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INVESTIGATING THE KEY DRIVERS IN THE TRANSITION TO SUSTAINABLE HYDROGEN TRANSPORTATION FUEL

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Introduction. Hydrogen is a promising energy carrier that can achieve net-zero carbon emissions and decrease fossil fuel dependency. However, the importance of the driving forces in hydrogen adaptation and acceptance during the transition to this technology should be emphasised. When assessing hydrogen as a sustainable transportation fuel, defining the success criteria is vital to comprehend the benefits of hydrogen in the transition process. The transport sector is a priority area for the transition to zero emissions, which requires an understanding of the links between the key drivers of hydrogen adoption in transportation.

Aim and tasks. This study aims to identify the key drivers of the hydrogen transition and explore the relationship between the transition drivers to hydrogen as a sustainable transport fuel based on a comprehensive literature review and an interpretative structural modelling approach to determine the relationship between the above-mentioned key drivers.

Results. This study identified key drivers for the transition to hydrogen as a sustainable transport fuel using the Interpretive Structural Modelling (ISM) approach. This study examines the potential of hydrogen transition, analyses the driving forces, and examines their interrelationships in terms of driving force and dependent force. The role of technological development and transition awareness in achieving the SDGs is revealed. Robust regulatory agendas and supportive strategies, Workforce development and training based on hydrogen deployment, and Industry partnerships and collaboration are the most fundamental drivers for achieving the transition to hydrogen as a sustainable transport fuel. In addition, the advancement of hydrogen technologies in production, storage, and transportation, as well as hydrogen production and use, aligns with environmental aims, which are key factors that depend mainly on the actions of other driving forces. However, the limitations of this study include subjectivity and potential differences in the driving forces across countries and sectors.

Conclusions. The deployment of green hydrogen transition for a clean energy source is critical in carbon-intensive sectors of the economy, which are characterised by key drivers and their interlinkages, such as regulatory strategies, workforce development, and industry partnerships. This has increased the flexibility of energy systems with the collaboration of the stakeholders for developing hydrogen technologies and infrastructure, considering the environmental safety, economic efficiency, and social acceptability of hydrogen.

Keywords: hydrogen transition, driving force, net-zero emissions, interpretive structural modelling.

1. Introduction.

The negative influence of climate change and human activities on the environment has led to increasing concerns and demand for sustainable energy bases (Hassan et al., 2023). According to the European Commission, greenhouse gas emissions must be halved to prevent the global average temperature from increasing by more than 1.5ºC (Sena et al., 2024). In order to reach the net zero emission goals stated by the Paris Agreement, the hydrogen transition is considered a clean and green shift (Kumar et al., 2023). Affordable and clean energy are also presenting one of a significant sustainable development goal (Santana et al. 2024).

The global hydrogen consumption in 2021 is estimated to be approximately 94 million tons, and it has been observed to increase by almost 5% compared to 2020 because of the increased awareness of the clean and green energy transition (IEA, 2022). According to 2030 and 2050 net carbon emissions, hydrogen consumption is expected to reach approximately 130 million tons by 2030 (IEA, 2022). One of the carbon-intensive sectors in the transportation sector depends mainly on fossil fuels. Therefore, this sector is critical for transitioning to net-zero carbon emissions.

The deployment of hydrogen has many advantages, such as providing affordable and clean energy with increasing demand and cooperation of stakeholders at a global level. Despite the many advantages of this hydrogen transition, there still needs to be concern about its risks, high cost, safety, and promising acceptance. Thus, to address these drawbacks of hydrogen, collaborative technical and feasibility studies of this transition are required (Ishaq et al., 2022).

Standards and agreements related to hydrogen technology must be adopted and managed effectively. Well-designed strategies are critical for handling the drawbacks of hydrogen transitions (Alises & Vassallo, 2015). Thus, to overcome these challenges, innovative approaches, increased efficiency, effective demand and risk management, incentives, and collaboration with supply chain stakeholders are required to achieve net zero emissions in the long run (Kwilinski et al., 2023).

Therefore, economic, social, and environmental factors must be considered holistically and dynamically. Therefore, these factors and their effects must be considered concurrently. Thus, this study proposes to determine the driving forces of hydrogen deployment and analyse the relationships between the proposed drivers.

From this perspective, drivers transitioning to hydrogen as a green transportation fuel must be analysed. In addition, the relationship between the proposed drivers in the transition to hydrogen as a maintainable transportation fuel was incorporated into this study (Xu & Zou, 2020).

Therefore, this study analyses the relationships between drivers in the transition to hydrogen as a sustainable transport fuel for net-zero carbon emissions and the following research question (RQ):

What are the critical drivers for adopting hydrogen as a sustainable transportation fuel, and what are the relationships between the proposed drivers for the hydrogen transition?

To answer this research question, the key drivers of adopting hydrogen as a sustainable transportation fuel were defined with the help of a literature review. Ten drivers were proposed through a literature review.

Then, to analyse the relationships between key drivers in the transition to hydrogen as a sustainable transportation fuel, Interpretive Structural Modelling (ISM) methodology is applied, and suggestions are proposed based on the results.

The proposed model was used to present and quantify causal relationship drivers. A structured model is needed to propose actions related to key drivers in transitioning to hydrogen as a sustainable transportation fuel.

2. Literature review.

The transition to hydrogen as a sustainable transportation fuel has many benefits considering environmental, economic, and social perspectives. Thus, many interrelated driving factors can be affected by this transition. One of the critical factors of the hydrogen transition is creating robust regulatory agendas and supportive strategies.

An improved regulation framework is required to standardise the policies and improve social acceptance by dealing with safety concerns about hydrogen deployment.

Increased awareness of the net zero carbon emission transition has led to hydrogen production and use aligned with environmental aims. Increasing the level of hydrogen adoption in the supply chain is critical to stakeholder collaboration and institutional cooperation to enhance workforce development and training based on hydrogen adoption.

Green hydrogen also creates various employment opportunities. This transition can also provide economic growth by providing different job opportunities to local economies. Recently, one of the crucial factors of this transition is to develop feasible and cost-competitive substitutes for fossil fuels. Through high-tech development and innovation, effective solutions can be developed to reach affordable and clean energy.

Singh et al. (2015) discussed new developments in hydrogen technologies based on the environmental and safety aspects. They emphasised that the hydrogen transition's infrastructure requirement and capital expenses require substantial funding and government support. It has been revealed that a need for cooperation by developing incentive systems in production and storage during the infrastructure and technology development phase.

Amoo and Fagbenle (2014) studied the economic aspects of hydrogen use in the energy and transportation sectors. Recently, hydrogen technologies have had high initial investment and operation costs, including storage, transportation, and distribution costs. Thus, the advancement of hydrogen technologies in the production, storage, and distribution of the whole hydrogen supply chain is needed to aim for a zero-carbon economy. Regional and global partnerships play a key role in developing various projects to provide a competitive advantage.

The adoption of hydrogen technologies in the supply chain causes increased efficiency in the production process. The transition to renewable energy sources, especially in carbon-intensive sectors, requires international collaborations and projects and the participation of all actors and stakeholders in the hydrogen supply chain (Hassan et al., 2023). Thus, with increased efficiency in the production process, hydrogen can become a feasible and cost-effective alternative to fossil fuels.

Driving factors of hydrogen technologies adoption is not only related to the operations cost and technical features, but also social acceptance is required for the achieving this transition. Thus, critical challenges are the social acceptance of this transition, coping with critical drawbacks, and encouraging hydrogen adoption, personnel progress, and training based on hydrogen deployment and industry partnership and collaboration (Itaoka et al., 2017). Increased demand and usage for hydrogen in the transportation industry have led to the scalability of the global and regional framework (Staffell et al., 2019).

International collaborations and projects provide dissemination of the implementation of hydrogen in the transportation sector. With large hydrogen valleys and hubs, the unit cost of hydrogen will decrease as hydrogen usage increases on larger scales, and it will become economically advantageous (Lebrouhi et al., 2022). Thus, hydrogen can become an affordable, clean, and feasible alternative to fossil fuels.

Therefore, this study aims to analyse the interrelationships of these proposed key drivers of hydrogen transition. Table 1 presents key drivers for the transition to hydrogen as a sustainable transport fuel. Based on the drivers mentioned above in the transition to hydrogen as a sustainable transportation fuel, relations are analysed using the ISM model discussed in the next section.

Table 1. Key Drivers for the Transition to Hydrogen as a Sustainable Transport Fuel.

	Key Drivers	References
D1	Advancement of hydrogen technologies in the production, storage, and distribution	Ishaq et al. (2022); Faye et al. (2022); Dincer & Aydin (2023)
D2	Feasible and cost-competitive substitute to fossil fuel	Bade et al. (2023); Shardeo et al. (2024); Amoo and Fagbenle (2014)
D3	Robust regulatory agendas and supportive strategies	Cheng and Lee (2022); Bade et al. (2023); Ehret & Bonhoff (2015)
D4	Public support and social acceptance of hydrogen	Itaoka et al. (2017); Emodi et al. (2021); Hassan et al. (2024)
D5	Hydrogen production and use align with environmental aims	Santana et al. (2024); Fascone et al. (2021); Hren et al. (2023)
D6	High-tech development and innovation	Lebrouhi et al. (2022); Zhou et al. (2024); Evro et al. (2024)
D7	Safety and effective risk management	Calabrese et al. (2024); Azadnia et al. (2024); Guo et al. (2024)
D8	Personnel progress and training based on the hydrogen deployment	Agarwal (2022); Beasy et al. (2023); Hassan et al. (2024)
D9	Industry partnership and collaboration	Emodi et al. (2021); Rattle & Taylor (2023); Oliveira et al. (2021)
D10	Scalability	Hassan et al. (2023); Sapkota et al. (2020); Ma et al. (2024)

3. Methodology.

Hydrogen has recently been considered a sustainable and innovative solution for achieving zero carbon emissions. In this direction, hydrogen has attracted attention as an essential energy carrier for achieving low-carbon goals because it does not emit harmful gases due to production from renewable energy sources (Singh et al., 2015). Hydrogen is a critical energy carrier for conversion to a zero-carbon economy because it is abundant in nature and can be formed from renewable energy sources (Acar & Dincer, 2018). The transition to hydrogen requires radical infrastructure, high initial investment, the need to develop robust strategies and policies, and essential changes in technology and infrastructure; thus, driving forces should be provided in these areas.

ISM methodology is applicable for identifying and understanding the relationships between the criteria and their influences. This method is also useful for dealing with complex systems affected by various factors and variables. Based on the problem structure, the relationships between the factors are represented in the digraph. This method is widely used to show the direct and indirect relationships of variables and to define the complex nature of the factors.

In addition, this method is useful for covering qualitative and quantitative approaches by visualising the relationships among the factors. Warfield first introduced this method and the steps to understand socioeconomic systems (Warfield, 1973).

The modelling process was summarised in six stages.

Step 1. Structural Self-Interaction Matrix (SSIM): Expert opinions are used to develop using the V, A, X, and O symbols.

Step 2. Reachability Matrix (RM): The RM is created using rules based on the above symbols. After finding the Initial RM, the subsequent phase is developing a final one.

Step 3. Developing Level Partitions: This stage covers the development of the digraph and the model.

Step 4. Creating a conical matrix: It is established by considering dependability and dependency power.

Step 5. Presenting Digraph: Digraph presents the relationship between the factors.

Step 6. ISM Model: This model was created with the help of a digraph. After developing the ISM model, a MICMAC (Matrices Impacts Croises-Multiplication Appliance Classement) analysis was conducted.

4. Results.

This methodology is based on the expert opinions of six experts who have worked on energy, sustainability and hydrogen conversion projects and have at least five years of experience in their field. The experts are appointed based on their expertise and knowledge in the field.

Information on the experts is presented in Table 2.

A Structural Self-Interaction Matrix based on experts' views is presented in Table 3. After presenting the SSIM interaction matrix, the primary Reachability Matrix is presented in Table 4.

Table 2. Details of experts.

	Experts	*Professional Background (Year)*
1	Sustainability Specialist	8
2	Energy Engineer	11
3	Renewable Energy Specialist	9
4	Environmental Engineer	9
5	Energy Project Specialist	10
6	Energy Project Engineer	7

Table 3. Structured Self-Interaction Matrix.

i, j	*D10*	*D9*	*D8*	*D7*	*D6*	*D5*	*D4*	*D3*	*D2*
D1	X	A	O	A	A	O	A	A	V
D2	X	A	O	O	A	V	A	A	1
D3	V	X	V	V	O	V	V	1	
D4	V	O	A	A	O	A	1		
D5	O	O	O	A	A	1			
D6	X	A	X	V	1				
D7	O	O	O	1					
D8	O	V	1						
D9	V	1							
D10	1								

Table 4. Initial RM.

i, j	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*	*D9*	*D10*
D1	1	1	O	O	O	O	O	O	O	1
D2	O	1	O	O	1	O	O	O	O	1
D3	1	1	1	1	1	O	1	1	1	1
D4	1	1	O	1	O	O	O	O	O	1
D5	O	O	O	1	1	O	O	O	O	O
D6	1	1	O	O	1	1	1	1	O	1
D7	1	O	O	1	1	O	1	O	O	O
D8	O	O	O	1	O	1	O	1	1	O
D9	1	1	1	O	O	1	O	O	1	1
D10	1	1	O	O	O	1	O	O	O	1

The final Reachability Matrix and driving and dependence power are discussed in Tables 5 and 6, respectively.

The MICMAC diagram designates the influences based on the driver, dependent, linkage, and autonomous measures.

Table 5. Final RM.

i,j	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*	*D9*	*D10*	*Driving Power*
D1	1	1	O	O	1*	1*	O	O	O	1	5
D2	1*	1	O	1*	1	1*	O	O	O	1	6
D3	1	1	1	1	1	1*	1	1	1	1	10
D4	1	1	O	1	1*	1*	O	O	O	1	6
D5	O	1*	O	1	1	1*	O	O	O	1*	5
D6	1	1	O	1*	1	1	1	1	1*	1	9
D7	1	1*	O	1	1	1*	1	O	O	1*	7
D8	1*	1*	1*	1	1*	1	1*	1	1	1*	10
D9	1	1	1	1*	1*	1	1*	1*	1	1	10
D10	1	1	O	1*	1*	1	1*	1*	1*	1	9
Dependence Power	9	10	3	9	10	10	6	5	5	10	77

Table 6. Driving and dependence power of ISM.

Drivers	*Driving Power*	*Dependent Power*
D1. Advancement of hydrogen technologies in the production, storage, and distribution	5	9
D2. Feasible and cost-competitive substitute	6	10
D3. Robust regulatory agendas and supportive strategies	10	3
D4. Public support and Social acceptance of hydrogen	6	9
D5. Hydrogen production and use align with environmental aims	5	10
D6. Technological development and innovation	9	10
D7. Safety and effective risk management	7	6
D8. Workforce development and training based on the hydrogen deployment	10	5
D9. Industry partnership and collaboration	10	5
D10. Scalability and flexibility	9	10
Summation	77	77

The MICMAC data are shown in Fig. 1. According to Figure 1, “Robust regulatory agendas and supportive strategies” (D3), “Workforce Development and Training based on the hydrogen deployment” (D8), and “Industry Partnership and Collaboration” (D9) are categorized as driver measures. Linkage measures are “Feasible and cost-competitive substitute” (D2), “Public support and Social acceptance of hydrogen” (D4), “Technological development and innovation” (D6), “Safety and Effective Risk Management” (D7) and “Scalability and Flexibility” (D10). Dependent measures are “Advancement of hydrogen technologies in the production, storage, and distribution” (D1) and “Hydrogen production and use align with environmental aims” (D5). Driver measures are critical for understanding this system. According to Figure 1, “Robust regulatory agendas and supportive strategies” (D3), “Workforce Development and Training based on the hydrogen deployment” (D8), and “Industry Partnership and Collaboration” (D8) are required for hydrogen transition. To achieve the other drivers, these critical measures need to be established. Dependent measures such as “Advancement of hydrogen technologies in the production, storage, and distribution” (D1) and “Hydrogen production and use align with environmental aims” (D5) mainly affected the other drivers. According to Figure 1, the Linkage factor is found as a “Feasible and cost-competitive substitute” (D2), “Public support and Social acceptance of hydrogen” (D4), “Technological development and innovation” (D6), “Safety and Effective Risk Management” (D7) and “Scalability and Flexibility” (D10) and any changes in these proposed factors affect consideration of the transition to hydrogen as a sustainable transportation fuel.

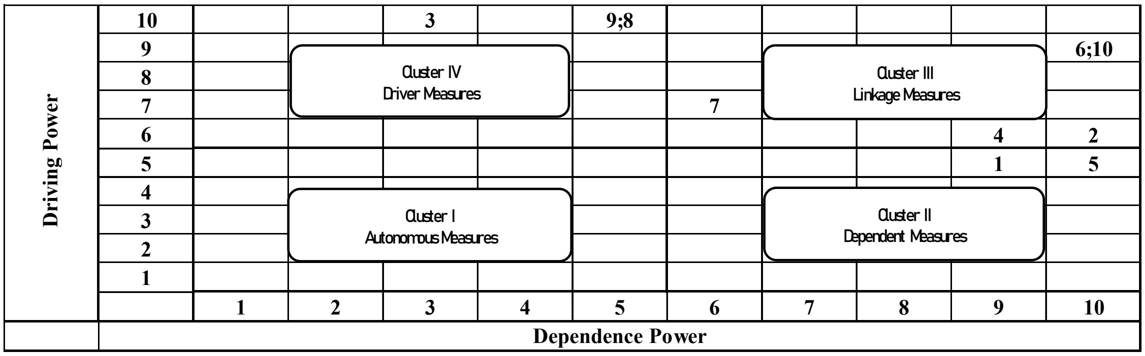

Fig. 1. MICMAC Analysis.

Based on Figure 2, "Robust regulatory agendas and supportive strategies", "Workforce development and training based on hydrogen deployment", and "Industry Partnerships and Collaboration" are defined as fundamental drivers in the transition to hydrogen as a sustainable transportation fuel. The drivers mentioned above are critical for achieving safe and effective risk management. Increased safety and risk management of hydrogen will drive public support and social acceptance of hydrogen.

A wide range of social acceptance for hydrogen technologies in production, storage, and distribution paves the way for the advancement of hydrogen technologies in the supply chain process as production, storage, and distribution. Improvements in hydrogen technologies and innovative technologies will trigger to become a viable and cost-competitive alternative to fossil fuel. It is critical to achieve a net zero emissions target and ensure that hydrogen production and use align with environmental goals.

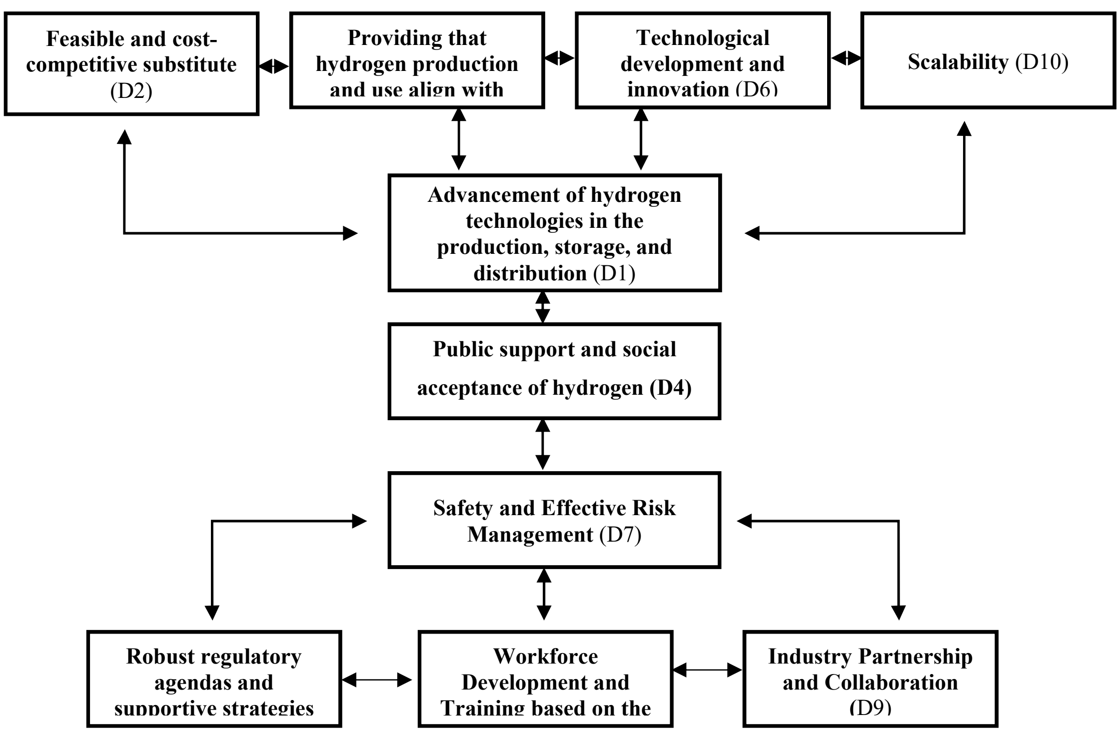

Fig. 2. ISM Diagraph for key drivers in the transition to hydrogen as a sustainable transportation fuel.

5. Discussion.

Hydrogen, an energy carrier obtained from renewable energy sources, has a high potential for zero-emission transformation, as it does not harm the environment and can be transported easily and efficiently. The shift to hydrogen instead of a clean energy source is necessary to decrease the ecological effects of fossil fuels and achieve targeted zero carbon emissions (Agarwal, 2022). The transportation sector, which is a carbon-intensive sector, is a priority area for transitioning to zero emissions. Zero emission strategies are critical for achieving this hydrogen transition. Considering this transition, determining the drivers and investigating the connections between drivers in the deployment of hydrogen for sustainable transportation fuel are required. Therefore, this study aims to comprehend the relationships among the proposed key drivers through the ISM. The Hydrogen supply chain and its processes are still improvements based on economics and technology. Efforts to improve the hydrogen supply chain processes by developing new technologies continue to increase.

In addition, hydrogen's energy storage and transportation capacity make energy systems more flexible, scalable, and sustainable (Calabrese et al., 2024). Therefore, it is necessary to develop hydrogen production policies and create roadmaps. This roadmap should address the short, medium, and long terms and determine the role of all stakeholders in this transformation, as well-planned hydrogen policies are essential for offering great opportunities for renewable energy integration and environmental sustainability (Agarwal, 2022).

These policies and strategies are crucial for developing a hydrogen infrastructure for transitioning to green hydrogen instead of fossil fuels in carbon-intensive areas, such as the transportation industry. Hydrogen technology and infrastructure innovation are achieved through cooperation between industries, research centres, and policymakers.

Collaborations between energy companies, universities, and research centres are required to accelerate the hydrogen transition. This technology has since been developed.

This technological transformation can only be achieved through coordinated research, and related companies cause this technology is still require technological improvements. Therefore, with cooperative teamwork, the technical properties of hydrogen can be studied, and feasibility analysis of this transition can be demonstrated through cost and emission analyses. The deployment of coordinated actions is inevitable for the acceleration of green hydrogen production to provide effective management. Public awareness should be created, young people should be directed towards this issue, and European project support should be supported by the government and research institutions (Emodi et al., 2021; Lee and Kim, 2021).

In addition, training and education in hydrogen technologies increase social acceptance by reducing safety concerns related to the adoption of hydrogen. Recent technological improvements in the storage and transportation of hydrogen can reduce safety concerns. However, the adoption of this technology can only be achieved through partnerships between research institutions, industry, technology, and energy companies. Research centres and universities' cooperation with the industry is of significant importance from both educational and social acceptance perspectives. To optimise demand management, a hydrogen hub that includes the required infrastructure for production, storage, transportation, and distribution is an effective solution for catalysing clean energy transition. This region is critical for increasing the coordination between stakeholders and the engagement of the communities critical to this transition.

Increased collaboration through the hydrogen hub lowers the cost of hydrogen production and enhances the training and development of hydrogen technologies. With the help of this hub, infrastructure and resources can be shared, and it provides economies of scale by reducing the per-unit cost of hydrogen. It also improves international collaboration and knowledge exchanges between partners. Incentives should be provided for the high costs and fundamental infrastructure changes, which are the most significant obstacles to this transformation.

With infrastructure that allows hydrogen to be produced on-site and developments in hydrogen production, storage, and transportation, hydrogen can be transformed into a cost-effective option compared with fossil fuels. As a result of R&D support, the efficiency of hydrogen supply chain processes is increased and cost-effective. A roadmap for the transition to green hydrogen should be presented to ensure sustainable development within a framework that considers environmental issues in the middle and long term.

6. Conclusions.

Hydrogen technology has strong potential in the conversion to zero carbon emissions, both in the long term. The main contribution of this study to the literature is to investigate the potential for the transition to green hydrogen, to determine the driving forces, and to analyse the relationships between these driving forces.

Thus, the role of technological development and awareness of the transition to green hydrogen in achieving sustainable development goals was revealed in this study. It is critical to evaluate and analyse all these factors in the transition to hydrogen and create a road map for the transition to hydrogen to produce effective solutions for sustainability. One of the limitations of this study is subjectivity because expert options are used to analyse driver relationships. Second, different drivers may emerge in other countries and sectors.

In future study, the key drivers in the transition to hydrogen as a sustainable transportation fuel can be enlarged, and various dynamic approaches can be used to analyse the relationships between these drivers. Future studies on hydrogen should focus on increasing its safety, cost-effectiveness, and social acceptability, thus ensuring that it has an advantage over conventional transportation fuels.

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