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Hydrogen: Properties and its Sustainable Potential

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ABSTRACT

This paper analyzes the thermal properties of hydrogen and its potential as a clean and sustainable energy source. Hydrogen possesses unique characteristics, such as low activation energy, a wide flammability range, high diffusion speed, low density, and high thermal conductivity, all governed by various physical laws. These properties make hydrogen promising for technological and energy applications, with significant implications in terms of safety, economy, and sustainability.

In Table 1, we identify the physical and chemical laws that are analyzed and their practical implications for its use in various energy applications, discussing aspects such as storage and safe handling. In Table 2, we indicate the typical values of hydrogen that would allow its use to be optimized and its efficiency maximized in transport, storage, and combustion, mitigating safety and infrastructure risks. In Table 3, we describe the current technologies for hydrogen production, storage, and use, which include methods such as electrolysis, natural gas reforming, and different storage techniques (cryogenic, high pressure, etc.).

Subsequently, we identified that the technological influence of hydrogen depends on the nature of its properties, being key factors for optimizing its application and integrating it into a sustainable economy (Table 4). Finally, we indicate the key factors that affect performance and the aspects to optimize to improve the efficiency and viability of hydrogen as a clean energy source, offering a critical assessment of how these properties impact its viability (Table 5).

Therefore, hydrogen has emerged as a clean energy source with potential in various sectors, despite the challenges related to safety and infrastructure. A multidisciplinary approach and safety measures are required to maximize its potential and mitigate the risks

INTRODUCTION [1-33]

Hydrogen, a fundamental chemical element, has emerged as a promising clean and renewable energy source in the contemporary search for sustainable alternatives to fossil fuels. Its importance lies in its ability to address both environmental concerns and energy needs efficiently and sustainably. In recent decades, hydrogen's potential has been widely recognized across a variety of applications, spanning multiple sectors, from transportation to industry, energy generation, and heating.

Therefore, hydrogen is essential for humanity and the environment due to the following advantages and benefits:

Reduction of Greenhouse Gas Emissions: Hydrogen does not produce carbon dioxide (CO_2) emissions or other greenhouse gases, contributing to the reduction of environmental impact and helping to combat climate change [1-3].

Versatility of Applications: It can be used in a wide range of applications, from transportation (hydrogen-powered electric vehicles) to electricity generation, as well as in industry and heating. This versatility makes it an attractive and multipurpose energy source [4-6].

Energy Efficiency: It is more efficient than conventional fuels; for example, in fuel cells, the efficiency of converting hydrogen's stored energy into electricity can be very high [7-9].

Energy Security: As an alternative fuel, hydrogen can help reduce dependency on fossil fuels, thus decreasing vulnerability to oil price volatility and promoting energy security [10-12].

Economic Development: Hydrogen can drive the development of a hydrogen economy, creating jobs in hydrogen production, storage, distribution, and use, as well as in the development of related technologies [13-15].

Energy Storage and Transport: Hydrogen serves as an efficient medium for storing and transporting energy, which is especially useful in addressing challenges associated with the intermittency of renewable energy sources, such as solar and wind power [16-18].

Reduction of Air Pollutants: Hydrogen has the potential to reduce emissions of greenhouse gases and other air pollutants. When used in fuel cells, the only byproduct is water, making it a much cleaner option compared to fossil fuels [19-21].

Abundance and Diversity of Sources: As the most abundant element in the universe, hydrogen can be produced from a variety of sources, such as water, biomass, and renewable energy, reducing dependence on fossil fuels and enhancing energy security [22-24].

Diverse Applications: Hydrogen can be used in a wide range of applications, from transportation to stationary energy generation. It can power fuel cell vehicles, buses, trains, and even airplanes, offering an alternative to internal combustion engines [25-27].

Superior Efficiency: Hydrogen can be up to three times more efficient than conventional internal combustion engines, meaning more useful energy can be obtained from the same amount of fuel, contributing to resource conservation and long-term cost reduction [28-30].

National Energy Security: Hydrogen can reduce dependence on imported fuels and help ensure national energy security [31-33].

POTENTIAL AND PROPERTIES OF HYDROGEN AS AN ALTERNATIVE ENERGY SOURCE [34-49]

The potential of hydrogen as an energy source lies in its intrinsic properties, which directly affect its efficiency and applicability in various fields. Scientific and technological research focuses on understanding and optimizing these properties to develop more efficient and safer technologies, promoting the adoption of hydrogen as a key energy resource [34, 35].

Intrinsic Properties of Hydrogen:

Low Activation Energy: This refers to the minimum amount of energy required to initiate a combustion reaction. Fuels with low activation energy ignite with a small amount of energy, making them relatively easy to combust. The activation energy can range from 1 to 100 kilojoules per mole [39].

Wide Flammability Range: The flammability range is the range of fuel concentrations in the air within which ignition and combustion can occur. For some fuels, this range can vary from approximately 5% to 15% fuel concentration in the air [40].

High Diffusion Speed: This refers to how quickly fuel molecules disperse in the air. In general, gaseous fuels like hydrogen diffuse faster than liquids or solids. Diffusion rates are measured in meters per second (m/s) or square centimeters per second (cm^2/s) [41].

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Low Density: The density of a fuel is its mass per unit volume. Fuels with low density, like hydrogen, have a relatively low mass compared to the volume they occupy. Density is expressed in grams per cubic centimeter (g/cm^3) or kilograms per cubic meter (kg/m^3) [42].

High Thermal Conductivity: This refers to a material's ability to transfer heat. Fuels with high thermal conductivity, such as hydrogen, transfer heat efficiently, which can influence their ability to ignite and burn uniformly. Thermal conductivity is expressed in watts per meter kelvin (W/m·K) or joules per second meter kelvin (J/s·m·K) [43].

Importance of Hydrogen as an Alternative Fuel:

Technological Advances and Research: Hydrogen drives research and development of new technologies, which can lead to significant advances in energy efficiency, refueling infrastructure, and sustainable hydrogen production [36].

Efficiency and Technological Applications: The thermal properties and thermal activity of hydrogen determine its efficiency in various technological applications [37, 38].

Potential for Innovation: The use of hydrogen as an alternative fuel offers significant advantages, including low environmental impact, abundance, versatility, and potential to promote technological innovation in the energy sector.

Therefore, Properties and Associated Laws: The intrinsic properties of hydrogen—low activation energy, wide flammability range, high diffusion speed, low density, and high thermal conductivity—are evaluated through the physical and chemical laws that govern them. Each property has practical implications for the efficient and safe use of hydrogen. The discussion focuses on how these properties can be optimized to promote the adoption of hydrogen as a key energy resource (See Table 1).

The large-scale adoption of hydrogen as an energy source will require a comprehensive approach that considers not only technological advances but also economic viability, necessary infrastructure, and social acceptance. Public education and awareness of the benefits and safety of hydrogen are key components for its successful implementation.

LIMITS OF HYDROGEN'S THERMAL PROPERTIES IN ENERGY APPLICATIONS [68-70]

The potential of hydrogen's thermal properties depends on the limits of its physical properties, which are key to efficiency in energy applications. For example, its low activation energy and wide flammability range are advantageous in applications requiring quick and reliable ignition, such as internal combustion engines or heating systems. This can lead to higher energy efficiency for hydrogen. When properly activated, these properties are responsible for the economic benefits, efficiency, and safety of hydrogen in industrial thermal applications and transportation.

Using hydrogen as an energy source also contributes to environmental sustainability, positioning it as a key fuel in the transition to a cleaner and more sustainable energy future, though it is characterized by certain limitations (see Table 2). This table identifies hydrogen's properties, and through their limits or typical values, is responsible for both the benefits and weaknesses associated with them. It demonstrates hydrogen's potential to revolutionize the global energy landscape, providing a clean and versatile energy source. Fully harnessing its benefits and mitigating its limitations will require a multifaceted approach, including technological innovations, supportive policies, and concerted efforts in education and awareness. With the right strategies, hydrogen can play a crucial role in the transition to a sustainable, carbon-free economy.

HYDROGEN TECHNOLOGIES: ANALYSIS, AVAILABILITY, AND VIABILITY ACCORDING TO THEIR PROPERTIES [79-102]

The deployment of hydrogen technologies requires a combination of advances in research, technological development, and supportive policies. Key technologies include water electrolysis, steam reforming, fuel cells, and various hydrogen storage and distribution techniques.

Water Electrolysis is a technology that uses electricity to break water down into hydrogen and oxygen. This process can be powered by renewable energy sources such as solar or wind, producing green hydrogen with zero carbon emissions. High-temperature electrolysis, a more efficient variant of conventional electrolysis, is gaining interest due to its potential to reduce costs and increase efficiency. However, the economic viability of this technology depends on the availability and cost of renewable electricity.

Steam Reforming is a mature technology that converts hydrocarbons into hydrogen and carbon dioxide using water vapor. Although this process is efficient and currently the most widely used method for hydrogen production, it generates CO2 emissions, requiring carbon capture and storage (CCS) technologies to mitigate its environmental impact.

Fuel Cells convert hydrogen and oxygen into electricity and water without combustion. They are a promising option for both stationary and mobile applications. Solid oxide fuel cells (SOFC) and proton exchange membrane (PEM) fuel cells are being widely researched and developed. SOFCs operate at high temperatures and can directly use gaseous fuels, while PEMs are better suited for vehicle applications due to their smaller size and weight.

Attached are Table 3 and Table 4, which provide a comprehensive overview of each technology, highlighting its potential to transform the global energy landscape. These technologies not only enable greater efficiency and sustainability but also offer practical solutions for decarbonizing multiple sectors. Their continued integration and development are critical to achieving global climate and energy goals. Table 4 indicates the relevance of hydrogen properties that influence the efficiency of its application (see Table 3).

Hydrogen technologies stand out because of their intrinsic properties, which influence hydrogen production, storage, distribution, and use in industrial and residential sectors. Their relevance lies in the transition to a clean, sustainable energy economy, and safety plays a crucial role in determining the "viability and effectiveness" of these technologies, depending on their intrinsic properties (See Table 4).

Hydrogen has the potential to be a cornerstone in the global energy transition. However, in Table 5, the limitations of each technology, which depend on its properties, are identified and described. These limiting factors reflect inherent barriers to the performance and implementation of hydrogen-based technologies.

Additionally, efficiency indicators provide a quantitative measure of each technology's performance under the identified limitations. These indicators, including faradaic efficiency, thermal efficiency, power density, and storage capacity, directly influence the overall performance of hydrogen technologies (see Table 5).

DISCUSSION AND CONCLUSIONS

Hydrogen, as a clean energy source, offers significant potential to transform the global energy landscape. However, its success depends on addressing several key challenges:

Versatility and Potential: Hydrogen stands out for its ability to adapt to various technological applications, from electricity generation in fuel cells to its use in transportation and industrial processes. Its versatility offers opportunities to replace fossil fuels and contribute to a cleaner economy.

Technical and Economic Challenges: Hydrogen's properties present both benefits and risks. Its low activation energy facilitates ignition in engines and heating systems but increases the risk of accidental ignition, requiring stringent safety measures. Its high diffusion rate promotes complete combustion in industrial applications but

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complicates the control of fuel mixtures. Low density makes transportation and storage easier but requires large volumes, which can increase costs and complicate logistics. Its wide flammability range allows efficient combustion but also poses explosion risks if not properly controlled. High thermal conductivity aids heat transfer but can lead to thermal losses that need efficient management. These challenges require advanced solutions in terms of storage, safety, and distribution to maximize efficiency and reduce costs.

Technologies and Advances: Hydrogen production is primarily carried out through water electrolysis and natural gas reforming. Electrolysis, which uses electricity to separate hydrogen from oxygen, is advancing towards more sustainable production with green hydrogen sourced from renewable energy. On the other hand, natural gas reforming is more cost-effective but has a greater environmental impact. Fuel cells, such as solid oxide fuel cells (SOFC) and proton exchange membrane (PEM) cells, use hydrogen to generate electricity cleanly, but improving their efficiency and durability is crucial. Hydrogen storage can be cryogenic, high-pressure, or underground, with each method presenting challenges in cost and safety. Research is focused on optimizing hydrogen efficiency and reducing costs to enable its widespread adoption as a clean and sustainable energy source.

Infrastructure and Regulations: Developing a robust infrastructure for hydrogen storage and distribution is essential. Uniform regulations are needed to ensure interoperability and safety in hydrogen use.

Innovation and Collaboration: Innovation in materials, advanced technologies, and storage systems is key to overcoming current barriers. Collaboration among researchers, industry, and governments will be essential to advancing hydrogen adoption and developing supportive policies.

Education and Awareness: Promoting public education on hydrogen and its benefits will help overcome social barriers and foster greater acceptance and support for hydrogen-related technologies.

Therefore, hydrogen has the potential to play a crucial role in the transition to a sustainable energy system. Achieving this goal will require a coordinated approach that integrates technological innovation, infrastructure development, international collaboration, and regulatory support. With the right commitment and investment, hydrogen can become a cornerstone of a clean and resilient energy future.

Table 1. Physical and Chemical Laws: Assessment of Hydrogen Properties and Practical Implications [50-67]

Property	**Laws Analyzing It**	**Practical Implications**	**Refs.**
Low Activation Energy	- Transition State Theory	The transition state theory helps understand how hydrogen can initiate chemical reactions with less energy, making it efficient for combustion processes and energy generation.	50, 51
Wide Flammability Range	- Fire Triangle - Explosivity Limits	The fire triangle and explosivity limits show that hydrogen can ignite easily with small amounts of oxygen, making it a versatile energy source but with significant explosion risks, requiring strict safety measures.	52, 53
High Diffusion Speed	- Fick's Law - Knudsen Effect	Fick's law and the Knudsen effect explain hydrogen's ability to quickly mix with other substances and permeate solid materials. This is crucial for its use in fuel cells and other energy technologies but also presents challenges in safely storing the gas.	54, 55
Low Density	- Boyle's Law - Charles's Law	Boyle's and Charles's laws indicate that hydrogen occupies a large volume at room temperature and pressure, making it ideal for applications requiring lightness, such as in aerospace vehicles. However, its sensitivity to temperature changes must be properly	62, 63, 64

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		managed.	
High Thermal Conductivity	- Fourier's Law - Heat Capacity	Fourier's law and heat capacity highlight that hydrogen can transfer heat quickly, making it useful in cooling and heating systems. Its high thermal conductivity enables efficient heat exchange, but it requires less energy to increase its temperature, optimizing energy efficiency in various industrial applications.	65, 66, 67

This table summarizes the properties of hydrogen, the physical and chemical laws that analyze them, and the practical implications for its use in various energy applications.

Table 2. Typical Hydrogen Values: Limitations and Benefits of Hydrogen [71-79]

Property	**Typical Values**	**Benefits**	**Limitations**	**Bibliography**
Low Activation Energy	1-100 kJ/mol (much lower than gasoline)	- Responsible for fast and reliable ignition. - Crucial for internal combustion engines and heating systems. - Can lead to greater energy efficiency. Fast and reliable ignition, higher energy efficiency.	- May result in a high risk of accidental ignition.	71, 72
Wide Flammability Range	5% - 15% (in air, at 25°C and 1 atm)	- Allows hydrogen to ignite easily in the presence of small amounts of oxygen. - Beneficial for applications requiring fast and efficient combustion. Easy ignition, efficient combustion.	- Higher risk of explosion in uncontrolled environments.	73
High Diffusion Speed	~1.4 times higher than air (at 25°C)	- Essential for applications that require rapid fuel dispersion in air. - Crucial for complete and uniform combustion in industrial burners and chemical reactors. Rapid mixing with air, complete combustion.	- May complicate fuel-air mixture control, requiring more complex systems.	74, 75
Low Density	~0.08988 kg/m³ (at 0°C and 1 atm)	- Facilitates transport and storage. - Important for mobile applications such as vehicles and aircraft. - Maximizes fuel efficiency and minimizes weight.	- Requires large volumes for storage, impacting infrastructure.	76, 77
High Thermal Conductivity	0.168 W/m·K (under standard conditions at 0°C)	- Contributes to more efficient and controlled combustion. - Crucial for ensuring safe and stable operation. - Applications in various areas, ensuring efficiency and control.	- May result in unwanted heat loss in poorly insulated systems.	78

The magnitude of typical values of hydrogen's properties allows for optimizing its use and maximizing the efficiency of technology in transportation, storage, and combustion, while mitigating risks related to safety and infrastructure.

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Table 3. Hydrogen Technologies [79-101]

Technology	**Description**
Water Electrolysis	Process that uses electricity to break water into hydrogen and oxygen.
Steam Reforming	Process that converts liquid or gaseous hydrocarbons into hydrogen and carbon dioxide using water vapor.
Fuel Cells	Electrochemical devices that convert hydrogen and oxygen into electricity and water without combustion.
Hydrogen Storage	Various technologies such as high-pressure tanks, cryogenic storage, absorbent materials, etc.
Hydrogen Distribution	Infrastructure for the safe transport and distribution of hydrogen through pipelines or tanker trucks.
Hydrogen Vehicles	Vehicles that use fuel cells or modified internal combustion engines to run on hydrogen.
Stationary Fuel Cells	Stationary systems that use fuel cells to generate electricity from hydrogen.
Underground Hydrogen Storage	Technology that stores hydrogen in underground caverns or porous geological formations.
Maritime Hydrogen Transport	Technologies to transport liquid hydrogen in bulk by sea using specialized tankers.
Portable Fuel Cells	Compact devices that convert hydrogen into electricity, used in portable applications like consumer electronics.
Hydrogen Injection into Natural Gas Networks	Controlled introduction of hydrogen into natural gas distribution networks to reduce carbon emissions.
Carbon Capture and Storage (CCS) with H2	Processes that use hydrogen to capture CO2 from industrial sources and store it safely.
High-Temperature Electrolysis	A variant of conventional electrolysis that operates at higher temperatures, potentially increasing efficiency and reducing costs.
CO2 Reduction Electrochemistry	Process that uses hydrogen generated from renewable sources to reduce atmospheric CO2 and produce valuable chemicals.
Hydrogen as Industrial Fuel	Use of hydrogen as fuel in industrial processes, such as steel production, petrochemicals, and oil refining.
Salt Cavern Storage	Technology that involves storing hydrogen in salt caverns for large-scale, long-term storage.
Electrochemical Solutions	Process that uses electrodes and membranes to break down water and produce hydrogen and oxygen, applied in the chemical industry.
Hydrogen for Residential	Use of hydrogen as fuel for residential heating systems, helping reduce

Heating	emissions in the residential sector.
Hydrogen as Aviation Fuel	Ongoing research into using hydrogen as aviation fuel, reducing carbon emissions in aviation.
Proton Exchange Membrane (PEM) Electrolysis	Type of electrolysis that uses polymer membranes to produce hydrogen, suitable for vehicles due to its size and weight.
Green Hydrogen	Hydrogen produced from renewable sources like solar or wind energy via electrolysis, with zero carbon emissions.
Solid Oxide Fuel Cells (SOFC)	Type of fuel cell that operates at high temperatures and uses gaseous fuels such as hydrogen or methane.
Natural Gas Reforming	Process that converts natural gas into hydrogen and CO2 via steam reforming. Used in industrial applications and vehicles.
Anion Exchange Membrane Fuel Cells (AEMFC)	Emerging fuel cell operating at low temperatures, potentially more cost-effective than PEMFC, suitable for various applications.
Carbon Capture and Storage (CCS)	Captures CO2 produced during hydrogen generation from fossil fuels, storing it safely.

Table 4. Key Properties: Influence on Technological Applications [79-101]

Technology	**Influencing Properties**	**Relevance and Efficiency**
Water Electrolysis	- Electrical conductivity, membrane efficiency, water purity.	Green hydrogen production, crucial for the renewable energy economy.
Steam Reforming	- Operating temperature, pressure, catalyst quality.	Main hydrogen source in industry, key to mass production.
Fuel Cells	- Electrochemical efficiency, membrane durability, hydrogen purity.	Efficient electricity generation with only water as a byproduct, crucial for clean applications.
Hydrogen Storage	- Storage capacity, stability, safety, energy density.	Essential for distribution and use in various applications, ensuring continuous availability.
Hydrogen Distribution	- Storage pressure, pipeline materials, safety.	Critical infrastructure for the safe and efficient transport of hydrogen from production to consumption.
Hydrogen Vehicles	- Fuel cell efficiency, storage capacity, tank weight.	Significant emissions reduction in transport, driving sustainable mobility.
Hydrogen Generators	- Process efficiency, operational stability, size, and portability.	On-site production for specific applications, improves local energy efficiency.
Stationary Fuel Cells	- Electrochemical efficiency, durability, hydrogen purity.	Provides continuous and clean energy for stationary applications, reducing the carbon

		footprint.
Underground Hydrogen Storage	- Cavern capacity, geological integrity, safety.	Large-scale, long-term solution, essential for balancing energy supply and demand.
Maritime Hydrogen Transport	- Energy density, safety, cryogenic storage efficiency.	Enables global hydrogen transport, facilitating international energy trade.
Portable Fuel Cells	- Electrochemical efficiency, size and weight, durability.	Energy source for portable devices, useful in emergencies and consumer technology.
Hydrogen Injection into Natural Gas Networks	- Compatibility with existing infrastructure, blending ratio.	Reduces carbon emissions in natural gas use, integrating hydrogen into existing infrastructures.
Carbon Capture and Storage (CCS)	- Capture efficiency, storage capacity, geological stability.	Mitigation of industrial CO2 emissions, essential for industrial sustainability.
High-Temperature Electrolysis	- Operating temperature, membrane efficiency, material durability.	Higher efficiency and lower cost compared to conventional electrolysis, enhancing its economic viability.
CO2 Reduction Electrochemistry	- Reduction efficiency, hydrogen purity, process stability.	Atmospheric CO2 reduction, production of valuable chemicals, contributing to the circular economy.
Hydrogen as Industrial Fuel	- Combustion efficiency, supply stability, hydrogen purity.	Used in industrial processes to reduce emissions, improving production sustainability.
Salt Cavern Storage	- Salt cavern capacity, geological integrity, safety.	Large-scale storage solution, crucial for energy supply stability.
Electrochemical Solutions	- Process efficiency, electrode quality, water purity.	Hydrogen production for industrial applications, increases chemical process efficiency.
Hydrogen for Residential Heating	- Combustion efficiency, supply safety, storage capacity.	Reduction of greenhouse gas emissions in the residential sector, improving energy efficiency.
Hydrogen as Aviation Fuel	- Combustion efficiency, energy density, storage weight.	Potential emissions reduction in aviation, significant progress towards sustainable flights.
PEM Electrolysis	- Membrane efficiency, durability, hydrogen purity.	Suitable for mobile applications, increasing the viability of hydrogen vehicles.
Green Hydrogen	- Electrolysis process efficiency, production capacity, hydrogen purity.	Clean fuel with zero carbon emissions, a pillar of the renewable energy economy.
SOFC Fuel Cells	- Operating temperature, electrochemical efficiency, durability.	Electricity generation from diverse fuels, flexibility in stationary applications.

Natural Gas Reforming	- Process efficiency, catalyst quality, operating temperature and pressure.	Important industrial hydrogen source, facilitating the transition to a hydrogen economy.
AEMFC Fuel Cells	- Electrochemical efficiency, durability, hydrogen purity.	Cost reduction in production, applicable in various areas, including stationary and vehicle applications.
Carbon Capture and Storage (CCS)	- Capture efficiency, storage capacity, safety.	Reduction of greenhouse gas emissions, key to environmental sustainability.

This table provides a clear view of how hydrogen properties influence the efficiency of each technology, from production and storage to transportation and final use. It identifies the key factors to optimize its application and improve its integration into a sustainable economy.

Table 5. Limitations and Efficiency Indicators of Hydrogen Properties in Each Application [79-101]

Technology	**Property Limitations**	**Efficiency Indicators**
Water Electrolysis	- Water's electrical conductivity - Electrode energy efficiency - High energy demand - Efficiency limited by overpotentials.	- Faradaic efficiency - Specific energy consumption - Specific energy consumed.
Steam Reforming	- Thermal stability - Catalytic reactivity - CO2 emissions - Requires high temperatures.	- Reforming yield - Thermal efficiency.
Fuel Cells	- Ionic conductivity of electrolytes - Material durability - High material cost - Component degradation.	- Electrical efficiency - Power density.
Hydrogen Storage	- Volumetric energy density - Material absorption capacity - Low volumetric energy density - Cryogenic storage costs.	- Storage capacity - Evaporation losses.
Hydrogen Distribution	- Storage pressure - Transport safety - Expensive infrastructure - Safety risks and leaks.	- Cost per

The table identifies the key factors that affect the performance of each technology and the aspects that need to be optimized to improve their efficiency and viability, helping to understand the challenges and opportunities in using hydrogen as a clean energy source.

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