*fire*

*Article*

# Synergistic Integration of Hydrogen Energy Economy with UK's Sustainable Development Goals: A Holistic Approach to Enhancing Safety and Risk Mitigation

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

1 Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, 1649-004 Lisbon, Portugal; he.li@centec.tecnico.ulisboa.pt
2 School of Computing, Engineering & Physical Sciences, University of the West of Scotland (UWS), London E14 2BE, UK
3 School of Engineering, Faculty of Science and Engineering, Macquarie University, Sydney, NSW 2109, Australia
4 School of Business and Law, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia; rm194@uowmail.edu.au
5 Department of Mathematical and Industrial Engineering, Polytechnique Montréal, Montreal, QC H3T 1J4, Canada; reza.ghasemi-pirbalouti@polymtl.ca
6 Industrial Engineering Department, Quchan University of Technology, Quchan 9477177870, Iran; arman.nedjati@qiet.ac.ir
* Correspondence: mohammad.yazdi@uws.ac.uk or mohammad.yazdi@mq.edu.au

**Abstract:** Hydrogen is gaining prominence as a sustainable energy source in the UK, aligning with the country's commitment to advancing sustainable development across diverse sectors. However, a rigorous examination of the interplay between the hydrogen economy and the Sustainable Development Goals (SDGs) is imperative. This study addresses this imperative by comprehensively assessing the risks associated with hydrogen production, storage, transportation, and utilization. The overarching aim is to establish a robust framework that ensures the secure deployment and operation of hydrogen-based technologies within the UK's sustainable development trajectory. Considering the unique characteristics of the UK's energy landscape, infrastructure, and policy framework, this paper presents practical and viable recommendations to facilitate the safe and effective integration of hydrogen energy into the UK's SDGs. To facilitate sophisticated decision making, it proposes using an advanced Decision-Making Trial and Evaluation Laboratory (DEMATEL) tool, incorporating regret theory and a 2-tuple spherical linguistic environment. This tool enables a nuanced decision-making process, yielding actionable insights. The analysis reveals that Incident Reporting and Learning, Robust Regulatory Framework, Safety Standards, and Codes are pivotal safety factors. At the same time, Clean Energy Access, Climate Action, and Industry, Innovation, and Infrastructure are identified as the most influential SDGs. This information provides valuable guidance for policymakers, industry stakeholders, and regulators. It empowers them to make well-informed strategic decisions and prioritize actions that bolster safety and sustainable development as the UK transitions towards a hydrogen-based energy system. Moreover, the findings underscore the varying degrees of prominence among different SDGs. Notably, SDG 13 (Climate Action) exhibits relatively lower overall distinction at 0.0066 and a Relation value of 0.0512, albeit with a substantial impact. In contrast, SDG 7 (Clean Energy Access) and SDG 9 (Industry, Innovation, and Infrastructure) demonstrate moderate prominence levels (0.0559 and 0.0498, respectively), each with its unique influence, emphasizing their critical roles in the UK's pursuit of a sustainable hydrogen-based energy future.

**Keywords:** hydrogen economy; sustainable development; decision-making process; regret theory; regulatory framework; DEMATEL



**Citation:** Li, H.; Yazdi, M.; Moradi, R.; Pirbalouti, R.G.; Nedjati, A. Synergistic Integration of Hydrogen Energy Economy with UK's Sustainable Development Goals: A Holistic Approach to Enhancing Safety and Risk Mitigation. *Fire* **2023**, *6*, 391. https://doi.org/10.3390/fire6100391

Academic Editor: Grant Williamson

Received: 21 September 2023
Revised: 7 October 2023
Accepted: 9 October 2023
Published: 11 October 2023

## 1. Introduction

The pursuit of smart cities' sustainable development and the transition to clean energy resources have become imperative in addressing global climate concerns [1–4]. In this context, hydrogen has wisely emerged as a promising solution, potentially revolutionizing the energy economy system, not only in the UK but also in various countries and regions [5,6]. Hydrogen, as a remarkably versatile fuel, boasts net-zero end-use emissions [7], making it an ideal candidate to drive the decarbonization of multiple high-emission sectors, including transportation, industry, electricity generation, and heat production. In countries such as Germany, Japan, and South Korea, hydrogen initiatives have gained considerable traction, showcasing successful strategies for hydrogen adoption. Germany's "National Hydrogen Strategy" [8], for instance, outlines a roadmap for hydrogen production and utilization, emphasizing its role in achieving carbon reduction goals. Japan's commitment to a "Hydrogen Society" [9] has led to significant advancements in hydrogen fuel cell technology and infrastructure, serving as a model for sustainable hydrogen integration. Meanwhile, South Korea's investments in hydrogen research and development underscore the global momentum towards harnessing hydrogen's potential [10]. Lessons learned from these international endeavors offer valuable insights for the UK's own hydrogen transition.

Its unparalleled versatility and environmental benefits set hydrogen apart as a game-changing energy source. Unlike fossil fuels, hydrogen produces no harmful emissions when consumed, emitting only water vapor and heat as byproducts [11,12]. This makes hydrogen an attractive option for decarbonizing sectors that have been historically challenging to clean, such as heavy industry and long-haul transportation. Moreover, hydrogen's ability to be stored and transported efficiently offers a solution to the intermittency of renewable energy sources like wind and solar [13,14]. It can store excess energy during periods of low demand and release it when needed, enhancing the reliability of the energy grid. Additionally, hydrogen can be produced from various sources, including renewable electricity, natural gas with carbon capture and storage, and even biomass, providing flexibility in its sourcing. These unique advantages position hydrogen as a key enabler of sustainable development, capable of addressing multiple environmental, economic, and societal challenges while fostering a cleaner and more resilient energy future for the UK and the world.

While hydrogen offers immense potential as a sustainable energy source, it has its challenges, especially regarding safety. Understanding the safety hazards and potential risks associated with hydrogen energy production, storage, transportation, and utilization is paramount. One of the primary concerns is hydrogen's high flammability and ability to form explosive mixtures with air over a wide concentration range [15]. This characteristic makes hydrogen incidents potentially more hazardous than those involving conventional fuels. Furthermore, hydrogen's low ignition energy and flame invisibility under certain conditions can pose unique challenges in detecting and mitigating leakages. Technical complexities in ensuring the safe operation of hydrogen infrastructure extend to hydrogen embrittlement, which can compromise the integrity of materials used in pipelines and storage tanks. Moreover, the cryogenic nature of liquid hydrogen presents challenges in handling and containment. In the event of a leak or rupture, the rapid release of gaseous or liquid hydrogen can result in fire or explosions with severe consequences.

These safety concerns necessitate a rigorous approach to safety risk management throughout the entire hydrogen value chain. Proper safety measures, risk assessments, and preventive strategies are imperative to ensure that hydrogen's promise as a clean energy source is realized without compromising public safety or environmental integrity. This paper aims to delve into these technical aspects of hydrogen safety, analyzing the nature and potential consequences of safety hazards. By doing so, it seeks to underscore the critical importance of robust safety risk management practices and the need for continuous innovation in ensuring the safe integration of hydrogen technologies into various applications. Hydrogen as an energy carrier has garnered substantial attention worldwide due to its potential to drive sustainable energy transitions and address pressing environmental concerns [16,17]. Recent global trends underscore the increasing momentum in hydrogen production and consumption, making exploring its integration within specific contexts, such as the UK's sustainable development goals, imperative. These trends set the backdrop for the investigation into the safe integration of hydrogen energy into the UK's sustainable development trajectory, emphasizing the need for a robust risk mitigation framework.

Given the UK's commitment to decarbonization and its ambitious target of achieving net-zero greenhouse gas emissions by 2050 [18,19], hydrogen is being recognized by the government as a critical driving factor for achieving sustainable development goals (SDGs). The UK is taking proactive measures to ensure a sustainable and decarbonized future by embracing and advancing the "Hydrogen Net Zero Investment Roadmap" [20]. As a frontrunner in this transition, the UK acknowledges the hydrogen key role in achieving its ambitious net-zero emissions target. The "Hydrogen Net Zero Investment Roadmap" outlines a comprehensive plan to navigate the hydrogen sector, encompassing investment, innovation, and infrastructure development. This roadmap paves the way for an energy system that is cleaner, more sustainable, and aligned with environmental goals. Supported by a robust policy framework, a collaborative regulatory environment, and targeted encouragement, the UK is strategically positioning itself as a global leader in harnessing the manifold advantages of hydrogen, both in addressing climate change and driving economic growth. Figure 1 highlights the UK's adoption and development of this roadmap, which unlocks the hydrogen capacity as a critical pillar of its energy transition, propelling significant progress toward a greener and more sustainable future.

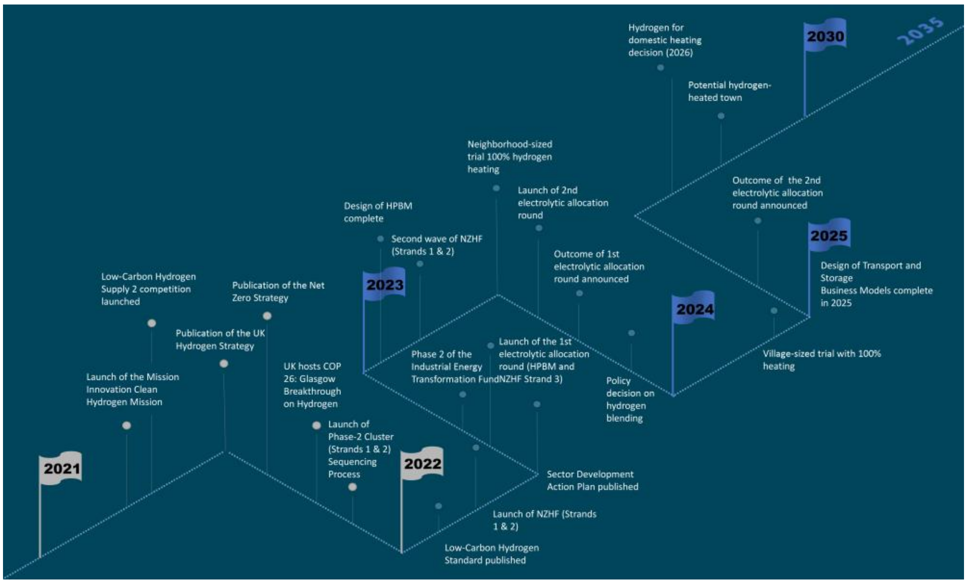


**Figure 1.** The "Hydrogen Net Zero Investment Roadmap": critical milestones through a series of strategic activities in developing the UK hydrogen economy.

With an unwavering commitment to this vision, the UK has raised proactive actions by implementing various supportive policies and regulatory measures across multiple sectors, including those designed to strengthen demand for hydrogen and tackle existing limitations, notably providing incentives for hydrogen adoption in power generation, transport, and industrial applications. In this context, considerable investments have been channeled into hydrogen production projects, facilitated through initiatives like the "Net Zero Hydrogen Fund" [21] and the "Hydrogen Production Business Model" [22]. With integration of continuous research and development efforts, such funding mechanisms can attract private investment and facilitate hydrogen technology deployment. For instance, it is clear that the UK aims to catalyze and accelerate investments in hydrogen production, with a bold objective of securing up to GBP 9 billion in funding to establish a significant 10 GW hydrogen production capacity. In addition, the government actively encourages investments in transport and storage infrastructure, allocating a substantial budget of up to GBP 2 billion to foster the nation's hydrogen economy's rapid growth [20].

However, it is crucial to emphasize the significance of safety and implementing effective risk mitigation measures throughout hydrogen adoption. By doing so, the UK government should also establish a robust basis that addresses potential risks and promotes the secure integration of hydrogen technologies into different applications. The UK can show a robust and resilient hydrogen sector by strategically upskilling the existing workforce and synergistically harnessing the expertise from high-tech industries, including oil and gas, marine, and power plants. This proactive approach can guarantee operation safety while effectively minimizing potential risks. This paper examines the UK government's holistic strategy for integrating the hydrogen energy economy with the SDGs. By studying and examining such multi-dimensional interrelationships among policies, infrastructure advancements, investment prospects, and safety measures, it aims to offer valuable insights into how the UK can successfully leverage hydrogen's capacities as safely and securely as possible. This approach will assist in advancing the nation's progress towards a low-carbon future and enhance its ability to address societal and environmental challenges more effectively.

In the ever-increasing body of literature, several valuable research works focus on different aspects of hydrogen energy in the context of UK sustainable development, as well as experiences from other countries and regions. One such study was conducted by Pulsar and Ferrier [23], who specifically evaluated the future decarbonization potential of the UK's iron and steel sector. This research also involved an assessment of various technological interventions aimed at reducing carbon emissions in this sector. A comprehensive investigation comparing UK electric and hydrogen buses in relation to emissions per person across varying vehicle capacity levels determined that electric buses outperform hydrogen buses in terms of environmental impact [24]. The study's authors reached a significant conclusion, emphasizing that electric buses exhibit notably lower cumulative emissions than their hydrogen counterparts, presenting a more favorable pathway for the UK to decarbonize its public transport system effectively. Valverde-Isorna et al. [25] presented a sophisticated and all-encompassing methodology for effectively modeling, simulating, and assessing the performance of wind-hydrogen systems situated in Fife, Scotland, offering valuable insights from this region's experience. Through their study, the authors demonstrated that their proposed model holds great promise in enhancing these systems' design and overall efficiency. Bellaby et al. [26] investigated the perception of the UK public regarding the infrastructure needed for supplying hydrogen in road transport as an unfamiliar type of fuel, shedding light on public acceptance, an aspect relevant in various regions. Over ten years, from 2011, researchers actively investigated the utilization of offshore electricity for hydrogen production in the UK [27], showcasing how regional resources can be harnessed for hydrogen generation. Another study [28] showed that hydrogen energy can be used as a low-carbon alternative to natural gas for domestic heating in the UK, possibly storing it in a few offshore gas fields to meet seasonal demand without competing with other low-carbon subsurface applications. There are several review papers conducted on various aspects of the hydrogen economy in the UK, particularly focusing on the hydrogen supply chain [29], hydrogen-fueled transportation [30], and hydrogen gas quality [31]. In addition, in the state of the art, there are some well-developed methodologies to enhance the system of hydrogen energy infrastructure, such as but not limited to [32–34].

While there is a growing body of literature on the hydrogen domain, it remains limited in its scope as most publications concentrate solely on hydrogen technologies within specific subject fields—whether technical, social, or policy-related. This narrow approach disregards the potential benefits of incorporating insights from diverse disciplines and experiences across regions. To fill this void in the existing literature, the primary objective of this article is to develop a reliable and robust decision-based framework for hydrogen energy's current state in the UK, considering global experiences and lessons learned, and how this aligns with SDGs. Moreover, this work seeks to stimulate a broader discourse surrounding the augmentation of hydrogen safety measures and the effective mitigation of associated risks. In this regard, the primary objective of this research work is to address the following research questions in a concise and precise manner:

- What are the critical safety driving factors associated with hydrogen production, storage, transportation, and utilization in the UK's hydrogen energy economy, taking into account global experiences? This research question aims to identify and analyze the critical safety concerns and risks involved in various stages of the hydrogen value chain, drawing insights from international experiences. Responses can contribute to developing effective risk mitigation strategies and safety protocols, ensuring the safe implementation and operation of hydrogen-based technologies in the UK.
- How does the integration of hydrogen energy into the UK's sustainable development trajectory impact the achievement of SDGs, in light of global experiences? This research question assesses the interrelationships between hydrogen energy adoption and the progress towards meeting the country's SDGs, while considering experiences from other regions. This response provides valuable insights for policymakers, industry stakeholders, and regulators to align their efforts with the broader sustainable development agenda, making transitioning to a hydrogen-based energy system a catalyst for achieving multiple environmental, social, and economic goals.
- How can an advanced adaptive DEMATEL tool, incorporating regret theory and a 2-tuple spherical linguistic environment, enhance the decision-making process for safely integrating hydrogen energy in the UK's sustainable development context, drawing from global best practices? The integration of an advanced adaptive DEMATEL tool, enriched with regret theory and a 2-tuple spherical linguistic framework, represents a groundbreaking leap in bolstering the decision-making process concerning the safe incorporation of hydrogen energy into the United Kingdom's sustainable development context, drawing inspiration from global best practices. This innovative approach offers multifaceted advantages, streamlining decision-making by providing enhanced visualization of complex relationships, capturing subjective expertise, facilitating quantitative and qualitative analysis, and integrating global insights. The innovative aspects of this methodology lie in its holistic approach, risk mitigation through regret theory, inclusivity through linguistic environments, and the ability to benchmark against successful global practices, collectively empowering stakeholders to make well-informed, forward-thinking decisions in this critical domain.

The response aims to demonstrate how this sophisticated decision-making process, informed by global experiences and lessons, can provide actionable suggestions and recommendations for policymakers and stakeholders, enabling them to prioritize safety and risk mitigation measures while strategically aligning hydrogen energy integration with the UK's sustainable development goals.

The structure of this paper is outlined as follows. Section 2 introduces a novel and advanced adaptive DEMATEL tool that incorporates regret theory and a 2-tuple spherical linguistic environment. This integration aims to enhance the decision-making process, making it more sophisticated and effective. Additionally, in Section 3, a practical application study on hydrogen as an emerging sustainable energy source in the UK is conducted, followed by the results and discussion in Sections 4 and 5, respectively. This study focuses on exploring the relationship between the hydrogen economy and the UK's SDGs and emphasizes safety and risk mitigation. Finally, in Section 4, the conclusion of the findings is presented, the challenges encountered during the research are discussed, and potential directions for future studies are outlined.

## 2. Materials and Methods

As depicted in Figure 2, the proposed methodology systematically addresses complex decision-making problems, concentrating on acquiring SDGs, assuring safety measures, and overcoming barriers. The process involves three key steps that leverage the insights of a diverse group of decision-makers and utilize regret theory to analyze and interpret the results. The first step involves clearly defining the objective of the decision-making process. The methodology recognizes that various factors contribute to the decision-making process. These factors could include SDGs, safety measures, potential obstacles, and other relevant considerations. In Step 2, a heterogeneous group of decision-makers is constructed, comprising diverse backgrounds, expertise, and perspectives to ensure a comprehensive analysis. A proper linguistic term facilitates the evaluation process, which provides a standardized way for decision-makers to express their preferences and opinions. Following the completion of Step 2, decision-makers gain additional insights into the contributing factors identified in Step 1. Step 3 investigates the influence and relationships among the contributing factors identified in Step 1. Decision-makers can use the obtained information to prioritize actions, make informed decisions, and develop strategies to achieve the stated objectives effectively. The details of each step are provided in the following subsections.

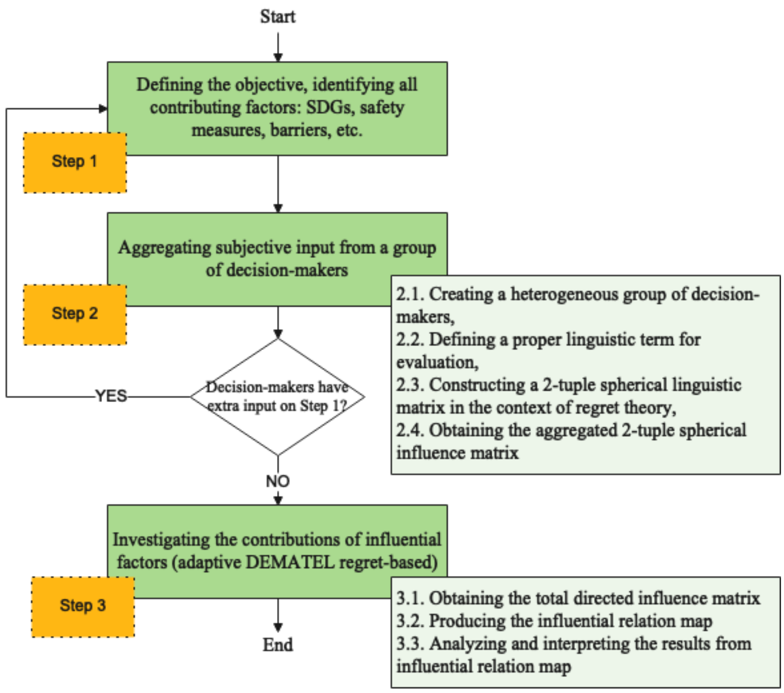


**Figure 2.** The proposed adaptive DEMATEL regret-based decision-making framework.

### *2.1. Defining the Objective, Identifying All Contributing Factors*

The first step of the research methodology aims to lay a strong foundation for the study by clearly defining the primary objective and identifying all the critical contributing factors relevant to integrating a hydrogen energy economy with the UK's SDGs. This step is vital as it ensures a comprehensive understanding of the multifaceted challenges and opportunities associated with successfully implementing hydrogen as a critical energy source while aligning with the nation's sustainability targets.

Here, a well-defined research objective that focuses on exploring the synergistic integration of a hydrogen-based energy economy with the UK's SDGs is communicated. Next, specific SDGs relevant to the UK's energy transition and decarbonization efforts are identified and analyzed. These SDGs will serve as a benchmark against which the compatibility and contribution of hydrogen-based energy solutions will be evaluated.

The existing safety measures and protocols associated with hydrogen production, storage, transportation, and utilization are investigated. Identifying potential risks and understanding how to mitigate them effectively will be essential to ensure the safe integration of hydrogen technologies within the existing energy infrastructure.

Ultimately, it is essential to identify and assess potential barriers and challenges. These may include technological limitations, regulatory obstacles, economic factors, public perception, and infrastructure requirements. Considering the issues mentioned above, the authors are able to propose targeted solutions and policy recommendations to overcome limitations and improve hydrogen-based technology adoption.

### 2.2. Aggregating Subjective Input from a Group of Decision-Makers

#### 2.2.1. Creating a Heterogeneous Group of Decision-Makers

The objective is to unite individuals with diverse backgrounds, perspectives, expertise, and experiences to form a decision-making group. The main idea behind this step is to ensure that the decision-making process benefits from a wide range of viewpoints and insights, which can lead to more robust and well-informed decisions. Therefore, it is essential to manage the group dynamics effectively and ensure everyone's contributions are valued and acknowledged. Some key characteristics of forming a heterogeneous group are diversity, inclusivity, expertise, leadership and facilitation, open communication, conflict resolution, decision-making methods (e.g., brainstorming, SWOT (Strengths, Weaknesses, Opportunities, and Threats), voting, consensus-building), and timeframe and commitment [35,36].

#### 2.2.2. Defining a Proper Linguistic Term for Evaluation

Defining a proper linguistic term for decision-making process evaluation promotes clarity, facilitates research and communication, encourages accountability and improvement, and fosters a learning culture and continuous growth in decision-making practices.

In this study, the 2-tuple spherical linguistic term sets (2-TSLTS) proposed by Abdullah et al. [37] are successfully employed to address uncertain information in a typical decision-making problem effectively.

**Definition 1 ([37]):** *Let us assume that there is a set of linguistic terms called* $S = \{s_1, s_2, \ldots, s_T\}$, *within odd cardinality. Then, the 2-TSLTS on the universe discourse* ($\mathcal{R}$) *can be represented as the following equation:*

$$R = \left\{ \left\langle s_{\mu(r)}, s_{\eta(r)}, s_{v(r)} \right\rangle | r \in \mathcal{R} \right\} \tag{1}$$

*where* $s_{\mu(r)}, s_{\eta(r)}, s_{v(r)}$ *all belong to* $S$, *and denote the positive, neutral, and negative memberships of* $r \in R$, *respectively. In addition, the following condition is satisfied,* $3 \leq \mu^2(r) + \eta^2(r) + v^2(r) \leq (1+\tau)^2$. *Following that, the degree of refusal membership for the specific element* $(r)$ *from the set* $R$ *is defined as* $S_{\pi(r)} = s_{\sqrt{(1+\tau)^2 - (\mu^2(r) + \eta^2(r) + v^2(r))}}$.

For the sake of simplicity, $\widetilde{r} = \langle (s_\mu, \ddot{a}), (s_\eta, \ddot{e}), (s_v, \ddot{u}) \rangle$ is called 2-tuple spherical linguistic number (2-TSLN), in which $(s_\mu, \ddot{a}), (s_\eta, \ddot{e}), (s_v, \ddot{u})$ are three 2-TSLTS and $\ddot{a}, \ddot{e}$, and $\ddot{u}$ are in the $[-0.5, 0.5)$.

**Definition 2 ([37]):** *Let us assume that there is a set of linguistic terms called*$S = \{s_1, s_2, \ldots, s_T\}$, *and* $\widetilde{r} = \langle (s_\mu, \ddot{a}), (s_\eta, \ddot{e}), (s_v, \ddot{u}) \rangle$ *is a TSLN and* $\alpha, \beta, \gamma \in [1, \tau]$ *are the three numbers showing the symbolic outcome of aggregation operations. Let us consider that* $\langle \alpha, \beta, \gamma \rangle$ *transfers the same information to* $\widetilde{r}$; *therefore, the* $\alpha, \beta, \gamma$ *can be transferred with each other using the following equations:*

$$\Delta : [1, \tau] \longrightarrow S \times [-0.5, 0.5), \begin{cases} \Delta(\alpha) = \begin{cases} s_\mu, \mu = round(\alpha); \\ \ddot{a} = \alpha - \mu,\ \ddot{a} \in [0.5,\ 0.5) \end{cases} \\ \Delta(\beta) = \begin{cases} s_\eta, \eta = round(\beta); \\ \ddot{e} = \beta - \eta,\ \ddot{e} \in [0.5,\ 0.5) \end{cases} \\ \Delta(\gamma) = \begin{cases} s_v, v = round(\gamma); \\ \ddot{u} = \gamma - v,\ \ddot{u} \in [0.5,\ 0.5) \end{cases} \end{cases} \tag{2}$$

$$\Delta^{-1} :\longrightarrow S \times [-0.5, 0.5) \longrightarrow [1, \tau], \begin{cases} \Delta^{-1}(s_\mu, \ddot{a}) = \ddot{a} + \mu = \alpha \\ \Delta^{-1}(s_\eta, \ddot{e}) = \ddot{e} + \eta = \beta \\ \Delta^{-1}(s_v, \ddot{u}) = \ddot{u} + v = \gamma \end{cases} \tag{3}$$

*where* $\tau$ *is the upper limit value in which the value of* $\alpha, \beta, \gamma$ *cannot be higher than* $\tau$*.*

**Definition 3 ([37]):** *Let us assume that* $\widetilde{R} = \left\{\widetilde{r}_i\right\}(i = 1, 2, \ldots, n)$ *is a collection of 2-TSLNs and* $\widetilde{r}_i = \langle (s_{\mu_i}, \ddot{a}_i), (s_{\eta_i}, \ddot{e}_i), (s_{v_i}, \ddot{u}_i) \rangle$*. Following that, the corresponding weight of* $\widetilde{r}_i$ *is denoted as* $w_i$*, which satisfies the condition that* $w_i \in [0,1](i = 1, 2, \ldots, n)$ *and* $\sum_{i=1}^{n} w_i$*. Then, the 2-TSLWA operator is defined according to the following equation:*

$$2 - TSLWA_w\left(\widetilde{r}_1, \widetilde{r}_2, \ldots \widetilde{r}_n\right) = \oplus_{i=1}^{n}\left(w_i \widetilde{r}_i\right)$$
$$= \langle \sqrt{\Delta\left(\tau^2\left(1 - \prod_{i=1}^{n}\left(1 - \frac{\Delta^{-1}\left(s_{\mu_i^2} \ddot{a}_i\right)}{\tau^2}\right)^{w_i}\right)\right)}, \Delta\left(\tau \prod_{i=1}^{n}\left(\frac{\Delta^{-1}\left(s_{\eta_i^2} \ddot{e}_i\right)}{\tau}\right)^{w_i}\right), \Delta\left(\tau \prod_{i=1}^{n}\left(\frac{\Delta^{-1}\left(s_{v_i^2} \ddot{u}_i\right)}{\tau}\right)^{w_i}\right) \rangle \quad (4)$$

**Definition 4 ([27]):** *Let us assume that* $\widetilde{r} = \langle (s_\mu, \ddot{a}), (s_\eta, \ddot{e}), (s_v, \ddot{u}) \rangle$ *is a TSLN; the score function can be computed according to the following equation:*

$$Sc\left(\widetilde{r}\right) = \Delta\sqrt{\frac{\tau^2 + \Delta^{-1}\left(s_{\mu^2}, \ddot{a}\right) - \Delta^{-1}\left(s_{\eta^2}, \ddot{e}\right) - \Delta^{-1}\left(s_{v^2}, \ddot{u}\right)}{9}} \quad (5)$$

2.2.3. Constructing a 2-Tuple Spherical Linguistic Matrix in the Context of Regret Theory

This step is conducted in the context of regret theory. Regret theory [38] is a behavioral decision theory that considers the impact of bounded rationality on individuals' decision-making processes. Due to cognitive limitations, people may only sometimes be able to fully explore and evaluate all available options before deciding. Consequently, when the chosen alternative turns out to be worse than the other options that they could have selected, decision-makers tend to experience feelings of regret for their choice.

To provide clearer and concise definitions for key technical terms to facilitate a quicker understanding for readers, a 2-TSLTS is a specialized linguistic framework used for expressing subjective opinions, preferences, or assessments [39,40]. It consists of two components: a linguistic term, which conveys qualitative information (e.g., "high", "low", "favorable"), and a numerical value, which quantifies the degree associated with the linguistic term. This approach combines linguistic expressions with numeric values to enable a more nuanced and precise representation of qualitative data in decision-making. A 2-TSLN is a mathematical representation within the 2-TSLTS framework that combines a linguistic label with a numerical value. It serves as a powerful tool for capturing and processing subjective information. For instance, a 2-TSLN might express the concept of "moderate importance" as "Moderate (0.6)", where 0.6 quantifies the degree of importance associated with the linguistic label "Moderate". This method allows for the incorporation of qualitative judgments into quantitative analyses, enhancing the comprehensiveness of decision-making processes. By offering these clearer definitions, readers will be better equipped to grasp the technical nuances of 2-TSLTS and 2-TSLN, ensuring a smoother understanding of the subsequent sections that utilize these concepts.

**Definition 5 ([38]):** *Let us assume that* $a$ *is the consequence of selecting contributing factor* $A$ *; thereafter, the utility value (UV) derived from contributing factor* $A$ *can be calculated using the following equation:*

$$UV(a) = a^\theta \quad (6)$$

*where* $(0 < \theta < 1)$ *shows the decision-makers' risk aversion. In case a decision-maker has a higher risk aversion, the value of* $\theta$ *should be set to as small a value as possible.*

In this context, when considering the two contributing factors, $A$ and $B$, constructing the 2-TSLN matrix based on regret theory involves defining the interaction between these factors. This matrix helps determine the extent to which they are expected to be influential in contributing to a specific outcome or response, addressing the question of their respective levels of influence.

2.2.4. Obtaining the Aggregated 2-Tuple Spherical Influence Matrix

Once constructed, the 2-TSLN matrix based on regret theory comprises single cells, each containing two sets of numbers. The first set illustrates the influence of row contributing factors, while the second number reflects the impact of column contributing factors. Using the advantages of definition 6, underlying the context of regret theory, the aggregation process can be completed.

**Definition 6 ([38]):** *Let us assume there are two consequences of contributing factors ($\boldsymbol{A}$ and $\boldsymbol{B}$) as $\boldsymbol{a_1}$ and $\boldsymbol{a_2}$, and the corresponding UVs are $\boldsymbol{UV}(\boldsymbol{a_1})$ and $\boldsymbol{UV}(\boldsymbol{a_2})$. Following that, the regret-rejoice value (RV) as an aggregation representation can be defined according to the following equation:*

$$\boldsymbol{RV}(\boldsymbol{a_1},\boldsymbol{a_2}) = \boldsymbol{1} - \boldsymbol{e}^{-\gamma(\boldsymbol{UV}(\boldsymbol{a_1})-\boldsymbol{UV}(\boldsymbol{a_2}))} \tag{7}$$

*where $\gamma > \boldsymbol{0}$ denotes the decision-makers' regret aversion, and $\boldsymbol{UV}(\boldsymbol{a_1}) - \boldsymbol{UV}(\boldsymbol{a_2})$.*

By satisfying the condition, the $\boldsymbol{RV}(\boldsymbol{a_1},\boldsymbol{a_2})$ is a respective of RV; otherwise, it indicates the rejoice value.

*2.3. Investigating the Contributions of Influential Factors*

2.3.1. Obtaining the Total Direct Influence Matrix

In this step, an advanced version of the DEMATEL method called adaptive DEMATEL is used as a much more dynamic and iterative approach to overcome the limitations of traditional DEMATEL when decision-makers' opinions might not be reliable or consistent due to various reasons such as cognitive biases. Adaptive DEMATEL can then incorporate the feedback mechanisms enabling the influence matrix's refinement through the iteration process [41,42].

Let us assume that $\boldsymbol{Z_k} = \left[z_{ij}\right]_{n\times n}$", represent the single influential matrix, where "$z_{ij}$" is $\boldsymbol{RV}(\boldsymbol{a_1},\boldsymbol{a_2})$ obtained from Step 2.4. The direct-influence matrix, denoted as "$\boldsymbol{X} = \left[x_{ij}\right]_{n\times n}$", is normalized as "$\mathrm{X} = \frac{\mathbf{1}}{\max \sum_{j=1}^{n} a_{ij}} \times \mathrm{Z}$", where $\mathbf{1} \le \boldsymbol{i} \le \boldsymbol{n}$. In this expression, $\boldsymbol{Z}$ represents the original direct influence matrix $\boldsymbol{X}$, and the maximum of the sum $\sum_{j=1}^{n} a_{ij}$ ensures normalization. It is important to note that all elements of matrix $\boldsymbol{X}$ are in the range $[\mathbf{0},\mathbf{1}]$. Additionally, "$\sum_{j=1}^{n} x_{ij} \ge \mathbf{0}$" or "$\sum_{j=1}^{n} x_{ij} \le \mathbf{1}$", 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 "$\boldsymbol{T} = \left[t_{ij}\right]_{n\times n}$", is determined as "$\boldsymbol{T} = \boldsymbol{X} + \boldsymbol{X}^2 + \boldsymbol{X}^3 + \ldots + \boldsymbol{X}^h$". Here, the indirect influence of factor $\boldsymbol{i}$ over factor $\boldsymbol{j}$ 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 $\boldsymbol{h}$ approaches infinity ("$\boldsymbol{h} \to \infty$"), the total direct influence matrix can be formulated as "$\boldsymbol{T} = \boldsymbol{X}(\boldsymbol{I} - \boldsymbol{X})^{-1}$", where $\boldsymbol{I}$ represents the unit matrix.

After obtaining the total direct influence matrix, the influential relation maps $\boldsymbol{C}$ and $\boldsymbol{R}$ can be generated. Map $\boldsymbol{C}$, represented as a row vector "$\boldsymbol{C} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n} = \left[t_{\cdot j}\right]_{1\times n}$", depicts the column summation of the total direct influence matrix, illustrating the cumulative influences received by each factor from other factors. Put simply, C captures the impacts each factor receives from other factors, whether directly or indirectly.

Similarly, map $\boldsymbol{R}$, denoted as a column vector "$\boldsymbol{R} = \left[\sum_{i=1}^{n} t_{ij}\right]_{n\times 1} = \left[t_{i\cdot}\right]_{n\times 1}$", represents the row summation of the total direct influence matrix, showcasing the collective influences dispatched by each factor to other factors, either directly or indirectly.

2.3.2. Producing the Influential Relation Map

The sum of $\boldsymbol{R}$ and $\boldsymbol{C}$, denoted as "$\boldsymbol{R} + \boldsymbol{C}$", 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. Similarly, the difference between $\boldsymbol{R}$ and $\boldsymbol{C}$, denoted as "$\boldsymbol{R} - \boldsymbol{C}$" is referred to as "Relation/Dependency". The Relation is obtained for the vertical axis and highlights the net effect of each factor. The influential relation map is then created using the scores of "$\boldsymbol{R} + \boldsymbol{C}$" and "$\boldsymbol{R} - \boldsymbol{C}$".

#### 2.3.3. Analyzing and Interpreting the Results from the Influential Relation Map

This influential relation map, tailored to any domain, constitutes a valuable tool for decision-makers to make informed decisions and improve the system over time. It offers specific insights into the interconnections among various factors, helping identify contributing factors categorized into distinct classes based on their location in the diagram [43,44]. Zone 1: Critical Factors (Givers); critical factors significantly influence other elements within the system. These factors hold a central position and have a crucial impact on the system's overall functioning. Zone 2: Driving Factors (Autonomous Givers); the driving factors in this zone exhibit a high level of autonomy and substantially influence other aspects. They play a proactive role in shaping the behavior and outcomes of the system. Zone 3: Autonomous Receivers (Independent Factors); factors situated in this zone receive influences from other elements in the system but have a relatively lower degree of leverage on different factors. They can act independently within the system. Zone 4: Impact Factors (Receivers); impact factors in this zone are subject to influence from other elements within the system but cannot be directly improved. It is essential to recognize that these factors cannot be instantly enhanced due to the influence they receive from other elements. It should be added that a system in this context "is a network of interconnected elements that work together to achieve specific objectives" [45–47].

In the upcoming section, as a practical illustration of the study, the focus of the system (UK) is established to be the development of the UK's sustainable strategy.

## 3. Application of Study

This section presents a case study focusing on the emerging role of hydrogen as a sustainable energy source in the UK and exploring the potential challenges and opportunities presented in achieving the SDGs while emphasizing safety and risk mitigation. Figure 3 illustrates the existing hydrogen net-zero investment leading to the UK's net-zero UK target of 2050 [48,49]. In the following subsections, the details of each step are given for the defined case study.

### *3.1. Defining the Objective, Identifying All Contributing Factors*

This study aims to explore and propose a synergistic integration of the hydrogen energy economy with the UK's SDGs. The primary focus is on developing a comprehensive and holistic approach to enhancing safety and risk mitigation within the hydrogen energy sector, considering the potential hazards and challenges associated with its implementation.

The synergistic integration of a hydrogen-based energy economy with the UK's SDGs could represent a strategic approach to address climate change and sustainable development challenges, contributing to a more sustainable and secure energy future for the nation and the world. The critical aspects of this integration in the context of sustainable development are as follows:

Climate Action (SDG 13)A: Hydrogen is considered a low-carbon energy carrier when produced using renewable energy sources or carbon capture and storage technologies. The UK can reduce its greenhouse gas emissions and contribute to mitigating climate change, aligning with SDG 13.

Clean Energy Access (SDG 7): Hydrogen can provide a clean and reliable energy source for communities and industries. Integrating hydrogen into the energy mix can enhance energy access while reducing the reliance on fossil fuels, aligning with SDG 7's goal of ensuring access to affordable, reliable, sustainable, and modern energy for all.

Industry, Innovation, and Infrastructure (SDG 9): Developing a hydrogen-based economy requires significant infrastructure and technological innovation investments, and by promoting research and development in this area, the UK can contribute to SDG 9, which focuses on building resilient infrastructure.

Responsible Consumption and Production (SDG 12): Hydrogen production should be carried out responsibly and sustainably, ensuring efficient use of resources and minimizing environmental impacts. Integrating hydrogen into the energy economy can support SDG 12's aim of promoting responsible consumption and production patterns.

Sustainable Cities and Communities (SDG 11): Hydrogen can achieve sustainable urbanization by delivering clean and efficient energy solutions for cities and communities. The integration of hydrogen technologies in public transportation, buildings, and other urban systems can contribute to SDG 11, focusing on creating inclusive, safe, resilient, and sustainable cities and communities.

Clean Water and Sanitation (SDG 6): Hydrogen production processes should be mindful of water usage, especially in electrolysis-based methods. A sustainable approach to hydrogen production can support SDG 6's goal of ensuring the availability and sustainable management of water and sanitation for all.

Affordable and Clean Energy (SDG 7): Hydrogen can provide an affordable and clean energy source when produced and utilized efficiently. Its integration can help advance SDG 7's target of ensuring access to affordable, reliable, sustainable, and modern energy.

Partnerships for the Goals (SDG 17): Achieving a successful integration of hydrogen-based energy with the UK's SDGs requires collaborative efforts among various stakeholders, including governments, industry, academia, and society. SDG 17 focuses on strengthening global partnerships to achieve sustainable development, and cooperation in promoting hydrogen energy aligns with this goal.

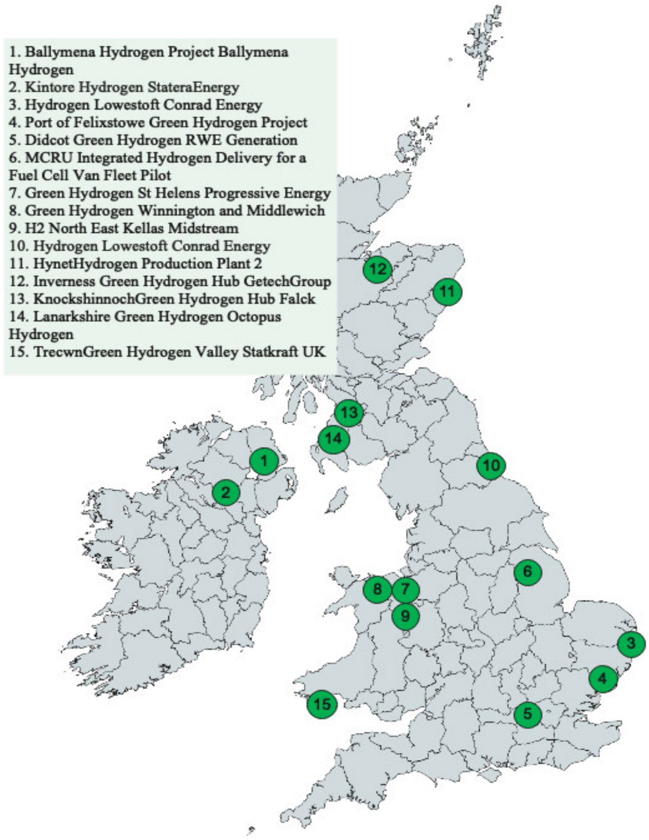


**Figure 3.** The existing hydrogen net-zero investment leading to the UK's net-zero target of 2050.

There are more factors, and by incorporating safety and risk mitigation considerations at every stage of the hydrogen value chain, the UK can ensure a secure and sustainable integration of hydrogen-based energy while achieving its SDGs. Safety should remain a top priority, and continuous improvement in safety practices and protocols will be vital for successfully developing the hydrogen energy economy. Some critical considerations for Enhancing Safety and Risk Mitigation (ESRM) are as follows:

Robust Regulatory Framework (ESRM 1): Establishing a comprehensive regulatory framework that governs the safe handling, transportation, and use of hydrogen is essential. This framework should be developed in consultation with experts, industry stakeholders, and relevant authorities to ensure it addresses all safety aspects effectively.

Risk Assessment and Management (ESRM 2): Conducting thorough risk assessments at each stage of the hydrogen value chain is critical. Identifying potential hazards and vulnerabilities will allow for implementing appropriate risk management strategies and safety measures to minimize or eliminate risks.

Safety Standards and Codes (ESRM 3): Developing and adhering to standards and codes specific to hydrogen technologies will help maintain high safety and consistency across the industry. These standards should cover hydrogen production, storage, transportation, and end-use applications.

Training and Awareness (ESRM 4): Providing adequate training and awareness programs for personnel involved in the hydrogen industry is vital. This includes educating workers, emergency responders, and the public about hydrogen safety, proper handling procedures, and emergency protocols.

Infrastructure Safety (ESRM 5): Ensuring that infrastructure, such as hydrogen storage facilities and refueling stations, meets safety standards is essential. Regular inspections and maintenance should be conducted to prevent potential leaks, ruptures, or other safety risks.

Integrated Safety Measures (ESRM 6): Taking an integrated approach to safety, which considers all aspects of the hydrogen energy system, is crucial. This includes safety measures for hydrogen production, distribution, transportation, and use in various sectors, such as transportation, industry, and power generation.

Incident Reporting and Learning (ESRM 7): Establishing a transparent system for reporting and investigating hydrogen-related incidents is essential for continuous improvement. Learning from past incidents and sharing knowledge across the industry can help prevent similar occurrences in the future.

Public Engagement and Communication (ESRM 8): Engaging with the public and communicating transparently about hydrogen safety is crucial for building trust and acceptance. Public perception and awareness can significantly influence the successful integration of hydrogen energy in the UK.

Research and Innovation (ESRM 9): Continued research and innovation in hydrogen technologies can lead to the development of safer and more efficient systems. Investing in R&D for safety-enhancing technologies and materials is essential to reduce potential risks.

Emergency Response Planning (ESRM 10): Developing comprehensive plans specific to hydrogen-related incidents is vital. These plans should involve coordination between relevant authorities, industry stakeholders, and emergency responders to ensure a swift and effective response in case of emergencies.

There may be ongoing arguments regarding including additional parameters in both sustainability developments and safety matters. However, this study has focused solely on the contributing factors mentioned earlier.

### *3.2. Aggregating Subjective Input from a Group of Decision-Makers*

#### 3.2.1. Creating a Heterogeneous Group of Decision-Makers

Creating a heterogeneous group of decision-makers in this step involves assembling a diverse team with varied backgrounds, perspectives, and expertise. Start by defining the decision's scope and identifying the required knowledge and skills. Reach beyond the usual network to include individuals from different industries, cultures, genders, and experiences. Foster an inclusive environment that encourages open communication, active participation, and constructive criticism. Utilize brainstorming and group exercises to generate creative solutions and new viewpoints. Address conflicts with a resolution process and be aware of cultural differences in communication and decision-making styles. Evaluate the process afterwards and learn from the experience to improve future decisions. Ultimately, this approach leads to more innovative solutions, better problem-solving, and a team dynamic that values and embraces diversity.

Five decision-makers with diverse educational backgrounds and varying experience levels were invited to participate in the present research. To simplify the analysis, it is assumed that all participating decision-makers' importance weights were equal in contributing to the well-developed adoptive DEMATEL method.

#### 3.2.2. Defining a Proper Linguistic Term for Evaluation

In this step, it is assumed that the five individual decision-makers are invited to give their evaluations regarding the problem, and they are noted as $\boldsymbol{DM} = \{\boldsymbol{DM_1}, \boldsymbol{DM_2}, \boldsymbol{DM_3}, \boldsymbol{DM_4}, \boldsymbol{DM_5}\}$. The group includes professional engineers and academic staff working in upper first-class technology. As was mentioned earlier, the importance weights of all five employed DM are assumed to be equal, i.e., $\boldsymbol{\lambda} = (\mathbf{0.2}, \mathbf{0.2}, \mathbf{0.2}, \mathbf{0.2}, \mathbf{0.2})$. The group of DMs considers and utilizes the following linguistic terms to describe the influential impact of contributing factors in the case study.

$$\boldsymbol{S} = \{\boldsymbol{s_0} = \textbf{\textit{No influence}}, \boldsymbol{s_1} = \textbf{\textit{Very Low influence}}, \boldsymbol{s_2} = \textbf{\textit{Low influence}}, \boldsymbol{s_3} = \textbf{\textit{Moderate influence}}, \\ \boldsymbol{s_4} = \textbf{\textit{High influence}}, \boldsymbol{s_5} = \textbf{\textit{Very High influence}}\}$$

For the sake of simplicity, for those contributing factors, where there are no interrelationships, it is assumed that $\boldsymbol{s_0} = \textbf{\textit{No influence}}$ is equal to zero.

#### 3.2.3. Constructing a 2-Tuple Spherical Linguistic Matrix in the Context of Regret Theory

At first, the DMs are requested to provide their evaluation regarding the influence of contributing factors under the environment of 2-TSLNs. As a result, the corresponding matrices generated from DM.1 are presented in Table 1, and for the rest of the DMs the matrices will be provided upon request.

#### 3.2.4. Obtaining the Aggregated 2-Tuple Spherical Influence Matrix

To begin, it is essential to emphasize that based on experiments conducted in the existing literature, a recommended value for $\boldsymbol{\theta}$ is 0.88, while a value of 0.3 is suggested for $\gamma$. These values have been derived from thorough investigations and analyses within the research field [50,51].

Utilizing Equation (5), the ensemble of 2-TSLNs can be consolidated, taking into account the UV value derived from DM risk aversion (as indicated in Equation (6)). Moreover, this aggregation process can be extended by incorporating Equation (7) to address the concept of regret aversion.

To illustrate, when examining the interactions between two contributing factors, denoted as A and B, the resulting 2-TPLNs can be exemplified as follows:

$\boldsymbol{DM_1} : \langle(\boldsymbol{s_4}, \mathbf{0}), (\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_3}, \mathbf{0})\rangle$,
$\boldsymbol{DM_2} : \langle(\boldsymbol{s_2}, \mathbf{0}), (\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_1}, \mathbf{0})\rangle$,
$\boldsymbol{DM_1} : \langle(\boldsymbol{s_2}, \mathbf{0}), (\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_4}, \mathbf{0})\rangle$,
$\boldsymbol{DM_1} : \langle(\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_4}, \mathbf{0})\rangle$, and
$\boldsymbol{DM_1} : \langle(\boldsymbol{s_2}, \mathbf{0}), (\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_4}, \mathbf{0})\rangle$.

Utilizing Equation (5) while taking into account the equal importance weights of the employed DMs, the normalization can be attained as outlined below:

$= \langle(\boldsymbol{s_2}, \mathbf{0.464}), (\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_4}, \mathbf{0.482})\rangle$, and followed by:
$= \langle(\boldsymbol{s_2}, \mathbf{0.464}), (\boldsymbol{s_3}, \mathbf{0}), (\boldsymbol{s_4}, \mathbf{0.482})\rangle$.

By contrasting with the two ideal points (UVs), the Relative Value (RV) is subsequently calculated using Equation (7) as $-0.128$. This value signifies the interrelationship and causality between contributing factors A and B.

Table 2 illustrates the aggregated matrix formulated by the decision makers (DMs) within the framework of regret theory. Elaborate computations are expounded upon in request.

### *3.3. Investigating the Contributions of Influential Factors*

#### 3.3.1. Obtaining the Total Direct Influence Matrix

The process of obtaining the total direct influence matrix in DEMATEL involves defining a problem and identifying relevant variables, creating a causal relationship graph with nodes and arrows representing influences, conducting pairwise comparisons to determine influence strengths, calculating the total result for each variable by summing incoming and outgoing influences, normalizing these values, interpreting their significance, constructing a square total direct influence matrix, and further analyzing to identify key variables and system dynamics. Thus, the total direct influence matrix is presented in Table 3.

#### 3.3.2. Producing the Influential Relation Map

Creating an influential relation map within the DEMATEL framework begins by identifying and charting pertinent variables on a causal relationship diagram. Subsequently, constructing the influential relation map entails positioning variables based on their significance, stratifying stronger influences into distinct zones. The map is then finessed to enhance clarity and facilitate the visual communication of intricate cause-and-effect dynamics, leveraging specialized software tools for streamlined visualization. The resultant depiction effectively conveys the relative importance of each factor by accounting for self-influences and external contributions. Figure 4 illustrates the produced influential relation map based on the Prominence and Relation values.

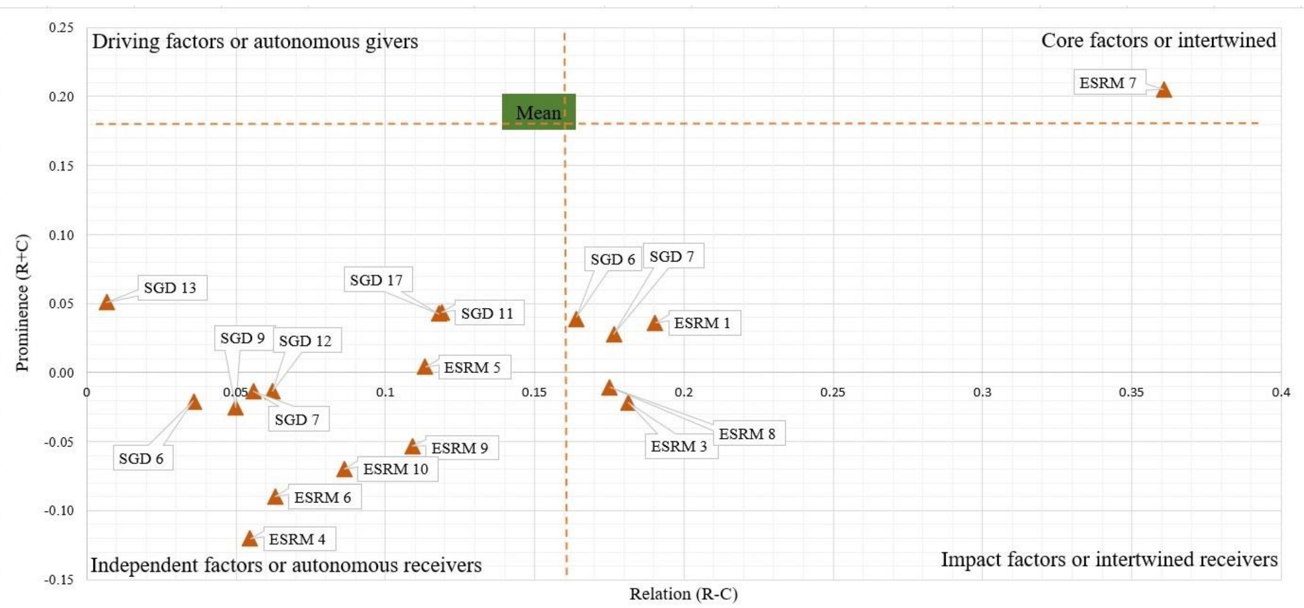


**Figure 4.** The produced influential relation map.

**Table 1.** The 2-TSLNs matrices derived from the employed group of DMs: DM.1.

| | SDG 13 | SDG 7 | SDG 9 | SDG 12 | SDG 11 | SDG 6 | SDG 7 | SDG 17 | ESRM 1 | ESRM 2 | ESRM 3 | ESRM 4 | ESRM 5 | ESRM 6 | ESRM 7 | ESRM 8 | ESRM 9 | ESRM 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SDG 13 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| SDG 7 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| SDG 9 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| SDG 12 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| SDG 11 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| SDG 6 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| SDG 7 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| SDG 17 | NO | NO | NO | NO | NO | NO | NO | NO | L | L | L | L | L | L | L | L | L | L |
| ESRM 1 | M | M | M | H | M | H | H | M | M | H | M | H | H | H | H | H | M | H |
| ESRM 2 | H | H | M | L | H | H | H | M | H | VH | M | VH | H | VH | H | H | VH | H |
| ESRM 3 | M | M | M | M | M | M | M | M | H | H | H | M | M | H | M | H | M | M |
| ESRM 4 | VH | VH | VH | VH | VH | VH | VH | VH | VH | VH | VH | H | VH | VH | H | VH | VH | M |
| ESRM 5 | M | H | M | M | H | M | M | H | H | M | H | H | M | H | H | M | H | H |
| ESRM 6 | M | H | VH | L | L | H | H | H | L | H | H | L | H | H | L | H | H | H |
| ESRM 7 | VL | VL | L | VL | L | VL | VL | VL | L | VL | VL | L | VL | VL | L | VL | VL | VL |
| ESRM 8 | L | M | L | M | L | M | M | M | H | M | H | H | M | H | H | M | M | H |
| ESRM 9 | M | H | M | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| ESRM 10 | L | L | VL | M | L | M | M | L | L | M | L | L | M | L | L | M | H | H |

**Table 2.** The aggregated 2-tuple spherical influence matrix.

| | SDG 13 | SDG 7 | SDG 9 | SDG 12 | SDG 11 | SDG 6 | SDG 7 | SDG 17 | ESRM 1 | ESRM 2 | ESRM 3 | ESRM 4 | ESRM 5 | ESRM 6 | ESRM 7 | ESRM 8 | ESRM 9 | ESRM 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SDG 13 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.0573 | −0.0573 | −0.0573 | −0.0573 | −0.0573 | −0.0573 | −0.0573 | −0.0573 | −0.0573 | −0.0573 |
| SDG 7 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.0573 | −0.0573 | −0.0152 | −0.0573 | −0.0152 | 0.0169 | −0.0573 | −0.0573 | −0.0573 | −0.0573 |
| SDG 9 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.0573 | 0.0911 | −0.0152 | 0.0270 | 0.0839 | 0.0169 | −0.0573 | −0.0573 | −0.0573 | −0.2093 |
| SDG 12 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.0573 | −0.0590 | 0.0418 | 0.0911 | −0.0405 | −0.0573 | −0.0573 | −0.2093 | −0.0128 | −0.1108 |
| SDG 11 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0169 | 0.0255 | −0.5195 | −0.2215 | −0.2811 | −0.0405 | −0.0128 | −0.1754 | −0.1647 | −0.2627 |
| SDG 6 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.1012 | −0.0887 | −0.1546 | −0.0887 | −0.3386 | −0.2205 | −0.2181 | −0.2093 | −0.2627 | −0.3274 |
| SDG 7 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.2117 | −0.2406 | −0.1885 | −0.2627 | −0.1843 | 0.0871 | −0.3065 | −0.3274 | −0.1108 | −0.2442 |
| SDG 17 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.0700 | −0.0317 | −0.0944 | −0.3712 | −0.2181 | −0.0359 | −0.0862 | −0.0899 | −0.1439 | −0.2093 | −0.2627 |
| ESRM 1 | 0.3209 | −0.1686 | −0.2093 | −0.1691 | −0.1686 | −0.3673 | −0.5366 | −0.0128 | −0.1617 | −0.0206 | −0.1889 | −0.1715 | −0.0405 | −0.1108 | −0.0104 | −0.1029 | −0.1157 | 0.0000 |
| ESRM 2 | 0.0000 | 0.0828 | −0.0573 | −0.1996 | −0.0017 | −0.0065 | −0.0527 | 0.1317 | 0.0342 | −0.0452 | 0.0174 | −0.1166 | 0.1060 | −0.0323 | −0.1691 | 0.2313 | −0.0172 | −0.0493 |
| ESRM 3 | 0.0422 | 0.0333 | 0.1686 | −0.0599 | 0.0405 | −0.1799 | −0.1775 | −0.2489 | −0.3137 | −0.3377 | −0.0222 | −0.0192 | 0.0120 | −0.0032 | −0.2249 | −0.0877 | −0.0406 | −0.1021 |
| ESRM 4 | −0.0138 | 0.2334 | 0.2129 | 0.0884 | 0.1375 | −0.0517 | 0.0498 | 0.0811 | −0.1563 | 0.2999 | 0.0016 | 0.0304 | 0.2228 | −0.0452 | 0.0248 | −0.2218 | −0.1599 | −0.0510 |
| ESRM 5 | −0.1771 | −0.2545 | −0.1181 | 0.0535 | −0.2093 | −0.1598 | −0.0647 | 0.0375 | −0.0206 | −0.0153 | −0.0001 | −0.0262 | −0.0688 | −0.2078 | −0.1285 | −0.0623 | 0.0990 | 0.1745 |
| ESRM 6 | 0.0407 | −0.1044 | −0.1371 | 0.0192 | −0.0144 | −0.1555 | −0.1285 | 0.1149 | −0.0438 | 0.1535 | 0.1891 | −0.1603 | 0.1171 | 0.0145 | 0.0584 | 0.2508 | 0.0303 | 0.0000 |
| ESRM 7 | 0.1023 | −0.5182 | −0.4723 | −0.3592 | −0.2658 | −0.3163 | −0.3777 | −0.5511 | −0.0949 | −0.1644 | −0.4988 | −0.1940 | −0.1984 | −0.4040 | −0.2817 | −0.5940 | −0.4186 | 0.0000 |
| ESRM 8 | 0.0742 | 0.0212 | −0.0785 | −0.2285 | −0.4077 | 0.1836 | −0.0638 | −0.0830 | −0.0012 | −0.0096 | −0.3274 | −0.1691 | −0.2331 | −0.3362 | 0.0422 | −0.0089 | −0.0510 | 0.0000 |
| ESRM 9 | 0.0407 | −0.0510 | 0.0828 | 0.1132 | 0.0446 | −0.1715 | −0.0493 | −0.0534 | −0.1514 | 0.0263 | 0.0232 | −0.1181 | −0.1691 | −0.1181 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ESRM 10 | 0.0000 | 0.0422 | −0.1320 | 0.0000 | −0.1181 | 0.0000 | −0.0510 | −0.0735 | −0.0438 | 0.0303 | 0.0742 | 0.0000 | 0.0407 | 0.0742 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

**Table 3.** The total direct influence matrix.

| | SDG 13 | SDG 7 | SDG 9 | SDG 12 | SDG 11 | SDG 6 | SDG 7 | SDG 17 | ESRM 1 | ESRM 2 | ESRM 3 | ESRM 4 | ESRM 5 | ESRM 6 | ESRM 7 | ESRM 8 | ESRM 9 | ESRM 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SDG 13 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | 0.0027 | 0.0027 | 0.0027 | 0.0027 | 0.0027 | 0.0027 | 0.0027 | 0.0027 | 0.0027 |
| SDG 7 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | 0.0027 | 0.0007 | 0.0027 | 0.0007 | −0.0008 | 0.0027 | 0.0027 | 0.0027 | 0.0027 |
| SDG 9 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | −0.0043 | 0.0007 | −0.0013 | −0.0040 | −0.0008 | 0.0027 | 0.0027 | 0.0027 | 0.0099 |
| SDG 12 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | 0.0028 | −0.0020 | −0.0043 | 0.0019 | 0.0027 | 0.0027 | 0.0099 | 0.0006 | 0.0053 |
| SDG 11 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | −0.0008 | −0.0012 | 0.0247 | 0.0105 | 0.0133 | 0.0019 | 0.0006 | 0.0083 | 0.0078 | 0.0125 |
| SDG 6 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0048 | 0.0042 | 0.0073 | 0.0042 | 0.0161 | 0.0105 | 0.0104 | 0.0099 | 0.0125 | 0.0155 |
| SDG 7 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0101 | 0.0114 | 0.0090 | 0.0125 | 0.0088 | −0.0041 | 0.0146 | 0.0155 | 0.0053 | 0.0116 |
| SDG 17 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0033 | 0.0015 | 0.0045 | 0.0176 | 0.0104 | 0.0017 | 0.0041 | 0.0043 | 0.0068 | 0.0099 | 0.0125 |
| ESRM 1 | −0.0152 | 0.0080 | 0.0099 | 0.0080 | 0.0080 | 0.0174 | 0.0255 | 0.0006 | 0.0077 | 0.0010 | 0.0090 | 0.0081 | 0.0019 | 0.0053 | 0.0005 | 0.0049 | 0.0055 | 0.0000 |
| ESRM 2 | 0.0000 | −0.0039 | 0.0027 | 0.0095 | 0.0001 | 0.0003 | 0.0025 | −0.0063 | −0.0016 | 0.0021 | −0.0008 | 0.0055 | −0.0050 | 0.0015 | 0.0080 | −0.0110 | 0.0008 | 0.0023 |
| ESRM 3 | −0.0020 | −0.0016 | −0.0080 | 0.0028 | −0.0019 | 0.0085 | 0.0084 | 0.0118 | 0.0149 | 0.0160 | 0.0011 | 0.0009 | −0.0006 | 0.0002 | 0.0107 | 0.0042 | 0.0019 | 0.0048 |
| ESRM 4 | 0.0007 | −0.0111 | −0.0101 | −0.0042 | −0.0065 | 0.0025 | −0.0024 | −0.0039 | 0.0074 | −0.0142 | −0.0001 | −0.0014 | −0.0106 | 0.0021 | −0.0012 | 0.0105 | 0.0076 | 0.0024 |
| ESRM 5 | 0.0084 | 0.0121 | 0.0056 | −0.0025 | 0.0099 | 0.0076 | 0.0031 | −0.0018 | 0.0010 | 0.0007 | 0.0000 | 0.0012 | 0.0033 | 0.0099 | 0.0061 | 0.0030 | −0.0047 | −0.0083 |
| ESRM 6 | −0.0019 | 0.0050 | 0.0065 | −0.0009 | 0.0007 | 0.0074 | 0.0061 | −0.0055 | 0.0021 | −0.0073 | −0.0090 | 0.0076 | −0.0056 | −0.0007 | −0.0028 | −0.0119 | −0.0014 | 0.0000 |
| ESRM 7 | −0.0049 | 0.0246 | 0.0224 | 0.0171 | 0.0126 | 0.0150 | 0.0179 | 0.0262 | 0.0045 | 0.0078 | 0.0237 | 0.0092 | 0.0094 | 0.0192 | 0.0134 | 0.0282 | 0.0199 | 0.0000 |
| ESRM 8 | −0.0035 | −0.0010 | 0.0037 | 0.0109 | 0.0194 | −0.0087 | 0.0030 | 0.0039 | 0.0001 | 0.0005 | 0.0155 | 0.0080 | 0.0111 | 0.0160 | −0.0020 | 0.0004 | 0.0024 | 0.0000 |
| ESRM 9 | −0.0019 | 0.0024 | −0.0039 | −0.0054 | −0.0021 | 0.0081 | 0.0023 | 0.0025 | 0.0072 | −0.0012 | −0.0011 | 0.0056 | 0.0080 | 0.0056 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| ESRM 10 | 0.0000 | −0.0020 | 0.0063 | 0.0000 | 0.0056 | 0.0000 | 0.0024 | 0.0035 | 0.0021 | −0.0014 | −0.0035 | 0.0000 | −0.0019 | −0.0035 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

#### 3.3.3. Analyzing and Interpreting the Results from the Influential Relation Map

The table presented in this section offers a comprehensive view of the significance and interconnections among SDGs and ESRM factors. The "Prominence (R+C)" values within the table indicate the overall importance of each category, shedding light on their respective contributions to the broader sustainability landscape. Meanwhile, the "Relation (R−C)" values provide insights into the dynamic between the "R Sum" and "C Sum" components, helping to discern which aspect exerts a stronger influence. This analytical framework proves invaluable for informed decision-making processes pertaining to sustainability, safety, and risk management, empowering stakeholders to effectively prioritize their efforts and allocate resources across these diverse yet interconnected factors.

The results include several SDGs associated with specific numerical values that reflect their influence and prominence. The following observations can be made:

SDG 13 (Climate Action): This category has a positive "R Sum" of 0.0289 and a negative "C Sum" of −0.0223. The "Prominence (R+C)" is 0.0066, indicating a relatively low overall prominence. The "Relation (R−C)" value is 0.0512, suggesting that the "R Sum" outweighs the "C Sum".

SDG 7 (Clean Energy Access): This category has a positive "R Sum" of 0.0211 and a positive "C Sum" of 0.0348. The "Prominence (R+C)" is 0.0559, indicating a moderate level of prominence. The "Relation (R−C)" value is −0.0136, suggesting that the "C Sum" has a slightly more substantial influence.

SDG 9 (Industry, Innovation, and Infrastructure): Within this category, the "R Sum" is calculated at 0.0125, and the "C Sum" stands at 0.0374, yielding a combined "Prominence (R+C)" score of 0.0498. This suggests a moderate level of prominence for SDG 9. Notably, the "Relation (R−C)" value is −0.0249, indicating a slightly stronger influence from the "C Sum" component.

Similarly, the ESRM categories are associated with numerical values that reflect their prominence and relationships:

ESRM 1 (Robust Regulatory Framework): This category has a positive "R Sum" of 0.1133 and a positive "C Sum" of 0.0771. The "Prominence (R+C)" is 0.1904, indicating a relatively high prominence. The "Relation (R−C)" value is 0.0362, showing that the "R Sum" has a slightly stronger influence.

ESRM 2 (Risk Assessment and Management): This category has a positive "R Sum" of 0.0075 and a positive "C Sum" of 0.0284. The "Prominence (R+C)" is 0.0359, suggesting a relatively low overall prominence. The "Relation (R−C)" value is −0.0209, indicating that the "C Sum" has a slightly more substantial influence.

Similar analyses have been conducted for the remaining ESRMs.

To provide a deeper understanding of the obtained dataset's dynamics and implications, it should be noted that ESRM 7 has the highest "R Sum" value of 0.2829, indicating a strong positive influence within the ESRM factors. This suggests that this factor is prominent in terms of the metrics involved in the "R Sum" calculation. ESRM 4 has the lowest "R Sum" value of −0.0328, suggesting a relatively limited positive influence or even a negative impact. This could imply that this factor may not be as effective in driving the metrics contributing to the "R Sum". ESRM 3 has the highest "C Sum" value of 0.1015, indicating a substantial positive contribution in the context of "C Sum" metrics. This suggests that the metrics associated with this factor collectively drive the positive influence. ESRM 2 has the lowest "C Sum" value of 0.0284, indicating a relatively lower positive contribution in the context of "C Sum" metrics. This could imply that this factor might have a lesser positive impact on the metrics contributing to the "C Sum".

ESRM 7 has the highest "Prominence (R+C)" value of 0.3608, signifying its overall prominence when both "R Sum" and "C Sum" metrics are combined. This suggests that ESRM 7 has a significant influence across multiple aspects. ESRM 2 has the lowest "Prominence (R+C)" value of 0.0359, implying a relatively lower overall prominence in the obtained dataset. The combined influence of its "R Sum" and "C Sum" metrics is comparatively modest. ESRM 7 has the highest "Relation (R−C)" value of 0.2052, indicating that its "R Sum" significantly outweighs its "C Sum". This suggests a strong positive influence, specifically from its "R Sum". ESRM 4 has the lowest "Relation (R−C)" value of −0.1203, implying that its "C Sum" has substantially more influence compared to its "R Sum". This could suggest that ESRM 4's "R Sum" values are weaker than its "C Sum".

### *3.4. Implications and Considerations*

ESRM 7 (Incident Reporting and Learning) stands out across all metrics, indicating its strong influence and prominence. ESRM 2 (Risk Assessment and Management) has relatively lower values across metrics, suggesting potential areas for improvement. Decision-makers can prioritize ESRM 7 for further development due to its high influence. ESRM 2 might benefit from targeted efforts to strengthen its influence within the obtained dataset.

Interpretations are based on provided values, and the meaning of these metrics could vary depending on the specific criteria used for calculations. This thorough analysis provides an in-depth understanding of the obtained dataset's dynamics, highlighting ESRM 7 as the most influential factor and ESRM 2 as relatively less effective. Such insights are valuable for informed decision-making, allowing stakeholders to allocate resources effectively and enhance the prominence of specific elements within SDGs and Environmental, Social, and Risk Management.

## 4. Results

In this section, a sensitivity analysis (SA) is conducted by selecting a range of gamma values (0.1, 0.5, 0.7, and 0.9) that span the spectrum between zero and one. While these specific gamma values were chosen to provide a diverse set of scenarios, their selection was not based on specific underlying factors or considerations but rather aimed to explore a wide range of possibilities. The significance of the SA becomes paramount when contemplating integrating hydrogen energy into sustainable development, as it systematically examines how fluctuations in input parameters ripple through results. This analysis unveils pivotal factors that mold system performance, safety, and sustainability within the hydrogen energy domain by pinpointing vulnerabilities, guiding decisions, and illuminating trade-offs. SA is vital in optimizing resource allocation, managing risks, and enabling adaptive planning, fostering system robustness, addressing public concerns, and ensuring alignment with evolving regulatory frameworks. As an ongoing enhancement tool, SA empowers stakeholders to make informed and effective choices, harmonizing with the intricate dynamics of hydrogen energy systems and contributing to fulfilling long-term SDGs.

The outcomes of the SA have been visually depicted in Figure 5. Upon close examination of Figure 5, a discernible shift becomes apparent within the category (zone) classifications of SDG 6, SDG 7, ESRM 1, ESRM 3, and ESRM 8. Previously regarded as independent factors, these categories have transformed into impactful ones. This intriguing observation suggests that variations in regret-rejoice values partially influence the input variables.

To put it briefly, the results underscore that manipulating the gamma value from 0.1 to 0.5 induces a noteworthy alteration in the categorization zone associated with contributing factors. This underscores the paramount significance of accurately selecting the gamma value. This finding highlights the imperative nature of meticulous value selection in shaping the resulting zone of contributing factors. It emphasizes the dynamic interplay between parameter values and their consequential effects on factor categorizations. This insight reveals the intricate interrelationships that govern the SA process, offering a deeper understanding of a notable positive impact within its category of the nuanced mechanisms that govern variable interdependencies and their impact on the overall outcome.

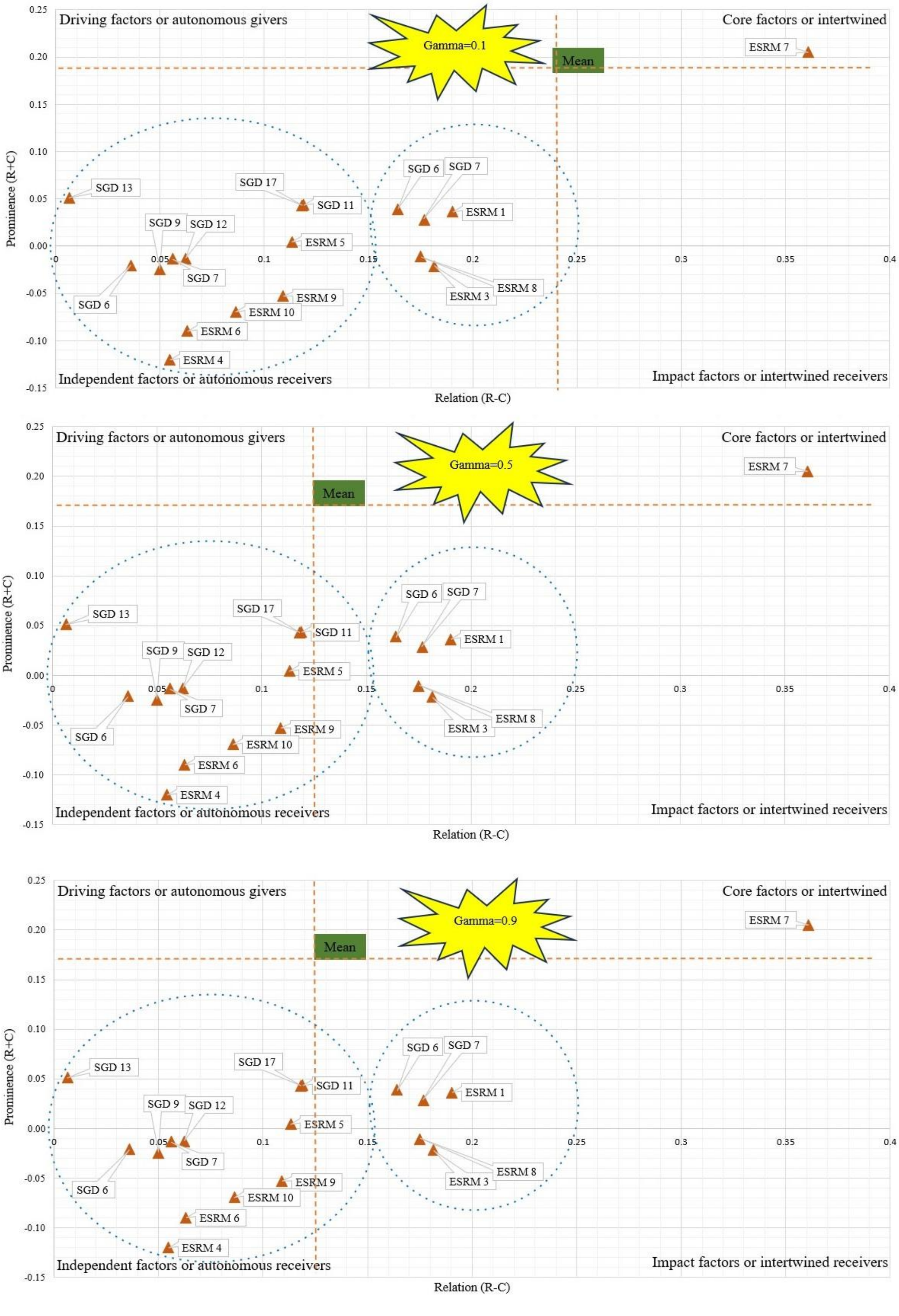


**Figure 5.** The sensitivity analysis outcomes.

## 5. Discussion

The results and discussion sections not only provide valuable insights into the SA conducted to assess the varying impact of different gamma values (0.1, 0.5, 0.7, and 0.9) on hydrogen energy and sustainable development outcomes but also explore the practical value and potential applications of these findings in various management scenarios.

Significance of SA and Its Practical Value: This section begins by emphasizing the SA's critical significance in integrating hydrogen energy into sustainable development. It is a systematic approach to understanding how changes in input parameters, such as the selection of different $\Gamma$ values, influence the performance, safety, and sustainability of hydrogen energy systems. Beyond this, the practical value of the SA becomes evident as it is positioned as an indispensable tool for real-world decision-making.

Resource Allocation and Risk Management: A central point of discussion is how the SA plays a pivotal role in optimizing resource allocation and managing risks. By identifying the key factors that impact the system's performance, stakeholders are empowered to make informed choices. This, in turn, allows for more efficient resource allocation and mitigating potential risks associated with hydrogen energy projects. The practical implications of these insights are far-reaching, as they enable more precise and effective management of hydrogen energy initiatives.

System Robustness and Regulatory Alignment: The discussion further highlights the SA's role in fostering system robustness and ensuring alignment with evolving regulatory frameworks. This dimension of the SA is particularly pertinent, as it contributes to building resilient hydrogen energy systems that meet regulatory requirements and address public concerns. In essence, the SA supports creating systems that are compliant and responsive to societal expectations.

Practical Applications in Other Scenarios: Beyond the immediate context of hydrogen energy, the SA methodology employed here holds significant potential for application in various other management scenarios. Whether in renewable energy projects, infrastructure development, or environmental management, the insights gained from this SA can be adapted to optimize resource allocation, manage risks, and enhance decision-making. By exploring these potential applications, this discussion broadens the horizons of the SA's utility beyond the present study.

Deeper Understanding and Future Applications: The SA results provide a deeper understanding of the intricate interrelationships governing variable dependencies. This knowledge can be leveraged in future applications, helping decision-makers anticipate and respond to complex interdependencies across various scenarios.

In sum, the results and discussion sections comprehensively analyze the SA conducted on gamma values in the context of hydrogen energy and sustainable development and highlight its practical implications. SA is a powerful tool for enhancing decision-making, optimizing resource allocation, and managing risks. Moreover, the dynamic nature of parameter values and their effects on system performance and factor categorizations suggest that this methodology has far-reaching applicability, offering valuable insights across various management scenarios.

## 6. Conclusions and Outlook

In this comprehensive study, the integration of hydrogen-based energy systems with the Sustainable Development Goals (SDGs) in the context of the United Kingdom has been meticulously examined, with a specific focus on fortifying safety and risk mitigation within the hydrogen energy sector. This harmonious fusion of hydrogen technologies with the UK's SDGs presents a strategic pathway to address the pressing challenges of climate change and sustainable development. By incorporating hydrogen solutions across various sectors while ensuring stringent safety measures, the UK can forge a more sustainable and secure energy future for itself and its global responsibilities.

Hydrogen energy integration with the SDGs has profound implications for advancing sustainability across critical domains. Primarily, in alignment with SDG 13 (Climate

Action), adopting hydrogen as a low-carbon energy carrier can significantly curtail greenhouse gas emissions, substantially contributing to the global fight against climate change. Concurrently, incorporating hydrogen solutions aligns with SDG 7 (Clean Energy Access), offering cleaner, more reliable energy sources that reduce reliance on fossil fuels and enhance energy accessibility for all segments of society. Embracing hydrogen-based energy technologies also resonates with SDG 9 (Industry, Innovation, and Infrastructure) by catalyzing substantial investments in infrastructure and technological innovation. This transformative approach extends its positive impact to SDG 12 (Responsible Consumption and Production) by emphasizing sustainable and efficient resource utilization, and SDG 11 (Sustainable Cities and Communities) by offering clean energy solutions for urbanization, promoting the development of resilient and inclusive cities. The link between hydrogen energy and SDG 6 (Clean Water and Sanitation) is accentuated by the imperative for environmentally conscious hydrogen production processes that minimize water consumption, ensuring responsible water resource management. The realization of affordable and clean energy, as envisaged by SDG 7, is further propelled through the widespread adoption of hydrogen-based energy systems.

The principle of collaboration and partnership is central to the successful integration of hydrogen energy with the UK's SDGs, as underscored by SDG 17 (Partnerships for the Goals). Achieving a harmonious and impactful synergy necessitates active engagement from various stakeholders, including governments, industry players, academia, and society, who must collectively work toward a shared vision of sustainable development.

Moreover, this study underscores the importance of safety and risk mitigation throughout the integration process. The UK can ensure the secure implementation of hydrogen energy systems by adhering to a robust regulatory framework, conducting thorough risk assessments, upholding safety standards, providing comprehensive training, and establishing incident response mechanisms. A proactive approach to safety safeguards communities' well-being and fosters public trust and confidence, which are essential elements for successfully adopting this transformative energy source.

Integrating the hydrogen energy economy with the UK's SDGs holds immense promise for addressing critical global challenges while nurturing a sustainable and secure energy future. This study highlights that safety is both a technical imperative and a fundamental enabler of successful integration. A proactive, multi-pronged approach to safety enhancement ensures that the potential benefits of hydrogen energy can be harnessed while minimizing risks to human life, the environment, and infrastructure. By placing safety at the forefront, as demonstrated in this study through initiatives like Public Engagement and Communication (ESRM 8), the UK can achieve its ambitious energy goals and uphold its commitment to sustainable development and the well-being of its citizens.

In this comprehensive study, we have meticulously examined the integration of hydrogen-based energy systems with the SDGs in the context of the UK, with a specific focus on fortifying safety and risk mitigation within the hydrogen energy sector. This harmonious fusion of hydrogen technologies with the UK's SDGs presents a strategic pathway to address the pressing challenges of climate change and sustainable development. However, it is essential to recognize that while this integration offers immense promise, it has limitations and must consider future directions for further enhancement.

Limitations:

- Technological challenges: The widespread adoption of hydrogen-based energy systems necessitates technological advancements, such as more efficient and cost-effective hydrogen production methods and reliable storage solutions. These technical hurdles may require significant research and development investments.
- Infrastructure investment: Integrating hydrogen into various sectors requires substantial infrastructure development, including hydrogen production facilities, transportation networks, and refueling stations. The financial and logistical challenges associated with this infrastructure development are significant.

- Resource constraints: Hydrogen production often relies on natural gas reforming or electrolysis, which have resource and environmental constraints. For instance, the availability of clean water for electrolysis is a critical concern in regions facing water scarcity.
- Safety risks: While safety measures are crucial, it is essential to acknowledge that hydrogen, as a highly flammable gas, poses inherent safety risks. Addressing these risks requires continuous vigilance, investment in safety technologies, and adherence to rigorous safety standards.

Futured:

- Technological advancements: Continued research and innovation are needed to make hydrogen production more sustainable and cost-efficient. This includes exploring new methods for green hydrogen production, such as renewable-powered electrolysis or biomass conversion.
- Infrastructure expansion: Governments and private sectors must collaborate to accelerate the development of a comprehensive hydrogen infrastructure, including pipelines, transportation, and storage facilities. This expansion should be guided by a long-term vision to ensure scalability.
- Global collaboration: Hydrogen integration should extend beyond national boundaries. International collaboration and partnerships can facilitate the exchange of knowledge, resources, and best practices, contributing to a global transition towards sustainable hydrogen-based systems.
- Environmental sustainability: Future research and development efforts should prioritize environmentally conscious hydrogen production methods that minimize water usage and emissions. This aligns with SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action).
- Safety enhancement: Continuous improvement in safety measures and technologies is imperative. This includes ongoing risk assessments, regular safety audits, and safety training and awareness program investments.
- Public engagement: Effective public engagement strategies should be developed and maintained to foster community trust and confidence. Public awareness campaigns, clear communication of safety measures, and transparent incident reporting mechanisms are essential components.
- Regulatory framework: Governments should establish and enforce a robust regulatory framework for hydrogen integration, ensuring compliance with safety standards, environmental regulations, and ethical considerations.
- Monitoring and evaluation: Continuous monitoring and evaluation of the integration process are necessary to promptly identify and rectify safety and environmental issues. Regular reporting and transparent communication are essential for accountability.

Integrating hydrogen-based energy systems with the Sustainable Development Goals in the United Kingdom is a transformative endeavor with vast potential. However, it is essential to address the limitations and chart future directions for sustainable and secure hydrogen energy integration. By doing so, the UK can play a pivotal role in addressing global challenges while upholding its commitment to sustainable development and the well-being of its citizens.

**Author Contributions:** Conceptualization, M.Y.; Methodology, R.M., H.L., A.N. and H.L.; Software, M.Y. and R.G.P.; Validation, R.M.; Formal analysis, H.L.; Investigation, R.G.P., A.N. and H.L.; Resources, R.G.P. and R.M.; Writing—original draft, M.Y. and H.L.; Writing—review & editing, R.G.P., A.N. and H.L.; Visualization, M.Y. and R.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available in study.

**Acknowledgments:** We extend our sincere appreciation to our esteemed industrial partner subject matter experts whose invaluable contributions and expert guidance significantly enhanced the quality and depth of this paper. Their unwavering commitment to excellence and their passion for the subject matter have been instrumental in shaping the direction of our research, elevating this work to a higher standard. We are truly grateful for their dedicated collaboration and look forward to the possibility of future endeavors together.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Declaration of Generative AI and AI-Assisted Technologies in the Writing Process:** During the preparation of this work, the author(s) utilized generative AI and AI-assisted technologies, including the Bing AI, to enhance the writing process. These tools were employed to improve language clarity and language fluency. Following the utilization of this tool/service, the author(s) thoroughly reviewed and edited the content, ensuring its coherence and accuracy in accordance with the intended message.

## References

1. Razmjoo, A.; Gandomi, A.H.; Pazhoohesh, M.; Mirjalili, S.; Rezaei, M. The key role of clean energy and technology in smart cities development. *Energy Strategy Rev.* **2022**, *44*, 100943. [CrossRef]
2. Khalil, M.I.; Jhanjhi, N.Z.; Humayun, M.; Sivanesan, S.; Masud, M.; Hossain, M.S. Hybrid smart grid with sustainable energy efficient resources for smart cities. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101211. [CrossRef]
3. Ekins, P. *Hydrogen Energy: Economic and Social Challenges*; Earthscan: Oxford, UK, 2010.
4. Pasman, H.; Sripaul, E.; Khan, F.; Fabiano, B. Energy transition technology comes with new process safety challenges and risks. *Process Saf. Environ. Prot.* **2023**, *177*, 765–794. [CrossRef]
5. UK Hydrogen Strategy. HM Government. 2021. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1175494/UK-Hydrogen-Strategy (accessed on 1 July 2023).
6. Edwards, R.L.; Font-Palma, C.; Howe, J. The status of hydrogen technologies in the UK: A multi-disciplinary review. *Sustain. Energy Technol. Assess.* **2021**, *43*, 100901. [CrossRef]
7. Blanco, H.; Nijs, W.; Ruf, J.; Faaij, A. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. *Appl. Energy* **2018**, *232*, 617–639. [CrossRef]
8. James, P.; Joshua, W.; Jordie, P. Comparing the Hydrogen Strategies of the EU, Germany, and Australia: Legal and Policy Issues (February 1, 2021). (2021) 19(2) Oil, Gas and Energy Law Intelligence, ANU College of Law Research Paper No. 21.21. Available online: https://ssrn.com/abstract=3875170 (accessed on 1 July 2023).
9. Behling, N.; Williams, M.C.; Managi, S. Fuel cells and the hydrogen revolution: Analysis of a strategic plan in Japan. *Econ. Anal. Policy* **2015**, *48*, 204–221. [CrossRef]
10. Stangarone, T. South Korean efforts to transition to a hydrogen economy. *Clean Technol. Environ. Policy* **2021**, *23*, 509–516. [CrossRef]
11. Yazdi, M.; Zarei, E.; Pirbalouti, R.G.; Li, H. A comprehensive resilience assessment framework for hydrogen energy infrastructure development. *Int. J. Hydrogen Energy* **2023**. [CrossRef]
12. Yazdi, M.; Moradi, R.; Pirbalouti, R.G.; Zarei, E.; Li, H. Enabling Safe and Sustainable Hydrogen Mobility: Circular Economy-Driven Management of Hydrogen Vehicle Safety. *Processes* **2023**, *11*, 2730. [CrossRef]
13. Rigas, F.; Amyotte, P. *Hydrogen Safety*; CRC Press: Boca Raton, FL, USA, 2012.
14. Hirayama, M.; Shinozaki, H.; Kasai, N.; Otaki, T. Comparative risk study of hydrogen and gasoline dispensers for vehicles. *Int. J. Hydrogen Energy* **2018**, *43*, 12584–12594. [CrossRef]
15. Sánchez, A.L.; Williams, F.A. Recent advances in understanding of flammability characteristics of hydrogen. *Prog. Energy Combust. Sci.* **2014**, *41*, 1–55. [CrossRef]
16. Yolcular, S. Hydrogen Production for Energy Use in European Union Countries and Turkey. *Energy Sources Part A Recover. Util. Environ. Eff.* **2009**, *31*, 1329–1337. [CrossRef]
17. Abdeen Mustafa, O. Energy, environment and sustainable development. *Renew. Sustain. Energy Rev.* **2008**, *12*, 2265–2300.
18. Transport and Environment Statistics 2022, n.d. Available online: https://www.gov.uk/government/statistics/transport-and-environment-statistics-2022/transport-and-environment-statistics-2022 (accessed on 1 July 2023).
19. Parra, D.; Gillott, M.; Walker, G.S. The role of hydrogen in achieving the decarbonization targets for the UK domestic sector. *Int. J. Hydrogen Energy* **2014**, *39*, 4158–4169. [CrossRef]
20. Hydrogen Net Zero Investment Roadmap, HM Government, n.d. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1166666/hydrogen-investment-roadmap.pdf (accessed on 1 July 2023).
21. Geels, F.W.; Sovacool, B.K.; Iskandarova, M. The socio-technical dynamics of net-zero industrial megaprojects: Outside-in and inside-out analyses of the Humber industrial cluster. *Energy Res. Soc. Sci.* **2023**, *98*, 103003. [CrossRef]

22. Pultar, A.; Ferrier, J. Next Steps for Decarbonising UK Industry: IDRIC Policy Synthesis Report 2022; 2022. Available online: https://idric.org/wp-content/uploads/IDRIC-Policy-Synthesis-Report-2022.pdf (accessed on 1 July 2023).
23. Griffin, P.W.; Hammond, G.P. Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective. *Appl. Energy* **2019**, *249*, 109–125. [CrossRef]
24. Logan, K.G.; Nelson, J.D.; Hastings, A. Electric and hydrogen buses: Shifting from conventionally fuelled cars in the UK. *Transp. Res. Part D Transp. Environ.* **2020**, *85*, 102350. [CrossRef]
25. Valverde-Isorna, L.; Ali, D.; Hogg, D.; Abdel-Wahab, M. Modelling the performance of wind–hydrogen energy systems: Case study the Hydrogen Office in Scotland/UK. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1313–1332. [CrossRef]
26. Bellaby, P.; Upham, P.; Flynn, R.; Ricci, M. Unfamiliar fuel: How the UK public views the infrastructure required to supply hydrogen for road transport. *Int. J. Hydrogen Energy* **2016**, *41*, 6534–6543. [CrossRef]
27. Giampieri, A.; Ling-Chin, J.; Roskilly, A.P. Techno-economic assessment of offshore wind-to-hydrogen scenarios: A UK case study. *Int. J. Hydrogen Energy* **2023**. [CrossRef]
28. Mouli-Castillo, J.; Heinemann, N.; Edlmann, K. Mapping geological hydrogen storage capacity and regional heating demands: An applied UK case study. *Appl. Energy* **2021**, *283*, 116348. [CrossRef]
29. Maryam, S. Review of modelling approaches used in the HSC context for the UK. *Int. J. Hydrogen Energy* **2017**, *42*, 24927–24938. [CrossRef]
30. Ling-Chin, J.; Giampieri, A.; Wilks, M.; Lau, S.W.; Bacon, E.; Sheppard, I.; Smallbone, A.J.; Roskilly, A.P. Technology roadmap for hydrogen-fuelled transportation in the UK. *Int. J. Hydrogen Energy* **2023**. [CrossRef]
31. Omoniyi, O.; Bacquart, T.; Moore, N.; Bartlett, S.; Williams, K.; Goddard, S.; Lipscombe, B.; Murugan, A.; Jones, D. Hydrogen Gas Quality for Gas Network Injection: State of the Art of Three Hydrogen Production Methods. *Processes* **2021**, *9*, 1056. [CrossRef]
32. Scafidi, J.; Wilkinson, M.; Gilfillan, S.M.; Heinemann, N.; Haszeldine, R.S. A quantitative assessment of the hydrogen storage capacity of the UK continental shelf. *Int. J. Hydrogen Energy* **2021**, *46*, 8629–8639. [CrossRef]
33. Zarei, E.; Khan, F.; Yazdi, M. A dynamic risk model to analyze hydrogen infrastructure. *Int. J. Hydrogen Energy* **2021**, *46*, 4626–4643. [CrossRef]
34. Pirbalouti, R.G.; Dehkordi, M.K.; Mohammadpour, J.; Zarei, E.; Yazdi, M. An advanced framework for leakage risk assessment of hydrogen refueling stations using interval-valued spherical fuzzy sets (IV-SFS). *Int. J. Hydrogen Energy* **2023**, *48*, 20827–20842. [CrossRef]
35. Li, H.; Yazdi, M. *Advanced Decision-Making Methods and Applications in System Safety and Reliability Problems*; Springer: Cham, Switzerland, 2022; Available online: https://link.springer.com/book/9783031074295 (accessed on 1 July 2023).
36. Adem, A.; Çolak, A.; Dağdeviren, M. An integrated model using SWOT analysis and Hesitant fuzzy linguistic term set for evaluation occupational safety risks in life cycle of wind turbine. *Saf. Sci.* **2018**, *106*, 184–190. [CrossRef]
37. Abdullah, S.; Barukab, O.; Qiyas, M.; Arif, M.; Khan, S.A. Analysis of Decision Support System Based on 2-Tuple Spherical Fuzzy Linguistic Aggregation Information. *Appl. Sci.* **2020**, *10*, 276. [CrossRef]
38. Loomes, G.; Sugden, R. Regret Theory: An Alternative Theory of Rational Choice Under Uncertainty. *Econ. J.* **1982**, *92*, 805–824. [CrossRef]
39. Martínez, L.; Rodriguez, R.M.; Herrera, F.; Martínez, L.; Rodriguez, R.M.; Herrera, F. *2-Tuple Linguistic Model*; Springer International Publishing: Cham, Switzerland, 2015; pp. 23–42.
40. Martinez, L.; Herrera, F. A 2-tuple fuzzy linguistic representation model for computing with words. *IEEE Trans. Fuzzy Syst.* **2000**, *8*, 746–752. [CrossRef]
41. Yazdi, M.; Khan, F.; Abbassi, R.; Rusli, R. Improved DEMATEL methodology for effective safety management decision-making. *Saf. Sci.* **2020**, *127*, 104705. [CrossRef]
42. Li, H.; Yazdi, M. *Dynamic Decision-Making Trial and Evaluation Laboratory (DEMATEL): Improving Safety Management System BT—Advanced Decision-Making Methods and Applications in System Safety and Reliability Problems: Approaches, Case Studies, Multi-Criteria Decision-Maki*; Li, H., Yazdi, M., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 1–14. [CrossRef]
43. Shieh, J.-I.; Wu, H.-H.; Huang, K.-K. A DEMATEL method in identifying key success factors of hospital service quality. *Knowl.-Based Syst.* **2010**, *23*, 277–282. [CrossRef]
44. Si, S.-L.; You, X.-Y.; Liu, H.-C.; Zhang, P. DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications. *Math. Probl. Eng.* **2018**, *2018*, 3696457. [CrossRef]
45. Yeh, T.-M.; Huang, Y.-L. Factors in determining wind farm location: Integrating GQM, fuzzy DEMATEL, and ANP. *Renew. Energy* **2014**, *66*, 159–169. [CrossRef]
46. Lee, H.-S.; Tzeng, G.-H.; Yeih, W.; Wang, Y.-J.; Yang, S.-C. Revised DEMATEL: Resolving the Infeasibility of DEMATEL. *Appl. Math. Model.* **2013**, *37*, 6746–6757. [CrossRef]
47. Xing, Y.; Meng, W.; Zhou, J.; Hu, F.; Meng, L. DEMATEL, AISM, and MICMAC-based research on causative factors of self-build housing fire accidents in rural areas of China. *Fire* **2023**, *6*, 179. [CrossRef]
48. Slorach, P.C.; Stamford, L. Net zero in the heating sector: Technological options and environmental sustainability from now to 2050. *Energy Convers. Manag.* **2021**, *230*, 113838. [CrossRef]
49. ApSimon, H.; Oxley, T.; Woodward, H.; Mehlig, D.; Holland, M.; Reeves, S. Integrated Assessment Modelling of Future Air Quality in the UK to 2050 and Synergies with Net-Zero Strategies. *Atmosphere* **2023**, *14*, 525. [CrossRef]

50. Tversky, A.; Kahneman, D. Advances in prospect theory: Cumulative representation of uncertainty. *J. Risk Uncertain.* **1992**, *5*, 297–323. [CrossRef]
51. Huang, L.; Mao, L.-X.; Chen, Y.; Liu, H.-C. New method for emergency decision making with an integrated regret theory-EDAS method in 2-tuple spherical linguistic environment. *Appl. Intell.* **2022**, *52*, 13296–13309. [CrossRef] [PubMed]