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Risk Analysis on the Implementation and Operation of Green Hydrogen and Its Derivatives in the Spanish Port System

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Abstract: The problem addressed in this paper is the identification and management of risks associated with the implementation and operation of green hydrogen in the Spanish port system. The growing demand for clean energy and environmental regulations are driving the adoption of green hydrogen as a viable solution to decarbonize shipping. However, this transition comes with significant challenges, including safety, infrastructure, and hydrogen handling risks. In the existing literature, several authors have used methodologies such as qualitative and quantitative risk analysis, techniques such as FMEA (*Failure Modes and Effects Analysis*), and the evaluation of impacts and probabilities of occurrence to identify and manage risks in similar projects. These approaches have made it possible to identify potential threats and propose effective mitigation measures. In this work, a combined methodology is proposed that includes the identification of threats, risk assessment through risk matrices, and classification of these risks for their proper management. The SWIFT method (*Structured What-If Technique*) and the use of impact-probability matrices are applied. The main conclusion of the work is that, although green hydrogen has great potential for the decarbonization of the port sector, its implementation requires careful management of the risks identified. The proposed mitigation measures are essential to ensure the safety and viability of green hydrogen projects in Spanish ports.

Keywords: risk analysis; port innovation; green H2; Spanish port system; port operational efficiency; energy transition

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1. Introduction

In recent decades, concern about climate change has grown exponentially, prompting governments and organizations to implement strict measures to reduce greenhouse gas emissions. The European Union (EU), in particular, has taken a leading role, imposing environmental sanctions and regulations that significantly affect the shipping sector and ports [1]. This situation has led shipping companies to look for cheaper alternatives outside the EU, especially in North African ports, which puts European ports, including Spanish ports, at a disadvantage due to their geographical proximity and volume of maritime traffic [2]. The transition to a more sustainable energy model in Spanish ports is an imperative need to meet climate objectives and maintain competitiveness in the global market [3].

To stay competitive and comply with environmental regulations, European ports and shipping companies are forced to adopt cleaner and more sustainable energy sources [4]. In this context, green hydrogen emerges as a promising solution. Produced by electrolysis of water using electricity from renewable sources, green hydrogen generates no carbon emissions during its production and use, making it an ideal energy vector for decarbonizing key sectors of the economy, including maritime transport [5].

However, the implementation of green hydrogen in the port environment presents significant challenges [6]. The transformation of energy to hydrogen, together with its transport, storage, and handling, poses a series of risks that must be properly assessed and managed to ensure the safety of people, infrastructure, and the environment [7]. These risks include potential leaks and explosions, adapting existing infrastructure, and training personnel to handle new technologies.

On the other hand, the global and European context around green hydrogen shows a strong commitment to the transition to a decarbonized economy. The EU has set ambitious targets through Directive (EU) 2018/2001 and the Hydrogen Strategy (2020) [8], which promote the use of renewable energy and the adoption of green hydrogen. Spain, in line with these objectives, has developed the National Integrated Energy and Climate Plan (PNIEC) and the Climate Change and Energy Transition Law, which establish a regulatory framework for the adoption of hydrogen technologies [9].

In addition, initiatives such as the REPowerEU Plan and the Important Projects of Common European Interest (IPCEI) reflect the importance of green hydrogen in the EU's energy strategy. These projects seek to develop innovative technologies and build suitable infrastructures to facilitate the adoption of hydrogen in various sectors, including maritime transport [10].

Green hydrogen not only offers environmental advantages, but also economic opportunities [11]. The reduction in energy dependence, the promotion of technological innovation, and job creation are some of the potential benefits associated with the adoption of hydrogen in Spain [5]. However, to fully take advantage of these opportunities, it is crucial to address the risks associated with their implementation effectively [12].

This study focuses on the analysis of these risks, proposing a methodological approach that combines qualitative and quantitative techniques to assess and manage the risks associated with the implementation of green hydrogen in Spanish ports. By doing so, the results of this study provide a solid basis for informed decision making, facilitating a safe and sustainable transition towards the use of green hydrogen in the port environment.

In conclusion, green hydrogen is presented as a viable and promising solution, but its implementation requires careful risk management. This study contributes to the understanding of these risks and offers practical recommendations for their mitigation, paving the way for a cleaner and safer energy future, both in Spain's seaports and for European society as a whole.

The aim of this study is to analyze in detail the risks associated with the implementation and operation of green hydrogen in the Spanish port system. It seeks to identify possible risk scenarios, assess their impact and probability, and propose mitigation measures that allow a safe transition to the use of cleaner energy in seaports.

To this end, an exhaustive review of the existing literature has been carried out, identifying methodologies and approaches used by other researchers in the analysis of risks associated with hydrogen and with the port management. Among the methodologies highlighted are the FMEA (*Failure Modes and Effects Analysis*), HAZOP (*Hazard and Operability Study*), and the SWIFT (*Structured What-If Technique*) method. These approaches provide a solid basis for systematically and structured assessment of potential risks and their consequences in complex systems.

This paper proposes a combination of these methodologies with fuzzy number theory to quantify the identified risks, providing a more accurate and manageable assessment of risk factors. The methodology includes the identification of threats through literature reviews and brainstorming sessions with experts, followed by the evaluation and classification of risks according to their impact and probability.

2. State of the Art

2.1. Green Hydrogen and Its Role in the Port Sector

With regard to the green hydrogen supply chain and its risk factors, the need to carry out this analysis is highlighted, since, although there are studies analyzing risks in supply chains, they did not exist for green hydrogen. In this research, risk factors are considered as threats, forces, and/or barriers [13], a risk analysis examines threats in critical business processes.

Spanish ports play a crucial role in the transition to clean energy, acting as strategic nodes in the green hydrogen supply chain [14]. Their privileged geographical location and advanced infrastructures position them as key points for the production, storage, and distribution of renewable hydrogen.

Spanish ports play a crucial role in the transition to clean energy, acting as strategic nodes in the green hydrogen supply chain. Their privileged geographical location and advanced infrastructures position them as key points for the production, storage, and distribution of renewable hydrogen. The European Maritime Safety Agency (EMSA) has recognized the potential of hydrogen as a maritime fuel and has published a report highlighting its feasibility, associated risks, and necessary safety measures for implementation in port environments. This report provides valuable insights into the regulatory and operational challenges of integrating hydrogen into maritime transport, reinforcing the importance of a structured risk analysis for its adoption [15].

In addition, initiatives such as the "Andalusian Green Hydrogen Valley" seek to transform regions such as Andalusia into renewable energy hubs, promoting projects in the ports of Huelva and Algeciras to supply sustainable fuels to the maritime sector [16].

These efforts not only contribute to the decarbonization of shipping but also strengthen the local economy and foster technological innovation in the energy sector.

Some studies begins with a Delphi method [7]. The main objective of the technique is to assist and structure the group's communication process. The selected experts evaluate a series of future projections in terms of expected probability, impact, and desirability. In addition, experts are asked to complement their quantitative assessments with qualitative arguments. This Delphi approach proves to be well suited to meet the challenges of a risk analysis in a deeply uncertain environment [17].

Green hydrogen is produced by electrolysis of water, using electricity from renewable sources such as wind or solar, ensuring production without greenhouse gas emissions.

In contrast, conventional hydrogen, known as gray hydrogen, is obtained from fossil fuels, such as natural gas, by processes that emit significant amounts of CO_2 [18].

This difference in production methods makes green hydrogen a more sustainable alternative and aligned with climate neutrality objectives. Although green hydrogen has historically been more expensive to produce, technological advances and increasing investment in renewable energy are driving down its costs, making it increasingly competitive against conventional hydrogen [19].

2.2. Risk Factors and Methodologies for Risk Assessment

The initial set 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" [7].

The experts classified the risk factors using the BWM (*best-worst method*), a technique that made it possible to determine the weights of importance of the categories and risk factors [20]. The results showed that the most important risk factor was the high capital investment for hydrogen production and delivery technology [7]. This was followed by the lack of sufficient capacity for electrolyzers and the development of policies and regulations.

Regarding the categorization of risk factors, experts were also asked to provide their input. For instance, government incentives could be classified under both economic and policy/regulation categories, according to previous studies on supply chain risk management [21]. However, based on expert opinions, these factors were retained under the policy and regulation category.

One potential risk factor to consider is hydrogen leakage. Hydrogen leaks can pose a safety hazard, as hydrogen is highly flammable and can ignite or explode when exposed to air or other oxidizers [22]. However, the likelihood of hydrogen leakage varies depending on specific circumstances and the measures taken to prevent and mitigate such leaks. A key risk related to hydrogen leakage is the potential for fire or explosion if hydrogen mixes with air and comes into contact with an ignition source.

Another risk associated with hydrogen leakage is its ability to displace oxygen in confined spaces, which could lead to asphyxiation [23]. This risk can be managed by ensuring proper ventilation and monitoring hydrogen levels in such spaces. Additionally, hydrogen leakage could contribute to greenhouse gas emissions if it escapes into the atmosphere. As hydrogen is a very light gas, it can escape more easily from containers and pipelines compared to other gases, like natural gas [24]. To minimize this risk, it is crucial to implement appropriate measures to prevent leaks. Managing the risks related to hydrogen leakage requires proper safety protocols.

Once the risk factors are identified and quantified, it is necessary to develop suitable mitigation strategies to minimize the negative impacts of risks in the green hydrogen supply chain, particularly for those risks with higher weights [25]. To develop these mitigation strategies, relevant studies were reviewed, including publications on hydrogen production, risk management, and policy papers. Furthermore, experts were consulted to assist in the development and validation of these mitigation strategies [7].

2.3. Risk Analysis in Ports and Practical Applications

Then, in the business, operational, and organizational environment of ports, there has been a growing concern about the threats posed by ports and maritime terminals to people, assets, and the environment, as a result of the operations and management of these ports and terminals. Research shows that almost all major accidents and losses in terms of delays and costs could be avoided with effective Risk Management (RM) programs [26].

Risk analysis that focuses on seaports and offshore terminals [26], analyses emerging issues related to GR in recent times, taking into account internal and external elements, such as pure risks (i.e., the uncertainty of property damage from fire, flood, or the possibility of premature death caused by accidents), and speculative risks (i.e., risks directly linked to the business function, decision-making processes, and management). A security risk assessment and management framework has also been developed that is able to reflect the logistical scope of transport networks. The focus was on the development, management, commercial, operational and, organizational issues of ports and terminals [27].

In ports, risk analysis involves developing a general risk estimate by collecting and integrating information on scenarios, frequencies, and consequences. It is one of the main components of the entire GR process of any particular company [28].

A proposed GR framework was used, and a generic risk analysis model was developed to assess and prioritize risk factors in the operations and management of ports and maritime terminals (*Port and offshore Terminals Operations and Management or PTOM*). The proposed framework consists of the following three main phases: threat identification, risk assessment, and risk mitigation [26].

Operational risk factors associated with ports and terminals *offshore* are identified in previous work, and the previously evaluated and classified operational risk factors are provided along with their relative (global) weights used to demonstrate the most significant risk factors within the PTOM. Operational risk factors were previously identified through the Hazard Identification Process (HAZID), which is one of the techniques for hazard identification. The previously identified operational risk factors of the PTOM have been prioritized and classified using the Fuzzy Hierarchical Analytical Process (FAHP) method [26].

For the risk analysis, the cause–consequence diagram method has been used [29]. Once a critical event has been identified, all the relevant causes of the event and its possible consequences are developed using two conventional methods of reliability analysis, i.e., FTA (Fault Tree Analysis) and ETA (Event Tree Analysis). FTA is used to describe the causes of an unwanted event. The ETA shows the consequences that a critical event can have on one or more protection systems that do not work as designed [26].

With the use of CCA (Cause-Consequence Analysis) and Fuzzy Set Theory (*Fuzzy Set Theory*), the probability of failure of a major event is estimated and also the consequences of the basic events for operational risk factors [30]. The selected risk factor is evaluated and analyzed through a case study. This will help to examine the risk analysis tool introduced. The article uses Fuzzy Set Theory, expert judgments, the conversion of linguistic terms into fuzzy numbers, and defuzzification processes (*Defuzzification*) to obtain the probabilities of the basic events, as well as the probability of occurrence of the superior event [31].

The theory of fuzzy sets for port operations has also been used in risk assessment. This is because much of the data in the system is uncertain and ambiguous. So a flexible and robust approach is needed to handle quantitative and qualitative data [32].

Also, the existing literature on similar processes has been reviewed, such as risk analysis of facilities and fuel supply operations in ports. For example, a study by the Universitat Politècnica de València carries out a risk analysis of a fuel supply facility for ships in the port of Valencia [33]. It proposes a methodology, analyzes the influence of a supply facility on the population, buildings and environment, and proposes preventive and corrective measures.

First, it was decided to use the SWIFT that was developed as a simpler alternative to the risk and operability study (HAZOP). This qualitative technique is used in the identification of possible risks, raising questions with all possible deviations from the normal operation of an installation. This first method is complemented by the use of Fuzzy Set Theory, which allows each risk identified in the SWIFT to be classified numerically, relating linguistic terms to fuzzy numbers [33].

However, the study assesses all possible operations within the supply of fuel to ships, while the work that is intended to be performed with this project refers to a more general phase, since green hydrogen is an immature technology that must be analyzed from a global point of view.

On the other hand, the SWIFT is a flexible, high-level risk identification technique that can be used independently or as part of a staged approach. In this way, it has been used for the identification of risks in this article, related to the management of port risks in container terminals [34].

In addition, to identify risks, the "what if" analysis or the structured "what if" technique (SWIFT) is a very adaptable tool for identifying risks. It starts with the collection of potential hazards and also uses a checklist that contains typical errors and failures that could also constitute hazards. The hazards are then organized into a worksheet and added to the column titled "What-if", eliciting their potential causes and effects, as well as the presentation of mitigation measures and recommendations, similar to HAZID and HAZOP [35].

On the other hand, the experience of important people in the field of energy has also been considered. In this case, there are very different and conflicting opinions. A historical review of energy in the world and hydrogen shows that the concept of using hydrogen as a fuel has always been very attractive and dates back to 1923. This idea was revived during the oil crisis during the 1970s. Finally, the idea of fighting climate change has brought it back and during all those years substantial amounts of money have been invested with the same result. It is a highly inefficient and very uneconomical method [23].

So why is there this current policy of pushing this technology? The first thing is that politically it is very interesting. It is a very powerful message to say that the future of energy is a fuel that only produces heat and water, and that everyone can have it, ending the wars for oil and energy poverty [23].

The methodologies described in this study have been successfully applied in various fields to assess and mitigate risks. For instance, in the mining sector, a risk analysis was conducted to evaluate the safety of green hydrogen implementation in open-pit mining. Techniques such as SWIFT, FTA, WRAC, and HCRA were employed to systematically identify and assess potential hazards, leading to the development of safety protocols for hydrogen-based operations. Similarly, in civil engineering, Fuzzy Set Theory has been used to assess the seismic vulnerability of bridges, addressing uncertainties in structural integrity and seismological parameters. This approach enabled a more precise evaluation of risks and facilitated decision making in infrastructure resilience [36,37].

Additionally, the Delphi method has been widely utilized in security risk management, particularly in studies focused on terrorist attack prevention. This methodology has allowed experts to reach a consensus on identifying and prioritizing security risks, leading to the formulation of effective mitigation strategies. These examples demonstrate the versatility and reliability of risk assessment methodologies, reinforcing their applicability in analyzing the risks associated with green hydrogen implementation in port environments [38].

3. Methodology

To carry out the risk analysis on the implementation and operation of green hydrogen and its derivatives in the port area, a structured methodology is followed that combines several recognized techniques in risk management with the aim of understanding the nature of the risk and determining the level of risk. Providing the basis for risk assessment and decisions regarding risk treatment.

To this end, the regulations described and the bibliography that exists in this area have been consulted. After this, it is decided that the SWIFT method will be used as the general basis of the risk analysis for this project. According to Table A.1 of the UNE-EN 31010 standard [39]. It is proven that it is a very applicable tool for this task.

The SWIFT (Structured What-If Technique) method aims to carry out the risk analysis as a whole, from the identification of threats to the assessment of impacts, the probability of occurrence, the risk factor, and its subsequent analysis.

The system is carefully defined before the study can begin. Normally, the system under study is divided into nodules or key elements to facilitate the analysis process, but this rarely occurs at the level of definition required by HAZOP. In this case, it is divided into different areas: "economic", "processes in the supply chain and governance", "technology and infrastructure", "environmental or by nature itself", "market", "social", and "policies, regulations and geopolitics".

Another important input is the technical knowledge and experience of the carefully selected study task force. The group for this project is made up of 20 experts in different fields, such as port management, energy, business administration, and risk analysis. The number of 20 experts is considered adequate for this methodology.

The general process is as follows [39]:

(a) Before beginning the study, the coordinator prepares a list of words or phrases of indication that can be based on a standardized set or can be created to allow for a complete review of threats or risks;
(b) In the working meeting, the external and internal context of the system and the field of application of the study are discussed and agreed;
(c) The coordinator asks questions to the participants to provoke and discuss known risks and dangers; previous experiences and incidents; known and existing controls and protections; regulatory requirements and restrictions;
(d) Debate is encouraged by asking a question that uses the phrase "what if...?" and a word or point of indication. The phrases "what if...?" are "what if...?", "what if...?", "could something or someone...?", "does someone or something about...?". The aim is to encourage the study group to explore possible scenarios, as well as their causes, consequences, impacts and probabilities of occurrence;
(e) A summary of the risks is made, along with their causes, consequences, impacts, and probabilities of occurrence;
(f) The work team confirms and records the description of the risk, its causes, consequences, etc;
(g) The task force considers risk management measures and defines possible measures;
(h) During this discussion, additional questions such as "what if...?" are asked to identify other risks, if any;
(i) The coordinator uses the list of prompts to monitor the discussion and to suggest additional issues and scenarios for the working group to discuss;
(j) It is normal to apply a qualitative or semi-quantitative method of risk assessment to classify the actions created in terms of priority. In this case, fuzzy numbers are used.

The process used in phases is described in detail below.

This comprehensive methodology (Figure 1) combines qualitative and quantitative approaches to ensure a thorough identification of threats and an adequate assessment of their impacts and probabilities, as well as risk factors, providing a basis for risk management in the deployment of green hydrogen in the port area.

Phase 1. Threat identification.

Phase 1.a. Bibliographic Review.

Objective: to collect existing information on risks and threats associated with the production and use of green hydrogen.

Process: a thorough review of academic literature, technical reports, case studies, and regulations related to green hydrogen and its supply chain is conducted.

Results: preliminary identification of potential threats based on previous experiences and studies.

Phase 1.b. Brainstorming.

Objective: to generate a broad and exhaustive list of possible threats.

Process: a brainstorming session is organized with a multidisciplinary team composed of experts in energy, port management, risk analysis, and other relevant fields such as business administration.

Results: Expansion of the list of threats with novel and specific ideas for the port context.

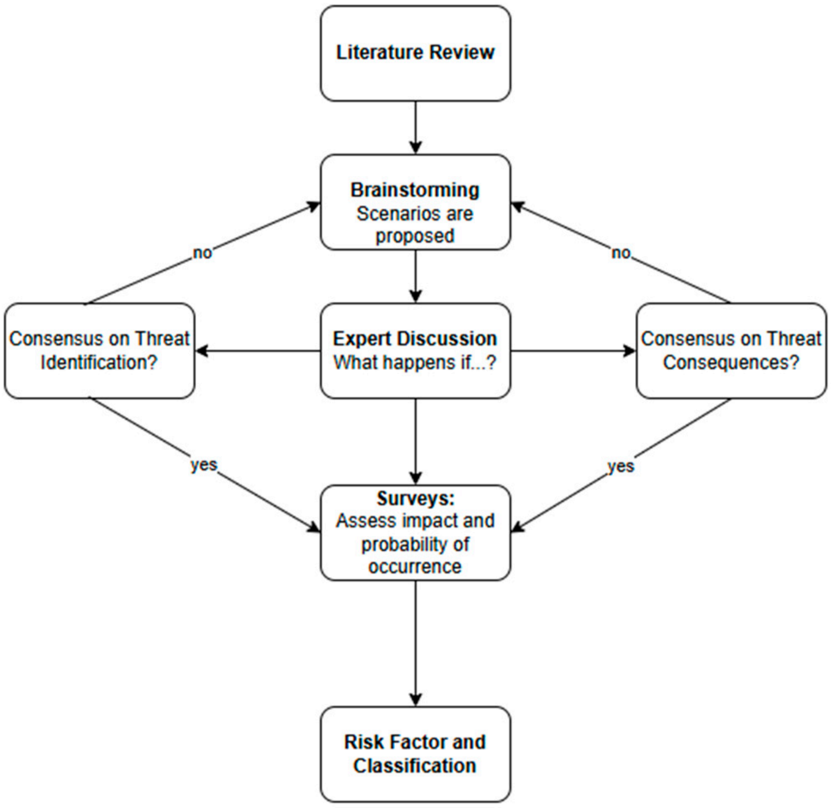

Figure 1. Methodology used, phases, and blocks. Source: own elaboration.

Phase 1.c. Expert consensus.

Objective: to refine and validate the list of identified threats, leveraging the knowledge and experience of experts.

Process: rounds of consultations are held with a panel of experts, gathering their opinions and reaching consensus on relevant threats.

Results: a consensus list of threats, validated by experts from the sectors involved.

Phase 2. Risk assessment.

Phase 2.a. Surveys of experts by rounds.

Objective: to reach a consensus on the consequences, impacts, and probabilities of occurrence of the identified threats.

Process: the feasible causes of each threat are debated through questions such as "what if...?" until a consensus is reached and then, through multi-round surveys, a consensus is reached on the impacts and probabilities of occurrence of the risks.

Results: a list of consequences, impacts and probabilities of occurrence.

Phase 2.b. Theory of Fuzzy Numbers.

Objective: to quantitatively quantify the impacts and probabilities of occurrence associated with hazards and to obtain an accurate assessment of risk factors.

Process: Fuzzy number theory is used to handle the uncertainty inherent in estimating impacts and probabilities. Qualitative results are assigned fuzzy values, i.e., the probabilities and consequences of the risks, allowing a quantitative and interpretable assessment. Then, knowing that the risk factor is calculated as the product of the impact and the probability of risk [26]:

$$FR = IR \times PR \quad (1)$$

where

FR = Risk factor

RI = Impact of risk/threat

PR = Probability of occurrence of the risk/threat

To perform this operation in the diffuse environment, it is performed as follows:

$$D1 \otimes D2 = (l1, m1, u1) \otimes (l2, m2, u2) = (l1 \times l2, m1 \times m2, u1 \times u2) \quad (2)$$

where

$\underline{D1}$ = A fuzzy number, where it represents IR

$\underline{D2}$ = A fuzzy number, where it represents PR

l, m, and u indicate the members of fuzzy numbers

After obtaining the risk factors as fuzzy numbers, they undergo the process known as defuzzification, in this case of triangular fuzzy numbers, obtaining the center of gravity:

$$FR = (l + m + u)/3 \quad (3)$$

In this way, the risk factors are obtained with real numbers, in order to classify them.

Results: calculated risk factors that numerically reflect risk and risk, providing a solid basis for decision making.

Phase 3. Risk classification.

Objective: to prioritize risks based on results.

Process: a classification is assigned based on the numerical values of the risk factors. The highest risk factors will be classified into higher categories than those with results closer to zero.

Results: a list of risks according to their relevance. Classified according to whether or not they are assumable for the subsequent proposal of risk mitigation measures.

4. Results and Discussion

The identification and classification of risks associated with the implementation of green hydrogen in Spanish ports follow a structured methodology to ensure a precise assessment of potential threats. The classification of risks is based on two key parameters: impact severity and probability of occurrence. The combination of these factors results in a risk factor, which is then categorized into different risk classes.

For this study, a fuzzy logic approach was applied to manage the inherent uncertainty in risk assessment. By converting qualitative assessments into numerical values, the methodology enables a more objective risk categorization. The risk classification is divided into four levels:

- Class I (negligible)—risks with very low probability and impact, requiring minimal intervention;
- Class II (acceptable)—risks that pose a moderate impact but do not significantly disrupt port operations or hydrogen adoption strategies;
- Class III (not acceptable)—risks that demand active mitigation measures due to their potential to impact economic viability, infrastructure, or safety;
- Class IV (intolerable)—risks that pose severe consequences and require immediate mitigation strategies to ensure project feasibility and operational safety.

The classification process was conducted through Delphi-based expert consultations and the application of the SWIFT methodology (Structured What-If Technique). A multidisciplinary team of experts was involved in evaluating the risks, ensuring a comprehensive perspective that includes technical, economic, regulatory, and environmental considerations.

Particular attention was given to risks related to financial viability, water resource constraints, and high capital investments, which emerged as the most critical factors influencing the feasibility of green hydrogen projects in ports. Furthermore, the study analyzed technological, regulatory, and social acceptance challenges, which, while less critical than economic risks, still pose significant barriers to widespread adoption.

The following Table 1 presents the categorized risks, ranked by their respective risk factors, providing a structured overview for decision makers and policymakers to develop targeted mitigation strategies. The numbering in the first column does not indicate risk ranking but corresponds to the identification code assigned during the risk analysis process. This numbering is used for traceability purposes, ensuring consistency with the initial list of threats evaluated by experts. Risks are classified based on their calculated risk factor rather than sequential order.

Table 1. List of risks. Source: own elaboration.

Threat		Risk Factor	Risk Classification	Priority
Number	**Name**			
5	Financial viability and long-term profitability	0.71	IV	1
26	Water scarcity	0.71	IV	1
1	High capital investment for green hydrogen production and delivery technology compared to other energy sources	0.60	III	2
20	Substitute product	0.60	III	2
27	Fertilizer manufacturing	0.60	III	2
30	Lack of international support	0.60	III	2
2	Fluctuation in unit costs of electricity	0.48	III	3
10	Lack of sufficient capacity for electrolyzers, H2 storage, transportation, delivery, and conversion	0.48	III	3
3	High operating and maintenance costs	0.42	III	4
8	Supplier failure	0.42	III	4
11	Integration of renewable energies	0.42	III	4
22	Qualified human resources	0.42	III	4
23	Consumer acceptance of H2	0.42	III	4
28	Government incentives, policy development and regulations	0.42	III	4
7	Grid intermittency	0.29	II	5
12	Rapid technological development and uncertainty in H2 production	0.29	II	5
18	Climate change and availability of renewable energy sources	0.29	II	5
4	Changes in the economy	0.23	II	6
14	Infrastructure failures	0.23	II	6
19	Fluctuating demand	0.23	II	6
21	Clients' bargaining power	0.23	II	6
29	Political instability	0.23	II	6
6	Improper location of facilities	0.17	II	7
13	Information and communication technology	0.17	II	7
15	Inability to implement clean technology	0.17	II	7
17	Soil, water and air pollution	0.17	II	7
24	Health and safety	0.17	II	7
31	Terrorism and war	0.06	I	8
9	Collaboration and transparency	0.04	I	9
16	Natural disasters and disease outbreaks	0.04	I	9
25	Labor strike	0.04	I	9

A total of 31 threats have been identified and have been categorized into four classes according to their associated risk factor: "negligible" (I), "acceptable" (II), "not acceptable" (III) and "intolerable" (IV).

In turn, after classifying, nine different groups are observed, within these classes, depending on the risk factor found.

1. In the first group and with the highest risk factor, there are "5. Financial viability and long-term profitability" and "26. Water scarcity." Both as class IV.
2. In the second place, "1. High Capital Investment", "20. Substitute product", "27. Manufacture of fertilizers", and "30. Lack of international support." Classified in class III.
3. In third place, there are "2. Fluctuation in unit costs of electricity" and "10. Lack of sufficient capacity." Classified in class III.
4. Then, "3. High operating and maintenance costs", "8. Failure of suppliers", "11. Integration of renewable energies", "22. Qualified human resources", "23. Acceptance of H2 by consumers", and "28. Government incentives, policy development and regulations". Classified in class III.
5. Then, "7. Intermittency of the electrical network", "12. Rapid technological development", and "18. Climate change". Classified in class II.
6. In sixth place, "4. Changes in the economy", "14. Failures in infrastructure", "19. Fluctuating demand", "21. Bargaining power of customers", and "29. Political instability." Classified in class II.
7. Subsequently, "6. Inadequate location of facilities", "13. Information and Communication Technology", "15. Inability to implement clean technology", "17. Soil, water and air pollution", and "24. Safety and health". Closing category II.
8. Then, we have "31. Terrorism and war". Classified in class I.
9. Finally, "9. Collaboration and transparency", "16. Natural disasters and disease outbreaks", and "25. Labor strike" are the remaining risks that close category I.

In addition, it can be noted that there are similarities with the results of the risk analysis of the green hydrogen supply chain consulted as a bibliography [7], since, among the risks with a higher weighting are those related to high investment, lack of electrolysers, high operation and maintenance costs, policies and regulations, supplier failure, hydrogen acceptance, etc. While those with the least risk are related to collaboration and transparency, terrorism and war, clean technology, labor strikes, fluctuating demand, etc.

In addition, this section sets out the mitigation measures proposed in this article, which are drafted in order of importance by risk factor:

- "5. Financial viability and long-term profitability": class IV. Hydrogen, and green hydrogen in particular, is not profitable mainly due to market demand and high production costs. Currently, the energy market is very well established, although it has changed in recent years. Renewable energies have been introduced into the electricity mix, which has been seen to increase the price of renewable energies. Electric cars have also been introduced, although they are in the minority. In the case of hydrogen, what is wanted to be achieved is a change in the energy paradigm with the combination of it and renewable energies [40]. That requires changes at a global level in an infrastructure that is difficult to change. However, improvements in renewable energy production technologies and electrolysis are expected in the future. On the other hand, grid-connected electrolyzers may be subject to taxes and fees, which make up a considerable proportion of the final price of electricity, resulting in a much higher operating cost that is added to the final cost of green hydrogen. However, there are already countries, such as Germany, that are proposing to exempt electrolyzers from all taxes and fees, such as the electricity tax and the surcharge for renewable energies, allowing hydrogen to be produced at a considerably lower cost [25]. Other feasible measures are to study the location of renewable sources for optimal efficiency, to promote technological progress with public–private investments and to establish a clear and favorable regulatory framework for these technologies.

- "26. Water scarcity": class IV. In a country like Spain, which is vulnerable to droughts, competition for water resources between different sectors, such as agriculture, industry, and human consumption, would intensify. In this case, water would have many priorities before being used in hydrogen production. However, in a production system close to the port and the sea, desalinated seawater can be used as long as the appropriate procedures are used to treat it and as long as the energy used is renewable, since, if it is not performed in this way, it would no longer be considered green hydrogen. Another recommendation is to implement the technology in places where it is known that there are sufficient resources for its production.
- "1. High capital investment": class III. It is a reality that the infrastructure to produce, store, and transport hydrogen has a high cost as has been seen in this project. However, the European Union's plans and projects will develop viable projects for investment, fostering cooperation between public and private actors, and providing public support to attract greater investments. Regulations, plans, and policies that are drafted and put in place in favor of this technology will be an opportunity to mitigate this risk [7].
- "20. Substitute product": class III. Nowadays, there is great energy competition, being a market that is mainly governed from an economic point of view, although there are also social and environmental implications. To mitigate this risk, green hydrogen must be mainly socially profitable, i.e., it must be economical and beneficial to society [23]. This requires advances in technology to lower costs and make it more efficient, requiring investments in research and development. Also, through policies, green hydrogen can be favored, reducing the taxes applied to it and promoting its development with investments.
- "27. Manufacture of fertilizers": class III. In a world with a growing population, if the demand for hydrogen for fertilizer production increases significantly, there could be pressures to use less expensive hydrogen production methods [23]. However, an opportunity also arises for green hydrogen if the localization of renewable energies (wind, photovoltaic, etc.) is propitious, and it can become a cheaper option than other types of hydrogen. This would also be favored, as mentioned above, through policies that favor green hydrogen, reducing the taxes applied to it and promoting its development with investments.
- "30. Lack of international support": class III. We live in a world where Europe is the region of greatest climate concern and, therefore, in developing this type of "clean" technologies. However, the global market is governed by what is most economically profitable and there is little European policies can do to influence the global market. However, it is the lowering of production costs that can make this technology be placed on the market so that it can be developed globally, favoring technological progress and cost reduction. This will be achieved with technological advances in renewable energy, electrolysers, etc. Therefore, a good measure is to support research into new materials and production systems.
- "2. Fluctuation in unit costs of electricity": class III. Electricity costs directly influence the price of green hydrogen. To mitigate this risk, isolated gas production systems can be created using renewable energy systems connected directly to electrolysers. In this way, the price will not depend on the price of energy in the country but will depend on the good choice and study of a project of this technology.

- "10. Lack of sufficient capacity of electrolyzers, etc.": class III. The reality is that there is still a long way to go technologically for the necessary components in the green hydrogen supply chain to be massively manufactured. This requires a demand for green hydrogen that does not yet exist. Therefore, new projects will have delays due to this lack of supply in terms of electrolyzers, technologies to store them, fuel cells, etc. Public policies and investments, along with technological advancement, are the ways forward to mitigate this risk.
- "3. High operating and maintenance costs": class III. The processes involved in the production of green hydrogen are labor-intensive, contributing to high operating and maintenance costs [25]. In addition, governments and policymakers can allocate more budget in order to mitigate this risk.
- "8. Failure of suppliers": class III. This risk is associated with the halt of the production chain due to lack of components or the slowness of new projects. That is why policymakers must ensure support for the expansion of electrolyzer manufacturing in the private sector. Therefore, a robust supplier selection process could be implemented to choose and manage a few qualified suppliers for critical materials and components [41].
- "11. Integration of renewable energies": class III. This risk relates to the various design aspects required to integrate any renewable energy source into the existing energy grid. There is a risk associated with the integration of electrolyzers and the electricity grid, as this connection could consume renewable energy at the expense of other electricity uses due to increased demand. When there is excessive demand, it is normally covered by a marginal plant, which is often fossil fuel plants [42]. On the other hand, the integration of this technology into the global energy system will depend on the positive advances that are progressively made, so research and development must first be advanced at this early stage of the technology.
- "22. Qualified human resources": class III. As mentioned, the processes involved in the production of green hydrogen are labor intensive [25]. As it is an immature technology, we find ourselves with the problem that there are no qualified personnel. However, to mitigate this fact, the training of personnel in the projects financed by the European Union or in which they participate in some way must be encouraged, since, by doing so jointly with private companies, it will favor feedback in all projects carried out in the European community, improving training and lowering training costs.
- "23. Acceptance of H2 by consumers": class III. As mentioned, hydrogen is a very volatile and explosive gas. In addition, compared to other conventional and renewable fuels, green hydrogen may not be as competitive in price. This implies a possible reluctance of customers to adopt it [7]. The EU's strategy to increase demand for green hydrogen also includes incentives and allocations for the use of green hydrogen in certain sectors [43].
- "28. Government incentives, policy development and regulations": class III. The risk of inadequate development of incentives, policies, and regulations could hinder the development of the green hydrogen supply chain. To mitigate this risk, various market mechanisms could be used, such as carbon tax systems and contracts for carbon differences [43]. Taxing gray or blue hydrogen will help make green hydrogen cost-competitive. Developing policies that offer fees for producing green hydrogen instead of gray hydrogen could also reduce the cost gap. Equivalently, offering aid with public–private investment in green hydrogen projects is an attractive policy [7].
- "7. Intermittency of the electricity grid": class II. Acceptable. It is an intrinsic problem of renewable energies, very difficult to change. As we have seen, electrolyzers that work well with this intermittency are being investigated.

- “12. Rapid technological development”: class II. Acceptable. While it may be difficult to keep pace with technological development economically for existing green hydrogen facilities, new developments also present an opportunity for this technology and for new investments.
- “18. Climate change”: class II. Acceptable. There is a lot of uncertainty about whether or not this risk will be unfavorable. However, a good study of the locations of renewable sources, taking into account the possible causes of climate change, is a good measure to mitigate this risk.
- “4. Changes in the economy”: class II. Acceptable. The economy is subject to continuous change by its very nature, affecting different sectors. It may also be an opportunity for green hydrogen if something similar to the oil crisis in the 1970s were to happen.
- “14. Infrastructure failures”: class II. Acceptable. Standardized safety controls must be in place both in parts factories and in production, storage, and transportation companies. Thus, ensuring proper operation.
- “19. Fluctuating demand”: class II. Acceptable. To reduce the risk associated with demand, green hydrogen must be an attractive market. To do this, it is sought to be as profitable as possible using the measures seen above.
- “21. Bargaining power of customers”: class II. Acceptable. The greater the supply of green hydrogen, the more negotiating power customers will have, being able to opt for cheaper options. However, this competition favors technological advances.
- “29. Political instability”: class II. Acceptable. It is an intrinsic problem of society and politics. It is difficult to mitigate, as ports and projects are subject to political changes. However, the European Union is a region with a certain stability.
- “6. Inadequate location of facilities”: class II. Acceptable. This is mitigated with a good prior study of the project related to this technology and the port.
- “13. Information and communication technology”: class II. Acceptable. You need to ensure that there are no failures by employing conventional security methods in industries, such as proper anti-malware, and having qualified personnel with the right tools.
- “15. Inability to implement clean technology”: class II. Acceptable. If any of the parties is unable to use clean technology, another supplier must be negotiated or found that does have that capacity.
- “17. Soil, water and air pollution”: class II. Acceptable. As we have seen, it is a much less polluting technology than other conventional energy technologies. It would be mitigated if the appropriate safety protocols are applied to prevent leaks, etc.
- “24. Health and safety”: class II. Acceptable. The production of green hydrogen involves several risk factors for workers. In addition, transporting green hydrogen is dangerous for the general population, as it is explosive and corrosive. However, the high levels of manual labor currently required to produce green hydrogen are expected to reduce over time, as rapid technological advances are made, too, the modernization of gas pipelines and other necessary infrastructure should ensure that these methods are suitable and do not pose a danger to the population in any given area [7].“31. Terrorism and war”: class I. Despicable. Although the impact could be very severe, the probability of occurrence has been considered very low. However, conventional security measures in strategic facilities such as energy or water resources could prevent terrorist attacks or vandalism.
- “9. Collaboration and transparency”: class I. Despicable. If any of the parties is unable to cooperate or places certain impediments, another supplier must be negotiated or found that does have that capacity.

- "16. Natural disasters and disease outbreaks": class I. Despicable. Although the impact may be very high, the probability of occurrence is very low.
- "25. Labor strike": class I. Despicable. Maintaining good working conditions is an appropriate measure to avoid this problem.

5. Conclusions

The first thing to highlight is that the proposed methodology, following the methods presented and based on the bibliography analyzed, is very suitable for the risk analysis carried out in this project. It combines several recognized techniques in risk management using the SWIFT method as the general basis of analysis. This qualitative technique is combined with fuzzy number theory to find quantitative values and account for the level of risk. In addition, according to Table A.1 of the UNE-EN 31010 standard [39] it is found to be a very applicable tool for this task.

On the other hand, thanks to this methodology, risks have been discovered that were not considered in the literature analyses and that should be considered in future risk analyses in this area. An example of this is the case of "26. Water scarcity", which was categorized in class IV or "intolerable". In this case, it has a high risk, since Spain is very vulnerable to this threat and is already being affected. This would intensify competition for water resources between different sectors, such as agriculture, industry, and human consumption. In this way, the production of green hydrogen could face challenges in ensuring an adequate supply of water in the face of other priority demands, which could affect its economic and operational viability. This could lead to increased production costs for green hydrogen, as companies may have to invest in more expensive technologies and processes to treat and conserve available water. This would include implementing water recycling systems, desalination, or other water management solutions. It must be considered that it is already an expensive technology compared to other energy sources. In addition, the production of green hydrogen is promoted as a clean and sustainable alternative to fossil fuels, but water scarcity could raise concerns about the water footprint and the availability of natural resources needed for its production.

It is also the case of "27. Manufacture of fertilizers", categorized in class III or "not acceptable". As has been seen, in a world with a growing population, if the demand for hydrogen for fertilizer production increases significantly, there could be pressures to use less expensive, but more polluting hydrogen production methods, such as natural gas reforming, instead of electrolysis with renewable energy. Social pressure may arise to lower the costs of such an essential resource as food, in addition to the choice of investors in other cheaper hydrogen production technologies.

This highlights on the one hand the usefulness and adequacy of the selected methodology, while also observing the importance of this project, analyzing the risks of green hydrogen in a broad environment that not involves society, workers, economy, and the environment in the local context of a port but also in the surroundings of the country. The ports being strategic points for the economy and society of Spain.

Based on the results, it is observed that the most important risk factors are "long-term financial viability and profitability" and "water scarcity", since, with public investments that allow the implementation of this technology, there is still a risk that it will not be profitable in the long term, being catastrophic for a society that has had to invest large amounts of money in this system. In addition, water scarcity added to the use of a basic resource for people in energy would negatively affect society, both by limiting water resources and economically or energetically if hydrogen production is stopped in a system where it is an essential part of the energy paradigm and where a lot of public money has been invested.

Therefore, this project serves not only ports, their economy, their environment, and the society directly affected by it, but is also useful to have a global vision of the risks that the new green hydrogen technology brings to a country like Spain and the European Union, through the port system. In addition, this project has added value of the measures proposed to mitigate these risks.

To conclude, as a foresight, it should be noted that there is still a long way to go for green hydrogen technology to be economically profitable, being limited to physical and chemical laws that are immovable. However, technological advances are being made in materials and infrastructure that will lower production costs.

On the other hand, it is difficult to predict whether the entire energy system will change towards a paradigm where renewable energies reign supreme, together with hydrogen as a vector for this energy to store and transport it. We are at a point of great uncertainty where technologies change rapidly. What is certain is that the risks analyses for the implementation and operation of green hydrogen and its derivatives in the Spanish port system must be considered.

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