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Subcommittee on Energy

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Chairman Bowman, Ranking Member Weber, and members of the Subcommittee, thank you for this opportunity to discuss the state of hydrogen research and development in the United States and how these efforts will benefit all Americans.

My name is Keith Wipke, and I have been the laboratory program manager for the Fuel Cell and Hydrogen Technologies program at the National Renewable Energy Laboratory (NREL) for almost a decade. In this role, I strive to ensure NREL's hydrogen and fuel cell research supports lowering the cost and increasing the scale of technologies to make, store, move, and use hydrogen across multiple energy sectors.

Prior to this role, for 9 years, I led NREL's participation in the U.S. Department of Energy (DOE) National Hydrogen Learning Demonstration,[1] where we were able to use this large-scale demonstration to feed back the current technology challenges into DOE's hydrogen research, development, demonstration, and deployment program[2] and, ultimately, help pave the way for California's launch of the light-duty fuel cell electric vehicle market. This effort was later expanded under NREL's Technology Validation activity to evaluate fuel cell technology in multiple applications, including cars, buses, forklifts, backup power, and stationary power. In 2013, DOE designated this capability as the National Fuel Cell Technology Evaluation Center at NREL.[3,4] I have served as NREL's senior hydrogen representative on several boards of state and national hydrogen coalitions and partnerships, and am a 35-year member of both the American Society of Mechanical Engineers and SAE International.

NREL's Fuel Cell & Hydrogen Technologies program includes research supporting renewable hydrogen production, storage, fuel cells, manufacturing quality control, analysis, infrastructure, technology validation, and helping to realize the larger vision of DOE's Hydrogen at Scale (H2@Scale) initiative.[5]

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1 National Renewable Energy Laboratory (NREL). 2022. "Hydrogen Fuel Cell Electric Vehicle Learning Demonstration." Accessed February 14, 2022. https://www.nrel.gov/hydrogen/learning-demo.html.

2 U.S. Department of Energy. 2022. "U.S. Department of Energy Hydrogen Program." Accessed February 14, 2022. https://www.hydrogen.energy.gov/.

3 U.S. Department of Energy Office of Energy Efficiency & Renewable Energy (EERE). 2013. "Energy Department Launches National Fuel Cell Technology Evaluation Center to Advance Fuel Cell Technologies." *EERE Network News*, September 12, 2013. https://www.energy.gov/eere/articles/energy-department-launches-national-fuel-cell-technology-evaluation-center-advance.

4 NREL. 2022. "National Fuel Cell Technology Evaluation Center." Accessed February 14, 2022. https://www.nrel.gov/hydrogen/nfctec.html.

5 Hydrogen and Fuel Cell Technologies Office (HFTO). 2022. "H2@Scale." Accessed February 14, 2022. https://www.energy.gov/eere/fuelcells/h2scale.

Our program has a clear vision: *Hydrogen will be a key means of transporting, storing, and transforming energy at the scale necessary to enable a clean and vibrant economy for all.* Our goal is that NREL's efforts will improve the economic viability of making, storing, moving, and using hydrogen technologies in conjunction with key government and industry partners who will accelerate their adoption.

In this testimony, I will discuss hydrogen research, development, and demonstration activities at NREL, including hydrogen production, storage, transportation, and utilization. I will also discuss the broader role of hydrogen in decarbonizing the energy and industrial sectors, as well as opportunities and challenges for hydrogen deployment and utilization.

As part of this testimony, I'll also be focusing on the role of NREL and other DOE national laboratories in this important work and our world-class capabilities throughout the DOE system. It's important to note the collaborations we've formed with partners, both nationally and globally, so I'll be highlighting some of those success stories as well.

Thank you, again, for the opportunity to testify today. I'd like to open with some background on NREL, our vision for the future, and how we continue to support DOE and the administration's goals.

NREL's Overarching Strategy

NREL plays a leading role in the transition to an advanced, sustainable, and low-carbon-emissions energy system for our nation and the world. Our long-term vision of "a clean energy future for the world" is ambitious, responding to the urgency and size of the challenges before us.

NREL executes its mission through a portfolio of research in renewable power technologies, energy efficiency, sustainable transportation, and integrated and optimized energy systems. NREL's foundational work in support of DOE's objectives has led the nation and the world in the transition to clean energy. Our work spans from basic science to demonstration and deployment—in other words, from atoms to applications. Looking forward, we must build off this foundation to scale our impact, accelerate our progress, and expand our capabilities to achieve our vision within a meaningful timeline.

Our science and technology mission is more important than ever. To respond with the urgency demanded by climate change, we must accomplish as much in the next 10 years as we have during the past 40. Realizing an energy sector that is free of carbon emissions will depend on significant achievement in technology development, deployment, and approaches yet to be defined. Even as we expand into new areas, NREL will remain focused on our science and technology mission. We deliver our mission in partnership with the Department of Energy and many other critical partners and collaborators.

Achieving NREL's vision and the ambitious goals of our nation will require accelerating the speed and scale at which we research, develop, and deploy clean energy technologies. Research and development (R&D) of technologies across DOE's energy portfolio has formed the foundation of NREL's science and engineering contributions for decades and will continue to be central to NREL's research agenda. Continued growth and impact of our core science and technology mission space is at the center of a transition to an electricity sector free of carbon emissions by 2035, as well as net-zero greenhouse gas emissions economywide by 2050. Across research areas in transportation, industry, utilities, and other sectors, NREL is conducting research that will deliver the benefits of clean energy more broadly, embedding environmental and energy justice every step of the way. NREL's work—in partnership with the Department of Energy, other national laboratories, academia, and others—will put our nation on a path toward achieving its clean energy goals.

The Opportunity

Throughout the world, hydrogen is increasingly recognized as the critical, central component for a clean, sustainable, efficient, and economic energy system. Hydrogen is remarkable for its ability to carry, store, and interconvert energy—its chemical energy can be used for clean and efficient chemical conversions to products and fuels, as well as electricity and heat generation. Hydrogen can be used as a storage medium, even for seasonal storage, to enable larger-scale deployment and use of renewable electricity. As an energy carrier, hydrogen is central to cross-sector coupling and clean, efficient transportation fuels and industrial processes, enabling decarbonization of products and services while meeting customer expectations.

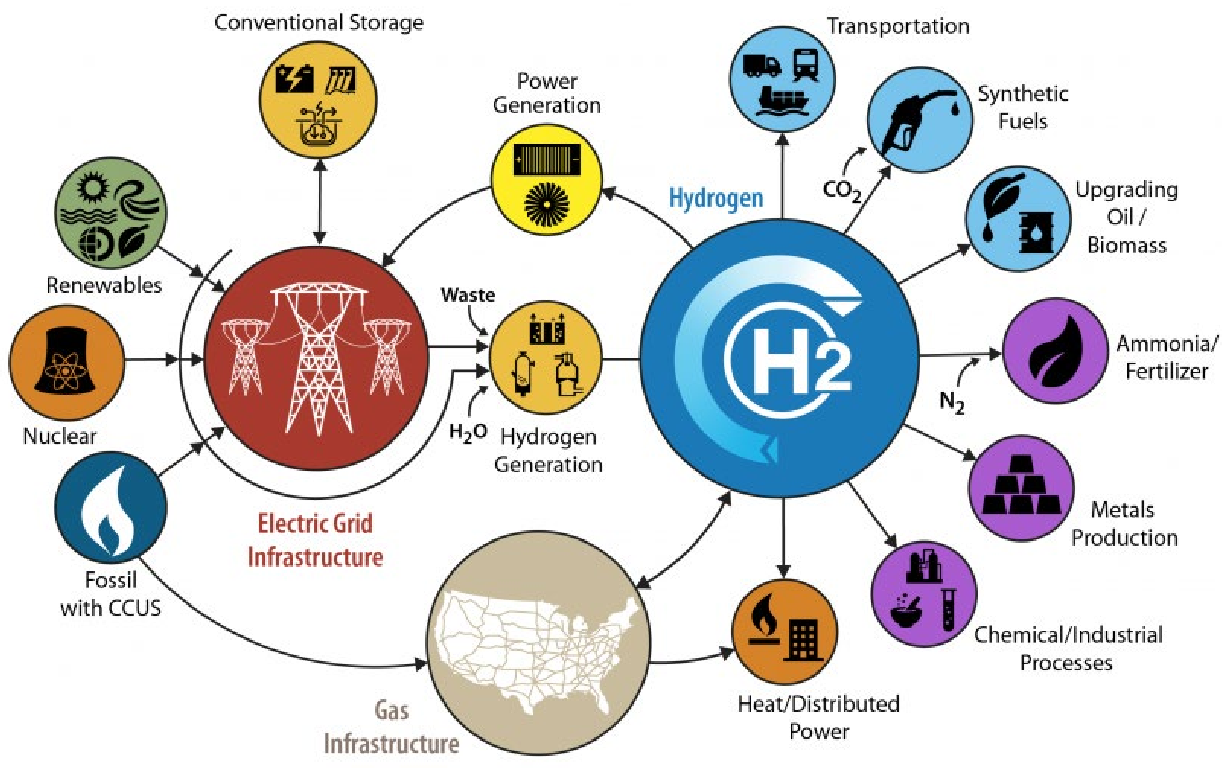

Figure 1. DOE's H2@Scale initiative supports the technology goals to make, move, store, and use hydrogen. Through this initiative, DOE's national laboratories are working with industry partners to advance the large-scale production, transport, storage, and use of hydrogen across multiple sectors of the economy.

H2@Scale Vision

DOE's H2@Scale vision is a comprehensive view of how hydrogen can play a major role of our future energy system. This vision encompasses all aspects of hydrogen: making it, moving it, storing it, and using it.

A unique aspect of hydrogen is its "sector-coupling" ability; it can connect industries that have not typically been able to engage with renewable power or decarbonization.

- **MAKE:** Any clean source of energy can be used to produce hydrogen, either on-site where it will be used, or stored and moved to the ultimate point of use.
- **MOVE:** Hydrogen can be transported through different means (dedicated hydrogen pipelines, natural gas pipelines, ship, rail, or truck) to get it to where it will be used.
- **STORE:** The hydrogen gas can be stored in bulk, such as in underground salt caverns, or in tanks as a pressurized gas or liquid. Hydrogen provides the unique ability to store large amounts of energy in a stable form to allow for long-duration energy storage. Another example is seasonal storage, which will be necessary to enable a high penetration of renewable energy.
- **USE:** In addition to being able to generate electricity, hydrogen can also be used to support our **transportation system**, either directly as a hydrogen fuel or through conversion into a liquid fuel for hard-to-decarbonize sectors such as trucks, marine, and aviation. It can also support our **agricultural sector** by creating green ammonia/fertilizer, replace the use of carbon fuels in **metal production** and **chemical or industrial processes**, or generate local heat or power for **buildings**.

Decarbonizing All Sectors of the U.S. Energy System

Hydrogen has a unique ability to couple different sectors of our economy in a way that electricity and batteries alone cannot, providing benefits far beyond just a zero-emissions transportation fuel.

One of the key hydrogen production technologies researchers are further developing is electrolysis, a technique that uses direct electric current to split water into hydrogen and oxygen. Because electrolysis is a controllable electric load, hydrogen production can improve the operation and stability of the grid, support increased penetration of wind and solar electricity generation, and support vehicle electrification. For example, through funding from DOE's Hydrogen and Fuel Cell Technologies Office (HFTO), NREL has demonstrated that a grid-integrated electrolyzer can stabilize fluctuations from a highly renewable grid as well as the demand of an electric vehicle fast-charging station, presenting opportunities to use electrolyzers to enable resiliency and grid stability.

Hydrogen can serve as a primary platform for the decarbonization of hard-to-abate sectors: industry, heavy-duty transportation, and a highly renewable grid enabled through long-duration storage. Hydrogen can connect the electric grid to transportation through low-greenhouse-gas fuels, either used directly as hydrogen or converted to other synthetic fuels where high-density liquid fuels are more critical.

Hydrogen can also be used as a feedstock in processes to produce renewable natural gas,[6] blended directly with natural gas in pipelines,[7,8] or combined with waste products such as carbon dioxide (CO_2) to store inexpensive renewable electricity as hydrogen and carbon bonds in the form of high-density liquid fuels and valuable chemicals.

Additionally, hydrogen is a way to decarbonize the industrial sector by providing energy, heat, and the basic elemental building blocks that can be combined with nitrogen and carbon to form compounds such as plastics and other materials required to make today's products.

Improved Economy and Energy Security

Developing the technologies to produce clean hydrogen could have a large economic impact on our country. The international Hydrogen Council roadmap[9] projects that by 2050, hydrogen will provide $2.5 trillion in global revenue, 30 million jobs, and 18% of the total global energy demand. The rest of the world sees this opportunity, and there is an international competition to become the dominant nation to produce cheap, clean hydrogen and export the production equipment to others.

The United States has an opportunity to bring those jobs and revenues here rather than letting other countries take the lead. Additionally, the implementation of H2@Scale in the United States enables increased energy security and valorization of U.S. renewable resources by providing competitive cost advantages in sectors such as fuels, products, and manufacturing.

Key Challenges

Cost

Widespread deployment of hydrogen will require cost reductions, as current large-scale clean production costs are typically $5–$6/kg or higher. DOE's Hydrogen Shot[10] initiative seeks to reduce the cost of clean hydrogen by 80% to $1/kg in a decade. Launched in June 2021, the initiative establishes a framework and foundation for clean hydrogen deployment in the American Jobs Plan,[11] which includes support for demonstration projects. Industries are beginning to implement clean hydrogen to reduce emissions, yet many hurdles remain to deploying it at scale. Achieving the Hydrogen Shot's 80% cost reduction goal can unlock new markets for hydrogen, including steel manufacturing, clean ammonia, energy storage, and zero-emission heavy-duty trucks.

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[6] NREL. 2021. "Breakthrough Methods Help Integrate Renewable Hydrogen With Waste Carbon Dioxide To Produce Clean Fuels, Chemicals, and More." *NREL News & Feature Stories*, August 31, 2021. https://www.nrel.gov/news/features/2021/breakthrough-methods-help-integrate-renewable-hydrogen-with-waste-carbon-dioxide.html.

[7] NREL. 2020. "HyBlend Project To Accelerate Potential for Blending Hydrogen in Natural Gas Pipelines." *NREL News & Feature Stories*, November 18, 2020. https://www.nrel.gov/news/program/2020/hyblend-project-to-accelerate-potential-for-blending-hydrogen-in-natural-gas-pipelines.html.

[8] HFTO. 2022. "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines." Accessed February 14, 2022. https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.

[9] Hydrogen Council. 2017. *Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition.* Brussels, Belgium: Hydrogen Council. https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf.

[10] HFTO. 2022. "Hydrogen Shot." Accessed February 14, 2022. https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[11] The White House. 2021. "Fact Sheet: The American Jobs Plan." *Briefing Room Statements and Releases*, March 31, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/.

There is an opportunity to achieve dramatic cost reductions in making clean hydrogen. Technologies like electrolysis liberate hydrogen from the oxygen in water, providing a zero-carbon energy carrier. The United States has an opportunity to lead the world in creating and domestically manufacturing technologies that provide market-accessible clean hydrogen at the same cost as conventional steam methane reforming within 10 years.

A recent U.S. analysis from NREL and other labs found that up to 10 times today's U.S. use of hydrogen is technically feasible, but only 2–4 times would likely happen based solely on today's market drivers.[12] R&D advances and favorable market and economic policies are expected to drive this opportunity even higher.

Scale

The announced and planned growth of electrolyzer deployments between 2025 and 2030 in the United States is modest compared to Europe, Asia-Pacific, and Latin America. The United States needs to accelerate its activities and support for large deployments to rapidly gain real-world experience to feed back into the R&D cycle.

There are two main factors driving the strong international investments in clean hydrogen:

- Low-cost renewables are changing the economics of clean hydrogen.
- Hydrogen can help countries meet their climate goals, especially in their hard-to-decarbonize sectors.

As recently as mid-2019, there were extremely limited electrolyzer deployments announced (~3.2 GW). However, since 2020, the number of planned and announced electrolyzer deployments by 2030 has grown exponentially (27.9 GW in June 2020 and 41.3 GW in February 2021).[13]

Government funding is flowing into these projects to help catalyze the installations, but private sector investments significantly increase the magnitude of effort. That is why collaboration and work with the private sector is key to advancing hydrogen technologies.

Durability and Manufacturability

Several technology challenges need to be overcome to achieve affordable hydrogen systems at scale.

Electrolyzer systems that produce hydrogen are commercially available today but are fabricated at low volumes and not sufficiently affordable, durable, or efficient to be deployed at large scale in grid-integrated applications. R&D is needed to enable manufacturable technologies that meet required cost, durability, and performance targets simultaneously.

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[12] Mark Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy. 2020. *The Technical and Economic Potential of the H2@Scale Concept within the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77610. https://www.nrel.gov/docs/fy21osti/77610.pdf.

[13] HFTO. 2021. "What's new with the Hydrogen and Fuel Cell Technologies Office (HFTO)?" Presented at the #H2IQ Hour, June 30, 2021. https://www.energy.gov/sites/default/files/2021-07/h2iqhour-june30.pdf.

The expected lifetime for a commercial long-haul truck is more than 1 million miles. For fuel cell trucks to achieve this challenging target, the industry needs efficient heavy-duty fuel cell systems that have four to five times better durability than the current fuel cell systems used for passenger cars.

World-Class National Capabilities

The United States has unique national capabilities—initially developed for the application of hydrogen in light-duty transportation—that are now being leveraged to institutionalize a strategic advantage to further develop hydrogen technologies. The nation's crown jewels of research staff and experimental capabilities reside in its national laboratory system. The nation's universities drive the innovation and create the future technical scientists and engineers to support this growth. Finally, industry provides not only the technical targets and market drivers, but also the means to scale up laboratory innovations into manufacturable solutions and domestic jobs.

NREL's Deep Roots in Hydrogen Production

NREL's research in hydrogen production began more than 30 years ago, when researchers modified high-efficiency solar cells to directly create hydrogen through photoelectrochemical (PEC) water splitting. In 2017, NREL recaptured the record for highest efficiency in solar hydrogen production via a PEC water-splitting process.[14] The new solar-to-hydrogen efficiency record is 16.2%, topping a reported 14% efficiency in 2015 by an international team. The record-setting PEC cell represents a significant change from the concept device developed at NREL in the 1990s.

The portfolio of renewable hydrogen production also included gasification of biomass, biological hydrogen production, and, ultimately, expertise in electrolysis by leveraging deep fuel cell research expertise. NREL has comprehensive research focusing on both fuel cell and electrolysis technologies. In a way, our work spans "powders to power." We are able to make our own materials—including catalysts, membranes, and hydrogen storage materials—and then characterize their performance compared to state-of-the art materials. We can also fabricate membrane electrode assemblies within the lab using a variety of highly controlled and repeatable techniques that ensure performance is maintained when moving from laboratory to manufacturing scale (for example, roll-to-roll manufacturing lines).

NREL's evaluation and validation capabilities cover multiple scales: evaluating the performance of single-cell electrolysis and fuel cell components, validating multiple cells in "short stacks" to verify use in more realistic system conditions, and validating entire fuel cell and electrolysis systems up to the megawatt scale in collaboration with industry partners. NREL has continued to add capabilities, facilities, and other investments that maintain our role as a leader in hydrogen technology research.

National Laboratory Collaborations

To achieve ambitious Hydrogen Shot goals of reaching \$1/kg H_2 in a decade, DOE's Hydrogen Program is taking an "all-hands-on-deck" approach. This effort can't be solved in a silo—big problems can only be

[14] NREL. 2017. "News Release: NREL Establishes World Record for Solar Hydrogen Production." April 12, 2017. https://www.nrel.gov/news/press/2017/1117-nrel-establishes-world-record-for-solar-hydrogen-production.html.

solved together ("No one can whistle a symphony. It takes an orchestra to play it."). The hydrogen community—especially the national laboratories—is pulling together to address worldwide challenges.

DOE's Hydrogen and Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy has already been seeding collaboration among this set of organizations through consortia,[15] including H2NEW,[16] M2FCT,[17] HydroGEN,[18] HyMARC,[19] and HyBlend.[20]

Hydrogen from Next-generation Electrolyzers of Water (H2NEW) is a consortium co-led by NREL and Idaho National Laboratory focused on lowering the capital cost of electrolyzers to $100/kW within 5 years while achieving long life and high efficiency.[21] H2NEW will focus on materials and component integration, manufacturing, and scale-up to help support large industry deployment of durable, efficient, and low-cost electrolyzers for hydrogen production, including both high- and low-temperature electrolysis.

As a complement to H2NEW, HydroGEN is conducting more foundational R&D to overcome critical materials challenges and accelerate the time to market for advanced water-splitting technologies that can enable clean, low-cost, and sustainable hydrogen production.[22] NREL leads this national laboratory consortium, which includes many other national laboratories.

Hydrogen storage is also a research priority. The Hydrogen Materials Advanced Research Consortium (HyMARC) was formed to address the scientific gaps limiting the advancement of solid-state hydrogen storage materials. This advanced materials research also focuses on developing core characterization capabilities designed to enable the development of novel materials with the potential to store hydrogen at near-ambient temperature, low to moderate pressures, and energy densities greater than either liquid or compressed hydrogen. HyMARC is also investigating hydrogen carriers—hydrogen-rich liquid- or solid-phase materials that are stable at ambient conditions but release hydrogen when initiated by a change in pressure or temperature, or even upon controlled exposure to light. Hydrogen carriers have the potential to meet the demands of applications beyond onboard vehicular storage, such as long-distance transport, backup power, and industrial uses.

Fuel cell research is key to continued advancements in zero-emission transportation. Million Mile Fuel Cell Truck (M2FCT) is a DOE-funded consortium of five primary national labs to overcome durability and

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[15] HFTO. 2022. "Hydrogen and Fuel Cell Technologies Office Consortia." Accessed February 14, 2022. https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-consortia.

[16] EERE. 2022. "Hydrogen from Next-generation Electrolyzers of Water (H2NEW)." Accessed February 14, 2022. https://h2new.energy.gov/.

[17] DOE. 2022. "Million Mile Fuel Cell Truck (M2FCT)." Accessed February 14, 2022. https://millionmilefuelcelltruck.org/.

[18] HFTO. 2022. "HydroGEN Advanced Water Splitting Materials Consortium." Accessed February 14, 2022. https://www.energy.gov/eere/fuelcells/hydrogen-advanced-water-splitting-materials-consortium.

[19] HFTO. 2022. "HyMARC: Hydrogen Materials Advanced Research Consortium." Accessed February 14, 2022. https://www.energy.gov/eere/fuelcells/hymarc-hydrogen-materials-advanced-research-consortium.

[20] HFTO. 2022. "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines." Accessed February 14, 2022. https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.

[21] NREL. 2020. "NREL To Lead New Lab Consortium To Enable Low-Cost Electrolyzers for Hydrogen Production." *News & Feature Stories*, October 8, 2020. https://www.nrel.gov/news/program/2020/nrel-to-lead-new-lab-consortium-to-enable-low-cost-electrolyzers-for-hydrogen-production.html.

[22] EERE. 2016. "Energy Department Launches $10 Million Effort to Develop Advanced Water Splitting Materials." October 24, 2016. https://www.energy.gov/eere/articles/energy-department-launches-10-million-effort-develop-advanced-water-splitting.

efficiency challenges in proton-exchange membrane fuel cells for heavy-duty applications, with an initial focus on long-haul trucks. The consortium coordinates national laboratory activities related to fuel cell efficiency and durability, provides technical expertise, and harmonizes activities with industrial developers across HFTO's research portfolio.

The Office of Science's Basic Energy Sciences (BES) program recently codified priority research opportunities for hydrogen production, storage, and use. Fundamental research in electrochemistry, materials science, and chemical science offers the potential for step changes in our understanding and development of new technologies. The Joint Center for Artificial Photosynthesis and other BES research programs have helped uncover the fundamentals of water splitting into hydrogen and oxygen. BES- and HFTO-funded R&D has led to world records in efficiency for direct PEC hydrogen production, but more research is needed to make these materials more durable.

DOE's applied R&D laboratories—NREL, Idaho National Laboratory, and the National Energy Technology Laboratory—are collaborating to conduct research and analysis on integrated energy systems incorporating renewable, nuclear, and fossil energy.[23] The team has published a series of workshop reports addressing R&D pathways,[24] modeling and analysis needs,[25] and opportunities and challenges associated with materials development and fabrication[26] for these integrated energy systems.

But how do we achieve a truly sustainable, highly integrated, zero-carbon transportation future? NREL believes a **whole system-integration approach will be key** to decarbonizing transportation, shaping mobility, and preserving a safe climate future. To accomplish these goals, NREL is focusing on a major initiative, supported by DOE: **Advanced Research on Integrated Energy Systems (ARIES).**

Virtual and physical connections among organizations can be made through the ARIES research platform.[27] ARIES matches the complexity of the modern energy system to conduct research to support the development and integration of groundbreaking new energy technologies, including hydrogen systems.

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[23] Douglas Arent, Shannon Bragg-Sitton, David Miller, Thomas Tarka, Jill Engel-Cox, Richard Boardman, Peter Balash, Mark Ruth, Jordan Cox, and David Garfield. 2021. "Multi-input, Multi-output Hybrid Energy Systems." *Joule* 5 (1): 47–58. https://www.sciencedirect.com/science/article/pii/S2542435120305122.

[24] Douglas Arent, Peter Balash, Richard Boardman, Shannon Bragg-Sitton, Jill Engel-Cox, David Miller, and Mark Ruth. 2018. *Summary Report of the Tri-Lab Workshop on R&D Pathways for Future Energy Systems, July 24–25, 2018*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A70-72926. https://www.nrel.gov/docs/fy19osti/72926.pdf.

[25] Shannon Bragg-Sitton, David Miller, Jill Engel-Cox, Peter Balash, Richard Boardman, Douglas Arent, Tom Tarka, and Mark Ruth National Energy Technology Laboratory. 2019. *Summary Report of the Tri-Lab Workshop on Modeling & Analysis of Current & Future Energy Systems, April 25-26, 2019*. National Energy Technology Laboratory. DOE/NETL-2020/2114. https://www.netl.doe.gov/energy-analysis/details?id=4449.

[26] Anne Gaffney, Richard Boardman, Shannon Bragg-Sitton, Gary Groenewold, Daniel Ginosar, Jeff Aguiar, Gabriel Ilevbare, et al. 2021. *Applied Energy Tri-Laboratory Consortium Workshop Report: Materials Challenges and Opportunities for Energy Generation, Conversion, Delivery, and Storage*. Idaho Falls, ID: Idaho National Laboratory; Pittsburgh, PA: National Energy Technology Laboratory; Golden, CO: National Renewable Energy Laboratory. INL-EXT-20-60038; DOE/NETL-2021/3207; NREL/TP-6A50-80054. https://doi.org/10.2172/1785315.

[27] NREL. 2022. "ARIES: Advanced Research on Integrated Energy Systems." Accessed February 14, 2022. https://www.nrel.gov/aries/.

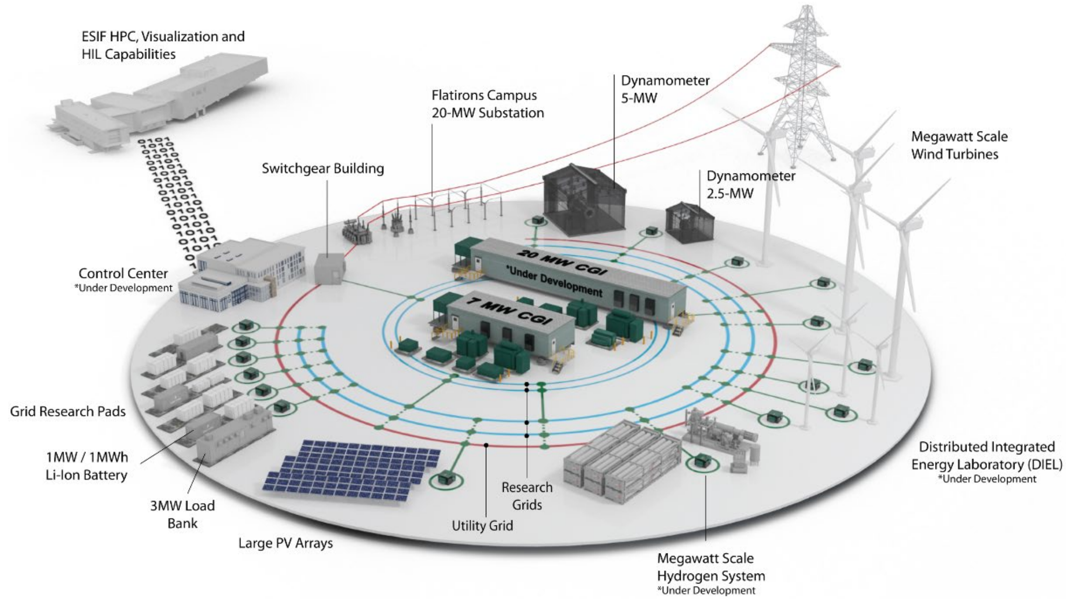

Figure 2. Hydrogen is one of the building blocks supporting the ARIES research platform. Capabilities being studied with several major industry partners include heavy-duty hydrogen fueling, validating the benefits of hydrogen and fuel cells with the grid and the transportation system, and performing large-scale simulations through the use of high-performance computers.

Through ARIES, NREL is already pursuing the development of a unique research platform designed to de-risk, optimize, and secure *current* energy systems, which will provide insight into the design and operation of *future* energy systems. It will address the fundamental challenges of:

- Variability in the physical size of new energy technologies being added to energy systems.
- Controlling large numbers (millions to tens of millions) of interconnected devices.
- Integrating multiple diverse technologies that have not previously worked together.

Addressing these challenges through ARIES has the potential to transform the movement of people and goods, enhance national energy security, boost the domestic economy, and save individuals and businesses both time and money.

The ARIES platform will help partners integrate hydrogen technologies at scale with other renewable resources and hydrogen end uses in a safe research and learning environment before moving to large-scale commercial deployment.

Through support from DOE, an ARIES project is underway to show how hydrogen and battery electric vehicles can be both complementary to each other and well-integrated with the grid. The energy that needs to be generated and transferred to heavy-duty vehicles (trucks, buses, ships, and planes) is expected to be significant, and, if not well integrated and managed, it can cause challenges for the grid. ARIES provides the platform for researching optimal ways to integrate hydrogen and electric vehicle technologies on a larger scale while validating resilience and stability for the electric grid.

Private Sector Partnerships

Partnerships are one of the most important pathways toward achieving a power sector free of carbon emissions by 2035 and an economy free of greenhouse gas emissions by 2050. NREL is the leading national laboratory in market-facing activities that commercialize clean energy technologies in partnership with government, industry, philanthropic organizations, and academia. In fiscal year 2020, NREL had more than 900 established partnership agreements with a range of entities. Laboratories can accelerate the translation of clean energy innovations from lab to marketplace to multiply the impact of DOE's energy science and technology investments.

Hydrogen continues to get a lot of attention in the marketplace, and companies are looking for help. NREL is ready to help them jump-start solutions to their problems, as well as assist those who already have a commercial product ready but need to rapidly progress their technology to remain competitive (internationally and nationally). They are looking for solutions to produce their technology at a larger scale and a lower cost. The U.S. government helps maintain competitive advantage and innovation through the support of its national laboratories. By strengthening the impact of our work, we can increase the impact of clean energy technologies worldwide.

Through the H2@Scale initiative, DOE's national labs are working with industry partners to advance the large-scale production, transport, storage, and use of hydrogen across multiple sectors of the economy. Power generators, technology developers, and automakers are leveraging lab expertise and capabilities through cooperative H2@Scale research projects[28] to address early-stage R&D challenges in hydrogen infrastructure, low-temperature electrolysis, energy storage, and renewables-to-grid integration.

Some recent examples of hydrogen technology partnerships with NREL include:

- Commercial electrolyzer manufacturers have turned to NREL to validate the long-duration performance and durability of megawatt-sized systems.
- Vehicle manufacturers and fuel suppliers are working with NREL to explore and demonstrate the technical feasibility of high-flow-rate (10-kg/min average) fueling for heavy-duty fuel cell trucks and machinery, and to develop fast and safe heavy-duty hydrogen fueling protocols.
- NREL's robust experimental capabilities are used by a range of industry partners—from technology startups to long-established original equipment manufacturers—to develop and validate durable materials, components, and stacks for new fuel cell applications, including trucking and aviation.
- Multiple industry and university partners are using NREL's capabilities in materials characterization, device design and evaluation, and manufacturing and systems integration to advance their low-temperature electrolysis technologies.
- Fuel cell component manufacturers have worked with NREL to develop novel quality control methods for characterizing the full production-roll quality of fuel cell membranes as they are being manufactured.

[28] HFTO. 2021. "H2@Scale CRADA Projects." February 4, 2021. https://www.energy.gov/eere/fuelcells/articles/h2scale-crada-projects.

- NREL collaborated with a natural gas utility and biological science company to develop and demonstrate a unique "power-to-gas" process that uses microorganisms to convert renewably produced hydrogen and waste CO_2 into renewable natural gas.

Energy for Everyone

NREL's vision supports leading an energy transition in which solutions are inclusively designed and benefits are equitably distributed. NREL is a leader in applied clean energy practices, working with thousands of communities nationally and around the world, many of which have been historically underserved in terms of access to clean energy and its benefits.

Clean hydrogen can be made anywhere there is clean electricity, enabling jobs for rural America while cleaning up the air in cities for those who often suffer from the worst air conditions. Urban underserved communities would truly benefit from a clean transportation system. Urban corridors typically have the worst air quality; hydrogen buses, trucks, rail, and ships can help clean up these corridors. Hydrogen can be produced close to the demand in cities by electrolysis with zero emissions.

Clean hydrogen is also an excellent opportunity for rural and remote underserved communities, allowing generation at the point of photovoltaic and wind power production. It also supports jobs for construction and operations in these remote locations, strengthening energy justice in these communities.

R&D Investments

Significant national investments will help accelerate development of hydrogen technologies and provide the opportunity for U.S. market leadership internationally. A high return on investments can be informed by integrated modeling and analysis across energy systems, amplified by high-performance computing. This will guide a combination of longer-term and higher-risk research with big payoffs, balanced with near-term demonstrations of existing technologies to accelerate the market and awareness of hydrogen as a zero-emission solution. Additional research, development, demonstration, and deployment are all essential ingredients to keep the innovation pipeline flowing toward market success.

R&D on Advanced Production Technologies

There are research opportunities in advanced water-splitting technologies such as water electrolysis, PEC water splitting, and solar thermochemical hydrogen production. These hydrogen production technologies can take advantage of today's renewable and nuclear power or use solar energy directly.

Alkaline membranes are also a promising technology at a low level of technology readiness with significant potential for decreasing costs and precious metal use in energy conversion devices.

Consortia like H2NEW and HydroGEN are working to achieve cost reductions and support promising technology developments, but the speed and scale of development must increase significantly to meet near-term cost goals.

Large-Scale Demonstrations

Large-scale demonstrations need to be performed to show how hydrogen can stabilize the future electricity grid, both with high renewable penetration and variability and using baseline nuclear power. Hydrogen infrastructure needs additional investment in the form of pipelines (both dedicated hydrogen and blended with natural gas) and hydrogen storage (high-pressure and liquid hydrogen, advanced materials, and bulk/geologic storage).

In June 2021, in conjunction with the energy secretary's announcement of the Hydrogen Shot goal of $1/kg in a decade, DOE put out a request for information (RFI) to gather input on this major initiative and how to enable low-cost, clean hydrogen at scale. The RFI specifically sought input on viable **hydrogen demonstration and deployment projects** that enable clean hydrogen production, infrastructure, and end use to reduce emissions, create jobs, and enable a net-zero-carbon-emissions economy by 2050.

The RFI responses from different parts of the country resulted in some common themes:

- Hydrogen has the ability to create jobs all across the country.
- Hydrogen's end uses will be more focused on certain end-use applications based on the region of the United States.
- The primary energy used to make hydrogen will be diverse (e.g., wind, solar, nuclear, hydro, fossil) in different parts of the country.

But the overarching message was that the expansion of our energy system to include hydrogen in a bigger way can engage and positively affect all parts of our country.

Expanded Hydrogen End Uses

Expanding hydrogen use into hard-to-decarbonize industrial sectors does more than just reduce emissions in these areas—multiple end uses of hydrogen create a market pull for clean hydrogen, which helps grow the scale while lowering the cost. NREL is working with industry, academia, and other national lab partners to grow hydrogen's potential in multiple end uses such as steel production, ammonia synthesis, and other chemical and industrial uses, as well as providing long-duration energy storage to support the grid at high penetrations of renewable power.

Further development is needed to integrate hydrogen into new pathways, such as making net-zero-CO_2 chemicals and liquid fuels.

Hydrogen Penetration into Heavy-Duty Transportation

Light-duty fuel cell vehicles were the primary focus worldwide for the past few decades and have resulted in significant technology advancement. Now, DOE and industry are focusing on hydrogen and fuel cell innovations to help decarbonize the heavy-duty transport sector, such as trucks, buses, ships, and aviation. Developing durable fuel cells for heavy-duty applications is the focus of the new M2FCT consortium, in which NREL is a contributor. NREL is also working with industry partners on heavy-duty hydrogen fueling infrastructure technologies, as well as analysis to determine where and how hydrogen can best support a transition to low-carbon transportation.

For hydrogen and fuel cells to become the optimal choice for heavy-duty applications, R&D is still needed to drive down the cost of producing clean hydrogen, increase the efficiency of fuel cells, accelerate development of new hydrogen storage technologies, and achieve reliability and durability targets.

Conclusion

Increasing our investment in developing hydrogen technologies will provide significant national security, economic, and environmental benefits to our country. **National security** will be improved by increasing U.S. energy competitiveness, increasing energy security, and decreasing the cost of manufacturing products domestically; the **economy** will be strengthened through new jobs and increasing gross domestic product; and **societal environmental benefits** include clean air and water and reduced climate impact through CO_2 reductions.

Our H2@Scale vision is that hydrogen will be a central component of a clean, sustainable, efficient, and economic energy system. Hydrogen technologies can help decarbonize hard-to-decarbonize sectors like transportation (including trucks, rail, ships, and aviation), agriculture, and industry. Hydrogen can also provide long-duration energy storage,[29] be used to produce sustainable fuels and chemicals,[30] and support greater renewable power integration.[31]

National laboratory research is lowering the cost and increasing the scale of technologies to make, store, move, and use hydrogen across multiple energy sectors. We look forward to working with you, the other DOE national laboratories, and our many esteemed partners to continue and expand on the investment and innovation needed to help the U.S. hydrogen industry remain competitive and meet the administration’s goals.

[29] NREL. 2020. “Answer to Energy Storage Problem Could Be Hydrogen.” *News & Feature Stories*, June 25, 2020. https://www.nrel.gov/news/program/2020/answer-to-energy-storage-problem-could-be-hydrogen.html.

[30] NREL. 2021. “Breakthrough Methods Help Integrate Renewable Hydrogen With Waste Carbon Dioxide To Produce Clean Fuels, Chemicals, and More.” *News & Feature Stories*, August 31, 2021. https://www.nrel.gov/news/features/2021/breakthrough-methods-help-integrate-renewable-hydrogen-with-waste-carbon-dioxide.html.

[31] Josh Eichman, Mariya Koleva, Omar J. Guerra, and Brady McLaughlin. 2020. *Optimizing an Integrated Renewable-Electrolysis System*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-75635. https://www.nrel.gov/docs/fy20osti/75635.pdf.