

POWERING THE FUTURE

Exploring the Potential of Hydrogen for a Sustainable Energy Transition

White paper by
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1 OF 3



As the world faces pressing challenges related to climate change, resource depletion, and energy security, the urgency to transition towards sustainable energy systems has never been greater. In this context, hydrogen emerges as a promising candidate for driving this transition. This paper is the first part of a three-part series which highlights the properties of hydrogen, hydrogen as an energy source, and explains the main principles of how a hydrogen fuel cell works.

The hydrogen hype

Hydrogen has captured widespread attention and enthusiasm for compelling reasons, chiefly due to its potential as a clean and adaptable energy carrier. Here are some of the key drivers fueling the excitement surrounding hydrogen:

- **Clean Energy:** Recognized as a pristine energy source, hydrogen yields water vapor as its sole byproduct when employed as a fuel.
- **Decarbonization:** Considered pivotal in efforts to decarbonize diverse sectors of the economy, encompassing transportation, industry, and power generation.
- **Energy Storage:** Hydrogen offers a feasible energy storage solution, facilitating the conversion of surplus renewable energy, such as wind or solar power, through electrolysis.
- **Government Support:** Governments worldwide are actively investing in hydrogen technologies and instituting incentives to foster its uptake and integration.
- **Hydrogen Economy:** Envisioning a future where hydrogen plays a central role in meeting energy demands, the concept of a “hydrogen economy” signifies a transformative shift towards sustainable energy solutions.



Properties of hydrogen

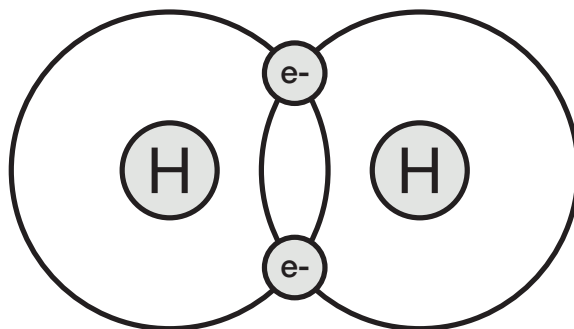


Image 1. Hydrogen Molecule H₂

LIGHTEST AND MOST ABUNDANT ELEMENT

- Extremely buoyant & fast to disperse, 14 times lighter than air
- Colourless, tasteless, odourless & non-toxic
- Low volumetric energy content, unless compressed or liquified
- High energy content by mass

FLAMMABLE WHEN MIXED WITH AIR

- Flammable between 4% and 75% concentration
- Explosive between 18% and 65% concentration
- Low energy but high temperature needed for ignition
- Ventilation needed to remain below flammable concentration

STORED IN LIQUID OR GASEOUS STATE

- Liquified hydrogen (LH₂) temperature -252°C
- Commercially compressed hydrogen typically at 350 bar or 700 bar
- Double wall piping or ventilated ducting

FAST BURNING, INVISIBLE, LOW-TEMP FLAME

- Low heat and IR radiation while burning
- Flame can be detected by UV sensors
- Rapid combustion but low explosive power

Image 2. Properties of Hydrogen



Hydrogen for energy production

Hydrogen has garnered significant interest for energy production due to several reasons:

- **Clean Energy Source:** When hydrogen is used in a fuel cell or combustion engine, the primary byproduct is water vapor in fuel cells. In combustion engines, it can also release near zero trace amounts of CO₂ (from ambient air and lubrication oil) and nitrogen oxides (NO_x). This makes it a clean energy source, especially when produced using renewable energy sources like wind or solar power.
- **Versatility:** Hydrogen can be used in a variety of applications, including transportation (fuel cell vehicles), electricity generation (fuel cells), industrial processes (chemical production), and heating. Its versatility makes it appealing for multiple sectors of the economy.
- **Energy Storage:** Hydrogen can be stored either as a gas or by converting it to other forms like ammonia or liquid organic hydrogen carriers (LOHCs). This makes it a promising candidate for storing excess energy generated from renewable sources when demand is low and supplying it when demand is high.
- **High Energy Density:** Hydrogen has a high energy density by weight, making it attractive for applications where weight is a concern, such as transportation. Typically, hydrogen quantity is measured in kilograms (kg).
 - 1kg of H₂ yields 33.3kWh of useable energy. Where 1kg of diesel yields about 12kWh (*Comparing the Lower Heating Value*)
 - 1kg of H₂ occupies 11.1Nm³ (Nm³ = Normal Cubic Metre at 0°C (273.15°K) and one atmospheric pressure (1.013 bara)

Note: H₂ has a low volumetric energy density (in terms of volume, hydrogen is outperformed by liquid fuels).

- 1Nm³ of H₂ yields 3kWh energy, which is about 0.003kWh/L. Where diesel typically yields 10kWh/L.

- **Decarbonization:** As the world seeks to reduce greenhouse gas emissions and combat climate change, hydrogen is seen as a key component of decarbonizing various sectors of the economy, particularly those that are difficult to electrify directly, such as heavy industry and long-haul transportation.
- **Technological Advancements:** Advances in hydrogen production technologies, such as electrolysis powered by renewable energy, are making hydrogen production more efficient and cost-effective, further driving interest in its use as an energy carrier.
- **Global Interest:** Many countries and regions have announced ambitious hydrogen strategies and investments as part of their efforts to transition to a low-carbon economy. This global interest has further propelled research, development, and deployment of hydrogen technologies.

Hydrogen presents an attractive option for achieving energy security, reducing greenhouse gas emissions, and transitioning to a more sustainable energy future. However, challenges such as cost, infrastructure development, and scaling up production still need to be addressed to realize its full potential.



Hydrogen as a storage medium

Hydrogen is often considered a storage medium because it can store energy in various forms, particularly as a fuel. Here's how hydrogen serves as a storage medium:

1. Chemical Energy Storage

- Hydrogen can be produced through various methods, such as electrolysis (splitting water into hydrogen and oxygen using electricity), steam reforming of natural gas, or biomass gasification.
- This stored chemical energy can be released when hydrogen is used as a fuel in fuel cells or combustion engines.
- When hydrogen reacts with oxygen in a fuel cell, it produces electricity, water, and heat. This electricity can be used to power vehicles, homes, or industries.

2. Renewable Energy Storage

- Hydrogen can act as a means of storing renewable energy, such as solar or wind power, for times when the energy demand exceeds the immediate supply.
- Excess electricity generated from renewable sources can be used to produce hydrogen through electrolysis. This hydrogen can then be stored for later use.
- When energy demand increases or when renewable energy generation is low, hydrogen can be converted back into electricity in fuel cells, providing a reliable source of power.

3. Energy Density

- Hydrogen has a high energy density by weight, which means it can store a large amount of energy per unit mass.
- This makes hydrogen a promising option for applications where energy storage space is limited, such as in vehicles or portable devices.

4. Transportation Fuel

- Hydrogen can be used as a fuel for vehicles, either in fuel cell electric vehicles (FCEVs) or in internal combustion engines.
- FCEVs use hydrogen to produce electricity through a chemical reaction with oxygen in fuel cells, powering electric motors that drive the vehicle.
- Hydrogen-powered vehicles offer the advantage of zero tailpipe emissions, with water vapor being the only byproduct of hydrogen fuel cells and near zero trace amounts of CO₂ and NO_x in hydrogen combustion engines.

In essence, hydrogen serves as a storage medium for energy, particularly renewable energy, offering a versatile and clean alternative to traditional fossil fuels.

Utilizing hydrogen in various industries

Hydrogen is increasingly being recognized as a versatile and sustainable energy carrier with applications across various industries. Here's an overview of some key industries that utilize hydrogen:

- 1. Energy Production:** Hydrogen plays a crucial role in the energy sector, particularly in the production of clean electricity through fuel cells and hydrogen combustion. It can be produced from renewable sources like wind and solar through electrolysis, offering a pathway to store and utilize intermittent renewable energy.
- 2. Transportation:** Hydrogen is gaining traction as a clean alternative fuel for transportation. Hydrogen fuel cell vehicles (FCVs) offer zero-emission transportation solutions, with fast refueling times and long driving ranges, making them suitable for various applications including cars, buses, trucks, trains, and even maritime vessels.
- 3. Chemical Industry:** The chemical industry is a major consumer of hydrogen, using it as a feedstock in various processes. Hydrogen is a key component in the production of ammonia, methanol, and other industrial chemicals. It's also used in refining petroleum products and removing sulfur from fuels.
- 4. Aerospace:** Hydrogen has been explored as a fuel for aerospace applications, particularly in rocket propulsion. Its high energy density and clean combustion make it an attractive option for powering spacecraft and satellites.
- 5. Steel Production:** Hydrogen is increasingly being considered as a cleaner alternative to coke in steelmaking. Direct reduction of iron ore using hydrogen can significantly reduce carbon emissions in the steel industry, paving the way for greener steel production methods.
- 6. Power Generation:** Hydrogen can be used in gas turbines to generate electricity, either through combustion or in combination with other fuels in advanced power generation systems like integrated gasification combined cycle (IGCC) plants. This offers a flexible and low-carbon option for power generation.
- 7. Energy Storage:** Hydrogen has the potential to serve as a means of long-term energy storage, complementing intermittent renewable energy sources. Excess energy from renewable sources can be used to produce hydrogen via electrolysis, which can then be stored and converted back into electricity or other forms of energy as needed.
- 8. Fertilizer Production:** The Haber-Bosch process, which is used to produce ammonia for fertilizer production, relies on hydrogen as a key reactant. Hydrogen is combined with nitrogen extracted from the air to produce ammonia, which is then used to make various fertilizers essential for agriculture.
- 9. Electronics Industry:** Hydrogen is used in the electronics industry for various applications, including semiconductor manufacturing and the production of flat-panel displays. It is employed in processes such as epitaxy and annealing, contributing to the production of advanced electronic devices.

These industries collectively illustrate the diverse range of applications for hydrogen across different sectors, highlighting its potential to drive a transition towards a more sustainable and low-carbon economy.

Utilizing hydrogen in a fuel cell

A hydrogen fuel cell works by converting the chemical energy stored in hydrogen into electrical energy through an electrochemical reaction. Unlike combustion engines, fuel cells operate without combustion, continuously generating direct current (DC) voltage as long as fuel and oxygen are provided. Here's a simplified explanation of the process of Polymer Electrolyte Membrane (PEM) fuel cell: (see image 3)

- 1. Hydrogen Gas Supply:** Pure hydrogen gas (H_2) is supplied to the anode (negative electrode) of the fuel cell.
- 2. Oxygen Supply:** Oxygen gas (O_2) from the air is supplied to the cathode (positive electrode) of the fuel cell.
- 3. Electrochemical Reaction:** At the anode, hydrogen molecules are split into protons (H^+) and electrons (e^-) through a process called electrolysis: $2H_2 \rightarrow 4H^+ + 4e^-$

The protons migrate through an electrolyte membrane to the cathode, while the electrons flow through an external circuit, creating an electrical current that can be used to power devices.

- 4. Reaction at the Cathode:** At the cathode, the protons and electrons combine with oxygen from the air to produce water vapor (H_2O) as the only byproduct: $4H^+ + 4e^- + O_2 \rightarrow 2H_2O$
- 5. Electrical Output:** The flow of electrons through the external circuit generates electrical energy that can be used to power electric motors, lights, or any other electrical devices connected to the fuel cell.

It's imperative to recognize that a fuel cell operates primarily as a current source rather than a voltage source. Typically, a single fuel cell maintains a voltage of around 0.6 to 0.8 volts, although this voltage diminishes over time with usage. Consequently, to sustain the requisite power output demanded by the load, the current must increase proportionally as the fuel cell ages. To achieve a higher DC output voltage, fuel cells are often stacked in series, a concept to be elaborated upon in the second installment of this paper series.

Overall, the hydrogen fuel cell generates electricity with high efficiency and minimal environmental impact, as the only emissions produced are water vapor and heat. This makes it a promising technology for powering various applications, including vehicles, stationary power generation, and portable electronics.

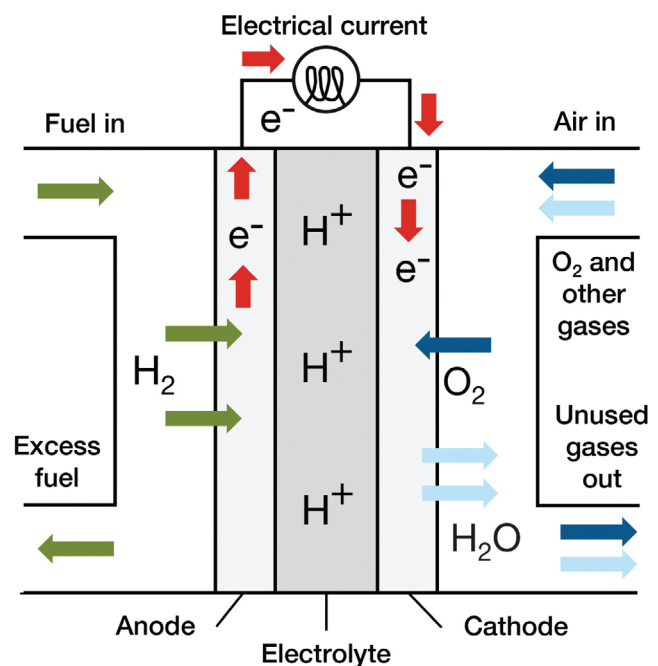


Image 3. PEM fuel cell

Fuel cell types comparison

Different fuel cell types are distinguished by the functional membrane materials used. These different membrane materials contribute to the unique operating characteristics and performance of each fuel cell type, making them suitable for various applications across different temperature ranges and operating conditions. Image 4 outlines some of the characteristics of these different fuel cell technologies.

Fuel Cell Type	Pros	Cons	Typical Applications	Operating Temperature Range	Efficiency	Startup Time
PEMFC (Proton Exchange Membrane Fuel Cell)	<ul style="list-style-type: none"> High power density Fast start-up time Low operating temperature 	<ul style="list-style-type: none"> Requires pure hydrogen fuel Sensitivity to impurities in hydrogen fuel Expensive catalysts 	<ul style="list-style-type: none"> Transportation (e.g. cars) Portable electronics Backup power systems Prime power systems 	Operates at 60°C-120°C	45 - 55%	< 1 minute
DMFC (Direct Methanol Fuel Cell)	<ul style="list-style-type: none"> Can use methanol as fuel Simpler fuel storage and handling Quiet operation 	<ul style="list-style-type: none"> Low power density Slower reaction kinetics Methanol crossover Limited Lifespan 	<ul style="list-style-type: none"> Portable electronics Packup power systems 	Operates at 60°C-130°C	20 - 25%	< 5 minutes
SOFC (Solid Oxide Fuel Cell)	<ul style="list-style-type: none"> High efficiency Fuel flexibility (can use various hydrocarbons) Long lifespan Reduced emissions 	<ul style="list-style-type: none"> High operating temperature Slow start-up time Mechanical fragility Susceptibility to fuel impurities 	<ul style="list-style-type: none"> Stationary power generation Remote power generation Micro combined heat and power (CHP) 	Operates at 800°C-1000°C	45 - 60%	60 minutes
PAFC (Phosphoric Acid Fuel Cell)	<ul style="list-style-type: none"> High efficiency Tolerant to carbon monoxide Long lifespan Mature technology 	<ul style="list-style-type: none"> Sensitive to fuel impurities Bulky and heavy Relatively low power density Requires pure hydrogen or reformat gas 	<ul style="list-style-type: none"> Stationary power generation Cogeneration (heat and power) Hospitals and universities Wastewater treatment plants 	Operates at 150°C-220°C	40 - 45%	1 to several hours

Image 4. Fuel cell types comparison

Summary

“Powering the Future (1 of 3): Exploring The Potential Of Hydrogen For A Sustainable Energy Transition” presents a comprehensive overview of hydrogen’s potential as a key player in the shift towards sustainable energy systems. The paper emphasizes hydrogen’s appeal as a clean, versatile, and efficient energy carrier, highlighting its role in decarbonization, energy storage, and various industrial applications.

Hydrogen’s allure stems from its status as a pristine energy source, emitting only water vapor when utilized as fuel in fuel cells, thus aiding in efforts to combat climate change and reduce greenhouse gas emissions. Governments worldwide are backing hydrogen technologies with investments and incentives, envisioning a future driven by a “hydrogen economy.”

Key properties of hydrogen, including its abundance, low toxicity, and high energy content by mass, make it an attractive option for a wide array of applications. However, its flammability and storage challenges necessitate careful handling and infrastructure development.

The paper delves into hydrogen’s role in energy production, emphasizing its cleanliness, versatility, and high energy density. Advances in production technologies, such as electrolysis powered by renewables, are driving interest in hydrogen as a decarbonization tool across industries.

Hydrogen serves as a potent energy storage medium, capable of storing renewable energy for future use through various methods like electrolysis. Its high energy density and zero-emission characteristics make it ideal for transportation, electricity generation, and industrial processes.

The versatility of hydrogen finds applications across diverse industries, from energy production and transportation to aerospace and electronics. Its potential to drive a transition to a low-carbon economy is evident in its adoption in steel production, power generation, and even fertilizer manufacturing.

The paper concludes by exploring hydrogen fuel cells, which convert hydrogen’s chemical energy into electricity with high efficiency and minimal environmental impact. Different fuel cell types cater to various applications, offering flexibility across different temperature ranges and operating conditions.

Overall, “Powering the Future (1 of 3)” presents hydrogen as a promising solution to the pressing challenges of climate change, resource depletion, and energy security, laying the groundwork for a sustainable energy future.

About the author



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Hassan Obeid is a Global Technical Sales Leader – New Energy Solutions at Cummins Inc., focusing on technical vision, business strategy, and solving a wide range of complex problems. Hassan has been with Cummins since 2007 in various roles, including global technical advising, power systems design engineering, project engineering, and applications engineering. He has designed power systems involving switchgear, controls, paralleling, BESS, PEM hydrogen fuel cells, transfer switches, generator sets, DERs, microgrids, and digital solutions. Additionally, Hassan has developed and conducted technical power seminars on several topics and products, including BESS, PEM hydrogen fuel cells, paralleling, grounding, power systems, and controls. He holds a bachelor's degree in Computer Science and a master's degree in Electrical Engineering from Minnesota State University, Mankato.



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