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Hydrogen RD&D Collaboration Opportunities: United States

As at 19 October 2022

Australian Government
Department of Climate Change, Energy, the Environment and Water

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Citation

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Acknowledgments

CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past and present. CSIRO recognises that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy and science.

We are grateful for the time and input of the stakeholders from industry, government, academia who were consulted throughout this project and across the report series. In particular, the CSIRO project team would like to thank:

- Colleagues at CSIRO, members of the Australian Hydrogen Research Network (AHRN) and staff at the Department of Industry, Science, Energy and Resources (DISER), DFAT, Austrade who provided invaluable contributions to the report.
- CSIRO's Intellectual Property team and IP Australia who contributed the hydrogen patent analytics used in this series of reports: Greg Maloney (CSIRO), Catriona Shaw (IP Australia), Pushpika Wijesinghe (IP Australia).
- CSIRO's Science Impact & Policy team who contributed the hydrogen research publication analysis used in this series of reports: Tadro Abbott (CSIRO)
- The project Working Group who provided valuable feedback throughout the course of the project: Ben Aldham (CSIRO), Linda Stalker (CSIRO), Craig Buckley (Curtin University), Amalia Pearson (DISER).
- The CSIRO-DISER Hydrogen RD&D International Collaboration Program leadership team who provided oversight and guidance throughout the project: James Hetherington (DISER), Amalia Pearson (DISER), Patrick Hartley (CSIRO), Vicky Au (CSIRO), Dan O'Sullivan (CSIRO).

Finally, we would like to thank the following organisations and individuals for their time and feedback on this country report:

CSIRO: Amelia Fyfield, Doki Yamaguchi, Greg Maloney, Joel Sarout, Nawshad Haque**,** Sebastian Charnock, Yuko Wakamatsu, Yunxia Yang**.**

AHRN: Andrew Dicks (Griffith University, AHRN Convenor), Peter Grubnic (Future Fuels CRC), Peter Majewski (University of South Australia)

International Stakeholders:
Lawrence Livermore National Laboratory (LLNL), United States
Fuel Cell & Hydrogen Energy Association (FCHEA), United States
Department of Energy (DOE), United States

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The United States (US) considers hydrogen an important component to realising its industry growth and climate change mitigation ambitions. The US has funded hydrogen research, development and demonstration (RD&D) over many years, and the US Department of Energy (DOE) has recently launched the Hydrogen Energy Earthshot (or Hydrogen Shot) dedicated to reducing the cost of clean hydrogen within a decade for widespread adoption across sectors. In 2021, the US signed the Infrastructure Investment and Jobs Act (IIJ Act), committing USD 1.2 trillion funding for clean energy infrastructure development, including USD 9.5 billion hydrogen RD&D.

The *Hydrogen RD&D Collaboration Opportunities: United States* chapter aims to enhance country-to-country engagement by providing an overview of the US's hydrogen priorities and ecosystem. This report also includes a publication and intellectual property (IP) scan, identifying the key stakeholders in US actively undertaking hydrogen RD&D, both at the early research and commercialisation stage.

The United States' hydrogen strategy

At present, the US's hydrogen strategy can be gleaned from a number of departmental and industry-led roadmaps and strategies. Following the 2021 IIJ Act, a clean hydrogen strategy and national roadmap will be developed by the DOE in 2022. The US's key drivers for a hydrogen economy include clean energy for industry, grid resilience, energy supply diversification, emissions reduction, economic and social benefits, and demonstrating US leadership in energy innovation. Given the economic diversity of each state, and recognising the versatility of hydrogen, the US prioritises all areas of the hydrogen value chain. That said, each state pursues their own state-specific transport and energy strategy and thus, their hydrogen-specific priorities may differ. California, which is the world's 5th largest economy in terms of GDP, is the most advanced state in terms of its development of a hydrogen economy. Other states are expected to experience an acceleration in hydrogen-related activity in the coming years.

The United States' targets and RD&D priorities

Announced in June 2021, the DOE's first Energy Earthshot – the Hydrogen Shot – sets a goal to reduce the cost of clean hydrogen by 80%, to USD $1 per kg in one decade. Recent DOE analysis indicates potential opportunities for clean hydrogen at ~10 MMT/year by 2030, ~20 MMT/year by 2040, and ~50 MMT/year by 2050.[1] Separately, a previous industry-led roadmap in the U.S. identified potential for hydrogen demand ranging from between 20 MMT/year for a base case and 63 MMT/year in an ambitious scenario by 2050, supporting the metal refining industry, chemicals and fuels, gas networks, electricity storage and transportation fuel.

[1] https://www.hydrogen.energy.gov/pdfs/review22/plenary4_satyapal_2022_o.pdf

The DOE’s hydrogen research and development (R&D) program outlines several key RD&D priorities across various sub-technology areas.

Production
Electrolysis of water using clean energy sources such as wind, solar, nuclear
Fossil fuel conversion with CCUS: methane reforming with CCUS, methane pyrolysis, coal gasification with CCUS
Biomass and waste conversion, including with CCUS
Early-stage pathways, such as photoelectrochemical or thermochemical water splitting

Storage and Distribution
Compressed gas: pressurised storage, pipelines, tube trailers
Liquid: liquefaction, cryogenic storage and transport
Chemical: Chemical carriers or materials-based storage

Utilisation
Transportation: fuel cells for heavy-duty vehicles, refuelling stations, aviation, marine fuels
Electricity generation and energy storage: ammonia turbines, hydrogen turbines, fuel cells (polymer electrolyte membrane, solid oxide, reversible)
Industrial Processes: ammonia, steel, combustion, synthetic fuels

Cross-cutting
Safety codes and standards
Manufacturing of hydrogen technologies and components

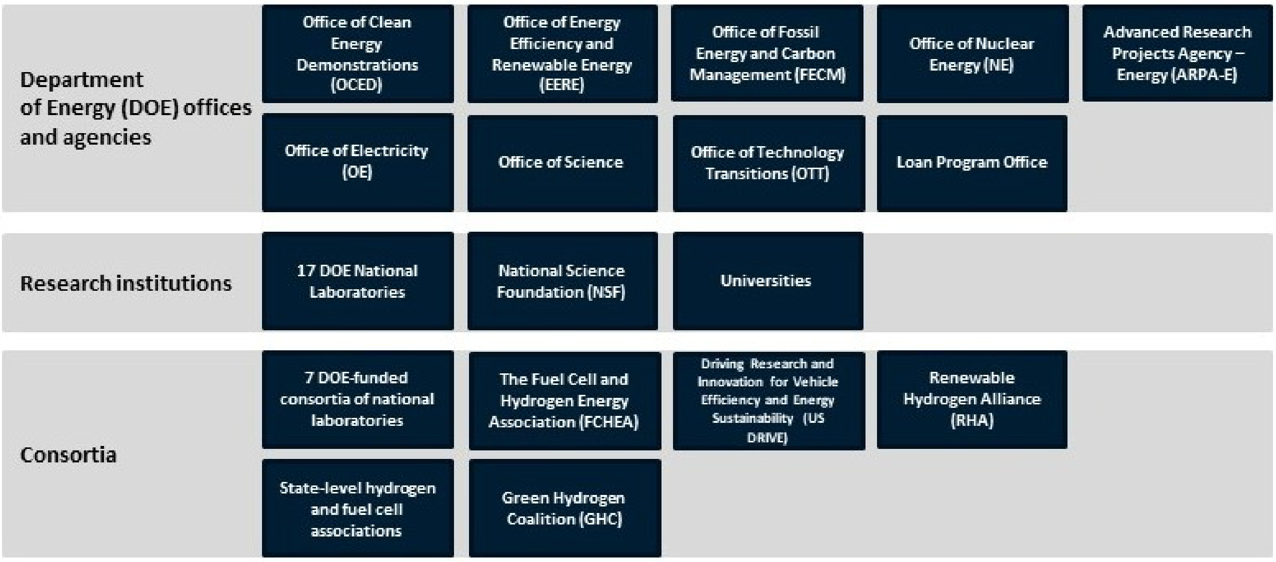
The United States’ domestic hydrogen landscape

Science, technology and innovation policy in the US are driven by the White House, Congressional Committees and advisory institutions of the President in the form of high-level goals and ambitious targets. Federal Departments and Executive Agencies then drive policy and implement programs. The main federal body and public research agency supporting hydrogen RD&D in the US is the DOE and its system of national laboratories. The DOE initiated the Hydrogen Shot and runs the Hydrogen Program,2 comprising multiple offices such as the Office of Energy Efficiency & Renewable Energy (EERE), the Office of Fossil Energy and Carbon Management (FECM), the Office of Nuclear Energy (NE), the Office of Science (SC), and the Advanced Research Projects Agency-Energy (ARPA-E), which is coordinated through EERE’s Hydrogen and Fuel Cell Technologies Office (HFTO). Additional US agencies supporting hydrogen-related RD&D include the National Science Foundation (NSF), the Office of Naval Research (ONR), among others.

The US also has several highly active peak bodies and public-industry-research consortia at the federal and state levels. The Fuel Cell and Hydrogen Energy Association (FCHEA) is a leading hydrogen association across the US. However, there are several other industry consortia driving hydrogen activity at the state level.

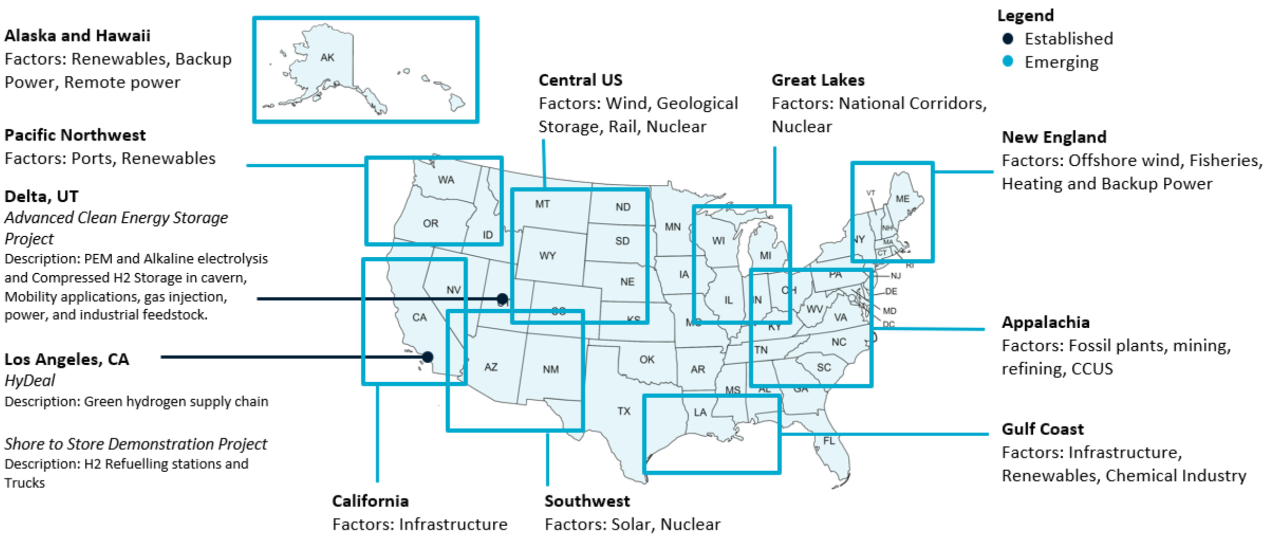
[2] https://www.hydrogen.energy.gov/

Figure 1: The United States' hydrogen RD&D ecosystem



Industry, academia and government are collaborating to establish hydrogen clusters (also known as hydrogen hubs, valleys or ecosystems). These are hydrogen value chain demonstrations and pilot projects that cut across sector applications. The IIJ Act requires at least four US regional clean hydrogen hubs to be selected in 2022, however the total number selected could be higher. Examples of US regional opportunities that could leverage local resources are illustrated in Figure 3.

Figure 2: The United States' hydrogen clusters



Adapted from Adapted from Mission Innovation (2021) Hydrogen Valleys; Green Hydrogen Coalition (2021) HyDeal; Sunita Satyapal et al (2021) The #H2IQ Webinar, DOE

IP and publications scan

Several universities, public research institutions and private companies are highly active in early-stage hydrogen research and late-stage technology commercialisation. This is reflected in hydrogen research publication output and patent output data.

Table 1: Top organisations active in early-stage and late-stage hydrogen RD&D

Rank	Top organisations (Research publication output)	Top organisations (Hydrogen patent output)
1	Lawrence Berkeley National Laboratory	GM Global Technology Operations
2	University of Chicago	Honeywell UOP (Universal Oil Products)
3	Stanford University	Intelligent Energy
4	University of California Berkeley	Air Products and Chemicals
5	Argonne National Laboratory	Saudi Arabian Oil

International collaboration

The US is active in several multilateral hydrogen platforms. These include the Clean Energy and Hydrogen Energy Ministerial Initiative, the International Energy Agency (IEA), the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Mission Innovation and the Transatlantic Energy Cooperation. Additionally, the recent Quadrilateral Security Dialogue (Quad) between Australia, the US, Japan and India included discussion on energy and hydrogen partnership. The DOE has engaged bilaterally with several countries including the Netherlands, Germany, Japan, South Korea, Ukraine, France and India.

1 Country analysis: United States

1.1 Introduction

The United States (US) considers hydrogen an important component to realising the country's industry growth and climate change mitigation ambitions. The US has funded hydrogen research, development and demonstration (RD&D)[3] over many years, and hydrogen has received renewed focus as part of the US DOE Hydrogen Energy Earthshot. In September 2022, the US released the draft DOE National Clean Hydrogen Strategy and Roadmap. The Strategy and Roadmap provides a snapshot of hydrogen production, transport, storage, and use in the United States today and outlines the opportunity that clean hydrogen could provide in contributing to national climate and environmental goals. Pathways for clean hydrogen to decarbonize applications are informed by demand scenarios for 2030, 2040, and 2050 – with strategic opportunities for 10 million metric tonnes (MMT) of clean hydrogen annually by 2030, 20 MMT annually by 2040, and 50 MMT annually by 2050,[4] and there are several available documents with respect to hydrogen technologies and accelerating their development. In addition, the U.S. DOE published the *Hydrogen Program Plan*[5], and US industry stakeholders have published a *Road Map to a US Hydrogen Economy.*[6] Given the diversity of individual states and their economies, US strategic priorities in hydrogen sit across the entire spectrum of the value chain, and across almost all hydrogen technologies. California has been the most active state in hydrogen development, particularly in the areas of production and mobility applications. However, hydrogen activity in other states is accelerating, with several regional clusters (also known as hubs, valleys, or ecosystems) currently being proposed across the country, which will receive federal support to develop.

The *Hydrogen RD&D Collaboration Opportunities: United States* chapter presents an overview of the hydrogen RD&D landscape in the United States, starting from the national strategy level, down to activity in specific hydrogen technology areas.

[3] As defined by the IEA Guide to Reporting Energy RD&D Budget/Expenditure Statistics, 2011

[4] https://www.hydrogen.energy.gov/roadmaps_vision.html

[5] https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[6] FCHEA (2020) Road Map to a US Hydrogen Economy https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

1.2 United States’ hydrogen drivers, strategy and RD&D priorities

1.2.1 The United States’ key drivers

Industry in the US sees clean hydrogen as an important part of the energy transition that can be utilised to overcome several challenges faced by an evolving energy system. Recognising hydrogen’s ability to cut across several sectors to drive decarbonisation, contribute to energy security, and generate economic benefits, US industry have set out a plan to increase the supply and use of hydrogen. Broadly, the United States sees the development of a hydrogen economy as a way to:[7]

- Pursue greenhouse gas reduction targets;
- Supply clean energy to a range of industries and end-use applications, and enhance the performance of energy sources to build grid resilience;
- Diversify and increase domestic energy supplies to ensure energy security;
- Lower energy costs for consumers;
- Extend leadership in energy innovation; and
- Drive economic, social, and environmental benefits associated with clean energy.

1.2.2 The United States’ strategic hydrogen industry priorities

In November 2021, the Infrastructure Investment and Jobs Act (IIJ Act) was enacted which requires the DOE to establish a clean hydrogen strategy and national roadmap to the US Congress.[8] In the meantime, the DOE has published several documents relating to hydrogen strategy and RD&D in the US and the federal government continues to provide funding to support hydrogen technology development.

The US has recognised the versatility of hydrogen across many industries and applications. Each state has a unique set of comparative advantages with respect to hydrogen, and each develops and implements their own energy and transport strategies. For example, California has been the most active in the deployment of hydrogen value chains, particularly in production of hydrogen from renewables and applications in mobility.[9] Other states are expected to experience an acceleration in hydrogen-related activity in the coming years, many with advantages in other areas such as nuclear energy, fossil fuel conversion with carbon capture and storage (CCS), key infrastructure, refineries and chemicals industry.

US initiatives, programs and strategies of note include:

- **Regional Clean Hydrogen Hubs**: The U.S. DOE opened applications for a $7 billion program to create regional clean hydrogen hubs (H2Hubs) across the country, which will form a critical arm of America's future clean energy economy. As part of a larger $8 billion hydrogen hub program funded through President Biden’s Bipartisan Infrastructure Law, the H2Hubs will be a central driver in helping communities across the country benefit from clean energy investments, good-paying jobs, and improved energy security – all while supporting President Biden’s goal of a net-zero carbon economy

[7] DOE (2020) Hydrogen Strategy: Enabling a Low-Carbon Economy https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf; DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[8] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America § 40313. Viewed at https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

[9] Ludwig-Bölkow-Systemtechnic GmbH (2020) International Hydrogen Strategies: A study commissioned by and in cooperation with the World Energy Council Germany. World Energy Council Germany https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf

by 2050. Projects funded under this funding opportunity are expected to include a Community Benefits Plan to:

- Support meaningful community and labor engagement;
- Invest in America's workforce;
- Advance diversity, equity, inclusion, and accessibility; and
- Contribute to the President's goal that 40% of the overall benefits of certain federal investments flow to disadvantaged communities.

- **Hydrogen at Scale (H2@Scale):**[10] H2@Scale is a DOE initiative that sets out an overarching vision for how hydrogen can enable energy pathways across end-use applications and sectors to create an interconnected energy system. This is the guiding framework for the DOE's *Hydrogen Program Plan.*[11] The H2@Scale program has published technical reports outlining possible demand scenarios for hydrogen in the US,[12] as well as the potential technical and economic benefits of the H2@Scale concept (see *Section 1.4* for the H2@Scale program).[13] Potential benefits include:
  - The ability to produce hydrogen from the US's resources, both renewable and 'conventional' (fossil fuels)
  - Additional applications from hydrogen beyond its current use in ammonia and refining: energy for transportation; feedstock for industry, including refining and synthetic fuels; heat for industry and buildings; and energy storage.
  - Hydrogen's flexibility allows it to integrate energy systems and link industry feedstocks. In doing so hydrogen can balance surplus and shortages in the energy and chemical markets.
- **Draft DOE National Clean Hydrogen Strategy and Roadmap**: the draft roadmap will satisfy a requirement in the Bipartisan Infrastructure Law once finalized and submitted to Congress. The Strategy and Roadmap is based on prioritizing three strategies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool and for maximum benefits for the United States. The strategies are:
  1. **Target strategic, high-impact uses for clean hydrogen**. This will ensure that clean hydrogen will be utilised in the highest value applications, where limited decarbonisation alternatives exist. Specific markets identified include: the industrial sector, heavy-duty transportation, and long-duration energy storage to enable a clean grid.
  2. **Reduce the cost of clean hydrogen**. This strategy, supported by the Hydrogen Energy Earthshot (Hydrogen Shot), aims to catalyse innovation and scale, stimulate private sector investments, spur development across the hydrogen supply chain, and dramatically reduce the cost of clean hydrogen. Efforts will also address critical material and supply chain vulnerabilities and design for efficiency, durability, and recyclability.
  3. **Focus on regional networks**. This includes regional clean hydrogen hubs to enable large-scale clean hydrogen production and end-use in proximity, enabling critical mass infrastructure, driving scale,

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[10] DOE (2021) H2@Scale: enabling affordable, reliable, clean and secure energy across sectors https://www.energy.gov/sites/default/files/2020/07/f76/hfto-h2-at-scale-handout-2020.pdf; Office of Energy Efficiency and Renewable Energy (2021) H2@Scale https://www.energy.gov/eere/fuelcells/h2scale

[11] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[12] Argonne National Lab (2020) Assessment of Potential Future Demands for Hydrogen in the US https://greet.es.anl.gov/files/us_future_h2; NREL (2020) Resource assessment for hydrogen production https://www.nrel.gov/docs/fy20osti/77198.pdf

[13] NREL (2020) Technical and economic potential of the H2@Scale concept within the US https://www.nrel.gov/docs/fy21osti/77610.pdf

and facilitating market lift off while leveraging place-based opportunities for equity, inclusion, and sustainability. Priorities will include near term impact, creating jobs - including good paying union jobs - and jumpstarting domestic manufacturing and private sector investment.

- **Integrated Energy Systems: 2020 Roadmap:** [14] This roadmap was published by the Office of Nuclear Energy (NE) in collaboration with the Office of Energy Efficiency & Renewable Energy (EERE) and the DOE H2@Scale Program. The Roadmap sets out a research and development (R&D) pathway to develop and utilise nuclear energy technology for commercial-scale hydrogen production. Under the Roadmap, R&D is focussed on three areas:
  - reforming technologies;
  - electrolysis; and
  - abstracting hydrogen from alkanes during alkane deprotonation to produce ethylene, propylene and butene.

The United States' hydrogen targets

The DOE has put forward a range of production cost goals, aiming for less than USD 2/kg for transport applications and less than USD 1/kg for industrial and bulk power applications.[15]

While the US is finalizing official targets for clean hydrogen production and use, the draft DOE National Clean Hydrogen Strategy and Roadmap modelled potential production and demand scenarios across different time frames. Absent formal targets, this modelling indicates the potential scale and use of hydrogen in the US.

Specifically, the draft Strategy and Roadmap outlined clean hydrogen use at 10 MMT H2/year by 2030, 20 MMT/year by 2040, and 50 MMT/year by 2050.[16] Key sectors that could drive this demand include the transportation sector (primarily medium- and heavy-duty transport), biofuel and power-to-liquid production (primarily for sustainable aviation fuel production), industrial sector (primarily for steel and ammonia), blending with natural gas (primarily for high-grade industrial heat), and the power sector (primarily for seasonal energy storage).

The FCHEA's *Road Map to a US Hydrogen Economy*[17] modelled predicted hydrogen demand and production across an 'ambitious scenario' and 'base scenario'. By 2050, the modelling predicted hydrogen demand to range between 20 MMT/year (base scenario) and 63 MMT/year (ambitious scenario). Respectively, this could account for between 1% and 14% of total energy demand in the US by 2050.[18]

Error! Reference source not found. shows the results from the DOE's low-cost electrolysis scenario, as well as the industry roadmap scenarios for 2030 and 2050. These figures do not include the potential for new emerging industry applications of hydrogen such as marine transport, and hydrogen for powering data centres.

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[14] NE (2020) Integrated Energy Systems: 2020 Roadmap https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_26755.pdf

[15] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[16] https://www.hydrogen.energy.gov/pdfs/review22/plenary4_satyapal_2022_o.pdf

[17] FCHEA (2020) Road Map to a US Hydrogen Economy https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

[18] FCHEA (2020) Road Map to a US Hydrogen Economy https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

1.2.3 The United States' hydrogen RD&D priorities

The DOE's 2020 *Hydrogen Program Plan*[19] is focused on addressing the key challenges outlined by the H2@Scale initiative to accelerate affordable hydrogen production, transport, storage, and utilisation. At a high level, those priorities are to:

- Reduce costs and improve the performance and durability of production, delivery, storage and conversion systems;
- Address technological, regulatory, and market barriers that both limit the integration of hydrogen with conventional energy systems, and reduce opportunities for exporting hydrogen;
- Explore opportunities for achieving large-scale adoption and use by aggregating disparate sources of supply and demand;
- Develop and validate integrated energy systems utilising hydrogen; and
- Demonstrate the value proposition for new and innovative uses.

The US' hydrogen RD&D priorities are articulated in the DOE's *Hydrogen Program Plan.*[20] Key items have been collated into Table 2 below.

Table 2: The US hydrogen RD&D priorities

Supply chain area	Sub-technology areas	US key RD&D priorities
Production	Electrolysis	Low temperature, including polymer electrolyte membranes (PEM) and alkaline electrolysis (AE) High temperature electrolysis. New catalysts and electrocatalysts, reducing the use of platinum group metals. Modular systems. Low-cost durable membranes and separation materials Improved balance of plant. Component design and materials integration for scale-up and manufacturing.
	Fossil fuels with CCS	Coal gasification and natural gas conversion with carbon capture, utilisation and storage (CCUS). Cost reductions through ongoing R&D in catalysis, separations, controls, polygeneration, capital cost reductions, process intensification, modularisation, use of artificial intelligence. Modular systems. Cost reductions for autothermal reforming.
	Biomass conversion	Biogas from waste streams. Overcoming challenges in economics by improving conversion efficiency through advanced catalysis, separation and process intensification.

[19] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[20] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Supply chain area	Sub-technology areas	US key RD&D priorities
		Reducing costs of pre-treating and transporting feedstocks. Novel thermal and non-thermal plasma-based processes.
	Emerging technologies	Biological production, solar thermochemical hydrogen, and photo-electrochemical water splitting. This includes novel, durable and low-cost materials.
Storage and distribution	Pipelines	Lowering the cost of pipelines, development of high-throughput compressors, assessing low-cost materials for use in pipelines, and demonstrating novel pipeline technologies. Materials compatibility at high and low pressure compression.
	Liquefaction	Overcome cost and energy efficiency challenges, including through novel non-mechanical processes such as with magnetocaloric materials and processes.
	Chemical carriers	Improve charge and discharge rates, reversibility, round-trip efficiency and hydrogen carrying capabilities. Examples cited include ammonia and liquid organic hydrogen carriers (LOHCs).
	Storage tanks	Reduce cost and improve safety. Develop low-cost carbon fibre to drive down costs of small-scale tank storage. Pursue novel designs, materials and controls for large-scale tank storage. Safety research efforts into materials compatibility issue and fatigue, setback distances and underground storage. Improve insulation and manage boil-off and venting for cryogenic or cryo-compressed storage. This requires component and system-level RD&D.
	Tube trailers	Enhance the lifetime of pressure vessels onboard tube trailers, reduce the cost of high-pressure composite tube trailers, and increase capacity of compressors at terminals.
	Refuelling and dispensing systems	Reduce the cost, improve reliability and increase the throughput of hydrogen dispensing. RD&D to achieve this includes enhancing reliability of materials in hoses and seals, improving the life of parts and materials, and novel designs for compressors and transfer pumps. Additionally, further materials research is needed to increase the life and capacity of onsite storage.
Utilisation	Gas turbines	Enable wider range of acceptable hydrogen concentrations (up to 100%) in simple and combined cycles. Improve understanding of combustion behaviour and optimisation of component designs for low NOx combustion. Apply and develop advanced computational fluid dynamics with reacting flows. Develop advanced manufacturing techniques for combustors. Develop new materials, coatings, and cooling schemes. Optimise conversion efficiency.

Supply chain area	Sub-technology areas	US key RD&D priorities
		Improve durability and lifetime and lower costs, including for operations and maintenance. Develop system-level optimisation and control schemes. Assess and mitigate moisture content effects on heat transfer and ceramic recession. Develop and test hydrogen combustion retrofit packages. Enable combustion of carbon-neutral fuels (i.e., ammonia, ethanol vapor).
	Fuel cells (transport and stationary)	**PEMFC (polymer electrolyte membrane fuel cell):** Materials R&D to reduce platinum group metal catalyst loading. High-temperature tolerant, low-cost, and durable membranes. Improved component-design and materials integration to optimise manufacturable and scalable electrode structures for membrane electrode assemblies. Internal reforming of carbon neutral fuels for directly fed fuel cells. Accelerated stress tests, improved understanding of degradation mechanisms, and stress mitigation approaches. Improved balance-of-plant (BOP) components, including compressors and power electronics. Standardised, modular stacks and systems for multiple heavy-duty applications. Improved hybridisation and optimised system design. **SOFC (solid oxide fuel cells):** Materials R&D to reduce cost and address issues related to high-temperature operation. Management of heat and gas flow across the stack. Addressing stack and BOP systems integration, controls, and optimisation for load following and modular applications. Improved BOP components, including compressors and power electronics. Standardised, modular stacks. Improved understanding of impacts of impurities on materials and performance. System design, hybridisation and optimisation Polygeneration of electricity and hydrogen
	Transport (maritime and aviation)	Explore hydrogen and chemical carrier options for transport sectors such as maritime and aviation. Studies into challenges related to the development of new supply chains and refuelling infrastructure, and the optimisation of onboard storage.

Supply chain area	Sub-technology areas	US key RD&D priorities
	Integrated energy systems	Multiple hybrid scenarios are being explored that could optimally leverage the benefits of integrated energy systems; such as integrating hydrogen production for long term storage, to take advantage or excess renewables or waste heat and improve grid reliability and resilience.
Cross-Cutting	Safety, codes and standards	Continued development and revision of codes and standards. Ongoing research and data collection and analysis to improve the understanding of hydrogen's physical and chemical properties. Improved hydrogen sensing and contaminant detection. Development of quantitative risk assessment tools and streamlined permitting processes to facilitate siting of hydrogen infrastructure and reduce barriers to deployment. Identification and evaluation of risk mitigation strategies, best safety practices, and lessons-learned. Develop and sustain collaborative institutional processes for disseminating safety information.
	Manufacturing	High-speed manufacturing techniques for processes such as forming, stamping, moulding, sealing, joining, coating, and roll-to-roll processing. Best practices for material and component handling. Additive and automated manufacturing and assembly processes. Technologies for in-line diagnostics and quality assurance. Sensors and other technologies to reduce manufacturing defects in high-throughput production. Manufacturing processes and technology designs that enable efficient recycling and/or upcycling, particularly of critical materials.

1.3 The United States' hydrogen RD&D ecosystem

1.3.1 Public bodies and policy ecosystem

Overview of the United States' STI policy landscape

The White House's STI (science, technology and innovation) policies are primarily driven by Congressional Committees and advisory institutions of the President.[21] Key Congressional Committees that design and inform STI policy include:

- The House Committee on Science, Space and Technology, which considers areas across energy, aviation, and environmental research;
- The Senate Committee on Commerce, Science and Transportation, which is involved in science, engineering and technology R&D and policy;

[21] Mark Knell (2021) The Main Science, Technology and Innovation Policy Actors in the United States, Forskingspolitikk https://www.fpol.no/the-main-science-technology-and-innovation-policy-actors-in-the-united-states-sti/

- The House Committee on Energy and Commerce and the Senate Committee on Health, Education, Labor and Pensions, which considers biomedical research policy; and
- The House Armed Services Committee and the Senate Committee on Armed Services which is involved in military-specific technology R&D.

There are three key bodies that advise the White House on matters relating to STI policy. These are:

- The Office of Science and Technology Policy (OSTP), which functions to advise the President on science and technology and the impact it has on domestic and international affairs. The Office also is tasked with developing STI policies and budgets. The Office sits within the Executive Office of the President.[22]
- The President's Council of Advisors on Science and Technology is administered by the OSTP and makes policy recommendations on STI matters. Recent reports by the Council have included climate change, antibiotic resistance and education technology.[23]
- The National Science and Technology Council coordinates science and technology policy across the various federal R&D agencies. The Council establishes national goals for federal science and technology investments spanning the mission areas of almost all of the Executive branch and creates R&D strategies to coordinate government agencies.[24]

The Department of State also plays an important role in the US STI policy landscape.[25] The Department leads the implementation of programs to build capacity in emerging markets and executes public diplomacy programs to promote science and technology and its value to society. Specific bureaus within the Department of State that contribute to STI policy include the Office of Science and Technology Cooperation, the Office of the Science and Technology Adviser to the Secretary of State and the Office of Space Affairs.[26] Other relevant executive departments include the Department of Education, Health and Human Services, Agriculture, Energy, and Defence.

Overview of United States' hydrogen policy landscape

The US Hydrogen Program sits within the DOE and is led by the Hydrogen and Fuel Cell Technologies Office (HFTO) which sits within the EERE.[27] Other offices that operate alongside the HFTO are the FECM, Office of Nuclear Energy, Office of Science, Office of Electricity, Office of Clean Energy Demonstrations, Advanced Manufacturing Office, and Advanced Research Projects Agency – Energy (ARPA-E). While hydrogen efforts under these offices are often conducted separately, there is a high level of coordination to avoid duplication of effort. Coordinated activities include funding opportunity announcements, merit reviews, program strategy, project reviews and ensuring a cohesive strategy to tackle the commercialisation of hydrogen and fuel cell technologies. Individually, the Offices manage their own funding processes and execution of projects, both through their field offices and procurement functions as well as through the national research laboratories.[28]

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[22] The White House (n.d.) Office of Science and Technology Policy https://www.whitehouse.gov/ostp/

[23] Office of Science (n.d.) President's Council of Advisors on Science and Technology (PCAST) https://science.osti.gov/About/PCAST

[24] The White House (n.d.) National Science and Technology Council https://www.whitehouse.gov/ostp/nstc/

[25] U.S. Department of State (n.d.) Policy Issues: Science, Technology, and Innovation https://www.state.gov/policy-issues/science-technology-and-innovation/

[26] U.S. Department of State (n.d.) Policy Issues: Science, Technology, and Innovation https://www.state.gov/policy-issues/science-technology-and-innovation/

[27] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[28] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Two interagency task forces coordinate external activities within the program: the Hydrogen and Fuel Cells Interagency Working Group (IWG) and the Hydrogen and Fuel Cell Interagency Task Force (ITF). The former meets regularly to evaluate progress of program activities, strengthen information exchange, provide recommendations for management practices and technical performance, and collaborate on system analysis activities.[29] The latter focuses its efforts on federal leadership and early adoption.[30]

There are also specific collaborations between offices. Between the EERE, the Office of Nuclear Energy and the FECM, areas of collaboration include reversible fuel cells, biomass, municipal solid waste, co-gasification with biomass and waste plastic, high-temperature electrolysis, and systems integration.[31]

Finally, the DOE's Hydrogen Program cuts across multiple offices and initiatives. This includes collaboration with the Office of Technology Transitions (OTT) and the Loan Program Office, and initiatives include the Energy Storage Grand Challenge which is under the DOE.

Figure 3 depicts the US hydrogen policy ecosystem. Key bodies within this ecosystem are expanded upon in Table 3.

Figure 3: Summary of the United States' hydrogen policy ecosystem

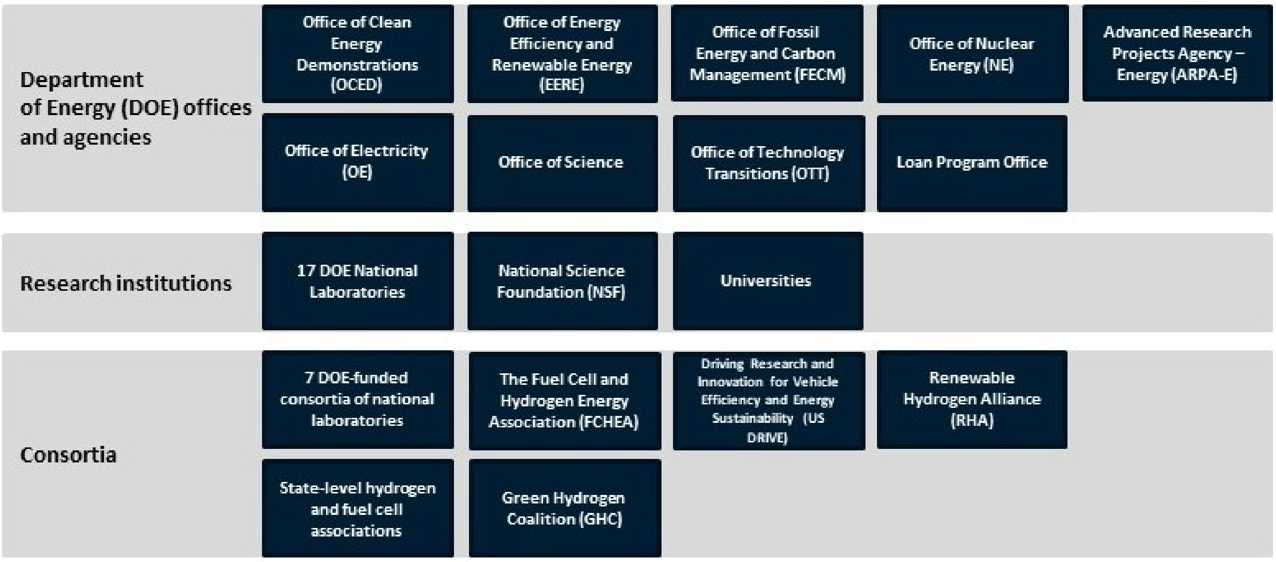


Table 3: Summary of key public bodies

Body	Role in RD&D ecosystem	Hydrogen initiatives
DOE *Department of Energy*	The DOE develops, implements and coordinates policy and research initiatives with respect of energy, the environment and nuclear power.[32] The DOE also coordinates and conducts energy-related research through its system of National Laboratories.	The DOE is responsible for the Hydrogen Program. All major participating offices within the program sit within the DOE.[33]

[29] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[30] DOE (n.d.) Hydrogen Program: External Coordination. https://www.hydrogen.energy.gov/external_coordination.html

[31] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[32] DOE (2021) About Us. https://www.energy.gov/about-us

[33] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Body	Role in RD&D ecosystem	Hydrogen initiatives
NRC *National Research Council*	The NRC is administered by the National Academies of Sciences, Engineering and Medicine. It provides evidence-based advice to the US around solutions to complex challenges and emerging opportunities. The NRC sets the vision, mission and strategic goals of the National Academies.[34]	The NRC periodically reviews the RD&D activities of the DOE Hydrogen Program.[35]
NSF *National Science Foundation*	The NSF is an independent federal agency that conducts early-TRL research in all non-medical fields.[36] The NSR funds approximately 25 per cent of all federally supported basic research conducted in American universities.[37]	Carries out early-TRL research related to hydrogen. There are several projects that the NSF currently supports in hydrogen and fuel cell research, including work on storage of hydrogen in novel materials, catalytic hydrogen production, and biological production of hydrogen.[38] The NSF is also a participant in the Hydrogen and Fuel Cell Interagency Working Group, led by the DOE.[39]
EERE *Office of Energy Efficiency & Renewable Energy*	EERE focuses on RD&D and innovations across several renewable energy, energy efficiency, transportation technologies, advanced manufacturing, and cross-cutting activities. EERE consists of several offices that support their broader mission including the Advanced Manufacturing Office, Bioenergy Technologies Office, the Vehicle Technologies Office, and the Renewable Power Offices.[40]	The Hydrogen and Fuel Cell Technologies Office, the Office leading the Hydrogen Program, sits within the EERE. This Office leads programs including H2@Scale and supports RD&D at the materials, component and systems-level. This Office also funds seven laboratory-led hydrogen consortia (ElectroCat, H2NEW, H-Mat, HyBlend, HydroGEN, HyMARC, and the M2FCT).[41] (See *Section 1.3.2* for more detail) EERE coordinates with offices outside EERE such as the FECM and the Office of Nuclear Energy on various research topics within hydrogen and fuel cells. Hydrogen activities under the EERE include: [42] The Advanced Manufacturing Office supports manufacturing innovations related

[34] NRC (2021) NRC Strategic Plan 2021-2026. Available https://www.nationalacademies.org/about

[35] DOE (2021) National Research Council. Hydrogen Program. https://www.hydrogen.energy.gov/advisory_nrc.html

[36] NSF (2021) About the National Science Foundation. https://www.nsf.gov/about/

[37] NSF (2021) About the National Science Foundation. https://www.nsf.gov/about/

[38] NSF (2021) About the National Science Foundation. <https://www.nsf.gov/about/

[39] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[40] DOE (2021) EERE Technology Areas and Offices. https://www.energy.gov/eere/eere-technology-areas-and-offices

[41] DOE (n.d.) Hydrogen and Fuel Cell Technologies Office Consortia. https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-consortia

[42] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Body	Role in RD&D ecosystem	Hydrogen initiatives
		to technologies such as electrolysers and hydrogen storage tanks. The Bioenergy Technologies Office, relating to hydrogen, focuses on RD&D on topics such as technologies that utilise hydrogen for production of biofuels and bioproducts and hydrogen production from biomass or bio-waste streams. The Vehicle Technologies Office focuses on next-gen technologies to improve battery-electric and other alternative-fuel vehicles. The Renewable Power Offices conducts RD&D relating to the integration of renewable power sources with technologies for hydrogen production and utilisation.
OCED *Office of Clean Energy Demonstrations*	The OCED was established in December 2021, as specified under the IIJ Act. The role of the office is to support clean energy technology demonstration projects in areas including, but not limited to, hydrogen, carbon capture, utilisation and storage (CCUS), and grid-sale energy storage. [43]	The Office of Clean Energy Demonstrations will serve as a hub for accelerating the development of clean energy technologies so as to achieve faster commercial adoption. These projects, including those pertaining to hydrogen, will be awarded funds through the new office. [44]
FECM *Office of Fossil Energy and Carbon Management*	The FECM aims to advance science and technologies that enable the reliable, efficient, affordable and environmentally sustainable use of fossil fuels. RD&D efforts focus on the areas of power generation, power plant efficiency, water management, and CCUS.	The FECM leads DOE's CCUS efforts. There are two major programs under the FECM that conduct hydrogen RD&D:[45] The Office of Clean Coal and Carbon Management focuses technologies relating to hydrogen production for fossil fuels with CCUS. This office collaborates with EERE on fuel cell RD&D and with the NE and other offices on hybrid energy systems. The Office of Oil and Natural Gas conducts RD&D to enable the use of natural gas production, distribution, and storage infrastructure and the large-scale delivery and storage of hydrogen.
NE *Office of Nuclear Energy*	The NE aims to advance nuclear power to meet the US's energy needs. High-level RD&D focuses include enhancing the long-term viability and competitiveness of the	Regarding hydrogen, NE is collaborating with the EERE and industry to conduct RD&D to enable commercial-scale hydrogen production from nuclear energy systems.

[43] DOE (2021) DOE Establishes New Office of Clean Energy Demonstrations Under the Bipartisan Infrastructure Law. https://www.energy.gov/articles/doe-establishes-new-office-clean-energy-demonstrations-under-bipartisan-infrastructure-law

[44] DOE (2021) DOE Establishes New Office of Clean Energy Demonstrations Under the Bipartisan Infrastructure Law. https://www.energy.gov/articles/doe-establishes-new-office-clean-energy-demonstrations-under-bipartisan-infrastructure-law

[45] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Body	Role in RD&D ecosystem	Hydrogen initiatives
	existing US reactor fleet and developing advanced nuclear reactor concepts. [46]	Efforts relating to hydrogen production include demonstration of both high-temperature and low-temperature electrolysis systems and development of advanced reactors that will operate at very high temperatures. [47]
OE *Office of Electricity*	The OE leads DOE efforts to ensure that critical energy infrastructure around the US is secure and able to withstand disruptions. Priorities include the North American Energy Resiliency Model; megawatt scale grid storage; sensing technology utilisation; and transmission. [48]	OE collaborates with the Hydrogen Program on RD&D related to power-to-gas applications and long duration energy storage.[49]
ARPA-E *Advanced Research Projects Agency-Energy*	ARPA-E advances disruptive energy technologies to enhance the economic and energy security of the US. ARPA-E provides funding for high-risk, high impact projects. [50]	Efforts relevant to hydrogen or related technologies from ARPA-E include programs such as the Methane Pyrolysis Cohort, the Renewable Energy to Fuels through Utilisation of Energy-dense Liquids, and the Reliable Electricity Based on Electrochemical Systems. [51]
OS *Office of Science*	The OS sits within the DOE and is tasked with delivering science and innovation to advance energy, national security and the US economy. [52]	The Office of Basic Energy Sciences within the OS supports fundamental research relating to the hydrogen value chain, complementing RD&D activities of other DOE offices. Key focus areas include advanced materials, membranes and catalysts, and solar hydrogen production. [53]
OTT *Office of Technology Transitions*	The OTT focuses on commercialisation, and the adoption and diffusion of technologies DOE's RD&D portfolio. This is to maximise the impact of the DOE's RD&D investments. Activities include working with the national laboratories to catalyse collaboration between research and industry. The OTT also oversees the Technology Commercialisation	The OTT is one of the key offices providing cross-cutting services within the DOE Hydrogen Program. [55]

[46] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[47] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[48] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[49] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[50] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[51] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[52] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[53] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[55] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Body	Role in RD&D ecosystem	Hydrogen initiatives
	Fund of the DOE which focuses on high-potential mature energy technologies. [54]	
LPO *Loan Program Office*	The LPO provides funding to US energy infrastructure projects. The LPO's Innovative Energy Loan Guarantee Program has a lending capacity of over USD 20 billion for energy projects that contribute to emissions reductions. The LPO aims to provide a repeatable financing model for first-of-a-kind commercial projects.	It is expected the LPO will play an important role in funding low-carbon hydrogen energy projects.

1.3.2 Hydrogen consortia

There are several hydrogen consortia across the United States, both at a federal and state level. There are several types of consortia, including DOE-funded research lab consortia, industry associations, non-governmental alliances.

Research lab consortia

The US Hydrogen and Fuel Cell Technologies office has funded laboratory-led consortia to coordinate R&D activity across the country. Each consortium is concerned with a specific hydrogen value chain area, and was established to deliver resources for universities and industry, as well as undertake innovation projects.

Table 4: Summary of research lab consortia

Consortium	Description
ElectroCat *The Electrocatalysis Consortium*	ElectroCat is a consortium of four national laboratories, co-led by the Argonne National Laboratory and the Los Alamos National Laboratory. This group aims to accelerate the development of catalysts manufactured with platinum group metals for use in fuel cell applications by performing multi-scale modelling, catalyst synthesis and characterisation and capability development. [56] ElectroCat is one of seven laboratory-led consortia funded by the DOE's HFTO.
H-Mat *Hydrogen Materials Compatibility Consortium*	H-Mat is comprised of five national laboratories, co-led by the Sandia National Laboratories and the Pacific National Laboratory. R&D focuses include effects of hydrogen on polymer performance and metals used in hydrogen infrastructure and storage.[57] H-Mat is one of seven laboratory-led consortia funded by the DOE's HFTO.
HydroGEN	HydroGEN is a consortium of six national laboratories led by the NREL.[58] Areas of interest include advance water splitting materials, including photoelectrochemical, solar

[54] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[56] DOE (2021) ElectroCat: Electrocatalysis Consortium. https://www.energy.gov/eere/fuelcells/electrocat-electrocatalysis-consortium

[57] DOE (2021) Hydrogen and Fuel Cell Technologies Office Consortia. https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-consortia

[58] DOE (2021) HydroGEN Advanced Water Splitting Materials Consortium. https://www.energy.gov/eere/fuelcells/hydrogen-advanced-water-splitting-materials-consortium

Consortium	Description
HydroGEN Advanced Water Splitting Materials Consortium	electrothermal, and advanced electrolytic hydrogen production pathways. HydroGEN is one of seven laboratory-led consortia funded by the DOE's HFTO.
HyMARC *The Hydrogen Materials-Advanced Research Consortium*	HyMARC aims to address challenges associated with hydrogen storage, including but not limited to, thermodynamic and kinetic limitations of materials, mass transport, and surface and interfacial processes.[59] HyMARC is one of seven laboratory-led consortia funded by the HFCTO of the DOE.
M2FCT *Million Mile Fuel Cell Truck Consortium*	Launched by the DOE in October 2020, the M2FCT is a consortium of five national laboratories and three affiliate laboratories that seek to identify ways to make hydrogen and related technologies more competitive. Specifically, M2FCT is focused on the commercialisation of fuel-cell trucks by improving the efficiency, durability and affordability of key technologies associated with the long-haul, heavy-duty truck market.[60] The M2FCT is one of seven laboratory-led consortia funded by the DOE's HFTO.
H2NEW *Hydrogen from Next-generation Electrolysers of Water*	Launched by the DOE in October 2020, the H2NEW is comprised of nine national laboratories and is primarily focused on improving the durability, efficiency and cost of large-scale electrolysers.[61] H2NEW is one of seven laboratory-led consortia funded by the DOE's HFTO.

Government-industry-research consortia

A non-exhaustive list of key peak hydrogen bodies and associations are detailed in Table 5 below. The table below includes key federal level consortia, and examples of State specific bodies and associations.

Table 5: Summary of other industry and public-private partnerships

Consortium	Description
FCHEA *The Fuel Cell and Hydrogen Energy Association*	The FCHEA is the largest, and the only national, hydrogen association in the US. It represents more than seventy leading companies and organisations with the aim to advance the commercialisation of fuel cell and hydrogen technologies. The FCHEA operates as a national advocate to facilitate the development and uptake of hydrogen technologies; provide advice on regulations, codes and standards; and educate all levels of government on the environmental and economic advantages of fuel cell and hydrogen technologies.[62]
U.S. DRIVE *Driving Research and Innovation for Vehicle Efficiency*	The U.S. DRIVE partnership is a government-industry partnership focused on R&D for mobility and relating infrastructure. The purpose of the partnership is to discuss R&D needs, develop technology roadmaps, and evaluate progress across several technology areas.[63]

[59] DOE (2021) HyMARC: Hydrogen Materials Advanced Research Consortium. https://www.energy.gov/eere/fuelcells/hymarc-hydrogen-materials-advanced-research-consortium

[60] Million Mile Fuel Cell Truck (n.d.) Home https://millionmilefuelcelltruck.org/

[61] H2NEW (n.d.) H2NEW: US DEPARTMENT OF ENERGY https://h2new.energy.gov/

[62] FCHEA (2021) About Us. https://www.fchea.org/aboutus

[63] DOE (2021) U.S. DRIVE https://www.energy.gov/eere/vehicles/us-drive

Consortium	Description
and Energy Sustainability	Technical focus areas include the entire hydrogen value chain relating to fuel cells and FCEVs. The partnership also focuses on cross-cutting areas such as mobility and energy systems, codes and standards, and storage and distribution infrastructure. Key members include the DOE, USCAR, Ford Motor Company, General Motors, DTE Energy Company, Southern California Edison Company, Electric Power Research Institute, American Electric Power, Duke Energy, BP America, Chevron Corporation, ExxonMobil Corporation, Shell Oil Products US.
Renewable Hydrogen Alliance	The Renewable Hydrogen Alliance engages in policy advocacy and education and outreach to regulators, legislators and the environmental community to advance the development and uptake of clean hydrogen power.[64] Members include project developers, electric and gas utility companies, clean energy advocacy organisations, law firms, transit agencies, and manufacturers of hydrogen electrolysers, fuel cells and fuel cell vehicles.
Green Hydrogen Coalition	The Green Hydrogen Coalition is an educational organisation that develops policies and practices to facilitate the development and uptake of renewable hydrogen production and utilisation across several sectors. The Coalition does so by supporting at-scale clean hydrogen projects and leveraging multi-sector opportunities to simultaneously scale supply and demand. The Green Hydrogen Coalition is led by 8minute Solar Energy, Intersect Power, the Los Angeles Department of Water and Power, Mitsubishi Power and Magnum Development, and is supported by several other organisations.[65]
The California Fuel Cell Partnership	The California Fuel Cell Partnership aims to expand the market for hydrogen fuel cell electric vehicles and collaborate on activities that advance this technology. Members include government (for example the EERE), industry (for example Ford, Nissan, Chevron and Toyota), and research (for example the NREL). [66]
The California Hydrogen Business Council	**The California Hydrogen Business Council** is a member-based trade association that represents and advocates for the hydrogen and fuel cell industry in California and promotes the use of hydrogen and fuel cells in the energy and transportation sectors. Members include auto manufacturers, bus and heavy duty vehicle manufacturers, government agencies, utility companies and fuel cell and electrolyser manufacturers.[67]
The California Stationary Fuel Cell Collaborative	**The California Stationary Fuel Cell Collaborative** is a public-private partnership that seeks to advance the use of fuel cell systems in distributed generation and other end-use applications in California. Organisations in this partnership collaborate to advance programs, activities and initiatives that accelerate fuel cell deployment, inform public policy, educate the market on stationary fuel cell applications and opportunities, and raise public awareness and acceptance of fuel cell systems.[68] The Collaborative is comprised of a core group of federal state and regional agencies – including the California Air Resources Board, the California Energy Commission, the California Public Utilities Commission and the National Fuel Cell

[64] Renewable Hydrogen Alliance (n.d.) About Us https://renewableh2.org/about-us/

[65] Green Hydrogen Coalition (n.d.) Overview https://static1.squarespace.com/static/5e8961cdcbb9c05d73b3f9c4/t/5f76c8536829a20ee72af865/1601620068934/GHC+overview+2020-10-01+B.pdf.

[66] California Fuel Cell Partnership (n.d.) Members https://cafcp.org/members

[67] California Hydrogen Business Council (n.d.) Mission and Vision https://www.californiahydrogen.org/aboutus/mission-and-vision/

[68] California Stationary Fuel Cell Collaborative (n.d.) About Us: What We DO http://www.casfcc.org/What_We_Do.html

Consortium	Description
	Research Centre – and is supported by an Industry Advisory Panel, which includes Bosch, Fuel Cell Energy, SoCalGas, Ballard and Ways2H.[69]
Colorado Hydrogen Network	The Colorado Hydrogen Network is a membership-based hydrogen advocacy organisation that promotes the environmental and economic benefits of hydrogen and fuel cell technology, particularly for transportation. It is formed under the parent organisation, the Colorado Cleantech Industries Association.[70] Members include Colorado State University, the NREL, Starfire Energy, the Colorado Division of Oil and Public Safety, and Lightning Systems.
New Jersey Hydrogen Coalition	The New Jersey Hydrogen Coalition is a group of industry, research and government leaders collaborating to strengthen New Jersey's fuel cell and hydrogen industries with the aim to support the State in achieving its clean energy and energy resiliency goals. The Coalition seeks to achieve this by educating relevant stakeholders on fuel cell and hydrogen technology (and the benefits of this technology), developing policies which accelerate the adoption of these technologies and coordinating fuel cell and hydrogen activities with the federal and other state governments.[71]
Massachusetts Hydrogen Coalition	The Massachusetts Hydrogen Coalition aims to accelerate the growth of the hydrogen and fuel cell industry in Massachusetts by increasing resource availability, expanding visibility of hydrogen and hydrogen technologies in the market, and establishing marketing and partnering opportunities. Key initiatives of the coalition include the Massachusetts Hydrogen Road Map, meetings, conferences, newsletters, promotion and press releases and conference representation.[72]
Ohio Fuel Cell Coalition	The Ohio Fuel Cell Coalition is group of industry, academic and government stakeholders seeking to strengthen Ohio's fuel cell industry and its presence in regional, national and global fuel cell discussions. The coalition works to build upon existing industry and academic R&D strengths across the fuel cell value chain, promote public awareness about fuel cell technology, expand networking and information sharing opportunities, and promote federal funding for fuel cell research and commercialisation in Ohio.[73]

1.3.3 Funding mechanisms

Overview of US hydrogen public budget allocations

Infrastructure Investment and Jobs (IIJ) Act funding

The IIJ Act (also known as the Bipartisan Infrastructure Law) contains hydrogen-specific funding provisions to promote large-scale investment in and acceleration of a domestic hydrogen industry. The IIJ Act includes several programs and initiatives to accelerate clean hydrogen R&D, production, distribution and utilisation across the US between FY2022-FY2026. In total USD 9.5 billion has been specifically allocated to DOE for clean hydrogen RD&D, however additional funding for hydrogen RD&D may also be available through

[69] California Stationary Fuel Cell Collaborative (n.d.) About Us: What We DO http://www.casfcc.org/What_We_Do.html

[70] Colorado Hydrogen Network (n.d.) About https://www.colorado-hydrogen.org/about

[71] New Jersey Fuel Cell Coalition (n.d.) About Us https://njfuelcells.org/about-us/

[72] Massachusetts Hydrogen Coalition (n.d.) Home http://massh2.org/default.html

[73] The Fuel Cell Corridor (n.d.) About Us https://www.fuelcellcorridor.com/about-us-1

broader clean energy programs established by the IIJ Act.[74] These programs are listed in Table 6 below. For more project details, see *Section 1.4 The United States' domestic hydrogen RD&D* projects

Table 6: IIJA Hydrogen Programs[75]

Distributing Body	Program	Description	Budget/Timeline	International eligibility to participate
DOE - Office of Clean Energy Demonstrations	**Regional Clean Hydrogen Hubs Program**	At least four regional clean hydrogen hubs will be established to accelerate hydrogen RD&D across the value chain. Various requirements and research priorities apply. For example, each hub must focus on a specific feedstock and end-use application. For example, the 'feedstock diversity requirements' at least one hub must focus on renewable hydrogen, one on fossil fuels and another on nuclear. Similarly, under the 'end-use diversity requirement' one hub must focus on power generation, one on the industrial sector, one on residential and commercial heating and another on transportation.	USD 8 billion FY2022-2026	*No data.*
DOE - EERE	**Clean Hydrogen Electrolysis Program**	Grants awarded on a competitive basis to projects that will demonstrate and accelerate the production and commercialisation of clean hydrogen through electrolysis.	USD 1 billion FY2022-2026	
DOE - EERE	**Clean Hydrogen Manufacturing & Recycling**	Multi-year grants awarded (through contracts and cooperative research agreements) for RD&D projects that seek to advance clean hydrogen supply chains, and the use the recycling and re-use of hydrogen technologies.	USD 500 million FY2022-2026 Open. Response deadline March 2022.	
DOE	**Clean Hydrogen Research and Development Program**	The DOE intends to re-establish an RD&D program, in partnership with the private sector, to commercialise clean hydrogen production across the transport, utility, industry, commercial and residential sectors.	Not Specified.	

[74] Department of Energy (2022) DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives

[75] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf; Department of Energy (2022) DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives

Distributing Body	Program	Description	Budget/Timeline	International eligibility to participate
DOT	**Electric Ferry Pilot Program**	Grants provided for the purchase of electric or low-emitting ferries including, but not limited to, those using hydrogen and fuel cell technology.	USD 250 million FY2022-2026	
EPA	**Clean School Bus Program**	Grants and rebates awarded on a competitive basis to replace school buses with 'clean' and 'zero-emission' equivalents. Contracts for eligible contractors are also available. 50% of funds are allocated for electric vehicles with the remaining 50% reserved for low-emission school buses, including hydrogen fuel cell electric vehicles (FCEVs).	USD 5 billion FY2022-2026	

While yet to be established, the IIJ Act requires the Federal Highway Administration to establish a funding program to award USD 2.5 billion in grants for the acquisition and installation of publicly accessible electric vehicle charging and alternative refuelling infrastructure (including hydrogen, propane, and natural gas).[76] The Alternative Fuel Corridor (AFC) Grants program are expected to be established by November 2022.[77]

Additional funding under the DOE Hydrogen Program and H2@Scale initiative

Funding for hydrogen-related projects is expected to total USD 400 million for the President's Fiscal Year 2022 (as per the FY 2022 Budget Request). This represents a 40% increase in hydrogen-related spending compared to FY 2021, which was USD 285 million.[78]

The DOE Hydrogen Program is funded through various competitive mechanisms. The most prominent are the funding opportunity announcements (FOAs) where projects from universities, industry, national laboratories and other private-sector projects are chosen.[79] These FOAs either form part of a broader RD&D program of the DOE, such as the Hydrogen Energy Earthshot Program or the H2@Scale concept, or are standalone R&D projects that align with the DOE's research portfolio. Each participating Office in the Hydrogen Program administers and maintains their own FOA opportunities. The DOE also issues cooperative research and development agreements (CRADA) calls, to encourage industry participation with the research sector in strategic partnership projects (SPPs).[80]

Figure 4 outlines the DOE's annual budget for hydrogen and fuel cell RD&D and related activities. The graph depicts the budgets for the DOE's Offices of EERE, FECM, NE, OS, and ARPA-E from FY2010 to FY2020. Budgetary information for FY2021 is not yet available. As shown, hydrogen funding has seen a significant increase in recent years, with increased funding across offices and the introduction of funding to ARPA-E.

[76] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

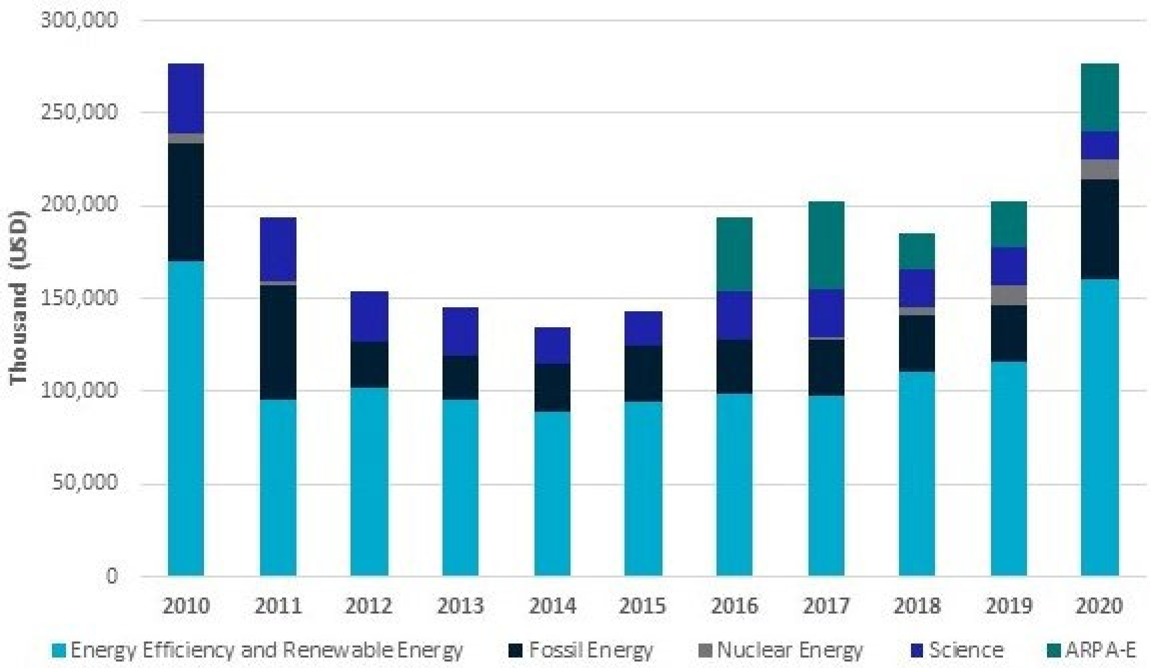
[77] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

[78] IPHE (2021) Partners: United States. Viewed at https://www.iphe.net/united-states

[79] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[80] DOE (2020) The Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Figure 4: Budget information for hydrogen and fuel cell RD&D at the DOE[81]



Private-public funding

Alongside their FOA solicitations and lab funding calls, the Hydrogen Program provides funding through Cooperative Research and Development Agreements (CRADAs). CRADAs are arrangements between DOE national laboratories and private industry or research institutions to collaborate on RD&D.[82]

In 2021, the DOE announced a USD 12 million CRADA call to support the H2@Scale initiative and the Advanced Research on Integrated Energy System (ARIES) from FY2021-2023. Between 9 and 14 awards will be issued. Topic areas include:[83]

Project	Total funding	International eligibility to participate
H2@ARIES - Integrated Hydrogen Energy System Testing and Validation: to advance integrated hydrogen systems	Total: USD 4 - 6 million Federal: USD 500,000 – 2 million Non-federal: minimum cost share of 30% (of which 10% must be a cash contribution)	Potentially. Previous CRADA partners have included foreign corporations.[84]

[81] DOE (2021) Hydrogen Program: Budget https://www.hydrogen.energy.gov/budget.html

[82] DOE (n.d.) Cooperative Research and Development Agreement (CRADA) https://www.directives.doe.gov/terms_definitions/cooperative-research-and-development-agreement-crada

[83] NREL (2021) H2@Scale Laboratory CRADA Call https://www.nrel.gov/hydrogen/h2-at-scale-crada-call.html; NREL (2021) 2021 H2@Scale CRADA Call Supporting Advanced Research on Integrated Energy Systems (ARIES). https://www.nrel.gov/hydrogen/assets/pdfs/2021-h2-at-scale-crada-call.pdf

[84] DOE (2021) H2@Scale CRADA Projects https://www.energy.gov/sites/default/files/2021/02/f82/h2-at-scale-crada-projects-2021.pdf

Project	Total funding	International eligibility to participate
Applied Risk Assessment and Modelling for H2@Scale Applications: applied risk assessments and modelling related to large-scale hydrogen deployment such as the ARIES-based energy systems.	Total: USD 3 - 4 million Federal: USD 500,000 – 1 million Non-federal: minimum cost share of 30% (of which 10% must be a cash contribution)	
Next-Generation Sensor Technologies: to develop advanced monitoring systems to address hydrogen safety challenges relating to large-scale infrastructure deployment	Total: USD 1-2 million Federal: USD 500,000 – 1 million Non-federal: minimum cost share of 30% (of which 10% must be a cash contribution)	

Office of Clean Coal and Carbon Management Hydrogen R&D Program[85]

This program is coordinated by the DOE's FECM. The program is focused on advancing technology R&D required to produce hydrogen from coal-derived synthesis gas. Key priorities include:

- Major CCUS demonstrations.
- Systems analysis: For example, environmental issues, policy, regulatory and financing, economic analysis and validation, data and tools that support analysis of advanced coal technologies.
- Cross-cutting research: For example, the CoalFIRST (Flexible, Innovative, Resilient, Small, Transformative) initiative developing future coal plants, University Training & Research, Coal Utilisation Science, and Small Business Innovation Research (SBIR).

Office of Oil and Natural Gas (ONG) Hydrogen R&D Program[86]

This program is coordinated by the DOE's FECM. The program aims to assess the feasibility of introducing hydrogen into the existing natural gas infrastructure, with the view to converting natural gas infrastructure to hydrogen infrastructure in the long-term. The Program also focuses on R&D to convert flared or vented gas to hydrogen products to include modular hydrogen production from natural gas. R&D funding for this area falls under the FECM FOA2006 Advanced Natural Gas Infrastructure Technology Development, which selected 16 projects in 2020.

1.3.4 Other key hydrogen policies, regulation and legislation

In addition to the governance, strategy and funding mechanisms for hydrogen RD&D programs, the US has several key policies, regulations and laws to support, incentivise and regulate the commercial uptake of hydrogen technologies. Notable policies and regulations are outlined below.

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[85] DOE (2020) Hydrogen Strategy: Enabling a Low-Carbon Economy https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf

[86] DOE (2020) Hydrogen Strategy Enabling a Low-Carbon Economy https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf

Legislation

The IIJ Act, signed into law in November 2021, is an appropriation act to provide approximately USD 1.2 trillion in funding for and investment in key US infrastructure, including roads, public transport and clean energy infrastructure.[87] While broadly covering key infrastructure, a particular focus is placed on clean energy infrastructure, such as the construction of clean hydrogen hubs. It is important to note that USD 9.5 billion of the total package is allocated to the DOE to advance the development and commercialisation of clean energy and clean hydrogen technologies. [88]

The IIJ Act builds upon an amended existing legislation, such as the Energy Policy Act 2005 and the Energy Independence and Security Act 2007, upon which the DOE's Hydrogen Program principles are based.[89]Key elements under the legislative act include:[90]

- The definition of 'clean hydrogen' as 'hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced at the site of production, per kilogram of hydrogen produced.' This definition is important as, in many cases, funding under the IIJ Act (and associated programs) is restricted to projects which seek to accelerate the development of clean hydrogen technologies. This definition can be updated after 5 years.
- The establishment of hydrogen-specific programs and initiatives, including the Regional Clean Hubs Program, Clean Hydrogen Electrolysis Program, Clean Hydrogen Manufacturing and Recycling Initiative, and Clean Hydrogen Research and Development Program. For project and funding details see *Sections 1.3.3 Funding* and *1.4 The United States' domestic hydrogen RD&D* projects
- The establishment of the Office of Clean Energy Demonstrations under the DOE to support RD&D projects in areas of clean hydrogen, carbon capture, grid-scale energy storage. This Office was officially established in December 2021.
- Mandates the development of a National Clean Hydrogen Strategy and Roadmap. The roadmap also must be updated every 3 years.
- Information sharing mechanisms to disseminate information across agencies and national laboratories.
- A proposal for the Energy Information Administration (EIA) to integrate large-scale demonstration projects (including CCUS and hydrogen production) into the National Energy Modelling System.
- Several actions and proposals to facilitate the commercialisation of carbon-based technologies and CCUS.

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[87] Moeller E et al. (2021) Hydrogen Highlights in the Bipartisan Infrastructure Bill. Pillsbury Law. https://www.pillsburylaw.com/en/news-and-insights/hydrogen-highlights-bipartisan-infrastructure-bill.html; Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

[88] Moeller E et al. (2021) Hydrogen Highlights in the Bipartisan Infrastructure Bill. Pillsbury Law. https://www.pillsburylaw.com/en/news-and-insights/hydrogen-highlights-bipartisan-infrastructure-bill.html; Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

[89] DOE (2021) Policies and Acts. Hydrogen Program. https://www.hydrogen.energy.gov/policies_acts.html

[90] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

In addition to the BIL provisions above, the IRA, signed into law in August 2022, provides a Hydrogen Production Tax Credit (PTC) that will further incentivize the production of clean hydrogen in the U.S.[91] The IRA may also incentivize the development of demand sectors for clean hydrogen through additional programs, including:

- Grants and loans for auto manufacturing facilities to manufacture clean vehicles, including FCEVs; [92]
- A tax credit for producing sustainable aviation fuels, which can require hydrogen feedstock;[93]
- Grants to reduce emissions at ports, which could fund deployments of fuel cells; [94] and
- Grants for clean heavy-duty vehicles, including FCEVs.[95]

Regulation

Various agencies regulate hydrogen in the US, including the DOE, the Federal Energy Regulatory Commission (FERC), the Occupational Safety and Health Administration (OSHA), the US Environmental Protection Agency (EPA), and the Pipeline and Hazardous Materials Safety Administration (PHMSA):[96]

- The Natural Gas Act under the FERC regulates natural gas pipelines and storage. While this does not regulate hydrogen, it could be used to regulate hydrogen blending in natural gas networks subject to the passing of new legislation. [97]
- The Occupation Health and Safety Standards outline minimum safety and technical specifications for the installation of hydrogen systems and facilities; [98]
- The PHMSA regulates 700 miles of hydrogen pipelines, however some aspects of hydrogen are not fully integrated into current regulations and design requirements; [99]
- The EPA's Greenhouse Gas Reporting Program imposes reporting requirements on hydrogen producers.[100]

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[91] Inflation Reduction Act, Pub. L. No. 117-169, sec. 13204, §45V (codified as 26 U.S.C. 45V (2022)).

[92] Inflation Reduction Act, Pub. L. No. 117-169, sec. 50142 and sec. 50143.

[93] Inflation Reduction Act, Pub. L. No. 117-169, sec. 13203, §40B (codified as 26 U.S.C. 40B (2022)).

[94] Inflation Reduction Act, Pub. L. No. 117-169, sec. 60102, §133.

[95] Inflation Reduction Act, Pub. L. No. 117-169, sec. 60101, §132.

[96] CMS Law (2021) Hydrogen Law and Regulation in the US https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/united-states-of-america

[97] CMS Law (2021) Hydrogen Law and Regulation in the US https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/united-states-of-america

[98] CMS Law (2021) Hydrogen Law and Regulation in the US https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/united-states-of-america

[99] CMS Law (2021) Hydrogen Law and Regulation in the US https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/united-states-of-america

[100] EPA (2021) Information Sheet: Subpart P- Hydrogen Production https://www.epa.gov/ghgreporting/information-sheet-subpart-p-hydrogen-production

Incentives

There are several US federal-level programs to incentivise the commercial uptake of hydrogen fuel cell vehicles. These are usually provided in the form of tax incentives, grants, or loan guarantees. As an example, these incentives include:

- **Energy Investment Tax Credits (ITC):** Section 48 of the Internal Revenue Code provides an investment tax credit (ITC) for energy-related property. Stationary fuel cells and fuel cells for material handling equipment are included under the code. A tax credit of 30% was offered for projects commencing in 2019, 26% in 2022, and 22% in 2023. The tax credit for fuel cells is also limited to USD 1500 per 0.5kW.[101]
- **The Alternative Fuel Refuelling Infrastructure Credit program:** A 30% credit of up to USD 30,000 for zero-emissions charging and refuelling infrastructure.[102] Fuels must consist of at least 85% hydrogen, or contain a minimum of 20% biodiesel to be eligible. Under the Build Back Better Act, the credit limit is proposed to be increased to USD 100,000 with an additional 20% uncapped credit for hydrogen refuelling stations.[103]
- **The Zero Emissions Airport Vehicle and Infrastructure Pilot Program:** This program provides grants to airports for up to 50% of the cost to acquire zero-emission vehicles and install supporting infrastructure. This funding must be used for airport-owned, on-road vehicles used exclusively for airport purposes. The funding of this program is focused on incentivising adoption of technology rather than on RD&D. [104]
- **The DOE Loan Guarantee Program:** The Loan Guarantee Program provides loans for projects involving the early commercial use of advanced technologies, including hydrogen. These loans are not for RD&D. Loan guarantees may be issued for up to 100% of the amount of the loan. Eligible projects include the deployment of hydrogen refuelling infrastructure, including associated hardware and software.[105]
- **The Alternative Fuel Excise Tax Credit:** A tax credit of USD 0.50 per gallon is available for alternative fuel that is sold for use or used as fuel for a motor vehicle. Among these alternative fuels is liquefied hydrogen.[106]
- **The Alternative Fuel and Advanced Vehicle Technology Research and Demonstration Bonds**: State and local governments may grant Qualified Energy Conservation bonds subsidised by the US Department of Treasury to fund capital expenditures for energy conservation projects.[107]

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[101] Congressional Research Service (2021) The Energy Credit or Energy Investment Tax Credit (ITC) [Updated April 23, 2021]. https://crsreports.congress.gov/product/pdf/IF/IF10479/6

[102] US House of Representatives (2021) Alternative fuel vehicle refueling property credit, 26 United States Code. §30C (2018). Office of the Law Revision Counsel, United States Code. Viewed January 24, 2022. https://uscode.house.gov/view.xhtml?hl=false&edition=prelim&req=granuleid%3AUSC-2020-title26-section30C&f=treesort&fq=true&num=0

[103] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

[104] Federal Aviation Administration (2020) Airport Zero Emissions Vehicle and Infrastructure Pilot Program https://www.faa.gov/airports/environmental/zero_emissions_vehicles/

[105] Loan Programs Office (n.d.) About Us Home https://www.energy.gov/lpo/about-us-home

[106] DOE (n.d.) Alternative Fuels Data Centre: Hydrogen Laws and Incentives in Federal https://afdc.energy.gov/fuels/laws/HY?state=us

[107] DOE (n.d.) Alternative Fuels Data Centre: Hydrogen Laws and Incentives in Federal https://afdc.energy.gov/fuels/laws/HY?state=us

State-level policies and legislation

- **State Energy Program:** To ensure state-level involvement in developing the hydrogen economy, the US has a State Energy Program to assist in designing, developing and implementing renewable energy and energy efficiency programs. Each state has an energy office that receives funding and manages projects funded by this program. This funding is distributed through competitive solicitations.[108]

California

California has developed a framework of hydrogen policies, regulation and legislation. Key bodies, incentive programs, policies and standards are outlined below:[109]

- **Renewable Portfolio Standard:** A Policy requiring utilities to deliver 50% of their retail electricity from clean, renewable sources by 2030.
- **California Energy Commission:** The Commission is California's energy policy and planning agency. The Commission has supported hydrogen FCEVs by expanding the state's hydrogen refuelling station network.
- **Low-Carbon Fuel Standard:** California's Low-Carbon Fuel Standard (LCFS) requires a reduction in the carbon intensity of California's transportation fuel pool by 10% by 2020. The LCFS provides credits to fuel producers.
- **Zero Emission Transit Bus Requirement:** The requirement aims to transition all public transit agencies to zero-emission bus fleets by 2040.
- **Hydrogen Fuel Specifications:** The specifications require that hydrogen fuel used in internal combustion engines must meet the SAE International J2719 standard for hydrogen fuel quality.

Alternative Fuels Data Center

A complete list of federal and state hydrogen laws and incentives relating to hydrogen as a fuel can be found on the following resource:

- https://afdc.energy.gov/fuels/laws/HY

[108] DOE (n.d.) State Energy Program https://www.energy.gov/eere/wipo/state-energy-program

[109] Dalia Majumber-Russell (2020) Hydrogen Law and Regulation in the US, CMS Legal https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/united-states-of-america

1.4 The United States' domestic hydrogen RD&D projects

1.4.1 Major domestic hydrogen RD&D projects

Infrastructure Investment Jobs Act (IIJ Act) projects

Regional Clean Hydrogen Hubs Program

The IIJ Act creates the Regional Clean Hydrogen Hubs Program, which will establish at least four regional hubs with the aim of accelerating the development and commercialisation of hydrogen production and hydrogen end-use applications. Under the IIJ Act, a hub is defined as a 'network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity.'[110] Applications for regional hub proposals are open until May 2022. Various conditions apply, including that:[111]

- at least one hub should produce hydrogen from nuclear energy, one from renewable energy, and one from fossil fuels;
- at least one hub should demonstrate the end-use application of hydrogen in electric power generation sector, one in the industrial sector, one in the residential and commercial heating sector, and one in the transport sector; and
- at least two hubs must be located in regions of the US with the most abundant natural gas resources.

In July 2021, the DOE Hydrogen Program opened a Request for Information (RFI) seeking applications for potential regional clean hydrogen demonstration projects. It is understood the information received will be used to inform the selection of hydrogen hubs under the Regional Clean Hydrogen Hubs Program.[112]

To further facilitate the creation of hydrogen hubs, the DOE launched the H_2 Matchmaker in 2021. H_2 Matchmaker is an interactive database which allows entities and research institutions to self-report their hydrogen projects. The aim is to connect hydrogen suppliers, project developers and relevant stakeholders to facilitate enhanced collaboration, increase hydrogen and fuel cell project awareness, support regional business development opportunities and facilitate private sector investment. A beta version of the H_2 Matchmaker is currently live, with the database expected to be fully operational by February 2022.[113]

Requests for information have begun to open for hydrogen programs initiatives under the IIJ. For more detail on the RD&D funding programs established under the IIJ, see *Section 1.3.3 Funding mechanisms*.

[110] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

[111] Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America. https://www.congress.gov/117/bills/hr3684/BILLS-117hr3684enr.pdf

[112] DOE (2021) H2IQ: The #H2IQ Hour. Viewed 19 January 2022, https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

[113] DOE (2021) H2IQ: The #H2IQ Hour. Viewed 19 January 2022, https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

Energy Earthshots Initiative – Hydrogen Shot and the H2@Scale initiative

On June 7 2021, the first Energy Earthshot initiative – known as the Hydrogen Shot – was launched. The aim of Hydrogen Shot is to achieve an 80% cost reduction in 'clean' hydrogen to USD 1 per kg in one decade.[114] The program has launched an RFI to address the following broad topics:[115]

- Hydrogen production, resources and infrastructure;
- End users for hydrogen based on specific regions, cost and value propositions;
- Greenhouse gas and other pollutant emissions reduction potential;
- Diversity, equity, inclusion, jobs and environmental justice; and
- Science and innovation needs and challenges.

In July 2021, USD 52.5 million was awarded to fund 31 private hydrogen R&D technology projects across the entire hydrogen value chain to support the Hydrogen Energy Earthshot initiative.[116] This includes USD 36 million from the EERE (funding 19 hydrogen projects) and USD 16.5 million from the FECM (funding 12 hydrogen projects). A summary of the project areas are as follows:

- Water electrolysis (including manufacturing methods of electrolysers), and clean hydrogen production including biological and electrochemical approaches.
- Reversible Solid Oxide Cells (r-SOC) materials, systems and manufacturing.
- CCUS for steam methane and autothermal methane reforming plants.
- Supply chain components and refuelling technologies.
- Improvements in fuel cell subsystems and components and heavy-duty applications.
- Gas turbine combustion systems for blended hydrogen and natural gas and 100% hydrogen firing.
- Analysis to assess cost and performance of production pathways, storage technologies and fuel cell systems.

A full list and descriptions of hydrogen projects under the EERE and the FECM can be found at the following resources:

- **19 EERE Projects:** https://www.energy.gov/eere/fuelcells/articles/hydrogen-and-fuel-cells-rd-fy-2021-foa-selections
- **12 FECM Projects:** https://www.energy.gov/fecm/articles/us-department-energy-selects-12-projects-improve-fossil-based-hydrogen-production

[114] DOE (2021) Energy Earthshots: Hydrogen https://www.energy.gov/eere/fuelcells/hydrogen-shot

[115] DOE (2021) DOE Hydrogen Program Request for Information # DE-FOA-0002529 https://www.energy.gov/sites/default/files/2021-06/rfi-de-foa-0002529.pdf

[116] DOE (2021) DOE Announces $52.5 Million to Accelerate Progress in Clean Hydrogen. https://www.energy.gov/articles/doe-announces-525-million-accelerate-progress-clean-hydrogen

In October 2021, the DOE's Office of Nuclear Energy also announced USD 20 million in funding under the H2@Scale Initiative for the Arizona Project at the Pal Verde Nuclear Generation Station in Phoenix. The project, once operational, will produce 200 megawatt hours (MWh) of electricity from six tonnes of stored hydrogen. This project will inform future at scale deployments of hydrogen production from nuclear energy. This project will be led by PNW Hydrogen LLC.[117]

H2@Scale CRADA Projects[118]

- **2021 H2@Scale CRADA Call:** The Hydrogen and Fuel Cell Technologies Office in mid-2021 sought proposals to support the H2@Scale vision and the NREL's Advanced Research on Integrated Energy Systems (H2@ARIES) program. Up to USD 12 million was available for RD&D under three topics: integrated hydrogen energy system testing/validation; applied risk assessment and modelling for H2@Scale applications; and next-generation sensor technologies.[119] In October 2021 the DOE awarded USD 8 million for nine CRADA projects under this area.[120]
- **2020 H2@Scale CRADA Call:** In mid-2020 the DOE announced a request for proposals to collaborate with DOE's national laboratories. Up to USD 24 million was made available across two priority areas: hydrogen refuelling technologies for medium and heavy-duty fuel cell vehicles; and hydrogen blending in natural gas pipelines.[121]
- Other CRADA projects of note in 2021 are shown in Table 7. These projects stem from older CRADA calls, and cover roughly 30 CRADA projects with the industry, research and non-profit sectors. Some of these projects were still ongoing in 2021. Topic areas covered modelling; materials compatibility; grid integration; safety; co-generation of hydrogen and added value products; and testing and verification.[122]

Table 7: Recent H2@Scale CRADA Projects[123]

Project	Partner(s)
Project advancing the design and operating strategies of high throughput stations, supporting light, medium and heavy-duty use applications	*Shell, NREL*
Development of a fully-integrated electrolyser and bioreactor prototype, which has since been licensed by Southern California Gas	Southern California Gas, NREL
Evaluating the performance of conventional and emerging pipeline materials in hydrogen blends	Southern California Gas, NREL
Designing hydrogen fuelling and fuel cell systems for heavy-duty vehicles, stationary power and resiliency at ports	Port of Seattle, PNNL

[117] DOE (2021) DOE Announces $20 Million to Produce Clean Hydrogen from Nuclear Power [Press Release]. Viewed at https://www.energy.gov/articles/doe-announces-20-million-produce-clean-hydrogen-nuclear-power

[118] DOE (2020) Energy Department Announces $33 Million to Advance Hydrogen and Fuel Cell R&D and the H2@Scale Vision. https://www.energy.gov/eere/articles/energy-department-announces-33-million-advance-hydrogen-and-fuel-cell-rd-and-h2scale

[119] National Renewable Energy Laboratory (2021) H2@Scale Laboratory CRADA Call https://www.nrel.gov/hydrogen/h2-at-scale-crada-call.html

[120] DOE (2021) H2@Scale < https://www.energy.gov/eere/fuelcells/h2scale>

[121] DOE (2020) DOE Announces Request for Proposals for H2@Scale https://www.energy.gov/eere/articles/doe-announces-request-proposals-h2scale

[122] DOE (2021) H2@Scale CRADA Projects https://www.energy.gov/sites/default/files/2021/02/f82/h2-at-scale-crada-projects-2021.pdf

[123] DOE (2021) H2@Scale CRADA Projects https://www.energy.gov/sites/default/files/2021/02/f82/h2-at-scale-crada-projects-2021.pdf

Hydrogen and Fuel Cell Technologies Office – H2@Scale Announcements

H2@Scale calls for proposals and funding award announcements are posted on the following online resource:

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

Advanced Research Project Agency – Energy (ARPA-E)

ARPA-E's OPEN 2021 funding announced USD 175 million for 68 R&D projects across 22 states, led by universities, national laboratories and the private sector. Projects cover a broad range of clean energy technologies, and aim to strengthen energy security and provide economic benefits and jobs.[124] Projects relating to hydrogen include:

Table 8: ARPA-E OPEN 2021 hydrogen-related projects[125]

Project	Project Lead
Lifted-Flame Combustion for High-Hydrogen Reheat Gas Turbines Novel combustion technology for using hydrogen using hydrogen and natural gas fuel blends. The technology has the potential to break efficiency limits imposed by current materials barriers.	General Electric Gas Power
A Zero-emission Process for Direct Reduction of Iron by Hydrogen Plasma in a Rotary Kiln Reactor Zero-carbon ironmaking that eliminates the use of coke and natural gas and uses less energy than current processes. The technology has the potential to achieve significant efficiency gains and CO2 emissions reductions.	Argonne National Laboratory
A Hybrid Electrochemical and Catalytic Compression System for Direct Generation of High-Pressure Hydrogen at 700 Bar A hybrid electrochemical and catalytic process for the direct generation of high pressure hydrogen. The technology has the potential to significantly reduce costs and achieve scalability compared to current technologies.	California Institute of Technology
High Capacity Electrolysers Based on Ultrathin Proton-Conducting Oxide Membranes Low temperature electrolysis using proton-conducting oxide membranes (POM). By significantly reducing the thickness of the membranes, the technology has the potential to achieve step-change progress in density and efficiency compared to PEM electrolysers.	Columbia University

[124] ARPA-E (2022) U.S. Department of Energy Announces $175 Million for Novel Clean Energy Technology Projects https://www.arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-175-million-novel-clean-energy

[125] ARPA-E (2022) OPEN 2021 Project Descriptions. https://www.arpa-e.energy.gov/sites/default/files/documents/files/OPEN%202021_Project%20Descriptions_Final.pdf

Project	Project Lead
Hydrogen Steam Injected Intercooled Turbine Engine (HySIITE) Novel, high efficiency hydrogen power turbines for commercial aviation. The technology has the potential to achieve greater thermal efficiency than fuel cells, and be more cost competitive than drop-in[126] sustainable aviation fuels.	Pratt & Whitney

More information on project proposals, RFIs and funding opportunity announcements can be found on the following online resources:

Advanced Research Project Agency – Energy (Projects)

- https://arpa-e.energy.gov/technologies/projects

ARPA-E Funding Opportunity Announcements

- https://arpa-e-foa.energy.gov/Default.aspx?Search=RFI&SearchType=

Projects by other government agencies

- In March 2021, President Biden's American Jobs Plan paired the investment of 15 decarbonised hydrogen demonstration projects in distressed communities with a new production tax credit to incentivise capital-project retrofits and installations.[127]
- In March 2021, the Douglas County Public Utility Division (Washington) commenced development of a 5MW electrolysis hydrogen production and storage demonstration project that will harness excess hydropower and convert it to renewable hydrogen.[128]

Projects by consortia

- In 2021, the California Energy Commission (CEC) and Southern California Gas, through the Hydrogen Fuel Cell Demonstrations in Rail and Marine Applications at Ports (H2RAM) grant program, provided USD 15.9 million to fund four projects to accelerate RD&D in marine and locomotive fuel cells and hydrogen refuelling stations at ports.[129]
- In 2020, Southern California Gas announced pilot testing of its HyET hydrogen technology, which separates and compresses hydrogen from a blend of hydrogen and natural gas, facilitating distribution via the existing natural gas pipeline to refuelling stations.[130]

[126] Drop-in fuels are alternatives to currently used fuels, that can be used without any significant changes to existing engines or infrastructure.

[127] The White House (2021) Fact Sheet: The American Jobs Plan https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/

[128] IEEFA (2021) Washington utility moves forward with 5MW hydrogen demonstration project https://ieefa.org/washington-utility-moves-forward-with-5mw-green-hydrogen-demonstration-project/

[129] Hydrogen Fuel Cell Demonstrations in Rail and Marine Applications at Ports (2021) https://www.energy.ca.gov/solicitations/2020-07/gfo-20-604-hydrogen-fuel-cell-demonstrations-rail-and-marine-applications

[130] HyET Hydrogen (2020) SoCalGas to test technology that could transform hydrogen distribution and enable rapid expansion of hydrogen fueling stations https://hyethydrogen.com/news/socalgas-to-test-technology-that-could-transform-hydrogen-distribution-and-enable-rapid-expansion-of-hydrogen-fueling-stations/

- In partnership with several national laboratories, the US DRIVE partnership highlights several RD&D project accomplishments in 2020 including:[131]
    - Hydrogen production: improvements in efficiency and durability for photoelectrochemical hydrogen production devices (led by the HydroGEN consortium).
    - Hydrogen delivery and storage: the H2FillS (Hydrogen Filling Simulation) enabling innovation in refuelling processes; and an innovative funding mechanism to achieve a 50% cost reduction in carbon fibre for high-pressure storage over 5 years.
    - Fuel cells: The development of novel catalyst materials; improved membrane electrode durability; and modelling and cost analyses identifying research opportunities for heavy-duty vehicles
    - Hydrogen codes and standards: the development of the Hydrogen Wide Area Monitor (HyWAM), a monitoring approach using temporal and spatial profiling.

1.4.2 Major domestic commercial hydrogen projects

The scope of this report is on research, development and demonstration (RD&D) projects. For information on commercial hydrogen projects, see *HyResource*, an online knowledge sharing platform across the hydrogen community led by CSIRO, Future Fuels CRC, NERA and the Australian Hydrogen Council.

HyResource provides a directory of publicly available databases and information sources on international projects:

- https://research.csiro.au/hyresource/projects/international/

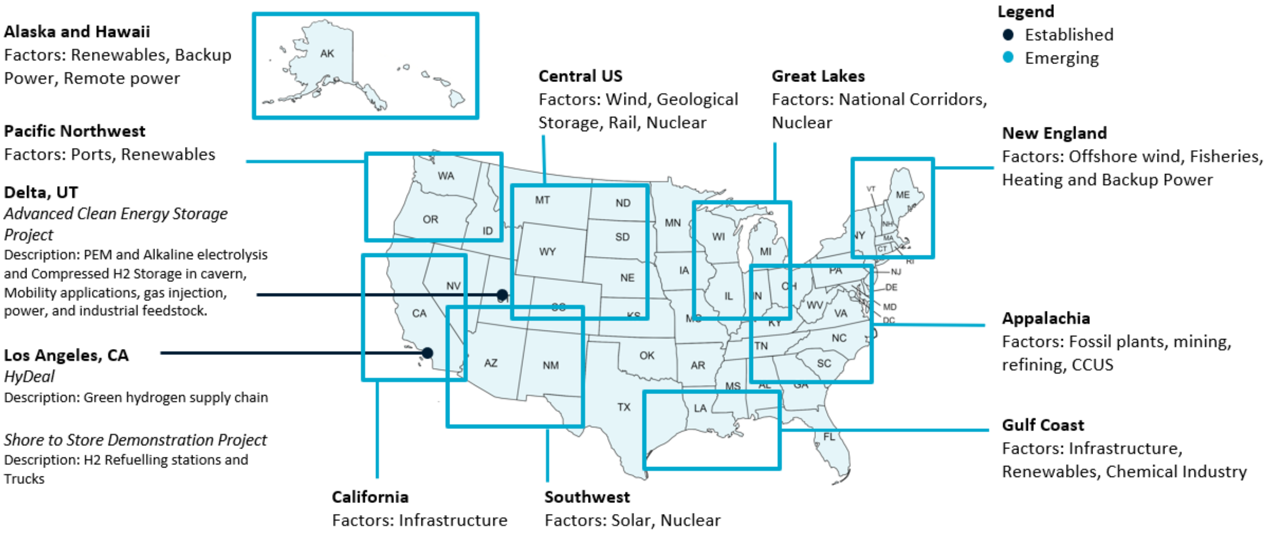
1.4.3 The United States' hydrogen RD&D clusters

Industry, research institutions and government agencies are collaborating to establish clusters (also known as hydrogen hubs or clusters) across the country. These clusters include research and pilot projects as well as integrated value chain demonstrations across various sector applications. Potential and emerging clusters are identified in Figure 5 below.[132]

[131] U.S. DRIVE (2021) U.S. DRIVE Highlights of Technical Accomplishments https://www.energy.gov/sites/default/files/2021-05/2020_US_DRIVE_Accomplishments_Report_5.19.2021.pdf

[132] Sunita Satyapal et al (2021) The #H2IQ Webinar. US Department of Energy https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

Figure 5: The United States' hydrogen clusters[133]



Emerging clusters

The H2@Scale program and Energy Earthshots Initiative have identified 9 regional areas for clean hydrogen RD&D clusters. The prospective clusters highlighted in the DOE's RFI findings were identified based on a number of considerations including resource availability, potential end use applications, and socio-economic considerations. The IIJA requires at least four to be selected in 2022, however the total number selected could be higher. [134]

Established clusters

Separate to the recent IIJ Act and DOE announcements, several cluster projects are already under way in California and Utah.

Hydrogen cluster	Location	Description
HyDeal	Los Angeles, California	HyDeal is an identified renewable hydrogen cluster which aims to produce hydrogen from renewable energy at a cost of USD 1.50/kg in the Los Angeles Basin by 2030.[135] This is the coalition's first regional initiative, with a view to expand a high-volume green hydrogen supply chain across North America.[136] The project is collaborating with renewable hydrogen off-takers, integrators, equipment manufacturers, investors and developers in the LA Basin.[137] Phase 1 of the project is focused on designing financing and contractual schemes, and establishing the structure of the supply chain – the network upstream and downstream stakeholders.[138]

[133] Adapted from Mission Innovation (2021) Hydrogen Valleys https://www.h2v.eu/hydrogen-valleys?populate=&field_ch_1_q_10_value=US; Green Hydrogen Coalition (2021) HyDeal https://www.ghcoalition.org/hydeal; Sunita Satyapal et al (2021) The #H2IQ Webinar. US Department of Energy https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

[134] Sunita Satyapal et al (2021) The #H2IQ Webinar. US Department of Energy https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

[135] Green Hydrogen Coalition (2021) HyDeal Los Angeles https://www.ghcoalition.org/hydeal-la

[136] Green Hydrogen Coalition (2021) HyDeal North America https://www.ghcoalition.org/hydeal

[137] Green Hydrogen Coalition (2021) HyDeal Los Angeles https://www.ghcoalition.org/hydeal-la

[138] Green Hydrogen Coalition (2021) HyDeal Los Angeles https://www.ghcoalition.org/hydeal-la

Hydrogen cluster	Location	Description
		Project partners for HyDeal Los Angeles include SoCalGas, Mitsubishi Power, 174 Power Global, 8 Minute Solar Energy, Clearway, Fortis BC, and Hydrogen Pro. [139] Partners for the HyDeal North America platform include the Colorado Hydrogen Network, CTE, Electronic Power Research Institute (EPRI), the California Governor's Office of Business and Economic Development, California Stationary Fuel Cells Collaborative (CaSFCC), and M-RETS Renewable Energy.[140]
Shore to Store Demonstration Project	Los Angeles, California	In June 2021, the Port of Los Angeles announced an USD 82.5 million project for a 12-month demonstration of five hydrogen-powered heavy-duty (class 8) FCEVs and two hydrogen fuelling stations. The project intends to expand to demonstrate a further five hydrogen-fuelled heavy-duty trucks, as well as battery-related mobility applications. [141] Project partners include the Port of Los Angeles as the lead developer, Toyota Motor North America, Toyota Logistics Services, NREL, United Parcel Service (UPS), California Air Resources Board, South Coast Air Quality Management District, Kenworth Trucks, Port of Hueneme, South Counties Express, Total Transportation Services. Other participants include Air Liquide supplying fuel and Shell designing the refuelling stations.[142]
Advanced Clean Energy Storage Project	Delta, Utah	Mitsubishi Power Americas and Magnum Development the Advanced Clean Energy Storage project aims to construct a green hydrogen hub with 200 MW of electrolysis facilities. The project will use natural geological salt caverns for bulk storage. The aim of the project is to connect renewable hydrogen production, storage and distribution in Utah to support industrial decarbonisation across various sectors (including power, transportation and manufacturing). DOE has issued a USD 504.4 million loan to finance the facility.[143]

H_2 Matchmaker

The US Hydrogen and Fuel Cell Technologies office has launched the H_2 Matchmaker initiative, an online information resource to assist hydrogen suppliers and users collaborate and identify opportunities to expand hydrogen development. More information can be found at:

- https://www.energy.gov/eere/fuelcells/h2-matchmaker

[139] Green Hydrogen Coalition (2021) HyDeal Los Angeles https://www.ghcoalition.org/hydeal-la

[140] Green Hydrogen Coalition (2021) HyDeal North America https://www.ghcoalition.org/hydeal

[141] Port of Los Angeles (2021) Port of Los Angeles Rolls Out Hydrogen Fuel Cell Electric Freight Demonstration. News Releases https://www.portoflosangeles.org/references/2021-news-releases/news_060721_zanzeff

[142] Port of Los Angeles (2021) Port of Los Angeles Rolls Out Hydrogen Fuel Cell Electric Freight Demonstration. News Releases https://www.portoflosangeles.org/references/2021-news-releases/news_060721_zanzeff

[143] Advanced Clean Energy Storage https://www.energy.gov/lpo/advanced-clean-energy-storage

1.5 International collaboration and joint RD&D projects

1.5.1 Overview of the United States' approach to international collaboration

The US has made clear its intention to strengthen hydrogen-specific international collaboration to achieve its hydrogen targets and broader decarbonisation ambitions. This is supported by various US hydrogen strategies that reference the importance of international collaboration.

Multilateral and international partnerships

The DOE Hydrogen Program engages multiple international forums and multilateral partnerships to foster international collaboration, facilitate knowledge and technology sharing, and advance mutual RD&D interests. 144

The US' multilateral activities and partnerships include:

- The International Energy Agency (IEA) Hydrogen Technology Collaboration Program (TCP) and Advanced Fuel Cells TCP; [145]
- The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) [146]
- Clean Energy Ministerial Hydrogen Initiative;[147]
- Mission Innovation Clean Hydrogen Mission;[148] and
- The Partnership for Transatlantic Energy and Climate Cooperation (P-TECC).[149]

The DOE Hydrogen Program aligns with global collaboration principles outlined in the 2019 *IEA Future of Hydrogen* report and the 2019 Global Action Agenda developed by the Hydrogen Energy Ministerial. These include: reducing investment risks for first movers; promoting information sharing and collaborative R&D to reduce costs and improve safety; coordinating and harmonising regulations, codes and standards; developing key infrastructure (including for international trade); and tracking international progress.[150]

1.5.2 The United States' bilateral hydrogen relationships

The US has established several bilateral hydrogen and low-emissions related agreements and partnerships. These are outlined in Table 9 below.

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[144] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[145] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[146] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[147] Clean Energy Ministerial (2021) Hydrogen Initiative https://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/hydrogen-initiative

[148] Mission Innovation (2021) Clean Hydrogen Mission http://mission-innovation.net/missions/hydrogen/

[149] DOE (2021) The Partnership for Transatlantic Energy and Climate Cooperation (P-TECC) https://www.energy.gov/ia/partnership-transatlantic-energy-and-climate-cooperation-p-tecc

[150] DOE (2020) Department of Energy Hydrogen Program Plan https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Table 9: US bilateral relationships with other countries

Country	Relationship	Description
The Republic of Korea	Dialogue	In November 2021, launched the ROK-US Energy Policy Dialogue to strengthen cooperation on clean energy and address the challenges of climate change. Collaboration areas include technology RD&D and commercial deployment as well as cross-cutting policy and planning. This builds on commitments made in May 2021, where President Moon and President Biden committed elevated the Energy Policy Dialogue to a ministerial level.[151]
Australia	Dialogue	Australia and the US are yet to establish a hydrogen-specific bilateral hydrogen partnership; however, the two countries share a strong working relationship through multilateral forums: The US and Australia co-leading for the Clean Hydrogen Mission from Mission Innovation. This mission focuses on cost reductions, and will achieve this by increasing R&D in hydrogen technologies and industrial processes and delivering 100 hydrogen valleys world-wide by 2030.[152] Both the US and Australia are members of the IEA Hydrogen Technology Collaboration Program which promotes collaborative RD&D hydrogen efforts. Joint project efforts are evidenced across numerous international publications released by the IEA upon the closing of their tasks. Current research engaged by this program includes energy storage and conversion based on hydrogen, hydrogen safety, and data and modelling.[153] The Quadrilateral Security Dialogue (the Quad), of which Australia and the US are both members, recently discussed the establishment of a clean-hydrogen Partnership. At a high-level, the Quad is a strategic and diplomatic partnership between the US, India, Japan, and Australia that commits to supporting an open region and advancing cooperation on various 21st century global challenges. The aims of a clean-hydrogen partnership revolve around reducing costs across the hydrogen value chain; promoting technological development and the scale-up of hydrogen production; identifying and developing infrastructure to safety store, transport and utilise hydrogen across various end-use applications; and stimulating market demand across the Indo-pacific for hydrogen and hydrogen related technologies.[154] In April 2020, Australia became a member of the US Center for Hydrogen Safety (CHS).[155] The CHS promotes hydrogen safety and best practice through a central, globally accessible knowledge sharing platform.[156] Australian organisations, companies and industry stakeholders who are members of the Center for

[151] DOE (2021) Minister Moon and Secretary Granholm Launch the Ministerial ROK-US Energy Policy Dialogue https://www.energy.gov/ia/articles/minister-moon-and-secretary-granholm-launch-ministerial-rok-us-energy-policy-dialogue

[152] Mission Innovation (n.d.) Clean Hydrogen Mission http://mission-innovation.net/missions/hydrogen/

[153] IEA (n.d.) Technology Collaboration Program: Open Tasks https://www.ieahydrogen.org/tasks/open-task/; IEA (n.d.) Technology Collaboration Program: Closed Tasks https://www.ieahydrogen.org/tasks/closed-task/; IEA (n.d.) Hydrogen TCP: History and Members. https://www.ieahydrogen.org/history-of-the-tcp/

[154] The White House (2021) Fact Sheet: Quad Leader's Summit [Statements and Releases]. Fact Sheet: Quad Leaders' Summit | The White House

[155] DISER (2020) National Hydrogen Strategy priorities and delivery for 2020 https://www.industry.gov.au/news/national-hydrogen-strategy-priorities-and-delivery-for-2020

[156] CHS (2021) The Center for Hydrogen Safety https://www.aiche.org/chs

Country	Relationship	Description
		Hydrogen Safety include DISER, the AHRN, CSIRO, Monash University, Woodside and Origin Energy.[157]
Ukraine	Statement of Intent	In August 2021, the US Secretary of Energy and Ukraine's Minister of Energy signed a Joint Statement of Intent to advance energy and climate cooperation through the existing US-Ukraine Strategic Energy and Climate Dialogue.[158] Areas of mutual benefit identified include hydrogen, energy storage, CCUS, and related supply and demand-side technologies.[159]
Germany	Partnership	In July 2021, President Biden and Chancellor Merkel launched the US-Germany Climate and Energy Partnership. The Partnership seeks to strengthen high-level collaboration on clean energy technologies and the policy necessary to achieve net-zero emissions. The Partnership includes three key areas of cooperation: 'Climate Action'; 'Transformational Energy Technologies'; and 'Energy Transitions in Emerging Economies'. With respect of the 'Transformation Energy Technologies pillar, key areas of focus include RD&D collaboration on sustainable hydrogen technologies; the development of resilient energy systems; and facilitation of technology commercialisation from research institutions.[160]
India	Partnership	In April 2021, President Biden and Prime Minister Modi announced the US-India Climate and Clean Energy Agenda 2030 Partnership which seeks to strengthen collaboration and enhance progress toward shared energy goals.[161] The Partnership has two tracks of engagement: the Strategic Clean Energy Partnership (SCEP) and the Climate Action and Finance Mobilisation Dialogue. Focus areas for the FCEP include advancing the use of hydrogen in transport and industry, and deploying CCUS technology. In June 2021, the DOE and the Indian Ministry of New and Renewable Energy (MNRE), in collaboration with the US-India Strategic Partnership Forum, launched the US-India Hydrogen Task Force. The Task Force is a high level bi-lateral collaboration that brings together the industry, research and government sectors with the aim of accelerating the hydrogen technology RD&D.[162] The US and India continue to lead joint R&D programs, including the US-India Partnership to Advance Clean Energy Research (PACE-R) and the South Asia Group for Energy, both of which focus on RD&D of advanced clean technologies.[163]

[157] CHS (2021) CHS Member Companies https://www.aiche.org/chs/member-companies

[158] DOE (2021) DOE Joins Ukraine to Advance Energy Security, Clean Energy, and Climate Solutions https://www.energy.gov/articles/doe-joins-ukraine-advance-energy-security-clean-energy-and-climate-solutions.

[159] DOE (2021) Joint Statement by and between the United States Department of Energy and the Ministry of Energy of Ukraine on Enhancing Bilateral Energy and Climate Cooperation. https://www.energy.gov/joint-statement-and-between-united-states-department-energy-and-ministry-energy-ukraine-enhancing

[160] The White House (2021) Fact Sheet: US-Germany Climate and Energy Partnership https://www.whitehouse.gov/briefing-room/statements-releases/2021/07/15/fact-sheet-u-s-germany-climate-and-energy-partnership/

[161] DOE (2021) US-India Strategic Clean Energy Partnership: Responsible Oil and Gas Pillar (September 2021) https://www.energy.gov/sites/default/files/2021-09/SCEP%20Pillars_Accomplishments.pdf

[162] US-India Hydrogen Task Force (2022) US-India Hydrogen Task Force https://hydrogen-task-force.usispf.org/

[163] FuelCellWorks (2020) US-India Strategic Energy Partnership Launches Hydrogen Task Force https://fuelcellsworks.com/news/us-india-strategic-energy-partnership-launches-hydrogen-task-force/

Country	Relationship	Description
		India is also a member of the Quad (with the US, Australia and Japan) and related hydrogen partnership initiatives.[164]
Japan	Dialogue	Japan is also a member of the Quad (with the US, Australia and India) and related hydrogen partnership initiatives.[165]
EU	Joint Statement	In June 2021, the US and EU issued the 'US-EU Summit Statement: Towards a Renewed Transatlantic Partnership'. While not specific to hydrogen, the statement affirmed the US-EU Energy Council's continued ambition to coordinate efforts on strategic energy issues. This includes sustainable energy supply chains, energy security; decarbonisation efforts; promoting clean energy innovation through Mission Innovation; and accelerating scale-up of technologies and policies to support a climate-neutral future.[166]
France	Joint Statement	In May 2021, the French Ministry for Ecological Transition and the DOE issued a joint statement expressing their commitment to collaborate on clean energy technology RD&D. This includes hydrogen and aims to decarbonise industry sectors and deliver breakthrough innovations and policies to achieve net-zero emissions by 2050.[167]
Netherlands	Statement of Intent	In October 2020, DOE's EERE and the Dutch Ministry of Economic Affairs and Climate Policy's Directorate General for Climate and Energy issued a statement of intent (SoI) to strengthen collaboration on the collection, analysis, and dissemination of information regarding hydrogen production and related infrastructure technologies. It is expected this information – and the partnership more broadly – will guide future RD&D efforts and facilitate the scale-up of a global hydrogen economy. As part of the SoI, the DOE's Office of Technology Transitions will assess the performance and durability of electrolysers.[168]
Japan & EU	Joint Statement	In June 2019, the DOE, the Ministry of Economy, Trade and Industry of Japan (METI) and the European Commission Directorate-General for Energy (ENER) signed a joint statement for future cooperation on hydrogen and fuel cell technologies.[169]

[164] The White House (2021) Fact Sheet: Quad Leader's Summit [Statements and Releases]. Fact Sheet: Quad Leaders' Summit | The White House

[165] The White House (2021) Fact Sheet: Quad Leader's Summit [Statements and Releases]. Fact Sheet: Quad Leaders' Summit | The White House

[166] The White House 92021) US-EU Summit Statement. Statements and Releases https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/15/u-s-eu-summit-statement/

[167] DOE (2021) Joint Statement of the United States and France Energy Ministers on Energy Technology and Policy Resolve https://www.energy.gov/articles/joint-statement-united-states-and-france-energy-ministers-energy-technology-and-policy

[168] DOE (202) Collaboration Between the United States and the Netherlands Focuses on Hydrogen Technology https://www.energy.gov/eere/articles/collaboration-between-united-states-and-netherlands-focuses-hydrogen-technology

[169] DOE (2019) Joint Statement of future cooperation on hydrogen and fuel cell technologies among the Ministry of Economy, Trade and Industry of Japan (METI), the European Commission Directorate-General for Energy (ENER) and the United States Department of Energy (DOE). https://www.energy.gov/articles/joint-statement-future-cooperation-hydrogen-and-fuel-cell-technologies-among-ministry

1.5.3 The United States' joint international RD&D projects

The US engages in multiple RD&D projects with international partners. Examples of key joint projects are listed below:

Table 10: Joint international hydrogen RD&D projects

Country	Projects
International	In November 2021, the US DOE announced the launch of H2 Twin Cities, an initiative under the Clean Energy Ministerial. The initiative aims to accelerate global hydrogen development by creating partnerships between cities, both within the US and globally, to promote sustainable practices, the sharing of information and facilitate greater collaboration.[170]
Australia	Australia and the US collaborate on hydrogen primarily through multilateral partnerships, such as Mission Innovation, the IEA and the IPHE (see *Section 1.5.2 The United States' bilateral hydrogen relationships*).
Ireland	In July 2021, Irish start-up EI-H2 and US oil and gas company Zenith Energy launched a joint to create a renewable hydrogen production facility of 3.2 gigawatt (GW). The project is expected to be complete in 2028 and a feasibility study is currently underway. The facility will be located in Southwest Ireland.[171]
The Republic of Korea	In February 2020, the DOE and Hyundai Motor Company announced a collaboration validate and demonstrate hydrogen and fuel cell applications. Hyundai will provide five Hyundai NEXO fuel cell vehicles to the DOE which will then have a SimpleFuel unit installed – a US-made small-scale hydrogen refuelling system.[172] In July 2021, Hyundai announced plans to deploy 30 Class 8 hydrogen fuel cell trucks in Oakland, California by 2023 as part of tis NorCAL ZERO initiative. The California Air Resources Board, the California Energy Commission, the Alameda County Transportation Commission, and the Bay Area Air Quality Management district have provided a total of $29 million in grant support funding. Activities will commence with a 1 year pilot of two Class 8 hydrogen fuel cell trucks, in partnership with Californian First Element Fuel. The pilot was awarded a USD 500,000 grant from the South Coast Air Quality Management District. [173] In April 2021, Bloom Energy, a US based producer of solid oxide fuel cells, collaborated with Republic of Korea-based SK Engineering and Construction Co on a pilot project in Ulsan, Republic of Korea. The pilot deployed 100kW of solid oxide fuel cells powered by hydrogen produced as a by-product of a SK Advanced chemical plant.[174]
Japan	The DOE and Japan's New Energy and Industrial Technology Development Organisation (NEDO) collaborated on hydrogen and fuel cell safety R&D data collection and sharing. The US and Japan

[170] DOE (n.d.) H2 Twin Cities. Viewed at https://www.energy.gov/eere/h2twincities/h2-twin-cities

[171] Zenith Energy (2021) Zenith Energy and El-H2 Announce Joint Venture for Green Energy Facility At Bantry Bay https://zenithterminals.com/news/zenith-energy-and-ei-h2-announce-joint-venture-for-green-energy-facility-at-bantry-bay#:~:text=Zenith%20Energy%20and%20EI%2DH2%20have%20announced%20plans%20for%20a,explore%20the%20project's%20full%20potential.

[172] DOE (2020) US Department of Energy Joins Industry to Collaborate on Transportation Technology Validation and Assessment https://www.energy.gov/eere/fuelcells/articles/us-department-energy-joins-industry-collaborate-transportation-technology

[173] Hyundai (2021) Hyundai's XCIENT Fuel Cell Hitting the Road in California. Newsroom. https://www.hyundai.com/worldwide/en/company/newsroom/-0000016695

[174] Bloom Energy (2021) Bloom Energy Successfully Deploys its First Fuel Cells Powered Solely by Hydrogen. https://www.bloomenergy.com/news/bloom-energy-successfully-deploys-its-first-fuel-cells-powered-solely-by-hydrogen/

Country	Projects
	will then work together to apply that data for guiding future research and safe deployment of hydrogen technologies.[175] Separate to this, in July 2020, Frontier Energy, Inc., in collaboration with The University of Texas and industry consortia including Texas Gas Service, SoCalGas, Toyota Motor North America, Shell and Mitsubishi Heavy Industries announced the launch of two projects under the H2@Scale Initiative. The first is the development of an integrated commercial-scale hydrogen production, storage, distribution and utilisation hub which intends to power a stationary fuel-cell to fuel a fleet of Toyota Mirai FCEVs and the Texas Advanced Computing Center. The second is a feasibility study for scaling up of hydrogen production and utilisation at the Port of Houston.[176]
Germany	In 2020, the NSF and the German Research Foundation (Deutsche Forschungsgemeinschaft) signed an MoU to engage in joint research projects related to renewable hydrogen production. The initiative specifically focuses on electrosynthesis and electrocatalysis.[177]

US International Partnership Programs[178]

Several bilateral and multilateral initiatives exist in the US to advance the use of renewable energy and energy efficiency, several of which include hydrogen. These are listed below:

Global Partner Programs: https://www.nrel.gov/international/global-partnerships.html

1.6 Data insights: The United States' hydrogen RD&D activity

The following section provides data-driven insights on the US' RD&D activity in hydrogen technologies. Research publication data, patent data, and commercial project data has been used to understand hydrogen related activity. While limitations exist with such an approach, these data sources do provide an opportunity to consider activity across the innovation spectrum from basic research to demonstration. It also aims to help identify technology areas that have received significant focus in each country and key organisations to support international collaboration efforts.

The data for this section was sourced from CSIRO's publications team, CSIRO's IP team, IP Australia, and the IEA's hydrogen projects database.

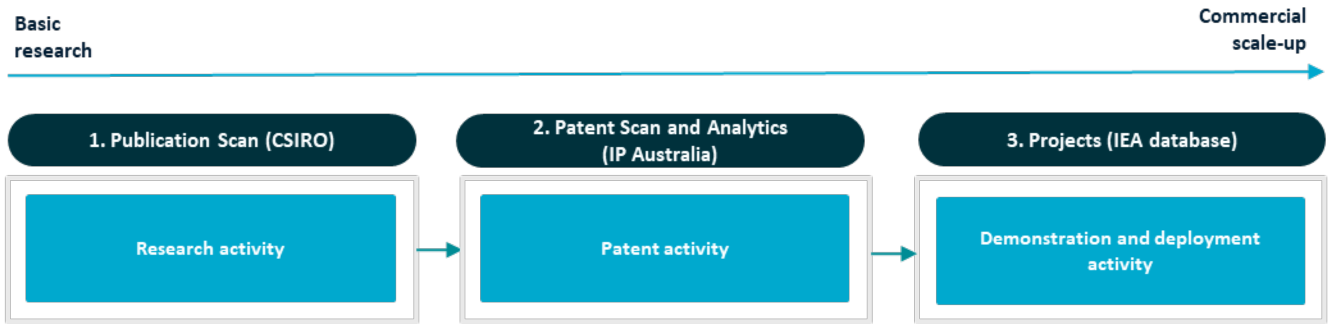
[175] DOE (2017) Energy Department Partners with Japanese Counterpart to Accelerate Hydrogen and Fuel Cell Technologies https://www.energy.gov/eere/fuelcells/articles/energy-department-partners-japanese-counterpart-accelerate-hydrogen-and-fuel

[176] The University of Texas (2020) H2@Scale Project Launched in Texas https://sites.utexas.edu/h2/h2scale-project-launched-in-texas/

[177] DFG (2020) NSF-DFG Lead Agency Activity in Electrosynthesis and Electrocatalysis (NSF-DFG EChem) https://www.dfg.de/foerderung/info_wissenschaft/2020/info_wissenschaft_20_27/index.html

[178] NREL (2021) International Activities https://www.nrel.gov/international/global-partnerships.html

Figure 6: Hydrogen innovation activity data



1.6.1 Research publication data

Research publications in hydrogen are an indicator of basic and applied research activity. CSIRO's publications team has conducted a research publication scan to identify US organisations conducting research across the hydrogen value chain. The publications search approach was developed in 2019 to support the report *Hydrogen Research, Development and Demonstration: Priorities and opportunities for Australia*. This search approach was applied in 2021 to provide an updated dataset for this report. The details of the search approach can be found in the *National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository*.[179]

Figure 7 shows US institutions ranked in terms of publication output across hydrogen production, storage and distribution, and utilisation from 2016-2020.

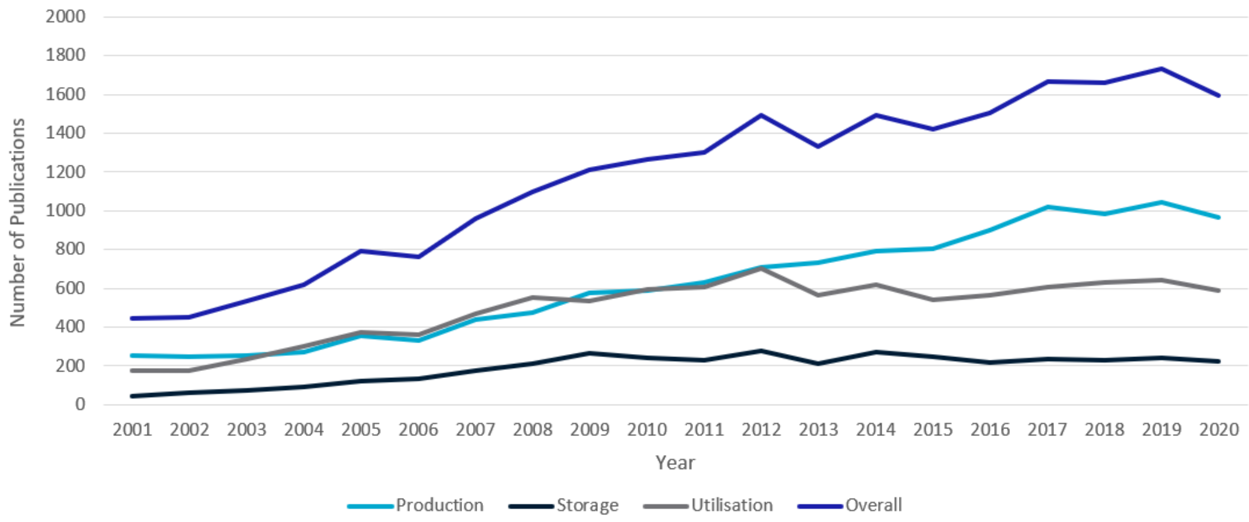
Figure 8 shows the US's country-wide research publication output trends across the hydrogen value chain.

Figure 7: Top institutions by publication output

Domestic Ranking	Production	Storage and Distribution	Utilisation	Overall
	2nd Global Rank	*2nd Global Rank*	*2nd Global Rank*	*2nd Global Rank*
1st	Lawrence Berkeley National Laboratory	Sandia National Laboratory	University of Chicago	Lawrence Berkeley National Laboratory
2nd	Stanford University	Lawrence Berkeley National Laboratory	Argonne National Laboratory	University of Chicago
3rd	University of California Berkeley	Massachusetts Institute of Technology (MIT)	Stanford University	Stanford University
4th	Massachusetts Institute of Technology (MIT)	Oak Ridge National Laboratory	Lawrence Berkeley National Laboratory	University of California Berkeley
5th	University of Minnesota Twin Cities	Stanford University	Oak Ridge National Laboratory	Argonne National Laboratory

[179] CSIRO (2019) National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository. Available at https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research

Figure 8: US hydrogen-related research publication output (2001-2020)



1.6.2 Patent data

Patent activity in hydrogen is an indicator of applied R&D and innovation occurring across the value chain. This section draws on two different patent analytics approaches. CSIRO developed a search approach in 2019 to support the *Hydrogen Research, Development and Demonstration: Priorities and opportunities for Australia*[180] report. CSIRO applied this approach to provide a patent landscape across the hydrogen value chain for each country. The details of the search approach and any limitations can be found in the *National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository*.[181] The second approach, performed by IP Australia, builds on the hydrogen technology taxonomy developed in CSIRO's 2019 report to provide information on specific hydrogen technologies that sit within production, storage and utilisation. The full data visualisations, details of the search approach and any limitations can be found at *Patent analytics of hydrogen technologies: an interactive visualisation.*[182]

It should be noted that analysis of patent data is not necessarily representative of patent impact. As such, this data should be viewed holistically with the other data presented in this section, particularly project deployment.

Patent landscape of hydrogen value chain

Performed by the CSIRO, this patent landscape analyses patent family[183] filings across the hydrogen value chain. Figure 9 outlines patent filings over time across the areas of hydrogen production, storage, distribution and utilisation.

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[180] SIRO (2019) Hydrogen Research, Development and Demonstration (RD&D): Priorities and Opportunities for Australia. Available at https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research

[181] CSIRO (2019) National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository. Available at https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research

[182] IP Australia (2021) Patent Analytics on Hydrogen Technology, Australian Government. Available at https://www.ipaustralia.gov.au/tools-resources/publications-reports/patent-analytics-hydrogen-technology

[183] Applications with the same priority, but filed in different jurisdictions, are known as patent families. Patent families enable us to analyse inventive activity regardless of the number of countries in which protection is sought. Patent families are used in analytics to represent a single invention.

Figure 10 shows the jurisdictions in which US patent applicants are filing patents, outside of the US. This provides an indication of which global markets, or manufacturing and commercialisation destinations are of interest to US patent applicants or inventors.

Note that patent databases have a delay of roughly 18 months, therefore 2020 and 2021 have been omitted from the graphs below. Some patent filings may also be counted twice as the categories of production, storage and utilisation may not be mutually exclusive in all instances and some could relate to multiple areas of the hydrogen value chain.

Figure 9: Patent filings over time across production, storage and distribution and utilisation

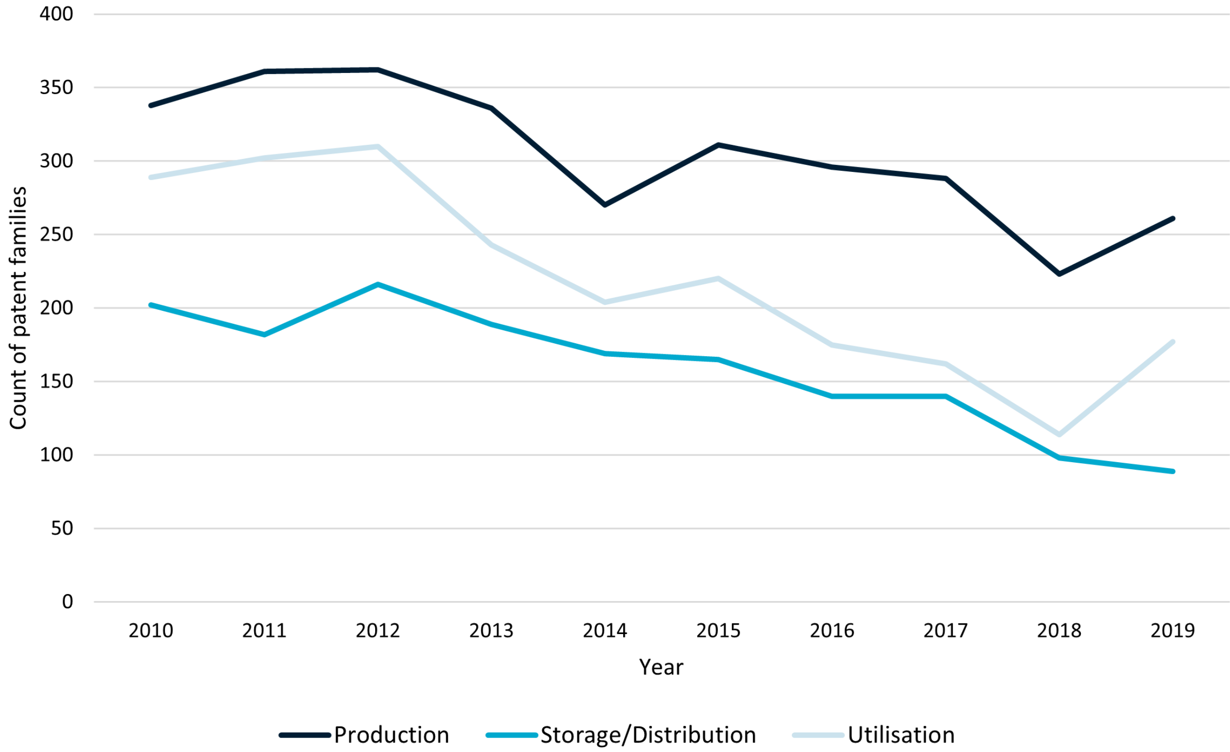
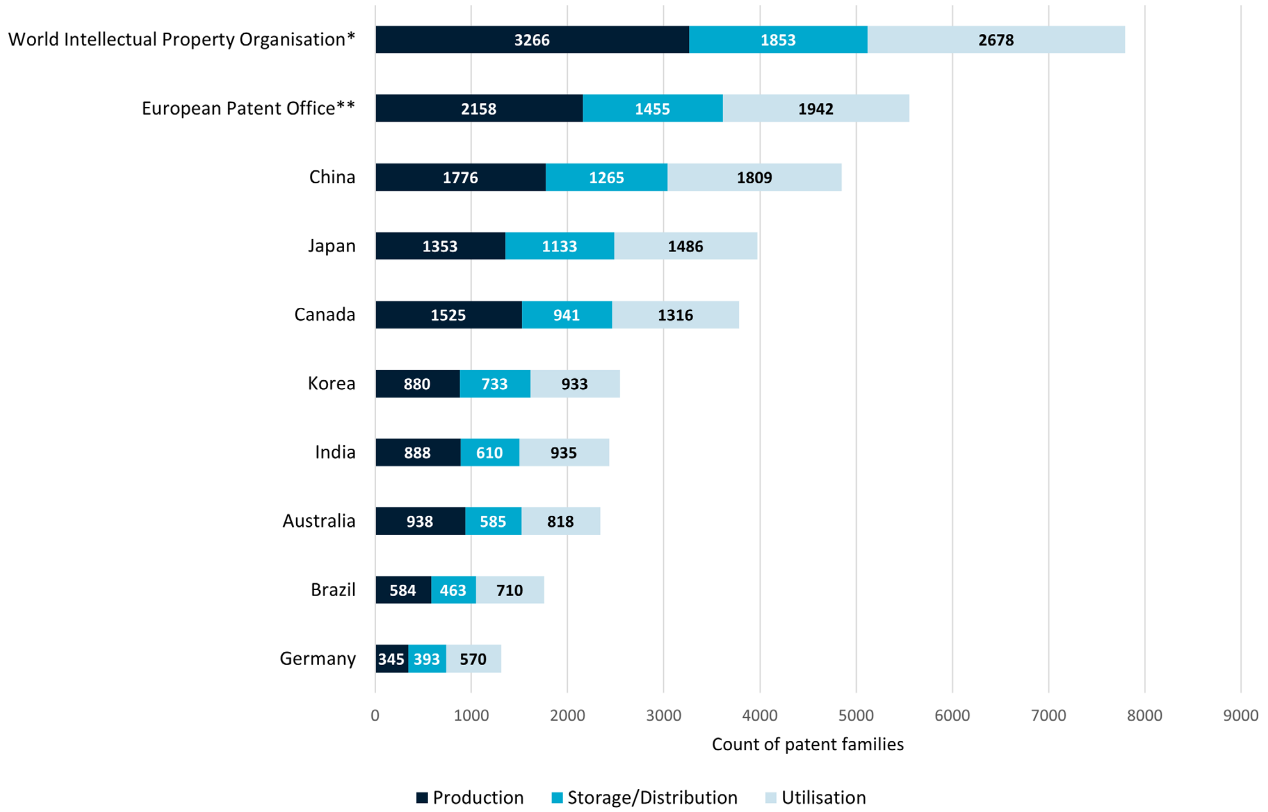


Figure 10: Location of patent filings by US patent applicants



*** The World Intellectual Property Organisation (WIPO) is an international organisation that promotes the protection of intellectual property and supervises administrative cooperation amongst the intellectual unions regarding protection of intellectual property. Patents filed in the WIPO enable applicants to obtain protection for their inventions in up to 153 of the parties to the Patent Cooperation Treaty.**

**** The European Patent Office enables investors, researchers, and companies to obtain protection for their inventions in up to 44 countries, including all 27 EU member states.**

Patent analytics of specific hydrogen technologies

Data extracted from IP Australia's interactive visualisation provides an in-depth analysis of specific hydrogen technology developments. Figure 11 shows the number of patent families filed since 2010 for specific technology areas by US applicants.

Table 11 shows the number of patent families filed by US applicants since 2010 by sub-technology area, expressed as a percentage of total global patent family filings. Table 11 also shows the top organisations in the US filing patents in each technology area. It should be noted that the majority of fuel cell technologies are categorised under the 'electricity generation' category.

Figure 11: The United States' patent family output by sub-technology area (2010-2020)

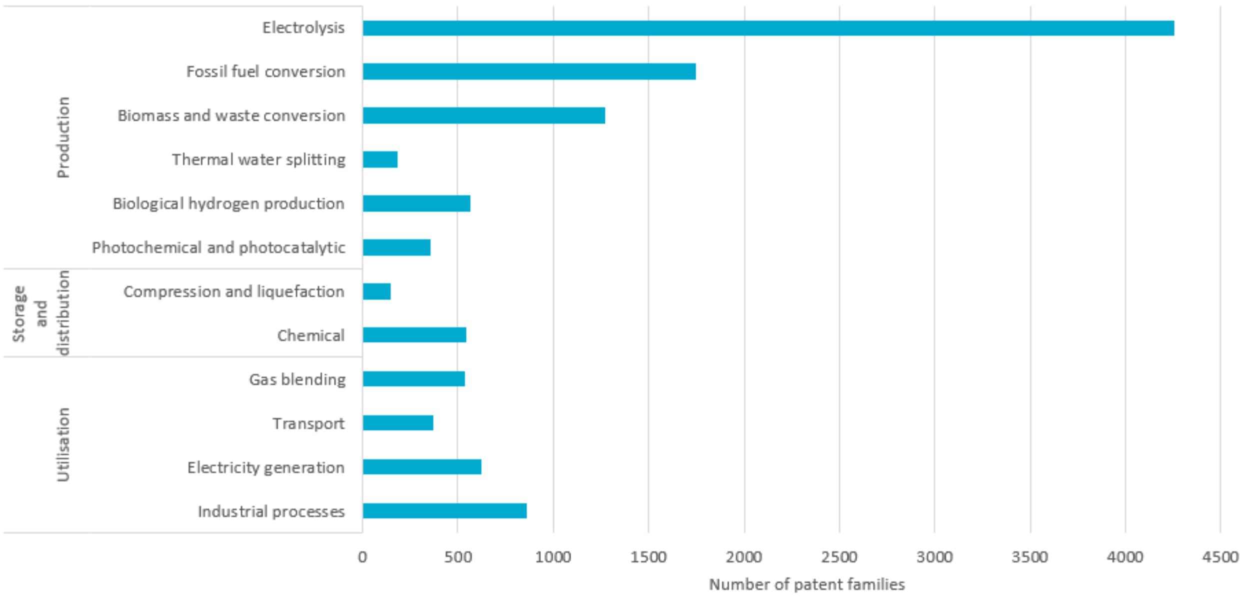


Table 11: IP output of the United States (number of patent families filed by US applicants) by sub-technology area from 2010-2020

Technology area		IP output (% of global)	Leading companies	Leading non-profit and universities
Production	Electrolysis	52.8%	3M Innovative Properties Company, Saudi Arabian Oil Company, Fuelcell Energy, Battelle Energy Alliance, Nuvera Fuel Cells	Battelle Memorial Institute, U.S Army Research Laboratory
	Fossil fuel conversion	28.2%	Royal Dutch Shell Plc, Exxon Mobil Corp, Honeywell International, Saudi Arabian Oil, General Electric	Northeastern University, Gas Technology Institute, Battelle Memorial Institute, Texas A & M University System
	Biomass and waste conversion	42.9%	Royal Dutch Shell Plc, Honeywell International, Air Products & Chemicals, Exxon Mobil Corp, Phillips 66	Gas Technology Institute, Battelle Memorial Institute, Gehz Teknolodzhi Instit'jut
	Photochemical and photocatalytic	18.6%	Calanese International Corporation, Soraa, Sunpower Technology Corporation, Brilliant Light Power	University Of California, Caltech, Northeastern University, North Carolina State University
	Biological	23.5%	Royal Dutch Shell Plc, Phillips 66, Honeywell International, American Sterilizer, Lummus Technology	RTI, Gas Technology Institute, University of Southern California, The University of Toledo
	Thermal water splitting	25.1%	Soraa, Sunpower Technology Corporation, Honeywell International, Soraa Laser Diode, Saudi Arabian Oil	University of California, North Carolina State University, University of Houston, Boston College, University of Alabama

Technology area		IP output (% of global)	Leading companies	Leading non-profit and universities
Storage and distribution	Compression and liquefaction	20.3%	General Motors, Air Liquide, Intelligent Energy, Eveready Battery	University Of Central Florida, Battelle Memorial Institute, Yuan Ze University, Battelle Memorial Institute and John Barclay
	Chemical storage	22.0%	BASF Se, General Motors, Tokyo Electron Limited, Air Products and Chemicals, Ford Global Technologies	The Regents of The University of California, University of California, Texas A & M University System
Utilisation	Gas blending	37.6%	UOP LLC., Air Products and Chemicals, Shell Oil, Praxair Technology, Dow Global Technologies	Ohio State Innovation Foundation, Georgia Institute of Technology, University of Texas System, University of South Carolina
	Transport	14.4%	Ford Global Technologies, GM Global Technology Operations, Calanese International Corporation, Lubrizol Corporation, Aramco Services	Lawrence Livermore National Security, University of California, MIT, U.S Army Research Laboratory
	Electricity generation	14.9%	Fuelcell Energy, Bloom Energy Corporation, ExxonMobil Research and Engineering Company, GE, Aramco Services Company	Syracuse University, Northeastern University, North Carolina State University, University of Southern California
	Industrial processes	19.7%	UOP LLC., Chevron Corporation, Ecolab, Air Products and Chemicals, ExxonMobil Research and Engineering Company	Northeastern University, Gas Technology Institute, University of Louisville, Washington State University

IP Australia patent analytics on hydrogen technology

IP Australia has developed an interactive visualisation tool to provide hydrogen insights to researchers, academics, business and policy sectors. For more hydrogen IP statistics including key destination markets, origin profiles, applicant profiles, collaborations and specific patent searches, refer to IP Australia's Hydrogen Patent Landscape tool:

- https://www.ipaustralia.gov.au/tools-resources/publications-reports/patent-analytics-hydrogen-technology

1.6.3 Project data

Data from the IEA Hydrogen Projects Database (as at October 2021)[184] provides insight on clean hydrogen technology value chains deployed at pilot and commercial scale across the US. Note that the following limitations should be taken into account:

- The database does not indicate whether the technologies used are indigenous or purchased from an overseas provider. While many countries often deploy their own technologies at scale, many countries purchase technologies from overseas to deploy locally. As such the database indicates deployment activity, but not necessarily the ability to translate indigenous R&D into commercial scale-up.
- This dataset counts only low-carbon hydrogen projects and their associated value chains. As such hydrogen production projects from gas, coal and oil without CCS are not included. Similarly, utilisation projects not related to a clean hydrogen project source are not included.
- The dataset reflects only projects occurring domestically, and therefore does not count projects undertaken by US companies outside of the US. As such, the table may understate the activity of the US, particularly its contribution to international supply chain development. This data should therefore be considered holistically with the rest of this report.
- Any limitations stated in the data collection methodology, definitions and assumptions should be taken into account (see IEA Hydrogen Projects Database for details).

For the purposes of this report, the dataset has been filtered to include only projects from 2010 through to projects expected to be operational by 2030 as this timespan best reflects current activities. Projects without a specified date have been excluded from the table below. Further, only projects that are at feasibility study stage, final investment decision, demonstration, and operational are included. Projects at the 'concept' stage are not included. It should be noted that the majority of projects listed span production, storage and multiple end-uses, and as such can be counted in more than one technology category.

Table 12: The United States' domestic clean hydrogen project data

Technology	Sub-technology		Domestic project count	% of global
Production	Electrolysis	PEM	18	9.8
		Alkaline	3	2.6
		SOE	3	11.1
		Other or unspecified	6	2.4
	Fossil fuel conversion	Coal gasification with CCS	1	16.7
		Natural gas with CCS	5	13.9
		Oil with CCS	2	33.3
		Methane pyrolysis	-	-

[184] IEA (2021) Hydrogen Projects Database. Available at <https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database>

Technology	Sub-technology		Domestic project count	% of global
	Biomass and waste conversion		4	26.7
	Photochemical and photocatalytic		-	-
	Biological production		-	-
	Thermal water splitting		-	-
Storage and distribution	Compression and liquefaction		36	7.1
	Chemical carriers	Ammonia	4	14.3
		Methane	1	1.9
		Methanol	1	4.8
		Synfuels	-	-
Utilisation	Gas blending		5	3.7
	Transport		14	5.9
	Electricity generation		11	8.2
	Industrial processes	Refining	-	-
		Ammonia	-	-
		Methane	-	-
		Iron and steel	-	-
		Biofuels	-	-
		Synfuel	-	-
		Other industry	7	5.1

IEA Hydrogen Projects Database

The latest version of the IEA Hydrogen Projects Database can be found at:

- https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

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