Green Hydrogen:
Powering a Low-Carbon Future

by Dr. **Ahad Esmaeilian**

Green hydrogen is considered a versatile and potentially transformative technology in the transition to a low-carbon energy system. Its ability to decarbonize various sectors and to store and transport renewable energy makes it a key player in the energy transition.

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Background

The history of hydrogen production dates to 1800s, when scientists first discovered that hydrogen could be produced from water through the process of electrolysis. However, it

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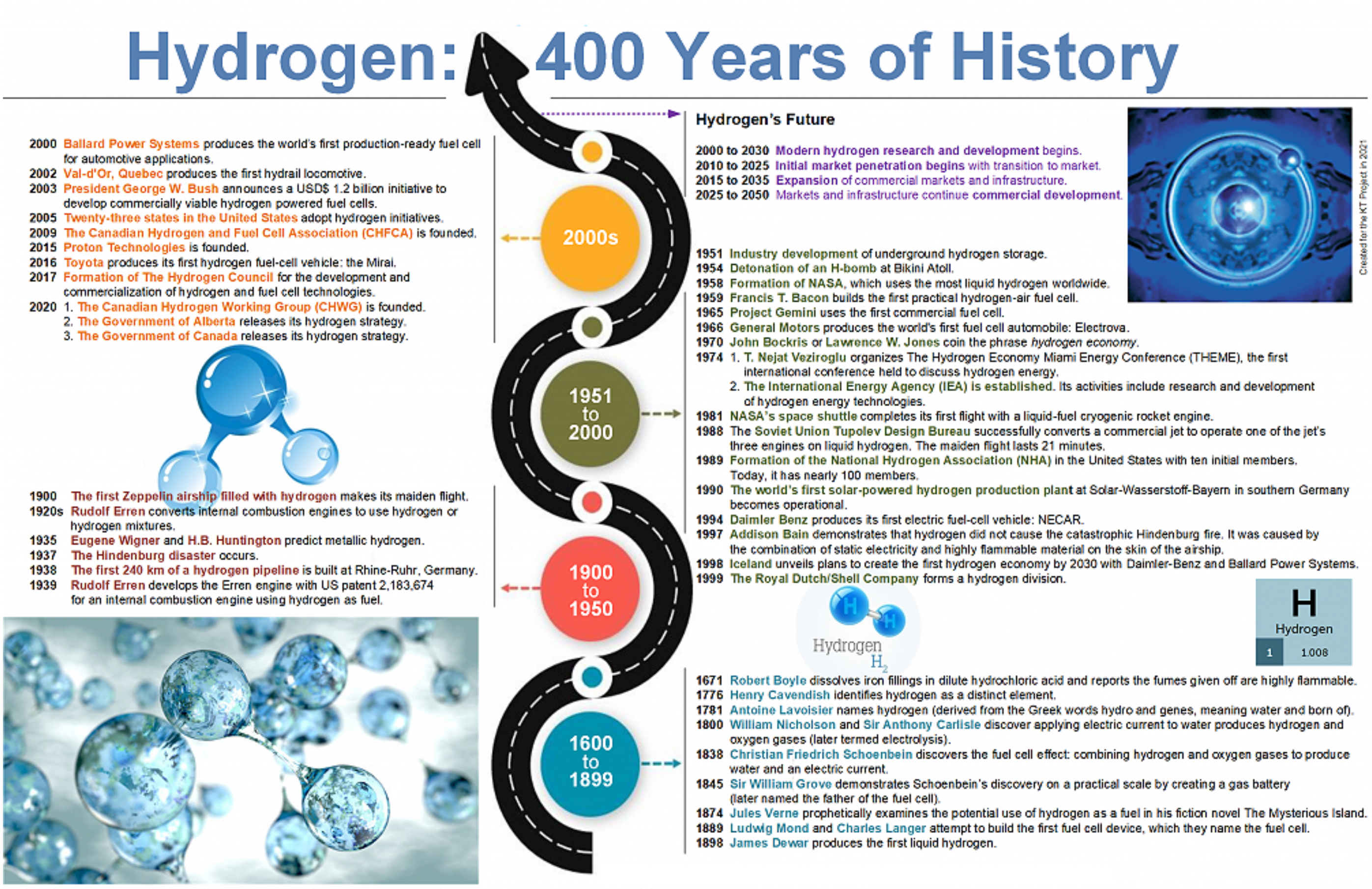
wasn't until the 20th century that hydrogen began to be used as a fuel on a large scale. Initially, hydrogen was mainly produced using fossil fuels such as natural gas, leading to the emission of greenhouse gases. Green hydrogen is produced using renewable energy sources such as wind or solar power, rather than fossil fuels. In recent years, interest in green hydrogen has grown as a means of using renewable energy to produce hydrogen without emitting carbon. The production of green hydrogen involves the electrolysis of water, where an electric current is passed through water, splitting it into hydrogen and oxygen. The electricity used in this process can come from a variety of renewable sources such as solar, wind, or hydroelectric power.



Hydrogen: 400 Years of History

Hydrogen's Future

2000 to 2030 **Modern hydrogen research and development** begins.
2010 to 2025 **Initial market penetration begins** with transition to market.
2015 to 2035 **Expansion** of commercial markets and infrastructure.
2025 to 2050 Markets and infrastructure continue **commercial development**.

2000 **Ballard Power Systems** produces the world's first production-ready fuel cell for automotive applications.
2002 **Val-d'Or, Quebec** produces the first hydrail locomotive.
2003 **President George W. Bush** announces a USD$ 1.2 billion initiative to develop commercially viable hydrogen powered fuel cells.
2005 **Twenty-three states in the United States** adopt hydrogen initiatives.
2009 **The Canadian Hydrogen and Fuel Cell Association (CHFCA)** is founded.
2015 **Proton Technologies** is founded.
2016 **Toyota** produces its first hydrogen fuel-cell vehicle: the Mirai.
2017 **Formation of The Hydrogen Council** for the development and commercialization of hydrogen and fuel cell technologies.
2020 1. **The Canadian Hydrogen Working Group (CHWG)** is founded.
2. **The Government of Alberta** releases its hydrogen strategy.
3. **The Government of Canada** releases its hydrogen strategy.

1951 **Industry development** of underground hydrogen storage.
1954 **Detonation of an H-bomb** at Bikini Atoll.
1958 **Formation of NASA**, which uses the most liquid hydrogen worldwide.
1959 **Francis T. Bacon** builds the first practical hydrogen-air fuel cell.
1965 **Project Gemini** uses the first commercial fuel cell.
1966 **General Motors** produces the world's first fuel cell automobile: Electrova.
1970 **John Bockris** or **Lawrence W. Jones** coin the phrase *hydrogen economy*.
1974 1. **T. Nejat Veziroglu** organizes The Hydrogen Economy Miami Energy Conference (THEME), the first international conference held to discuss hydrogen energy.
2. **The International Energy Agency (IEA) is established.** Its activities include research and development of hydrogen energy technologies.
1981 **NASA's space shuttle** completes its first flight with a liquid-fuel cryogenic rocket engine.
1988 The **Soviet Union Tupolev Design Bureau** successfully converts a commercial jet to operate one of the jet's three engines on liquid hydrogen. The maiden flight lasts 21 minutes.
1989 **Formation of the National Hydrogen Association (NHA)** in the United States with ten initial members. Today, it has nearly 100 members.
1990 **The world's first solar-powered hydrogen production plant** at Solar-Wasserstoff-Bayern in southern Germany becomes operational.
1994 **Daimler Benz** produces its first electric fuel-cell vehicle: NECAR.
1997 **Addison Bain** demonstrates that hydrogen did not cause the catastrophic Hindenburg fire. It was caused by the combination of static electricity and highly flammable material on the skin of the airship.
1998 **Iceland** unveils plans to create the first hydrogen economy by 2030 with Daimler-Benz and Ballard Power Systems.
1999 **The Royal Dutch/Shell Company** forms a hydrogen division.

1900 **The first Zeppelin airship filled with hydrogen** makes its maiden flight.
1920s **Rudolf Erren** converts internal combustion engines to use hydrogen or hydrogen mixtures.
1935 **Eugene Wigner** and **H.B. Huntington** predict metallic hydrogen.
1937 **The Hindenburg disaster** occurs.
1938 **The first 240 km of a hydrogen pipeline** is built at Rhine-Ruhr, Germany.
1939 **Rudolf Erren** develops the Erren engine with US patent 2,183,674 for an internal combustion engine using hydrogen as fuel.

1671 **Robert Boyle** dissolves iron fillings in dilute hydrochloric acid and reports the fumes given off are highly flammable.
1776 **Henry Cavendish** identifies hydrogen as a distinct element.
1781 **Antoine Lavoisier** names hydrogen (derived from the Greek words hydro and genes, meaning water and born of).
1800 **William Nicholson** and **Sir Anthony Carlisle** discover applying electric current to water produces hydrogen and oxygen gases (later termed electrolysis).
1838 **Christian Friedrich Schoenbein** discovers the fuel cell effect: combining hydrogen and oxygen gases to produce water and an electric current.
1845 **Sir William Grove** demonstrates Schoenbein's discovery on a practical scale by creating a gas battery (later named the father of the fuel cell).
1874 **Jules Verne** prophetically examines the potential use of hydrogen as a fuel in his fiction novel The Mysterious Island.
1889 **Ludwig Mond** and **Charles Langer** attempt to build the first fuel cell device, which they name the fuel cell.
1898 **James Dewar** produces the first liquid hydrogen.

Source: https://ktproject.ca/hydrogen-an-introduction-to-the-clean-energy-of-the-future/

Electrolysis Technologies

There are several different electrolysis technologies currently available, each with its own set of advantages and disadvantages. The three major electrolysis technologies are:

Alkaline electrolysis

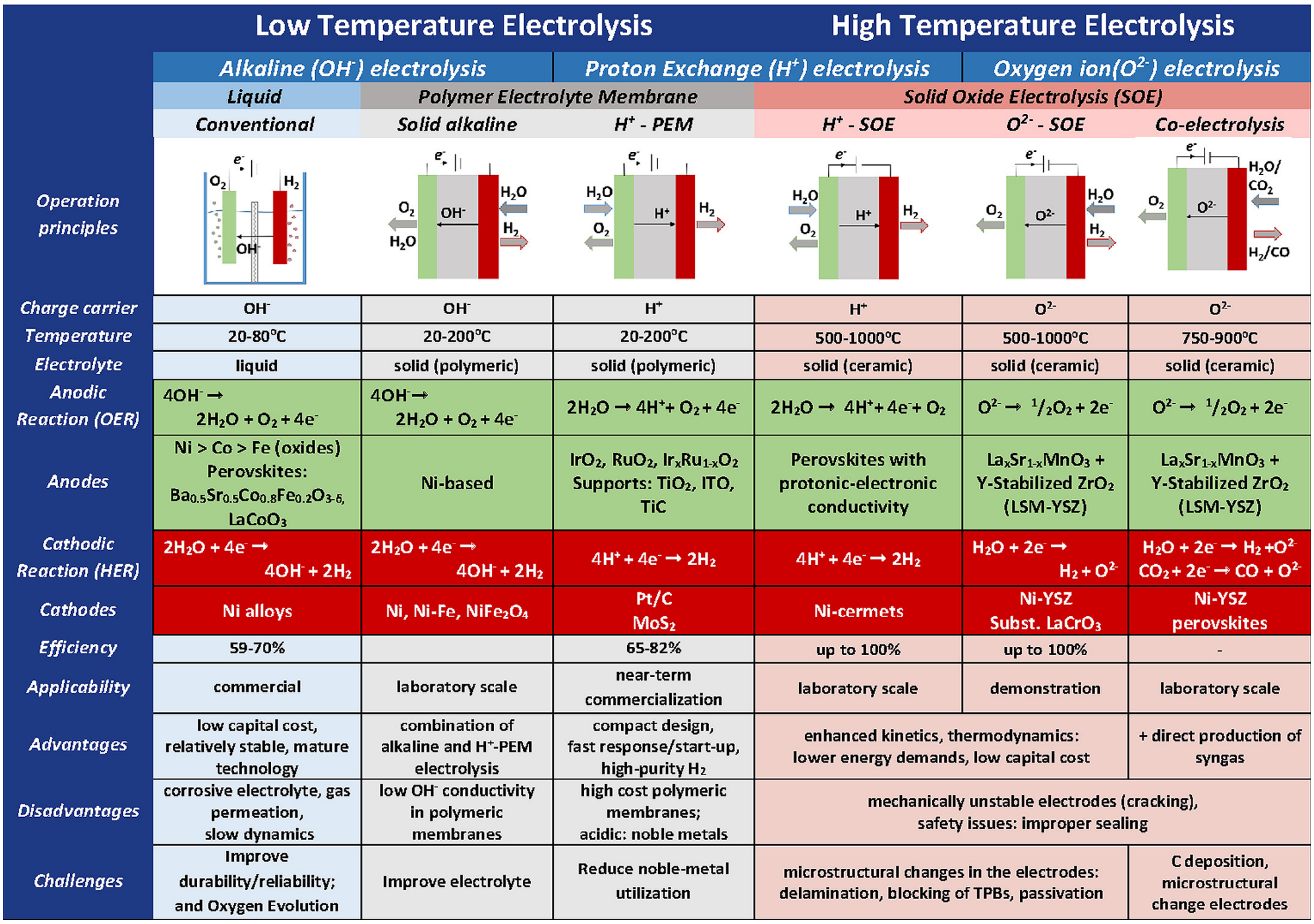
Alkaline electrolysis is one of the oldest and most mature electrolysis technologies. It uses an alkaline solution, such as potassium hydroxide (KOH), as the electrolyte. Alkaline electrolysis cells have a relatively high efficiency and are able to operate at relatively low temperatures, which makes them well suited for use in large-scale hydrogen production. The efficiency of alkaline electrolysis cells ranges from 70-80%, with an operational temperature range of 25-80°C. Moreover, alkaline electrolysis is relatively tolerant to impurities in the water, which can decrease the capital costs. However, the use of an alkaline electrolyte, such as KOH, can be corrosive, resulting in higher maintenance costs over time. Additionally, the efficiency of alkaline electrolysis decrease as the temperature increases above 80°C.

Proton exchange membrane (PEM) electrolysis.

PEM is a type of electrolysis technology that utilizes a proton-conducting polymer membrane as the electrolyte. The membrane selectively allows protons to pass through, but not electrons, resulting in high electrical efficiency of around 60-70%. PEM electrolysis cells are relatively compact and lightweight, making them well suited for small-scale and portable hydrogen production systems. Additionally, PEM electrolysis cells are able to operate at a relatively low temperature range of 20-80°C. This range of temperature and efficiency makes PEM electrolysis well suited for a wide range of applications, particularly in the transportation and power generation sectors. However, PEM electrolysis cells can be sensitive to impurities in the water, which can decrease the cell's lifespan and efficiency. Furthermore, PEM electrolysis cells require the use of a precious metal catalyst such as platinum, which increases the cost of the technology.

Solid oxide electrolyzer (SOE)

SOE is a type of electrolysis technology that utilizes a solid oxide material as the electrolyte. The electrolyte is typically composed of ceramics such as zirconia or yttria-stabilized zirconia. The solid oxide electrolyte allows for the movement of both ions and electrons, resulting in high electrical efficiency of around 60-80%. SOE cells are able to operate at high temperatures, typically 700-1000°C, which allows for high efficiency and the ability to use waste heat as a source of energy. This high operational temperature also allows SOE cells to be used in a variety of applications such as hydrogen production, power generation, and carbon capture. However, SOE cells are a relatively new technology and further research is needed to optimize their performance, decrease their costs and improve their reliability.

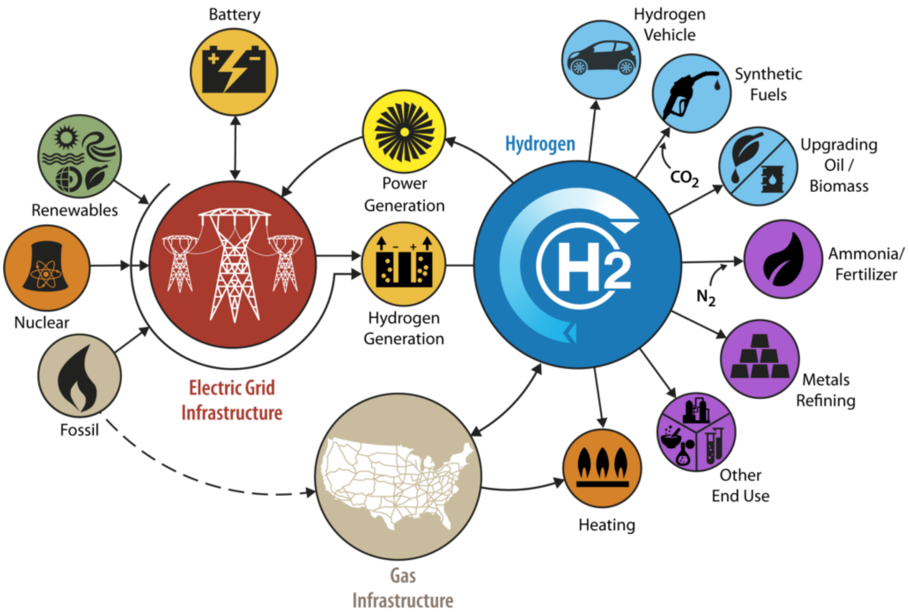


	Low Temperature Electrolysis			High Temperature Electrolysis		
	Alkaline (OH^-) electrolysis		Proton Exchange (H^+) electrolysis		Oxygen ion(O^{2-}) electrolysis	
	Liquid	Polymer Electrolyte Membrane		Solid Oxide Electrolysis (SOE)		
	Conventional	Solid alkaline	H^+ - PEM	H^+ - SOE	O^{2-} - SOE	Co-electrolysis
Operation principles						
Charge carrier	OH^-	OH^-	H^+	H^+	O^{2-}	O^{2-}
Temperature	20-80°C	20-200°C	20-200°C	500-1000°C	500-1000°C	750-900°C
Electrolyte	liquid	solid (polymeric)	solid (polymeric)	solid (ceramic)	solid (ceramic)	solid (ceramic)
Anodic Reaction (OER)	$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$	$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$	$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$	$2H_2O \rightarrow 4H^+ + 4e^- + O_2$	$O^{2-} \rightarrow {}^1/_2O_2 + 2e^-$	$O^{2-} \rightarrow {}^1/_2O_2 + 2e^-$
Anodes	Ni > Co > Fe (oxides) Perovskites: $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$, $LaCoO_3$	Ni-based	IrO_2, RuO_2, $Ir_xRu_{1-x}O_2$ Supports: TiO_2, ITO, TiC	Perovskites with protonic-electronic conductivity	$La_xSr_{1-x}MnO_3$ + Y-Stabilized ZrO_2 (LSM-YSZ)	$La_xSr_{1-x}MnO_3$ + Y-Stabilized ZrO_2 (LSM-YSZ)
Cathodic Reaction (HER)	$2H_2O + 4e^- \rightarrow 4OH^- + 2H_2$	$2H_2O + 4e^- \rightarrow 4OH^- + 2H_2$	$4H^+ + 4e^- \rightarrow 2H_2$	$4H^+ + 4e^- \rightarrow 2H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$ $CO_2 + 2e^- \rightarrow CO + O^{2-}$
Cathodes	Ni alloys	Ni, Ni-Fe, $NiFe_2O_4$	Pt/C MoS_2	Ni-cermets	Ni-YSZ Subst. $LaCrO_3$	Ni-YSZ perovskites
Efficiency	59-70%		65-82%	up to 100%	up to 100%	-
Applicability	commercial	laboratory scale	near-term commercialization	laboratory scale	demonstration	laboratory scale
Advantages	low capital cost, relatively stable, mature technology	combination of alkaline and H^+-PEM electrolysis	compact design, fast response/start-up, high-purity H_2	enhanced kinetics, thermodynamics: lower energy demands, low capital cost		+ direct production of syngas
Disadvantages	corrosive electrolyte, gas permeation, slow dynamics	low OH^- conductivity in polymeric membranes	high cost polymeric membranes; acidic: noble metals	mechanically unstable electrodes (cracking), safety issues: improper sealing		
Challenges	Improve durability/reliability; and Oxygen Evolution	Improve electrolyte	Reduce noble-metal utilization	microstructural changes in the electrodes: delamination, blocking of TPBs, passivation		C deposition, microstructural change electrodes

Source: https://www.sciencedirect.com/science/article/pii/S0360128516300260#f0010

Industry Applications

Green hydrogen has the potential to revolutionize multiple sectors across industries. From transportation to heating and cooling, and from industrial processes to power generation, green hydrogen offers a clean, efficient, and sustainable energy solution. With its versatility and scalability, green hydrogen has the potential to significantly reduce carbon emissions and contribute to a low-carbon future, making it a key enabler in the transition to a sustainable energy system. The adoption of green hydrogen across various sectors has the potential to drive economic growth, create new jobs, and provide energy security, making it a critical component in the global energy mix.



Source: https://www.energy.gov/eere/fuelcells/h2scale

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Power Generation, Heating & Cooling

Green hydrogen can be used by utilities to decarbonize their natural gas distribution pipelines, and thermal power generations to provide their customers with lower carbon emission electricity, heating and cooling solutions. This can be achieved through a process known as hydrogen blending, where a small percentage of hydrogen is added to the existing natural gas pipeline, reducing the overall carbon intensity of the delivered energy. As the percentage of hydrogen in the blend increases, the carbon emissions from the natural gas pipeline will decrease. This provides a stepping-stone for utilities to transition their customers to a low-carbon

energy source, without requiring significant infrastructure changes. Additionally, green hydrogen can also be used as a standalone energy source for heating and cooling, either through direct use or through conversion to electricity through fuel cells. This can help to significantly reduce the carbon emissions from the heating and cooling sector and contribute to a more sustainable energy system. In the power and utilities sector, green hydrogen can be used to store excess renewable energy, which can then be used to meet demand during periods of low renewable energy generation. Green hydrogen can also be used to balance the electricity grid, helping to integrate more renewable energy into the system.

Hydrogen blending into the natural gas power generation turbines or distribution pipelines faces several challenges, including:

- **Technical compatibility:** Hydrogen is a highly reactive gas, and blending it with natural gas requires ensuring that the existing natural gas pipelines, appliances, and meters are compatible with hydrogen gas.
- **Safety concerns:** Hydrogen is a flammable gas and requires special handling and storage procedures to ensure safety. This requires the development of appropriate safety protocols, risk assessments, and hydrogen leak detection systems.
- **Cost:** The production and transportation of hydrogen, as well as the retrofitting of existing natural gas infrastructure to accommodate hydrogen blending, can be expensive. The development of cost-effective hydrogen production and transportation technologies is critical to the success of hydrogen blending.
- **Hydrogen production and distribution infrastructure:** The development of a hydrogen production and distribution infrastructure is necessary to support the widespread adoption of hydrogen blending. This requires significant investment in renewable energy sources, hydrogen electrolyzers, hydrogen storage, and hydrogen transportation technologies.
- **Regulatory and policy support:** The development of appropriate regulations and policies to support hydrogen blending is necessary to ensure its safe and efficient deployment. This includes the development of standards for hydrogen blending, safety protocols, and the licensing of hydrogen production and distribution activities.

Transportation Sector

Green hydrogen has the potential to decarbonize the transportation sector that is currently reliant on fossil fuels. In the transportation sector, green hydrogen can be used to power fuel cell vehicles, which convert hydrogen into electricity to power the vehicle's electric motor. According to a study by the European Commission, hydrogen fuel cell vehicles could account for up to 14% of new car sales in Europe by 2050. The technology for light-duty fuel cell cars is currently at a mature stage and several Original Equipment Manufacturers (OEMs) such as Toyota, Honda, Hyundai, and General Motors are currently producing and selling fuel cell vehicles. The state-of-the-art technologies in light-duty fuel cell cars include the use of PEM fuel cells and high-pressure hydrogen storage systems. These technologies have enabled the development of fuel cell vehicles with a high driving range, and low emissions.

Captive fleets, such as buses, delivery vans, port and airport ground support equipment, can also rely on green hydrogen as the fuel source. These vehicles typically operate within a specific area and return to a central depot at the end of each day. This makes it feasible to build a hydrogen refueling station at the depot, providing a convenient and reliable source of fuel for the fleet.

Several OEMs such as Toyota, Daimler, Volvo, and Nikola Motors are investing in the development of hydrogen fuel cell trucks. These companies are currently testing and demonstrating prototypes of hydrogen fuel cell trucks, and some have even started to take pre-orders for commercial production. According to a study by the Hydrogen Council, a global CEO-led initiative, it is estimated that by 2030, hydrogen fuel cell trucks could account for around 14% of the global truck market, which is expected to be worth around $230 billion. The study also estimates that by 2050, hydrogen fuel cell trucks could reduce CO_2 emissions by 6 gigatons per year, which is equivalent to taking 1.5 billion cars off the road.

Green hydrogen can also be used as a marine fuel, reducing the carbon emissions of ships and helping the shipping industry to meet its emission reduction targets. According to a study by the International Transport Forum, hydrogen fuel cell ships could reduce CO_2 emissions by up to 90% in comparison to conventional ships. In the aviation sector, green hydrogen has the potential to power aircrafts, as well as to be used in the production of synthetic jet fuels. Several OEMs and startups are investing into designing and piloting vessels and airplanes that could rely on green hydrogen/ammonia as their source of fuel. According to a study by the International Civil Aviation Organization, hydrogen has the potential to reduce the aviation sector's CO_2 emissions by up to 80%.

The use of green hydrogen in the transportation sector faces several challenges, including:

- **Infrastructure:** The development of hydrogen fueling infrastructure is necessary to support the widespread adoption of green hydrogen in the transportation sector. This includes the construction of hydrogen production and fueling stations, as well as the deployment of hydrogen storage and transportation technologies.
- **Cost:** Green hydrogen production and fueling are currently more expensive than traditional fossil fuel-based transportation systems. The development of cost-effective green hydrogen production and fueling technologies, as well as economies of scale in the production and distribution of green hydrogen, is critical to making green hydrogen a viable alternative to fossil fuels in the transportation sector.
- **Fuel cell technology:** The use of green hydrogen in transportation requires the development of advanced fuel cell technologies that can effectively convert hydrogen into electrical energy to power vehicles. These technologies need to be cost-effective, durable, and reliable, and they need to meet the performance requirements of the transportation sector.
- **Regulatory and policy support:** The development of appropriate regulations and policies to support the use of green hydrogen in the

transportation sector is necessary to ensure its safe and efficient deployment. This includes the development of standards for hydrogen fueling, vehicle safety protocols, and the licensing of hydrogen production and distribution activities.

- **Public awareness and perception:** The public perception of green hydrogen as a safe and viable energy source for transportation is critical to its widespread adoption. Raising awareness about the benefits of green hydrogen, including its clean and sustainable characteristics, will be necessary to overcome any public skepticism.

Industry Feedstock

Green hydrogen can be utilized as a feedstock in the production of fertilizer, chemicals, fuels, steel, cement, glass, and microchips. The versatility and scalability of green hydrogen make it a promising solution for reducing the carbon footprint of these industries and advancing towards a more sustainable future. According to a study by the Hydrogen Council, hydrogen has the potential to reduce CO_2 emissions in the industrial sector by up to 6 Gt by 2050.

The use of green hydrogen in the production of fertilizers can help reduce the carbon footprint of this industry, which currently accounts for approximately 2% of global greenhouse gas emissions. In the fertilizer industry, hydrogen is used as a feedstock for the production of ammonia, which is the basic building block for many fertilizers. The process of producing ammonia starts with the reaction of nitrogen from the air with hydrogen to form ammonia, Haber-Bosch process, which traditionally uses natural gas as the source of hydrogen. The ammonia can then be processed further to produce various fertilizers, such as urea and ammonium nitrate. By 2030, the market size for green hydrogen in the fertilizer industry is estimated to reach $3.8 billion.

The chemical industry is one of the largest energy consumers and greenhouse gas emitters, with hydrogen being used in the production of various chemicals such as ammonia and methanol. Green hydrogen has the potential to replace the use of fossil fuels in this industry, leading to significant reductions in carbon emissions. The market size for green hydrogen in the chemicals industry is estimated to reach $17.5 billion by 2050.

In the oil and gas industry and refineries, hydrogen can be used in a variety of processes to improve efficiency, reduce emissions, and upgrade heavy crude oil into lighter products. Some specific applications include hydrotreating, hydrocracking, and hydrogenation. Hydrogen can also be used as a fuel to power operations in the industry, replacing fossil fuels and reducing emissions. The market size for green hydrogen in the oil and gas industry and refineries by 2030 is estimated to reach $18.2 billion.

The steel industry is one of the largest producers of carbon dioxide emissions, with the production of steel using significant amounts of energy and hydrogen. In the steel manufacturing process, green hydrogen can be used to replace as a reducing agent in the production of iron, removing oxygen from the ore to produce pig iron. The use of green hydrogen in this process can reduce the carbon footprint of the steel industry and make it more sustainable. The market size for green hydrogen in the steel industry is estimated to reach $7.3 billion by 2050.

The cement industry is also a significant contributor to global carbon emissions, with the production of cement consuming a large amount of energy. Green hydrogen can be used to heat the kilns used to produce cement clinker, which is then ground into cement powder. The use of green hydrogen in this process can reduce the carbon footprint of the cement industry, making it more sustainable and environmentally friendly. The market size for green hydrogen in the cement industry is estimated to reach $5.2 billion by 2030.

The production of glass requires high temperatures and energy, making it a significant contributor to carbon emissions. Green hydrogen can be used as an energy source in the melting process of glass to heat the furnaces that melt the raw materials into liquid glass. The use of green hydrogen in this process can reduce the carbon footprint of the glass industry and make it more sustainable, as it replaces traditional energy sources such as natural gas. The market size for green hydrogen in the glass industry is estimated to reach $1.9 billion by 2050.

In the microchip industry, hydrogen is used as a reducing agent in the production of silicon wafers, the basic building blocks of microchips. During the process, hydrogen reacts with silicon dioxide to form silicon and water, producing a purified silicon crystal. The use of green hydrogen in this process can help reduce the carbon footprint of the microchip industry, as it replaces traditional hydrogen made from fossil fuels. The market size for green hydrogen in the microchip industry is estimated to reach $3.6 billion by 2030.

The applications of green hydrogen as a feedstock in various industries extend beyond the few examples discussed previously. Although the challenges specific to each industry may differ, the general challenges faced by the transportation and utility sectors are also relevant to these other industries. The challenges facing the wider adoption of green hydrogen in various industries include factors such as the current high cost of production, the lack of scalable production methods, difficulties in storage and transportation due to hydrogen's low density and the need for specialized infrastructure, a shortage of technical expertise in utilizing green hydrogen, and an uncertain policy and regulatory environment. Addressing these challenges will be crucial to expanding the use of green hydrogen as a feedstock in a wider range of industries.

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What is Next?

In conclusion, green hydrogen is considered a versatile and potentially transformative technology in the transition to a low-carbon energy system. Its ability to decarbonize various sectors and to store and transport renewable energy makes it a key player in the energy transition. The global green hydrogen market is expected to reach around $80 billion by 2030, and

over $2.5 trillion by 2050. Despite the potential benefits of green hydrogen, its large-scale production and use are still in their early stages. The cost of producing green hydrogen currently ranges from $3 to $6 per kilogram. This is significantly higher than the cost of hydrogen produced from natural gas, which is around $1 to $2 per kilogram. However, as the technology and economies of scale improve, the cost is expected to decrease to $1 to $2 per kilogram by 2030, making it competitive with hydrogen produced from natural gas. The additional governmental subsidies and incentives in USA and across the world will further enable the cost reduction and technology advancement.