green hydrogen from consumers. Several mitigation strategies, practical implications and recommendations were provided for the high-rank risk factors. It is crucial for the EU countries' policymakers in the area of RE, to develop and implement strategies for mitigating the identified risk factors.

Green hydrogen supply chain is in its infancy stage and needs to be looked after by providing dedicated and tailored policies and regulations. Although there have been efforts in recent years to boost the production of green hydrogen by focusing on research and development, these projects have made little impact on commercial development for the market as they are small-scale projects and suffer to deliver a feasible business case for the green hydrogen supply chain. Furthermore, incentive policies and supports do not furnish the required investment volume for commercial purposes. Lacking generous incentives would lead to a higher production cost compared to fossil fuels and consequently less competitiveness for green hydrogen. In addition, the current policy and regulatory atmosphere and low cost of alternative fuels put barriers to the commercialisation of green hydrogen. Moreover, there are very limited dedicated regulations and policies to incentivise the usage of green hydrogen for commercial purposes. Most of the policies and regulations were developed to grow the share of renewable energy in the energy source market mix.

In order to overcome barriers and resistance to making green hydrogen a key energy carrier in the market there is a need for developing an integrated policy approach.

Based on the results of our study several policies and regulations can be developed. High investment of capital for green hydrogen and lack of enough capacity for electrolyser are the most important risk factors. There should be a national and international green hydrogen strategy with relevant action plans that set electrolyser capacity targets, national/international loan plans, and setting feed-in premiums specifically for green hydrogen. Some market mechanisms policies and regulations can be developed to support green hydrogen supply chain implementation. For instance, policymakers and governments can put a threshold as the minimum amount of green hydrogen usage for hard-to-abate sectors. In addition, putting mechanism such as cap-and-trade and carbon pricing for using green hydrogen in place would mitigate some risks regarding demand and market. Finally, the green hydrogen supply chain is an international supply chain as several countries can play roles in that. Therefore, it requires international collaborations for developing supportive policies.

In this study, an improved version of BWM was used to find more reliable results regarding the global weights of the risk factors. However, there are still some limitations to the BWM. For example, if the number of risk factors in a risk category increases the number of pairwise comparisons will be increased which causes confusion for the experts and consequently a higher inconsistency ratio. In order to deal with the situation, structured interviews are recommended rather than a traditional questionnaire for doing the pairwise comparison. For future studies, there could be some avenues of research for developing mitigation strategies for all of the identified risk factors from this study. Finally, there is an opportunity for future studies to examine the interrelations between the identified risk factors in various regions.

Credit author statement

Amir Hossein Azadnia: Supervision, Conceptualization, Methodology, Data curation, Writing- Reviewing and Editing. **Conor McDaid:** Methodology, Analysis, Data curation, Writing- Original draft preparation. **Amin Mahmoudzadeh Andwari:**. Conceptualization, Writing – review & editing. **Seyed Ehsan Hosseini:** Supervision, Reviewing and Editing.

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

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113371.

References

[1] International Energy Agency. The future of hydrogen. 2019.
[2] International Renewable Energy Agency. Green hydrogen supply: a guide to policy making. 2021.
[3] International Renewable Energy Agency. Green hydrogen for industry: a guide to policy making. 2022.
[4] Rao Pala LP, Peela NR. Green hydrogen production in an optofluidic planar microreactor via photocatalytic water splitting under visible/simulated sunlight irradiation. Energy Fuel 2021;35:19737–47.
[5] European Clean Hydrogen Alliance. The European Clean Hydrogen Alliance: reports of the alliance roundtables on barriers and mitigation measures. Online: European Commission; 2021.
[6] Manna J, Jha P, Sarkhel R, Banerjee C, Tripathi AK, Nouni MR. Opportunities for green hydrogen production in petroleum refining and ammonia synthesis industries in India. Int J Hydrogen Energy 2021;46:38212–31.
[7] Hosseini SE, Andwari AM, Wahid MA, Bagheri G. A review on green energy potentials in Iran. Renewable and Sustainable Energy Reviews2013. p. 533-545..
[8] Pein M, Neumann NC, Venstrom LJ, Vieten J, Roeb M, Sattler C. Two-step thermochemical electrolysis: an approach for green hydrogen production. Int J Hydrogen Energy 2021;46:24909–18.
[9] Cha J, Park Y, Brigljević B, Lee B, Lim D, Lee T, et al. An efficient process for sustainable and scalable hydrogen production from green ammonia. Renew Sustain Energy Rev 2021:152.
[10] Segawa Y, Endo N, Shimoda E, Maeda T. Pilot-scale hydrogen energy utilization system demonstration: a commercial building case study on on-site green hydrogen production and use. Int J Hydrogen Energy 2022;47:15982–91.
[11] Qiu Z, Martín-Yerga D, Lindén PA, Henriksson G, Cornell A. Green hydrogen production via electrochemical conversion of components from alkaline carbohydrate degradation. Int J Hydrogen Energy 2022;47:3644–54.
[12] Bigerna S, Bollino CA, Micheli S. The sustainability of renewable energy in Europe. Springer International Publishing; 2015.
[13] International Renewable Energy Agency, European C. Renewable Energy Prospects for the European Union: c (IRENA) 2018.
[14] Yu M, Wang K, Vredenburg H. Insights into low-carbon hydrogen production methods: green, blue and aqua hydrogen. Int J Hydrogen Energy 2021;46:21261–73.
[15] Kim JH, Hansora D, Sharma P, Jang JW, Lee JS. Toward practical solar hydrogen production-an artificial photosynthetic leaf-to-farm challenge. Chemical Society Reviews: Royal Society of Chemistry; 2019. p. 1908–71.
[16] Dong ZY, Yang J, Yu L, Daiyan R, Amal R. A green hydrogen credit framework for international green hydrogen trading towards a carbon neutral future. Int J Hydrogen Energy 2022;47:728–34.
[17] Abdel-Basset M, Mohamed R. A novel plithogenic TOPSIS-CRITIC model for sustainable supply chain risk management. J Clean Prod 2020;247:119586.
[18] Lahane S, Kant R. Evaluation and ranking of solutions to mitigate circular supply chain risks. Sustain Prod Consum 2021;27:753–73.
[19] Moktadir MA, Dwivedi A, Khan NS, Paul SK, Khan SA, Ahmed S, et al. Analysis of risk factors in sustainable supply chain management in an emerging economy of leather industry. J Clean Prod 2021;283:124641.
[20] de Oliveira UR, Marins FAS, Rocha HM, Salomon VAP. The ISO 31000 standard in supply chain risk management. J Clean Prod 2017;151:616–33.
[21] Ciotola A, Fuss M, Colombo S, Poganietz W-R. The potential supply risk of vanadium for the renewable energy transition in Germany. J Energy Storage 2021;33:102094.
[22] Pathak SK, Sharma V, Chougule SS, Goel V. Prioritization of barriers to the development of renewable energy technologies in India using integrated Modified Delphi and AHP method. Sustain Energy Technol Assessments 2022;50:101818.
[23] Rezaei J. Best-worst multi-criteria decision-making method. Omega 2015;53:49–57.
[24] Kakoulaki G, Kougias I, Taylor N, Dolci F, Moya J, Jäger-Waldau A. Green hydrogen in Europe – a regional assessment: substituting existing production with electrolysis powered by renewables. Energy Convers Manag 2021:228.
[25] International Energy A. Global hydrogen review 2021. 2021.
[26] New Zealand. Ministry of Business I, Employment. A vision for hydrogen in New Zealand : green paper 2019.
[27] Swennenhuis F, de Gooyert V, de Coninck H. Towards a CO2-neutral steel industry: justice aspects of CO2 capture and storage, biomass- and green hydrogen-based emission reductions. Energy Res Social Sci 2022;88:102598.
[28] Choi W, Kang S. Greenhouse gas reduction and economic cost of technologies using green hydrogen in the steel industry. J Environ Manag 2023;335:117569.
[29] Kim J, Qi M, Kim M, Lee J, Lee I, Moon I. Biogas reforming integrated with PEM electrolysis via oxygen storage process for green hydrogen production: from design to robust optimization. Energy Conversion and Management; 2022. p. 251.
[30] Atilhan S, Park S, El-Halwagi MM, Atilhan M, Moore M, Nielsen RB. Green hydrogen as an alternative fuel for the shipping industry. Current Opinion in Chemical Engineering 2021;31:100668.
[31] Azevedo SG, Santos M, Antón JR. Supply chain of renewable energy: a bibliometric review approach. Biomass Bioenergy 2019;126:70–83.
[32] Etemadi N, Borbon-Galvez Y, Strozzi F, Etemadi T. Supply chain disruption risk management with blockchain: a dynamic literature review. Information 2021;12:70.
[33] Jelti F, Allouhi A, Büker MS, Saadani R, Jamil A. Renewable power generation: a supply chain perspective. Sustainability 2021;13:1271.
[34] Jianying F, Bianyu Y, Xin L, Dong T, Weisong M. Evaluation on risks of sustainable supply chain based on optimized BP neural networks in fresh grape industry. Comput Electron Agric 2021;183:105988.
[35] Kim C. A review of the deployment programs, impact, and barriers of renewable energy policies in Korea. Renew Sustain Energy Rev 2021;144:110870.
[36] Rangel DA, de Oliveira TK, Leite MSA. Supply chain risk classification: discussion and proposal. Int J Prod Res 2015;53:6868–87.
[37] Rostamzadeh R, Ghorabaee MK, Govindan K, Esmaeili A, Nobar HBK. Evaluation of sustainable supply chain risk management using an integrated fuzzy TOPSIS-CRITIC approach. J Clean Prod 2018;175:651–69.
[38] Shahbaz MS, Sohu S, Khaskhelly FZ, Bano A, Soomro MA. A novel classification of supply chain risks. Engineering. Technology & Applied Science Research 2019;9:4301–5.
[39] Song W, Ming X, Liu H-C. Identifying critical risk factors of sustainable supply chain management: a rough strength-relation analysis method. J Clean Prod 2017;143:100–15.
[40] Wee H-M, Yang W-H, Chou C-W, Padilan MV. Renewable energy supply chains, performance, application barriers, and strategies for further development. Renew Sustain Energy Rev 2012;16:5451–65.

[41] Barnes A, Yafimava K. EU Hydrogen Vision: regulatory opportunities and challenges. 2020.

[42] Enkvist P-A, Westerdahl R, Elmqvist A. Mainstreaming green hydrogen in Europe. Online. Breakthrough Energy; 2022.

[43] Bianco E, Blanco H. Green hydrogen: a guide to policy making. 2020.

[44] Jovan DJ, Dolanc G. Can green hydrogen production be economically viable under current market conditions. Energies 2020;13:6599.

[45] Mayyas AT, Ruth MF, Pivovar BS, Bender G, Wipke KB. Manufacturing cost analysis for proton exchange membrane water electrolyzers. Golden, CO (United States): National Renewable Energy Lab.(NREL); 2019.

[46] Solangi YA, Longsheng C, Shah SAA. Assessing and overcoming the renewable energy barriers for sustainable development in Pakistan: an integrated AHP and fuzzy TOPSIS approach. Renew Energy 2021;173:209–22.

[47] Shekarian M, Mellat Parast M. An Integrative approach to supply chain disruption risk and resilience management: a literature review. Int J Logist Res Appl 2021;24:427–55.

[48] Scita R, Raimondi PP, Noussan M. Green hydrogen: the holy grail of decarbonisation? An analysis of the technical and geopolitical implications of the future hydrogen economy. 2020.

[49] Turner G, Roots S, Wiltshire M, Trueb J, Brown S, Benz G, et al. Profiling the risks in solar and wind: a case for new risk management approaches in the renewable energy sector. Zurich: Swiss Reinsurance; 2013.

[50] Maestre V, Ortiz A, Ortiz I. Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications. Renew Sustain Energy Rev 2021;152:111628.

[51] Tarkowski R, Uliasz-Misiak B. Towards underground hydrogen storage: a review of barriers. Renew Sustain Energy Rev 2022;162:112451.

[52] Bacquart T, Arrhenius K, Persijn S, Rojo A, Auprêtre F, Gozlan B, et al. Hydrogen fuel quality from two main production processes: steam methane reforming and proton exchange membrane water electrolysis. J Power Sources 2019;444:227170.

[53] Azadnia AH, Geransayeh M, Onofrei G, Ghadimi P. A weighted fuzzy approach for green marketing risk assessment: empirical evidence from dairy industry. J Clean Prod 2021;327:129434.

[54] Hydrogen Council. A perspective on hydrogen investment, deployment and cost competitiveness. 2021.

[55] Liu L, Ye J, Zhao Y, Zhao E. The plight of the biomass power generation industry in China–A supply chain risk perspective. Renew Sustain Energy Rev 2015;49:680–92.

[56] Ghadimi P, Donnelly O, Sar K, Wang C, Azadnia AH. The successful implementation of industry 4.0 in manufacturing: an analysis and prioritization of risks in Irish industry. Technol Forecast Soc Change 2022;175:121394.

[57] Abad-Velazquez A, Dodds PE. Green hydrogen characterisation initiatives: definitions, standards, guarantees of origin, and challenges. Energy Pol 2020;138:111300.