El Cezeri
Journal of Science and Engineering
ISSN: 2148-3736

Review Paper

Hybrid Offshore Wind and Hydrogen Energy Risk Analysis

Ayşe Nuray Canat[1a], Coşkun Özkan[2b]

[1]Industrial Engineering Department, Faculty of Engineering and Natural Sciences, Istanbul Sabahattin Zaim University, Istanbul, Türkiye
[2]Industrial Engineering Department, Faculty of Mechanical Engineering, Yildiz Technical University, Istanbul, Türkiye

ayse.canat@izu.edu.tr

DOI : 10.31202/ecjse.1420397
Received: 15.01.2024 Accepted: 01.09.2024
How to cite this article:
Ayşe Nuray Canat, Coşkun Özkan, "Hybrid Offshore Wind and Hydrogen Energy Risk Analysis", El-Cezeri Journal of Science and Engineering, Vol: 12, Iss: 2, (2025), pp.(xx-xx).
ORCID: [a]0000-0002-8527-550X; [b]0000-0002-0318-8614.

Abstract : The importance of clean energy is gradually increasing for the depletion of fossil fuels, preventing global warming, and livable and sustainable life. The renewable energies used to achieve this are very diverse. Wind energy and hydrogen energy, which are among these sources, are the subject of this study. In wind energy, it is possible to produce higher power energy by installing wind turbines on the sea, due to the stronger and uninterrupted wind blowing in the seas. There is no continuity of wind energy, it is important to store renewable energy to ensure the continuity of the energy to be supplied to the grid and to create the electricity supply and demand balance. In this study, hydrogen storage energy was preferred in terms of having different usage areas and not harming the environment during energy storage. There are various hazards and associated risks during the installation, transportation, production, and storage of energy production facilities. These risks need to be identified, analyzed, and prevented. In this study, the risks that may be encountered in the offshore wind and hydrogen hybrid power generation and storage facility will be analyzed through a literature review, and evaluations for prevention will be made.

Keywords: Offshore wind energy, hydrogen storage, risk assessment, hazard, hybrid energy.

1. Introduction

The world is facing problems such as global warming, depletion of fossil resources and energy shortages. The Paris Lesson was signed in 2015 to put a stop to this wrong course, to use resources efficiently and to produce environmentally friendly green energy. According to this agreement, taking the necessary measures against the negative effects of climate change will be possible with the right investments in the energy of the countries themselves. To achieve this, countries have given importance to investing in renewable energy sources. With a rapidly increasing momentum, the production of electrical energy is tried to be provided with these resources. One of the sources used for this is offshore wind energy. The fact that the wind blows more strongly in the seas and that there is no obstacle to block the wind, and its continuity has increased the orientation to offshore wind energy. In addition, there is a tendency towards offshore wind farms, since the large turbine to be located does not cause any visual problems and can produce higher energy. However, energy from nature is not continuous and this can lead to problems in meeting energy demand. For this, it is important to provide energy storage in renewable energy sources. In this way, stored energy can be utilized during periods of high energy demand. Energy storage technologies are a field that has been studied extensively in recent years. It has been pointed out in the literature that energy storage technology plays an important role in line congestion management, ensuring power quality, increasing power supply reliability, and absorbing highly renewable energy. [1] Among these technologies, hydrogen energy is preferred because it is both green and has many usage areas in the following years. Comparative studies among energy storage technologies have shown that hydrogen storage energies will play a leading role for future decarbonization targets, while being economically comparable [2]–[4]. The analysis of hydrogen storage and transportation for various forms of hydrogen (compressed hydrogen gas, liquid hydrogen, pipeline hydrogen, liquid organic hydrogen carriers) shows that hydrogen storage and transportation is economical [5]. Hydrogen energy can be obtained in many ways, but electrolysis is the easiest method. There are many reasons why hydrogen is preferred. The first of these is that it can be integrated with renewable energy. Renewable energy sources are utilized for the electrolysis process in the production of green hydrogen. There are many articles in the literature on hydrogen production from renewable energy sources such as solar [6]–[11], geothermal [12]–

[14], biomass [15]–[17], wind [18]–[20] and wave energy [21]–[24]. Obtaining hydrogen by electrolysis alone is more expensive than fossil sources in terms of cost. With the development of technology, it is predicted that prices will be more affordable and supply will become easier [25].

In this study, offshore wind energy and hydrogen energy, among the renewable energy types, which are an important factor of the green energy society, are mentioned and evaluations are made on what the risks are in these branches and how they can be eliminated to ensure the sustainability of development. For a better understanding of the components of the hybrid energy system in this study, a graphical representation of the hybrid energy system is given in Figure 1. Even though both energy types have been produced before, studies have shown that risk assessment has not yet been made at sufficient maturity. When the literature was scanned, specific regions in the energy production part were discussed, and the whole framework was not examined. The novelty of this study is to hybridize these energies, which are two different types of energy, with each other and to analyze this hybrid energy under the headings of hazard, risk, and risk assessment.

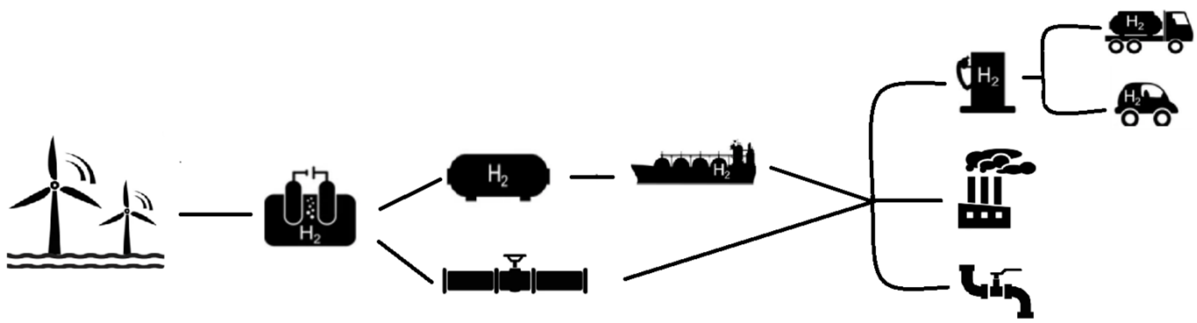

Figure 1. Graphical representation of a hybrid energy system

2. Research Methods

Searches were made with the keyword phrases "offshore wind energy, risk assessment, hazard, risk analysis, risk evaluation, hydrogen energy, energy storage" in article search engines such as WOS (Web of Science), IEEE (Institute of Electrical and Electronics Engineers), and Scopus.

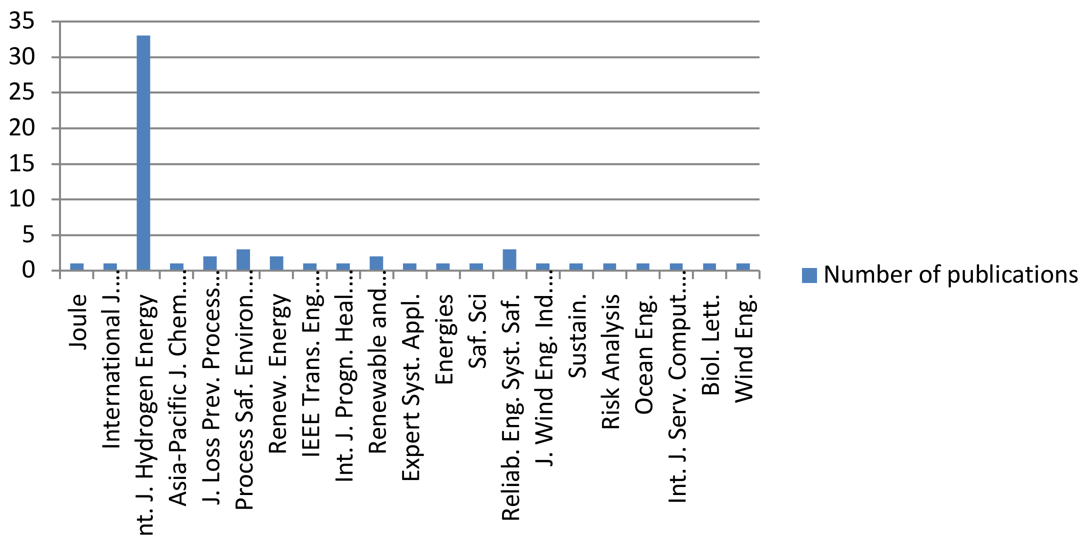

Figure 2. Name of the journals in which the articles were published and the number of articles

The studies found were evaluated from the perspective of risk analysis. As a result of the searches made in search engines, the pie chart of the journals in which the articles on the subject were published and the number of articles is shown in Figure 2.In addition, the percentage of publication of the relevant articles according to journals is shown in Figure 3. The journal in which the most articles related to the subject were published is the International Journal of Hydrogen Energy with a percentage of 55%. In addition, when the research on offshore wind energy and hydrogen energy and storage used as a hybrid was evaluated from the perspective of risk analysis, no article was found that conducted such a study. In the majority of studies on hydrogen energy, it has been observed that there are answers to the questions of what dangers can occur when hydrogen is used as a fuel and how these dangers can be eliminated. In most of the studies on this subject, the dangers of hydrogen filling stations and the precautions to be taken to eliminate these hazards are mentioned. The studies on this subject have been completed with the methods used and the explanations of these methods. Offshore wind energy is one of the topics that has been studied extensively in the literature in recent years. When this issue is narrowed down to hazards, risks and the assessment of these risks, it has been determined that there are not many studies and no detailed examination has been made. The studies carried out are on the accidents that may occur in installation and maintenance-repair and they are few.

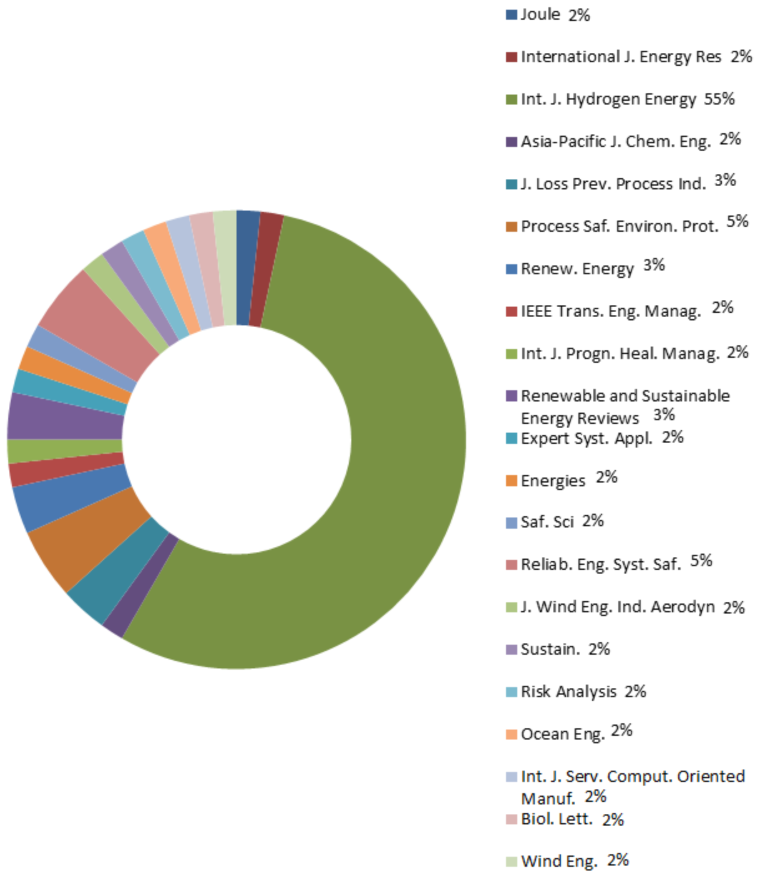

Figure 3. Percentage of related articles published according to journals

3. Risk Analysis and Assessment Studies Related to Hydrogen Energy

The increase in population, the development of technology, and the increasing energy need have increased the search for new energy sources. One of these energy sources is hydrogen energy. Hydrogen energy is seen by the International Energy Agency as one of the energy providers of the future [26]. Hydrogen is an ambitious candidate for green and clean energy when properly produced. But not only the right production method is enough, it is also necessary to ensure safety. For the production, transportation, storage, and use of hydrogen as a fuel, it is necessary to identify the hazards and ensure safety. In Najjar's study on hydrogen energy, these issues were addressed and general information was provided [27]. To achieve net zero emissions by 2050, carbon-free production of hydrogen energy must be achieved. One of the most suitable ways for this is the electrolysis way.

Although electrolysis is an old technology, it is still very new to separate water and use it for hydrogen energy production. There are studies on this, but it is still in its infancy. This is because hydrogen production from fossil sources is currently more cost-effective.

There are studies on the production of hydrogen by electrolysis, but these studies can be evaluated within the field of chemistry. There are only a few studies in which hydrogen is obtained by electrolysis and its risk analysis is done. In this study, 133 possible accident scenarios were evaluated for the system. The effectiveness of the security measures was analyzed and the risks that may arise as a result of the hazards were evaluated with risk matrixes [28]. Another study in which hydrogen production was done by electrolysis method and risk analysis was carried out by Zarei et al. [29]. In the study, uncertainties in hydrogen release scenarios in hydrogen systems are handled holistically and dynamically. The created model was applied to the electrolysis system and a clearer understanding of the accident scenarios related to uncertainty was provided. In the studies on risk analysis and evaluation in hydrogen energy, hazards in hydrogen filling facilities take the first place. Next, come studies examining the risks associated with transporting hydrogen to storage areas. Hydrogen has a lower boiling density due to its structure. In addition, the burning velocity is high with low ignition energy. It can be deflagration-to-detonation-transition. For these reasons, fires pose a great danger to hydrogen plants. It is necessary to take precautions to eliminate this danger.

There are several purposes for assessing risks. The first is to have detailed information about the activities and processes in the system under study and to systematize uncertainties. The other is to assess and identify which of these uncertainties are tolerable and which are not as a result of the analysis. Finally, it is determined what options can be designed in the face of these uncertainties and what applications can be made to reduce the risk. There are inherent uncertainties associated with most risk analysis, especially for complex systems and emerging technologies. The hazard identification process is particularly challenging for industries where there is no framework for systematic reporting of accidents and near misses. There is often insufficient data to estimate exact and current expectation values for event frequencies. Finally, there is significant uncertainty often associated with predicted outcomes. Therefore, the result depends not only on the choice of methodology, data, and tools but also on the experience and competence of the personnel involved. Due to the lack of experience in relatively new technologies and facilities such as hydrogen energy, all possible dangers should be taken into account. The consequences of these dangers should be analyzed in advance so that the necessary measures can be taken.

In technologies up to nuclear energy, risk assessment was not seen as essential for energy production, but rather the hazards were combated by trial and error. After nuclear power, risk research and assessment and making appropriate arrangements have become a priority to prevent potential accidents. Along with the changing energy sources, risk assessment methods applied to these technologies have also developed. The same is true for hydrogen energy production. For this purpose, the HIAD (Hydrogen Incident and Accident Database) was created. In this database, there is information about the accidents that occur in the supply chain from the production process of hydrogen until it reaches the end user. The purpose of keeping this information is to guide future accidents [30]. Various project frameworks were established for this study, in which academics and industry representatives specializing in hydrogen energy sought to provide a basis that would allow the removal of safety-related barriers to the application of hydrogen as an energy carrier.

In some of the studies on hydrogen safety, the hydrogen risk assessment model software toolkit called HyRAM (Hydrogen Risk Assessment Models) is mentioned. In this model, a standard methodology is established, working with relevant quantitative risk assessment and independent outcome analysis, to assess the safety of hydrogen refueling and storage infrastructure [31]. The HyRAM toolkit integrates deterministic and probabilistic models to quantify accident scenarios, predict physical effects, and characterize the impact of hydrogen hazards on people and structures. The main purpose of the paper by Skjold et al. is to demonstrate the use of three-dimensional risk management in the prototype of a hypothetical hydrogen filling station. It also addresses critical knowledge gaps in understanding flame propagation, including the transition from flash to detonation. In the study, a scenario that can be observed as a result of 672 gas emissions was created. While calculating the scenarios, the probability of occurrence was calculated by multiplying the probabilities for the frequency of occurrence, the direction of the leakage of the relevant leakage frequency, the wind condition, sudden (fire) - delayed (burning) ignition, and ignition location [32]. There are similar studies in the literature on this subject, and one of them is the article by the authors Groth and Hecht, in which the current situation and vision of Hyram is discussed. In this article, it is emphasized that certain points should be considered to improve the system. It is mentioned that various hazard scenarios for using hydrogen infrastructure should include the possibility of progressing with the latest available data, what are the characteristics of physical phenomena in hydrogen releases, what latest data are available to predict the results in ignition events that may cause, and how modeling is done. In addition, subjects such as observable physical values such as injuries and death numbers required to create systemic codes, comparison of risks and facilitating the taking of necessary precautions as a result of this, and obtaining graphics that provide convenience to the end user are emphasized [31].

In the article where HyRAM is explained in the most detailed way, it is stated that this platform was developed by Sandia National Laboratories (SNL) for the Fuel Cell Technologies Office (FCTO) of the US Department of Energy's Energy Efficiency and Renewable Energy Office (EERE). The use of a standardized platform to conduct a Hydrogen Quantitative Risk Assessment (QRA) mentions that it was created to enable various industry stakeholders to produce repeatable, verifiable results. The hydrogen gas emission and jet flame models used in the HyRAM platform were validated against the available experimental and computational data for hydrogen in the parameter range of interest for hydrogen transport systems. Probability data encoded in HyRAM was developed concerning hydrogen data. This report provides technical documentation of algorithms, models, and data included in HyRAM 1.1 [33]. One of the databases containing hydrogen events is the Hydrogen Event Reporting Database, abbreviated as HIRD. In the study, 32 hydrogen processing events selected from HIRD were analyzed to find out their root causes. As a result of the study, a checklist with statistical values about their effects, causes and consequences has been developed to avoid these events. Support for risk assessment is mainly directed towards the analysis of weak points and system optimization. Extending incident analysis and documentation to support various aspects of risk analysis is among the recommendations of this study [34].

It is undoubtedly important to benefit from databases and platforms when assessing risk for hydrogen production, which is considered to be the technology of the future. When talking about hydrogen energy, it should not be seen only as an energy source. Hydrogen is also used as a fuel in new technology vehicles. With the use of hydrogen as a fuel in vehicles, new risk situations have emerged for hydrogen. Both the hazards that may occur when hydrogen is used as a fuel and the hazards during the transportation and storage of the hydrogen to be used for fuel should be carefully analyzed and analyses should be made for the risks that will occur. There are also studies related to this. One of them is the work, which serves as a template for the implementation of a performance-based design method for an outdoor hydrogen refueling station. Performance-based design refers to the specification of a working procedure based on the Society of Fire Protection Engineers (SFPE) Engineering Guidelines for Performance-Based Fire Protection Analysis and Design of Buildings. Code-based requirements are based on the National Fire Protection Association's (NFPA) Hydrogen Technologies Code. Prescriptive requirements are followed whenever possible and used as a point of comparison with performance-based design to create a risk-equivalent design. Many prescriptive requirements in NFPA 2 are based on a quantitative risk assessment process, but requirements such as bulk liquefied hydrogen separation distances have not been updated as such. The SFPE Guidelines define a Fire Protection Engineering Design Brief that documents the early parts of the design and serves as a record of all stakeholder agreements for the methods and performance criteria to be used in evaluating trial designs [35]. Several countries are incentivizing the use of hydrogen (H_2) fuel cell vehicles, thereby increasing the number of hydrogen refueling stations (HRSs), particularly in urban areas with high population density and heavy traffic. Therefore, it is necessary to assess the risks of gaseous hydrogen refueling stations (GHRSs) and liquefied hydrogen refueling stations (LHRSs). This study aimed to perform a quantitative risk assessment (QRA) of GHRSs and LHRSs. LHRSs present lower hazard risk than GHRSs. However, both station types require additional safety barrier devices for risk reduction, such as detachable couplings, hydrogen detection sensors, and automatic and manual emergency shutdown systems, which are required for risk acceptance [36].

The lack of reliable data for on-site bulk liquid hydrogen (LH_2) storage systems at gas stations limits the use of QRAs. This hinders the ability to develop the necessary security codes and standards that enable the worldwide distribution of these stations. This study focuses on identifying relevant scenario and probability data currently available and identifying future data collection requirements regarding risks specific to liquid hydrogen releases, through QRA-based analysis of an LH_2 storage system. The developed work consists of an analysis of a general bulk LH_2 storage system design in a hydrogen fuel station. Based on this analysis, scenario, and reliability data needs are identified to add LH_2-related components to the QRA to improve the future safety and risk assessment of these systems [37]. There are many quantitative risk assessment studies for hydrogen refueling stations. However, there is no study stating the general framework for all stations. In the study of Honselaar et al., the quantitative risk assessment applied to hydrogen fuel stations in the Netherlands was examined and compared. It has been determined what are the deficiencies and the aspects that need improvement [38]. Another study on liquid hydrogen is on the liquefaction, transport, and storage of hydrogen. In the study conducted by Lowesmith et al., it was stated that hydrogen transport as liquid is more advantageous than gas. The accidents that occurred during the production, transportation, and storage of liquid hydrogen were compiled and the causes of the accident were determined. Statistical evaluations were made on the results of the hazards [39]. Many articles have been written about the dangers of leakage in hydrogen filling stations. Over the years, it has been possible to gain more experience on the subject and to eliminate the dangers with the developing technology. Suzuki et al. conducted a recent quantitative risk assessment on Japanese hydrogen filling stations [40]. Pu et al. studied the leakage of liquid hydrogen in fuel filling stations and public vehicles. In the study, research was conducted on the smoke distribution behavior and what causes it. Relevant hazards were identified and numerical research was carried out [41]. Another risk analysis study related to leakage in hydrogen production plants was done by Chang et al. In this study, a Dynamic Bayesian Network approach methodology is proposed for the risk of hydrogen leakage. Recommendations that can be taken to reduce the risk of leakage of the hydrogen generation unit are presented as critical events. When the relevant evaluations are made, it has been reported that the risk of accidents will be significantly reduced when equipment maintenance and repair are planned and controlled [42]. In another study on the gas hydrogen refueling station, the people affected by the gas leak were categorized. Personnel working at the station were classified as first-degree affected, refueling customers second-degree, and passers-by and those living nearby were classified as third-degree affected. How they were affected by the risk was evaluated [43]. In a similar study, the same categorization was used, but only the results of the compressor's effects were discussed when making the evaluation [44].

Hadef et al. carried out risk analysis and evaluation studies on the hydrogen production system EGA-9000. In the study, process safety analysis was applied with functional and non-functional methods. As a result of the analysis, it was decided that additional security measures should be taken [45]. One of the comprehensive studies on hydrogen safety is the statistical analysis of 120 events based on historical data. Based on the results of this analysis, key issues related to hydrogen safety including hydrogen leakage and diffusion, hydrogen ignition, and explosion are reviewed. The source of the hazards, the reason why they occur, and the solution method are stated [46].

One of the resources used in the hydrogen production process is the natural gas reforming method. The study describing the generation of hydrogen by the natural gas reforming process was done by Jafari et al. In this study, hazard definitions related to the process were made and scenario frequency was estimated using literature data. Quantitative risk methods were used in the study [47]. In the reliability risk model for a hydrogen production facility in an oil refinery, a comprehensive risk analysis framework was created by analyzing major accidents [48]. He drew attention to the importance of using a risk simulator because of the large amount of data used in the study. The explosion risk analysis (ERA) method can be used to investigate potential accidents that may occur in hydrogen production facilities. Using this method alone suffers from significant parametric uncertainty. Thousands of Computational Fluid Dynamics (CFD) scenarios need to be calculated to better understand the uncertainty. These calculations create high costs. A stochastic procedure integrating Bayesian Regulatory Artificial Neural Network (BRANN) methodology with ERA to effectively manage uncertainty and reduce stimulus intensity is presented in this study. With the BRANN method, a lot of data about hydrogen distribution and explosion are generated. The generated data is used to develop scenario-based probability models [49].

Another study on hydrogen infrastructure is on which phase of hydrogen use and transport poses less risk. An attempt was made to determine the estimated hazard distance for each phase, as well as the frequency assessments of risk screening for release, dispersal, fire, and explosion. An optimum design approach has been demonstrated [50]. A comprehensive results analysis of liquid hydrogen boiling liquid expanding vapor explosions (BLEVE) for both small and medium-sized tests has been carried out by evaluating hazard consequences such as pressure waves and fireballs in liquid hydrogen vessels. Theoretical and analytical models were compared with the experimental results and deficiencies were observed [51].

The hazards in the hydrogen production and storage phase should not be identified as only leakage and explosion. When the results of the accident are examined, there are other consequences arising from the fire. These results can be personnel injuries and deaths due to plant/equipment failures caused by high temperature, radiant heat flow, and explosion. A harm criterion is used to translate the consequences of an accident into the probability of harming people, structures, or components. The article by LaChance et al. presents a survey of the different methods that can be used to determine hazard criteria and makes recommendations on criteria that should be used for hydrogen-related hazards [52]. Another study for fire and explosion events at hydrogen refueling stations involved mapping the hydrogen refueling station surroundings with a grid-based risk map. In the study, the region is divided into small parts so that it can be scanned more effectively and in detail. A risk analysis is made for each small piece of settlement, then a collective risk map display is created [53].

A different methodology was used in the study by Kim et al., from the studies on hydrogen infrastructure (production, distribution, and storage). This methodology is a convenient index-based risk assessment model. In the model, the relative risk ranking of hydrogen activities was made and the hydrogen infrastructure was evaluated using the relative impact levels of the different regions where the study was conducted [54].

Hydrogen is stored for different purposes. The first is to reuse hydrogen in power generation when needed. Another is for fuel use by gaseous or liquefying hydrogen. The development of hydrogen storage technologies is as important as producing hydrogen. Because energy can be stored in this era, which creates significant advantages in energy choice. In the study of Moradi and Groth, developments in hydrogen storage technologies were evaluated in terms of safety and reliability [55]. Proton exchange membrane fuel cells are used for hydrogen storage and transport. In this study by Spada et al., a comparative risk assessment of energy-related accidents was conducted by focusing on the hydrogen energy chain and selected fuel cell systems such as proton exchange membrane (PEM), phosphoric acid (PAFC), alkaline (AFC) and molten carbonate (MCFC). Also in the study, the framework created by PSI (Paul Scherrer Institut) for comparative risk assessment is used to comprehensively assess accident risks for hydrogen energy chain and fuel cell systems in the EU28 and compare them with fossil, hydro, and new renewable Technologies [56]. One of the most widely used methods for hydrogen production today is methane steam reforming. Li et al. conducted a study to evaluate the dangers and possible risks of this production method. A new methodology consisting of TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and Fuzzy DEMATEL (The Decision Making Trial and Evaluation Laboratory) is presented in this study to make a comprehensive risk assessment of the hydrogen production unit [57].

Simulation studies are also carried out to develop strategies to reduce problems in hydrogen safety. Computational fluid dynamics (CFD) methods were used to analyze hydrogen leakage in a semi-enclosed ventilation plant. In the first step, the technological risks of hydrogen were identified and characterized to create a so-called hydrogen energy chain. Later, historical accidents related to the hydrogen chain were collected and added to PSI (Paul Scherrer Institut)'s ENSAD (Energy-related Severe Accident Database) as a separate subsection. Different combinations of hydrogen release pressure and leak hole size were considered in the study. The effectiveness of forced ventilation in semi-enclosed spaces was also investigated. The hydrogen distribution in the aeration plant was studied through experimental research and CFD simulation results were verified [58]. Another article examining studies using the CFD technique was written by Abohamzeh et al. In the study, the works aiming to ensure safety in hydrogen storage, transmission, and application processes has been examined, and mainly CFD studies have been emphasized [46].

Making large-scale deployment and use of hydrogen successfully will require adequate risk control. Despite many years of experience, in general, methods to determine risk lack still robustness: results are highly dependent on choices made by the analyst due to uncertainties, lack of data, and divergent views. This can be disappointing among people depending on the results. A paper talked about current methodological weaknesses and make recommendations for improving quality. Scenario generation will leverage historical incident data and newer methods such as Bayesian belief networks and will cover the entire hydrogen delivery system, not just garages and refueling stations; analyses should more clearly present the confidence intervals for the results. Information gaps will be identified and filled [59]. One of the first studies on the use of Bayesian networks in hydrogen safety applications is the paper by Haugom and Friis-Hansen. In the content of this article, the advantages of using the Bayesian network compared to fault trees and event trees are explained, and this superiority is proven over the virtual hydrogen refueling station [60]. It has been chosen as the subject of another article about what the risk factors are in hydrogen logistics and how they affect it. While examining this subject, it has been evaluated from the perspective of the network modeling approach. For the study, historical accident databases in hydrogen logistics were examined and related event chains were created. Relevant dependencies have been identified [61]. Hydrogen energy can be transported via pipelines, just like natural gas. Pipeline transportation of hydrogen is mostly similar to natural gas. The different chemical properties of the transported gases and their different reactions to the effects reveal that a separate risk analysis and evaluation process should be performed. Related to this, Lins and Almeida conducted a multidimensional risk analysis of hydrogen pipelines in their study [62]. In another study on the risk analysis of hydrogen transport in natural gas pipelines, many failure events that may occur along the pipeline are discussed. Individual risks in the event of hydrogen jet fire have been evaluated for different scenarios [63]. Many studies have conducted risk assessment studies for the distribution and storage of hydrogen. Moonis et al.'s work is about identifying the data we need to do this risk assessment, finding missing hazard definitions to develop quantitative methodology, and what the gaps are in modeling and frequency assessment. It determines the effects of using ammonia as a hydrogen carrier, and its regulatory applications on hydrogen refueling or landfills [64].

The efficiency of the gas mixture obtained with hydrogen mixed with natural gas is higher than natural gas. This has commercial benefits. This will reduce both installation costs and end-user downtime. However, before hydrogen can provide domestic heat, the 'risk' of its distribution in direct comparison to natural gas needs to be assessed. Quantitative risk assessment has also been carried out for studies where hydrogen is mixed with natural gas and given to the local network. Here, a comprehensive and versatile quantitative risk assessment tool has been developed to assess the 'risk' difference between existing natural gas distribution networks and potential conversion to a hydrogen-based system [65]. In another article examining hydrogen and hydrogen-containing fuel gases, it was mentioned what their dangers could be. In this study, the explosion intervals of hydrogen and hydrogen natural gas mixtures are shown. The dependence of the explosion limits of the mixtures on pressure and temperature was investigated. Maximum experimental safety gaps have been determined for the classification and assignment of mixtures made with hydrogen gas to explosion groups [66]. Other work on injecting hydrogen into natural gas was done by Messaoudani et al. This study does not mention the safe transportation of hydrogen mixed with natural gas, but it is mentioned that there is enough theoretical knowledge on this subject, but the vastness of the experimental data gap [67].

When the studies are examined, there are several existing QRA tools including models developed and approved for use in small-scale hydrogen applications. However, in the last few years, significant progress has been made in the development and validation of deterministic physical and engineering models for hydrogen dispersion, ignition, and flame behavior. In parallel, progress has been made in developing defensible probability models for the occurrence of events such as hydrogen release and ignition. While models and data are available, using this knowledge is difficult due to the lack of ready-made tools to integrate deterministic and probabilistic components into a single analysis framework. This article written by Groth and Tchouvelev discusses the first steps of creating an integrated toolkit to perform QRA on hydrogen transport technologies and proposes guidelines for expanding the toolkit [68].

Many studies have conducted risk assessment studies for the distribution and storage of hydrogen. The work of Moonis et al. is about identifying the data needed to conduct this risk assessment, finding the missing hazard definitions to develop a quantitative methodology, and identifying what the gaps are in modeling and frequency assessment. It determines the effects of using ammonia as a hydrogen carrier, and its regulatory applications on hydrogen refueling or landfills [64].

The comparison tables of the studies we have mentioned regarding the risks in hydrogen energy are given in Table 1. Table 2 shows the usage area of hydrogen and the structural form of hydrogen in the hydrogen energy studies examined.

4. Risk Analysis and Assessment Studies Related to Offshore Wind Energy

Offshore wind farms have a relatively new technology compared to other renewable energy types. For wind turbines to operate with maximum efficiency, the wind must be continuous and the wind speed must be high. Since the seas do not have any blockage compared to the land, they can offer more uninterrupted wind. In addition, the fact that more offshore wind turbines are larger than onshore wind turbines does not cause any environmental and visual problems. They can have higher energy power. But there are big gaps in where, how, and under what conditions the turbine should be installed. For this, various disciplines come together and try to achieve the optimum result. The location, installation, construction, maintenance, and repair of offshore wind power plants and the formation of energy transmission lines contain many dangers. It is necessary to benefit from various databases, simulations, and analyses to predict the risks that may occur. However, data on offshore power plants and the challenges they face are difficult to find. Since offshore gas and oil fields are based on an older history, a database has been created on these subjects. There are similarities between offshore wind farms and other offshore gas and oil power plants in terms of environmental, logistics, and accessibility. There are only major differences in operational terms. For these reasons and more, it is necessary to establish a database on this subject [72].

Table 1. Comparison table on hydrogen energy risk studies

Reference	Method																					
	FDEMATEL	BTM	DNT	BWM	DBN	CFD	FA	QRA	FEA	HAZID	FAST	HAZOP	RM	ETA	PRA	ERA	BN	GRMM	FMEA	RIM	TOPSIS	NA
[28]													✓									
[69]		✓	✓	✓	✓																	
[32]						✓	✓	✓	✓													
[33]								✓														
[35]								✓														
[36]								✓														
[37]								✓														
[70]								✓														
[39]									✓													
[40]								✓														
[41]						✓																
[42]					✓																	
[43]								✓														
[44]								✓														
[45]											✓	✓										
[46]						✓																
[47]								✓														
[48]								✓														
[49]												✓		✓	✓							
[50]						✓																
[52]								✓														
[53]																	✓	✓				
[71]																			✓	✓		
[57]	✓																				✓	
[58]						✓																
[59]						✓																
[60]								✓									✓					
[61]																						✓
[63]								✓														
[64]										✓			✓									
[65]																						
[66]								✓														
[68]								✓														

Abbreviation: Risk Matrix (RM), Bow-tie method (BTM), D Numbers Theory (DNT), Best-Worst Method (BWM), Dynamic Bayesian Network (DBN), Computational fluid dynamics (CFD), Frequency analysis (FA), Quantitative risk assessment (QRA), Finite element analysis (FEA), HAZID, Functional Analysis System Technique (FAST), HAZOP (HAZard and Operability), Preliminary Risk Analysis (PRA), Event Tree Analysis (ETA), Explosion risk analysis (ERA), Bayesian network (BN), Grid-based risk mapping method (GRMM), Failure mode and effects analysis (FMEA),Risk index method (RIM),Fuzzy DEMATEL (FDEMATEL) ,TOPSIS, Network Analysis (NA).

In this study, a limited number of articles on offshore wind turbines and power plants have been compiled within the risk framework. Some of the articles are related to maintenance and repair, some to the main part of the turbine and some to the supply chain of wind turbines.

The study by Mogre et al. is about the measures that can be taken to reduce the risks that may occur in the supply chain network in the offshore wind industry. In the study, the relevant literature was scanned and some gaps (such as probability estimation, choice of measure, and assessment of interdependence of risks and precautions) were identified. It is stated that these gaps will be covered with the new decision support methodology to be created [73]. In the study by Dinmohammadi and Shafiee, a different methodological perspective was brought to the risk assessment approach applied to offshore wind turbines. In studies using traditional FMEAs (Failure Mode Effect Analysis), fuzzy set theory was used to clarify expert opinions. The Fuzzy FMEA and Gray theory approach were evaluated on the same data and the results were compared [74]. In the study of Leimeister and Kolios, risk analysis studies on the offshore industry were compiled and separated by various classifications. As a result of the study, it was observed that qualitative methods were predominantly used due to the lack of sufficient and reliable data in this industry branch [75]. Shafiee's work is a fuzzy analytical network process study to reduce the associated risks in offshore wind farms. The risks specified herein as related risks are; Changes in offshore site layout, Improving maintenance services, Upgrading control and monitoring systems, and Changing the design of wind turbine sub-assemblies are the risks that are predicted to be mitigated [76]. In the study by Luengo and Kolios, the failure modes of offshore wind turbines were defined and various scenarios were discussed for offshore wind turbines that completed their working life [77]. Drilling should be done according to the turbine foundation type to be used when constructing offshore wind farms. Khadzad et al used the bow tie and bayesian network approach to analyze the risks in offshore drilling operations. It has been reported that using the Bayesian network method provides more value than using the bow tie method [78].

Table 2. Risk studies related to hydrogen energy, areas where hydrogen is used and the structural form of hydrogen

Reference	Application Area			The form of hydrogen	
	Production	Construction	Operation and maintenance	Gaseous	Liquid
[27]	✓	✓	✓	✓	
[69]				✓	
[32]				✓	
[33]				✓	
[34]				✓	
[39]	✓	✓	✓		✓
[42]	✓			✓	
[44]				✓	
[45]	✓			✓	
[46]		✓	✓		
[47]	✓			✓	
[48]	✓			✓	
[49]	✓			✓	
[51]			✓		✓
[52]	✓			✓	✓
[53]			✓	✓	
[71]	✓	✓	✓	✓	✓
[55]		✓	✓	✓	
[57]	✓			✓	
[58]			✓	✓	
[59]			✓		
[61]		✓		✓	
[62]		✓			
[63]		✓		✓	
[64]		✓	✓	✓	
[65]		✓		✓	
[66]		✓		✓	
[67]		✓		✓	
[68]		✓		✓	

Working in open sea conditions involves different challenges than working on land. It is necessary to analyze these difficulties and the risks posed by these difficulties. These difficulties cause occupational accidents such as slipping, tripping, and falling from height. In the study of Song et al., a dynamic risk assessment was made for the reduction of occupational accidents, which is called STF (slips, trips and falls from height) for short. Bayesian network approach and bow tie method were also preferred in this study [79]. Offshore wind turbines may differ according to their basic structure. Although not very common yet, it is thought that the use of floating offshore wind turbines will increase day by day. Zhang et al. have conducted a study to have the necessary breakdown and maintenance information for wind turbines with this foundation type. In the study, the system components were examined, the interrelationship network between them was created and the failure modes analysis was made [80].

In the article written by Tafladinis et al., a risk measurement and assessment was made for an offshore wind turbine exposed to extreme wind and wave conditions. In the study, a simulation study was carried out on the probabilistic characterization of uncertainty. Different risk quantifications are discussed [81].

Nielsen and Sorensen's work is also related to the maintenance of offshore wind turbines. In the study, which evaluates the costs for a single-component wind turbine, it is mentioned that maintenance that is not done on time and properly poses a risk. Risk-based maintenance alternatives are emphasized [82].

In the study of Chou et al., the cause of the accidents occurring during the construction and operation phases of the offshore wind power plant is investigated. Risk management practices at the operational stage were examined. It is in a structure that can be used as a predictive guide for the offshore wind farm personnel planned to be built shortly [83].

Staid and Guikema tried to establish a risk analysis framework for the offshore wind turbine, which was planned to be built for the first time in the United States at the time of the study. An answer has been sought to the question of what dangers the power plants to be built may face in ocean conditions. It has been tried to find answers to the questions of how the risks that may arise as a result of these hazards affect the system [84].

Kang et al. chose the floating turbine model as the offshore wind turbine foundation structure and made a risk assessment based on this basis. The floating turbine foundation structure is still under development and unlike other turbines, it is not driven into the ground with solid piles. It floats on the water with its pontoon system. This situation poses different dangers. In this study, different risks that may occur were evaluated and FMEA application was made together with the PNET method, and the results were evaluated [85].

Gkoumas used Hierarchical Holographic Modeling to analyze the risk of offshore wind turbines in his study. Along with this modeling, he created a large number of risk scenarios organized hierarchically into clusters and subsets [86].

Alvarez et al. used genetic algorithms and simulation methods to manage and, if possible, reduce risks in offshore wind farms. Thanks to these methodologies, generation strategies, and plant layout designs were optimized. In addition, experimental results have been obtained by simulation for the piles to be driven into the seabed depending on the turbine foundation structure [87].

Zhou and Yang conducted a risk management study using the AHP (The analytic hierarchy process) method in distributed wind energy. They classified and evaluated the risks as economic, political, social, and technical risks [88].

Another risk factor for offshore wind farms is bird collisions. Migratory birds migrate towards warm regions during certain seasons and do this in flocks. Offshore wind turbines should not be deployed in these areas. However, this environmental factor has not been taken into account in previous studies. Related to this issue, Desholm and Kahlert conducted a study investigating the risk of bird collisions in offshore wind farms in Denmark [89].

Creating a database for offshore wind farms is an extensive, difficult, and costly activity. This is an important task for offshore wind farms with huge energy potential at a time when renewable sources are being turned to to provide the energy consumed on their own. As a result of this study, the risks of power plants can be evaluated in an integrated way. In his study, Ram emphasized that offshore wind power plant decision-makers and stakeholders should have an integrated database to be informed [90].

Various risks may occur during the construction of an offshore wind turbine. Various hazards may occur while loading, transporting, and assembling the turbine parts on the crane. Apart from these, there are additional difficulties brought by the working environment. Bai et al. conducted a study to rate and evaluate the risks posed by these hazards [91].

Gatzert and Kosub present a comprehensive study of the risks of onshore and offshore wind parks. Various sector researches were evaluated mutually and the appropriateness of the risks was determined. The main point of the study is whether the current insurance products cover the risks and if so, to what extent [92].

The comparison tables of the studies we have mentioned regarding the risks in offshore wind energy are given in Table 3.

Table 3. Comparison table for offshore wind energy risk analysis and assessment literature review

Authors	Year	Application Area			Method																		
		Supply Chain	Construction	Operation and maintenance	DSS	FMEA	FFMEA	ANP	AHP	FANP	BTM	BN	SS	FTA	DFTA	BPDT	DEMATEL	PNET	PRA	HHM	GA	SM	RPNM
(Hameed et al.)	2011			✓																			
(Mogre et al.)	2016	✓			✓																		
(Dinmohammadi & Shafiee)	2013			✓		✓	✓																
(Shafiee)	2015			✓				✓	✓	✓													
(Luengo& Kolios)	2007			✓																			
(Khakzad et al.)	2013		✓								✓	✓											
(Song et al.)	2016	✓	✓	✓							✓	✓											
(Zhang et al.)	2016		✓	✓											✓								
(Taflanidis et al.)	2013			✓									✓										
(Nielsen& Sorensen)	2011			✓												✓							
(Chou et al.)	2021		✓	✓													✓						
(Kang et al.)	2017			✓		✓												✓					
(Gkoumas)	2010		✓																✓	✓			
(Álvarez et al.)	2018		✓																		✓	✓	
(Zhou & Yang)	2020		✓	✓					✓														
(Ram)	2011		✓	✓																			
(Bai et al.)	2012	✓	✓			✓								✓									✓

Abbreviation: Decision support systems (DSS), Failure Mode and Effects Analysis (FMEA),Fuzzy FMEA (FFMEA), Analytic Network Process (ANP), Fuzzy ANP (FANP), Analytical Hierarchy Process (AHP), Bow Tie Methodology (BTM), Bayesian Network (BN), Fault Tree Analysis (FTA), Dynamic FTA (DFTA), Stochastic Simulation (SS), Bayesian pre-posterior decision theory (BPDT), Decision-Making Trial and Evaluation Laboratory (DEMATEL), Probability Network Evaluation Technique (PNET), Probabilistic Risk Analysis (PRA), Hierarchical Holographic Modeling (HHM), Genetic algorithm (GA), simulation model (SM), Risk Priority Number Method(RPNM)

5. Discussion

When the studies are examined, it has been observed that risk analysis and evaluation studies on hybrid energy systems have not been carried out. The examined hydrogen energy studies and offshore wind energy studies are very scattered from a risk perspective. As of yet, no developed database for offshore wind energy describes the causes and consequences of past accidents. This is a major disadvantage for researchers who want to do risk analysis and assessment studies. Offshore gas and oil explorations are leading in this regard. There are databases created on hydrogen energy. The usage area of hydrogen energy alone is quite wide. The database is built on a very large area. The hydrogen energy analyzed in this paper is the part that can be used and stored for electrical energy. But in terms of risk, all hydrogen energy studies are mentioned above.

Since hydrogen has the potential to create danger due to its structure, risk studies are carried out intensively. It is necessary to carry out risk mitigation studies such as the fact that the region where hydrogen is located is not located very close to the residential area, the creation of protection barriers for human safety and the strengthening of structures [53]. Studies should be carried out not only to reduce the potential risk, but also to eliminate the factors that pose risk in the first place. The quality assurance process is important for this [30]. The development and selection of an appropriate risk mitigation strategy for offshore wind farms is a very complex and critical task [76]. Effective risk mitigation and prevention tools are needed for the development of this energy sector [74].

While creating this study, it was considered to generate electricity with an offshore wind power plant and supply it to the grid. In renewable energy types, due to their nature, energy should be consumed as soon as it is produced. In case of low electricity demand supplied to the grid, it should be able to be stored and reused whenever required. Thanks to the research and developing technology, electrical energy storage studies are carried out. Hydrogen energy is a good alternative for energy storage as well as generating electrical energy. The excess energy generated can be used for electrolysis with platforms to be built on the sea. Hydrogen obtained by electrolysis of seawater can be stored in tanks. If desired, the hydrogen stored in the tanks can be used for different purposes – raw materials for different industries, energy sources, and fuel for hydrogen vehicles.

For these power plants to work properly and uninterruptedly, the system should be evaluated as a whole and the situations that would prevent the system from working should be eliminated. For this reason, this study will guide the joint evaluation of risks in hybrid energy systems and find solutions.

6. Conclusion and Policy Implications

When the literature for hydrogen energy is searched by the terms risk, risk analysis and assessment, hazard, safety, and reliability, the articles after 2010 are mentioned above. Most of the articles are about the use of hydrogen as a fuel in new-generation vehicles. Qualitative and quantitative risk analysis methods were applied for the precautions to be taken against the risks of leakage, explosion, and fire during the transportation, storage, and filling of liquid and gaseous hydrogen at hydrogen filling stations and for possible results. In addition, hydrogen is a substance that can be produced by different methods. The risks that may occur according to the production method are different. The risks and effects that may occur for several different production methods are stated in related studies. In some of the studies carried out to predict the hazards related to hydrogen, simulation programs were used and risk assessments were made for possible accidents. In addition, there are many studies describing hydrogen databases, how they work, and how they rank risks.

Although offshore wind power plants are similar to onshore wind power plants, they face different dangers due to their environment. These differences bring along various risks during installation, omaintenance repair, and energy transfer. Risk analysis and assessment studies related to offshore wind power plants are not sufficient. If the previous studies are to be classified, they are mainly related to the construction of the wind turbine. Offshore wind turbine basic structures are diverse. Starting from the drilling for the foundation, the logistics of the turbine materials, and the risks that may occur during the construction of the turbine, the majority of the studies are carried out. The risks posed by ships arriving for maintenance-repair, the risks posed by delayed maintenance for the turbine engine room, the risks posed by the impact of migratory birds, and the risks occurring in the working equipment of the turbine due to environmental effects are the subject of other studies.

In this century, when countries with energy resources are stronger, countries want to gain their energy independence. In countries that do not have fossil resources, what needs to be done is to develop the power of renewable energy sources. Ensuring the supply-demand balance in energy with their resources is the most important point that countries take into consideration while executing their energy policies. To ensure this energy policy, energy production must be sustainable. One of the factors that ensure sustainability is to make risk analyses and assessments correctly and to ensure energy production and distribution. The study provides all the necessary information to serve this purpose through a conceptual study.

Acknowledgments

This research was supported by the Council of Higher Education (YÖK) 100/2000 Doctoral Project.

Authors' Contributions

ANC and CO designed the structure. ANC carried out the work, in collaboration with CO, and wrote up the article. CO is the overall supervisor of the project. Both authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

References

[1] P. Albertus, J. S. Manser, and S. Litzelman, “Long-Duration Electricity Storage Applications, Economics, and Technologies,” Joule, vol. 4, no. 1, pp. 21–32, Jan. 2020, doi: 10.1016/J.JOULE.2019.11.009.

[2] F. Zhang, P. Zhao, M. Niu, and J. Maddy, “The survey of key technologies in hydrogen energy storage,” Int. J. Hydrogen Energy, vol. 41, no. 33, pp. 14535–14552, 2016, doi: 10.1016/j.ijhydene.2016.05.293.

[3] T. Zhang, “Techno-economic analysis of a nuclear-wind hybrid system with hydrogen storage,” J. Energy Storage, vol. 46, no. September 2021, p. 103807, 2022, doi: 10.1016/j.est.2021.103807.

[4] L. Li et al., “Comparative techno-economic analysis of large-scale renewable energy storage technologies,” Energy AI, vol. 14, no. June, p. 100282, 2023, doi: 10.1016/j.egyai.2023.100282.

[5] Y. Rong et al., “Techno-economic analysis of hydrogen storage and transportation from hydrogen plant to terminal refueling station,” Int. J. Hydrogen Energy, vol. 52, pp. 547–558, 2024, doi: 10.1016/j.ijhydene.2023.01.187.

[6] Y. E. Yüksel and M. Öztürk, “Thermodynamic Analysis of an Integrated Solar-based Chemical Reactor System for Hydrogen Production,” El-Cezerî J. Sci. Eng., vol. 2, no. 2, pp. 19–27, 2015.

[7] M. Ozturk and I. Dincer, “Thermodynamic analysis of a solar-based multi-generation system with hydrogen production,” Appl. Therm. Eng., vol. 51, no. 1–2, pp. 1235–1244, 2013, doi: 10.1016/j.applthermaleng.2012.11.042.

[8] Y. Bicer and I. Dincer, “Development of a new solar and geothermal based combined system for hydrogen production,” Sol. Energy, vol. 127, pp. 269–284, 2016, doi: 10.1016/j.solener.2016.01.031.

[9] A. S. Joshi, I. Dincer, and B. V. Reddy, “Effects of various parameters on energy and exergy efficiencies of a solar thermal hydrogen production system,” Int. J. Hydrogen Energy, vol. 41, no. 19, pp. 7997–8007, 2016, doi: 10.1016/j.ijhydene.2016.01.025.

[10] K. Saka and A. S. Canbolat, “an Evaluation on Solar Powered Hydrogen Production,” Int. J. Energy Eng. Sci., vol. 3, no. 2, p. 2016, 2018.

[11] S. Keykhah, E. Assareh, R. Moltames, A. Taghipour, and H. Barati, “Thermoeconomic Analysis And Multi-Objective Optimization Of An Integrated Solar System For Hydrogen Production Using Particle Swarm Optimization Algorithm,” J. Therm. Eng., vol. 7, no. 4, pp. 746–760, 2021, doi: 10.18186/thermal.915413.

[12] M. Ghazvini, M. Sadeghzadeh, M. H. Ahmadi, S. Moosavi, and F. Pourfayaz, “Geothermal energy use in hydrogen production: A review,” Int. J. Energy Res., vol. 43, no. 14, pp. 7823–7851, 2019, doi: 10.1002/er.4778.

[13] G. K. Karayel, N. Javani, and I. Dincer, “Effective use of geothermal energy for hydrogen production: A comprehensive application,” Energy, vol. 249, p. 123597, 2022, doi: 10.1016/j.energy.2022.123597.

[14] A. Karapekmez and I. Dincer, “Modelling of hydrogen production from hydrogen sulfide in geothermal power plants,” Int. J. Hydrogen Energy, vol. 43, no. 23, pp. 10569–10579, 2018, doi: 10.1016/j.ijhydene.2018.02.020.

[15] Z. Akyürek, A. Ö. Akyüz, and A. Güngör, “Potential of Hydrogen Production from Pepper Waste Gasification,” El-Cezeri J. Sci. Eng., vol. 6, no. 2, pp. 382–387, 2019, doi: 10.31202/ecjse.532770.

[16] S. Kaya, B. Ozturk, and H. Aykac, “Hydrogen production from renewable source: Biogas,” Proc. 2013 Int. Conf. Renew. Energy Res. Appl. ICRERA 2013, no. October 2013, pp. 633–637, 2013, doi: 10.1109/ICRERA.2013.6749832.

[17] H. Ishaq and D. Ibrahim, “An Efficient Energy Utilization of Biomass Energy-Based System for Renewable Hydrogen Production and Storage,” J. Energy Resour. Technol., vol. 144, no. 1, p. 011701, 2022.

[18] R. D’Amore-Domenech and T. J. Leo, “Sustainable Hydrogen Production from Offshore Marine

Renewable Farms: Techno-Energetic Insight on Seawater Electrolysis Technologies," ACS Sustain. Chem. Eng., vol. 7, no. 9, pp. 8006–8022, 2019.
[19] J. Chi and H. Yu, "Water electrolysis based on renewable energy for hydrogen production," Chinese J. Catal., vol. 39, no. 3, pp. 390–394, Mar. 2018, doi: 10.1016/S1872-2067(17)62949-8.
[20] H. Dagdougui, A. Ouammi, and R. Sacile, "A regional decision support system for onsite renewable hydrogen production from solar and wind energy sources," Int. J. Hydrogen Energy, vol. 36, no. 22, pp. 14324–14334, Nov. 2011, doi: 10.1016/J.IJHYDENE.2011.08.050.
[21] Á. Serna and F. Tadeo, "Offshore hydrogen production from wave energy," Int. J. Hydrogen Energy, vol. 39, no. 3, pp. 1549–1557, 2014, doi: 10.1016/j.ijhydene.2013.04.113.
[22] A. Colucci et al., "An inertial system for the production of electricity and hydrogen from sea wave energy," Ocean. 2015 - MTS/IEEE Washingt., pp. 1–10, 2016, doi: 10.23919/oceans.2015.7404569.
[23] T. C. Moralesa, V. R. Olivab, and L. F. Velázquezc, "Hydrogen from renewable energy in Cuba," Energy Procedia, vol. 57, pp. 867–876, 2014, doi: 10.1016/j.egypro.2014.10.296.
[24] F. Posso, J. Sánchez, J. L. Espinoza, and J. Siguencia, "Preliminary estimation of electrolytic hydrogen production potential from renewable energies in Ecuador," Int. J. Hydrogen Energy, vol. 41, no. 4, pp. 2326–2344, 2016, doi: 10.1016/j.ijhydene.2015.11.155.
[25] N. Norouzi, "An overview on the renewable hydrogen generation market," -International J. Energy Res., vol. 7513, no. 1, pp. 1–2, 2021.
[26] J. M. Bermudez and İ. Hannula, "Hydrogen," iea, 2021. https://www.iea.org/reports/hydrogen
[27] Y. S. H. Najjar, "Hydrogen safety: The road toward green technology," Int. J. Hydrogen Energy, vol. 38, no. 25, pp. 10716–10728, Aug. 2013, doi: 10.1016/J.IJHYDENE.2013.05.126.
[28] N. Kasai, Y. Fujimoto, I. Yamashita, and H. Nagaoka, "The qualitative risk assessment of an electrolytic hydrogen generation system," Int. J. Hydrogen Energy, vol. 41, no. 30, 2016, doi: 10.1016/j.ijhydene.2016.05.231.
[29] E. Zarei, F. Khan, and M. Yazdi, "A dynamic risk model to analyze hydrogen infrastructure," Int. J. Hydrogen Energy, vol. 46, no. 5, 2021, doi: 10.1016/j.ijhydene.2020.10.191.
[30] M. Cristina Galassi et al., "HIAD – hydrogen incident and accident database," Int. J. Hydrogen Energy, vol. 37, no. 22, pp. 17351–17357, Nov. 2012, doi: 10.1016/J.IJHYDENE.2012.06.018.
[31] K. M. Groth and E. S. Hecht, "HyRAM: A methodology and toolkit for quantitative risk assessment of hydrogen systems," Int. J. Hydrogen Energy, vol. 42, no. 11, 2017, doi: 10.1016/j.ijhydene.2016.07.002.
[32] T. Skjold et al., "3D risk management for hydrogen installations," Int. J. Hydrogen Energy, vol. 42, no. 11, 2017, doi: 10.1016/j.ijhydene.2016.07.006.
[33] K. M. Groth, E. S. Hecht, and J. T. Reynolds, "Methodology for assessing the safety of Hydrogen Systems : HyRAM 1 . 0 technical reference manual," Sandia Rep., no. March, 2015.
[34] N. R. Mirza, S. Degenkolbe, and W. Witt, "Analysis of hydrogen incidents to support risk assessment," Int. J. Hydrogen Energy, vol. 36, no. 18, 2011, doi: 10.1016/j.ijhydene.2011.06.080.
[35] A. C. LaFleur, A. B. Muna, and K. M. Groth, "Application of quantitative risk assessment for performance-based permitting of hydrogen fueling stations," Int. J. Hydrogen Energy, vol. 42, no. 11, pp. 7529–7535, Mar. 2017, doi: 10.1016/J.IJHYDENE.2016.06.167.
[36] B. H. Yoo, S. Wilailak, S. H. Bae, H. R. Gye, and C. J. Lee, "Comparative risk assessment of liquefied and gaseous hydrogen refueling stations," Int. J. Hydrogen Energy, vol. 46, no. 71, pp. 35511–35524, Oct. 2021, doi: 10.1016/j.ijhydene.2021.08.073.
[37] C. Correa-Jullian and K. M. Groth, "Data requirements for improving the Quantitative Risk Assessment of liquid hydrogen storage systems," Int. J. Hydrogen Energy, vol. 47, no. 6, 2022, doi: 10.1016/j.ijhydene.2021.10.266.
[38] M. Honselaar, G. Pasaoglu, and A. Martens, "Hydrogen refuelling stations in the Netherlands: An

intercomparison of quantitative risk assessments used for permitting," Int. J. Hydrogen Energy, vol. 43, no. 27, pp. 12278–12294, Jul. 2018, doi: 10.1016/J.IJHYDENE.2018.04.111.
[39] B. J. Lowesmith, G. Hankinson, and S. Chynoweth, "Safety issues of the liquefaction, storage and transportation of liquid hydrogen: An analysis of incidents and HAZIDS," Int. J. Hydrogen Energy, vol. 39, no. 35, pp. 20516–20521, Dec. 2014, doi: 10.1016/J.IJHYDENE.2014.08.002.
[40] T. Suzuki et al., "Quantitative risk assessment using a Japanese hydrogen refueling station model," Int. J. Hydrogen Energy, vol. 46, no. 11, pp. 8329–8343, Feb. 2021, doi: 10.1016/J.IJHYDENE.2020.12.035.
[41] L. Pu, X. Shao, S. Zhang, G. Lei, and Y. Li, "Plume dispersion behaviour and hazard identification for large quantities of liquid hydrogen leakage," Asia-Pacific J. Chem. Eng., vol. 14, no. 2, 2019, doi: 10.1002/apj.2299.
[42] Y. Chang, C. Zhang, J. Shi, J. Li, S. Zhang, and G. Chen, "Dynamic Bayesian network based approach for risk analysis of hydrogen generation unit leakage," Int. J. Hydrogen Energy, vol. 44, no. 48, 2019, doi: 10.1016/j.ijhydene.2019.08.065.
[43] L. Zhiyong, P. Xiangmin, and M. Jianxin, "Quantitative risk assessment on 2010 Expo hydrogen station," Int. J. Hydrogen Energy, vol. 36, no. 6, 2011, doi: 10.1016/j.ijhydene.2010.12.068.
[44] L. Zhiyong, P. Xiangmin, and M. Jianxin, "Quantitative risk assessment on a gaseous hydrogen refueling station in Shanghai," Int. J. Hydrogen Energy, vol. 35, no. 13, 2010, doi: 10.1016/j.ijhydene.2010.04.031.
[45] H. Hadef, B. Negrou, T. G. Ayuso, M. Djebabra, and M. Ramadan, "Preliminary hazard identification for risk assessment on a complex system for hydrogen production," Int. J. Hydrogen Energy, vol. 45, no. 20, 2020, doi: 10.1016/j.ijhydene.2019.10.162.
[46] E. Abohamzeh, F. Salehi, M. Sheikholeslami, R. Abbassi, and F. Khan, "Review of hydrogen safety during storage, transmission, and applications processes," J. Loss Prev. Process Ind., vol. 72, p. 104569, Sep. 2021, doi: 10.1016/J.JLP.2021.104569.
[47] M. J. Jafari, E. Zarei, and N. Badri, "The quantitative risk assessment of a hydrogen generation unit," Int. J. Hydrogen Energy, vol. 37, no. 24, 2012, doi: 10.1016/j.ijhydene.2012.09.082.
[48] I. Mohammadfam and E. Zarei, "Safety risk modeling and major accidents analysis of hydrogen and natural gas releases: A comprehensive risk analysis framework," Int. J. Hydrogen Energy, vol. 40, no. 39, 2015, doi: 10.1016/j.ijhydene.2015.07.117.
[49] J. Shi et al., "Stochastic explosion risk analysis of hydrogen production facilities," Int. J. Hydrogen Energy, vol. 45, no. 24, 2020, doi: 10.1016/j.ijhydene.2020.03.040.
[50] O. R. Hansen, "Hydrogen infrastructure—Efficient risk assessment and design optimization approach to ensure safe and practical solutions," Process Saf. Environ. Prot., vol. 143, pp. 164–176, Nov. 2020, doi: 10.1016/j.psep.2020.06.028.
[51] F. Ustolin, N. Paltrinieri, and G. Landucci, "An innovative and comprehensive approach for the consequence analysis of liquid hydrogen vessel explosions," J. Loss Prev. Process Ind., vol. 68, Nov. 2020, doi: 10.1016/j.jlp.2020.104323.
[52] J. Lachance, A. Tchouvelev, and A. Engebo, "Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure," Int. J. Hydrogen Energy, vol. 36, no. 3, 2011, doi: 10.1016/j.ijhydene.2010.03.139.
[53] Y. Huang and G. Ma, "A grid-based risk screening method for fire and explosion events of hydrogen refuelling stations," Int. J. Hydrogen Energy, vol. 43, no. 1, pp. 442–454, Jan. 2018, doi: 10.1016/J.IJHYDENE.2017.10.153.
[54] J. Kim, Y. Lee, and I. Moon, "An index-based risk assessment model for hydrogen infrastructure," Int. J. Hydrogen Energy, vol. 36, no. 11, pp. 6387–6398, Jun. 2011, doi: 10.1016/J.IJHYDENE.2011.02.127.
[55] R. Moradi and K. M. Groth, "Hydrogen storage and delivery: Review of the state of the art

technologies and risk and reliability analysis," Int. J. Hydrogen Energy, vol. 44, no. 23, pp. 12254–12269, May 2019, doi: 10.1016/J.IJHYDENE.2019.03.041.
[56] M. Spada, P. Burgherr, and P. Boutinard Rouelle, "Comparative risk assessment with focus on hydrogen and selected fuel cells: Application to Europe," Int. J. Hydrogen Energy, vol. 43, no. 19, pp. 9470–9481, May 2018, doi: 10.1016/j.ijhydene.2018.04.004.
[57] X. Li, Z. Han, R. Zhang, Y. Zhang, and L. Zhang, "Risk assessment of hydrogen generation unit considering dependencies using integrated DEMATEL and TOPSIS approach," Int. J. Hydrogen Energy, vol. 45, no. 53, pp. 29630–29642, Oct. 2020, doi: 10.1016/j.ijhydene.2020.07.243.
[58] A. A. Malakhov, A. V. Avdeenkov, M. H. du Toit, and D. G. Bessarabov, "CFD simulation and experimental study of a hydrogen leak in a semi-closed space with the purpose of risk mitigation," Int. J. Hydrogen Energy, vol. 45, no. 15, pp. 9231–9240, Mar. 2020, doi: 10.1016/j.ijhydene.2020.01.035.
[59] H. J. Pasman, "Challenges to improve confidence level of risk assessment of hydrogen technologies," Int. J. Hydrogen Energy, vol. 36, no. 3, 2011, doi: 10.1016/j.ijhydene.2010.05.019.
[60] G. P. Haugom and P. Friis-Hansen, "Risk modelling of a hydrogen refuelling station using Bayesian network," Int. J. Hydrogen Energy, vol. 36, no. 3, 2011, doi: 10.1016/j.ijhydene.2010.04.131.
[61] C. Y. Lam, M. Fuse, and T. Shimizu, "Assessment of risk factors and effects in hydrogen logistics incidents from a network modeling perspective," Int. J. Hydrogen Energy, vol. 44, no. 36, pp. 20572–20586, Jul. 2019, doi: 10.1016/J.IJHYDENE.2019.05.187.
[62] P. H. C. Lins and A. T. De Almeida, "Multidimensional risk analysis of hydrogen pipelines," Int. J. Hydrogen Energy, vol. 37, no. 18, pp. 13545–13554, Sep. 2012, doi: 10.1016/J.IJHYDENE.2012.06.078.
[63] H. A. J. Froeling, M. T. Dröge, G. F. Nane, and A. J. M. Van Wijk, "Quantitative risk analysis of a hazardous jet fire event for hydrogen transport in natural gas transmission pipelines," Int. J. Hydrogen Energy, vol. 46, no. 17, pp. 10411–10422, Mar. 2021, doi: 10.1016/j.ijhydene.2020.11.248.
[64] M. Moonis, A. J. Wilday, and M. J. Wardman, "Semi-quantitative risk assessment of commercial scale supply chain of hydrogen fuel and implications for industry and society," Process Saf. Environ. Prot., vol. 88, no. 2, 2010, doi: 10.1016/j.psep.2009.11.006.
[65] J. Mouli-Castillo, S. R. Haszeldine, K. Kinsella, M. Wheeldon, and A. McIntosh, "A quantitative risk assessment of a domestic property connected to a hydrogen distribution network," Int. J. Hydrogen Energy, vol. 46, no. 29, pp. 16217–16231, Apr. 2021, doi: 10.1016/J.IJHYDENE.2021.02.114.
[66] M. Molnarne and V. Schroeder, "Hazardous properties of hydrogen and hydrogen containing fuel gases," Process Saf. Environ. Prot., vol. 130, pp. 1–5, Oct. 2019, doi: 10.1016/j.psep.2019.07.012.
[67] Z. labidine Messaoudani, F. Rigas, M. D. Binti Hamid, and C. R. Che Hassan, "Hazards, safety and knowledge gaps on hydrogen transmission via natural gas grid: A critical review," Int. J. Hydrogen Energy, vol. 41, no. 39, pp. 17511–17525, Oct. 2016, doi: 10.1016/J.IJHYDENE.2016.07.171.
[68] K. M. Groth and A. V. Tchouvelev, "A toolkit for integrated deterministic and probabilistic risk assessment for hydrogen infrastructure," 2014.
[69] E. Zarei, F. Khan, and M. Yazdi, "A dynamic risk model to analyze hydrogen infrastructure," Int. J. Hydrogen Energy, vol. 46, no. 5, pp. 4626–4643, Jan. 2021, doi: 10.1016/J.IJHYDENE.2020.10.191.
[70] M. Honselaar, G. Pasaoglu, and A. Martens, "Hydrogen refuelling stations in the Netherlands: An intercomparison of quantitative risk assessments used for permitting," Int. J. Hydrogen Energy, vol. 43, no. 27, pp. 12278–12294, 2018, doi: 10.1016/j.ijhydene.2018.04.111.
[71] J. Kim, Y. Lee, and I. Moon, "An index-based risk assessment model for hydrogen infrastructure," Int. J. Hydrogen Energy, vol. 36, no. 11, 2011, doi: 10.1016/j.ijhydene.2011.02.127.
[72] Z. Hameed, J. Vatn, and J. Heggset, "Challenges in the reliability and maintainability data collection

for offshore wind turbines," Renew. Energy, vol. 36, no. 8, pp. 2154–2165, Aug. 2011, doi: 10.1016/J.RENENE.2011.01.008.
[73] R. Mogre, S. S. Talluri, and F. Damico, "A decision framework to mitigate supply chain risks: An application in the offshore-wind industry," IEEE Trans. Eng. Manag., vol. 63, no. 3, 2016, doi: 10.1109/TEM.2016.2567539.
[74] F. Dinmohammadi and M. Shafiee, "A fuzzy-FMEA risk assessment approach for offshore wind turbines," Int. J. Progn. Heal. Manag., vol. 4, no. SPECIAL ISSUE 2, 2013, doi: 10.36001/ijphm.2013.v4i3.2143.
[75] M. Leimeister and A. Kolios, "A review of reliability-based methods for risk analysis and their application in the offshore wind industry," Renewable and Sustainable Energy Reviews, vol. 91. 2018. doi: 10.1016/j.rser.2018.04.004.
[76] M. Shafiee, "A fuzzy analytic network process model to mitigate the risks associated with offshore wind farms," Expert Syst. Appl., vol. 42, no. 4, pp. 2143–2152, Mar. 2015, doi: 10.1016/J.ESWA.2014.10.019.
[77] M. M. Luengo and A. Kolios, "Failure Mode Identification and End of Life Scenarios of Offshore Wind Turbines: A Review," vol. 8, pp. 8339–8354, 2007, doi: 10.3390/en8088339.
[78] N. Khakzad, F. Khan, and P. Amyotte, "Quantitative risk analysis of offshore drilling operations: A Bayesian approach," Saf. Sci., vol. 57, 2013, doi: 10.1016/j.ssci.2013.01.022.
[79] G. Song, F. Khan, H. Wang, S. Leighton, Z. Yuan, and H. Liu, "Dynamic occupational risk model for offshore operations in harsh environments," Reliab. Eng. Syst. Saf., vol. 150, pp. 58–64, Jun. 2016, doi: 10.1016/J.RESS.2016.01.021.
[80] X. Zhang, L. Sun, H. Sun, Q. Guo, and X. Bai, "Floating offshore wind turbine reliability analysis based on system grading and dynamic FTA," J. Wind Eng. Ind. Aerodyn., vol. 154, pp. 21–33, Jul. 2016, doi: 10.1016/J.JWEIA.2016.04.005.
[81] A. A. Taflanidis, E. Loukogeorgaki, and D. C. Angelides, "Offshore wind turbine risk quantification/evaluation under extreme environmental conditions," Reliab. Eng. Syst. Saf., vol. 115, 2013, doi: 10.1016/j.ress.2013.02.003.
[82] J. J. Nielsen and J. D. Sørensen, "On risk-based operation and maintenance of offshore wind turbine components," in Reliability Engineering and System Safety, 2011, vol. 96, no. 1. doi: 10.1016/j.ress.2010.07.007.
[83] J. S. Chou, P. C. Liao, and C. Da Yeh, "Risk analysis and management of construction and operations in offshore wind power project," Sustain., vol. 13, no. 13, 2021, doi: 10.3390/su13137473.
[84] A. Staid and S. D. Guikema, "Risk Analysis for U.S. Offshore Wind Farms: The Need for an Integrated Approach," Risk Analysis, vol. 35, no. 4. 2015. doi: 10.1111/risa.12324.
[85] J. Kang, L. Sun, H. Sun, and C. Wu, "Risk assessment of floating offshore wind turbine based on correlation-FMEA," Ocean Eng., vol. 129, 2017, doi: 10.1016/j.oceaneng.2016.11.048.
[86] K. Gkoumas, "A risk analysis framework for offshore wind turbines," 2010. doi: 10.1061/41096(366)179.
[87] D. C. Álvarez, A. L. Rodríguez, and J. A. M. Dono, "Risk management and design of mitigation plans through discrete events simulation and genetic algorithms in offshore wind processes," Int. J. Serv. Comput. Oriented Manuf., vol. 3, pp. 274–292, 2018.
[88] S. Zhou and P. Yang, "Risk management in distributed wind energy implementing Analytic Hierarchy Process," Renew. Energy, vol. 150, 2020, doi: 10.1016/j.renene.2019.12.125.
[89] M. Desholm and J. Kahlert, "Avian collision risk at an offshore wind farm," Biol. Lett., vol. 1, no. 3, pp. 296–298, 2005, doi: 10.1098/rsbl.2005.0336.
[90] B. Ram, "Assessing integrated risks of offshore wind projects: Moving towards gigawatt-scale deployments," Wind Eng., vol. 35, no. 3, 2011, doi: 10.1260/0309-524X.35.3.247.

[91] X. Bai, L. Sun, and H. Sun, “Risk assessment of hoisting aboard and installation for offshore wind turbine,” in Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE, 2012, vol. 2, pp. 107–144. doi: 10.1115/OMAE2012-83187.
[92] N. Gatzert and T. Kosub, “Risks and risk management of renewable energy projects: The case of onshore and offshore wind parks,” Renew. Sustain. Energy Rev., vol. 60, pp. 982–998, Jul. 2016, doi: 10.1016/J.RSER.2016.01.103.