Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)
Washington, D.C.

14 July 2020

The Honorable Dan Brouillette
Secretary of Energy
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Mr. Secretary:

On behalf of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC), I am pleased to submit the Committee's 2019 Annual Report. HTAC duties under Title VIII of the Energy Policy Act of 2005 (EPACT), Sec. 807, are to review and make recommendations to you, the Secretary, on (1) implementation of programs and activities identified in Title VIII; (2) safety, economic, and environmental consequences of technologies for the production, distribution, delivery, storage and/or use of hydrogen energy and fuel cells; and (3) the U.S. Department of Energy (DOE) plan under Section 804.

HTAC seeks to provide timely input to the DOE budgeting process, and to encourage DOE to consider how hydrogen infrastructure can become a part of the potential U.S. federal government fiscal infrastructure stimulus package as a response to the coronavirus pandemic. The hydrogen industry ended 2019 with a general feeling of excitement and a growing sense of optimism, hitting the important milestone of over 1,000 MW of fuel cells shipped globally, but along with the rest of the U.S. economy, this industry has been severely and negatively affected by the coronavirus pandemic. Including hydrogen infrastructure as part of a U.S. infrastructure fiscal stimulus package will put the U.S. hydrogen industry not only back on its feet but also on a path to advancing the U.S. leadership position and delivering on investments and jobs in the United States over the long term.

The United States has been a leader in hydrogen technology since the days of the Apollo space mission program. Today, governments from around the world have recognized the important role hydrogen will play in the global energy landscape and, as a result, are initiating investments in hydrogen infrastructure. Recently, the Hydrogen Council posted that the "decade of hydrogen" is here and published a report forecasting that the cost of hydrogen solutions will fall sharply within the next decade, sooner than previously expected. The report forecasts cost reductions of up to 50 percent by 2030 through the economic scale-up of hydrogen production and distribution and system component manufacturing. During the past year, industry groups and countries have produced hydrogen roadmaps for major economies such as Japan, Korea, Australia, and the European Union. These roadmaps lay out in detail the opportunities and benefits of a coordinated approach to investing in hydrogen infrastructure. We anticipate that countries will seize upon this confluence of events to both stimulate their economies and advance their positions within the hydrogen energy economy. For example, the European Commission is already working on a stimulus plan to include hydrogen infrastructure as part of a post-coronavirus economic recovery plan. A number of countries are targeting leadership positions in the emerging global hydrogen economy, including export of technology and components, to capitalize on economic and job

creation opportunities. Several companies (e.g., Nikola Motors, Ballard, Plug Power, and NEL) offering hydrogen economy solutions have seen striking increases in valuations since 2019.

For the United States specifically, an industry report produced in coordination with the Electric Power Research Institute and McKinsey & Company highlights that the nation is uniquely positioned to build a world-leading hydrogen economy because of its abundant, low-cost primary energy sources such as nuclear, wind, solar, hydropower, and natural gas with carbon capture and storage. What lies at stake is the potential for 500,000 new manufacturing- and construction-related jobs by 2030 and a pathway to 3.4 million jobs by 2050. Pursuit of an expanded role for hydrogen across multiple sectors to achieve economies of scale, when integrated and aligned with broader electrification goals, can offer strategic benefits for the country in energy security, resilience, and flexibility.

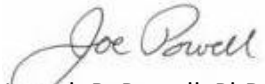
Overall opportunities include cost-competitive uses for hydrogen domestically and export opportunities for technology, components, and hydrogen itself, leveraging the U.S. potential for production of clean hydrogen derived both from renewable resources and from low-cost natural gas combined with geologic options for carbon storage.

Looking forward, capturing the potential benefits of hydrogen requires public–private partnership between industry, universities, and local, state, and federal governments. DOE can continue to catalyze the process by acting on the following recommendations, which seek to maintain U.S. leadership and to optimize economic and job creation opportunities:

- Pursue stimulus funding with private-sector participation for the development and deployment of hydrogen solutions for ground transit, marine, and aviation applications where fuel cells offer distinct advantages.
- Conduct a cost–benefit analysis to determine where targeted short-term subsidies, loans, or policy incentives might facilitate and enable commercial hydrogen deployments with near-term payback via U.S. economic growth and jobs creation.
- Coordinate with other U.S. government organizations, such as the U.S. Departments of Transportation and Defense, in the development of U.S. hydrogen infrastructure and systems that can help position and maintain the United States as a global economic leader, noting that hydrogen and fuel cell systems can complement electrification options including grid storage and fast charging, especially where higher energy density is advantaged.
- Continue funding systems analysis for H_2@Scale to identify the best opportunities for integration of hydrogen into the U.S. energy infrastructure.
- Expand R&D funding to target cost reduction and improved durability for commercial electrolyzers and fuel cells.

HTAC members hope you will find these recommendations and the information contained within the 2019 Annual Report useful. We remain committed to providing ongoing support to DOE and are available to address any questions regarding the annual report.

Sincerely,



Joseph B. Powell, PhD
Chairman, Hydrogen and Fuel Cell Technical Advisory Committee, on the Committee's behalf

2019 ANNUAL REPORT of
The Hydrogen and Fuel Cell Technical Advisory Committee

Hydrogen and Fuel Cell Technical Development and Commercialization Activity

SUMMARY

The 2019 Annual Report of the United States Department of Energy (DOE) Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) summarizes global advances and opportunities for the hydrogen and fuel cell industry in technology research, development, and commercialization, as well as progress and challenges in policy, regulations, standardization, and the financial climate for investment.

2019 marked a year of expansion and acceleration within the industry, as well as broader global recognition of the important role hydrogen will play in the future energy landscape.

Highlights include the following:

- An extensive study, *Roadmap to a US Hydrogen Economy*, was conducted by major industrial companies and McKinsey & Company. The roadmap concluded that by 2030, the hydrogen economy in the United States could generate an estimated $140 billion per year in revenues and support 500,000 new jobs across the hydrogen value chain.[1]
- Significant early growth: Globally, just over 1 GW of fuel cells were shipped, resulting in roughly 40 percent year-over-year growth.[2] Despite this annual increase, the total still represents a tiny fraction of the potential market.
- Global investment: China purports to spend $17 billion on fuel cell technologies (including $7.6 billion in heavy-duty trucks) through 2022 in the public and private sectors. Japan's 2019 government investment was approximately $560 million, versus an estimated $110 million for Germany and $150 million for the United States.[1, 3]
- Major international corporations made large investments (excess of $100 million) in the industry through acquisitions or partnerships with technology providers, illuminating an emerging "bullish" environment for strategic investment in hydrogen.[4,5] An estimated $1 billion in capital was raised in 2019 via public and private investment.[6]
- Commercial transportation vehicles such as trucks, buses, trains, and delivery vehicles have come into focus leveraging centralized hydrogen infrastructure and scale economies.[7] Significant investment and commitments in heavy-duty trucking were made in the European Union, China, and Japan.[8]
- California continues to lead the United States and is on track to meet 2005 Energy Policy Act (EPACT) goals with 40 retail stations and 7,994 passenger fuel cell vehicles deployed at the end of 2019.[9]
- DOE invested more than $58 million in fiscal year 2019 toward projects to advance the H2@Scale vision of large-scale hydrogen production, storage, transport, and use across sectors, including 18 projects specifically directed at medium- and heavy-duty transport.[10]

Challenges and Opportunities

The opportunity to have simultaneous impacts on job creation, wealth generation, energy security, and climate change has been clearly defined. The challenge remains to chart a clear program to capture these opportunities and to ensure that the United States retains its share of the global market in emerging hydrogen and fuel cell industries, both within the United States and via global exports.

In addition to the aggregate challenges of reducing the cost of hydrogen generation and distribution and reducing the cost of fuel cells, important questions remain for addressing hydrogen and fuel cell opportunities:

- What are the key technologies to focus on and develop to unlock near-term commercialization opportunities and maintain long-term leadership in hydrogen and fuel cells?
- Where are the commercialization leverage points where public–private partnerships will facilitate robust growth in these new industry segments?
- How can we ensure the United States captures and retains economic and job creation opportunities in the globally driven emerging hydrogen economy?
- Can U.S. leadership in natural gas provide abundant export opportunities to meet emerging global demand for clean hydrogen fuel?

To help address these and other questions, HTAC has commissioned a subcommittee to examine and comment on the U.S. Roadmap report[1] and offer recommendations to DOE for consideration in its planning process.

Industrial Progress and Activity

The hydrogen and fuel cell industry accelerated in 2019, doubling its annual growth rate in terms of megawatts of fuel cells shipped. While there is growing enthusiasm within the industry, it is still a nascent industry in the early stages of commercialization and requires large deployments to reduce costs through scale of manufacturing. The following are noteworthy 2019 events and announcements:

- Cummins acquired 81 percent of Hydrogenics, one of the world's leading companies in fuel cell and hydrogen production technologies; Air Liquide owns the remaining 19 percent.[11]
- Plug Power purchased EnergyOr, a leader in lightweight compact polymer electrolyte membrane (PEM) fuel cell systems,[12] and expanded its Rochester, New York, manufacturing facility.[13]
- Bosch acquired an 11 percent stake in PowerCell of Sweden in its effort to supply fuel cell stacks for transportation.[14] Bosch also increased its stake in Ceres Power, a leading solid oxide fuel cell technology company, to approximately 18 percent.[15]
- CNH Industrial N.V., a Dutch multinational industrial manufacturing company, made a $250 million strategic investment in Nikola Corporation, a U.S.-based designer and manufacturer of heavy-duty fuel-cell-powered trucks.[16]

Partnerships

Several important partnership and cooperative agreements were announced in 2019.[17]

- DOE released a Joint Statement with Japan's Ministry of Economy, Trade, and Industry and the European Commission Directorate-General for Energy detailing future cooperation on hydrogen and fuel cell research to reduce cost and enable scale-up to ensure hydrogen's role in the global economy.
- Canada and California signed a new cooperation agreement to accelerate the adoption of zero-emission vehicles. The memorandum of understanding (MOU) commits both governments to working together on developing their respective regulations to cut greenhouse gas emissions from light-duty vehicles.
- Cummins announced collaboration with Hyundai on fuel cell powertrains.
- Anglo-American, Engie, NEL Hydrogen, and Plug Power announced agreements to develop a fuel-cell-powered ultra-class heavy-duty mining truck and accompanying hydrogen production and fueling equipment.
- ExxonMobil and FuelCell Energy expanded their agreement to jointly develop fuel cell technology for carbon capture at power plants and industrial facilities.
- Air Liquide, Hyundai, NEL Hydrogen, Nikola Motors, Shell, and Toyota signed an MOU to test state-of-the-art heavy-duty hydrogen fueling hardware.

Global Fuel Cell Shipments

E4tech[18] has provided the following 2019 industry assessment:

- Global shipments totaled more than 1 GW, a 40 percent increase over 2018 shipments.
- The transport sector continues to dominate with 908 MW. Stationary applications came in second at 221 MW.
- North America (384 MW) lost its recently gained lead in adoption to Asia (677 MW), though both regions have had comparable average exponential growth since 2015 (Table 1). 2019 growth in Asia is driven by Hyundai NEXO sales into Korea.[19]

Megawatts by region of adoption					
Megawatts	**2015**	**2016**	**2017**	**2018**	**2019**
Europe	27.7	27.4	38.9	41.2	68.6
North America	108.4	213.6	331.8	425.3	384.1
Asia	159.7	273.8	285.8	337.9	676.7
Rest of World	2.3	1.7	2.1	1.2	0.2
Total	**298.1**	**516.5**	**658.6**	**805.8**	**1,129.6**

Table 1: Global fuel cell adoption
Source: E4tech[15]

Global hydrogen fuel cell bus deployments are growing, as reported by Ballard (see Figure 1).

Figure 1: Fuel cell buses
Source: Fuel Cell Electric Bus [20]

Progress toward Policy Goals

As detailed in the 2018 HTAC Annual Report,[21] 2020 represents a milestone year (vs. the 2005 base year) in EPACT for availability of light-duty hydrogen fuel cell vehicles offering improved fuel economy and lower emissions, together with infrastructure to provide safe and convenient refueling.[22]

The state of California has made substantial progress toward program goals through 2019, with 40 public retail fueling stations operational, and three automakers (Honda, Hyundai, and Toyota) providing more than 7,994 fuel cell electric vehicles on the road.[7, 23] U.S. totals are given in Figure 2.

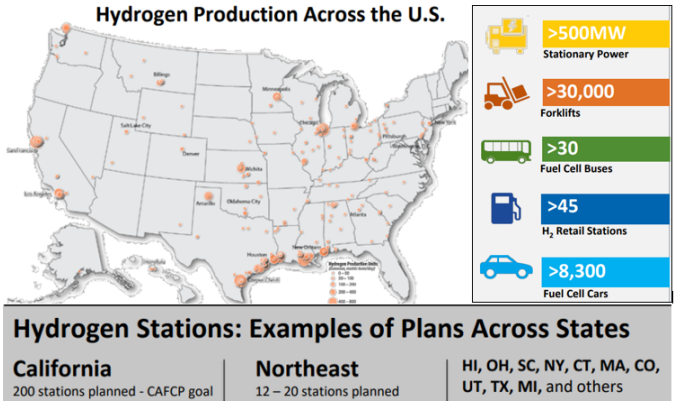


Figure 2: U.S. fuel cell applications (2019)
Source: DOE Hydrogen and Fuel Cell Technologies Office[24]

Commercialization Initiatives

Transportation

Hyundai and Toyota continue to lead the field in passenger fuel cell vehicles, together accounting for about two-thirds of fuel cells shipped by capacity. Meanwhile, truck and bus programs, led by China ($7.8 billion in 2019 heavy-duty truck funding[25, 26]) and Europe, accounted for 69 MW shipped.[27] Additionally, two fuel cell trains have been running for a year, with more on order. Investments and acquisitions in this sector by Bosch, CNH, and Cummins point toward a growing push for heavy-duty fuel cell applications. Global totals are provided in Table 2.

Vehicles	2018	2019
Truck, bus, other commercial	20,953	30,346
Passenger vehicle	9,289	12,007

Table 2: Global fuel cell vehicles
Source: IPHE[28]

Material Handling

After military and space uses, forklifts represent one of the most commercially successful fuel cell applications. Over 30,000 fuel cell forklifts (most made by Plug Power) are operating in the United States and are being supplied by 85 material handling hydrogen fueling stations using 30 tons of hydrogen per day. A compelling case exists for differentiation relative to battery electric options,[29] with rapid refueling and increased uptime being key considerations. Reduced cost of hydrogen could further expand deployment in the United States and open export opportunities in China, Europe, and Japan.

Stationary Power

Bloom, Doosan, and FuelCell Energy continue to manufacture and sell products within the stationary market. FuelCell Energy was able to secure a US$200 million line of credit.[30] Ceres Power announced partnerships with Doosan and Miura, as well as an increased investment from Bosch. FuelCellWorks[31] reported that Japan's EneFarm program deployed over 300,000 micro-CHP (combined heat and power) fuel cell units in Japan. Europe saw deployment of 100,000 CHP units, some of which were from Japan. Grid resilience is a driving force in the stationary marketplace. In this regard, data centers are a key emerging market for hydrogen and fuels cells. In one example, Microsoft and Power Innovations (PI) completed a successful 24-hour full load test for a 320 kW server powered by 400 kg of hydrogen using PI's ¼ MW modular fuel cell system.

Hydrogen Infrastructure

Hydrogen fueling infrastructure is emerging as a key factor for unlocking large commercial applications. In California, the cost and time to construct new refueling stations have decreased substantially since 2015.[32]

The Intermountain Power Agency approved the construction of an 840 MW natural-gas-fired combined-cycle plant[33] capable of transitioning to a 30 percent hydrogen mix by 2025. The project will use excess renewable electricity to produce hydrogen and store it in a large underground salt dome.[34]

Various sources report the growth of hydrogen refueling stations (HRSs) for vehicles (Table 3 provides a compilation of public and private stations from the H2Stations.org website). Of the 432 global vehicle stations reported, 330 are open to the public. California's 40 public stations represent a majority of the 61 U.S. stations deployed by year end 2019, including a cluster of 5 public stations in the Northeast.[35] Estimates of the number of reported HRSs in China range from 27 to 35. More than 1,100 stations are counted world-wide if material handling is included.

Hydrogen refueling stations	2018	2019
North America	**66**	**74**
California	44	48
Europe	**141**	**177**
Germany	65	87
Asia	**140**	**178**
Japan	103	114
Korea	15	33
Worldwide	**349**	**432**

Table 3: Global hydrogen refueling stations
*Source: **Ludwig-Bölkow-Systemtechnik**[36]*

Military/Defense

As the United States looks past its longest war, the Pentagon released its ten-year force design in which major segments of the U.S. military are retooled to engage in future conflicts. In many cases, this includes an emphasis on mobility, unmanned aerial vehicles (UAVs), communications, and stealth technologies (reduced noise and heat signatures).[37] The plan also increases emphasis on methods to reduce logistical burdens on the military and thus reduce the exposure of troops and equipment, as they manage complex supply routes.

An example is the U.S. Army's work on a liquid-hydrogen- and fuel-cell-powered UAV, which can fly longer than battery-powered options and is significantly quieter, with a lower heat signature than gasoline-powered versions.[38] The hydrogen-fueled drone maximizes the vehicle's time on station, which optimizes the mission profile and asset utilization. The U.S. Navy recognizes similar benefits with drones and completed 1,000 hours of successful underwater testing of an unmanned undersea vehicle equipped with a General Motors fuel cell.

The military has also identified additional benefits from hydrogen-fuel-cell-powered ground vehicles, which include flexibility to leverage multiple energy sources, production of water as a by-product of operation, efficiency, and silent watch. These characteristics were evaluated using a Chevrolet Colorado ZH2 vehicle, powered by a General Motors hydrogen fuel cell. Hydrogen and fuel cells are currently being evaluated in an increasingly wide range of applications, highlighting the importance of the United States' maintaining its technological leadership.[39]

In October, DOE announced a collaboration with the U.S. Department of Defense's U.S. Army Ground Vehicle Systems Center and the U.S. Army Corps of Engineers to develop and demonstrate "H2Rescue"—a hydrogen-fuel-cell-powered emergency relief truck capable of providing power, heat, and potable water.[40] This initiative expands on the demonstration of the use of a fuel-cell-powered bus for similar civilian applications.[41]

2019 HTAC Activities

Hydrogen Safety

The Center for Hydrogen Safety (CHS)[42] was launched following HTAC's 2018 recommendations. CHS incorporates activities of the Hydrogen Safety Panel (HSP), initially formulated by DOE and coordinated by Pacific Northwest National Laboratory, under the broader umbrella of the American Institute of Chemical Engineers. Activities and accomplishments include the following:

- Through its affiliation with the American Institute of Chemical Engineers (AIChE), CHS promotes hydrogen safety and best practices worldwide, providing 60,000 stakeholders with access to hydrogen safety, codes and standards across 110 countries.
- Services include operation of the HSP as well as operator and first responder training, public outreach, project/facility design review and hazard analysis, and sharing of best practices and incident response learnings.
- Companies and organizations can gain access to the HSP within two weeks, with access to a best practices database through the CHS's Hydrogen Tools Portal.[43]
- CHS was featured prominently in the spring and fall 2019 AIChE national meetings and via a specialty conference with 75 attendees from diverse organizations and backgrounds. In 2019, membership grew to more than 25 entities, including extensive international participation.
- CHS introduced new incident management resources, including incident briefs on recent events, safety fact sheets, and an incident management guide.

Competitiveness Subcommittee

In October 2019, HTAC issued a report on competitiveness and competition. The report provides recommendations for maintaining and leveraging technology leadership in hydrogen and fuel cells, with a focus on PEM fuel cells and related hydrogen fueling infrastructure, across multiple regions of the world.[44]

HTAC Dashboard

The Committee is exploring the potential for using an HTAC "dashboard" as a framework for assessing the status of achievement of EPACT 2005 Title VIII goals, identifying areas within the HTAC's purview requiring special attention and communication in the HTAC annual report. The concept ties together the elements of both the HTAC's oversight duties under EPACT and the DOE's HTAC Charter. The full Committee will review a draft of the dashboard in

2020. The dashboard is designed to provide the following benefits:

- Clear linkage to Committee responsibilities as defined by Congress in EPACT 2005, Title VIII,
- Grounding and context for HTAC discussion and deliberation, including a common language,
- A foundation from which to identify areas for HTAC focus and to structure Committee debate,
- Consistency and continuity from year to year as membership and leadership change, and
- Organization for HTAC reviews, recommendations, and reporting.

Significant Technical Challenges Remain to Meet Goals

DOE has set a number of targets and technical goals in the areas of transportation, power generation, and other market applications. These objectives are detailed in the Hydrogen and Fuel Cell Technologies Office[☼] Multi-Year Plan, which DOE is currently updating.

HTAC will review and comment on the revised plans and targets in the 2020 HTAC Annual Report and has convened a hydrogen roadmap subcommittee to review the multi-year plan and other roadmaps and provide feedback on gaps, challenges, and recommended DOE actions.

Research and Development

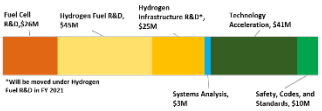
The DOE hydrogen and fuel cell R&D funding breakdowns and impacts are shown in Figures 3 and 4.

Hydrogen and Fuel Cell Technologies Office (HTFO) within Energy Efficiency and Renewable Energy (EERE)

	FY 2018	FY 2019	FY 2020
Fuel Cell R&D	32,000	30,000	26,000
Hydrogen Fuel R&D	54,000	39,000	45,000
Hydrogen Infrastructure R&D*	-	21,000	25,000
Technology Acceleration	19,000	21,000	41,000
Safety, Codes, and Standards	7,000	7,000	10,000
Systems Analysis	3,000	2,000	3,000
Total	$115,000	$120,000	$150,000

*Will be moved under Hydrogen Fuel R&D in FY 2021

Hydrogen and Fuel Cell Technologies Office (HTFO) Hydrogen and Fuel Cells Breakdown FY 2020



DOE Hydrogen and Fuel Cells FY 2020 Appropriations

DOE Office	Funding (in thousands)
EERE (HFTO)	$150,000
Fossil Energy (SOFC)	$30,000
Nuclear Energy (coordinated with FCTO)	$11,000

- Office of Science, Basic Energy Sciences Funding for projects relevant to H_2 and fuel cells (e.g. catalysis, etc.) was $20.5 M in FY 19, TBD in FY 20
- ARPA-E: Funding is based on specific program selected each year: TBD in FY 20

Figure 3: Federal R&D budget FY 2017–2019
Source: DOE Hydrogen and Fuel Cell Technologies Office

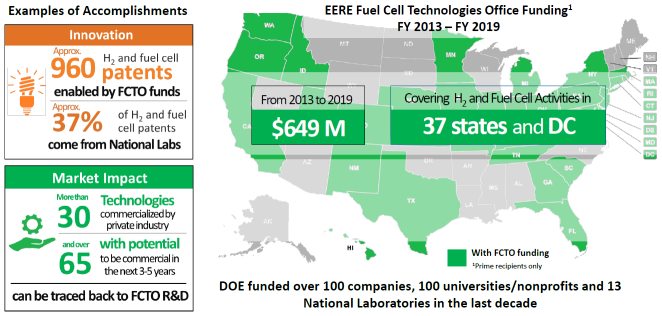


Figure 4: Impact of federal R&D budget funding
Source: DOE Hydrogen and Fuel Cell Technologies Office

2019 R&D Highlights

Highlights from the Hydrogen and Fuel Cells Technology Office include the following:[45]

- Three of the selected projects for H2@Scale will demonstrate integrated systems in Florida, Illinois, and Texas. An additional project, funded through DOE's Office of Nuclear Energy,[46] will incorporate hydrogen production with a nuclear power plant to supply regional demands for hydrogen, such as steelmaking or fleet fuel cell vehicles.
- A successful DOE collaboration between the Hydrogen and Fuel Cells, Vehicles, and Bioenergy Technology offices resulted in a $50 million investment in 24 projects[47] that will address R&D challenges in gaseous fuels, including hydrogen and fuel cell R&D for medium- and heavy-duty transportation.
- The research community, government, and the private sector came together in DOE workshops to identify R&D gaps in and next steps for large-scale hydrogen use, including in data centers[48] and the rail[49] and maritime[50] sectors.
- Modeling and analysis of heavy-duty fuel cell trucks was conducted to set development targets to enable competitive deployment.[51]
- A platinum group metal (PGM)-free fuel cell cathode operating at 29.6 mA/cm^2 was demonstrated, representing an 85 percent improvement over the 2016 baseline of 16 mA/cm.^{2}
- PGM-free testing protocols were finalized through the Electrocatalysis Consortium (ElectroCat).[52]
- The HydroGEN consortium[53] held a benchmarking workshop, while supporting 11 new R&D projects and 20 existing projects, 2 Materials Research Society Symposia, 30 publications, and 104 presentations.

[☼] In May 2020, DOE's Fuel Cell Technologies Office (FCTO) was changed to the Hydrogen and Fuel Cell Technologies Office (HFTO).

- A 24% improvement in hydrogen production was demonstrated via bio-fermentation of pretreated biomass using an engineered strain of *Clostridium thermocellum*.
- Machine-learning methods were developed to guide perovskite materials selection for low-cost hydrogen production.
- The Hydrogen Materials—Advanced Research Consortium (HyMARC)[54] initiated 11 new projects for hydrogen storage and carrier materials.
- A metal–organic framework (MOF) with binding energy predicted to enable room-temperature hydrogen sorption was identified; light-emitting diode (LED) light-activated hydrogen desorption was demonstrated for two titanium-based systems.
- More than 10 partners were added to the Hydrogen Materials Compatibility (H-Mat) consortium to address hydrogen materials compatibility.[55]
- An open-source license option was developed for dissemination and improvement of Hydrogen Risk Assessment Model (HyRAM)[56] risk assessment tools.
- A laser diagnostic method was developed, and calibrations were improved for modeling hydrogen releases.

ENDNOTES

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