Feb. 17, 2022

Congressional Testimony of
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Before the
Committee on Science, Space, and Technology
Energy Subcommittee
United States House of Representatives
2nd Session, 117th Congress

Chairman Bowman, Ranking Member Weber, and Members of the Committee, thank you for inviting me here today to discuss hydrogen innovation and technology. My name is Dr. Julio Friedmann and I am the Chief Scientist at Carbon Direct, a science-based carbon management firm that works with corporate clients to actualize their carbon commitments and that makes direct investments into emerging carbon companies to scale removal technologies. I am also a non-resident fellow at Columbia University's Center on Global Energy Policy. It is an honor, and a timely one, to appear before this Committee to discuss the status of hydrogen technology as well as key R&D strategies and investments for innovation.

Uses and Benefits

In my last House Committee testimony in September 2019,[1] I called hydrogen the first, best option for clean energy across many applications, and made the point that innovation investments would serve the nation well. Since then, hydrogen has grown in importance as a commercial opportunity for investment and trade, as a key tool for deep decarbonization, and as a means to maintain U.S. competitiveness.

Today, hydrogen delivers essential clean energy and feedstocks to heavy industries[2,3], including refining, petrochemicals, and fertilizer (where 10 million tons of hydrogen are used in the U.S. each year). It is projected to grow into new industrial applications that will include steel, cement, and glass. These sectors are essential to the U.S. economy and national security, and are major employers across the nation for underserved communities. Moreover, they are important sources of local pride, high-paying jobs, thriving communities, and state revenues, yet they are at risk from emerging

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[1] https://www.energypolicy.columbia.edu/research/testimony/challenges-and-solutions-us-industrial-decarbonization

[2] https://www.iea.org/reports/global-hydrogen-review-2021

[3] https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/

international border tariffs based on carbon content, such as those recently announced by the European Union. [4,5] While these industries are significant sources of emissions – localized in large central facilities in a few states, notably Texas, Louisiana, Oklahoma, New Jersey, California, and along the Great Lakes – hydrogen could help improve air and water quality in these communities and position these sectors for the fierce competition of international markets.

Hydrogen will also directly or indirectly play a massive role in providing clean energy to shipping, aviation, trains, and long-haul trucking.[6,7] For some types of heavy-duty transport, in particular long-haul trucking, hydrogen is projected to play a substantial role directly as a fuel. For shipping and aviation, clean hydrogen will serve as a principal feedstock for sustainable fuels,[8] including ammonia, methanol, and jet fuel. Fuel cells will play an important role in the use of transportation fuels (instead of internal combustion engines) as fuel cells do not actually burn fuels and instead directly convert hydrogen to energy, greatly improving overall efficiency and reducing pollution and associated human health impacts – the basis for the DOE's hydrogen and fuel cell technology program (see below).

Global Competitive Landscape

Although recent legislation by the 117th Congress will help position the U.S. for leadership in hydrogen, much more investment is needed. This includes investment in innovation, comprising traditional RD&D, new business models and new policies, as well as infrastructure and incentives.

Most notable is the Infrastructure Investment and Jobs Act (IIJA).[9] This created $8 billion for a set of dedicated hydrogen hubs; additional funding for hydrogen fueling infrastructure analysis and build out; creation of a national energy modeling system; requirements for reports to congress; and funding for hydrogen school buses and ferries. Central to this Committee's work are the Hydrogen Research and Development provisions (Subtitle B, Secs..40311-40315) with applications in transportation, industry, commercial, residential, and power sector applications. Key provisions include: establishing a hydrogen roadmap and national strategy; formalizing definitions of "clean" hydrogen; setting measurable goals; focusing on both the production and use of hydrogen, as well as synthetic fuels ("hydrogen carriers"); awarding clean hydrogen equipment manufacturing facilities; and scaling hydrogen electrolysis and hydrogen storage. One example of successful goal setting

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[4] https://ec.europa.eu/taxation_customs/green-taxation-0/carbon-border-adjustment-mechanism_en

[5] https://www.bcg.com/publications/2021/eu-carbon-border-tax

[6] https://www.energy-transitions.org/publications/mission-possible/

[7] https://www.iea.org/reports/the-future-of-hydrogen

[8] https://carbon-direct.com/wp-content/uploads/2021/11/Transportation-Decarbonization-White-Paper.pdf

[9] https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf

includes the DOE's recent Hydrogen Shot announcement as part of the Earthshot program series,[10] setting a goal of clean hydrogen production at $1/kg. The law outlines sustained, multi-year, substantial funding for these programs that will help to place the U.S. on sound competitive footing.

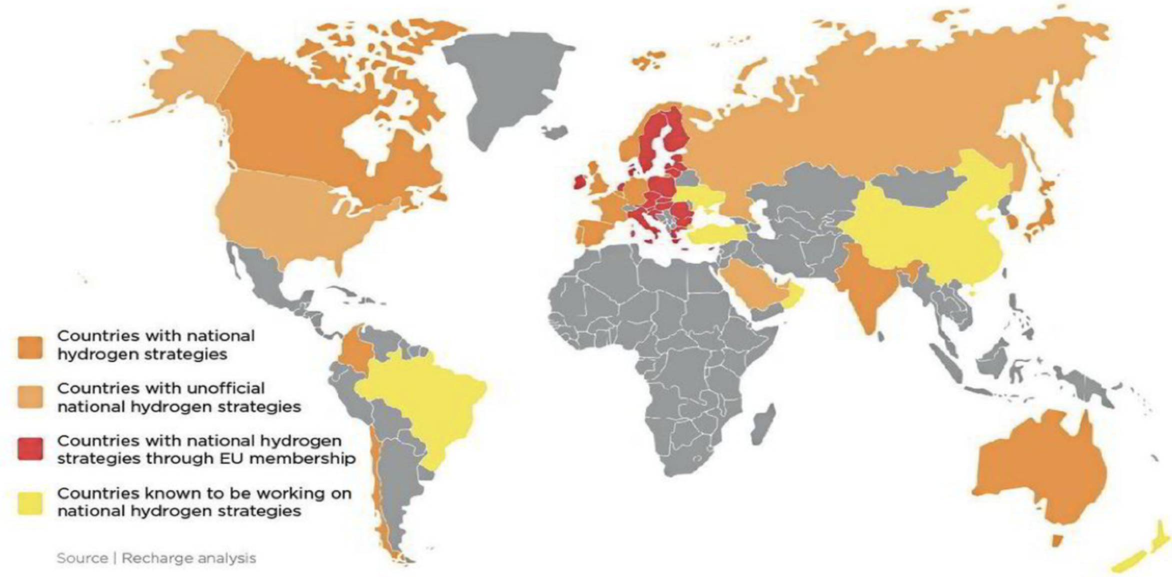

Figure 1: National hydrogen strategies by country in Q4 2021. L. Collins News, 2021[11]

The rest of the world has already financed similar efforts, and in many cases provided more certainty, infrastructure, and support (Figure 1). Notable countries include Japan,[12] South Korea,[13] Germany,[14] Canada,[15] Saudi Arabia, Australia,[16] and the UAE[17], as well as the European Union.[18]

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[10] https://www.energy.gov/eere/fuelcells/hydrogen-shot

[11] https://www.rechargenews.com/energy-transition/hydrogen-now-firmly-at-the-heart-of-the-global-race-to-net-zero-for-better-or-worse/2-1-1058073

[12] https://www.ifri.org/sites/default/ files/atoms/files/nagashima_japan_hydrogen_2018_.pdf

[13] https://www.ifri.org/sites/default/files/atoms/files/sichao_kan_hydrogen_korea_2020_1.pdf

[14] https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6.

[15] https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

[16] https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy

[17] https://www.wam.ae/en/details/1395302988986

[18] https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)689332

Together, they represent deliberate strategies to dominate hydrogen production, trade, use, and technology, as well as associated goods and services that range from green steel to fuel-cell manufacturing to low-carbon shipping fuels. To remain competitive, the U.S. must match these investments with a redoubled investment in innovation that will catalyze new technologies, patents, companies, and commercial opportunities.

Production and Supply

The opportunities to produce more low-C hydrogen are many and profound (Figure 2), and would benefit from focused investment across the innovation pipeline: from early stages through demonstration to commercialization.

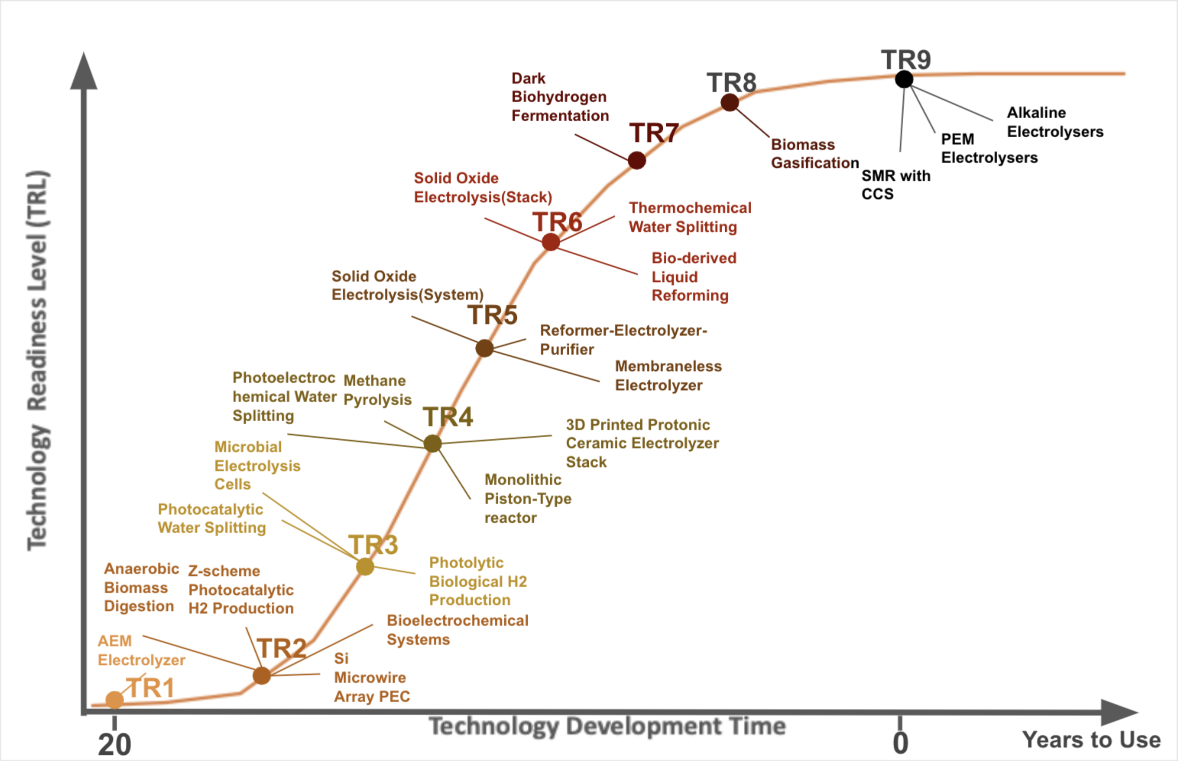

Figure 2: Technical Readiness of low-C hydrogen supply technologies. from Fan et al. 2021[19]

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[19] https://www.energypolicy.columbia.edu/research/report/green-hydrogen-circular-carbon-economy-opportunities-and-limits

- **Novel electrolyzers**: Most green hydrogen today is provided by alkali electrolyzers and some proton exchange membrane electrolyzers (PEM). Advanced technologies such as solid-oxide electrolyzer cells (SOECs) and membrane-less electrolyzers could make hydrogen with greater efficiency and lower cost using earth abundant materials.
- **Biomass conversion and CO_2 removal**: For many years, companies and governments have converted wood, trash, and agricultural residues into syngas and hydrogen. To become commercial, these approaches required applied research to reduce cost, improve performance, and operate with sustainable feedstocks. If combined with carbon capture and storage, these approaches could produce hydrogen that removes CO_2 in large volumes and restores climate equilibria,[20,21] requiring R&D on system integration and operation.
- **Emerging new pathways**: Dozens of approaches hold promise, including solar water splitting, microbial hydrogen production, and methane pyrolysis. Many of these approaches require new reactors, new catalysts, and new materials. Use-inspired research, applied research, piloting, and demonstration all have roles in bringing new and advanced pathways to the market.

Conversion and Use

The International Energy Agency found that the world's major economies allocate too much funding to "supply-side technologies, rather than the types of end-use innovations needed for sectors that currently have no commercially available and scalable options for achieving deep emissions reductions."[22] While innovation in low-cost, low-carbon hydrogen supply is important, much more innovation must focus on the use of hydrogen across multiple applications. This includes: bringing hydrogen into new industrial and transportation systems; developing low-cost earth abundant fuel cells; integrating these new technologies into existing infrastructure and systems; and designing improved systems for the nation's industries, communities, and citizens.

- **Industrial applications**: Hydrogen has partial use today in refining, chemicals, and fertilizer sectors. It has almost zero use today in steel, cement, ceramics, or glass, where it could provide both industrial heat and chemical energy.[23,24,25] This enormous prospective market

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[20] https://www.globalccsinstitute.com/resources/publications-reports-research/blue-hydrogen/

[21] https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf

[22] https://www.iea.org/reports/energy-technology-perspectives-2020

[23] https://www.energy-transitions.org/publications/mission-possible/

[24] https://www.energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today

[25] https://www.energypolicy.columbia.edu/research/report/green-hydrogen-circular-carbon-economy-opportunities-and-limits

requires research of all kinds, including simulation and computational design, integrations with existing assets and faculties, new reactors and heavy equipment, and more complete representation of potential environmental impacts. .

- **Low-C fuels and CO_2 recycling**: Low-carbon fuels can provide energy in a modern economy with much lower greenhouse gas emissions and much lower pollution. RD&D is essential to improve the economics and performance of these low-C fuel systems through the direct synthesis of fuels electrochemically, greater conversion efficiency in manufacturing, and integration of hydrogen use with CO_2 recycling to create chemicals and fuels.[26]
- **Electricity balancing and long-term storage**: Hydrogen in fuel cells generates electricity. To maintain a resilient, clean grid, many see hydrogen as the lowest-cost and best application for long-term power storage, especially for multi-week and seasonal power storage. This would allow for much higher levels of renewable power integration and provide reliable power during storms and unusual weather events, which are projected to increase in the coming decades. To achieve low costs, high performance, and resilience, research should focus on novel hydrogen storage systems (including salt domes and advanced tanks) and systems of control for better integration.
- **Fuel cell technology and manufacturing**: Although fuel cells are established technology, especially in military and aerospace applications, R&D can deliver cost reductions, novel manufacturing methods, and improved performance (like durability, longevity, and corrosion resistance). Research on new seals, membranes, materials, and production would help maintain American manufacturing competitiveness while accelerating a transition to clean energy systems.

Focus of Government Research

In the report "Energizing America,"[27] my co-authors and I recommended a number of dramatic changes to the government's RD&D approach across many sectors and applications, including fuels, heavy industry, and carbon capture.[28] We recommended augmenting the DOE's traditional R&D applications in the transportation sector within the Office of Fuel Cells and Hydrogen Vehicles with new missions and expanded roles for many DOE offices.

- The Advanced Manufacturing Office within EERE (industrial applications);

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[26] https://www.energypolicy.columbia.edu/research/report/opportunities-and-limits-co2-recycling-circular-carbon-economy-techno-economics-critical

[27] https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/EnergizingAmerica_FINAL_DIGITAL.pdf

[28] https://www2.itif.org/2018-innovation-agenda-decarbonization.pdf

- Office of Fossil Energy and Carbon Management (synthetic fuels production);
- Biomass Energy Technology Office (carbon-restorative hydrogen production with biomass);
- Office of Nuclear Energy Reactor Concepts Office (novel hydrogen production cycles);
- Office of Electricity (long-term power storage & reliability)
- ARPA-E (cutting edge hydrogen production, storage and use); and
- Foundational and use-inspired science in the Office of Science (e.g., catalysts and novel materials; Energy Frontier Research Centers).

"Energizing America" also recommended a dramatic increase in budget for many offices, such as a 150% increase for the Hydrogen and Fuel Cell Technology program to a total of $375 million in 2022. These increases represent the largest fractional increase for those fields that historically have received low funding levels and show the greatest potential for growth and improvement (Figure 3). The report also recommends increasing budgets for other government agencies like NSF, DOD, DHS, NIST, and FERC for both analysis and fundamental research. This would further diversify the RD&D approaches and create more solutions across the innovation ecosystem.

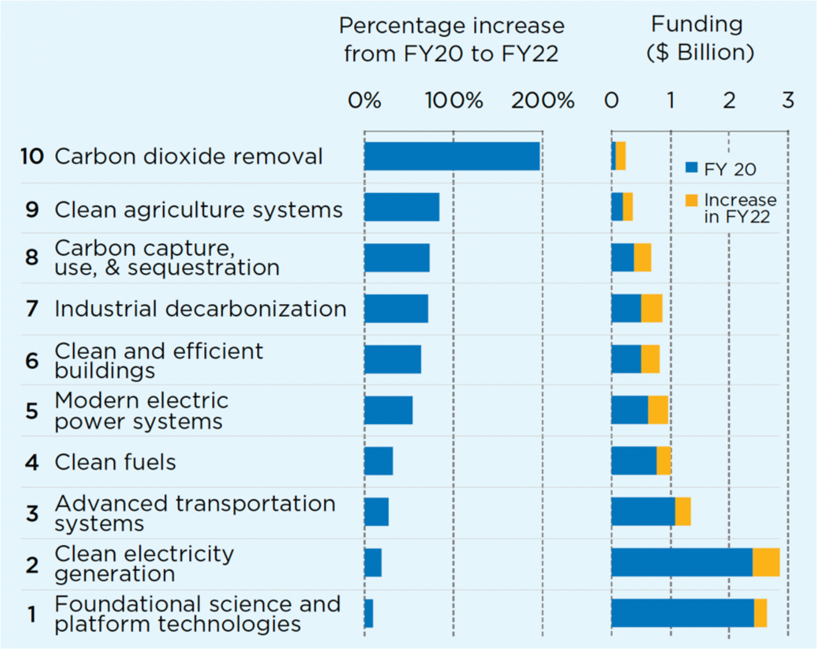

Figure 3: Proposed FY 22 Federal energy innovation budget by technology pillar, compared to FY20 levels. From Energizing America, 2020

Three National Labs carry missions associated with the applied energy offices. The National Renewable Energy Lab (NREL) currently receives most of the funding and mission around clean hydrogen production and use. This work can and should expand. In addition, production and conversion of clean hydrogen from nuclear and fossil energy should expand at Idaho National Lab (INL) and National Energy Technology Lab (NETL) respectively. Much more can and should be done to serve the nation's hydrogen needs, and I propose that National Labs take on the following mission-aligned work:

- **Cross-functional working group**: The three Labs should establish a cross-functional working group to share learnings. That work should expand to include industrial, commercial, residential and power-sector applications.
- **Electrical pathways and assessments**: All three labs should prioritize electrical pathways, including: the electrocatalysis of hydrogen production and electrofuel synthesis; improved selectivity and reduction of overpotential; efficiency improvements; fuel cell manufacturing and use (methanol and ammonia systems); use of earth abundant materials; and implications for communities, the environment, jobs, commercial growth, and equity.
- **Federated, open database:** They should also create a federated database to provide accessible information on hydrogen technology, science, production, transportation, storage, conversion, and use.
- **Discovery and development**: The eight Labs managed by the Office of Science should focus on materials discovery and development, advanced technology (e.g., electrocatalysis), life-cycle analysis, and simulation.
- **National energy missions:** The three NNSA labs (LLNL, LANL, SNL) should repurpose some existing simulation and laboratory capabilities to national energy missions associated with hydrogen, including advanced manufacturing/3D printing; simulation; systems analysis; reactor design; national security applications; geopolitics; and infrastructure development, operation, and hardening (e.g., at ports).
- **Safety and risk mitigation:** All National Labs should explore technologies for hydrogen safety, leakage detection, and leakage mitigation (see below); and
- **Carbon removal:** All National Labs should explore potential for clean hydrogen in CO_2 removal, agricultural decarbonization, and development of expertise and human capital (see below).

Supplemental programs

In addition to conventional RD&D approaches discussed above, the Federal Government and the DOE in particular should create or sustain key supplemental programs necessary for national success, including:

- **Leakage**: Today, most companies monitor hydrogen leakage from the perspective of safety alone as a response to regulations. Although it is not a greenhouse gas, it appears that hydrogen leakage could indirectly increase the longevity of short-lived, non-CO_2 greenhouse gases. ***There is almost no scholarship or technology on this subject***. To avoid future environmental and operational risks and to enable the safe, sustainable production and use of hydrogen, these programmatic actions are imperative:

  - Require all pilots and demonstrations to instrument for hydrogen leakage detection at levels below 0.75% annual production
  - Support a subset of new hydrogen infrastructure buildout to instrument for hydrogen leakage detection at levels below 0.75% annual throughput and use
  - Support a subset of new hydrogen applications in industry, transportation, power, commercial, and residential sectors to instrument for hydrogen leakage detection at levels below 0.75% annual throughput and use;
  - Gather, curate, and share this data through a public, open database for use by the general public; and
  - Work with agencies like NIST, EPA, DOT, and others to develop new standards to minimize and manage hydrogen leakage, especially for new applications and systems.
- **Energy System Analysis**: The IIJA has some important new provisions for energy system analysis. Today, the models and tools for such analysis are grossly insufficient for the rapidly evolving hydrogen markets, infrastructure, and global application set. Substantial dedicated new funding is needed solely to support hydrogen analysis systems and works.
- **Human Capital**: America lacks the human capital and expertise to successfully develop, scale, and commercially operate a hydrogen-rich economy. The DOE Offices and National Labs should work with universities, trade associations, labor groups, and companies to develop and implement programs to train people on hydrogen ecosystems and infrastructure. This should include skill sets like welding for hydrogen systems, manufacturing of equipment and devices, operation of key facilities and infrastructure, and regulatory requirements. Emphasis should be placed on universities advancing underserved communities including tribal universities and HBCUs, and where possible, should include additional capacity building and training programs for these communities.
- **Procurement**: Unlike in the power sector, Federal, State and City governments directly or indirectly buy enormous fractions and volumes of industrial products. For example, roughly 50% of cement and concrete, 20% of steel and 5% of fuels[29] are procured by these governments alone. This gives government procurement enormous leverage in these markets. A well-designed national zero-emissions "buy clean" standard would immediately create demand for low-carbon industrial products and stimulate private investment in decarbonizing industrial sources, especially for sectors where hydrogen could play an outsized role in trade, environmental benefits, and climate benefits. Recent state legislative proposals and new laws provide a model for how this might be enacted.[30]

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[29] https://www.climateworks.org/report/build-clean-industrial-policy-for-climate-and-justice/

[30] CA Legislature, 2017, public contract code amendment 3500-3505 https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?division=2.&chapter=3.&part=1.&lawCode=PCC&article=5. And https://www.dgs.ca.gov/PD/Resources/Page-Content/Procurement-Division-Resources-List-Folder/Buy-Clean-California-Act

- **Hydrogen and Ammonia Fleets:** A special case for both procurement and RD&D opportunities involves federally owned trucks, trains, and ships. Within IIJA, provisions exist for some of these vehicles to be hydrogen vehicles. These provide learning opportunities for researchers around use, efficiency, performance, and controls. One potential example of high national merit and impact: translate the Coast Guard's operations to 100% clean ammonia fuel by 2030.

In summary, we should act decisively. To remain globally sustainable and globally competitive, it is essential that we accelerate investments in innovation around a hydrogen economy in a way that respects the limits of physics and chemistry, contextualizes economic realities, and accounts for the needs of communities and industries – all with an eye towards meeting the urgency of this challenge, namely to scale low-carbon and equitable energy systems. With that, I look forward to your comments and questions.