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Enabling Safe and Sustainable Hydrogen Mobility: Circular Economy-Driven Management of Hydrogen Vehicle Safety

Mohammad Yazdi [1,*], Rosita Moradi [2], Reza Ghasemi Pirbalouti [3], Esmaeil Zarei [4,5] and He Li [6]

1 School of Computing, Engineering & Physical Sciences, University of the West of Scotland (UWS), London E14 2BE, UK
2 School of Business and Law, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia; rm194@uowmail.edu.au
3 Department of Mathematical and Industrial Engineering, Polytechnique Montréal, Montreal, QC H3T 1J4, Canada; rereza.ghasemi-pirbalouti@polymtl.ca
4 Department of Safety Science, College of Aviation, Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA; zareie@erau.edu
5 Robertson Safety Institute (RSI), Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
6 Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, 1649-004 Lisbon, Portugal; he.li@centec.tecnico.ulisboa.pt
* Correspondence: mohammad.yazdi@uws.ac.uk

Abstract: Hydrogen vehicles, encompassing fuel cell electric vehicles (FCEVs), are pivotal within the UK's energy landscape as it pursues the goal of net-zero emissions by 2050. By markedly diminishing dependence on fossil fuels, FCEVs, including hydrogen vehicles, wield substantial influence in shaping the circular economy (CE). Their impact extends to optimizing resource utilization, enabling zero-emission mobility, facilitating the integration of renewable energy sources, supplying adaptable energy storage solutions, and interconnecting diverse sectors. The widespread adoption of hydrogen vehicles accelerates the UK's transformative journey towards a sustainable CE. However, to fully harness the benefits of this transition, a robust investigation and implementation of safety measures concerning hydrogen vehicle (HV) use are indispensable. Therefore, this study takes a holistic approach, integrating quantitative risk assessment (QRA) and an adaptive decision-making trial and evaluation laboratory (DEMATEL) framework as pragmatic instruments. These methodologies ensure both the secure deployment and operational excellence of HVs. The findings underscore that the root causes of HV failures encompass extreme environments, material defects, fuel cell damage, delivery system impairment, and storage system deterioration. Furthermore, critical driving factors for effective safety intervention revolve around cultivating a safety culture, robust education/training, and sound maintenance scheduling. Addressing these factors is pivotal for creating an environment conducive to mitigating safety and risk concerns. Given the intricacies of conducting comprehensive hydrogen QRAs due to the absence of specific reliability data, this study dedicates attention to rectifying this gap. A sensitivity analysis encompassing a range of values is meticulously conducted to affirm the strength and reliability of our approach. This robust analysis yields precise, dependable outcomes. Consequently, decision-makers are equipped to discern pivotal underlying factors precipitating potential HV failures. With this discernment, they can tailor safety interventions that lay the groundwork for sustainable, resilient, and secure HV operations. Our study navigates the intersection of HVs, safety, and sustainability, amplifying their importance within the CE paradigm. Using the careful amalgamation of QRA and DEMATEL methodologies, we chart a course towards empowering decision-makers with the insights to steer the hydrogen vehicle domain to safer horizons while ushering in an era of transformative, eco-conscious mobility.

Keywords: fuel cell electric vehicles (FCEVs); sustainable development goals; net-zero emissions; adaptive DEMATEL; decision-making; hydrogen vehicle safety

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1. Introduction

In today's world, sustainable development and the circular economy (CE) have become critical imperatives for addressing environmental concerns and reducing our reliance on fossil fuels [1,2]. As part of the global effort to achieve sustainable development goals, the UK has placed considerable emphasis on hydrogen energy, considering it a crucial component of its sustainable development and CE agenda. In 2020, the transportation sector in the UK emerged as the leading contributor to greenhouse gas emissions, responsible for releasing over 90 Mt of CO2e. This amounted to approximately 25% of the country's greenhouse gas emissions [3]. Hydrogen is gaining prominence as a viable fuel alternative with low to zero carbon emissions, playing a crucial role in the decarbonization of the worldwide transportation sector. In particular, the UK recognises the importance of hydrogen vehicles (HVs) in advancing its goals [4,5]. As the UK strives to curb carbon emissions, enhance air quality, and transition to cleaner energy sources, HVs are emerging as a compelling solution with substantial relevance to the country. Similarly, as the global pursuit of sustainable transportation gains momentum, HVs are emerging as a promising solution to reduce emissions and dependence on fossil fuels. However, the successful integration of HVs into mainstream transportation systems hinges on the rigorous assurance of their safety. Ensuring the utmost safety of these vehicles is paramount not only for the well-being of passengers and pedestrians but also for establishing public trust in this innovative technology. In light of these considerations, this study aims to comprehensively analyze and address the critical safety aspects of hydrogen vehicle operation, maintenance, and potential failures, thereby contributing to the overarching goal of fostering a resilient and secure environment for the widespread adoption of HVs. This introduction will explore why HVs are capturing notable attention in the UK and emphasise their contributions to sustainable development and the CE. It will also consider the specific challenges and opportunities faced by the nation in adopting HVs.

HVs are crucial in promoting a sustainable and circular transportation system in the UK using various means. They contribute to renewable energy integration, sustainable fuel production, localised production and distribution, circular business models, recycling and reuse, and job creation and economic growth. The following provides a detailed description of some of these contributions. To begin with, the UK strongly emphasises renewable energy integration, focusing on wind, solar, and tidal power [6,7]. HVs provide a solution for integrating and storing surplus renewable energy, mainly through hydrogen production using electrolysis. This approach optimises the utilisation of renewable resources, preventing waste and contributing to establishing a more circular energy system. Moreover, the UK aligns hydrogen production for vehicle fuelling with CE principles, utilising various waste streams such as agricultural residues, organic waste, and wastewater as feedstocks [8–10]. By converting these waste materials into hydrogen, the country reduces its reliance on fossil fuels, minimises waste generation, and creates a closed-loop system that maximises resource efficiency. Additionally, HVs enable the localised production and distribution of hydrogen fuel, reducing the need for long-distance transportation of fuels [11,12]. This minimises associated carbon emissions and promotes regional self-sufficiency, further enhancing the sustainability and circularity of the transportation system.

However, in addition to the numerous benefits associated with adopting HVs, ensuring the safety of these vehicles is of paramount importance. To fully achieve sustainability goals and realise the potential of HVs within a CE context, it is essential to implement robust supportive safety intervention actions and risk management protocols. Thorough investigation and management of safety concerns related to hydrogen storage, handling, and infrastructure are necessary to ensure public confidence, mitigate risks, and prevent accidents or incidents that could hinder progress towards sustainability goals. Public acceptance of hydrogen transport technology hinges on its ability to achieve a safety level comparable to that of existing gasoline vehicles [13]. UK stakeholders are crucial in fostering public trust and confidence in HV technology by prioritizing supportive safety intervention actions. In addition, it is essential to establish comprehensive safety standards and regulations that guide the design, manufacturing, and operation of HVs, including storage systems and refuelling infrastructure, which should be updated over time by subject matter experts (SMEs) [14]. By adhering to these guidelines, stakeholders can instil confidence in the safety and reliability of HV technology, encouraging wider adoption and supporting the transition towards a more sustainable future.

In practical terms, hydrogen's high energy-to-weight ratio is counterbalanced by the substantial weight of hydrogen storage tanks and related equipment. Consequently, HV storage systems tend to be bulkier and heavier than those used for gasoline or diesel [15,16]. A summary is provided below to refine the understanding of the hazards associated with hydrogen compared to conventional fossil fuels such as methane and gasoline [17].

- Hydrogen, being 14.5 times lighter than air, has greater buoyancy than methane (1.8 times lighter) and gasoline vapour (heavier than air). This causes hydrogen to rise quickly, leading to increased turbulent diffusion and faster reduction of its concentration below the lower flammability limit (LFL).
- Hydrogen presents a higher explosive threat than methane or gasoline due to its broader flammability, detonability limits, and rapid burning velocity. While the lower flammability limit is similar for hydrogen and methane, hydrogen has a significantly more comprehensive range between the LFL and the lower detonability limit. This means a much higher hydrogen concentration is needed than methane to create a detonable mixture.
- Fires develop most rapidly with hydrogen in fuel spill scenarios, followed by methane and gasoline. Gasoline fires last the longest, while hydrogen fires have the shortest duration. However, all three fuels burn at similar flame temperatures.
- Hydrogen used as an industrial gas or fuel cell vehicle fuel is not odorized because adding odorants can contaminate fuel cell catalysts. Additionally, hydrogen is odourless, making leak detection challenging.
- Hydrogen and methane have high autoignition temperatures (585 °C and 540 °C, respectively), while gasoline is more hazardous with a lower range (227 °C to 477 °C).
- Hydrogen fires produce less radiant heat than hydrocarbon fires due to the absence of carbon combustion and the presence of water vapour, reducing the risk of secondary fires.
- Hydrogen burns with a nearly invisible flame during daylight due to its low visibility, although air contaminants may slightly increase visibility. However, hydrogen flames are visible at night.
- Hydrogen molecules, being the smallest, can leak through porous materials, unlike methane and gasoline. However, the difference in leakage rates is minimal. In terms of energy content, hydrogen has three times the energy of methane by mass but only one-third of the energy by volume. Therefore, for pinhole-sized leaks from high-pressure systems, approximately three times the volume of hydrogen will leak compared to methane.

Because of hydrogen's distinctive properties, its safety profile diverges significantly from that of conventional fuels like gasoline and natural gas [18]. Hydrogen has a long history of safe use and storage in the industry as compressed gas or liquefied hydrogen, and metal hydride storage is expected to be equally safe or even safer [19]. While manageable safety concerns exist for future hydrogen applications in industrial and commercial sectors, efforts have been made to address these concerns. However, further safety analyses are necessary, particularly for HVs and transportation purposes.

This paper demonstrates a well-structured organization, commencing with a "Literature review" surrounding hydrogen vehicle safety that underscores its importance in the evolving sustainable energy landscape. This section searches critical aspects of the existing research, providing insights into the significance, challenges, and advancements in hydrogen vehicle safety. It is followed by Section 3, delineating the research approach, data collection methods, and analysis techniques used in this paper. This section provides a comprehensive understanding of this study's execution. Proceeding further, Section 4 undertakes a meticulous analysis and interpretation of the research results, exploring their significance, comparing them with existing literature, and addressing any limitations or discrepancies. Subsequently, Section 5 articulates the practical implementation of the research findings and real-world relevance, specifically within a particular field or industry. It effectively emphasizes this study's implications. Lastly, Section 6 summarizes the essential findings and their implications and suggests potential directions for future research works.

2. State of the Art Review on Hydrogen Safety

As depicted in Figure 1, Part A, the subject of "Hydrogen Safety" has garnered significant attention across diverse application domains. Notably, it has been extensively explored and researched in the fields of energy fuels (29%, 508 records), physical chemistry (25%, 426 records), electrochemistry (25%, 4256 records), chemical engineering (8.8%, 141 records), nuclear science technology (3.4%, 58 records), and others. These statistics highlight the widespread interest and ongoing advancements in enhancing hydrogen safety. A concise bibliometric and meta-data analysis was conducted using the Biblioshiny software package (https://www.bibliometrix.org, accessed on 3 August 2023), implemented in the R programming language [20]. This powerful tool enabled the examination of relevant bibliographic data, providing valuable insights and facilitating a comprehensive understanding of the subject matter. Bibliometric analyses yield invaluable insights for scientists and practitioners investigating a particular field. Examining publication patterns and citation metrics provides a deeper understanding of academic gaps, identifies areas for improvement in the existing literature, and highlights emerging trends or hotspots within a field.

The significance of conducting a bibliometric analysis lies in its ability to provide a comprehensive overview of research trends, publication patterns, and critical contributors within a specific field. It helps identify gaps in the existing literature and informs researchers about the evolving landscape, aiding them in making informed decisions regarding the direction of their research [21,22].

These outcomes offer valuable guidance for further research and aid in shaping the direction of scholarly inquiries and practical applications. An analysis of published articles in the Web of Science database, using the keywords "Hydrogen Safety," unveiled a total of 789 records that specifically address the aspects of operation management within the field of hydrogen safety, as of the end of May 2023. Figure 1, Part B illustrates the thematic evolution of hydrogen safety over time. The main critical observation is the significant increase in scholarly attention devoted to this topic as time has progressed. This indicates the growing importance and recognition of hydrogen safety within the field. Furthermore, the depiction highlights the interconnected nature of this topic and its influence on other related subjects over time. The topics depicted in the evolution of hydrogen safety can build upon or react against previous ones, leading to new interpretations and directions. This interconnectedness contributes to the overall thematic evolution within the realm of hydrogen safety, reflecting the dynamic nature of research and advancements in this field. These records shed light on the intersection between hydrogen safety and operational practices, providing valuable insights for researchers and practitioners in the field. Figure 2 presents the prominent keywords associated with "Hydrogen Safety" investigations, as identified using the "Keywords Plus" analysis. This analysis considers authors and index keywords, with a minimum occurrence threshold of 15. The "Keywords Plus" analysis utilizes a precise algorithm that considers the titles of referenced articles to generate keyword associations [23]. This analysis primarily serves a descriptive purpose rather than focusing solely on keyword analysis. Our data analysis, combined with the relevant literature, supports this observation [24]. In the visual representation, the keyword "Hydrogen" occupies a central position, surrounded by related terms such as "Hydrogen Safety," "Hydrogen Storage," "Computational Fluid Dynamics," "Fuel Cells," and "Risk Assessment." This arrangement signifies the importance and widespread usage of "Hydrogen" in the operation management of hydrogen safety studies. Additionally, close to "Hydrogen," we find keywords related to causal analysis, supply chain, safety engineering, and hydrogen protection approaches. These approaches encompass quantitative and qualitative methodologies and address data and model uncertainties challenges.

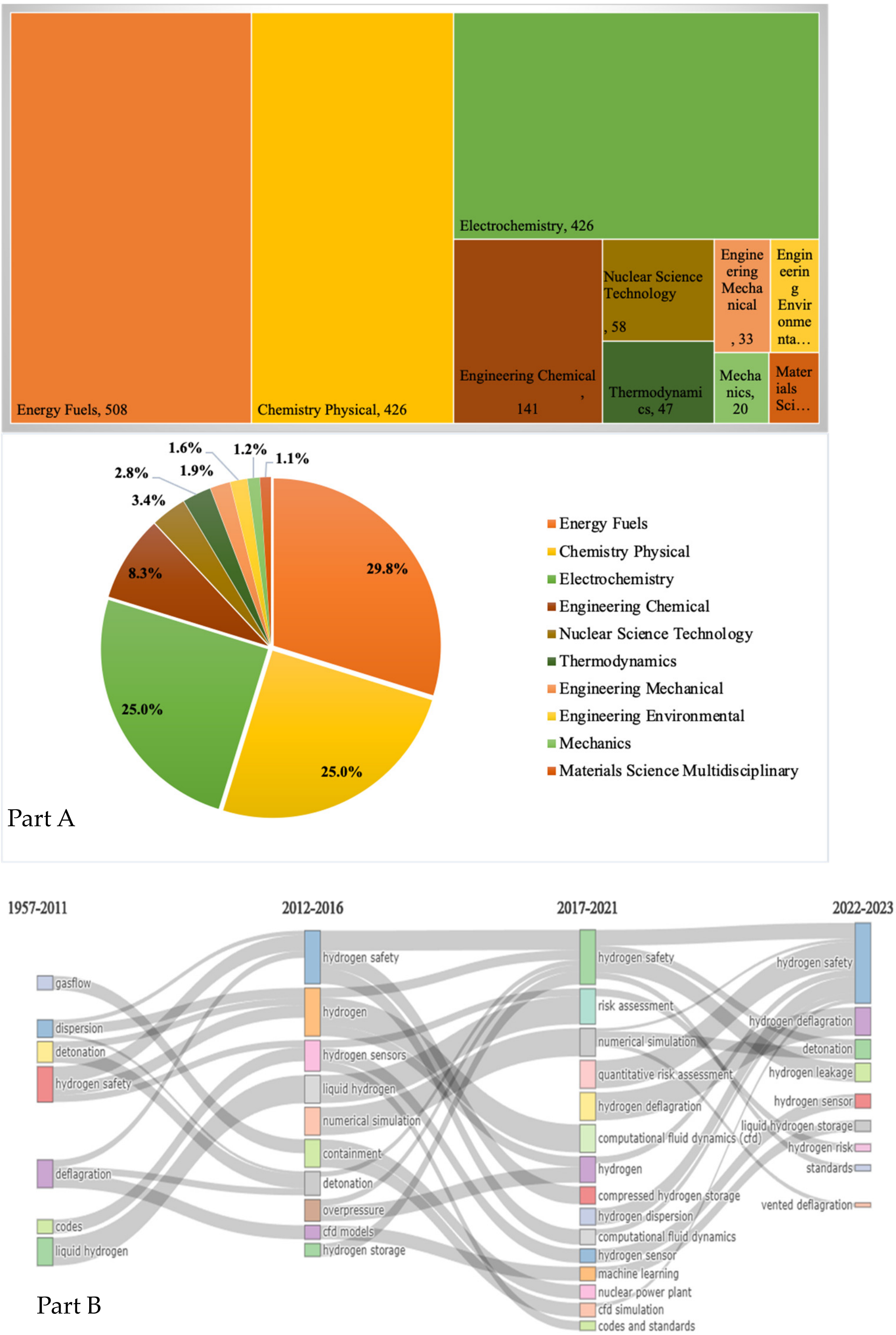

Figure 1. The distribution of the reviewed articles in terms of application domain, which were published by the end of May 2023 (Source: From WoS), Part A, the subject of "Hydrogen Safety" has garnered significant attention across diverse application domains, and Part B illustrates the thematic evolution of hydrogen safety over time.

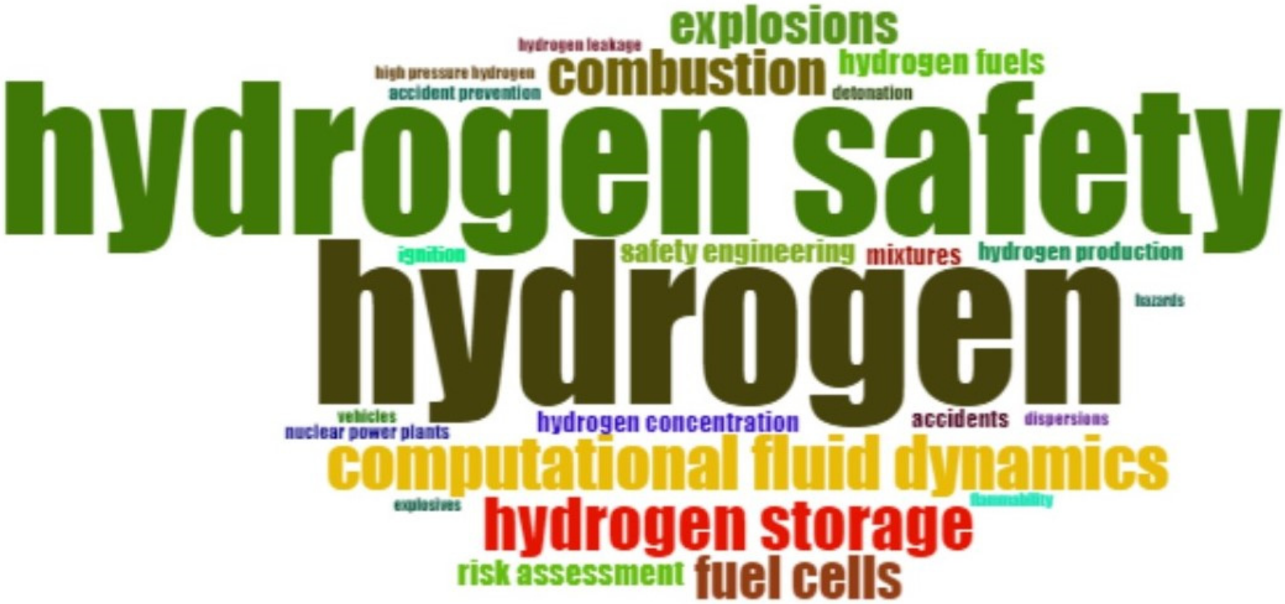

Figure 2. The co-occurrence importance of related keywords (Note: the size and centrality of keywords show the importance rate of each one).

The theoretical analysis in our study reveals significant insights that collectively shape the landscape of hydrogen safety and operational management. We ascertain the interdisciplinary nature of hydrogen safety using attention garnered across diverse application domains, spanning energy fuels, physical chemistry, electrochemistry, chemical engineering, nuclear science technology, and more. This confluence underscores the comprehensive significance of hydrogen safety in multifaceted contexts. Moreover, our examination of thematic evolution over time highlights a noticeable upsurge in scholarly attention, signalling growing importance within the field. The visual representation underscores interconnections among related subjects and their cascading impact on the trajectory of hydrogen safety, reflecting the dynamic evolution of the research. Our analysis of prominent keywords associated with "Hydrogen Safety" unveils central concepts, with "Hydrogen" positioned at the core, surrounded by terms like "Hydrogen Safety," "Hydrogen Storage," "Computational Fluid Dynamics," "Fuel Cells," and "Risk Assessment." This arrangement emphasizes hydrogen's pivotal role in operational management strategies. Its proximity to keywords related to causal analysis, supply chain, safety engineering, and hydrogen protection approaches underscores the diverse methodologies used to address data uncertainties and model challenges. Collectively, the theoretical insights illuminate an intricate tapestry where hydrogen safety intersects with disciplines, evolves, and is anchored by fundamental concepts and operational strategies, enriching our understanding for subsequent empirical investigations.

The existing state-of-the-art research assesses the risk of hydrogen safety and HVs primarily with theoretical-based approaches utilizing common risk assessment methods such as the failure mode and effect analysis (FMEA) [25], the bow-tie technique [26], and hazard and operability studies (HAZOP) [27–30]. For instance, Park et al. [31] conducted a study that examined the risk associated with hydrogen refuelling stations (HRSs) using toolkit software [32]. In a related study, a hybrid framework based on a fuzzy fault tree (FT) and HAZOP was used to assess the leakage risk of liquid HRS [33]. Wang et al. [34] utilised a DBN-based risk assessment system for hydrogen leakage in the diesel hydrogenation process. Watanabe et al. [35] introduced an innovative integrated equipment set designed for the safety assessment of HVs. With an examination of the existing literature, it becomes evident that new FCEVs are increasingly popular. Consequently, studying hydrogen energy and the fire hazards related to HVs has attracted substantial attention from researchers and experts. In light of this, an endeavour was undertaken to develop a model that simulates the slow release of hydrogen in accidental scenarios [36]. In a separate study [37], the authors used a transient hydrogen leak simulation in a closed cylinder chamber to identify a high-risk condition. Their findings effectively increased awareness regarding potential safety concerns associated with hydrogen, highlighting the importance of addressing such issues. A high-potential accidental hydrogen leak scenario was simulated with the development of a mobile hydrogen refuelling station platform (HRPP). The results highlighted the crucial role of ventilation in enhancing hydrogen safety during leakage scenarios. The findings emphasize the continuous need to consider ventilation measures to mitigate risks associated with hydrogen leaks [38]. The research conducted by Qian et al. [39] delved into the intriguing dynamics of hydrogen leaks in HRS. Their findings indicated that combustible gas clouds exhibit a larger contour when a hydrogen leak occurs in a direction opposing the wind. These insights offer practical implications for enhancing safety protocols and designing efficient mitigation strategies in HRS, emphasizing the significance of considering wind conditions in the operation management of hydrogen safety. Shen et al. [40] investigated hydrogen leakages from HVs in outdoor car parks, considering different hydrogen leak diameters and parking configurations. The results underscore the significance of considering both leak size and parking layout as crucial factors in effectively mitigating the potential hazards of hydrogen leakage in outdoor car parks. These findings offer valuable insights for enhancing supportive safety intervention actions and designing appropriate infrastructure to minimize the risks of hydrogen leakage in HVs within car park environments. In another research study [41], the authors conducted a simulation of a hydrogen leak at a HRS. Their objective was to examine the influence of wind directions, leak directions, and different equipment on the outcomes of the leak scenario. In their analysis, Sun and Li [42] examined the typical progressions of accidents involving hydrogen car collisions on the road. Their investigation specifically focused on the notable hydrogen-related consequences of such accidents, including impinging jet fires and catastrophic tank ruptures.

The process flow diagram of HVs is carefully examined in this study. Using a comprehensive review of the existing literature and consultation with SMEs in the field, the most severe and likely failures are identified. The authors make their best effort to understand and assess the critical root causes using a fault tree analysis. Subsequently, a series of practical and feasible supportive safety intervention actions, such as corrective and intervention actions, are proposed to effectively address the criticality of the identified root causes of HV failures. These measures are designed to mitigate the risks associated with the identified failure modes in the HV system. Furthermore, the causality and relationships between root causes and supportive safety intervention actions are examined using a progressive decision-making framework within the context of DEMATEL and an advanced extension of fuzzy set theory. This framework facilitates a comprehensive analysis of the cause–effect relationships and provides insights into the interdependencies between the root causes and effectiveness of the suggested supportive safety intervention actions. Keeping in mind the superiority of the DEMATEL [43,44] technique compared with the other structural causal dependency decision-making tools like fuzzy cognitive maps (FCMs) [45,46], interpretive structural modelling (ISM) [47,48], and dynamic Bayesian networks (DBNs) [23,49,50], DEMATEL is applied to examine the role of divining factors in sustainable operations management of HV safety in a CE. As a result, decision-makers are empowered to implement, promote, and revise practical strategic plans for sustainable operations management of HV safety in a CE framework. It is important to note that the objective of this study is not limited solely to the UK; instead, it aims to shed light on the most vulnerable contributing factors for establishing sustainable operations management of HV safety in a CE context over time. This knowledge can be applied globally to enhance HV safety in pursuing a sustainable CE.

Based on the comprehensive review of the existing literature, coupled with the notable progress in sustainable operations management and the increasing significance of hydrogen safety highlighted in recent scholarly publications, the primary objective of this research work is to address the following research questions in a concise and precise manner:

- What are the critical root causes of HV failures, and how can they be addressed using effective supportive safety intervention actions?
- What are the key driving factors for implementing supportive safety intervention actions for HVs in a CE?
- What are the key implications and recommendations for decision-makers to ensure the safe deployment and sustainable operation of HVs in a CE context?

3. Methodology

This section aims to enhance and elaborate on the proposed framework for assessing and evaluating the sustainable operations management of HV safety from a CE perspective. By integrating CE principles into the evaluation process, a more comprehensive and environmentally conscious approach can be used for the operation of HV safety. Figure 3 provides an overview of the key four-step framework. This developed framework provides practical decision-makers and policymakers with valuable insights to operate HVs safely and achieve their sustainability objectives effectively. In the pre-step, the study's system and scope are defined and all necessary process information is gathered. Step one involves implementing a risk assessment technique, specifically using fault tree analysis, to identify the root causes of the worst-case HV scenarios. If sufficient information is available at this stage, then the process can proceed. However, if additional data are required, it is necessary to return to the pre-step and complete further data collection. Step two focuses on establishing the causal relationships between the critical root causes identified in step one and formulating corresponding safety intervention actions. These actions are designed to support and address the identified root causes effectively. In step three, a validation process is conducted to demonstrate the robustness and resilience of the proposed approach. This validation serves to ensure the reliability and effectiveness of the framework. Step four entails a subjective examination of the role played by the supportive actions in achieving sustainability goals. This step explores how qualitatively the identified interventions contribute to the overall sustainability objectives. Finally, if new information becomes available during the evaluation process, then it is necessary to return to step one to reassess and update the risk assessment and intervention actions accordingly.

The details of each step are explained as follows.

3.1. Pre-Step: Collecting Process Information and Defining Scope

The process of collecting information and defining the scope is crucial for any project. It involves gathering relevant data using various means, such as conducting interviews with SMEs, reviewing existing documentation like process manuals, standard operating procedures, or previous project reports, and observing workflows to understand the processes involved comprehensively. This collected information serves as the basis for determining project objectives, identifying project boundaries, establishing requirements, and defining success criteria. It is essential to document all these details in a scope statement, ensuring that decision-makers such as project managers and policymakers, as well as all stakeholders, have a clear understanding of the project's goals and limitations. This clarity facilitates effective planning and execution. In this study, the initial pre-step of collecting information and defining the scope is of utmost importance as it not only serves as a reference point but also lays the foundation for the subsequent steps of the proposed approach, including its planning and execution.

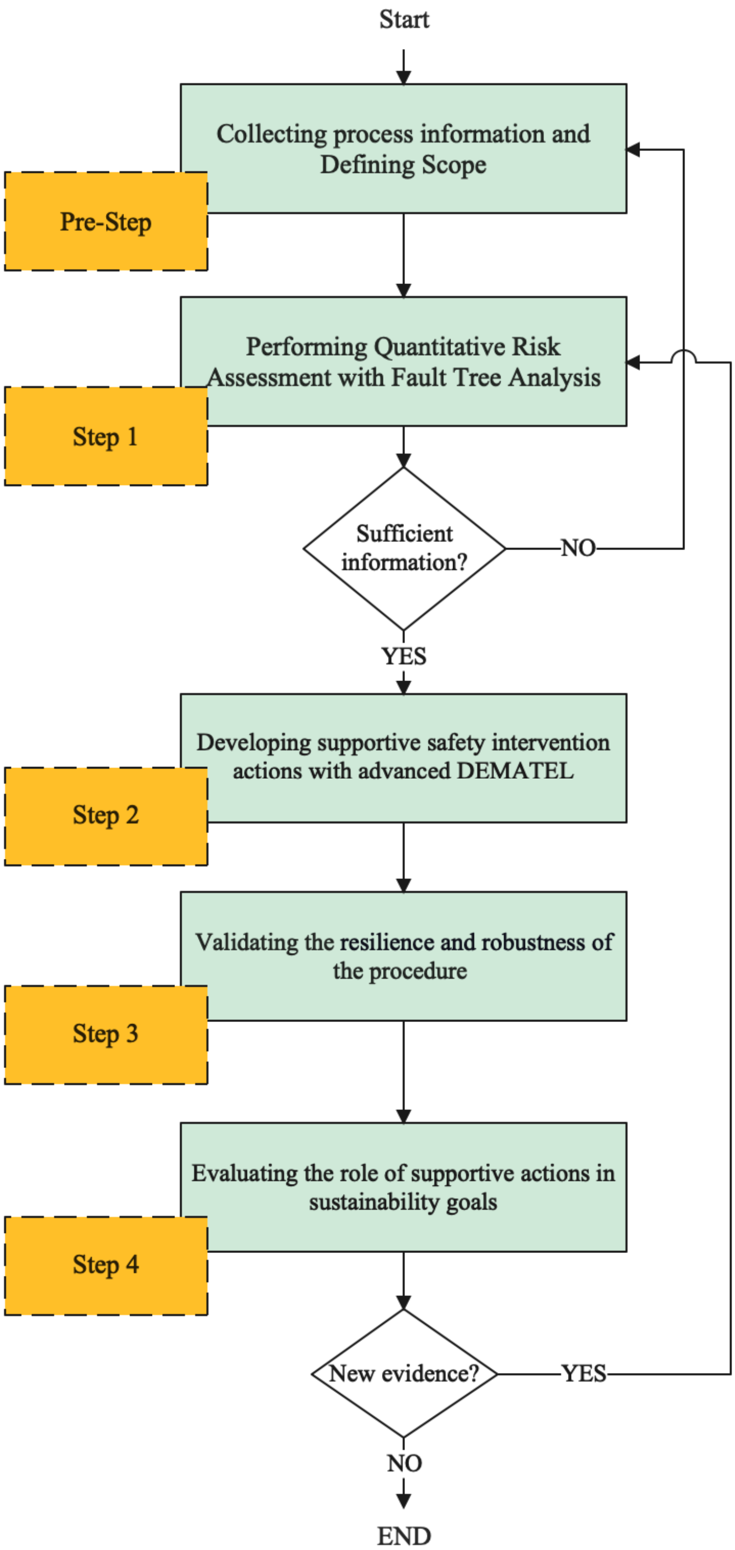

Figure 3. The developed framework for assessing and evaluating the sustainable operations management of HV safety from a CE perspective.

3.2. *Step Two: Performing a Quantitative Risk Assessment with a Fault Tree Analysis*

In this step, FTA, a deductive technique, is performed by defining the top event (TE-specific loss event [51]) to analyse. Then, basic events (BEs) contributing to the TE are identified, and logical gates (e.g., AND, OR, NOT) are determined to represent their relationships. A fault tree is constructed by graphically representing these events and gates from top to down. Probabilities are assigned to the BEs (i.e., from historical data, the existing literature, reliability analyses, statistical analyses, SMEs, and industry standards and guidelines [23,52–54]) and the following calculations are performed in a common FTA to determine the probabilities of intermediate and TEs.

$$P_{OR} = 1 - \prod_{i=1}^{n}(1 - P_i) \tag{1}$$

$$P_{AND} = \prod_{i=1}^{n}(P_i) \tag{2}$$

$$P_{TE} = \prod_{j \in M}\left(1 - \prod_{BE_i \in Q_j}(1 - P_i)\right) \tag{3}$$

where P_i indicates the BE_i probability and Q_j denotes a solo or a group of BEs in a constructed FT for all $j \in M$.

In order to assess the importance of BEs in contributing to the occurrence of a TE and identify critical factors or components that significantly impact system reliability, the Birnbaum importance measure (BIM) is used as a quantitative metric [55]. The BIM quantifies the extent to which a particular BE affects the probability of the TE by evaluating the change in probability when that BE occurs or fails to occur.

The BIM is calculated as the difference between the probability of the TE, given that the BE occurs, and the probability of the TE, given that the BE does not occur. A higher BIM value indicates a more significant influence of the corresponding BE on the occurrence of the TE.

Mathematically, the BIM is expressed as P(TE | BE occurs)—P(TE | BE does not occur). By comparing the probabilities of the TE under different conditions (when the BE occurs and when it does not occur), the BIM provides insights into the relative significance of each BE in the constructed FT.

3.3. Step Three: Developing Supportive Safety Intervention Actions with Adaptive DEMATEL

The DEMATEL technique, in its advanced adaptation, is a powerful method used in this step to analyse the complex interconnections among critical BEs and supportive safety intervention actions. Its primary objective is to identify the direct influence matrix by examining the logical relationships between these elements. This influence matrix quantifies the impact of two factors on each other within the system. Moreover, DEMATEL has the unique capability to discern whether a factor acts as a cause or an effect, and it accomplishes this without requiring extensive information [56]. Instead, its focus lies on identifying the critical criteria that exert significant influence on other criteria.

In this step, a set of supportive safety intervention actions is implemented to develop strategies and measures pertaining to BEs, which are critical elements that significantly impact safety within the HV system. The aim is to enhance safety within the HV system while aligning with targeted sustainability goals. To develop effective and supportive international safety actions, it is highly recommended to account for keynotes including, but not limited to, the following:

i. Safety Gaps and Risks Identification: Perform a comprehensive analysis to identify potential safety gaps and risks within the HV system. This involves conducting a thorough assessment to identify areas where supportive safety intervention actions may be lacking or where risks are present.
ii. Safety Objectives Clarification: Clearly define safety objectives that align with the country's overall sustainability goals and priorities. It is important to have well-defined and specific safety objectives that guide the development of intervention actions.
iii. Stakeholders Engagement: Engage with stakeholders to ensure that different viewpoints are considered and that the intervention addresses all parties' needs and con-

cerns. This includes involving key stakeholders such as industry experts, policymakers, regulatory bodies, and community representatives.

iv. Supportive Safety Intervention Action Generation: Brainstorm and generate various intervention options to reduce the probability of BE occurrence and address the identified safety gaps. Consider proactive measures, such as training programs and safety protocols, as well as reactive measures, such as incident response procedures and emergency preparedness.

v. Action Evaluation and Prioritization: Evaluate and prioritize each intervention option's potential effectiveness, feasibility, and cost. This step involves assessing the impact and feasibility of each proposed action, considering factors such as resources required, timeframes, and potential risks and benefits.

vi. Continuous Improvement: Continuously review and improve the effectiveness of the implemented safety interventions. This can be achieved by collecting feedback from stakeholders, conducting audits to assess compliance and performance, and analysing safety data to identify areas for improvement. The goal is to continually enhance the supportive safety intervention actions and effectively address the identified safety gaps.

It should be noted that developing supportive safety intervention actions is an ongoing process that requires a proactive approach, collaboration, and a commitment to continuous improvement to enhance system safety. Once a well-defined set of safety intervention actions has been developed, proceeding with the following key steps of adaptive DEMATEL is crucial:

A. Clearly define the problem that requires analysis and decision-making.

B. Identify the factors or variables that are relevant to the problem. Let us denote all contributing factors as $F_1, F_2, F_3, \ldots, F_n$.

C. Construct "$Z_k = [z_{ij}]_{n\times n}$" as the single influential matrix, where "z_{ij}" signifies the influence of F_i on F_j, where $i, j = 1, 2, \ldots, n$. In this study, the evaluation scale used for pairwise comparison with adaptive DEMATEL consists of nine levels: −4, −3, −2, −1, 0, 1, 2, 3, and 4 [57]. These levels correspond to different degrees of influence, where −4 represents "very high negative influence," −3 stands for "high negative influence," −2 denotes "medium negative influence," −1 indicates "low negative influence," 0 signifies "no influence," 1 signifies "low positive influence," 2 denotes "medium positive influence," 3 stands for "high positive influence," and 4 represents "very high positive influence." This comprehensive scale allows for a nuanced assessment of the impact of factors under consideration.

D. The direct-influence matrix, denoted as "$X = [x_{ij}]_{n\times n}$", is normalized as "$X = \frac{1}{max\ \sum_{j=1}^{n} a_{ij}} \times Z$", where $1 \le i \le n$. In this expression, Z represents the original direct-influence matrix X, and the maximum of the sum $\sum_{j=1}^{n} a_{ij}$ ensures normalization. It is important to note that all elements of matrix X are in the range [0, 1]. Additionally, "$\sum_{j=1}^{n} x_{ij} \ge 0$" or "$\sum_{j=1}^{n} x_{ij} \le 1$", meaning that the sum of each row in matrix X is non-negative and no greater than 1. The total direct-influence matrix, denoted as "$T = [t_{ij}]_{n\times n}$", is determined as "$T = X + X^2 + X^3 + \ldots + X^h$". Here, the indirect influence of factor i on factor j is represented by "t_{ij}". The total direct-influence matrix captures the entire relationship among the contributing factors, incorporating both direct and indirect influences. As h approaches infinity ("$h \to \infty$"), the total direct-influence matrix can be formulated as "$T = X\,(I - X)^{-1}$". In this formulation, I represents the unit matrix based on Markov chain theory and "X^h" indicates the matrix X raised to the power of h.

E. After obtaining the total direct-influence matrix, we can produce the "influential relation map" C and the "influential relation map" R. The influential relation map C is a row vector, denoted as "$C = [\sum_{i=1}^{n} t_{ij}]_{1\times n} = [t_{\cdot j}]_{1\times n}$". It represents the column summation of the total direct-influence matrix and shows the summation of influences on each factor. In other words, C captures the influences on each factor from other factors. Similarly, the influential relation map R is a column vector, denoted as "$R = \left[\sum_{i=1}^{n} t_{ij}\right]_{n\times 1} = [t_{i.}]_{n\times 1}$". It represents the row summation of the total direct-influence matrix and shows the summation of influences that each factor has on the other factors, either directly or indirectly.

F. For each factor i, consider that the sum of R and C, denoted as "$R + C$," is referred to as "Prominence/Influence Power". This represents the relative importance of each contributing factor in terms of the influences it receives from itself and other factors. The prominence power provides insights into the specific control degree of the complex system, such as in system safety and reliability analysis. Similarly, the difference between R and C, denoted as "$R - C$" is referred to as "Relation/Dependency". The relation is obtained for the vertical axis and highlights the net effect of each factor. If the condition "$\left(t_{.j} - t_{i.}\right) > 0$" is satisfied, then the contributing factor F_j becomes the cause factor since it influences (net) the other contributing factors. On the other hand, if the condition "$\left(t_{.j} - t_{i.}\right) < 0$" is satisfied, then the contributing factor F_j is influenced by other contributing factors, making it part of the effect group. The influential relation map is then created using the scores of "$R + C$" and "$R - C$". This influence diagram provides specific insights for decision-makers in system safety and reliability analysis. It allows for the identification of contributing factors belonging to different classes based on their location in the diagram:

- Zone 1: Critical factors (givers)—These factors have a significant influence on the other factors.
- Zone 2: Driving factors (autonomous givers)—These factors have a high degree of autonomy and influence the other factors significantly.
- Zone 3: Autonomous receivers (independent factors)—These factors receive influences but have a lower degree of influence on the other factors.
- Zone 4: Impact factors (receivers)—These factors are influenced by the other factors and cannot be directly improved. The critical point to note is that contributing factors belonging to Zone 4 cannot be improved directly due to the influence they receive from other factors.

A. To derive the importance weights for the contributing factors, the "Prominence/Influence Power)" score is used. The importance weight of each factor i, denoted as w_i, is calculated using a normalization process. The formula for calculating w_i is "$w_i = \frac{t_{i.} + t_{.j}}{\sum_{i=1}^{n}\sum_{j=1}^{n}(t_{i.} + t_{.j})}$". In this formula, i and j range from 1 to n, representing the contributing factors. The numerator $(t_{i.} + t_{.j})$ represents the prominence score of factor i and factor j, which captures their relative importance in terms of the influences they receive and dispatch. The denominator $(\sum_{i=1}^{n}\sum_{j=1}^{n}(t_{i.} + t_{.j}))$ is the summation of all prominence scores across the entire system, accounting for the total influence dynamics. By dividing the numerator by the denominator, the importance weight w_i is normalized, ensuring that the weights of all factors sum to 1.

B. Analyse and interpret the results obtained using the DEMATEL analysis. Identify the key factors that significantly influence the system and require attention in decision-making.

C. Based on the insights gained from the DEMATEL analysis, make informed decisions and develop action plans to address the identified influential factors. These actions aim to improve the system's safety performance.

The adaptive DEMATEL method represents a progressive augmentation of the standard DEMATEL technique, integrating adaptive methodologies to amplify its efficacy and precision. It revolves around an iterative mechanism where the initial DEMATEL analysis is executed, followed by collecting feedback and validation from stakeholders and SMEs. Subsequently, causal relationships and factor interdependencies undergo thorough re-evaluation and modification based on the received feedback, culminating in an enhanced analysis. This iterative framework facilitates ongoing refinement, accounting for dynamic scenarios and fresh insights and yielding a heightened grasp of the subject system. This iterative process remains in motion until a desirable level of accuracy and consensus is attained. The proficiency of adaptive DEMATEL resides in its ability to empower decision-makers with the integration of real-time data, evolving viewpoints, and changing circumstances, fostering insights that are more reliable and attuned to the latest developments.

3.4. Step Four: Validating the Resilience and Robustness of the Procedure

In this step, the resilience and robustness of the utilized procedure for sustainable operations management of HV safety in a CE are demonstrated using three different assessments.

The first assessment involves conducting a sensitivity analysis (SA), which is a powerful tool for validating the proposed procedure. SA consists of analysing the effects of changes in input variables on the output or results of the procedure [58,59]. This analysis helps determine the reliability of the procedure in different scenarios. By identifying the variables that have the most significant impact on the procedure's outcomes, SA provides a better understanding of their importance. Moreover, SA can uncover potential interactions and dependencies among variables, thereby shedding light on the overall stability of the procedure. A resilient procedure should consistently produce similar results even when input values vary, demonstrating its ability to withstand uncertainties and variations.

The second assessment focuses on evaluating the transitivity property (TP) of the approach. The TP serves as a crucial criterion in determining the effectiveness of a decision-making tool [60]. This property establishes that if a decision-making method ranks a set of contributing factors in a particular order, and the problem is subsequently divided into smaller sub-problems involving two contributing factors at a time, then the rankings obtained from these sub-problems should adhere to the TP. In simpler terms, if contributing factor A is ranked higher than contributing factor B in the original problem, and contributing factor B is ranked higher than contributing factor C within the same problem, then it is expected that contributing factor A will also be ranked higher than contributing factor C in the derived rankings from the smaller sub-problems. Applying the TP ensures consistency and logical coherence in the decision-making process. It prevents situations where conflicting or illogical hierarchies arise when comparing different contributing factors.

The third assessment aims to evaluate the suboptimal nature of contributing factors. A robust decision-making method should maintain the ranking of the most influential contributing factor even when another factor replaces a non-optimality contributing factor with a lower priority. To elucidate this concept, we can examine a hypothetical scenario in which a decision-making approach initially prioritizes influential factors. Within this context, a suboptimal element, labelled as factor A, is substituted with an alternative element, designated as factor B, possessing a lower ranking than factor A. In this case, the method should still indicate that the previously top-ranked contributing factor remains the highest-ranked when the contributing factors are reassessed using the same method. In other words, even though contributing factor B is inferior to contributing factor A, the ranking should not suggest that contributing factor B is now the highest-ranked factor. Additionally, the relative rankings of the remaining contributing factors that have not changed should remain unaffected. By satisfying this assessment, the method ensures consistency and stability in the rankings, irrespective of introducing new contributing factors that have less superiority over the existing ones.

3.5. Step Five: Evaluating the Role of Supportive Actions in Sustainability Goals

Practical safety intervention actions are essential for attaining sustainability goals, encompassing environmental, social, and economic multi-dimensions while ensuring the well-being of future worldwide generations. Sustainability concerns "*meeting present needs without compromising the ability of future generations to meet their own needs*" [61]. This necessitates collective action at various levels to tackle complex challenges such as climate change, resource depletion, pollution, and social inequality [62,63].

During this step, the objective is to evaluate this study's outcomes against the predefined goals set by the United Nations (UN) for sustainability. The UN has established 17 Sustainable Development Goals (SDGs) (https://sdgs.un.org/goals, accessed on 9 June 2023) that provide a comprehensive framework for addressing global challenges and achieving sustainable development. These goals cover many issues: poverty eradication, health and well-being, quality education, gender equality, clean energy, responsible consumption and production, climate action, and sustainable cities and communities. To conduct the assessment, it is necessary to establish specific criteria for each sustainability goal. These criteria are unique and vary depending on the respective goal, while they generally revolve around crucial indicators and targets associated with each SDG. For example, the criteria for evaluating progress towards clean energy include renewable energy adoption, reduced greenhouse gas emissions, and access to affordable and sustainable energy sources.

Examining this study's outcomes against these criteria makes it possible to determine the extent to which this study's results align with the defined objectives and contribute to fulfilling the UN sustainability goals. The benchmark of this study's results against the 17 UN sustainability goals allows for a systematic and accurate assessment of its impact and alignment with broader sustainability objectives. It also delivers valuable insights into areas where further advancements might be required to enhance sustainability developments.

4. Application of This Study

This section applies the proposed approach to a real-world case study concerning an HV to assess its safety and evaluate the effectiveness of the methodology. Focusing on HVs aims to address the specific concerns and challenges associated with adopting hydrogen as a fuel source in the UK transportation sector and discovering their environmental and economic benefits.

Light-duty vehicles, comprising cars, taxis, and vans, accounted for almost 70% of the UK transportation sector's emissions in 2020. However, despite their substantial contribution to emissions, the demand for hydrogen-fuelled commercial vehicles in the UK market still needs to grow [3,11]. This application allowed us to gain practical insights into the risks and potential failures related to HVs, while also testing the feasibility and applicability of our integrated approach in a real context and contributing to the broader efforts of achieving a sustainable and safe transportation system.

The performance details of each individual step are provided below.

4.1. Pre-Step: Collecting Process Information and the Defining Scope

Figure 4 illustrates the breakdown of a hydrogen fuel cell vehicle's performance into three key sectors. The initial stage involves storing hydrogen obtained from the refuelling process in specialized tanks designed to withstand pressures ranging from 35 to 70 MPa. Various safeguards were implemented to enhance the reliability of the storage section and mitigate the potential risks associated with hydrogen. These include implementing safe design regulations, incorporating pressure safety valves, and utilizing thermal pressure relief devices (PRDs) [42]. The second section of the system is responsible for delivering hydrogen to the fuel cell at a precise and controlled pressure. This section comprises a supply line, regulator valves that step down the pressure in three stages to a range of 0.3–0.7 MPa, and safety valves. The final section is the fuel cell, which converts the energy stored in hydrogen into electrical power. Supporting subsystems, including the hydrothermal and air supply system, ensure the fuel cell's proper functioning. The electrical power generated is then utilized to drive the electric motor and propel the vehicle [64,65].

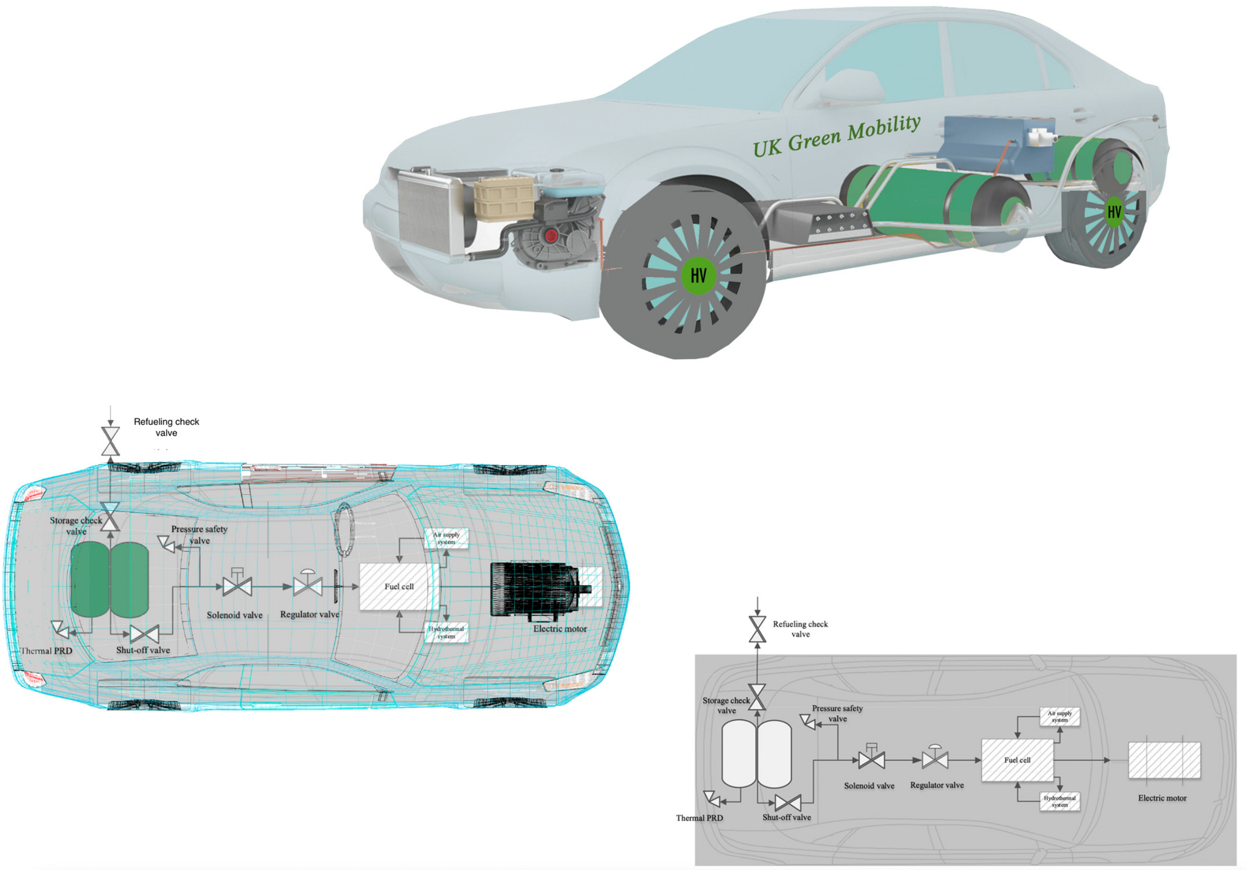

Figure 4. The schematic process of a hydrogen fuel vehicle.

4.2. Step Two: Performing Quantitative Risk Assessment with Fault Tree Analysis (FTA)

To conduct a fault tree analysis for hydrogen leakage, the initial step involves identifying the fundamental events that can contribute to such leakage. These events have been determined using hazard identification conducted on HVs. However, due to specific data gaps in HV research, risk assessments of natural gas cars and comparable components were utilized to supplement this analysis. Based on the hazards associated with hydrogen, the primary concern for HVs is the loss of hydrogen containment, which can result in fire, explosion, injuries to users under high-pressure conditions, or frostbite in cryogenic conditions [66]. Therefore, the first step in enhancing HV safety involves assessing the risk of hydrogen leakage. In HVs, hydrogen leakage can occur due to several reasons, which can be categorized into two main groups. The first category relates to equipment failure caused by non-operational factors, including poor manufacturing, material defects, inadequate inspection and maintenance, operation in harsh environments, and accidents. It should be noted that during accidents, different components of the system have varying probabilities of being damaged [28,67]. The second category of hydrogen leakage in HV is associated with operational reasons that result in system overpressure. Two types of causes can lead to overpressure. External causes encompass events like external fires, collisions, and improper behaviour of passengers and users. Internal causes vary across different sections of the fuelling system. Failure of control valves within the system is a significant reason for overpressure. In the storage system, which poses a primary safety concern due to the high-pressure hydrogen storage [64], the rapid filling can also cause overpressure in the storage tanks [68]. Additionally, the performance of a fuel cell is influenced by the functioning of the fuel stack. Fuel impurities, which can chemically degrade the membrane, along with failures in the air supply system and the hydrothermal cooling system, present three threats that can compromise fuel cell performance and lead to excessive temperatures and overpressure [25].

Thus, this analysis includes the consideration of hydrogen leakage as a TE. Using the root cause analysis process, all potential BEs that contribute to the occurrence of the TE are identified. The logical relationships between the BEs, intermediate events, and the TE are represented using logical AND/OR gates. A depiction of the FT analysis is illustrated in Figure 5. Subsequently, using a comprehensive approach involving an analysis of historical data, examination of the existing literature, reliability analysis, and input from SMEs, the appropriate failure probabilities are assigned to the BEs. Equations (1)–(3) are then applied to calculate the probabilities of the intermediate events and TE. The TE is obtained as 2.69×10^{-1}.

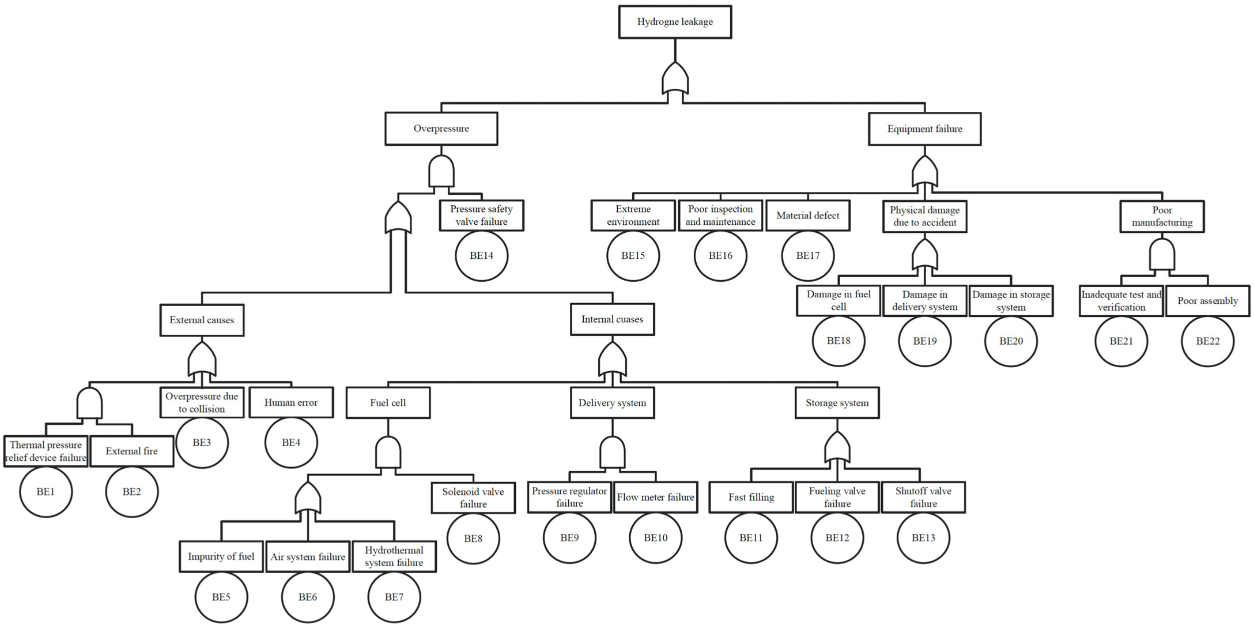

Figure 5. Fault tree analysis of hydrogen leakage as a top event.

It should be added that, in the context of our study, "human error" refers to unintentional or inadvertent actions or decisions made by individuals involved in various aspects of hydrogen vehicle operations. These errors can arise due to factors such as miscommunication, lack of training, fatigue, distraction, or inadequate procedures. Human errors have the potential to contribute to safety incidents or failures within the hydrogen vehicle system. Addressing human error involves understanding the underlying factors that lead to these errors and implementing measures to minimize their occurrence, often with improved training, standardized procedures, and design modifications to mitigate their impact on system safety. A "material defect" pertains to a flaw, imperfection, or irregularity within the components or materials used in hydrogen vehicles. These defects can result from manufacturing processes, material inconsistencies, or external factors. Material defects can potentially compromise the integrity, performance, or safety of hydrogen vehicle components, leading to operational failures. Identifying and addressing material defects involves rigorous quality control, testing, and adherence to industry standards to ensure that members meet the required specifications and are free from defects that could lead to vulnerabilities or failures within the system.

A comprehensive BIM analysis determined the significance of the BEs in influencing TE occurrence and identifying critical factors that substantially impact system reliability. The outcomes of the criticality analysis are presented in Table 1. It can be concluded that the most critical BEs are BE.15, BE.20, BE.19, BE.18, and BE.17.

Table 1. The criticality analysis results of BEs using BIM.

BE Tag.	BEs Description	Probability	Reference(s)	BIM	Ranking
BE.1	TRPD failure	0.220%.	[69]	0.000%	16
BE.2	External fire	0.454%	[42]	0.000%	21
BE.3	Overpressure due to collision	0.050%	[67]	0.022%	11
BE.4	Human error	1.000%	[70,71]	0.019%	13
BE.5	Impurity of fuel	0.100%	[15]	0.000%	18
BE.6	Air system failure (blower)	0.001%	[72]	73.837%	6
BE.7	Hydrothermal system failure (pump)	1.000%	[73]	0.000%	17
BE.8	Solenoid valve failure	0.005%	[72]	0.000%	15
BE.9	Pressure regulator valve failure	0.000%	[72]	0.000%	19
BE.10	Flow meter failure	0.000%	[74]	0.000%	20
BE.11	Fast filling due to overpressure in dispenser	3.000%	[33]	0.019%	12
BE.12	Fueling valve failure	0.001%	[75]	0.018%	14
BE.13	Shutoff valve failure	0.026%	[75]	73.837%	5
BE.14	Pressure safety valve failure	0.000%	[76]	0.000%	8
BE.15	Extreme environment	10.000%	[77]	92.296%	1
BE.16	Poor inspection and maintenance	13.000%	[78]	73.837%	7
BE.17	Material defect	0.048%	[34]	73.872%	4
BE.18	Damage in fuel cell	0.763%	[28]	74.404%	3
BE.19	Damage in delivery system	0.763%	[28]	74.404%	3
BE.20	Damage in storage system	6.230%	[28]	78.742%	2
BE.21	Inadequate test and verification	1.900%	[78]	0.044%	10
BE.22	Poor assembly	0.060%	[33]	3.692%	9

4.3. Step Three: Developing Supportive Safety Intervention Actions with Adaptive DEMATEL

In this step, a comprehensive array of safety intervention measures is implemented to strategically formulate a range of responses. These responses are meticulously tailored to address the top ten critical BEs effectively identified using their respective BIM values. By focusing on these pivotal BEs, we aim to establish a framework that mitigates potential risks and bolsters the overall safety landscape. As outlined in step three of the methodology, the objective is to improve safety within the HV system while aligning with the predetermined sustainability objectives. Considering the mentioned keynotes in step three, a thorough evaluation led to the generation of the most practical and viable supportive safety intervention actions, as summarised in Table 2.

Next, the adaptive DEMATEL technique is used to identify the key driving factors using a cause-and-effect analysis among the critical BEs and supportive safety intervention actions. For further reference, the specific computations involved in the adaptive DEMATEL methodology are provided in Supplementary Materials. It is important to emphasise that adaptive DEMATEL involves an ongoing process. In this study, we used a proactive approach with a strong emphasis on collaboration and a significant commitment to continuous improvement, all aimed at enhancing the safety of the HV system.

Table 2. The generated supportive safety intervention actions for critical BEs.

Tag	Descriptions
SSIA.1	To facilitate troubleshooting the motor and mechanical components, inspecting electrical connections, performing preventive maintenance, testing the system, and documenting the process for future reference.
SSIA.2	To facilitate future maintenance and troubleshooting; involves inspecting, repairing or replacing the valve and its components if needed, ensuring proper connections and seals, and testing functionality.
SSIA.3	To facilitate inspecting and cleaning the valve, repairing or replacing it if necessary, calibrating and adjusting the valve, evaluating the system for contributing factors, testing and validating the repaired or replaced valve, and implementing regular maintenance procedures. In critical cases, the possibility of implementation of redundant safety valves should be evaluated.
SSIA.4	To implement systems for continuous monitoring of environmental conditions, such as temperature, humidity, air quality, and radiation levels, enabling the timely detection of changes and potential risks. To ensure optimal performance in extreme environments, it is advisable for manufacturers to design and manufacture cars specifically tailored to the prevailing weather conditions in which they will be used. This approach recognises that vehicles utilised in such challenging settings require distinct characteristics and features compared with those intended for regular municipal usage. By customising the design and manufacturing process to suit specific weather conditions, manufacturers can enhance the overall functionality and durability of cars, thereby providing better performance and safety in extreme environments.
SSIA.5	To promote a culture of safety and maintenance, educate and train vehicle owners and encourage them to follow the recommended maintenance schedule, address any concerns promptly, and document maintenance history. In addition, it is recommended that manufacturers provide regulations for monitoring and aiding customers to follow the rules about the maintenance plan and train expert repairmen.
SSIA.6	Conduct a thorough investigation to identify the defective material or component; depending on the nature and extent of the material defect, repair or replacement of the affected component may be required. Maintain detailed documentation of the material defect, the actions taken, and any communication with the manufacturer or service providers.
SSIA.7	Evaluate the extent and nature of the damage to the fuel cell (e.g., visual inspection, diagnostic tests) and isolate the damaged fuel cell to prevent any potential leaks or further damage, reassuring the reliability of solenoid valve and that the area around the fuel cell is secured to avoid accidental ignition or environmental contamination. Depending on the severity of the damage, repair, or replacement of the fuel cell may be necessary.
SSIA.8	To assess the impact of the damage on the delivery syst, determine whether it affects the overall operation or specific components such as vehicles, storage areas, or handling equipment; if the damage compromises the safety or integrity of the delivered hydrogen, take measures to secure them. Develop safety measures for improving impact resistance can help decrease the probability of delivery system failure, since pipelines and regulator valves connect the storage tank to the fuel cell. Its responsibility is to decrease the pressure of hydrogen and deliver low-pressure hydrogen to fuel cell.
SSIA.9	To assess the impact of the damage on the storage system, determine whether it affects the structural integrity, security, or functionality of the storage compartments or racks. If the damage compromises the safety or organisation of the items stored in the system, take measures to secure and protect them; thoroughly document the damage by taking photographs, recording details, and collecting relevant evidence; repair or replace the damaged components of the storage system; take the opportunity to reorganise and optimise the storage system while making repairs; and establish a regular inspection and maintenance schedule for the storage system. Developing safety measures for improving impact resistance can help decrease the probability of storage tank failure.
SSIA.10	To introduce or enhance test automation techniques and tools that improve efficiency and effectiveness, ensure adequate and representative test data are available to simulate real-world scenarios, enhance the test environment to resemble the production environment closely and determine if the tests conducted are comprehensive, relevant, and aligned with the intended purpose and requirements of the system or product.
SSIA.11	To conduct a thorough inspection to identify the areas or components that have been poorly assembled, thoroughly document the assembly defects by taking photographs, recording details, and collecting relevant evidence, establish correct assembly procedures, implement rigorous quality control checks throughout the assembly process, conduct post-assembly functional tests or performance checks to ensure that the vehicle operates as intended, and establish a system for continuous monitoring and improvement of the assembly process.

The value of prominence (R + C) and relation (R − C) are then computed, and the results are presented in Table 3. The preference point and plot the cause and effect relationship diagram in two-dimensional space, as depicted in Figure 6. As seen from Figure 6, the indicator SSIA.5 is the highest driving factor, followed by BE.15. There are no observed deriving or impact factors. The rest of the factors are in the autonomous factors category: SSIA.7 ≻ BE.4 ≻ SSIA.2 ≻ SSIA.8 in which most of the factors belong to this category. It is worth mentioning that BE.15 is an external factor that makes it impossible to accomplish a particular HV product. However, the HV should be well-developed, and its instruments should have appropriate reliability and quality to resist extreme environments. In addition, an HV and its mechanisms should possess high resilience and performance functionality.

Table 3. The scores of prominences and relation among the valuations of identified contributing factors.

Row	Contributing Factors	Prominence (R + C)	Relation (R − C)
1	BE.6	0.0572	−0.0572
2	BE.13	0.0435	−0.0435
3	BE.14	0.0435	−0.0435
4	BE.15	0.3586	0.2085
5	BE.16	0.0593	−0.0593
6	BE.17	0.0572	−0.0572
7	BE.18	0.0442	−0.0442
8	BE.19	0.0294	−0.0294
9	BE.20	0.0286	−0.0286
10	BE.21	0.0290	−0.0290
11	BE.22	0.0435	−0.0435
12	SSIA.1	0.0854	0.0257
13	SSIA.2	0.0865	−0.0031
14	SSIA.3	0.1182	0.0286
15	SSIA.4	0.1609	−0.0183
16	SSIA.5	0.3899	0.2406
17	SSIA.6	0.0854	0.0257
18	SSIA.7	0.1014	−0.0181
19	SSIA.8	0.0875	−0.0319
20	SSIA.9	0.0576	−0.0021
21	SSIA.10	0.0726	−0.0170
22	SSIA.11	0.0864	−0.0031

4.4. Step Four: Validating the Resilience and Robustness of the Procedure

In this step, we use three distinct methods to demonstrate the validity and robustness of the procedure. Firstly, we perform SA by manipulating the input values in the adaptive DEMATEL method. This analysis allows us to examine the impact of changes in input variables on the output or results of the procedure. To facilitate this analysis, we gather three different inputs to evaluate the preference point and add the importance weights (the details are in Supplementary Materials). Subsequently, we plot the cause-and-effect relationship diagram in a two-dimensional space, illustrating the interdependencies between various factors. Based on the findings, it can be inferred that altering the input values in the adaptive DEMATEL method does not lead to a change in the category of contributing factors in the cause-and-effect relationship diagram. Consequently, the utilised approach remains consistent with the variations observed according the first assessment tool.

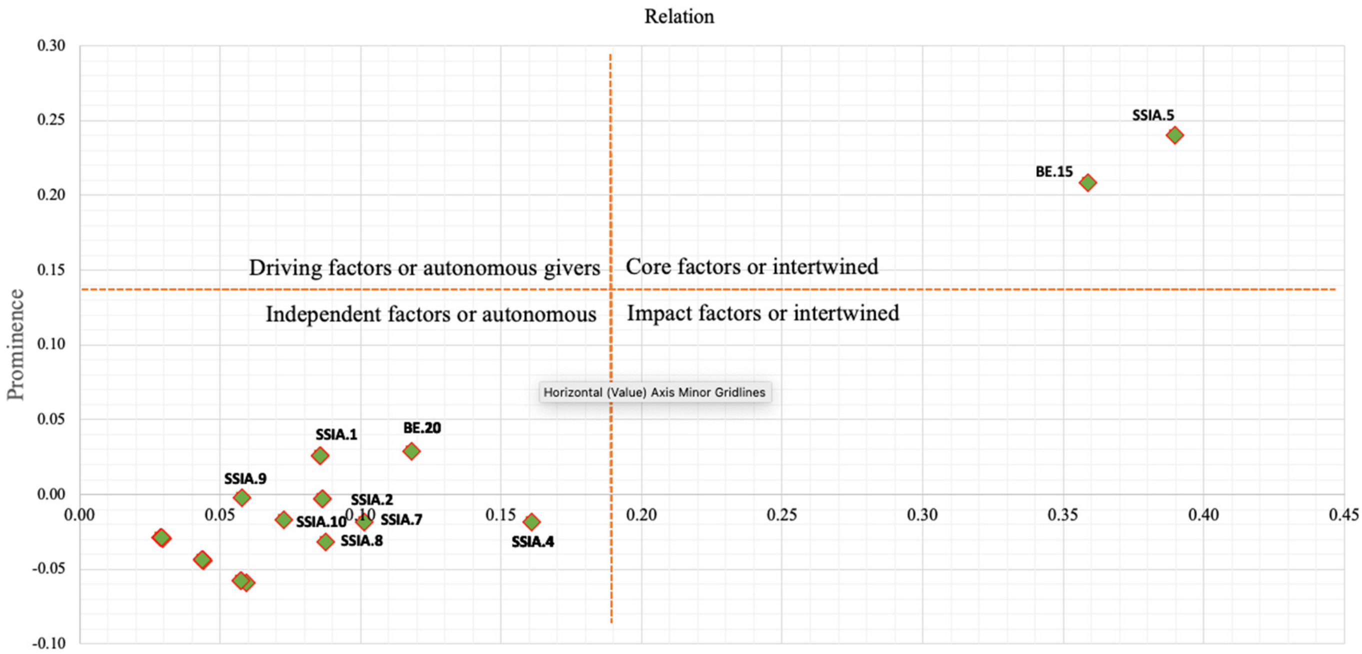

Figure 6. The cause−and−effect relationship between the contributing factors (driving and dependence power diagram).

In the second assessment, the TP of the approach is evaluated. This evaluation involves dividing the problem into smaller sub-problems, each focusing on two contributing factors simultaneously. The same input values are considered for this assessment. The first group includes the Tag numbers from 5–15, and second group includes the remaining Tag numbers. The same computation process is performed, and it is observed that the contributing factors satisfy the TP, in which, as an example, the contributing factor SAIA.4 in the original problem is ranked higher than contributing factor SAIA.4, which is ranked higher than contributing factor SAIA.7 within the same problem. SAIA.4 also is ranked higher than the contributing factor SAIA.8 in the derived rankings from the smaller sub-problems. The results emphasise the consistency and logical coherence of the decision-making process used in the proposed approach. By avoiding situations where conflicting or illogical hierarchies emerge while comparing different contributing factors, the method ensures the integrity and reliability of the results. This further enhances the robustness and effectiveness of the decision-making process.

In the third assessment, we evaluate the suboptimal nature of contributing factors. To illustrate this, let us consider a scenario where a method initially ranks contributing factors. In this scenario, two non-optimal contributing factors, BE.20 and SAIA.7, are replaced with another contributing factor, BE.10 and SAIA.8, respectively, which have lower ranks than BE.20 and SAIA.7, respectively. After recomputing the same process, the results show that the previously top-ranked contributing factor remains the highest-ranked. The relative rankings of the remaining contributing factors remain unchanged. Therefore, the utilised approach is consistent and stable in its rankings, regardless of introducing new contributing factors that are less superior to the existing ones.

4.5. Step Five: Evaluating the Role of Supportive Actions in Sustainability Goals

As obtained from previous steps, this study's findings highlight that BE.15, BE.20, BE.19, BE.18, and BE.17 are the main underlying causes of HV failures, and SSIA.5 and BE.15 are identified as the crucial driving factors for implementing practical safety intervention actions to address these concerns. In this step, an evaluation of this study's outcomes against the United Nations' 17 SDGs is carried out to provide a comprehensive framework for assessing its impact and alignment with sustainability objectives. The authors conducted multiple brainstorming sessions to establish at most five specific criteria for each goal collaboratively. During each session, they reviewed the current state of the art, examined the UN SDGs descriptions (including individual infographics and the published "Why It Matters" documents), explored relevant CE perspectives, and sought assistance from AI tools, specifically ChatGpt Plus [79,80].

Appendix A outlines various criteria underlying the relevant SDGs. The authors used an interactive and subjective approach to assess the impact of supportive actions on the 17 SDGs established by the UN. Throughout various sections of this study, the authors consolidated their individual perceptions of the issue using the Likert scale satisfaction method to assess the positive impact of enhancing HV safety on each single SDG. The Likert scale satisfaction ranged from "Strongly Disagree" (score: 0) to "Disagree" (score: 1), "Neither Agree nor Disagree" (score: 2), "Agree" (score: 3), and "Strongly Agree" (score: 4).

Upon the culmination of the assessment, the results derived using the subjective-based approach are presented visually in a radar chart. As depicted in Figure 7 and Table 4, the outcomes of the current study resonate harmoniously with the principles of the SDGs and CE. This holistic analysis presents a compelling narrative, highlighting this study's efficacy in addressing a substantial spectrum of SDGs. Among these, the five preeminent satisfied SDGs are distinguished as follows: SDG7 ("Affordable and Clean Energy") leads the cohort, followed by SDG12 ("Responsible Consumption and Production") and SDG9 ("Industry, Innovation, and Infrastructure").

Table 4. The alignment of this study's outcomes with SDGs and CE principles in tabular format.

	Criteria					
SGDs	**CRx**	**CRx**	**CRx**	**CRx**	**CRx**	**Sum**
SG1	0	0	2	2	1	5
SG2	0	3	0	3	2	8
SG3	0	0	0	0	3	3
SG4	0	0	1	2	2	5
SG5	3	3	2	2	3	13
SG6	3	0	3	4	3	13
SG7	4	4	4	4	4	20
SG8	3	3	3	4	4	17
SG9	4	4	4	2	4	18
SG10	2	2	3	3	1	11
SG11	4	2	3	4	4	17
SG12	4	3	4	4	4	19
SG13	4	4	4	2	3	17
SG14	0	2	1	1	1	5
SG15	0	4	0	0	4	8
SG16	2	2	2	3	4	13
SG17	3	3	4	4	4	18

CRx indicates the determined criteria in Appendix A for each SDG.

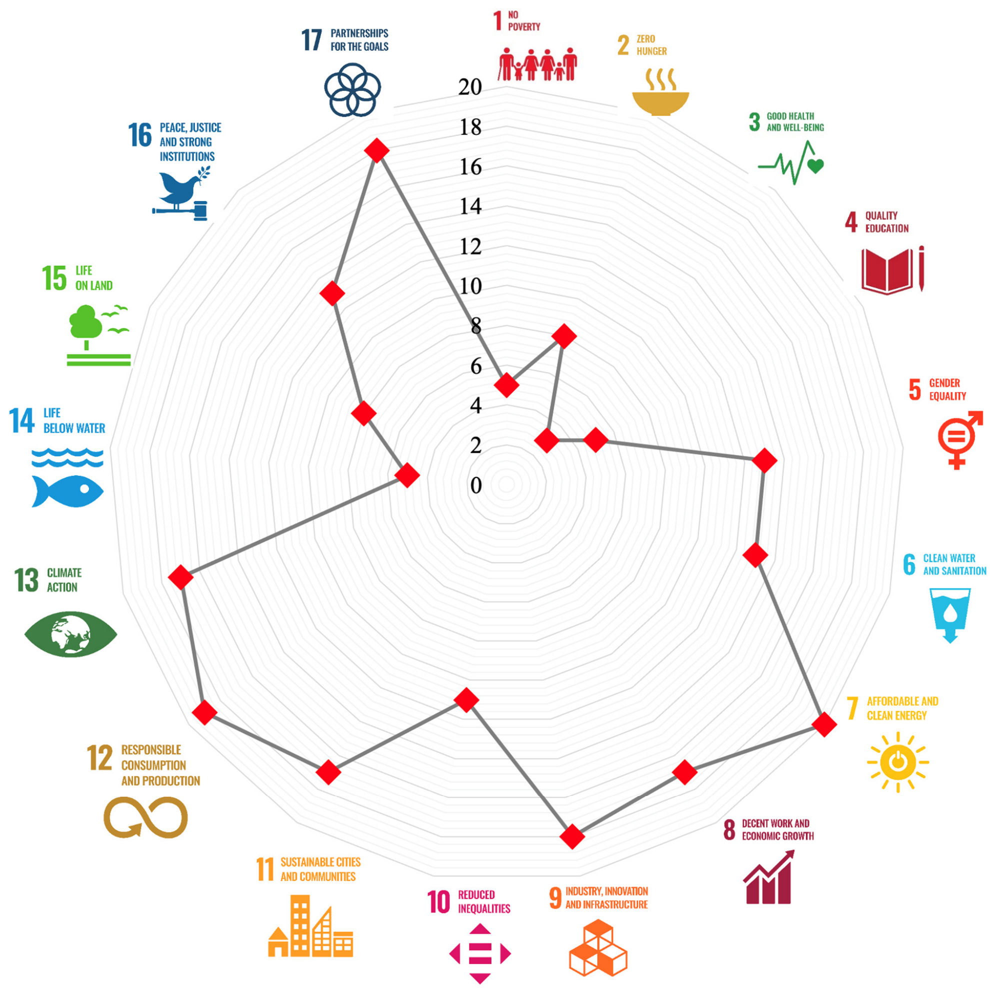

Figure 7. The alignment of this study's outcomes with SDGs and CE principles.

However, even as notable strides are made towards these affirmative SDGs, there lies a prospect for advancement in areas aligned with the five remaining SDGs that need more attention. This category encompasses SDG3 ("Good Health and Well-being"), SDG14 ("Life Below Water"), and SDG4 ("Quality Education"). This systematic and objective evaluation, serving as a compass for progress, not only pinpoints domains necessitating refinement but also serves as a blueprint for strategic interventions to foster a more sustainable circular economy.

By orchestrating an intrinsic alignment with the broader sustainability agenda, coupled with a steadfast commitment to enhancing the safety of HVs, this study contributes to sculpting a future wherein resources are harnessed with efficiency, waste is substantially curbed, and economic prosperity thrives independent of environmental harm. This comprehensive alignment with the tenets of a circular economy epitomises the pursuit of harmonious coexistence between growth and ecological preservation, resonating as a beacon for the future trajectory of sustainable progress.

5. Implications and Recommendations for Future Work Prospects

The outcomes of this study are in direct alignment with the UK hydrogen strategy, reinforcing the government's commitment to nurturing a thriving hydrogen economy by 2030—a critical initiative that paves the way for the country's ambitious transition to net-zero emissions by 2050. Central to this strategy is ensuring ongoing updates that offer clarity and support to industry stakeholders and investors. The government's proactive engagement with diverse stakeholders will be crucial in scaling the hydrogen value chain, establishing robust policy frameworks, and seizing promising economic prospects. International collaboration must be seamlessly integrated to affirm that low-carbon hydrogen significantly contributes to the global net-zero transition.

Such a strategy presents a distinctive opportunity to cultivate an entirely new clean energy industry that can play a meaningful role in the UK's journey towards net-zero emissions, simultaneously delivering widespread economic advantages nationwide. To ensure successful implementation and sustained progress, the government must diligently monitor advancements, engage in continual dialogues with stakeholders, and uphold a commitment to improvement while advancing the UK's hydrogen economy.

The strategy's implications must recognise the paramount importance of the present decade as a foundational period, calling for a holistic approach encompassing industry, research, innovation communities, and international partnerships. This exceptional change holds the potential to fulfil carbon reduction objectives and generate dynamic economic prospects, firmly establishing the UK as a leading hydrogen economy.

In the context of future work prospects, the UK's hydrogen strategy, particularly concerning HVs, can offer profound implications and pragmatic recommendations.

Firstly, it should highlight the urgent need for investment and collaboration in research and development to advance hydrogen technologies, infrastructure, and storage capabilities. The strategy implications would present a promising opportunity for researchers, engineers, and innovators to contribute to developing and optimising hydrogen-related solutions (e.g., HVs safety concerns).

Secondly, the strategy should emphasise the importance of fostering a skilled workforce to support the hydrogen economy's growth over time. This strategy would demand training programs, educational initiatives, and courses that equip individuals/practitioners with all essential knowledge and skills to work in the emerging hydrogen sector. Job opportunities should arise in hydrogen production, transportation, storage, and utilisation, offering prospects for individuals seeking career paths in clean energy.

Also, the strategy should focus on international collaboration and highlight the potential for cross-border cooperation, knowledge interaction, and market elaboration. Future work prospects should involve opportunities for global partnership, collective experiences, and the export of hydrogen-related technologies and expertise.

To comprehensively capitalise on the opportunities presented by the hydrogen economy in the UK [6], all stakeholders must align their efforts effectively, including decision-makers, practitioners, scholars, entrepreneurs, businesses, policymakers, and educational institutions. Collaboration and coordination among these parties are essential in realising the highest hydrogen sector potential and maximising its economic benefits, safety, and environmental aspects.

6. Conclusions

This study emphasises the pivotal role of HVs in the UK's transition towards a sustainable CE as part of its commitment to achieving net-zero emissions by 2050. The widespread adoption of HVs in the UK would yield numerous benefits, such as efficient resource utilisation, zero-emission transportation, integration of renewable energy sources, versatile energy storage solutions, and cross-sectoral interconnections. However, addressing the safety and risk concerns associated with HV adoption is crucial to realise these benefits comprehensively.

This study uses a comprehensive approach that combines QRA and an adaptive DEMATEL framework to ensure the safe deployment and effective operation management of HVs. This integrated framework enables decision-makers to identify the primary root causes of potential HV failures and develop appropriate supportive safety intervention actions to mitigate these risks effectively.

The findings of this study indicate that factors BE.15, BE.20, BE.19, BE.18, and BE.17 are the direct root causes of HV failures. In contrast, factors SSIA.5 and BE.15 are identified as critical contributing factors for implementing supportive safety intervention actions. By utilising the QRA and DEMATEL framework, decision-makers and policymakers gain valuable insights into the safety concerns associated with HVs, enabling them to make informed decisions to address these concerns. This contributes to the secure and efficient operation management of HVs, supporting the UK's ambitious goal of achieving net-zero emissions by 2050 and fostering a sustainable future for future generations.

However, considering the current limitations of hydrogen reliability data, exploring extended risk and reliability data requirements for hydrogen systems is essential. Therefore, as a future direction, it is crucial to develop novel and reliable frameworks for generating, collecting, and analysing data to close the safety knowledge gaps in this context. Investing in research and development, documenting data collection initiatives, encouraging international collaboration, setting industry practices (e.g., standards, codes, and guidelines), providing government support, facilitating public-private partnerships, creating data-sharing platforms, and increasing education and awareness are necessary. These efforts will simplify collecting extensive and standardised data on hydrogen production, consumption, and other applicable parameters, enabling informed decision-making, policy formulation, and technological advancements in the hydrogen sector.

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Abbreviations

FCEVs	fuel cell electric vehicles
BEs	basic events
BIM	Birnbaum importance measure
CE	circular economy
DBN	dynamic Bayesian network
DCM	fuzzy cognitive map
DEMATEL	decision-making trial and evaluation laboratory
FMEA	failure mode and effect analysis
FT	fault tree
FTA	fault tree analysis
HAZOP	hazard and operability studies
HRS	hydrogen refuelling stations
HRSP	hydrogen refuelling station platform
HV	hydrogen vehicle
LFL	lower flammability limit
QRE	quantitative risk assessment
PRDs	pressure relief devices
SA	sensitivity analysis
SDGs	Sustainable Development Goals
SMEs	subject matter experts
TE	top event
TP	transitivity property
UN	United Nations

Appendix A Assessing the Impact of the Present Study and Its Alignment with Sustainability Objectives: Determined Criteria

SDG1. No Poverty:

- **CR1.** Percentage of population living below the national poverty line.
- **CR2.** Gini coefficient or income inequality index.
- **CR3.** Access to social protection programs and services.
- **CR4.** Proportion of population with access to basic infrastructure (water, sanitation, and electricity).
- **CR5.** Poverty gap and severity of poverty indicators.

SDG2. Zero Hunger:

- **CR6.** Prevalence of undernourishment and malnutrition rates.
- **CR7.** Agricultural productivity growth and yield improvements.
- **CR8.** Access to safe and nutritious food for all population groups.
- **CR9**. Food loss and waste reduction along the supply chain.
- **CR10.** Investment in small-scale agriculture and rural development.

SDG3. Good Health and Well-being:

- **CR11.** Maternal and child mortality rates.
- **CR12.** Disease incidence and prevalence (e.g., HIV/AIDS, malaria, and non- communicable diseases).
- **CR13.** Immunisation coverage and access to essential healthcare services.
- **CR14.** Availability of healthcare facilities and skilled health workers.
- **CR15.** Health promotion and education programs.

SDG4. Quality Education:

- **CR16.** Enrolment rates and out-of-school children and youth.
- **CR17.** Literacy and numeracy proficiency among children and adults.
- **CR18.** Quality of education infrastructure, curriculum, and learning materials.
- **CR19.** Gender parity in primary, secondary, and tertiary education.
- **CR20.** Education expenditure as a percentage of GDP.

SDG5. Gender Equality:

- **CR21.** Proportion of women in leadership positions and decision-making roles.
- **CR22.** Gender wage gap and gender disparities in employment.
- **CR23.** Rates of gender-based violence and harmful practices.
- **CR24.** Access to sexual and reproductive health services and rights.
- **CR25.** Legal frameworks and policies promoting gender equality.

SDG6. Clean Water and Sanitation:

- **CR26.** Proportion of population with access to clean and safe drinking water.
- **CR27.** Adequate sanitation facilities and hygiene practices.
- **CR28.** Efficient water resource management and sustainable water use.
- **CR29.** Reduction in water pollution and wastewater treatment.
- **CR30.** Water-related ecosystems conservation and restoration.

SDG7. Affordable and Clean Energy:

- **CR31.** Proportion of the population with access to affordable and reliable energy services.
- **CR32.** Share of renewable energy in the total energy mix.
- **CR33.** Energy efficiency improvements in buildings, industries, and transportation.
- **CR34.** Research and development of clean energy technologies.
- **CR35.** Reduction in greenhouse gas emissions from the energy sector.

SDG8. Decent Work and Economic Growth:

- **CR36.** Employment-to-population ratio and unemployment rates.
- **CR37.** Decent work conditions and labour rights protection.
- **CR38.** GDP growth rates and productivity levels.

- **CR39.** Economic diversification and value-added employment opportunities.
- **CR40.** Access to financial services and entrepreneurship support.

SDG9. Industry, Innovation, and Infrastructure:

- **CR41.** Infrastructure development and accessibility (transport, communication, and energy).
- **CR42.** Research and development expenditure and innovation capacity.
- **CR43.** Proportion of industries using sustainable practices.
- **CR44.** Access to affordable and reliable internet connectivity.
- **CR45.** Investment in resilient and sustainable infrastructure.

SDG10. Reduced Inequalities:

- **CR46.** Gini coefficient or income inequality index.
- **CR47.** Proportion of income earned by the bottom 40%.
- **CR48.** Social inclusion and non-discriminatory policies.
- **CR49.** Empowerment of marginalised and vulnerable groups.
- **CR50.** Access to basic services and resources for all.

SDG11. Sustainable Cities and Communities:

- **CR51.** Urban planning and management for sustainable development.
- **CR52.** Access to affordable and adequate housing.
- **CR53.** Efficient public transportation systems and infrastructure.
- **CR54.** Protection and restoration of cultural and natural heritage.
- **CR55.** Inclusive and safe public spaces for all residents.

SDG12. Responsible Consumption and Production:

- **CR56.** Resource efficiency and waste reduction measures.
- **CR57.** Adoption of sustainable production and consumption practices.
- **CR58.** Recycling rates and promotion of circular economy principles.
- **CR59.** Sustainable public procurement policies and practices.
- **CR60.** Environmental impact assessment and management.

SDG13. Climate Action:

- **CR61.** Reduction in greenhouse gas emissions and carbon intensity.
- **CR62.** Adaptation and resilience measures to climate change impacts.
- **CR63.** Renewable energy capacity and transition to low-carbon technologies.
- **CR64.** Conservation and enhancement of carbon sinks (forests, wetlands).
- **CR65.** Financial and technical support to developing countries for climate action.

SDG14. Life Below Water:

- **CR66.** Conservation and sustainable use of marine and coastal ecosystems.
- **CR67.** Reduction in marine pollution and littering.
- **CR68.** Sustainable fisheries management and restoration of fish stocks.
- **CR69.** Protection of marine biodiversity and vulnerable species.
- **CR70.** Strengthened capacity for ocean governance and monitoring.

SDG15. Life on Land:

- **CR71.** Forest area and biodiversity conservation measures.
- **CR72.** Restoration and sustainable management of degraded lands.
- **CR73.** Prevention and control of invasive alien species.
- **CR74.** Protection of endangered species and their habitats.
- **CR75.** Community-based conservation and sustainable land use practices.

SDG16. Peace, Justice, and Strong Institutions:

- **CR76.** Rule of law, access to justice, and accountable institutions
- **CR77.** Reduction in violence, crime rates, and corruption.
- **CR78.** Protection of human rights and fundamental freedoms.
- **CR79.** Participation and representation of all groups in decision-making processes.

- **CR80.** Strengthened national and international institutions for sustainable development.

SDG17. Partnerships for the Goals:

- **CR81.** Multi-stakeholder partnerships for sustainable development.
- **CR82.** Official development assistance (ODA) and resource mobilisation.
- **CR83.** Technology transfer and capacity-building support to developing countries.
- **CR84.** Knowledge sharing and exchange of best practices.
- **CR85.** Alignment of national policies and strategies with the SDGs.

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