



*An Online CPD Course
brought to you by
CEDengineering.ca*

Hydrogen and Fuel Cells

Course No: R08-003

Credit: 8 PDH

Elie Tawil, P.E., LEED AP



Continuing Education and Development, Inc.

P: (877) 322-5800

info@cedengineering.ca

*This course was adapted from the United States Department of Energy website, Office of Energy Efficiency and Renewable Energy:
<https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>*

Table of Contents

Hydrogen and Fuel Cell Technologies Office.....	1
Key Activities	1
Research, Development, and Demonstration.....	1
Advisory Panels for the DOE's Hydrogen Program	2
The DOE's Lab-Led Consortia Approach.....	3
H2@Scale	3
Systems Integration.....	4
Partnerships and International Activities	4
Plans, Implementation & Results.....	5
Overview.....	5
Accomplishments.....	5
Hydrogen Uses.....	6
Hydrogen Production	6
The Importance of Studying Hydrogen Production.....	7
Hydrogen Production Pathways.....	7
Research and Development Goals	8
Hydrogen Resources: From Diverse Domestic Resources to Emerging Technologies.....	8
Hydrogen Production Processes	12
1. Thermal Processes for Hydrogen Production	12
2. Electrolytic Processes	22
3. Biological Processes	34
Hydrogen Delivery	38
The Importance of Studying Hydrogen Delivery	38
How Hydrogen Delivery Works	38
Research and Development Goals	39
Challenges.....	39
Hydrogen Delivery, On-site Storage, And Dispensing Technologies	40
Gaseous Hydrogen Delivery	40
Gaseous hydrogen compression.....	41

Liquid Hydrogen Delivery	45
On-Site and Bulk Hydrogen Storage	47
Dispensing Hydrogen Fuel to Vehicles	50
Hydrogen Storage	52
The Importance of Studying Hydrogen Storage	52
How Hydrogen Storage Works	52
Research and Development Goals	53
Challenges.....	54
Physical Hydrogen Storage.....	56
Fuel Cells.....	59
The Importance of Studying Fuel Cells	59
How Fuel Cells Work	60
Research and Development Goals	60
Parts of a Fuel Cell.....	61
Fuel Cell Systems	64
Fuel Cell Types.....	66
References	71

List of Figures

Figure 1. Hydrogen Production.....	7
Figure 2. Natural Gas Reforming.....	14
Figure 3. Concentrating sunlight onto a reactor tower using a field of mirror heliostats	20
Figure 4. Two examples of thermochemical water splitting cycles.....	21
Figure 5. Electrolysis	24
Figure 6. PEC reactor approaches.....	29
Figure 7. PEC reactor design schemes.....	30
Figure 8. Microbial electrolysis cells (MECs).....	36
Figure 9. Electrochemical compressors.....	42
Figure 10. Metal hydride compressor.....	42
Figure 11. Tube Trailer.....	43
Figure 12. Pipelines	44

Figure 13. Hydrogen Liquefier	45
Figure 14. Liquid Tanker	46
Figure 15. Type I hydrogen storage cylinder.....	48
Figure 16. Cryogenic liquid hydrogen storage tank.....	49
Figure 17. Potential Geologic Storage Areas in the U.S. For Hydrogen.....	50
Figure 18. Hydrogen Storage.....	53
Figure 19. 2010 U.S. light-duty vehicle sales distribution by driving range.....	54
Figure 20. Comparison of specific energy (energy per mass or gravimetric density) and energy density (energy per volume or volumetric density) for several fuels based on lower heating values.	55
Figure 21. Components of a Pressurized Hydrogen Storage Tank.....	56

List of Tables

Table 1 The four types of common high pressure gaseous storage vessels.....	48
---	----

Hydrogen and Fuel Cell Technologies Office

The U.S. Department of Energy's (DOE) Hydrogen and Fuel Cell Technologies Office (HFTO) is at the forefront of driving critical advancements in clean energy solutions. Through comprehensive, strategic efforts, the HFTO is working to overcome the technological, economical, and institutional barriers that have historically hindered the widespread adoption of hydrogen and fuel cell technologies.

Aligned closely with the DOE's overarching vision and goals, the HFTO's work aims to secure America's leadership in the development and deployment of transformative clean energy innovations. By making targeted investments and coordinating multi-stakeholder collaboration, the office is poised to bolster the nation's economic competitiveness and scientific prowess in this rapidly evolving field.

This course will provide students with an in-depth understanding of the HFTO's pivotal role in accelerating the hydrogen economy. We will explore the office's work across several key areas, including hydrogen production, storage, distribution, and the advancement of fuel cell applications for transportation, stationary power, and beyond. Through a combination of lectures, case studies, and hands-on activities, students will gain insights into the technical, policy, and market factors shaping the future of this transformative energy technology.

By the end of this course, students will be equipped with a comprehensive understanding of the HFTO's comprehensive efforts to unlock the potential of hydrogen and fuel cells, and their critical contribution towards a sustainable, clean energy future.

Key Activities

Research, Development, and Demonstration

Key areas of research, development, and demonstration (RD&D) include the following:

- Fuel cell R&D, which seeks to improve the durability, reduce the cost, and improve the performance of fuel cell systems, through advances in fuel cell stack and balance of plant components
- Hydrogen fuel R&D, which focuses on enabling the production of low-cost hydrogen fuel from diverse renewable pathways and addressing key challenges to hydrogen delivery and storage
- Manufacturing R&D, which works to develop and demonstrate advanced manufacturing technologies and processes that will reduce the cost of fuel cell systems and hydrogen technologies

- Technology validation, which demonstrates and validates pre-commercial technologies before the deployment phase.

To ensure that advances in the laboratory can be realized in the marketplace, the Hydrogen and Fuel Cell Technologies Office conducts a range of activities to address economic and institutional barriers:

- Education and outreach activities aim to increase public awareness and understanding of the technologies, facilitating the implementation of near-term demonstration projects and early market fuel cell installations, while easing the way for long-term market adoption.
- Market transformation activities provide financial and technical assistance for the use of hydrogen and fuel cell systems in early market applications, with the goals of:
 - Achieving sales volumes that will enable cost reductions through economies of scale,
 - supporting the development of a domestic industry, and
 - providing feedback to testing programs, manufacturers, and potential technology users.

Advisory Panels for the DOE's Hydrogen Program

The U.S. Department of Energy's (DOE) Hydrogen Program benefits from the technical and strategic guidance of two key advisory panels: the National Research Council (NRC) and the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC).

Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)

Established under the Energy Policy Act of 2005, the HTAC is a critical advisory body that provides the Energy Secretary with expert insights on the development of hydrogen and fuel cell technologies. Convened in June 2006, the committee's members offer their specialized knowledge and recommendations to help drive progress in this dynamic field.

National Research Council (NRC)

As directed by the Energy Policy Act of 2005, the National Academy of Sciences, through its National Research Council (NRC), conducts a comprehensive review of the DOE Hydrogen Program's research and demonstration efforts every four years. This independent assessment leverages the multidisciplinary expertise of the NRC, which is jointly administered by the National Academy of Science, the National Academy of Engineering, and the Institute of Medicine.

Both the HTAC and NRC play pivotal roles in shaping the strategic direction and technical priorities of the DOE Hydrogen Program. By providing expert guidance and impartial analysis, these advisory panels help ensure the program's initiatives are aligned with the latest scientific advancements and industry needs. Students enrolled in this course will have the opportunity to

explore the valuable contributions of these advisory bodies and their impact on the hydrogen economy.

The DOE's Lab-Led Consortia Approach

A core component of the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cell Technologies Office (HFTO) strategy is its support for lab-led research and development (R&D) consortia. These collaborative initiatives bring together the vast expertise and capabilities of the national laboratory system to drive coordinated advancements in hydrogen and fuel cell technologies.

By funding these lab-led consortia, the HFTO is able to leverage the specialized knowledge and cutting-edge facilities of the national laboratories. These consortia serve as a vital resource for universities, industry partners, and other stakeholders, facilitating the exchange of ideas and accelerating the translation of innovative concepts into real-world applications.

Through this collaborative approach, the HFTO is able to tackle the complex, multifaceted challenges inherent in developing hydrogen and fuel cell technologies. The synergies created by these lab-led consortia enable the integration of research across disciplines, ensuring a holistic, systems-level approach to problem-solving.

H2@Scale

At the heart of the U.S. Department of Energy's (DOE) efforts to advance the hydrogen economy is the transformative H2@Scale initiative. This groundbreaking program brings together a diverse array of stakeholders – from national laboratories to industry partners – to address the complex challenges of affordable hydrogen production, transportation, storage, and utilization.

H2@Scale serves as a collaborative framework, enabling national laboratories and private sector entities to work in tandem on government co-funded projects. This strategic approach accelerates the research, development, and demonstration of innovative hydrogen technologies, unlocking new revenue opportunities across multiple energy sectors.

By fostering this cross-cutting collaboration, H2@Scale harnesses the collective expertise and resources of the scientific and industrial communities. This synergistic model allows for the rapid advancement of technologies that can unlock the full potential of hydrogen as a clean, versatile energy carrier.

Through H2@Scale, the DOE is pioneering a new paradigm in energy research and development, one that transcends traditional siloes and catalyzes transformative solutions.

Systems Integration

The U.S. Department of Energy's (DOE) Hydrogen Program encompasses a breadth and complexity of research, development, and demonstration (RD&D) efforts that demand an integrated, systems-level approach. By recognizing the intricate interactions and dependencies between the program's various elements, the DOE can strategically navigate the inherent risks and maximize the potential for transformative success.

At the core of this integrated approach is the focus on systems integration. This critical component involves understanding the complex interdependencies among the program's diverse focus areas, components, and the trade-offs that must be carefully navigated. By adopting a holistic perspective, the DOE can better coordinate its RD&D activities, ensuring the synergistic advancement of hydrogen production, storage, distribution, and end-use applications.

This systems-level integration is essential for overcoming the technological, economic, and institutional barriers that have historically hindered the widespread adoption of hydrogen energy solutions. By aligning the program's various elements, the DOE can leverage the collective impact of its investments, accelerating the development and deployment of cutting-edge hydrogen technologies.

Partnerships and International Activities

As the world navigates the transition to a more sustainable energy future, cooperative research and development (R&D) on hydrogen and fuel cell technologies will play a pivotal role. By fostering strategic partnerships and aligning global efforts, the path to widespread adoption of these transformative solutions is being paved.

At the forefront of this collaborative approach is the H2USA initiative, a public-private partnership dedicated to tackling the key challenges of hydrogen infrastructure development. By bringing together government agencies, industry leaders, and other stakeholders, H2USA is driving progress in areas such as production, distribution, and fueling station deployment.

Beyond the national level, international cooperation is also crucial. Through the International Energy Agency (IEA), member countries from around the globe are working together to address the technological, financial, and institutional barriers that have historically hindered the commercialization of hydrogen and fuel cell technologies.

Further complementing these efforts is the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), a multinational collaboration that coordinates research, development, and deployment programs. By aligning global priorities and resources, the IPHE is accelerating the transition to a hydrogen-powered future.

Plans, Implementation & Results

The U.S. Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office (HFTO) in the Office of Energy Efficiency and Renewable Energy (EERE) carries out technology research, development, and demonstration through an ongoing process of planning and analysis, implementation, and review.

Overview

The Hydrogen and Fuel Cell Technologies Office (HFTO) leads federal efforts to promote the commercial viability of hydrogen and fuel cell technologies through a comprehensive portfolio of research, development, and demonstration initiatives.

The HFTO also spearheads a range of enabling activities, such as advancing manufacturing capabilities, establishing safety protocols and industry standards, and cultivating a skilled workforce. These complementary efforts further support the widespread deployment and market adoption of hydrogen and fuel cell solutions.

Ultimately, the HFTO's multifaceted approach is designed to help realize a clean, equitable energy future. By driving innovation and building a robust domestic economy, the office is paving the way for the large-scale commercialization and integration of these transformative technologies.

Accomplishments

The Hydrogen and Fuel Cell Technologies Office (HFTO) spearheads federal initiatives to advance the commercial viability of hydrogen and fuel cell technologies through a comprehensive portfolio of research, development, and demonstration projects.

In addition to these core R&D activities, the HFTO also undertakes a range of enabling efforts in areas such as manufacturing processes, safety protocols, industry standards, and workforce development. These complementary initiatives further support the widespread deployment and market adoption of these transformative energy solutions.

Ultimately, the HFTO's multifaceted approach aims to help realize a clean, equitable energy future. By driving innovation and fostering a robust domestic economy, the office is paving the way for the large-scale commercialization and integration of hydrogen and fuel cell technologies.

Hydrogen Uses

Hydrogen can be used to power vehicles, generate electricity, power industry and heat our homes and businesses. It could make a huge difference to our carbon emissions and will be critical to achieving net zero. Hydrogen is a clean alternative to methane, also known as natural gas. It's the most abundant chemical element, estimated to contribute 75% of the mass of the universe. Hydrogen can be produced from a variety of resources, such as natural gas, nuclear power, biogas and renewable power like solar and wind. The challenge is harnessing hydrogen as a gas on a large scale to fuel our homes and businesses. The hydrogen produced can be differentiated in to two types depending on the production method:

- Blue hydrogen is produced using natural gas as a feedstock by using one of two primary methods: Steam methane reformation is the most common method for producing bulk hydrogen and accounts for most of the world's production. This method uses a reformer, which reacts steam at a high temperature and pressure with methane and a nickel catalyst to form hydrogen and carbon monoxide (CO). Autothermal reforming uses oxygen and carbon dioxide (CO₂) or steam to react with methane to form hydrogen. The downside of these two methods is that they produce carbon as a by-product, so carbon capture and storage (CCS) is essential to trap and store this carbon.
- Green hydrogen is produced by using electricity to power an electrolyser that splits the hydrogen from water molecules. This process produces pure hydrogen, with no harmful by-products. An added benefit is that, because this method uses electricity, it also offers the potential to divert any excess electricity – which is hard to store (like surplus wind power) – to electrolysis, using it to create hydrogen gas that can be stored for future energy needs.

Hydrogen Production

Hydrogen is the simplest element on earth—it consists of only one proton and one electron—and it is an energy carrier, not an energy source.

Hydrogen can store and deliver usable energy, but it doesn't typically exist by itself in nature and must be produced from compounds that contain it.

- CCUS: carbon capture, utilization, and storage
- SMR: steam methane reforming
- ADG: anaerobic digester gas
- STCH: solar thermochemical hydrogen
- PEC: photoelectrochemical



Figure 1. Hydrogen Production

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

The Importance of Studying Hydrogen Production

The United States currently produces around 10 million metric tons (MMT) of hydrogen annually, with the majority of this demand coming from the petroleum refining and ammonia production industries. However, the potential applications of hydrogen extend far beyond these traditional sectors.

Hydrogen can be leveraged across a diverse array of industries to enable the transition to zero or near-zero emissions. Emerging hydrogen markets are taking shape in areas such as data centers, port operations, steel manufacturing, and medium- to heavy-duty transportation.

As the energy landscape evolves, these emerging hydrogen applications are poised to play a vital role in the development of integrated clean energy systems. By harnessing the versatility of hydrogen, industries can unlock new pathways to decarbonization and contribute to a more sustainable, equitable future.

The HFTO's multifaceted efforts aim to accelerate the commercialization and widespread adoption of hydrogen solutions, unlocking their transformative potential across the economy. By fostering innovation and collaboration, the office is driving the expansion of hydrogen's role in the clean energy transition.

Hydrogen Production Pathways

The United States has access to a diverse array of domestic resources that can be leveraged to produce hydrogen through low-carbon pathways:

- Fossil fuels, such as natural gas and coal, coupled with carbon capture and storage technologies
- Nuclear energy

- Renewable energy sources, including wind, solar, geothermal, and hydroelectric power
- Biomass, through biological processes

This versatility in hydrogen production allows for the integration of multiple energy sources and the development of comprehensive, sustainable hydrogen ecosystems. By harnessing these diverse pathways, the HFTO is working to expand the role of hydrogen in the clean energy transition and enable a decarbonized future.

Research and Development Goals

The U.S. Department of Energy (DOE) is spearheading efforts to develop a wide range of technologies that can produce hydrogen economically and via net-zero-carbon pathways. This is a critical challenge, as the overall cost of hydrogen production is a significant barrier to its widespread adoption.

The DOE's Hydrogen and Fuel Cell Technologies Office is focused on achieving the Hydrogen Energy Earth shot goal of reducing the cost of clean hydrogen by 80% to \$1 per 1 kilogram in 1 decade. Specifically, the office is working towards producing hydrogen at \$2/kg by 2026 and \$1/kg by 2031 via net-zero-carbon pathways.

Currently, most hydrogen in the United States is produced through large-scale natural gas reforming without carbon capture and storage. While this established technology has the potential to reach the cost targets, the goal is to achieve these targets through low-carbon production pathways.

To address this, the DOE is supporting the research and development of various technologies, including:

- Near- and mid-term: Electrolysis pathways, where electricity is used to split water into hydrogen and oxygen, are anticipated to begin reaching the cost targets.
- Mid- to long-term: Innovative approaches, such as those using waste streams and solar energy-based methods, are expected to become viable options for economical, net-zero-carbon hydrogen production.

By investing in this diverse portfolio of technological solutions, the DOE is working to unlock the full potential of hydrogen as a clean energy carrier and enable its widespread adoption across the economy.

Hydrogen Resources: From Diverse Domestic Resources to Emerging Technologies

Hydrogen can be produced from a wide range of domestic resources, allowing for the development of comprehensive, sustainable hydrogen ecosystems. Currently, most hydrogen is produced from fossil fuels, particularly natural gas. Additionally, electricity—sourced from the grid or from

renewable energy sources like wind, solar, geothermal, and biomass—is also utilized for hydrogen production.

However, as the energy landscape evolves, the longer-term outlook for hydrogen production is poised to shift. In the mid- to long-term, more direct methods of generating hydrogen from solar energy and biomass are expected to become viable options. These emerging technologies hold the potential to further diversify the hydrogen production landscape and enable the transition to net-zero-carbon pathways.

By harnessing the versatility of domestic resources and fostering the development of innovative production methods, the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office is working to unlock the full potential of hydrogen as a clean energy carrier. This multifaceted approach aims to support the widespread adoption of hydrogen solutions and drive the clean energy transition.

Natural Gas and Other Fossil Fuels

Fossil fuels, such as natural gas and coal, can be reformed to release the hydrogen contained within their hydrocarbon molecules. This is currently the primary source of hydrogen production in the United States, accounting for 95% of total hydrogen generated.

Natural gas reforming, in particular, is an advanced and mature hydrogen production process that leverages the existing natural gas infrastructure. This makes it an important near-term pathway for scaling up hydrogen availability.

However, the carbon dioxide emissions associated with fossil fuel-based hydrogen production are a significant concern. To address this, the Department of Energy is supporting the development and deployment of carbon capture, utilization, and storage (CCUS) technologies. By integrating CCUS with fossil fuel-based hydrogen production, the carbon dioxide emissions can be reduced, moving towards a lower-carbon hydrogen future.

While fossil fuel-based hydrogen production with CCUS is a crucial near-term solution, the Department of Energy is also investing in the research and development of alternative, lower-carbon hydrogen production pathways. These emerging technologies, which leverage renewable energy sources and innovative processes, will be essential for achieving the long-term goals of widespread, affordable, and sustainable hydrogen availability.

Solar Energy

Sunlight can be leveraged as an energy source to produce hydrogen, either directly or indirectly. This presents an attractive option, as solar energy is an abundant and renewable resource.

However, the diffuse nature of sunlight and its intermittent availability, only being present for a portion of the day, pose challenges for utilizing it as the sole energy source for hydrogen production. This intermittent and low energy density of solar radiation require the development of efficient and cost-effective technologies to harness this energy effectively.

To address these challenges, the Department of Energy is supporting research and development into innovative solar-based hydrogen production pathways. This includes exploring direct solar-to-hydrogen conversion through processes like photoelectrochemical water splitting, as well as indirect methods that integrate solar energy with other technologies, such as electrolysis or thermochemical water splitting.

By overcoming the technical and economic barriers associated with solar-based hydrogen production, the Department of Energy aims to unlock the full potential of this renewable energy source in the hydrogen economy. Integrating solar energy with hydrogen generation can help drive the transition towards a more sustainable and diversified hydrogen supply.

Biomass

Biomass, derived from organic materials such as agricultural waste, forestry residues, and dedicated energy crops, represents an abundant and renewable resource that can be leveraged for domestic hydrogen production. This resource can be converted into hydrogen and other valuable byproducts through a variety of processing methods.

A key advantage of biomass-based hydrogen production is its potential to achieve low net carbon emissions. As biomass is grown, it captures carbon dioxide from the atmosphere, and this carbon can be effectively sequestered when the biomass is converted into hydrogen and other products. This closed-loop, carbon-neutral approach aligns with the Department of Energy's goals of developing sustainable, net-zero-carbon hydrogen pathways.

By harnessing the versatility and domestic availability of biomass, the Department of Energy is supporting the research and development of innovative biomass-to-hydrogen technologies. These include thermochemical, biochemical, and hybrid processes that can unlock the hydrogen potential of this renewable resource.

Integrating biomass-based hydrogen production into the broader hydrogen ecosystem can help diversify the supply, enhance domestic energy security, and contribute to the transition towards a more sustainable and environmentally friendly energy future.

Wind

Wind energy represents an abundant, yet variable, renewable resource for electricity generation. While the intermittent nature of wind power presents challenges, the Department of Energy is exploring ways to harness this resource for the production and storage of hydrogen.

One promising approach is to utilize wind-generated electricity to power water electrolysis, a process that splits water molecules into hydrogen and oxygen. The resulting hydrogen can then be used to fuel vehicles or stored for later use. This stored hydrogen can be leveraged in fuel cells to generate electricity during periods when the wind resource is low, providing a complementary solution to the variability of wind power.

By integrating wind power with hydrogen production and storage, the Department of Energy aims to create a more resilient and flexible energy system. This approach can help overcome the inherent variability of wind resources, allowing for the efficient and reliable production and utilization of clean hydrogen.

The development of technologies that seamlessly integrate wind power and hydrogen production is a key focus area for the Department of Energy. By capitalizing on the synergies between these two renewable energy sources, the Department is working to unlock the full potential of wind-powered hydrogen and contribute to the broader transition towards a sustainable, low-carbon energy future.

Renewable and Grid Electricity

One of the most well-established methods for producing hydrogen is through the process of electrolysis. This technology uses electricity to split water molecules into their constituent elements: hydrogen and oxygen.

Electrolysis systems are commercially available and continue to undergo technological advancements. Of particular interest are electrolysis systems that can efficiently utilize renewable sources of electricity, such as wind, geothermal, or solar power, to generate hydrogen.

By harnessing renewable electricity to power the electrolysis process, the Department of Energy is working to develop a more sustainable and environmentally friendly pathway for hydrogen production. This approach can help reduce the carbon footprint associated with hydrogen generation and contribute to the broader transition towards a clean energy economy.

The Department of Energy is supporting research and development efforts to improve the efficiency, scalability, and cost-competitiveness of renewable-powered electrolysis technologies. This includes exploring innovative electrolyzer designs, advanced materials, and integrated system configurations that can seamlessly integrate with intermittent renewable energy sources.

As the renewable energy landscape continues to evolve, the ability to leverage electricity from wind, solar, geothermal, and other clean sources to produce hydrogen holds significant promise. The Department of Energy's focus on advancing electrolysis technology is a critical step towards realizing a more diverse and sustainable hydrogen supply.

Hydrogen Production Processes

Hydrogen can be generated through a diverse array of production processes, each with its own unique advantages and considerations.

Thermochemical processes leverage heat and chemical reactions to extract hydrogen from organic feedstocks, such as fossil fuels and biomass. By harnessing the inherent hydrogen content in these materials, thermochemical methods offer a scalable pathway for hydrogen production.

Alternatively, water (H_2O) can be split into its constituent elements - hydrogen (H_2) and oxygen (O_2) - through the application of electricity in the process of electrolysis. This approach is particularly compelling when the electricity is derived from renewable energy sources, enabling the production of clean, low-carbon hydrogen.

Beyond these thermal and electrical methods, biological processes involving microorganisms, including bacteria and algae, can also generate hydrogen through their metabolic activities. These biologically driven pathways present opportunities for innovative hydrogen production solutions.

1. Thermal Processes for Hydrogen Production

Thermal processes leverage the energy content of various feedstocks, such as natural gas, coal, or biomass, to extract hydrogen from their molecular structure. Additionally, some thermal processes utilize heat in combination with closed-chemical cycles to produce hydrogen directly from materials like water.

The Department of Energy is exploring several key thermochemical pathways for hydrogen generation, including:

1. Natural gas reforming (also known as steam methane reforming or SMR): This process uses heat and steam to extract hydrogen from natural gas.
2. Biomass gasification: Heat is applied to biomass feedstocks to generate hydrogen-rich syngas.
3. Biomass-derived liquid reforming: Liquid fuels derived from biomass are reformed using heat to produce hydrogen.
4. Solar thermochemical hydrogen (STCH): Concentrated solar energy is used to drive high-temperature, closed-loop chemical cycles that split water molecules to generate hydrogen.

By advancing these thermal hydrogen production technologies, the Department of Energy aims to diversify the hydrogen supply and capitalize on the energy-dense nature of various fossil and renewable feedstocks.

Natural Gas Reforming

How Does It Work?

One of the key thermal processes for generating hydrogen is natural gas reforming. This method leverages the methane (CH₄) content of natural gas as feedstock.

The primary approach is steam-methane reformation, which utilizes high-temperature steam to extract hydrogen from the methane molecules. In this endothermic process, methane and steam react to produce hydrogen, carbon monoxide, and other byproducts.

Alternatively, the partial oxidation of natural gas can also be used to produce hydrogen. This exothermic process involves the controlled combustion of methane with limited oxygen, generating a hydrogen-rich synthesis gas.

Both steam-methane reformation and partial oxidation leverage the inherent hydrogen content of natural gas to create a valuable hydrogen stream that can be further purified and utilized. These natural gas-based pathways are well-established and widely deployed in industrial applications.

Steam-Methane Reforming

Steam-methane reforming is the most widely used method for producing hydrogen in the United States today. This mature process involves the use of high-temperature steam (700°C to 1,000°C) to extract hydrogen from a methane source, typically natural gas.

In the steam-methane reforming reaction, methane (CH₄) reacts with the steam under moderate pressure (3-25 bar) in the presence of a catalyst. This endothermic process generates a stream of hydrogen, carbon monoxide, and a small amount of carbon dioxide.

Carbon monoxide is then converted to additional hydrogen through the water-gas shift reaction, where the carbon monoxide and steam are catalytically reacted to produce carbon dioxide and more hydrogen.

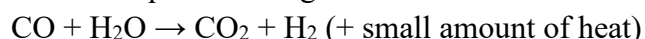
Finally, a pressure-swing adsorption step is used to remove the carbon dioxide and other impurities, yielding a stream of nearly pure hydrogen.

Beyond natural gas, steam reforming can also be applied to other hydrocarbon fuels, such as ethanol, propane, or even gasoline, to produce hydrogen.

The steam-methane reforming reaction can be summarized as follows:



The subsequent water-gas shift reaction is:



By optimizing these thermal processes, the Department of Energy aims to continue improving the efficiency, cost-effectiveness, and environmental performance of steam-methane reforming for large-scale hydrogen production.

Although today most hydrogen is produced from natural gas; the Hydrogen and Fuel Cell Technologies Office is exploring a variety of ways to produce hydrogen from renewable resources.



Figure 2. Natural Gas Reforming

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Partial Oxidation

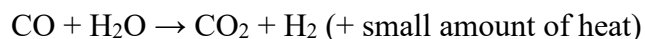
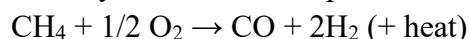
In the partial oxidation process for hydrogen production, the methane and other hydrocarbons in natural gas undergo a reaction with a limited amount of oxygen, typically from air. This controlled combustion is carried out with less than the stoichiometric amount of oxygen required for complete oxidation to carbon dioxide and water.

With the oxygen supply constrained, the primary reaction products are hydrogen and carbon monoxide, along with smaller amounts of carbon dioxide and other compounds. The process also produces nitrogen if air is used as the oxygen source, rather than pure oxygen.

In a subsequent step, the water-gas shift reaction is used to convert the carbon monoxide into additional hydrogen and carbon dioxide. This exothermic reaction involves the catalytic interaction of carbon monoxide and steam.

Compared to steam-methane reforming, the partial oxidation process is generally faster and requires a smaller reactor vessel, as it is an exothermic (heat-releasing) reaction. However, the initial hydrogen yield per unit of input fuel is typically lower than that of steam reforming.

The key reactions in the partial oxidation process can be summarized as follows:



By optimizing the partial oxidation of natural gas, the Department of Energy aims to develop a cost-effective and efficient pathway for large-scale hydrogen production to support the growing demand for this clean energy carrier.

Why Is This Pathway Being Considered?

Reforming low-cost natural gas is a viable option for producing hydrogen today to power fuel cell electric vehicles (FCEVs) as well as other applications. This approach provides a near-term solution to increasing the availability of clean hydrogen.

Over the long term, the Department of Energy expects that hydrogen production from natural gas will be supplemented by other low-carbon, domestic energy sources, such as renewable, nuclear, and coal with carbon capture and storage technologies.

Compared to traditional gasoline-powered vehicles, the use of FCEVs offers significant environmental benefits. The only tailpipe emission from an FCEV is water vapor. Even when accounting for the upstream processes of producing hydrogen from natural gas and delivering/storing the fuel, the total greenhouse gas emissions are cut in half, and petroleum usage is reduced by over 90% relative to today's gasoline vehicles.

By leveraging the abundant and cost-effective natural gas resources in the United States, hydrogen production can play a crucial role in the near-term deployment of FCEVs. As renewable and other low-carbon hydrogen production pathways mature, they will complement the natural gas-based approach to create a diverse, sustainable hydrogen economy.

Biomass Gasification

Biomass gasification is a mature technology that uses a controlled process involving heat, steam, and oxygen to convert biomass into hydrogen and other products, without combustion. Since growing biomass removes carbon dioxide from the atmosphere, the net carbon emissions of this method can be low, especially if coupled with carbon capture, utilization, and storage in the long term. Gasification plants for biofuels are being built and operated and can provide best practices and lessons learned for hydrogen production. The U.S. Department of Energy anticipates that biomass gasification could be deployed in the near-term timeframe.

What Is Biomass?

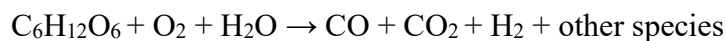
Biomass is a renewable organic resource that includes agriculture crop residues, forest residues, special energy crops, organic municipal solid waste, and animal wastes. This renewable resource can be used to produce hydrogen, along with other byproducts, by gasification.

How Does Biomass Gasification Work?

Gasification is a process that converts organic or fossil-based carbonaceous materials at high temperatures (above 700°C), without combustion, using a controlled amount of oxygen and/or steam. This process produces a gas mixture containing carbon monoxide, hydrogen, and carbon dioxide.

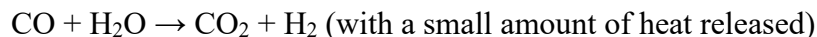
The carbon monoxide then reacts with water through a water-gas shift reaction to form additional hydrogen and carbon dioxide. Adsorbers or specialized membranes can be used to separate the hydrogen from this gas stream.

An example simplified reaction is:



Note that this reaction uses glucose as a representative for the more complex and variable composition of actual biomass, which often has cellulose as a major component.

The water-gas shift reaction is:



Pyrolysis, the gasification of biomass in the absence of oxygen, generally produces a gas mixture with additional hydrocarbon compounds. These hydrocarbons typically require an extra step of reforming with a catalyst to yield a clean syngas mixture of hydrogen, carbon monoxide, and carbon dioxide.

Finally, as in the overall gasification process, a shift reaction with steam is used to convert the remaining carbon monoxide to carbon dioxide. The hydrogen produced can then be separated and purified.

Why Is This Pathway Being Considered?

The pathway of hydrogen production via biomass gasification is being considered for a few key reasons:

Biomass as an Abundant Domestic Resource:

- The United States has more biomass available than is required for food and animal feed needs.
- Estimates suggest that up to 1 billion dry tons of biomass could be available annually for energy use, with anticipated improvements in agricultural practices and plant breeding.

Biomass as a Carbon-Neutral Feedstock:

- Biomass "recycles" carbon dioxide - plants consume CO₂ from the atmosphere during growth, offsetting the CO₂ released during the hydrogen production process via gasification. This results in low net greenhouse gas emissions.

Overcoming Technical Challenges:

The key challenges for this pathway involve reducing costs associated with capital equipment and biomass feedstocks:

Capital Cost Reduction Research:

- Replacing cryogenic air separation with new membrane technologies
- Developing improved membrane technologies for hydrogen separation and purification
- Intensifying processes to combine steps and increase efficiency

Feedstock Cost Reduction Research:

- Improvements in agricultural practices and breeding to lower and stabilize feedstock costs
- As biomass gasification is a mature technology, advancements in these areas and lessons learned from commercial demonstrations will determine the viability of this pathway for cost-competitive hydrogen production.

Biomass-Derived Liquid Reforming

Liquids derived from biomass resources, such as ethanol and bio-oils, can be reformed to produce hydrogen in a process similar to natural gas reforming. This pathway offers some advantages:

Easier Transportation and Distributed Production:

- Biomass-derived liquids can be transported more easily than solid biomass feedstocks, allowing for semi-central production or potentially distributed hydrogen production at fueling stations.

Mid-Term Technology Pathway:

- Biomass-derived liquid reforming is considered a mid-term technology pathway for hydrogen production.

How Does It Work?

Biomass resources can be converted into various liquid biofuels, such as cellulosic ethanol and bio-oils.

Some of these liquid biofuels can be transported at relatively low cost to refueling stations or other points of use, where they can be reformed to produce hydrogen. Other liquid biofuels, like bio-oils, may be reformed on-site.

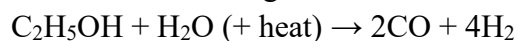
The process of reforming biomass-derived liquids to hydrogen is very similar to natural gas reforming. It involves the following steps:

Liquid fuel is reacted with steam at high temperatures in the presence of a catalyst, producing a reformat gas composed mainly of hydrogen, carbon monoxide, and some carbon dioxide.

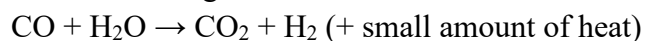
The carbon monoxide is then reacted with high-temperature steam in the water-gas shift reaction, generating additional hydrogen and carbon dioxide.

Finally, the hydrogen is separated and purified.

The steam reforming reaction for ethanol can be represented as:



And the water-gas shift reaction is:



Biomass-derived liquids can be produced at large, centralized facilities located near the biomass source. This allows for economies of scale and reduced costs of transporting the solid biomass feedstock.

These liquid biofuels have a high energy density and can be transported with minimal new infrastructure to distributed refueling stations, semi-central production facilities, or stationary power sites for reforming into hydrogen.

Research Focuses on Overcoming Challenges

The key research focuses on overcoming the challenges associated with reforming biomass-derived liquids to produce hydrogen:

1. Reforming Biomass-Derived Liquids:
 - The process is very similar to the relatively mature technology of reforming natural gas.
 - However, biomass-derived liquids are composed of larger molecules with more carbon atoms compared to natural gas, making them more difficult to reform.
2. Improving Yields and Selectivity:
 - Research is needed to identify better catalysts that can improve the yields and selectivity of the reforming process for these larger, more complex biomass-derived molecules.
3. Reducing Costs:
 - Reducing the cost of producing biomass-derived liquid fuels is a critical challenge.
 - This research is being conducted by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy Bioenergy Technologies Office.

4. Improving Process Efficiency:

- Reducing the capital equipment costs, as well as the operation and maintenance costs, and improving the overall process efficiency are challenges similar to those faced in natural gas reforming.

Overcoming these technical and economic barriers is crucial for enabling the effective reforming of biomass-derived liquids to produce hydrogen in a cost-competitive manner.

Solar thermochemical hydrogen (STCH)

Thermochemical water splitting is a process that utilizes high temperatures to produce hydrogen and oxygen from water. These high temperatures can be obtained from two main sources:

1. Concentrated solar power
2. Waste heat from nuclear power reactions

By leveraging these high-temperature heat sources and applying specific chemical reactions, the thermochemical water splitting process is able to split water molecules into their constituent elements of hydrogen and oxygen.

This technology pathway is considered a long-term approach for hydrogen production. Importantly, thermochemical water splitting has the potential to generate hydrogen with low or even zero greenhouse gas emissions, making it an attractive option for clean energy development.

However, as a long-term technology, further research and development is still needed to fully realize the benefits and overcome any technical challenges associated with thermochemical water splitting.

How Does It Work?

The process utilizes high-temperature heat, ranging from 500°C to 2,000°C, to drive a series of chemical reactions that split water molecules into hydrogen and oxygen. This high-temperature heat can be obtained through two main methods:

1. Concentrating sunlight using a field of mirror "heliostats" onto a reactor tower, effectively harnessing concentrated solar power.
2. Using the waste heat generated by advanced nuclear reactor operations.

Numerous thermochemical water-splitting cycles have been studied and developed, with over 300 such cycles described in the literature. These cycles involve different sets of operating conditions, engineering challenges, and hydrogen production opportunities.

Two specific examples of thermochemical water-splitting cycles are:

1. The "direct" two-step cerium oxide thermal cycle
2. The "hybrid" copper chloride cycle

Generally, the direct cycles are less complex with fewer steps, but they require higher operating temperatures compared to the more complicated hybrid cycles.

The key aspect of these thermochemical processes is that the chemicals used are continually recycled within the closed loop, consuming only water and producing hydrogen and oxygen as the outputs.

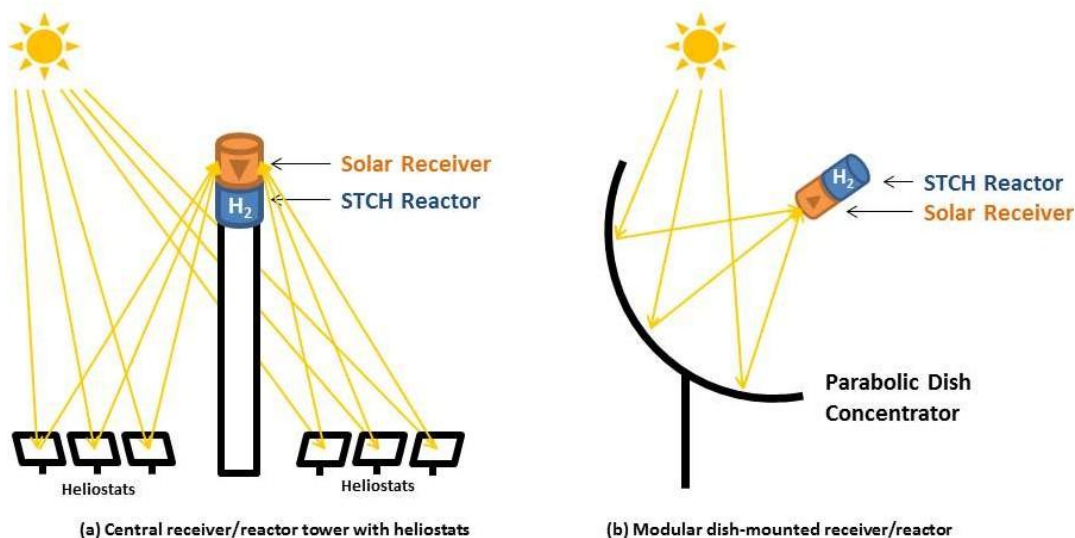


Figure 3. Concentrating sunlight onto a reactor tower using a field of mirror heliostats

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

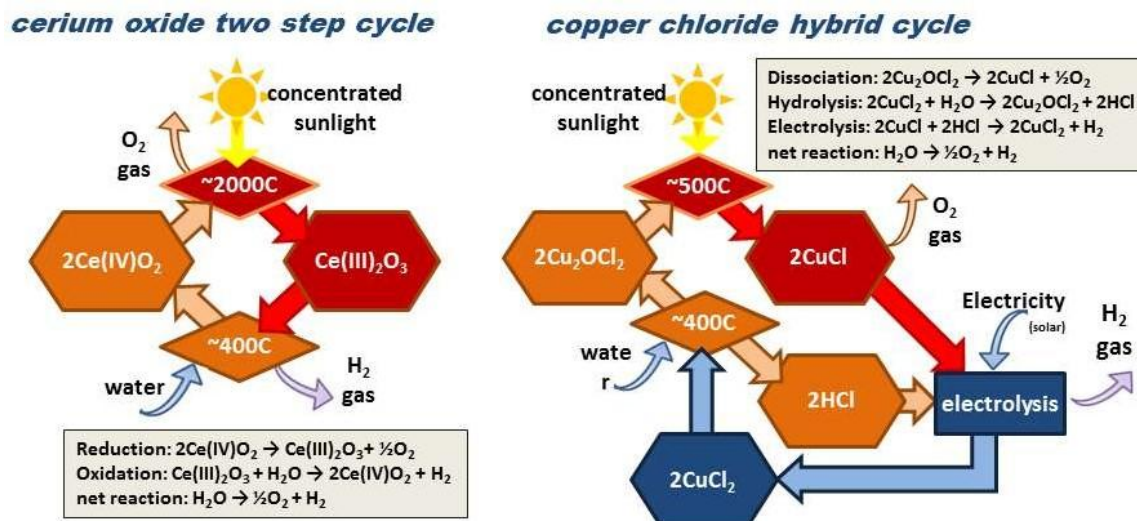


Figure 4. Two examples of thermochemical water splitting cycles

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Why Is This Pathway Being Considered?

Thermochemical water splitting is being considered as a promising pathway for several key reasons:

1. Emissions-Free Hydrogen Production:
 - Solar- and nuclear-driven high-temperature thermochemical water-splitting cycles can produce hydrogen with near-zero greenhouse gas emissions.
 - The process only requires water and either sunlight or nuclear energy as inputs, making it a potentially clean hydrogen production method.

Overcoming Technical Challenges:

However, there are still challenges that need to be overcome through continued research and development:

1. Improving Efficiency and Durability of Materials:
 - The efficiency and durability of the reactant materials used in the thermochemical cycling process need to be improved.
2. Developing Robust Reactor Designs:
 - Efficient and robust reactor designs that can withstand the high temperatures and heat cycling required for the process need to be developed.
3. Reducing Costs of Solar Concentrating Systems:
 - For solar-driven thermochemical systems, the cost of the concentrating mirror systems needs to be reduced to improve the overall economic viability.

Overcoming these technical and cost-related challenges is crucial for enabling the widespread adoption of thermochemical water splitting as a commercially viable pathway for clean hydrogen production.

2. Electrolytic Processes

Electrolysis is a well-established technology for producing hydrogen and oxygen by splitting water using electricity. This approach is commercially available and has been widely adopted.

Importantly, efforts are underway to develop electrolysis systems that can efficiently utilize intermittent renewable power sources, such as wind and solar. This is a key focus area, as it allows electrolyzers to leverage the growing availability of clean, renewable electricity to generate hydrogen in a sustainable manner.

Compared to the high-temperature thermochemical water-splitting processes, electrolysis is a more mature and commercially viable technology for hydrogen production. The ability to pair electrolyzers with renewable energy sources makes this approach particularly attractive for transitioning towards a more sustainable hydrogen economy.

However, continued research and development is still needed to further improve the efficiency, reliability, and cost-effectiveness of electrolysis systems, especially those designed to operate with variable renewable energy inputs.

Electrolysis

Electrolysis is a promising option for producing carbon-free hydrogen from renewable and nuclear energy sources. In this process, electricity is used to split water molecules into hydrogen and oxygen.

The water-splitting reaction takes place within a specialized unit called an electrolyzer. Electrolyzers can vary greatly in size and scale:

Small, appliance-size equipment: These are well-suited for small-scale, distributed hydrogen production applications.

Large-scale, central production facilities: These larger electrolyzers can be directly tied to renewable energy sources, such as wind or solar, or to nuclear power plants, allowing for centralized, high-volume hydrogen production without greenhouse gas emissions.

The flexibility in electrolyzer size and the ability to couple them with clean electricity sources, such as renewables and nuclear, make electrolysis a compelling technology pathway for generating hydrogen with zero direct carbon emissions.

Continued research and development are focused on improving the efficiency, reliability, and cost-competitiveness of electrolysis systems, particularly those designed to operate with variable renewable energy inputs. As these advancements are made, electrolysis could play an increasingly important role in the transition towards a sustainable hydrogen economy.

How Does It Work?

The electrolysis process for hydrogen production works in a similar way to fuel cells, but in reverse. Electrolyzers consist of an anode and a cathode separated by an electrolyte material.

The key difference lies in the type of electrolyte material used and the ionic species it conducts. Depending on the specific electrolyzer design, the process can vary:

1. Alkaline Electrolyzers:
 - These use a liquid alkaline electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH).
 - The electrolyte allows the transport of hydroxide ions (OH⁻) from the cathode to the anode.
2. Proton Exchange Membrane (PEM) Electrolyzers:
 - These use a solid polymer electrolyte membrane that conducts protons (H⁺) from the anode to the cathode.
3. Solid Oxide Electrolyzers:
 - These utilize a ceramic solid oxide electrolyte that conducts oxygen ions (O₂⁻) from the cathode to the anode.

The specific electrolyte material and ionic species involved in the electrochemical reactions are the key factors that distinguish the different types of electrolyzers and their operating principles.

Regardless of the electrolyzer design, the core function is to use electricity to split water molecules, producing hydrogen gas at the cathode and oxygen gas at the anode. This process enables the generation of clean, carbon-free hydrogen from renewable or nuclear electricity sources.

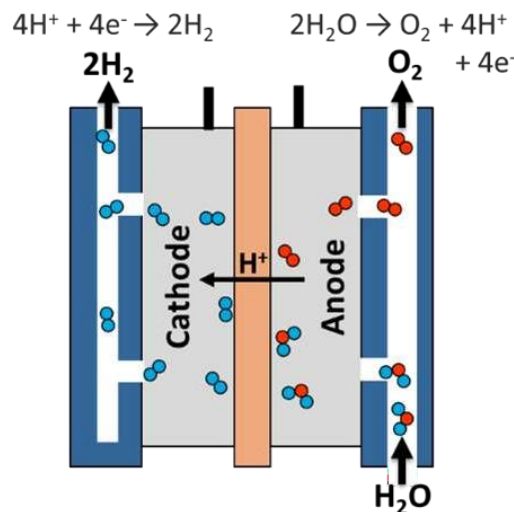


Figure 5. Electrolysis

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

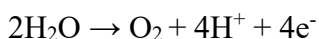
Polymer Electrolyte Membrane Electrolyzers

In a Proton Exchange Membrane (PEM) electrolyzer, the electrolyte is a specialized solid plastic material, known as a polymer electrolyte membrane.

The water-splitting process in a PEM electrolyzer occurs as follows:

1. Anode Reaction:

At the anode, water reacts to form oxygen gas, positively charged hydrogen ions (protons), and electrons.

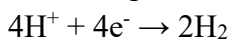


2. Proton Transport:

The hydrogen ions (protons) selectively move across the PEM from the anode to the cathode.

3. Cathode Reaction:

At the cathode, the hydrogen ions combine with the electrons flowing through the external circuit to produce hydrogen gas.



The key feature of the PEM electrolyzer is the use of the solid polymer electrolyte membrane, which allows the selective transport of protons from the anode to the cathode while keeping the hydrogen and oxygen gas streams separate.

This design enables efficient and safe hydrogen production, as the hydrogen and oxygen are generated at different electrodes and can be easily collected and stored separately.

Alkaline Electrolyzers

In alkaline electrolyzers, the water-splitting process occurs via the transport of hydroxide ions (OH^-) through the electrolyte from the cathode to the anode. Hydrogen gas is generated at the cathode side of the electrolyzer.

Alkaline electrolyzers have been commercially available for many years, utilizing a liquid alkaline solution of either sodium hydroxide (NaOH) or potassium hydroxide (KOH) as the electrolyte.

More recently, there have been developments in using solid alkaline exchange membranes (AEM) as the electrolyte material in alkaline electrolyzers. This solid electrolyte approach is showing promise at the laboratory scale, as it can potentially offer advantages in terms of efficiency, durability, and ease of operation compared to the traditional liquid alkaline electrolyzers.

The key advantage of the AEM approach is that the solid membrane allows for the selective transport of hydroxide ions (OH^-) from the cathode to the anode, while keeping the hydrogen and oxygen gas streams separate, similar to the operation of PEM electrolyzers.

Ongoing research and development in solid alkaline exchange membrane electrolyzers aim to further improve their performance and scalability, with the goal of making them a commercially viable option for large-scale, sustainable hydrogen production.

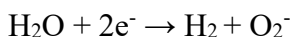
Solid Oxide Electrolyzers

Solid oxide electrolyzers operate using a different mechanism compared to PEM and alkaline electrolyzers. These systems utilize a solid ceramic material as the electrolyte, which selectively conducts negatively charged oxygen ions (O^{2-}) at elevated temperatures.

In a solid oxide electrolyzer:

1. Cathode Reaction:

At the cathode, steam reacts with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions.

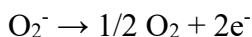


2. Oxygen Ion Transport:

The oxygen ions pass through the solid ceramic electrolyte membrane to the anode.

3. Anode Reaction:

At the anode, the oxygen ions react to form oxygen gas and generate electrons for the external circuit.



Solid oxide electrolyzers must operate at high temperatures, typically around 700°C to 800°C , for the solid oxide membranes to function properly. This contrasts with PEM electrolyzers, which

operate at 70°C to 90°C, and commercial alkaline electrolyzers, which typically operate below 100°C.

However, advanced lab-scale solid oxide electrolyzers based on proton-conducting ceramic electrolytes are showing promise for lowering the operating temperature to 500°C to 600°C. This reduction in operating temperature can help decrease the amount of electrical energy needed to produce hydrogen from water, as the solid oxide electrolyzers can effectively utilize the available heat at these elevated temperatures.

The high-temperature operation and the ability to leverage waste heat make solid oxide electrolyzers a potentially attractive option for large-scale, efficient, and sustainable hydrogen production.

Why Is This Pathway Being Considered?

Electrolysis is a leading hydrogen production pathway that is crucial for achieving the Hydrogen Energy Earthshot goal. The Hydrogen Energy Earthshot aims to reduce the cost of clean hydrogen by 80% to \$1 per kilogram within a decade ("1 1 1").

Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used for the electrolysis process. This makes electrolysis an attractive option for sustainable hydrogen production.

However, when evaluating the benefits and economic viability of hydrogen production via electrolysis, it is important to consider the source of the required electricity, including its cost, efficiency, and the emissions resulting from the electricity generation process.

In many regions, the current power grid may not be ideal for providing the electricity required for electrolysis, as the greenhouse gas emissions and the amount of fuel consumed due to the low efficiency of the electricity generation process can be problematic.

To address this, hydrogen production via electrolysis is being pursued using renewable energy sources, such as wind, solar, hydropower, and geothermal, as well as nuclear energy options. These hydrogen production pathways can result in virtually zero greenhouse gas and criteria pollutant emissions.

However, the production cost of hydrogen from these clean electricity sources needs to be decreased significantly to become competitive with more mature carbon-based pathways, such as natural gas reforming.

Overcoming the cost and efficiency challenges associated with electrolysis-based hydrogen production from clean electricity sources is crucial for realizing the full potential of this technology in achieving the Hydrogen Energy Earthshot goals.

Potential for synergy with renewable energy power generation

Hydrogen production via electrolysis may offer opportunities for synergy with dynamic and intermittent power generation, which is characteristic of some renewable energy technologies, such as wind power.

Despite the continued drop in the cost of wind power, the inherent variability of wind is a challenge to the effective use of wind power. However, this challenge can be addressed by integrating hydrogen fuel and electric power generation at a wind farm.

This integration allows for flexibility in production, allowing the system to shift production to best match resource availability, system operational needs, and market factors. In times of excess electricity production from wind farms, instead of curtailing the electricity as is commonly done, this excess electricity can be used to produce hydrogen through electrolysis.

It is important to note that today's grid electricity is not the ideal source of electricity for electrolysis, as most of the electricity is generated using technologies that result in greenhouse gas emissions and are energy intensive. To overcome these limitations, electricity generation using renewable or nuclear energy technologies, either separate from the grid or as a growing portion of the grid mix, is a possible option for hydrogen production via electrolysis.

The U.S. Department of Energy and others continue efforts to bring down the cost of renewable-based electricity production and develop more efficient fossil-fuel-based electricity production with carbon capture, utilization, and storage. For example, wind-based electricity production is growing rapidly in the United States and globally, making it a promising source for sustainable hydrogen production via electrolysis.

Research Focuses on Overcoming Challenges

To meet the Hydrogen Shot clean hydrogen cost target of \$1 per kilogram by 2030 (and the interim target of \$2 per kilogram by 2025), the following key focus areas are crucial:

1. Improved understanding of the performance, cost, and durability trade-offs of electrolyzer systems under predicted future dynamic operating modes using CO₂-free electricity. This will help optimize the systems for cost-effective and sustainable hydrogen production.
2. Reducing the capital cost of the electrolyzer unit and the balance of the system. Lowering the upfront costs is essential for achieving the targeted hydrogen production costs.

3. Improving energy efficiency for converting electricity to hydrogen over a wide range of operating conditions. Enhancing the conversion efficiency can significantly contribute to reducing the overall hydrogen production costs.
4. Increasing the understanding of electrolyzer cell and stack degradation processes and developing mitigation strategies to increase the operational life of the systems. Improving the durability and longevity of the electrolyzer components can help drive down the lifecycle costs of hydrogen production.

Addressing these key focus areas through research, development, and innovation will be crucial for the electrolyzer technology to meet the ambitious Hydrogen Shot cost targets and enable the widespread adoption of clean hydrogen production through electrolysis.

Direct Solar Water Splitting Processes

Direct solar water splitting, or photolytic processes, uses light energy to split water into hydrogen and oxygen. These processes are currently in various early stages of research, but they offer long-term potential for sustainable hydrogen production with low environmental impact.

The two main solar water splitting processes that are being explored are:

1. Photoelectrochemical (PEC) water splitting: In this process, specialized photoelectrochemical cells capture solar energy and use it to directly split water molecules into hydrogen and oxygen.
2. Photobiological water splitting: This process utilizes photosynthetic organisms, such as algae or cyanobacteria, to convert water and carbon dioxide into hydrogen and oxygen using sunlight as the energy source.

Both of these solar water splitting approaches are still in the early stages of research and development, but they hold significant promise for the future of sustainable hydrogen production. The direct use of sunlight to split water has the potential to create hydrogen with minimal environmental impact, making it an attractive option for clean energy generation.

However, the current technological and cost limitations of these processes need to be addressed through continued research, development, and innovation before they can be widely deployed for commercial-scale hydrogen production. Overcoming these challenges could unlock the long-term potential of these solar water splitting technologies to contribute to the Hydrogen Shot goals of affordable clean hydrogen.

Photoelectrochemical Water Splitting

Photoelectrochemical (PEC) water splitting is a promising long-term technology pathway for producing hydrogen with the potential for low or no greenhouse gas emissions.

In the PEC water splitting process, hydrogen is produced from water using sunlight and specialized semiconductors called photoelectrochemical materials. These materials are able to use the energy from light to directly dissociate water molecules into hydrogen and oxygen.

Here's how the PEC water splitting process works:

The PEC process uses semiconductor materials, similar to those used in photovoltaic solar electricity generation, but in this case, the semiconductor is immersed in a water-based electrolyte. When sunlight energizes the semiconductor, it initiates the water-splitting reaction, converting the solar energy directly into chemical energy in the form of hydrogen.

PEC reactors can be constructed in panel form, similar to photovoltaic panels, or as slurry-based particle systems, each approach with its own advantages and challenges. Panel systems have been the most widely studied so far, as they leverage the similarities with established photovoltaic panel technologies.

The figures provided illustrate some different possible implementations of both the panel and slurry reactor concepts for PEC water splitting. These various reactor designs are being researched and developed to optimize the efficiency, cost, and scalability of this promising technology for sustainable hydrogen production

Video 1: NREL Photoelectrolysis

This is a GaInP2/GaAs tandem semiconductor splitting water with no applied bias. Electrode is short circuited to a RuO₂ coated platinum electrode in a 0.5M H₂SO₄ electrolyte. Hydrogen can be seen evolving from the semiconductor surface after it is connected to the counter electrode where oxygen is produced.

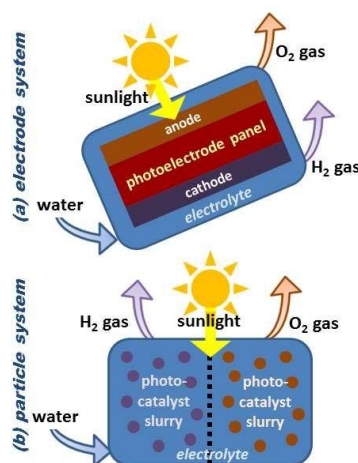


Figure 6. PEC reactor approaches.

(Source: Youtube, “NREL Photoelectrolysis”, youtube.com, Retrieved April 2024 from <http://youtu.be/6GT4Oiig1-8>)

Two different approaches to PEC solar hydrogen production reactors: (a) electrode systems similar to flat-plate photovoltaic panels; and (b) particle systems comprised of slurries of PEC semiconductor particles.

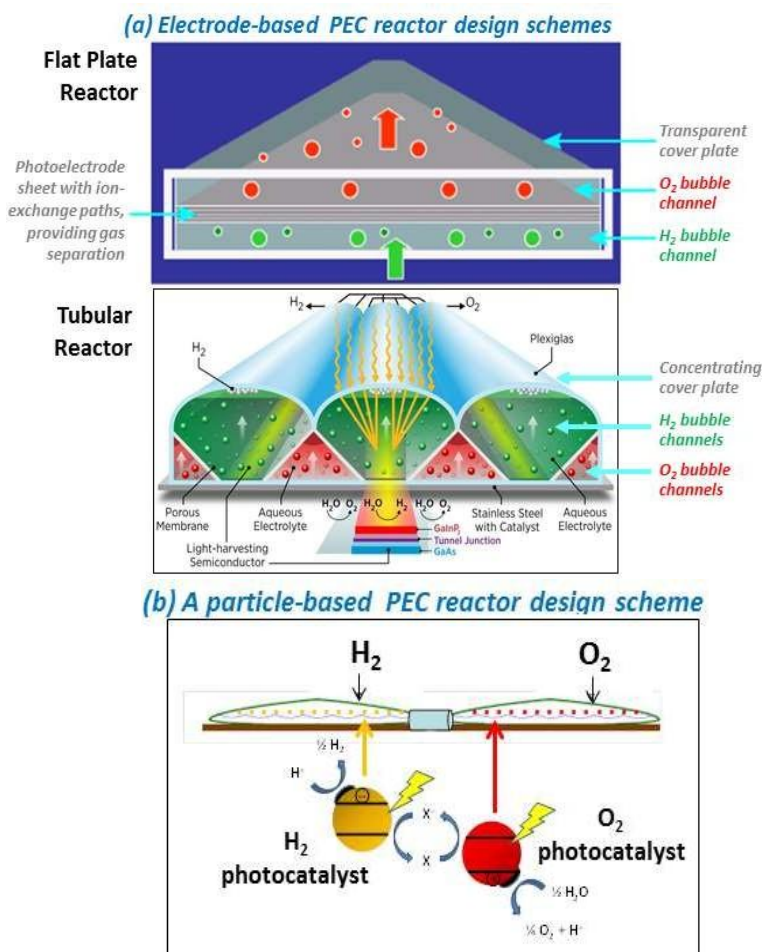


Figure 7. PEC reactor design schemes.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Possible PEC reactor design schemes for (a) electrode systems, including a flat plate and a tubular reactor (providing moderate solar concentration onto one electrode strip); and (b) a plastic "baggie" covered dual bed particle reactor with wide-by-side photocatalyst slurries.

Why Is This Pathway Being Considered?

Photoelectrochemical (PEC) water splitting is a promising solar-to-hydrogen conversion pathway that offers several key advantages:

1. High conversion efficiency potential: PEC systems have the ability to achieve high solar-to-hydrogen conversion efficiencies, potentially surpassing the performance of other solar-driven hydrogen production methods.

2. Low operating temperatures: PEC water splitting can operate at relatively low temperatures, which can help reduce the overall system complexity and costs compared to high-temperature processes.
3. Use of cost-effective materials: PEC systems can leverage thin-film and/or particle semiconductor materials, which are generally more cost-effective than traditional semiconductor fabrication techniques.

These attributes make PEC water splitting a highly attractive approach for sustainable and large-scale hydrogen production using solar energy. The ability to directly convert sunlight into hydrogen, without the need for intermediate energy conversion steps, is a key advantage of this technology pathway.

Ongoing research and development efforts are focused on further improving the efficiency, durability, and cost-effectiveness of PEC systems to enable their widespread adoption and deployment for clean hydrogen generation. The continued advancements in PEC water splitting could play a crucial role in meeting the Hydrogen Shot cost targets and driving the transition towards a sustainable hydrogen economy.

Research Focuses on Overcoming Challenges

While photoelectrochemical (PEC) water splitting holds great promise as a solar-to-hydrogen conversion pathway, continued improvements in efficiency, durability, and cost-effectiveness are still needed to achieve viable market deployment.

Ongoing research and development efforts in this area are making important strides, benefiting from strong synergies with contemporary research in related fields such as photovoltaics, nanotechnologies, and computational materials science.

Specifically, the efficiency of PEC systems is being improved through enhanced sunlight absorption and better surface catalysis. Researchers are exploring advanced semiconductor materials and nanostructured designs to maximize the capture and utilization of solar energy for the water-splitting reaction.

The durability and operational lifetime of PEC devices are also being enhanced through the development of more rugged materials and protective surface coatings. This helps to mitigate the degradation of key components and improve the reliability of the systems over long-term operation.

Furthermore, significant progress is being made in reducing the hydrogen production costs associated with PEC water splitting. This is being achieved through innovations that lower the

materials and materials processing costs, making the technology more economically viable for large-scale deployment.

The advancements in PEC materials, devices, and systems, leveraging cross-cutting research collaborations, are crucial for overcoming the remaining technical and economic barriers. Continued progress in these areas will be essential to realizing the full potential of PEC water splitting as a cost-effective and sustainable pathway for clean hydrogen generation.

Photobiological

Photobiological hydrogen production is an emerging technology pathway that utilizes microorganisms and sunlight to convert water, and sometimes organic matter, into hydrogen. This process is still in the early stages of research, but it holds long-term potential for sustainable hydrogen generation with low environmental impact. By leveraging the natural photosynthetic and metabolic processes of certain microbes, such as algae and cyanobacteria, the photobiological approach aims to directly produce hydrogen from renewable feedstocks and solar energy, offering an attractive alternative to conventional hydrogen production methods. Though currently faced with technical and economic challenges, continued research and development in this field could unlock the full potential of photobiological hydrogen production as a viable solution for clean and sustainable hydrogen generation.

How Does It Work?

Photolytic biological systems leverage the natural processes of certain microorganisms, such as green microalgae and cyanobacteria, to produce hydrogen. In these systems, the microbes use sunlight to split water into oxygen and hydrogen ions. The hydrogen ions can then be combined through direct or indirect routes and released as hydrogen gas.

However, this technological pathway faces several challenges. One of the key issues is the low rates of hydrogen production. Additionally, the splitting of water also produces oxygen, which can quickly inhibit the hydrogen production reaction and poses safety concerns when mixed with hydrogen in certain concentrations. Researchers are working to develop methods that allow the microbes to produce hydrogen for longer periods and increase the overall rate of hydrogen production.

An alternative approach is known as photo fermentative hydrogen production, where photosynthetic microbes use sunlight as the driver to break down organic matter, releasing hydrogen. Unfortunately, this pathway also suffers from very low hydrogen production rates and low solar-to-hydrogen conversion efficiencies, making it commercially unviable at the moment.

Ongoing research efforts are focused on finding ways to enhance the microbes' ability to collect and utilize energy more effectively, as well as to modify their biological pathways to increase the

rate of hydrogen production. Overcoming these technical challenges is crucial for realizing the full potential of photolytic and photo fermentative biological systems as sustainable and scalable hydrogen production pathways.

Why Is This Pathway Being Considered?

Photobiological hydrogen production is being actively considered as a potential long-term technology pathway for several compelling reasons:

Firstly, in the long run, these photobiological systems hold the promise of providing economical hydrogen production directly from sunlight with low to net-zero carbon emissions. This aligns with the growing global imperative to transition towards sustainable and clean energy sources.

Additionally, the microorganisms used in these processes, such as algae and bacteria, can potentially be grown in water sources that are unsuitable for drinking or agricultural purposes. This includes the possibility of utilizing wastewater, which could help address water scarcity concerns and provide a cost-effective feedstock for hydrogen generation.

The ability to produce hydrogen using marginal water resources and without competing with conventional agriculture or water supplies is a significant advantage of the photobiological approach. This could make it an attractive option for regions with limited access to freshwater resources but abundant sunlight - a combination that is crucial for the viability of this technology.

While the current technical and economic challenges of photobiological hydrogen production are well recognized, the long-term potential of this pathway to deliver clean, sustainable, and cost-effective hydrogen generation continues to drive ongoing research and development efforts in this field. Overcoming the remaining barriers could unlock the transformative benefits of this technology for the emerging hydrogen economy.

Research Focuses on Overcoming Challenges

In recent years, research into photobiological hydrogen production has seen notable progress, though the technology remains in its early stages of development.

Both photolytic and photo fermentative biological approaches to hydrogen generation face several common challenges that require further research and innovation. Many of these fundamental challenges are being addressed through the efforts of organizations like the U.S. Department of Energy's Office of Science.

Some of the key research priorities include:

1. Improving the activity and efficiency of the enzymes responsible for hydrogen production, as well as the metabolic pathways involved in the overall reactions. This aims to significantly increase the rates of hydrogen generation.

2. Developing more robust and optimized strains of microorganisms that can efficiently utilize sunlight and other inputs to maximize hydrogen yields.
3. Engineering strains and reactor configurations that can be scaled up for commercial-scale hydrogen production, overcoming the limitations of current small-scale systems.

Addressing these fundamental scientific and technological barriers is crucial for realizing the long-term potential of photobiological hydrogen production as a sustainable and cost-effective pathway for clean energy generation. The ongoing research efforts in this field hold promise for unlocking the transformative benefits of this emerging technology.

3. Biological Processes

Certain microorganisms, such as bacteria and microalgae, possess the inherent ability to produce hydrogen through biological processes. Two distinct technology pathways are being explored in this regard:

3. Photobiological hydrogen production: This approach utilizes microbes, like green algae and cyanobacteria, to split water using sunlight as the energy source. The hydrogen generated can then be captured and utilized.
4. Microbial biomass conversion: In this process, photosynthetic microbes break down organic matter, releasing hydrogen as a byproduct.

While these biological hydrogen production technologies are currently in the research and development stage, with ongoing pilot-scale demonstrations, they hold significant long-term potential. If the technical and economic challenges can be overcome, these pathways could enable the sustainable and low-carbon generation of hydrogen in the future.

The research and development efforts in this field are focused on improving the efficiency and scalability of these biological processes, as well as developing optimized strains of microorganisms that can maximize hydrogen yields. Continued progress in this area could unlock the transformative benefits of photobiological and microbial biomass conversion approaches for the emerging hydrogen economy.

Microbial Biomass Conversion

Microbial biomass conversion processes leverage the inherent capability of certain microorganisms to consume and break down organic biomass, ultimately releasing hydrogen as a byproduct.

Depending on the specific pathway being explored, the research and development efforts in this domain could potentially result in the development of commercial-scale hydrogen production systems within a mid- to long-term timeframe.

The key advantage of the microbial biomass conversion approach is its ability to utilize renewable and widely available organic feedstocks, such as agricultural waste or municipal solid waste, as the primary input. By harnessing the natural metabolic processes of specialized microbes, this technology has the potential to generate hydrogen in a sustainable and cost-effective manner.

However, significant research and optimization is still required to overcome the current technical and economic barriers, which include low hydrogen production rates and overall conversion efficiencies. Ongoing efforts are focused on improving the activity and selectivity of the microbial strains, as well as developing efficient reactor designs and process configurations that can be scaled up for large-scale commercial deployment.

If the remaining challenges can be addressed through continued research and development, the microbial biomass conversion pathway could emerge as a viable option for future hydrogen production, complementing other renewable energy technologies and contributing to the transition towards a sustainable hydrogen economy.

How Does It Work?

Fermentation-based systems for hydrogen production leverage the natural capabilities of certain microorganisms, such as bacteria, to break down organic matter and release hydrogen as a byproduct.

The organic feedstock for these processes can vary widely, ranging from refined sugars to raw biomass sources like corn stover, and even wastewater. Since these systems do not rely on light, they are often referred to as "dark fermentation" methods.

In the direct hydrogen fermentation approach, the microbes themselves are responsible for producing hydrogen. These microbes can break down complex organic molecules through various metabolic pathways, and the byproducts of some of these pathways can be combined by specialized enzymes to generate hydrogen.

Researchers are actively studying ways to optimize these fermentation systems to improve the hydrogen production rate and increase the overall yield per unit of organic matter. This involves understanding the complex microbial processes and engineering strategies to enhance the efficiency of hydrogen generation.

Another fermentation-based approach is the use of microbial electrolysis cells (MECs). In these devices, the energy and protons produced by microbes breaking down organic matter are harnessed, along with the application of a small additional electric current, to enable the production of hydrogen.

MEC technology is still in the early stages of development, and researchers are working to address various challenges, such as finding lower-cost materials and identifying the most effective microbial strains for optimal performance.

Ongoing research and innovation in both direct hydrogen fermentation and MEC systems aim to unlock the full potential of these biological pathways for sustainable and cost-effective hydrogen production.

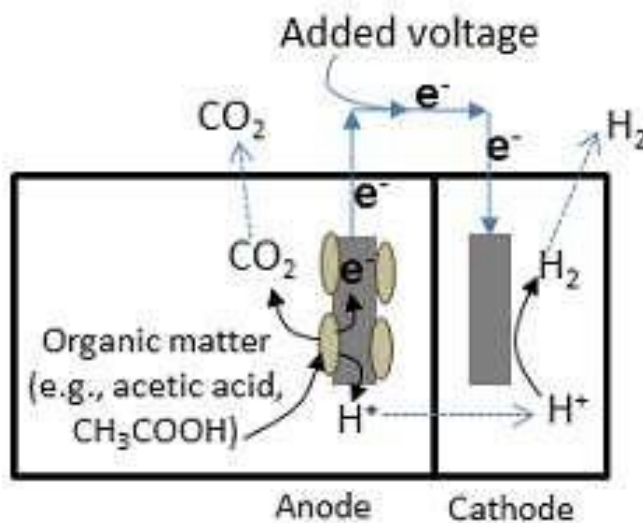


Figure 8. Microbial electrolysis cells (MECs).

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Why Is This Pathway Being Considered?

Biomass represents a plentiful domestic resource, and many microorganisms have naturally evolved the ability to efficiently break down biomass and convert it into valuable products, including hydrogen.

Fermentation is already an established industrial technology for generating biofuels and other chemicals. While some of the general challenges in scaling up fermentation systems have been addressed for different products, hydrogen production does present unique challenges that researchers are currently focused on overcoming.

Microbial electrolysis cell (MEC) systems offer the potential to generate hydrogen from resources that may not be suitable for conventional fuel production, such as wastewater. These MEC-based approaches could also help reduce the substantial energy requirements typically associated with wastewater treatment, while concurrently producing hydrogen as a valuable fuel.

The combination of fermentation-based and MEC-based pathways presents an opportunity to maximize the overall hydrogen yield from a given biomass feedstock. By leveraging the complementary strengths of these two biological approaches, researchers aim to develop integrated systems that can optimize the conversion of biomass into sustainable hydrogen.

The advances made in the broader biofuels and industrial biotechnology sectors provide a strong foundation for accelerating the development of these microbial-based hydrogen production technologies. Overcoming the remaining technical and economic hurdles could unlock the full potential of biomass as a reliable and renewable source of hydrogen.

Research Focuses on Overcoming Challenges

The research efforts in the field of microbial biomass conversion for hydrogen production have seen notable progress in recent years. However, the U.S. Department of Energy (DOE) is actively working to address several key challenges in this domain. The main areas of research and development focus include:

4. Improving the rates and yields of hydrogen production from fermentation processes:
3. Optimizing microbial strains through genetic engineering or selective breeding to enhance their hydrogen-producing capabilities.
4. Developing advanced reactor systems and process configurations to improve the efficiency and productivity of the fermentation-based hydrogen generation.
5. Identifying and utilizing feedstock sources and processing methods that can maximize the hydrogen yields from the available biomass.
5. Scaling up microbial electrolysis cell (MEC) systems:
6. Transitioning the promising MEC technology from the bench scale to commercially relevant sizes while maintaining the high production rates and system efficiencies observed in smaller-scale experiments.
7. Minimizing the costs associated with the reactor components and other materials used in the MEC systems to improve their economic viability.

By addressing these key research and development priorities, the DOE-supported efforts aim to overcome the current technical and economic barriers that have hindered the large-scale deployment of microbial biomass conversion for sustainable hydrogen production.

Advances in these areas could unlock the full potential of harnessing the inherent capabilities of microorganisms to convert diverse biomass feedstocks into clean and renewable hydrogen, contributing to the broader transition towards a more sustainable energy landscape.

Hydrogen Delivery

A viable hydrogen infrastructure requires that hydrogen be able to be delivered from where it is produced to the point of end use, such as an industrial facility, power generator, or fueling station. Infrastructure includes the pipelines, liquefaction plants, trucks, storage facilities, compressors, and dispensers involved in the process of delivering fuel.

Delivery technology for hydrogen infrastructure is currently available commercially, and several U.S. companies deliver bulk hydrogen today.

Growth in hydrogen demand will require regional expansion of this infrastructure and development of new technologies, such as chemical carriers to transport hydrogen at high density and high throughput fueling technologies for heavy-duty fuel cell transportation.

The Importance of Studying Hydrogen Delivery

Studying hydrogen delivery is important for several key reasons. First, hydrogen is the lightest element, with a gallon of hydrogen weighing only 0.00075 kg compared to 2.75 kg for a gallon of gasoline. This low density means that transporting large quantities of hydrogen presents unique challenges.

To transport hydrogen effectively, it must either be compressed into a gas or liquefied. The method of delivery can have a significant impact on the overall cost. Large, centralized production facilities can generate hydrogen at a lower per-unit cost due to economies of scale, but the transportation costs to deliver the hydrogen over longer distances may be higher. In contrast, distributed production facilities located closer to the point of use can minimize transportation costs, but the hydrogen production costs may be higher due to smaller production volumes.

Understanding these tradeoffs between production location, delivery method, and associated costs is crucial for developing an efficient and cost-effective hydrogen infrastructure. Careful study of hydrogen delivery logistics is therefore an important area of research and development as the hydrogen economy continues to evolve.

How Hydrogen Delivery Works

Hydrogen is currently transported from production facilities to points of use through a few primary methods. In regions with substantial, long-term demand, dedicated pipelines are often deployed to move large quantities of hydrogen efficiently. For smaller-scale or emerging markets, liquefaction and cryogenic liquid tanker trucks or gaseous tube trailers are more common delivery approaches.

Demonstrations are also underway to explore the use of chemical carriers, such as shipping hydrogen via barges, for large-scale export applications. At the point of use, additional infrastructure is required, including compression, storage, dispensers, meters, and contaminant detection/purification technologies.

The specific requirements for hydrogen delivery and dispensing can vary, but medium- and heavy-duty fuel cell vehicles typically need hydrogen compressed to 350-700 bar and dispensed at flow rates up to 10 kg/min. Developing the high-throughput technologies to meet these performance needs is an active area of research and development.

The optimal hydrogen delivery method depends on factors like the scale and stability of demand in a given region. Continued innovation across the storage, transportation, and dispensing components of the hydrogen supply chain will be crucial to support the growing hydrogen economy.

Research and Development Goals

Hydrogen delivery infrastructure is already commercially available, with several U.S. companies currently providing bulk hydrogen transport. This is in part because hydrogen has long been used in industrial applications, establishing some of the necessary supply chains and logistics.

However, widespread growth of hydrogen demand will require further research, development, and expansion of the existing infrastructure. One key challenge is that hydrogen has a relatively low volumetric energy density compared to other fuels. As a result, the transportation, storage, and final delivery of hydrogen to end-users can be a significant cost driver and contribute to energy inefficiencies.

Overcoming these transportation and logistics hurdles through continued innovation will be crucial to enable the large-scale adoption of hydrogen as an energy carrier. While the foundational delivery technology is commercially available today, the hydrogen economy's expansion will necessitate further R&D, supply chain development, and new infrastructure deployments.

Challenges

The key challenges to expanding hydrogen delivery infrastructure include reducing costs, improving energy efficiency, maintaining hydrogen purity, and minimizing leakage. Addressing these technical hurdles through continued research and development will be crucial.

Additionally, analyzing the tradeoffs between hydrogen production and delivery options as an integrated system is an important area for further study. Building a nationwide hydrogen infrastructure is a significant logistical challenge that will likely involve a combination of diverse technologies and approaches.

The specific delivery infrastructure needs and resources will vary regionally, depending on factors like the target market (urban, interstate, rural, etc.). As hydrogen demand grows and delivery technologies continue to evolve, the optimal infrastructure solutions are also expected to change over time.

Overall, overcoming the technical, economic, and logistical barriers to developing a robust, efficient, and widespread hydrogen delivery network is a complex, multifaceted challenge that will require sustained research, development, and strategic planning. Addressing these key issues will be crucial to enabling the large-scale adoption of hydrogen as an energy carrier.

Hydrogen Delivery, On-site Storage, And Dispensing Technologies

Hydrogen can be transported in several forms, including compressed gas, cryogenic liquid, and novel carrier materials. Gaseous hydrogen delivery methods include compression, pipelines, and tube trailers. Liquid hydrogen is another option for long-distance transport.

In addition to transportation, hydrogen requires on-site and bulk storage solutions. The stored hydrogen then needs to be efficiently dispensed to end-use applications, such as fueling vehicles.

The specific technologies used for hydrogen storage and dispensing can vary depending on the scale, location, and end-use requirements. Continued research and development are focused on improving the safety, cost-effectiveness, and efficiency of these critical hydrogen infrastructure components.

Overcoming the technical challenges across the hydrogen supply chain, from production to delivery and dispensing, will be essential to enable the widespread adoption of hydrogen as a clean energy carrier. Identifying the optimal combinations of hydrogen transport, storage, and fueling technologies for different applications and regions remain an active area of innovation.

Gaseous Hydrogen Delivery

Gaseous hydrogen is mostly transported either by truck-mounted storage tanks or through dedicated pipeline networks. As hydrogen is typically produced at relatively low pressures (20-30 bar), compression is required prior to transport.

Pipelines offer an efficient means of long-distance, high-volume hydrogen delivery, similar to how natural gas is transported today. This pipeline-based approach is widely used at oil refineries, where hydrogen is a critical input for petroleum upgrading processes.

While existing hydrogen pipelines are largely confined to industrial facilities, the development of larger-scale pipeline networks could enable broader distribution of gaseous hydrogen as an energy carrier. The ability to leverage established pipeline infrastructure and expertise is an advantage of this delivery method.

Ongoing research and investment continue to explore ways to enhance the safety, cost-effectiveness, and scalability of both truck-based and pipeline-based gaseous hydrogen transport solutions to support the growing hydrogen economy.

Gaseous hydrogen compression

Hydrogen is typically produced at relatively low pressures, between 20-30 bar, and must undergo compression prior to transportation. The most common compressor technologies used for this purpose are positive displacement compressors and centrifugal compressors.

Positive displacement compressors can be either reciprocating or rotary in design. These types of compressors physically trap a volume of gas and reduce its volume, thereby increasing the pressure.

In contrast, centrifugal compressors use rotating impellers to accelerate the gas flow, converting the kinetic energy into pressure rise. The choice between positive displacement and centrifugal technologies often depends on factors like flow rate, pressure ratio, and efficiency requirements.

Continued innovation in hydrogen compression technology, including improvements to reliability, energy efficiency, and cost-effectiveness, will be important to support the large-scale deployment of hydrogen infrastructure. The compression step is a critical midstream component of the hydrogen supply chain.

Reciprocating compressors use a motor with a linear drive to move a piston or a diaphragm back and forth.

1. This motion compresses the hydrogen by reducing the volume it occupies.
2. Reciprocating compressors, sometimes called recips for short, are the most used compressors for applications that require a very high compression ratio.

Rotary compressors compress through the rotation of gears, lobes, screws, vanes, or Rollers.

1. Hydrogen compression is a challenging application for positive displacement compressors due to the tight tolerances needed to prevent leakage.

Ionic compressors are similar to reciprocating compressors but use ionic liquids in place of piston.

1. These compressors do not require bearings and seals, two of the common sources of failure in reciprocating compressors.
2. Ionic compressors are available today at the capacities and pressures required at hydrogen fueling stations.

Centrifugal compressors are the compressor of choice for pipeline applications due to their high throughput and moderate compression ratio.

- Centrifugal compressors rotate a turbine at very high speeds to compress the gas.
- Hydrogen centrifugal compressors must operate at tip speeds 3 times faster than that of natural gas compressors to achieve the same compression ratio because of the low molecular weight of hydrogen.

Alternatives to mechanical compression that are currently in the research and development stage include the use of electrochemical reactions, metal hydrides, and ionic liquids.

Electrochemical compressors use proton exchange membranes flanked by electrodes and an external power source to drive the dissociation of hydrogen at the anode and its recombination at higher pressures at the cathode.

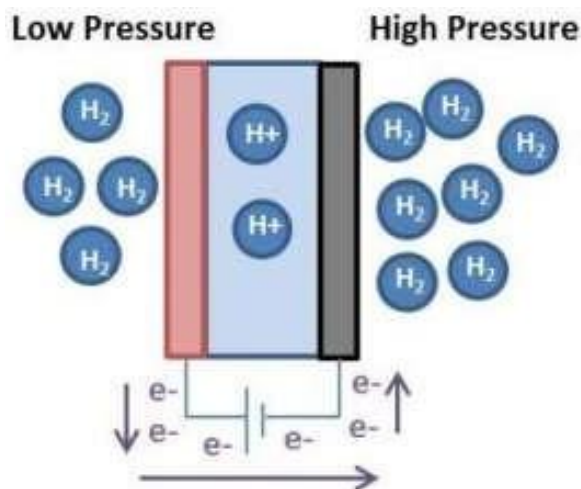


Figure 9. Electrochemical compressors.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Metal hydride compressors use metals that form hydrides via exothermic reactions and then release hydrogen at high pressures when heat is applied.



Figure 10. Metal hydride compressor.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Hydrogen Tube Trailers

Gaseous hydrogen is commonly transported via specialized truck-mounted tube trailers. These trailers consist of long, high-pressure storage cylinders that are stacked and secured on the vehicle. The hydrogen is compressed to very high pressures, typically 180 bar (2,600 psi) or higher, to maximize the carrying capacity.

Current Department of Transportation regulations in the U.S. limit standard tube trailers to a maximum pressure of 250 bar, though some exemptions have been granted to allow for even higher-pressure operation, up to 500 bar or more.

The most prevalent tube trailer designs utilize steel storage cylinders, which can carry roughly 380 kg of hydrogen per trailer. However, the use of lighter-weight composite storage vessels has enabled increased capacities of 560-900 kg per trailer.

This trailer-based gaseous hydrogen transport method is similar to how compressed natural gas is delivered in other parts of the world. As the hydrogen economy continues to grow, optimizing the capacity, safety, and cost-effectiveness of tube trailer technology will be crucial.



Figure 11. Tube Trailer.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Hydrogen Pipelines

Gaseous hydrogen can be transported through dedicated pipeline networks, much like the existing infrastructure used for natural gas delivery. Currently, there are approximately 1,600 miles of hydrogen pipelines operating in the United States, primarily owned by merchant hydrogen

producers and concentrated in regions with large industrial hydrogen users, such as oil refineries and chemical plants.

Leveraging existing pipeline infrastructure offers a relatively low-cost option for delivering large volumes of hydrogen. However, the high upfront capital costs of constructing new dedicated hydrogen pipelines present a significant barrier to expanding this delivery method.

Research efforts are focused on addressing technical challenges related to hydrogen pipeline transport, including the potential for hydrogen embrittlement of steel components, the need to control permeation and leaks, and the requirement for reliable and durable compression technology.

One promising solution being explored is the use of fiber-reinforced polymer (FRP) pipelines, which can offer up to 20% lower installation costs compared to traditional steel pipelines due to reduced welding requirements.

Another possibility is to adapt part of the existing natural gas pipeline network to accommodate hydrogen transmission, either by blending hydrogen with natural gas (up to around 15%) or by converting the pipelines to deliver pure hydrogen, though the latter may require more substantial modifications.

Overcoming the technical and economic barriers to expanding hydrogen pipeline infrastructure will be crucial to enabling the large-scale, cost-effective delivery of hydrogen as an energy carrier.



Figure 12. Pipelines

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Liquid Hydrogen Delivery

When high-volume transport is required in the absence of pipelines, hydrogen is commonly transported and delivered in liquid form. Liquefying hydrogen requires cooling it to cryogenic temperatures, below -253°C (-423°F), through an energy-intensive liquefaction process.

The trucks used to transport liquid hydrogen are referred to as liquid tankers or cryogenic liquid trucks. Liquefied hydrogen can be stored in large, insulated tanks at the liquefaction plant. However, some amount of the stored hydrogen will be lost through evaporation or "boil-off," especially when using smaller tanks with a high surface-to-volume ratio.

Liquefaction

The liquefaction process itself consumes a significant portion of the hydrogen's energy content, more than 30% using current technology. This makes the liquefaction step an expensive part of the hydrogen supply chain. Research to improve liquefaction efficiency and achieve greater economies of scale could help reduce the energy requirements and costs associated with this process.

Delivering liquid hydrogen can offer advantages over gaseous transport, particularly for high-volume applications where pipelines are not available. Ongoing efforts to optimize liquefaction technology and mitigate boil-off losses will be important to making liquid hydrogen logistics more viable and cost-effective.



Figure 13. Hydrogen Liquefier

(Source: U.S. DOE, "Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy", Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Liquid Tankers

For longer-distance hydrogen transport, the liquid form is often more economical than gaseous delivery. Liquid hydrogen is stored and transported in specialized, super-insulated cryogenic tanker trucks. After the hydrogen is liquefied, it is then loaded onto these delivery trucks and transported to distribution sites.

At the distribution sites, the liquid hydrogen is vaporized back into a high-pressure gaseous state for final dispensing and use. Transporting hydrogen in liquid form is advantageous over gaseous tube trailers, as the liquid tankers can carry a much larger mass of hydrogen per vehicle.

However, liquid hydrogen transport does present some challenges, including the potential for "boil-off" losses during the delivery process due to evaporation of the cryogenic liquid. Minimizing these boil-off losses through improved insulation and delivery logistics is an important consideration for the wider adoption of liquid hydrogen transport over longer distances.

Overall, the ability to leverage liquid hydrogen logistics enables more economical long-haul transport compared to gaseous delivery methods, making it a valuable option as the hydrogen infrastructure continues to expand.



Figure 14. Liquid Tanker

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Novel Hydrogen Carriers

Rather than storing and transporting hydrogen in its pure gaseous or liquid form, hydrogen can be stored in an alternative chemical state using specialized carrier materials. These hydrogen carriers allow the hydrogen to be more easily handled and transported compared to pure hydrogen.

Ongoing research is investigating various novel liquid and solid hydrogen carrier compounds and materials, such as metal hydrides, carbon nanostructures, and reversible hydrocarbons. The goal is to develop carriers that can efficiently "store" and then "release" the hydrogen at the point of use, such as during delivery to a fueling station or when loaded onto a fuel cell vehicle.

This carrier-based approach to hydrogen delivery represents a significant departure from the current methods of transporting pure hydrogen gas or liquid. However, the technology is still in the early stages of research and development, and it has not yet been demonstrated to be energy or cost-efficient compared to conventional hydrogen logistics.

Developing effective and practical hydrogen carrier systems could provide an alternative pathway for more convenient and potentially safer hydrogen distribution. But additional analyses and advances will be required before carrier-based hydrogen transport can be widely implemented.

On-Site and Bulk Hydrogen Storage

Hydrogen storage is utilized at various points along the supply chain, including at centralized production facilities, transportation hubs, and end-use locations. The current storage options for these on-site applications primarily consist of insulated liquid tanks and pressurized gaseous storage tanks.

These on-site storage systems allow hydrogen to be temporarily held and buffered at different stages of the supply and distribution process. This helps enable the efficient movement and delivery of hydrogen from production to consumption.

The choice between liquid or gaseous on-site storage depends on factors such as the scale of operations, delivery logistics, and the specific requirements of the given facility or application. Both insulated cryogenic liquid tanks and high-pressure gas tanks play important roles in managing hydrogen inventories and ensuring reliable supply across the hydrogen infrastructure.

Continued advancements in storage tank materials, designs, and integration will be important to further optimizing the on-site storage capabilities that support the growing hydrogen economy.

Table 1 The four types of common high pressure gaseous storage vessels.

Type I	All-metal cylinder
Type II	Load-bearing metal liner hoop wrapped with resin-impregnated continuous filament
Type III	Non-load-bearing metal liner axial and hoop wrapped with resin-impregnated continuous filament
Type IV	Non-load-bearing, non-metal liner axial and hoop wrapped with resin-impregnated continuous filament

(Source: Structurae, “Quebec Bridge”, Structurae.net, Retrieved June 2023 from <https://structurae.net/en/structures/quebec-bridge>)



Figure 15. Type I hydrogen storage cylinder.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

The most common hydrogen storage vessels are Type I metal cylinders. However, the newer Type III and Type IV composite-wrapped vessels, while currently more costly, are expected to become more economical as carbon fiber and manufacturing processes are improved.

Cryogenic liquid hydrogen tanks, known as dewars, are the predominant method for storing large quantities of hydrogen. These super-insulated, low-pressure vessels operate at the extremely low temperature of -253°C (-423°F) to maintain the hydrogen in a liquefied state.

Even with advanced insulation, some heat will inevitably enter the liquid hydrogen tank over time, causing the hydrogen to slowly boil off and the internal pressure to rise. To prevent the pressure from exceeding safe limits, the generated hydrogen gas must be regularly vented or captured and recompressed for alternative storage.

The tradeoffs between the different storage vessel technologies, as well as the challenges of managing liquid boil-off, are important considerations in developing efficient and cost-effective hydrogen storage and delivery infrastructure.



Figure 16. Cryogenic liquid hydrogen storage tank.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

To handle seasonal and other variations in hydrogen demand, a national hydrogen network may require the use of large-scale underground storage options. Certain geologic formations, such as salt caverns and aquifers, could potentially be leveraged for this bulk storage, similar to how the natural gas industry utilizes underground storage.

While there are already a few existing salt cavern facilities used for hydrogen storage today, the broader deployment of geologic storage for hydrogen, particularly to support transportation applications like fuel cell vehicles, would require further investigation. Potential concerns include understanding what impurities or contaminants could be introduced to the hydrogen through underground storage and ensuring the integrity and safety of the geologic storage systems.

Developing the capability for large-scale, centralized geologic hydrogen storage could play an important role in creating a reliable and responsive national hydrogen supply network. However, the viability and optimal application of this storage approach would depend on regional geological conditions and addressing any technical challenges related to underground hydrogen storage.

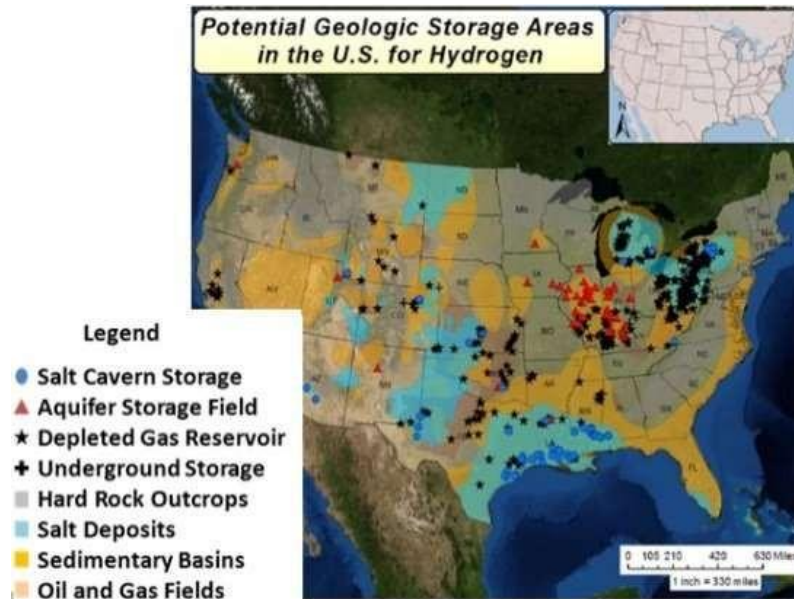


Figure 17. Potential Geologic Storage Areas in the U.S. For Hydrogen.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Dispensing Hydrogen Fuel to Vehicles

The design and infrastructure requirements for hydrogen fuel delivery are closely tied to the onboard storage technology used in vehicles. For the initial commercial hydrogen vehicles, 700 bar high-pressure gaseous storage has been the chosen approach, while 350 bar is common for heavier vehicles like buses and forklifts.

Standardized fueling protocols, such as those defined in the SAE J2601 document, have been established to enable safe and consistent hydrogen dispensing at these pressure levels. However, one of the major technical challenges is accurately metering the amount of hydrogen delivered during fueling.

Additional challenges include the limited number of hydrogen dispenser manufacturers and a lack of component standardization across the industry. To help address these issues, the U.S. Department of Energy is funding research to evaluate the performance and durability of hydrogen fueling hardware after extended use.

In parallel, alternative delivery approaches, such as cryogenic liquid or cryo-compressed hydrogen, are also being explored as potential options to improve the efficiency and user experience of hydrogen fueling infrastructure.

Overcoming the technical and logistical obstacles to reliable and accurate hydrogen dispensing will be crucial for enabling the widespread adoption of hydrogen-powered vehicles.

Hydrogen Storage

The Hydrogen and Fuel Cell Technologies Office (HFTO) is developing onboard automotive hydrogen storage systems that allow for a driving range of more than 300 miles while meeting cost, safety, and performance requirements.

The Importance of Studying Hydrogen Storage

Hydrogen storage is a critical enabling technology for the broader adoption and application of hydrogen and fuel cell systems. This includes use cases in stationary power, portable power, and transportation.

One key advantage of hydrogen is that it has the highest energy content per unit of mass compared to any other fuel. However, hydrogen has a low volumetric energy density at ambient conditions, necessitating the development of advanced storage methods that can achieve higher energy densities.

Overcoming the challenges of hydrogen's inherent low-density properties through innovative storage approaches is essential to unlocking the full potential of hydrogen as an energy carrier across a diverse range of end-use sectors. Advancing hydrogen storage solutions is a crucial step in driving the further commercialization and widespread deployment of hydrogen technologies.

How Hydrogen Storage Works

Hydrogen can be physically stored in two primary states - as a compressed gas or as a cryogenic liquid. Gaseous hydrogen storage typically requires high-pressure tanks operating at pressures between 350-700 bar (5,000-10,000 psi).

Storing hydrogen in a liquid state necessitates the use of cryogenic temperatures, as the boiling point of hydrogen at atmospheric pressure is -252.8°C. This presents significant technical and energy challenges for maintaining the liquid state.

Beyond physical storage as a gas or liquid, hydrogen can also be stored by adsorption on solid material surfaces or through absorption within solid-state media. These solid-state hydrogen storage approaches represent alternative methods for increasing the volumetric and gravimetric energy density compared to compressed or liquefied storage.

The selection of the optimal hydrogen storage technology depends on the specific application requirements, balancing factors like storage capacity, pressure/temperature demands, refueling needs, and overall system efficiency and cost.

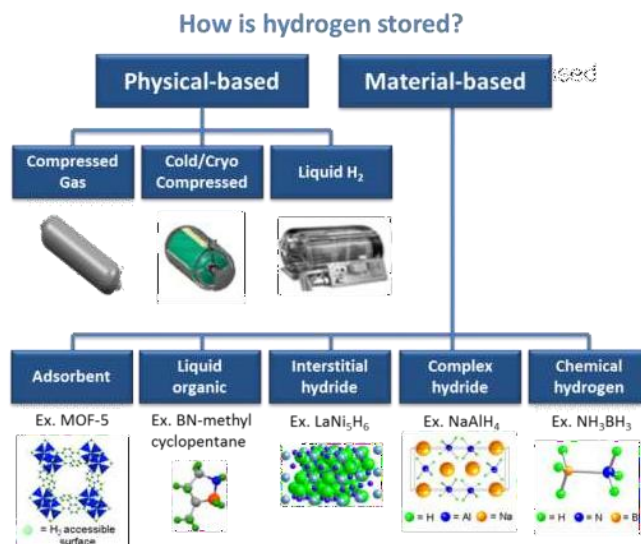


Figure 18. Hydrogen Storage

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Research and Development Goals

Hydrogen Fuel Technologies Office (HFTO) R&D Goals:

- Advance hydrogen storage system technologies and develop novel storage materials
- Meet DOE hydrogen storage targets for light-duty vehicles, material handling, and portable power applications
- By 2020, develop and verify automotive hydrogen storage systems that enable vehicle performance expectations for range, space, refueling time, and overall performance
 - Specific targets:
 - 1.5 kWh/kg system (4.5 wt.% hydrogen)
 - 1.0 kWh/L system (0.030 kg H₂/L)
 - \$10/kWh (\$333/kg stored H₂ capacity)

Challenges to Hydrogen Dispensing:

- Accurate metering of delivered hydrogen
- Limited manufacturers and lack of component standardization
- DOE funding research to characterize durability of fueling hardware
- Exploring alternative delivery options like cryo-compressed hydrogen

Supporting R&D Initiatives:

- Hydrogen Storage Engineering Center of Excellence conducts storage system analysis
- Hydrogen Materials—Advanced Research Consortium (HyMARC) studies hydrogen-material interactions for storage materials

Challenges

High-density hydrogen storage remains a significant challenge, particularly for transportation applications. Currently available storage options typically rely on storing hydrogen in a compressed gaseous state, which requires large-volume systems.

While the large storage footprint is less critical for stationary applications, it poses a greater challenge for mobile and portable use. Fuel cell vehicles, for example, require enough onboard hydrogen to provide a driving range of over 300 miles and enable quick refueling.

Some light-duty fuel cell electric vehicles (FCEVs) have achieved this target range using high-pressure compressed gas storage in large, bulky composite tanks. However, providing sufficient hydrogen storage across all light-duty vehicle platforms remains an engineering obstacle.

The importance of the 300-mile range target is underscored by the sales distribution data, which shows that most vehicles sold today exceed this minimum range requirement. Overcoming the density and volume constraints of hydrogen storage is crucial to enabling widespread FCEV adoption and broader deployment of hydrogen technologies beyond stationary uses.

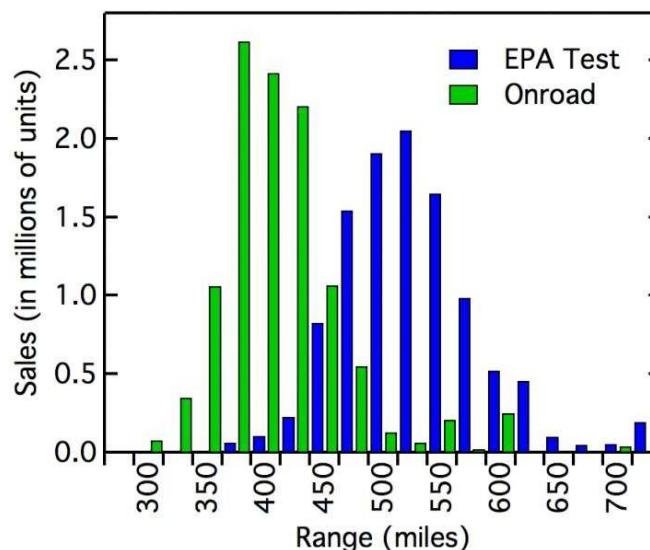


Figure 19. 2010 U.S. light-duty vehicle sales distribution by driving range

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

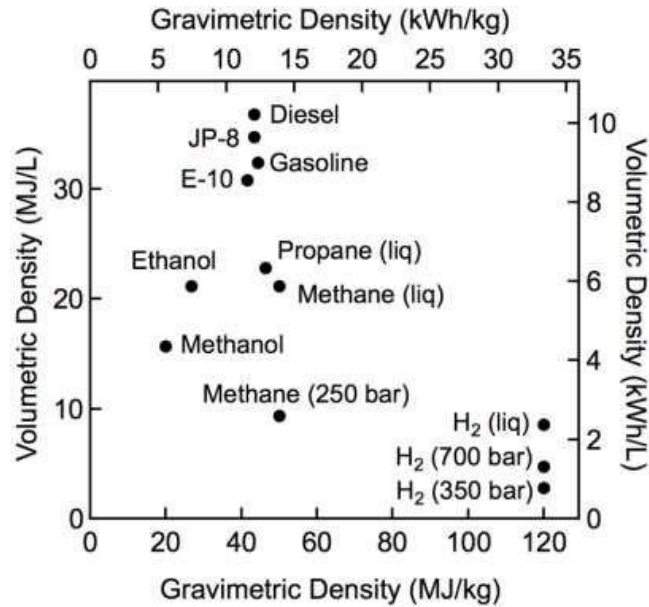


Figure 20. Comparison of specific energy (energy per mass or gravimetric density) and energy density (energy per volume or volumetric density) for several fuels based on lower heating values.

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

While hydrogen has a significantly higher specific energy content compared to gasoline - about 3 times higher at 120 MJ/kg vs 44 MJ/kg - the situation is reversed in terms of volumetric energy density. Liquid hydrogen has an energy density of only 8 MJ/L, whereas gasoline is 32 MJ/L.

This lower volumetric energy density of hydrogen presents challenges for onboard vehicle storage, where 5-13 kg of hydrogen is required to achieve the desired driving range across light-duty vehicle platforms.

To address these hydrogen storage challenges, the Hydrogen Fuel Technologies Office (HFTO) is pursuing a two-pronged strategic approach:

Near-term Pathway: Focus on compressed gas storage using advanced high-pressure (700 bar) fiber-reinforced composite vessels, with an emphasis on reducing system costs.

Long-term Pathway: Explore cold/cryo-compressed hydrogen storage to increase density through cryogenic temperatures and insulated pressure vessels. Also investigate materials-based storage technologies like sorbents, chemical hydrides, and metal hydrides that have the potential to meet DOE hydrogen storage targets.

The goal is to develop hydrogen storage solutions that can enable widespread adoption of fuel cell vehicles and other hydrogen applications by overcoming the inherent low-density challenges of hydrogen as an onboard fuel.

Physical Hydrogen Storage

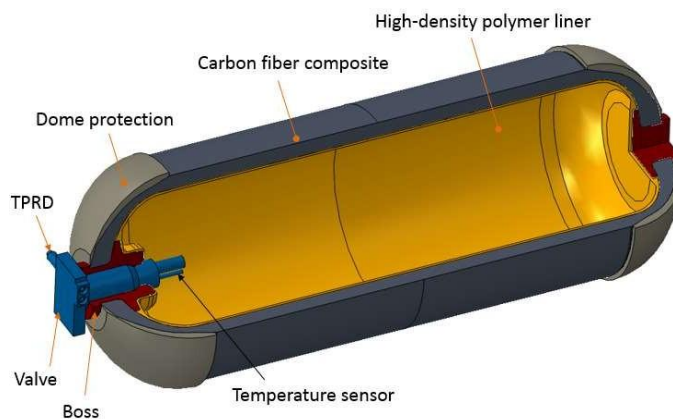
Compressed Gas Storage:

- Physical storage, using compressed gas tanks, is the most mature hydrogen storage technology
- The current near-term approach for onboard automotive storage is 350-700 bar (5,000-10,000 psi) compressed gas vessels

Liquid and Cryo-Compressed Storage:

- Liquid hydrogen storage (at the normal boiling point of 20 K) is commonly used for bulk transport, but has seen little development for onboard automotive applications
- "Cold" (sub-ambient above 150 K) and "cryogenic" (below 150 K) compressed hydrogen storage are being investigated as they can achieve higher hydrogen densities at reduced temperatures compared to ambient compressed gas

Overall, the physical storage of hydrogen, whether in compressed gas, liquid, or cryo-compressed forms, represents the most established technology pathway for onboard and bulk hydrogen storage applications. Continuing research aims to optimize the density, cost, and safety of these physical storage approaches.



TPRD = Thermally Activated Pressure Relief Device

Credit: Process Modeling Group, Nuclear Engineering Division, Argonne National Laboratory (ANL)

Figure 21. Components of a Pressurized Hydrogen Storage Tank

(Source: U.S. DOE, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>)

Technical Targets and Status

Compressed Hydrogen Storage Progress:

- Compressed hydrogen storage systems have been demonstrated and are commercially available, though at low production volumes, in hundreds of prototype fuel cell vehicles.
- While compressed storage has not yet fully met all of the U.S. Department of Energy's (DOE) targets for onboard automotive applications, significant progress has been made, with only a few key areas requiring further improvement.

Remaining Challenges:

- The key areas requiring further advancement for compressed hydrogen storage include improving the gravimetric density (weight), volumetric density (volume), and reducing the overall system cost.

Overall, compressed hydrogen storage represents an established technology that has made substantial progress in meeting the DOE's technical targets for onboard automotive applications. However, continued research and development is still needed to optimize the weight, volume, and cost of these compressed gas storage systems.

Materials-Based Hydrogen Storage

The Hydrogen and Fuel Cell Technologies Office (HFTO) is focusing its applied materials-based hydrogen storage R&D on developing materials and systems that have the potential to meet DOE's long-term targets for light-duty vehicle applications.

Materials Research Pathways:

- Metal hydrides: Improving volumetric/gravimetric capacity, kinetics, cycle life, and thermodynamics
- Chemical hydrogen storage: Enhancing capacity, transient performance, reducing impurities, and developing efficient regeneration
- Sorbents: Increasing adsorption temperatures, volumetric/gravimetric capacity through pore optimization

Measurement Best Practices:

- Understanding how material properties are influenced by composition, structure, pressure, temperature, and sample size is critical
- HFTO has commissioned a best practices manual to guide researchers on reliable hydrogen storage property measurement techniques

HyMARC Initiative:

- The Hydrogen Materials Advanced Research Consortium (HyMARC) was launched in 2015 as a collaborative national lab effort
- HyMARC focuses on foundational research to understand hydrogen interaction and release from storage materials

The overarching goal is to develop advanced materials-based hydrogen storage technologies that can meet DOE's long-term performance and cost targets for widespread adoption in light-duty vehicle applications.

Technical Targets and Status

Potential of Materials-Based Storage:

- Materials-based hydrogen storage research offers a long-term solution for onboard automotive applications, as well as opportunities for stationary and portable power
- This approach has the potential to significantly reduce storage pressures, increase gravimetric and volumetric capacities, and lower costs compared to conventional compressed gas storage

Past Materials Research Efforts:

- From 2005-2010, the DOE Hydrogen Storage program supported collaborative centers investigating over 400 materials for hydrogen storage applications
- These included the Metal Hydride, Hydrogen Sorption, and Chemical Hydrogen Storage Centers of Excellence

Current System Analysis:

- The Hydrogen Storage Engineering Center of Excellence (HSECoE) has analyzed the current status of systems using these materials
- HSECoE has developed system projection graphs comparing modeled material-based storage systems against DOE's 2020 targets

Overall, the materials-based hydrogen storage research pathway holds significant promise to address the key challenges facing onboard, stationary, and portable hydrogen storage applications if the materials can be further optimized and integrated into viable storage systems.

Fuel Cells

Fuel Cell Basics:

- Fuel cells use the chemical energy of hydrogen or other fuels to generate electricity in a clean and efficient manner.
- When hydrogen is the fuel, the only byproducts are electricity, water, and heat.

Versatility of Fuel Cells:

- Fuel cells are unique in their wide range of potential applications.
- They can utilize a diverse array of fuels and feedstocks.
- Fuel cell systems can scale from large utility power stations down to small laptop computers.

In essence, fuel cells leverage the chemical energy of hydrogen or other fuels to produce electricity through an electrochemical process that results in minimal emissions, making them a versatile and environmentally friendly power generation technology across a broad spectrum of applications.

The Importance of Studying Fuel Cells

Fuel cells offer a versatile and environmentally friendly power generation solution across a wide range of applications. Their ability to convert the chemical energy of fuels directly into electricity sets them apart from traditional combustion-based technologies.

In the transportation sector, fuel cells can power vehicles, from passenger cars to heavy-duty trucks, providing clean and efficient mobility. Beyond transportation, fuel cells can also be deployed in industrial, commercial, and residential buildings, supplying reliable and distributed power. Additionally, fuel cells show promise for long-term energy storage applications, such as reversible systems that can store excess renewable energy on the grid.

Compared to combustion engines, fuel cells can operate at higher efficiencies, often exceeding 60% in converting the chemical energy of the fuel directly into electricity. This direct conversion process avoids the energy losses inherent in combustion-based power generation.

Another key advantage of fuel cells is their significantly reduced emissions compared to combustion technologies. Hydrogen fuel cells emit only water, completely eliminating carbon dioxide emissions and addressing critical climate change challenges. Fuel cells also avoid the production of air pollutants that contribute to smog and health problems in local communities. Operationally, fuel cells are known for their quiet performance due to their few moving parts. This silent operation is an additional benefit, especially for applications in buildings and transportation.

Overall, the versatility, efficiency, and environmental benefits of fuel cells make them a promising clean energy technology that can enable the transition away from traditional combustion-based

power generation across multiple sectors. As fuel cell technologies continue to advance, their adoption is expected to grow, contributing to a more sustainable energy future.

How Fuel Cells Work

Fuel cells operate on a principle similar to batteries, but with a key difference - they do not need recharging. As long as fuel is supplied, a fuel cell can continuously generate electricity and heat.

At the core of a fuel cell is an electrolyte sandwiched between two electrodes - a negative anode and a positive cathode. Fuel, such as hydrogen, is fed to the anode, while air is supplied to the cathode.

At the anode, a catalyst separates the hydrogen molecules into protons and electrons. Protons are able to pass through the electrolyte to the cathode, while the electrons are forced to travel through an external circuit, generating an electric current.

At the cathode, the protons reunite with the electrons and oxygen from the air, producing water and heat as byproducts. This electrochemical process continues as long as the fuel and oxidant (air) are supplied to the respective electrodes.

Unlike batteries that store energy and need recharging, fuel cells convert the chemical energy of the fuel directly into electrical energy in a continuous process. This makes them a reliable and efficient source of power that can be utilized across a wide range of applications.

Research and Development Goals

The U.S. Department of Energy (DOE) is collaborating closely with national laboratories, universities, and industry partners to address critical technical challenges in fuel cell development. The key focus areas are:

Cost:

The DOE's research, development, and demonstration (RD&D) efforts aim to develop low-cost fuel cell stack and balance of plant (BOP) components, as well as advanced high-volume manufacturing approaches to reduce the overall system cost. Particular emphasis is placed on reducing the content of platinum group metals (PGMs) in catalysts, either through increased activity and utilization, or by exploring PGM-free catalyst alternatives for long-term applications.

Performance:

To improve fuel cell efficiency and performance, the RD&D work focuses on innovative materials and integration strategies. This includes developing ion-exchange membrane electrolytes with enhanced efficiency and durability at lower cost, improving membrane electrode assemblies (MEAs) for high power density, modeling system design and operating conditions, and developing

high-efficiency stacks with advanced BOP components like air management systems with low parasitic losses.

Durability:

Fuel cell applications require the maintenance of adequate performance over extended periods. The DOE has set lifetime targets of 8,000 hours for light-duty vehicles, 30,000 hours for heavy-duty trucks, and 80,000 hours for distributed power systems. To ensure reliability and robustness under dynamic and harsh operating conditions, the RD&D efforts focus on identifying and understanding fuel cell degradation mechanisms and developing materials and strategies to mitigate their effects. These include addressing challenges related to starting and stopping, freezing and thawing, impurities in the fuel and air, and humidity and dynamic load cycles that can stress the chemical and mechanical stability of fuel cell system materials and components.

Parts of a Fuel Cell

Polymer Electrolyte Membrane (PEM) fuel cells are the primary focus of research for fuel cell vehicle applications. The core of a PEM fuel cell is the Membrane Electrode Assembly (MEA), which consists of the ion-exchange membrane, catalyst layers, and gas diffusion layers (GDLs). To incorporate the MEA into a functional fuel cell, additional hardware components are used, such as:

- Gaskets - These provide a seal around the MEA to prevent leakage of the gaseous fuel and air.
- Bipolar Plates - These are used to assemble individual PEM fuel cells into a fuel cell stack. They also feature channels that allow the flow of the gaseous reactants (fuel and air) to the MEA.

The combination of the MEA and these supporting hardware components results in the complete PEM fuel cell structure, which is the subject of extensive research and development efforts to improve cost, performance, and durability for vehicle applications.

Membrane Electrode Assembly

The Membrane Electrode Assembly (MEA) is the core component of a PEM (Polymer Electrolyte Membrane) fuel cell. The MEA consists of the following key elements:

- Polymer Electrolyte Membrane (PEM):
 - Also known as a proton exchange membrane, the PEM is a specially treated polymer material that resembles common plastic wrap.
 - The PEM is the critical component that allows only positively charged ions to pass through, while blocking the passage of electrons.
 - This selective ion conductivity is essential for the proper functioning of the fuel cell's electrochemical reaction.

- For transportation applications, the PEM is made very thin, often less than 20 microns.
- Catalyst Layers:
 - The anode and cathode catalyst layers are located on either side of the PEM.
 - These layers facilitate the electrochemical reactions that generate the electrical current.
- Diffusion Media:
 - The diffusion media, or gas diffusion layers, are placed on the outer surfaces of the catalyst layers.
 - These porous materials allow the reactant gases (fuel and air) to access the catalyst layers effectively.

The careful integration of these three key components - the polymer electrolyte membrane, catalyst layers, and diffusion media - forms the membrane electrode assembly, which is the heart of a PEM fuel cell.

Catalyst Layers

The catalyst layers are critical components located on both sides of the polymer electrolyte membrane in a PEM fuel cell:

- Anode Catalyst Layer:
 - This layer, situated on one side of the membrane, contains nanometer-sized platinum particles dispersed on a high-surface-area carbon support.
 - The platinum catalyst facilitates the splitting of hydrogen molecules into protons and electrons on the anode side.
- Cathode Catalyst Layer:
 - This layer, located on the other side of the membrane, also contains the platinum-based catalyst.
 - The platinum catalyst in the cathode layer enables the reduction of oxygen, allowing it to react with the protons generated at the anode to produce water.
- Ionomer Integration:
 - An ion-conducting polymer, known as an ionomer, is mixed into the catalyst layers.
 - The ionomer allows the protons to travel through the catalyst layers, facilitating the overall electrochemical reaction.

The intimate integration of the platinum-based catalyst, carbon support, and ionomer polymer creates an effective catalyst layer that enables the key electrochemical processes in the PEM fuel cell - the oxidation of hydrogen at the anode and the reduction of oxygen at the cathode.

Gas Diffusion Layers

The Gas Diffusion Layers (GDLs) are critical components situated outside the catalyst layers in a PEM fuel cell. The GDLs serve two key functions:

1. Reactant Transport:

1. The porous structure of the GDLs allows the reactant gases (hydrogen and oxygen) to rapidly diffuse into the catalyst layers.
2. This ensures an effective supply of the necessary reactants to the electrochemical reaction sites.
2. Water Management:
 1. The GDLs are typically made of carbon paper, with the carbon fibers partially coated with polytetrafluoroethylene (PTFE).
 2. The hydrophobic PTFE coating helps prevent excessive water buildup within the pores, keeping them open for efficient gas diffusion.
 3. In many cases, the inner surface of the GDL is further coated with a thin layer of high-surface-area carbon mixed with PTFE, known as the microporous layer.
 4. This microporous layer can help balance water retention (needed to maintain membrane conductivity) and water release (needed to keep the pores open for reactant access).

The strategic design of the GDLs, incorporating porous structures and hydrophobic coatings, is crucial for ensuring the effective transport of reactants to the catalyst layers and the proper management of water, both of which are essential for the optimal performance of the PEM fuel cell.

Hardware

The Membrane Electrode Assembly (MEA) is the core component where power is generated in a fuel cell, but additional hardware components are required to enable effective MEA operation:

1. Bipolar Plates:
 - Each individual MEA produces less than 1 V under typical operating conditions, so multiple MEAs are usually connected in series to provide a usable output voltage.
 - The MEAs are stacked on top of each other, with each cell sandwiched between two bipolar plates.
 - These bipolar plates, made of materials like metal, carbon, or composites, serve two main purposes:
 1. Provide electrical conduction between the cells in the stack.
 2. Offer physical strength and support to the overall fuel cell stack.
 - The surfaces of the bipolar plates typically contain a "flow field" - a set of channels machined or stamped into the plate to allow the reactant gases to flow over the MEA.
 - Additional channels inside the bipolar plates may be used to circulate a liquid coolant for thermal management.
2. Gaskets:
 - Each MEA in the fuel cell stack is sandwiched between two bipolar plates, but gaskets must be added around the edges of the MEA to create a gas-tight seal.

- These gaskets are usually made of a rubbery polymer material to ensure proper sealing between the components.

The bipolar plates and gaskets, in addition to the MEA, are the critical hardware components that enable the effective operation of a fuel cell system by facilitating electrical connectivity, gas distribution, and mechanical integrity.

Fuel Cell Systems

Fuel cell systems are complex, with the specific design varying depending on the fuel cell type and target application. However, there are several common core components found in many fuel cell systems:

1. Fuel Cell Stack
2. Fuel Processor
3. Power Conditioners
4. Air Compressors
5. Humidifiers

These core components work together to enable the efficient and reliable operation of a fuel cell system, converting the primary fuel into usable electrical power.

Fuel Cell Stack

The fuel cell stack is the core component of a fuel cell power system. It generates electricity through electrochemical reactions, producing direct current (DC) output. A single fuel cell generates less than 1 volt, which is insufficient for most applications. To increase the voltage, multiple fuel cells are typically combined in series to form a fuel cell stack, with a typical stack containing hundreds of individual cells.

The power output of a fuel cell stack depends on various factors, including the fuel cell type, cell size, operating temperature, and the pressure of the reactant gases supplied to the cells. By optimizing these parameters, fuel cell stacks can be designed to meet the specific power requirements of different applications.

Fuel Processor

The fuel processor is responsible for converting the input fuel into a form that can be used by the fuel cell. Depending on the type of fuel and fuel cell, the fuel processor may range from a simple sorbent bed to remove impurities, to a complex combination of reactors and purification systems.

If the system uses a hydrogen-rich conventional fuel, such as methanol, gasoline, diesel, or gasified coal, a reformer is typically employed to convert the hydrocarbons into a hydrogen-rich "reformat" gas mixture. The reformat then undergoes further processing, including conversion of carbon monoxide to carbon dioxide and removal of other impurities, before being supplied to

the fuel cell stack. This purification step is crucial to prevent "poisoning" of the fuel cell catalysts, which can degrade the efficiency and lifespan of the fuel cell.

Some fuel cell types, such as molten carbonate and solid oxide, operate at high enough temperatures to enable internal reforming within the fuel cell itself. However, even in these cases, impurities must be removed from the unreformed fuel before it reaches the fuel cell.

Regardless of the fuel processing approach, fuel cells generally emit less carbon dioxide compared to internal combustion engines due to their higher energy conversion efficiency.

Power Conditioners

Fuel cells produce electricity in the form of direct current (DC), where electrons flow in a single direction. However, many applications, such as homes and workplaces, use alternating current (AC), where the flow of electrons reverses direction on alternating cycles.

To interface the fuel cell's DC output with AC-based equipment or the utility grid, power conditioning is required. This includes controlling the current, voltage, frequency, and other electrical characteristics to meet the specific needs of the application.

Power conversion and conditioning devices, such as inverters and conditioners, are used to adapt the fuel cell's electrical output to the appropriate form, be it AC or DC. While this conversion process results in a slight reduction in overall system efficiency, typically in the range of 2-6%, it is necessary to ensure the fuel cell's electricity can be utilized effectively.

By properly conditioning the power, fuel cell systems can be integrated with a wide variety of electrical loads, from simple motors to complex utility grids, enabling their broad application across various sectors.

Air Compressors

Increasing the pressure of the reactant gases, such as air and hydrogen, can improve the performance of fuel cells. To achieve this, many fuel cell systems incorporate air compressors that raise the pressure of the inlet air to 2-4 times the ambient atmospheric pressure.

This is particularly important for transportation applications, where the air compressor should have an efficiency of at least 75% to optimize the overall system performance.

In some cases, an expander may also be included in the system to recover power from the high-pressure exhaust gases. The expander should have an efficiency of at least 80% to maximize the energy recovery and improve the overall system efficiency.

By carefully managing the reactant gas pressures using compressors and expanders, fuel cell systems can operate at optimal performance levels, making them more suitable for a wide range of applications, including transportation.

Humidifiers

Fuel cells, particularly those with polymer electrolyte membranes (PEM), require the membrane to be well-hydrated to function efficiently. To maintain the appropriate moisture level, many fuel cell systems incorporate a humidifier for the inlet air.

The humidifier typically consists of a thin membrane, which may be made of the same material as the PEM itself. By flowing the dry inlet air on one side of the humidifier and the moist exhaust air on the other side, the water produced during the fuel cell's operation can be recycled to keep the PEM properly hydrated.

This humidification process is crucial for ensuring the PEM fuel cell operates at its optimal performance level, as a dry membrane can significantly degrade the cell's efficiency. By recycling the water produced by the fuel cell, the humidifier helps to maintain the required moisture levels within the system.

Fuel Cell Types

Fuel cells are primarily classified based on the type of electrolyte they employ. This electrolyte choice determines the specific electrochemical reactions that take place within the cell, the required catalysts, the operating temperature range, the suitable fuels, and various other characteristics.

These inherent differences between fuel cell types ultimately impact the applications for which they are best suited. For example, some fuel cell designs may be more appropriate for transportation, while others may be better suited for stationary power generation.

Currently, there are several fuel cell types under development, each with its own unique advantages, limitations, and potential use cases. The specific electrolyte material is a key factor that distinguishes these fuel cell technologies and shapes their respective performance, efficiency, and applicability across different sectors.

Polymer Electrolyte Membrane (PEM) Fuel Cells

PEM fuel cells, also known as proton exchange membrane fuel cells, offer several advantages that make them well-suited for various applications. They deliver high power density and have a relatively low weight and volume compared to other fuel cell types.

PEM fuel cells utilize a solid polymer as the electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. This design allows them to operate on hydrogen fuel and oxygen from the air, with water as the only byproduct.

These fuel cells typically run at relatively low temperatures, around 80°C (176°F), which enables quick start-up and better durability due to reduced wear on system components. However, the use of a noble-metal catalyst, such as platinum, adds to the overall system cost.

Additionally, the platinum catalyst is sensitive to carbon monoxide poisoning, requiring an additional reactor to reduce carbon monoxide levels in the fuel gas if the hydrogen is derived from a hydrocarbon source. This further increases the system's complexity and cost.

PEM fuel cells are well-suited for transportation applications, including cars, buses, and heavy-duty trucks, as well as some stationary power generation scenarios. Their combination of high-power density, low weight and volume, and relatively low-temperature operation make them a promising technology for various sectors.

Direct Methanol Fuel Cells

While most fuel cells are powered by hydrogen, which can be fed directly or generated through reforming of hydrogen-rich fuels, direct methanol fuel cells (DMFCs) utilize pure methanol as the fuel source.

In a DMFC, the methanol is typically mixed with water and fed directly to the fuel cell anode, eliminating the need for a separate hydrogen generation step. This simplifies the fuel cell system design compared to those that rely on hydrogen.

Furthermore, methanol has a higher energy density than hydrogen, though less than traditional liquid fuels like gasoline or diesel. This advantage, along with methanol's ease of transportation and distribution using existing infrastructure, makes DMFCs well-suited for portable applications such as powering cell phones or laptop computers.

The direct use of methanol in these fuel cells avoids many of the fuel storage challenges associated with some other fuel cell technologies. This makes DMFCs an attractive option for small-scale, portable power generation needs where the energy density and infrastructure compatibility of methanol can be leveraged.

Alkaline Fuel Cells

Alkaline fuel cells (AFCs) are one of the earliest fuel cell technologies developed and were widely used in the U.S. space program to generate electricity and water onboard spacecraft. These fuel

cells use a potassium hydroxide solution as electrolyte and can employ a variety of non-precious metal catalysts.

In recent years, a new type of AFC has been developed that uses a polymer membrane as the electrolyte, similar to conventional proton exchange membrane (PEM) fuel cells but with an alkaline membrane instead of an acid membrane. This high-performance design is enabled by the rapid electrochemical reactions that occur in these cells, allowing for efficiencies exceeding 60% in space applications.

A key challenge for both liquid electrolyte and membrane-based alkaline fuel cells is susceptibility to carbon dioxide (CO₂) poisoning. Even small amounts of CO₂ from the air can degrade performance and durability due to carbonate formation. Liquid electrolyte AFCs can mitigate this to some degree through electrolyte recirculation, but this introduces other issues like shunt currents.

Alkaline membrane fuel cells (AMFCs) address many of the concerns with liquid electrolyte AFCs, including reduced CO₂ sensitivity. However, CO₂ tolerance, membrane conductivity and durability, water management, and other technical hurdles still need to be overcome for AMFCs to match the performance and longevity of PEM fuel cells. AMFCs are currently being explored for applications in the watt to kilowatt power range.

Phosphoric Acid Fuel Cells (PAFCs)

Phosphoric acid fuel cells (PAFCs) use a liquid phosphoric acid electrolyte contained within a Teflon-bonded silicon carbide matrix, along with porous carbon electrodes containing a platinum catalyst. This electrochemical design is considered the "first generation" of modern fuel cells and is one of the most commercially mature cell types.

PAFCs are typically used for stationary power generation, though some have also powered larger vehicles like city buses. Compared to proton exchange membrane (PEM) fuel cells, PAFCs are more tolerant of impurities in reformed fossil fuels, as they are less susceptible to carbon monoxide poisoning of the platinum catalyst.

When used for combined heat and power (cogeneration) applications, PAFCs can achieve over 85% overall efficiency. However, their standalone electricity generation efficiency of 37-42% is only slightly better than conventional combustion-based power plants. PAFCs also tend to be larger, heavier, and more expensive than other fuel cell types, due in part to the higher platinum loadings required in the electrodes.

Despite these drawbacks, PAFCs represent an important milestone in the development of practical fuel cell technologies, paving the way for further advancements in both stationary and mobile applications.

Molten Carbonate Fuel Cells (MCFCs)

Molten carbonate fuel cells (MCFCs) are high-temperature fuel cell technology being developed for power generation applications such as natural gas and coal-based power plants. The electrolyte in MCFCs is a molten carbonate salt mixture suspended in a porous, inert ceramic matrix.

The high operating temperature of around 650°C allows MCFCs to use non-precious metal catalysts, reducing costs compared to other fuel cell types like phosphoric acid fuel cells (PAFCs). This high-temperature design also enables internal reformation of hydrocarbon fuels like natural gas and biogas, eliminating the need for a separate external reformer.

When coupled with a turbine, MCFC systems can reach electrical generation efficiencies of 65%, significantly higher than the 37-42% efficiency of PAFC plants. With waste heat recovery, overall MCFC system efficiencies can exceed 85%.

The primary challenge with current MCFC technology is durability - the high temperatures and corrosive electrolyte accelerate component breakdown and reduce cell lifetimes, which are currently around 40,000 hours or 5 years. Ongoing research is exploring corrosion-resistant materials and cell designs to improve MCFC longevity without sacrificing performance.

Solid Oxide Fuel Cells (SOFCs)

Solid oxide fuel cells (SOFCs) use a hard, non-porous ceramic compound as an electrolyte. This high-temperature design, with operating temperatures up to 1,000°C, offers several key advantages over other fuel cell types:

1. High conversion efficiency of around 60%, which can exceed 85% when capturing waste heat for combined heat and power (CHP) applications.
2. The ability to internally reform a variety of hydrocarbon fuels like natural gas and biogas, eliminating the need for a separate external reformer.
3. Tolerance of impurities like sulfur and carbon monoxide, which can even be used as fuel.
4. No requirement for precious metal catalysts, reducing material costs.

However, the high operating temperatures also present challenges, such as:

1. Slow startup times and the need for extensive thermal shielding, which may limit transportation applications.
2. Stringent material durability requirements due to the corrosive environment.

To address these drawbacks, ongoing research is exploring the potential for developing lower-temperature SOFC systems operating at 700°C or below. While these lower-temperature SOFCs

have not yet matched the performance of higher-temperature designs, the focus is on identifying suitable materials that can function reliably in this more moderate temperature range.

Reversible fuel cells

Reversible fuel cells are a versatile technology that can both generate electricity from hydrogen and oxygen, as well as store excess energy by using electricity to split water into hydrogen and oxygen through electrolysis.

Unlike conventional fuel cells which only operate in the electricity generation mode, reversible fuel cell systems can switch between power generation and energy storage functions. When there is excess power available from sources like solar or wind, the reversible fuel cell can utilize this electricity to produce and store hydrogen fuel. Then, when electricity is needed, the stored hydrogen can be converted back into power through the fuel cell process.

This bidirectional capability makes reversible fuel cells a promising technology to support the integration of intermittent renewable energy sources onto the grid. They can help store excess renewable generation during high-production periods and then release that stored energy as needed, providing an effective way to balance supply and demand.

The ability to both generate electricity from hydrogen and produce hydrogen from electricity gives reversible fuel cells a unique flexibility that could be a key enabler for increasing the penetration of variable renewable energy technologies in the future.

References

1. Office of Energy Efficiency and Renewable Energy of the United States Department of Energy (U.S. DOE) website, “Learn How DOE and Other Federal Agencies Are Implementing the National Clean Hydrogen Strategy”, Energy.gov, retrieved April 2024 from <https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office>
2. Youtube, “NREL Photoelectrolysis”, youtube.com, Retrieved April 2024 from <http://youtu.be/6GT4Oiig1-8>
3. *Hydrogen – what is it?* Hydrogen energy explained | National Grid Group. <https://www.nationalgrid.com/stories/energy-explained/what-is-hydrogen>