INTERNATIONAL JOURNAL OF RESEARCH AND SCIENTIFIC INNOVATION (IJRSI)
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XI Issue VII July 2024

Hydrogen: Challenges and Solutions for Safe and Effective Implementation

Carlos Vital Paixão de Melo[1], Ayrton de Sá Brandim[2], Hubert. A. A. Alvarez[3*]

[1]Department of Chemistry – Federal University of Espírito Santo-UFES.

[2]Department of Materials and Metallurgical Engineering/ Plasma – Federal Institute of Education, Science and Technology-IFPI-Teresina/PI

[3]Former Senior Manager PMESUT-BID/ Lima-Peru

[*]Corresponding Author

DOI: https://doi.org/10.51244/IJRSI.2024.1107093

Received: 09 July 2024; Accepted: 24 July 2024; Published: 22 August 2024

ABSTRACT

Hydrogen represents a promising energy source due to its unique properties, but its safe and effective implementation faces numerous challenges. Its low activation energy facilitates rapid and efficient reactions, reducing energy consumption and promoting the production of clean fuels. However, hydrogen also presents significant risks due to its wide flammability range and high diffusion rate, increasing the risk of explosions, fires, and leaks. To address these challenges, it is essential to develop and implement rigorous safety measures, specialized infrastructure, and advanced technologies.

Emerging technologies such as water electrolysis and solid oxide fuel cells and proton exchange membrane (PEM) cells offer promising solutions for the efficient production and use of green hydrogen, although they face obstacles such as competition with other renewable energy sources, price fluctuations, and the need for robust infrastructure.

Hydrogen storage and distribution require innovative solutions to overcome issues of volume, energy density, and leak risk. Storage technologies include high-pressure tanks and cryogenic methods, while distribution can be done through pipeline networks, tanker trucks, and maritime transport.

Additionally, hydrogen injection into natural gas networks and underground storage are explored strategies to enhance the viability and safety of hydrogen as an energy source. In summary, the successful implementation of hydrogen as a safe and effective energy solution requires a combination of technological advances, infrastructure development, and supportive policies. It is crucial to balance its energy efficiency and emission reduction benefits with operational and environmental challenges through the adoption of robust regulations and the promotion of technological innovations.

INTRODUCTION [1-6]

Hydrogen, considered one of the most abundant and versatile elements in the universe, has captured the attention of the scientific and technological community as a potential solution to the energy challenges of the 21st century. Its ability to act as a clean energy carrier and its application in a variety of industrial and transportation sectors position it as a key component in the transition towards a low-carbon economy.

However, the safe and effective implementation of hydrogen presents multiple technical, economic, and safety challenges that must be addressed to fully harness its benefits. This text will focus on analyzing the fundamental properties of hydrogen, its associated risks, strengths, opportunities, weaknesses, and threats (SWOT), as well as the emerging technologies that facilitate its use.

PROPERTIES AND LAWS OF HYDROGEN AND ANALYSIS [7-11]

Hydrogen represents a promising energy source due to its unique properties and its ability to reduce carbon emissions in various industrial and transportation applications. However, its implementation faces significant technical and socioeconomic challenges that must be comprehensively addressed to understand the potential of hydrogen properties responsible for both its strengths and weaknesses. For example, its low activation energy, analyzed through Transition State Theory and the Arrhenius Equation, facilitates rapid and efficient reactions, which is advantageous for the production of clean fuels. However, this same characteristic increases the risk of explosions and fires, requiring specialized equipment and materials for safe handling.

The wide flammability range of hydrogen, covered by the Fire Triangle and explosive limits, makes it a versatile and efficient energy source. This property allows its application in various industries, from power generation to transportation. Nonetheless, it also implies a higher risk of accidents and explosions, demanding strict safety measures and limiting its storage and transport.

Another notable property of hydrogen is its high diffusion rate, governed by Fick’s Law and the Knudsen Effect. This facilitates its rapid mixing with other substances and permeation through solid materials, which is useful in gas separation and thermal treatment of materials. However, the high diffusion rate also poses risks of leaks and contamination, complicating its storage and increasing the risk of explosion.

The low density of hydrogen, explained by Boyle’s and Charles’s Laws, is ideal for applications requiring lightness, such as the aerospace industry and hydrogen vehicles. However, this property also means that hydrogen has a lower energy density compared to other fuels, requiring larger storage volumes and presenting challenges in its compression and transport.

The high thermal conductivity of hydrogen, described by Fourier’s Law and its heat capacity, allows rapid heat transfer, useful in cooling and thermal transfer applications. However, this can lead to heat losses and corrosion problems in materials, in addition to the difficulty in temperature control. Attached is Table 1

TECHNOLOGICAL OPPORTUNITIES AND CHALLENGES [18-25]

Current technologies for hydrogen production, storage, and usage include water electrolysis, steam reforming, fuel cells, and various storage and distribution technologies. Each of these technologies has its own strengths, opportunities, weaknesses, and threats. For instance, water electrolysis, especially when powered by renewable energy, offers a clean pathway to produce green hydrogen with zero carbon emissions. However, this process is expensive and requires advancements in efficiency and cost reduction to be competitive on a large scale.

Storage and transportation of hydrogen present significant challenges. Storage in high-pressure tanks or cryogenically is effective but costly and complex, while distribution requires robust infrastructure to ensure safety and efficiency. Additionally, the implementation of fuel cell technologies in vehicles and stationary applications can help reduce emissions but faces challenges in terms of cost and public acceptance.

A SWOT analysis reveals that hydrogen possesses notable strengths, such as its low activation energy that favors efficient reactions and the Transition State Theory that optimizes chemical processes. The Arrhenius

Law and wide flammability range enhance its industrial and energy applicability, while the Fire Triangle and explosive limits improve its safety. Opportunities include technological development, appropriate regulations, specialized infrastructure, and political support. However, weaknesses such as safety and storage risks, data complexity, and public acceptance must be addressed. Threats like economic competition, regulatory changes, environmental impacts, and natural disasters also require attention.

Overcoming these challenges will enable the effective integration of hydrogen into the global energy transition, maximizing its potential as a clean and sustainable source. A detailed analysis of hydrogen properties and laws will reveal both its potential as an energy source and critical challenges to define a safe and effective implementation.

Therefore, the strengths of hydrogen are due to its low activation energy that facilitates efficient chemical reactions, the transition state theory that optimizes processes, and the wide flammability range that makes it ideal for various energy applications. Opportunities lie in continuous technological development, including advancements in catalysts, safe storage systems, and adapted infrastructures for hydrogen distribution and utilization. Implementing effective regulations and creating economic incentives are also crucial to accelerate the adoption of hydrogen-based technologies and ensure their successful integration into the global economy.

Weaknesses encompass safety risks such as explosions and fires, difficulties in storage and transportation, and complexity in predicting and controlling its behavior. Public acceptance is also a significant challenge due to a lack of understanding and perceived risks. Threats include competition with other renewable energy sources, fluctuations in hydrogen prices, political and regulatory changes, as well as associated environmental and health impacts.

Maximizing hydrogen’s potential as a sustainable energy source requires addressing these challenges through technological innovation, effective regulation, adequate infrastructures, and public education. This will enable the safe and effective integration of hydrogen into the global energy transition, mitigating risks and leveraging its benefits for a cleaner and more sustainable energy future.

In conclusion, harnessing the potential of hydrogen as a safe, clean, and sustainable energy source requires a holistic approach that balances opportunities and challenges. Continuous innovation, effective regulation, adequate infrastructure, and public education are key elements to ensure a successful transition towards a more sustainable and resilient energy future. We attach the following Tables (2-4).

SAFETY AND REGULATION [38-41]

Safety is a primary concern in the implementation of hydrogen. The flammable and explosive nature of hydrogen requires advanced safety systems, strict regulations, and training programs for the safe handling of hydrogen. The development of sensors and alarm systems to detect hydrogen leaks, along with the creation of specific standards and regulations, is crucial to prevent accidents and ensure the safe and effective adoption of hydrogen.

In conclusion, although hydrogen presents a series of challenges, its potential advantages as a clean and efficient energy source are undeniable. Maximizing its benefits and mitigating its risks requires a multidisciplinary approach, including technological advances, infrastructure development, safety regulations, and educational programs. With proper implementation, hydrogen has the potential to be a fundamental pillar in the transition towards a more sustainable energy economy and less dependence on fossil fuels.

IMPLEMENTATION OF HYDROGEN TECHNOLOGIES [42, 43]

The deployment of hydrogen technologies represents a significant advancement in the transition towards a more sustainable energy future. Hydrogen offers multiple benefits, including the reduction of greenhouse gas emissions and the diversification of energy sources. Its ability to integrate into various applications, from energy storage to transportation and electricity generation, demonstrates its flexibility and potential to contribute to energy security and reduce dependence on fossil fuels.

Progress in research and technological development, especially in hydrogen production through processes like electrolysis and pyrolysis, drives innovation, reduces costs, and improves efficiency. Supportive policies are crucial to scaling these technologies, ensuring their economic viability, and fostering investment in the necessary infrastructure.

Moreover, the adoption of hydrogen technologies can generate a positive economic impact by creating jobs, fostering new industries, and improving competitiveness in an evolving energy market. Hydrogen’s ability to store renewable energy, contribute to a more resilient energy grid, and align with circular economy principles are key aspects of its potential.

The implementation of hydrogen technologies is also closely linked to global climate goals, promoting decarbonization and meeting carbon reduction targets. Collaboration between industrial sectors, universities, and research centers, as well as the adoption of favorable policies, accelerates technological development and facilitates the energy transition.

The widespread adoption of hydrogen can have a positive impact on public health by reducing pollutants associated with fossil fuels, improving air quality, and decreasing pollution-related diseases.

Hydrogen emerges as a comprehensive solution to address the energy and environmental challenges of the future. Its ability to provide clean energy, diversify energy options, and enhance energy resilience is essential for a successful transition to a sustainable energy system. However, the success of this transition will depend on a combination of technological advancements, supportive policies, and continuous investment in research and development.

Effective implementation of hydrogen technologies will not only contribute to emission reductions and meeting climate goals but also offer economic opportunities, foster innovation, and improve public health. Thus, hydrogen not only represents an energy alternative but an integral opportunity to advance towards a more equitable, sustainable, and resilient future. Table 5

STORAGE AND DISTRIBUTION [53,54]

The storage and distribution of hydrogen present significant technical and economic challenges. Storage technologies include high-pressure tanks, cryogenic storage, and absorbent materials like metal hydrides. Each option has its advantages and limitations. For instance, high-pressure tanks are effective but expensive, while cryogenic storage requires advanced infrastructure to keep hydrogen at extremely low temperatures.

Hydrogen distribution can be carried out via pipeline networks, tanker trucks, and maritime transport. Injecting hydrogen into natural gas networks is also being explored as a way to reduce carbon emissions. However, developing robust and safe infrastructure for hydrogen distribution is crucial for its widespread adoption.

INNOVATIONS AND FUTURE OF HYDROGEN [55-61]

Electrocatalyst technology involves the use of different metallic elements from various groups of the periodic table, including s, d, and f groups. Each group has unique properties that can influence the technological development of electrocatalysts in several ways:

Group s Elements (alkali and alkaline earth metals):

Properties: Low melting points, high chemical reactivity, good electrical conductivity.

Applications: While less common in direct electrocatalyst applications due to high reactivity and low stability in corrosive environments, they can be used in composite forms or as additives to improve specific properties like electrical conductivity or surface stability.

Group d Elements (transition metals):

Properties: High electrical and thermal conductivity, high chemical stability, variety of oxidation states.

Applications: Transition metals like platinum (Pt), iridium (Ir), nickel (Ni), copper (Cu), and others are fundamental in electrocatalysis due to their ability to catalyze electrochemical reactions efficiently and stably. These metals are commonly used in electrolysis cells and other systems that generate hydrogen from water.

Group f Elements (lanthanides and actinides):

Properties: High density, unique magnetic properties, stability at high temperatures, wide range of oxidation states due to f-electron configuration.

Potential Applications: Although less common in direct electrocatalyst applications, due to their particular nature and properties, Group f elements can play important roles in developing advanced composite materials to improve conductivity, thermal stability, and corrosion resistance in specific electrocatalysts.

Considering this context, the technological development of electrocatalysts, the selection, and manipulation of these metallic elements (s, d, f) are crucial to optimize the efficiency, durability, and cost-effectiveness of hydrogen production technologies and other electrochemical applications. Continuous research and the development of new materials and synthesis methods are essential to advance this area, leveraging the unique properties of each group of elements to enhance electrocatalyst performance under diverse and demanding operating conditions.

Overall, the combination of properties of metallic elements from groups s, d, and f plays a crucial role in the technological development of electrocatalysts. Transition metals from Group d are the most commonly used due to their ability to efficiently catalyze electrochemical reactions, such as hydrogen production from water in electrolysis or in the synthesis of composite materials that enhance the efficiency and stability of catalysts in advanced industrial and energy applications.

CONCLUSION

Hydrogen has the potential to play a crucial role in the transition to a clean and sustainable energy economy. Its unique properties, such as low activation energy and high diffusion speed, make it ideal for a wide range of applications. However, the technical and safety challenges associated with its production, storage, and use must be addressed through technological advancements and robust infrastructure.

Current and emerging technologies for the production, storage, and use of hydrogen offer a promising path towards decarbonizing various sectors, from industry to transportation. The successful implementation of hydrogen as a viable energy source depends on collaboration between researchers, industry, and governments to overcome challenges and capitalize on the opportunities presented by this versatile element.

Hydrogen can be a fundamental pillar in the fight against climate change and the energy transition, provided that risks are adequately addressed and its strengths are maximized through the development of advanced technologies and supportive policies.

Hydrogen represents an energy resource with unique characteristics that promote significant opportunities as well as considerable challenges. Its low activation energy facilitates efficient chemical reactions, translating to higher speed and lower energy consumption, driving the production of clean fuels. However, its wide flammability range and high diffusion speed require rigorous safety measures and advanced technologies for storage and transport. Hydrogen’s high thermal conductivity offers advantages in cooling and heat transfer but comes with associated risks such as leakage and temperature control difficulties.

Despite these challenges, the development of technologies like water electrolysis and fuel cells shows promising potential for integrating hydrogen into sustainable energy systems. However, effective implementation will require adequate infrastructure and robust regulations to ensure its safety and efficiency in various industrial and everyday applications.

The high diffusion speed of hydrogen facilitates its transport and utilization in various industrial and energy applications but poses challenges in terms of control and safety. Its low energy density implies the need for bulky storage systems and specialized infrastructure for distribution. Additionally, its high thermal conductivity, while allowing efficient heat transfers, entails risks of losses and corrosion.

In terms of legislation and technological development, rigorous regulations and continuous advances in safety and storage are needed to mitigate potential risks. The integration of green hydrogen, generated from renewable sources, offers a promising solution to reduce environmental impacts but requires significant investments and a solid regulatory framework.

Finally, hydrogen presents a dual landscape of opportunities and challenges that must be addressed through technological innovation, international collaboration, and robust energy policies to achieve safe, sustainable, and effective implementation in the global energy future.

Table 1. Risks and Strengths of Hydrogen Characterized through its Properties and Respective Laws [12-17]

Property	**Laws Analyzing It**	**Definition**	**Strengths**	**Opportunities for Use**
Low Activation Energy	– Transition State Theory – Arrhenius Equation	– Requires less energy to initiate reactions. – Facilitates the dissociation of H_2 and the formation of H radicals. – Reactions with hydrogen are faster.	– Higher reaction rate. – Lower energy consumption. – Facilitates the production of clean fuels.	– Greater risk of explosions and fires. – Requires specialized materials and equipment. – Greater complexity of processes.

Property	Laws Analyzing It	Definition	Strengths	Opportunities for Use
Wide Flammability Range	– Fire Triangle – Explosive Limits	– Ignites in the presence of small amounts of oxygen. – Versatile energy source.	– Wide range of applications as fuel. – Higher energy efficiency. – Reduction of pollutant emissions.	– Greater risk of accidents. – Requires strict safety measures. – Limitations in storage and transport.
High Diffusion Rate	– Fick's Law – Knudsen Effect	– Mixes with other substances quickly. – Permeates through solid materials. – Can be problematic in storage.	– Gas separation. – Thermal treatment of materials. – Coatings and paints.	– Losses due to leaks. – Difficulty in controlling diffusion. – Risk of contamination.
Low Density	– Boyle's Law – Charles's Law	– Occupies a large volume at ambient temperature and pressure. – Ideal for applications requiring lightness. – Sensitive to temperature changes.	– Aerospace industry. – Hydrogen vehicles. – Inflatables and balloons.	– Lower energy density than other fuels. – Requires larger storage volume. – Difficulty in compression and transport.
High Thermal Conductivity	– Fourier's Law – Heat Capacity	– Transfers heat quickly. – Good thermal conductor. – Requires less energy to increase its temperature.	– Cooling. – Heat transfer. – Heat exchangers.	– Heat losses. – Material corrosion. – Difficulty in temperature control.

Table 2: Potential of Hydrogen Properties: Strength, Opportunity, Weakness, and Threat [26-27]

Property/Law	Strengths	Opportunities	Weaknesses	Threats
Low Activation Energy	– Favors the initiation of chemical reactions.	– Development of more efficient and specific catalysts.	– Risk of explosions and fires.	– Competition with other renewable energy sources.

Property/Law	**Strengths**	**Opportunities**	**Weaknesses**	**Threats**
	– Lower energy consumption in industrial processes.	– Implementation of green hydrogen production technologies.	– Need for strict safety measures.	– Fluctuations in hydrogen prices.
	– Greater efficiency in fuel production.	– Creation of incentives for adopting hydrogen-based technologies.	– Difficulty in storage and transportation.	– Lack of infrastructure for hydrogen distribution and use.
Transition State Theory	– Allows understanding of chemical reaction mechanisms.	– Development of more accurate computational models.	– Complexity of calculations and simulations.	– Uncertainty in technology evolution.
	– Optimizes reaction conditions for better results.	– Conducting experimental studies to better understand the transition state.	– Difficulty in obtaining precise experimental data.	– Changes in energy policies.
	– Facilitates the design of new catalysts.	– Implementation of the theory in practical applications.	– Limitations in predicting the behavior of complex systems.	– Difficulty in commercializing hydrogen-based products.

Table 3: Potential of Hydrogen Properties/Laws: Strength, Opportunity, Weakness, and Threat [28-30]

Property/Law	**Strengths**	**Opportunities**	**Weaknesses**	**Threats**
Arrhenius Law	– Allows calculation of reaction rate at different temperatures.	– Development of methods to measure reaction rates more accurately.	– Limitations in predicting the rate of complex reactions.	– Increase in raw material prices.
	– Determines the optimal temperature for a reaction.	– Creation of more complex kinetic models.	– Difficulty in determining the pre-exponential factor.	– Scarcity of natural resources.
	– Facilitates the design of chemical reactors.	– Implementation of the law in industrial applications.	– Influence of other factors on reaction rate.	– Environmental impact of hydrogen production.
Wide Flammability Range	– Greater versatility in energy applications.	– Development of more efficient safety systems.	– Risk of accidents and explosions.	– Changes in environmental regulations.
	– Possibility to use hydrogen in a wide range of sectors.	– Implementation of standards and regulations for hydrogen use.	– Need for specialized infrastructure for storage and transport.	– Development of new energy storage technologies.
	– Facilitates the production of synthetic fuels.	– Creation of training programs for hydrogen handling.	– Difficulty in public acceptance of hydrogen.	– Competition with other clean energy sources.

Property/Law	**Strengths**	**Opportunities**	**Weaknesses**	**Threats**
Fire Triangle	– Allows understanding of the elements necessary for combustion.	– Development ofmore efficient fire-resistant materials.	– Difficulty in controlling fire spread in confined spaces.	– Natural disasters.
	– Prevents fires and explosions.	– Implementation of fire safety measures.	– Health and environmental risks in case of fire.	– Climate change.
	– Facilitates the design of fire suppression systems.	– Creation of educational programs for fire prevention.	– Economic impact of fires.	– Water resource scarcity.

Table 4: Potential of Hydrogen Properties/Laws: Strength, Opportunity, Weakness, and Threat [31-37]

Property/Law	**Strengths**	**Opportunities**	**Weaknesses**	**Threats**
Explosive Limits	– Determines the safe concentration of hydrogen in the air.	– Development of sensors to detect hydrogen presence in the air.	– Difficulty in determining explosive limits in complex mixtures.	– Population increase.
	– Prevents explosions and fires.	– Implementation of alarm systems to prevent explosions.	– Influence of temperature and pressure on explosive limits.	– Urban growth.
	– Facilitates the design of ventilation systems.	– Creation of standards and regulations for hydrogen use.	– Explosion risks in case of hydrogen leaks.	– Increased energy demand.
High Diffusion Rate	– Allows rapid transport of hydrogen through membranes.	– Development of membranes more permeable to hydrogen.	– Leakage losses: security risks and reduced system efficiency.	– Environmental contamination: negative impact on air quality.
	– Facilitates the separation of hydrogen from other gases.	– Implementation of more efficient gas separation technologies.	– Difficulty in controlling diffusion: limitations in applications requiring precise hydrogen concentration control.	– Human health damage: risk of inhaling large amounts of hydrogen.
	– Accelerates chemical reactions.	– Creation of new materials for hydrogen storage.	– Explosion or fire risk: danger to people and facilities.	

Table 5. Description and Strengths of Electrolysis Technologies [44-52]

Technology	**Detailed Description**	**Strengths of the Technology**
Alkaline Electrolysis (AEL)	Alkaline Electrolysis (AEL) employs an alkaline solution, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), as an electrolyte in an electrolytic cell. The applied electric current splits water into hydrogen and oxygen. At the anode, water is oxidized, producing oxygen and hydroxyl ions. At the cathode, hydroxyl ions are reduced to hydrogen. It is a mature technology widely used in the industry.	– Technological Maturity: Extensive experience and robustness in the field. – Material Cost: Uses relatively inexpensive materials. – Scalability: Suitable for large-scale industrial applications. – Versatility: Suitable for different operating conditions.
Proton Exchange Membrane Electrolysis (PEM)	Proton Exchange Membrane (PEM) Electrolysis uses a solid polymer membrane to separate the electrolysis products. The membrane allows protons to pass from the anode to the cathode, while electrons travel through an external circuit, generating high-purity hydrogen. It operates at low temperatures, allowing for a quick response to demand fluctuations.	– High Energy Efficiency: Provides high energy conversion efficiency – Pure Hydrogen Production: Generates high-purity hydrogen, suitable for high-tech applications. – Low Voltage Operation: Allows operations at lower voltages, reducing system wear.
High-Temperature Electrolysis (HTE)	High-Temperature Electrolysis (HTE) operates at elevated temperatures (700°C – 1000°C) using solid ceramic electrolytes, such as zirconium oxides, to separate water into hydrogen and oxygen. The increased temperature reduces the required electrical energy, improving thermodynamic efficiency. This technology is suitable for coupling with residual heat sources from industrial processes.	– High Thermodynamic Efficiency: High efficiency in converting thermal energy into chemical energy. – Integration with Residual Heat: Can utilize residual heat from industrial processes. – High Energy Density: Produces hydrogen at high energy density.

Microbial Electrolysis	Microbial Electrolysis uses microorganisms to catalyze the decomposition of organic materials in an electrochemical cell. The microorganisms generate electrons that are usedto reduce protons to hydrogen. This bioelectrochemical process allows hydrogen production from organic waste and is noted for its sustainable approach and ability to treat waste.	– Sustainability: Uses organic resources and waste for hydrogen production. – Low Cost: Microorganisms are generally cheaper than metal catalysts. – Environmental Applications: Can treat wastewater while producing hydrogen.
Ammonia Electrolysis	In Ammonia Electrolysis, ammonia (NH_3) is decomposed in an electrolytic cell to produce hydrogen and nitrogen. The technology allows hydrogen production with lower electrical consumption compared to water electrolysis. However, handling ammonia requires precautions due to its toxicity.	– Lower Energy Consumption: Relatively lower energy consumption compared to water electrolysis. – Hydrogen Storage: Ammonia is an efficient medium for hydrogen storage. – Industrial Applications: Can be integrated into existing industrial processes that use ammonia.
Solid Oxide Electrolysis Cell (SOEC)	Solid Oxide Electrolysis Cell (SOEC) uses a solid ceramic electrolyte to conduct oxygen ions at high temperatures (700°C – 1000°C). The process enables the decomposition of water or carbon dioxide into hydrogen and oxygen. Solid electrolytes are resistant to corrosion and operate efficiently at high temperatures, improving continuous production efficiency.	– High Energy Efficiency: High efficiency in energy conversion, especially when combined with residual heat. – Continuous Production: Suitable for continuous hydrogen production applications. – Integration with High-Temperature Processes: Can integrate with other industrial thermal processes.

Seawater Electrolysis	Seawater Electrolysis uses seawater for hydrogen production, requiring pretreatment to remove salts and contaminants before electrolysis. This process takes advantage of an abundant and low-cost water source, reducing the dependence on freshwater and allowing hydrogen production in coastal regions.	– Abundant Water Source: Utilizes seawater, an abundant and economical resource. – Reduced Water Costs: Lowers the costs associated with using demineralized water. – Sustainability: Increases sustainability by using a non-freshwater source.
Demineralized Water Electrolysis	Demineralized Water Electrolysis uses purified water to remove salts and minerals, which improves electrical conductivity and reduces internal resistance during electrolysis. This results in higher efficiency and purity of the produced hydrogen, making it ideal for applications requiring high-quality hydrogen and minimizing cell component corrosion.	– High Purity Hydrogen: Produces high-purity hydrogen. – Energy Efficiency: High energy conversion efficiency. – High Conductivity: High water purity allows good conductivity, improving process efficiency.
Solar-Assisted Electrolysis	Solar-Assisted Electrolysis combines the electrolysis process with solar energy. Solar panels provide electricity for the water electrolysis process, integrating hydrogen generation with renewable energy sources. This technology contributes to the sustainability of the process and reduces dependence on non-renewable energy sources.	– Sustainability: Utilizes solar energy, a renewable and sustainable energy source. – Reduced Energy Costs: Decreases reliance on conventional energy sources. – Energy Integration: Contributes to integrating renewable energies into the electrolysis process.

BIBLIOGRAPHIC REFERENCE

INTRODUCTION [1-6]

[1] Bockris, J. O'M., & Veziroglu, T. N. (2007). "The Hydrogen Economy: Empowering a Sustainable Future". Springer., http://dx.doi.org/10.34049/bcc.55.4.5600 https://www.researchgate.net/publication/377896855_The_evolution_of_hydrogen_technologies_paving_the_way_t

[2] .Bossel,. Does A Hydrogen Economy Makes Sense., Prooceding IEEE., Actas del IEEE > Volumen: 94 Número: 10.,https://doi.org/10.1109/JPROC.2006.883715/

[3]. Balat, M., & Kirtay, E. (2010). “Hydrogen from biomass – Present scenario and future prospects”. International Journal of Hydrogen Energy, 35(14), 7416-7430./

https://doi.org/10.1016/j.ijhydene.2010.04.137.,

[4]. Satyapal, S., Petrovic, J., Read, C., Thomas, G., & Ordaz, G. (2007). “The U.S. Department of Energy’s National Hydrogen Storage Project: Progress towards meeting hydrogen-powered vehicle requirements”. Catalysis Today, 120(3-4), 246-256/ https://www.sciencedirect.com/science/article/abs/pii/S0920586106006146.

[5]. Mostafa El-Shafie * , Shinji Kambara, Yukio Hayakawa., Descripción general de las tecnologías de producción de hidrógeno.,https://doi.org/10.4236/jpee.2019.71007/.

[6].Crabtree, G. W., Dresselhaus, M. S., & Buchanan, M. V. (2004). “The Hydrogen Economy”. Physics Today, 57(12), 39-44./https://doi.org/10.1063/1.1878333.

2.-PROPERTIES OF HYDROGEN AND ITS ANALYSIS.[7-11]

[7]. Züttel, A., Borgschulte, A., & Schlapbach, L. (2003). “Hydrogen as a Future Energy Carrier.” Wiley-VCH./ http://www.gammaexplorer.com/wp-content/uploads/2014/03/Hydrogen-as-a-Future-Energy-Carrier-

Malestrom.pdf

[8]. Yixiang Shi, Yu Luo, Wenying Li, Meng Ni, and Ningsheng Cai .,High Temperature Electrolysis for Hydrogen or Syngas Production from Nuclear or Renewable Energy., https://doi.org/10.1002/9781118991978.hces146

[9].Canán Acar., Sistemas de conversión de energía de hidrógeno., https://doi.org/10.1016/B978-0-12-809597-3.00441-

[10]. Diego Bairrão., joão soares., jose almeida., Juan F. Franco., Zita Vale., Hidrógeno verde y transición energética: estado actual y perspectivas en Portugal., *Energías 2023* , *16* (1),551;

https://doi.org/10.3390/en16010551

[11]. Mostafa El-Shafie., Shinji Kambara,Yukio Hayakawa., Descripción general de las tecnologías de producción de hidrógeno., Revista de Ingeniería de Potencia y Energía Vol.7 No.1, enero de 2019., https://doi.org/10.4236/jpee.2019.71007

TABLE 1 :[12-17]

[12]. Low Activation Energy: Transition State Theory:

a) Levine, I. N. (2012*). Fisicoquímica.* McGraw-Hill..,

b) Atkins, P., & de Paula, J. (2010). *Physical Chemistry.* Oxford University Press.

c) [13]. Arrhenius Law:

a) Levine, *N. (2012). Fisicoquímica.* McGraw-Hill.

[14]. Wide Flammability Range: Fire Triangle and Explosive Limits:

a) Crowl, D. A., & Louvar, J. F. (2011*). Chemical Process Safety: Fundamentals with Applications. Prentice Hall.,Lees,* P. (2005). *Loss Prevention in the Process Industries: Hazard Identification, b)Assessment and Control.* Butterworth-Heinemann.

[15]. High Speed of Diffusion: Fick's Law and Knudsen Effect:

a) Bird, R. B., Stewart, W. E., & Lightfoot, E. N. (2007). *Transport Phenomena. John Wiley & Sons.*

b) Cussler, E. L. (2009). *Diffusion: Mass Transfer in Fluid Systems. Cambridge University Press.*

[16]. Low Density: Boyle and Charles Laws:

a) Feynman, R. P., Leighton, R. B., & Sands, M. (2011). *The Feynman Lectures on Physics, Vol. 1. Basic Books.*

b) Hill, T. L. (1986). *An Introduction to Statistical Thermodynamics.* Dover Publications.

c) [17]. High Thermal Conductivity: Fourier's Law and Heat Capacity:

a) Incropera, F. P., DeWitt, D. P. (2006*). Fundamentals of Heat and Mass Transfer.* John Wiley & Sons.

b) Çengel, Y. A., & Ghajar, A. J. (2015). *Heat and Mass Transfer: Fundamentals and Applications.* McGraw-Hill Education.

3.- TECHNOLOGICAL OPPORTUNITIES AND CHALLENGES[18 – 25]

[18]. Hydrogen Production: Water Electrolysis

B. A. Horri., H. Ozcán.,Producción de hidrógeno verde mediante electrólisis del agua: situación actual y desafíos., Opinión actual en química verde y sostenible

Volumen 47, junio de 2024 , 100932., https://doi.org/10.1016/j.cogsc.2024.100932

[19]. Steam Reforming

R.kumar., R. Singh., S. Dutta**.,** Revisión y perspectivas de la producción de hidrógeno mediante procesos catalíticos., *Combustibles energéticos* 2024 , 38 , 4 , 2601–2629., https://doi.org/10.1021/acs.energyfuels.3c04026

[20]. Fuel Cells

W. Olbrich., T. Kadyk., U. Sauter., M. Eikerling., J. Gostick., Estructura y conductividad del ionómero en capas de catalizador de pilas de combustible PEM: un análisis basado en modelos., Scientifc Reports | (2023) 13:14127 |., https://doi.org/10.1038/s41598-023-40637-0.

[21]. Hydrogen Storage and Transportation.

a) MM Rampai., CB Mtshali., NS Seroka., L. Khotseng**.,** Producción, almacenamiento y transporte de hidrógeno: avances recientes., *RSC Adv.*, 2024, 14 , 6699-6718., https://doi.org/10.1039/D3RA08305E

b) A.I. Osman.,M. Nasr., A.S. Eltaweil.,M. .Hosny.,M. Farghali., A. S.Al-Fatesh, David W. Rooney, Eman M. Abd El-Monaem., .Avances en materiales de almacenamiento de hidrógeno: aprovechamiento de tecnologías innovadoras, desde el aprendizaje automático hasta la química computacional, para soluciones de almacenamiento de energía., International Journal of Hydrogen Energy., Volume 67, 20 May 2024, Pages 1270-1294

https://doi.org/10.1016/j.ijhydene.2024.03.223**.**

[22] Infrastructure and Distribution

Grupo BCG., Construyendo la economía verde del hidrógeno., Estrategia de Infraestructura 2023., 21 DE MARZO DE 2023., https://www.bcg.com/publications/2023/strategies-to-build-green-hydrogen-economy

Hassan.,A. Z. Sameen., H. M.Salman, M. Jaszczur,,A. Khudhair Al., El futuro de la energía del hidrógeno: avances en las tecnologías de almacenamiento e implicaciones para la sostenibilidad., Revista de almacenamiento de energía

Volumen 72, Parte B, 20 de noviembre de 2023 , 108404.https://doi.org/10.1016/j.est.2023.108404

[23]. SWOT Analysis of Hydrogen

T. T. Le, P. Sharma, B. Jyoti Bora,Viet Dung Tran, Thanh Hai Truong, Huu. Le, Phuoc Quy Phong Nguyen., Impulsando el futuro: una revisión exhaustiva de los sistemas de energía del hidrógeno y sus desafíos., Revista internacional de energía del hidrógeno., Volumen 54, 7 de febrero de 2024 , páginas 791-816., https://doi.org/10.1016/j.ijhydene.2023.08.044.

[24]. Safety and Regulations

H.Bartolomé, M.Weber, F.Barbierb., Almacenamiento de hidrógeno: mejoras recientes y perspectivas industriales., Revista internacional de energía del hidrógeno

Volumen 42, Número 11, 16 de marzo de 2017 , páginas 7254-7262., https://doi.org/10.1016/j.ijhydene.2016.03.178

Sherif, S. A., Goswami, D. Y., & Stefanakos, E. K. (2014). Handbook of Hydrogen Energy. *CRC Press*.

[25]. Environmental and Health Impact

Qusay Hassan ,Sameer Algburib ,Aws Zuhair Sameen ,Hayder M. Salman ,Marek Jaszczur., Hidrógeno verde: un camino hacia un futuro energético sostenible

333. 50, Parte B, 2 de enero de 2024 , pág. 310-333., https://doi.org/10.1016/j.ijhydene.2023.08.321

TABLE 2 [26 – 27]

[26]. Low Activation Energy:

Strengths:

IEA (2021). “The Future of Hydrogen”. International Energy Agency. Disponible en: IEA/ https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-

f2a4024909b4/GlobalHydrogenReview2021.pdf

Ephraim Bonah Agyekum, Christabel Nutakor, Ahmed M. Agwa , Salah Kamel·, A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation., https://doi.org/10.3390/membranes12020173/

Opportunities:

Saba, S. M., Müller, M., Robinius, M., & Stolten, D. (2018). "The investment costs of electrolysis – A comparison of cost studies from the past 30 years". International Journal of Hydrogen Energy, 43(3), 1209-1223., https://doi.org/10.1016/j.ijhydene.2017.11.115

Crabtree, G. W., Dresselhaus, M. S., & Buchanan, M. V. (2004). "The hydrogen economy". Physics Today, 57(12), 39-44. Disponible en: ResearchGate

Weaknesses:

A. Salva., E. Tapia., A. Iranzo., F. Pino., J. Cabrera., F. Rosa.,Estudio de seguridad de una fuga de hidrógeno en un vehículo de pila de combustible mediante dinámica de fluidos computacional., Revista internacional de energía del hidrógeno., Volumen 37, Número 6, marzo de 2012 , páginas 5299-5306., https://doi.org/10.1016/j.ijhydene.2011.12.046

Mori, D., Hirose, K. (2009). "Recent challenges of hydrogen storage technologies for fuel cell vehicles". International Journal of Hydrogen Energy, 34(10), 4569-4574. https://www.sciencedirect.com/science/article/abs/pii/S0360319908009439

Threats:

Hosseini, S. E., Wahid, M. A. (2016). "Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development". Renewable and Sustainable Energy Reviews, 57, 850-866.

https://doi.org/10.1016/j.ijhydene.2008.07.115

[27]. Theory of the Transition State:

Strengths:

Truhlar, D. G., Garrett, B. C., Klippenstein, S. J. (1996). "Current status of transition-state theory". The Journal of Physical Chemistry, 100(31), 12771-12800. https://doi.org/10.1021/jp953748q

Laidler, K. J., King, M. C. (1983). "Development of transition-state theory". The Journal of Physical Chemistry, 87(15), 2657-2664., Laidler, K. J., & King, M. C. (1983). "Development of transition-state theory". The Journal of Physical Chemistry, 87(15), 2657-2664. https://doi.org/10.1021/j100238a002

Opportunities:

Fernández-Ramos, A., Miller, J. A., Klippenstein, S. J., & Truhlar, D. G. (2006). "Modeling the kinetics of bimolecular reactions". Chemical Reviews, 106(11), 4518-4584.

Johnston, H. S. (1966). "Gas phase reaction rate theory". Ronald Press Company.,

https://doi.org/10.1002/ange.19680800821

Weaknesses:

Baboul, A. G., Curtiss, L. A., Redfern, P. C., & Raghavachari, K. (1999). “Gaussian-3 theory using density functional geometries and zero-point energies”. The Journal of Chemical Physics, 110(16), 7650-7657. Disponible en: AIP/ https://inis.iaea.org/search/search.aspx?orig_q=RN:30037762

Carpenter, B. K. (1996). “Nonstatistical dynamics in thermal reactions of polyatomic molecules”. Angewandte Chemie International Edition, 35(14), 1454-1476.

Threats

Crabtree, G. W., Dresselhaus, M. S., & Buchanan, M. V. (2004). “The hydrogen economy”. Physics Today, 57(12), 39-44., https://doi.org/10.1063/1.1878333.

Michael C Clarke., Can the hydrogen economy concept be the solution to the future energy crisis?., AUSTRALIAN JOURNAL OF MULTI-DISCIPLINARY ENGINEERING., Published 4 April 2022., https://doi.org/10.1080/14488388.2022.2046325/

TABLE 3 [28-30]

[28]. Arrhenius Law:

Strengths: Atkins, P., & de Paula, J. (2014). “Atkins’ Physical Chemistry”. Oxford University Press.

Opportunities: Johnston, H. S. (1966). “Gas phase reaction rate theory”. Ronald Press Company.

Weaknesses: Truhlar, D. G., Garrett, B. C., & Klippenstein, S. J. (1996). “Current status of transition-state theory”. The Journal of Physical Chemistry, 100(31), 12771-12800. https://doi.org/10.1021/jp953748q

Threats: Crabtree, G. W., Dresselhaus, M. S., & Buchanan, M. V. (2004). “The hydrogen economy”.

Physics Today, 57(12), 39-44. https://doi.org/10.1063/1.1878333

[29]. Wide Flammability Range:

Strengths: Mori, D., & Hirose, K. (2009). “Recent challenges of hydrogen storage technologies for fuel cell vehicles”. International Journal of Hydrogen Energy, 34(10), 4569-4574.

Opportunities: Züttel, A. (2003). “Materials for hydrogen storage”. Materials Today, 6(9), 24-33. https://doi.org/10.1016/S1369-7021(03)00922-2

Weaknesses: Hosseini, S. E., & Wahid, M. A. (2016). “Hydrogen production from renewableand sustainable energy resources: Promising green energy carrier for clean development”. Renewable and Sustainable Energy Reviews, 57, 850-866. https://doi.org/10.1016/j.rser.2015.12.112

Threats: IEA (2021). “The Future of Hydrogen”. International Energy Agency. Available at: IEA.

[30]. Fire Triangle:

Strengths: Truhlar, D. G., Garrett, B. C., & Klippenstein, S. J. (1996). “Current status of transition-state theory”. The Journal of Physical Chemistry, 100(31), 12771-12800. Available at: ACS Publications

Opportunities: Baboul, A. G., Curtiss, L. A., Redfern, P. C., & Raghavachari, K. (1999). “Gaussian-3 theory using density functional geometries and zero-point energies”. The Journal of Chemical Physics, 110(16), 7650-7657. Available at: AIP

Weaknesses: Hosseini, S. E., & Wahid, M. A. (2016). “Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development”. Renewable and Sustainable Energy Reviews, 57, 850-866.

Threats: IEA (2021). “The Future of Hydrogen”. International Energy Agency. Available at: IEA.; Crabtree, G. W., Dresselhaus, M. S., & Buchanan, M. V. (2004). “The hydrogen economy”. Physics Today, 57(12), 39-44. Available at: ResearchGate

TABLE 4. [31-37]

[31] E. Bonah Agyekum, C. Nutakor, A.M. Agwa, S. Kamel, et al., A critical review of renewable hydrogen production methods: factors affecting scalability and their role in future energy generation. Membranes 2022, 12(2), 173. DOI: 10.3390/membranes12020173.

[32]. Matthew R. Shaner, Harry A. Atwater, Eric W. McFarland, et al., Comparative techno-economic analysis of renewable hydrogen production using solar energy. Energy Environ. Sci., 2016, 9, 2354. DOI: 10.1039/C5EE02573G.

[33]. S.A. Sherif, Frano Barbir, Wind energy and the hydrogen economy: technology review. Solar Energy 78(5):647-660. DOI: 10.1016/j.solener.2005.01.002.

[34]. G. Ertl, Reactions at surfaces: From atoms to complexity. Angewandte Chemie International Edition, 2008, 47(19), 3524-3535. DOI: 10.1002/anie.200800480.

[35]. D. Stolten, B. Emonts (Eds.), Hydrogen Science and Engineering: Materials, Processes, Systems and Technology. Wiley-VCH, 2010. Link to sample chapter

[36]. L. Zhang, M. Ramezan, Chemical looping technologies for efficient and clean utilization of energy: An overview. Chemical Engineering Journal, 2007, 129(1-3), 109-123. Link to researchgate.

[37].P.J. Megía, A.J. Vizcaíno, J.A. Calles, A. Carrero, Hydrogen production technologies: from fossil fuels to renewable sources. A mini review. Energy Fuels, 2021, 35, 20, 16403–16415. DOI: 10.1021/acs.energyfuels.1c02501.

4. – SAFETY AND REGULATION [38 – 41]

[38]. Nigel Rambhujun, Muhammad Saad Salman, Ting Wang, Chulaluck Pratthana, Prabal Sapkota, Mehdi Costalin, Qiwen Lai, and Kondo-Francois Aguey-Zinsou, Renewable hydrogen for the chemical industry. MRS Energy and Sustainability, page 1 of 16. Link to article.

[39]. B. Reda, A.A. Elzamar, S. AlFazzani, S.M. Ezzat, Green hydrogen as a source of renewable energy: a step towards sustainability, an overview. Environment, Development and Sustainability, Received: 29 March 2023 / Accepted: 3 April 2024. DOI: 10.1007/s10668-024-04892-z.

[40]. Hassan Qusay, Itimad DJ Azzawi, Aws Zuhair Sameen, Hayder M. Salman, Hydrogen fuel cell vehicles: opportunities and challenges. Sustainability 2023, 15(15), 11501. DOI: 10.3390/su151511501.

[41]. Marcella Calabrese, Maria Portarapillo, Alessandra Di Nardo, Virginia Venezia, Maria Turco, Giuseppina Luciani, Almerin da Di Benedetto, Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. Energies 2024, 17, 1350. DOI: 10.3390/en17061350

5. IMPLEMENTATION OF HYDROGEN TECHNOLOGIES. [42]

[42]. I. Staffell, D.l Scamman, A. Velazquez, A. P. Balcombe, P. E. Dodds, P. Ekins, N. Shah, K. R. Ward, The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science. DOI: 10.1039/c8ee01157e.

TABLE 5: [43-52]

[43]. T. Ahad,, M. Hossain Bhuiyan., A.N. Sakib,A. Becerril Corral, Z.Siddique., Una visión general de los desafíos para el futuro del hidrógeno., Materiales (Basilea). 2023 octubre; 16(20): 6680.,https://doi.org/10.3390/ma16206680/

[44]. Electrólisis Alcalina (AEL)

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis – a review. *Journal of Cleaner Production*, 85, 151-163~~.,~~ https://doi.org/10.1016/j.jclepro.2013.07.048

[45]. Electrólisis de Membrana de Intercambio de Protones (PEM)

Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). A comprehensive review on PEM water electrolysis. *International Journal of Hydrogen Energy*, 38(12), 4901-4934.

https://doi.org/10.1016/j.ijhydene.2013.01.151

[46]. Electrólisis de Alta Temperatura (HTE)

Ebbesen, S. D., Jensen, S. H., Hauch, A., & Mogensen, M. B. (2014). High temperature electrolysis in alkaline cells, solid proton conducting cells, and solid oxide cells. *Chemical Reviews*, 114(21), 12288-12306. DOI: 10.1021/cr500310b., http://dx.doi.org/10.1021/cr5000865

[47]. Electrólisis Microbiana

Pant, D., Van Bogaert, G., Diels, L., & Vanbroekhoven, K. (2010). A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production. *Bioresource Technology*, 101(6), https://doi.org/10.1016/j.biortech.2009.10.017

[48]. Electrólisis de Amoníaco

Rouwenhorst, K. H. R., et al. (2019). “A review of sustainable hydrogen production using ammonia as the feedstock”. *Renewable and Sustainable Energy Reviews*, 114, 109339.

https://doi.org/10.1016/j.rser.2019.109339

[49]. Electrólisis de Membrana de Óxido Sólido (SOEC)

Ebbesen, S. D., et al. (2014). "High temperature electrolysis in alkaline solutions: A review". *Journal of the Electrochemical Society*, 161(9), F1075-F1087. DOI: 10.1149/2.021409jes https://doi.org/10.1021/cr5000865

[50]. Electrólisis de Agua Seawater

Z. Yu., L. Liang., Avances recientes en la electrólisis híbrida de agua de mar para la producción de hidrógeno., Adv. Mater.2024 Mar;36(13):e2308647.,https://doi.org/10.1002/adma.202308647

[51]. Electrólisis de Agua Desmineralizada

Els van der Roest, Ron Bol,Theo Fens,Ad van Wijk ., Aprovechamiento del calor residual de los electrolizadores PEM: cómo optimizarlo localmente., Revista internacional de energía del hidrógeno.,Volumen 48, número 72, 22 de agosto de 2023 , Páginas 27872-27891

https://doi.org/10.1016/j.ijhydene.2023.03.374

[52]. Electrólisis Asistida por Energía Solar

Turner, J. A. (2004). Sustainable hydrogen production. *Science*, 305(5686), 972-974. DOI: 10.1126/science.1103197., https://doi.org/10.1126/science.1103197

6.- STORAGE AND DISTRIBUTION [53,54]

[53]. Zhu, Y., Li, H., Wang, X., & Song, C. (2015). "Recent advances in hydrogen storage in metal–organic frameworks and related materials." Materials Today, 18(2), 85-96.

[54]. Kleijn, R., van der Giesen, C., & Kramer, G. J. (2011). "Metal resources, use and criticality." Science, 337(6095), 1198-1201.

7. Innovaciones y Futuro del Hidrógeno [55-57]

[55]. Elementos del Grupo s (Metales Alcalinos y Alcalinotérreos)

Greenwood, N. N., & Earnshaw, A. (1997). Chemistry of the Elements (2nd ed.). Butterworth-Heinemann.

[56]. Elementos del Grupo d (Metales de Transición)

Van Der Lingen, E., & Ramesh, R. (2005). Transition Metals in Catalysis. In Encyclopedia of Inorganic Chemistry. John Wiley & Sons.

Somorjai, G. A., & Li, Y. (2010). Introduction to Surface Chemistry and Catalysis (2nd ed.). John Wiley & Sons.

[57]. Elementos del Grupo f (Lantánidos y Actínidos)

Evans, W. J. (1990). Tutorial on the Coordination Chemistry of Lanthanides and Actinides. In Inorganic Chemistry.

Cotton, S. (2006). Lanthanide and Actinide Chemistry. John Wiley & Sons.

Larminie, J., & Dicks, A. (2016). “Fuel cell systems explained.” John Wiley & Sons.

Leary, E. (2019). “The role of hydrogen in the decarbonisation of the global economy.” IEA Clean Coal Centre Report, CCC/306.///