Written Testimony to the
Subcommittee on Energy,
House Committee on Science, Space and Technology,
U.S. House of Representatives

H2Success: Research and Development to Advance a Clean Hydrogen Future

Rachel Fakhry
Senior Advocate
Natural Resources Defense Council

February 17, 2022

Chair Bowman, Ranking Member Weber, and distinguished Members of the Subcommittee: Thank you for the opportunity to offer recommendations on how the United States Department of Energy (DOE) can strategically advance hydrogen technology in a manner that enables Americans to reap its benefits and mitigate its risks.

My name is Rachel Fakhry, and I lead the hydrogen portfolio at the Natural Resources Defense Council (NRDC). NRDC is an international nonprofit of scientists, lawyers, and environmental specialists dedicated to protecting natural resources, public health, and the environment. Founded in 1970, NRDC has more than 3 million members and online activists, and we are committed to tackling the climate crisis by driving greenhouse gas emissions down to net-zero by no later than mid-century.

I structure my testimony as follows:

1. The opportunities, challenges, and risks of hydrogen as a decarbonization tool as uncovered by the best available analytical and scientific evidence;

2. The current structure of DOE's hydrogen research, development, demonstration, and deployment (RDD&D) program and the disconnect between the program's focus and hydrogen's highest value proposition;

3. Recommendations to address the disconnect and render the program more fit-for-purpose to leverage hydrogen's potential to help tackle the climate crisis and minimize unintended climate, economic and public health consequences.

Executive Summary

Hydrogen technology has become a central focus in the global clean energy innovation arena due to its potential to play a critical role in achieving countries' deep decarbonization goals. In particular, hydrogen – and hydrogen-based fuels– offer unique potential to substitute for fossil fuels in sectors where few decarbonization options exist, such as aviation, maritime shipping, and steelmaking. The U.S. DOE is well-positioned to leverage its state-of-the art innovation capacities to advance the technology at a critical time in the fight against the climate crisis. However, hydrogen also carries a series of risks to which decision makers must be acutely sensitive, and which require robust safeguards and caution. It is therefore critical that federal policy implement guardrails around hydrogen innovation and deployment programs to ensure that the technology's advancement is aligned with our long-term climate goals, protects the health of our communities and does not place undue economic burden on U.S. households.

We recommend that the following three guiding principles underpin DOE's hydrogen work (with our fuller recommendations detailed in part III):

1. **Hydrogen RDD&D should be targeted to a limited number of applications.** Hydrogen production and use are energy-intensive, meaning that outside of the narrow set of hard-to-abate applications where few alternatives exist, hydrogen is inefficient and expensive relative to other clean energy solutions. For example, heating a home with a hydrogen boiler can require up to 5 times more renewable electricity than heating that same home with a high-efficiency heat pump. It is therefore critical for DOE to prioritize the advancement of hydrogen use– or the use of hydrogen-based fuels– in the hardest-to-electrify sectors of the economy–such as maritime shipping, aviation, and steelmaking– to avoid saddling Americans with wasteful solutions and complicating the task of decarbonizing our economy.

2. **Only green hydrogen should be prioritized.** The vast majority of hydrogen used in our economy today is derived from methane gas, in a process that emits carbon dioxide and harmful air pollutants that negatively impact public health. In light of efforts to significantly scale up hydrogen deployment, it is critical that hydrogen production is cleaned up and subject to the highest standards of climate and public health integrity. Several emerging production pathways are being touted as "clean," but zero-emissions green hydrogen–produced by splitting water into hydrogen and oxygen in a process powered by renewable electricity–has primacy over others from the climate, public health, and economic standpoints, and only its development and deployment should be prioritized. In addition, it is imperative that DOE adopt an ambitious and rigorous hydrogen production standard based on carbon intensity and public health metrics to guide its investments.

3. **Further Assessments Are Necessary to Avoid Detrimental Climate and Public Health Effects.** More research and investigations are necessary to ensure that there will not be detrimental climate and public health impacts linked to hydrogen production, transport, storage, and use. For instance, when burned, hydrogen may produce even more air pollution than methane gas, if not managed. Further, emerging science is finding that hydrogen is a stronger indirect greenhouse gas than broadly perceived, which may undermine its climate benefits when it leaks from infrastructure. It is therefore imperative for DOE to further assess hydrogen's climate and public health impacts before making investments that may unwittingly damage the climate and our communities' health and develop practices and solutions to mitigate them.

DOE's hydrogen portfolio must thus strike a balance between ambition, strategic prioritization, robust safeguards, and caution.

Context and Summary

The hydrogen goal posts have plainly shifted in the past two or so years, warranting a reevaluation of DOE's hydrogen innovation and deployment efforts.[1] NRDC agrees with the emerging consensus that when substituting for fossil fuels in the sectors of the economy that are the hardest to directly electrify- such as maritime shipping, steelmaking and aviation- and with robust safeguards to mitigate the technology's risks, zero-emitting green hydrogen can play a key role in supporting our bid to stave off the worst of the climate crisis and achieve a net-zero greenhouse gas emitting global economy by 2050. However, robust RD&D is still required in the very short time window to 2030 and beyond to enable those important hydrogen uses to achieve commercial viability. The International Energy Agency estimates that, to achieve international climate goals, $90 billion of global public money should be channeled into clean energy R&D by 2030-- around half of which should be allocated to hydrogen-related technology-- with notable innovation gaps in heavy industrial applications, shipping, and aviation (all of which hydrogen or hydrogen-based fuels are capable of decarbonizing).[2] Hydrogen has thus become a central focus of global clean energy innovation efforts. The U.S. DOE, with its state-of-the-art innovation capabilities and commendable track record of successes, stands to have a central and far-reaching role in the bid to drive the technology forward in a climate and public health-aligned manner, at a critical point in our fight to stave off the worst of the climate crisis.

A targeted and clearly prioritized DOE hydrogen program could enable Americans to reap the full benefits of hydrogen technology, bolster the bid to decarbonize our economy by 2050, propel the U.S. to the vanguard of the global clean energy innovation race, and establish a U.S. competitive edge in a clean global economy. However, it is vitally important to be cognizant of hydrogen technology's risks and limitations which, absent proper guardrails, can increase costs for consumers, jeopardize our bid to safeguard our public health and climate, and undercut much of the technology's potential benefits.

DOE's hydrogen innovation work has delivered– and is delivering– a series of successes, the latest of which is the globally pioneering Hydrogen Shot initiative targeting the most ambitious and rapid cost reductions in the production of clean hydrogen[3]. However, important opportunities have emerged for the program's reevaluation to render it more fit-for-purpose to help support the efficient and beneficial decarbonization of the U.S. economy, deliver benefits to America and mitigate the technology's serious risks.

---

[1] DOE's hydrogen work was originally largely linked to fostering energy independence and resilience, with a focus on hydrogen use in cars and as a rocket fuel. Outside of RD&D, hydrogen is currently mainly used in industry, for oil refining and fertilizer production. Emerging interest in hydrogen as a potentially key climate solution for the decarbonization of the U.S. and global economies envisions a new, cross-sectoral role for hydrogen. Consequently, the technology's research, development, and deployment targets – or goal posts- have largely shifted.

[2] IEA reports that currently, roughly $25 billion is budgeted for R&D through 2030. International Energy Agency, "Net-Zero by 2050, A Roadmap for the Global Energy Sector," May 2021, https://iea.blob.core.windows.net/assets/0716bb9a-6138-4918-8023-cb24caa47794/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf ; International Energy Agency, "Global Hydrogen Review 2021," 2021, https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf

[3] In a number of avenues, clean hydrogen refers to hydrogen produced in a manner that emits significantly less greenhouse gas emissions relative to today's incumbent and highly-emitting gas-based hydrogen; U.S. DOE, "2021 Annual Merit Review Awards," https://www.hydrogen.energy.gov/annual-review/annual_review21_awards.html

First, while the DOE's hydrogen work was originally largely linked to fostering energy independence and resilience, hydrogen is now being touted as a key climate solution for the decarbonization of the U.S. and global economies, signaling a change in the technology's development priorities.

Second, DOE's pioneering RD&D efforts across clean energy technologies have helped spur incredible advancements in solar energy, wind energy, battery storage, high-efficiency heat pumps, and electric vehicles; those technologies are now able to reliably and affordably meet much of Americans' energy needs in a transition to a clean economy, as evidenced by abounding independent analyses and projections.[4] Consequently, robust evidence suggests that hydrogen's unique value proposition lies in its targeted deployment in sectors where other clean energy solutions may be limited- such as maritime shipping, aviation, steelmaking, and seasonal electricity storage. Otherwise, it is woefully inefficient, and carries risks of saddling consumers with expensive options and complicating the task of decarbonizing our economy. Similarly, a range of hydrogen production pathways touted as "clean" carry climate and public health risks and have unfavorable economics; zero-emitting, green hydrogen presents the only judicious investment pathway owing to its primacy from a climate, public health, and economic standpoint relative to other hydrogen resources.

Further, more research and investigations are necessary to ensure that there will not be detrimental climate and public health impacts linked to hydrogen production, transport, storage, and use. For instance, emerging science is finding that hydrogen is a stronger indirect greenhouse gas than broadly perceived, which may undermine the anticipated climate benefits of decarbonization efforts when it leaks from infrastructure; this highlights the need for developing best practices to mitigate those climate risks.

We recommend that the DOE:

1. Conduct periodic assessments investigating hydrogen's highest value proposition relative to other readily available and cost-effective clean energy solutions in holistic pathways to net-zero greenhouse gas emissions by 2050;
2. Only prioritize the advancement of zero-emitting, green hydrogen in the hardest-to-electrify sectors of the economy, placing the U.S. at the vanguard of the global clean energy innovation race;
3. Bridge critical knowledge gaps related to the public health and climate warming impacts of hydrogen transport and use patterns before launching into related investments; and
4. Engage in proactive, transparent, and inclusive stakeholder engagement.

I look forward to further discussing these issues and working with Congress to aid in directing DOE's hydrogen program in a manner that will deliver the best value for the U.S. and the global fight against climate change.

---

[4] Princeton University, "Net-Zero America Project," December 2020, https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/; National Academies of Science, "Accelerating Decarbonization of the U.S. Energy System," 2021, https://www.nap.edu/download/25932# ; Energy Innovation, "A 1.5°C NDC for Climate Leadership by the United States," April 2021, https://energyinnovation.org/wp-content/uploads/2021/04/A-1.5-C-Pathway-to-Climate-Leadership-for-The-United-States_NDC-update-2.pdf ;

I. The Opportunities, Risks and Shortcomings of Hydrogen as a Decarbonization Tool

Hydrogen offers a potential solution to the hardest-to-decarbonize sectors of the economy and requires targeted RDD&D in this decade to unlock its unique potential.

In today's economy, hydrogen is mainly used as an essential feedstock in a number of industries, most notably for crude oil refining and fertilizer production. However, the recent growing interest in hydrogen envisions a role for the technology that is in stark departure to its current scope and uses.

In analyses of deeply decarbonizing the national—and global--economy, hydrogen has emerged as a key climate solution, capable of simultaneously bolstering deep decarbonization, economic, and public health goals. The renewed interest in hydrogen is largely driven by the proliferating national commitments to achieving net-zero greenhouse gas emissions by midcentury. Those targets have driven countries to grapple with the necessity of finding clean energy solutions to substitute for fossil fuels in the most challenging sectors of the economy, including aviation, maritime shipping, and steelmaking.[5] Those applications require either a chemical feedstock to drive a chemical reaction – as in steelmaking – or dense forms of energy to propel heavy equipment like vessels, aircrafts, and large trucks across long distances. Electrification powered by carbon-free resources like wind and solar– the solution to decarbonize much of the economy – faces technical hurdles in those applications because it may either require an entirely new process to forgo chemical reactions which require a molecule – as in steelmaking-- or may require very large batteries to propel heavy equipment across long distances, creating potential weight and payload issues for freight trucks, aircrafts, and shipping vessels. In contrast, hydrogen —or a hydrogen-derived product, such as ammonia— offer many of the attributes that those challenging applications demand: it has high energy density by mass– nearly three times that of diesel or gasoline – and can act as a chemical feedstock in heavy industry applications. Hydrogen has thus emerged as a compelling potential tool for decarbonization and a complement to established climate solutions like electrification, efficiency, and renewable energy.

A growing evidence base of global and U.S.-focused analyses of pathways to net-zero greenhouse gas emissions by 2050, in line with the goal of keeping global temperature increase to no more than 1.5C, project a significant increase in the deployment of hydrogen across the economy relative to today. They further demonstrate the key role that hydrogen stands to play in supporting climate goals, albeit a more narrow role relative to established climate solutions like electrification, efficiency, and renewable energy. Figure 1 below compares the various projections of the scope of hydrogen in a decarbonized global economy, ranging between meeting 12 percent and 22 percent of final global energy demand. Similarly, independent studies investigating pathways towards a net-zero emissions U.S. economy by 2050 project

[5] Michael Liebreich, "Separating Hype from Hydrogen – Part Two: The Demand Side," Bloomberg New Energy Finance, October 2020, https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/ ; Simon Evans, John Gabbatiss, "In-Depth Q&A: Does the World Need Hydrogen to Solve Climate Change,", CarbonBrief, November 2020, https://www.carbonbrief.org/in-depth-qa-does-the-world-need-hydrogen-to-solve-climate-change

low or zero-carbon hydrogen production on the order of 40 to 135 million tonnes by mid-century—roughly 4 to 14 times the amount of today's U.S. hydrogen production. [6]

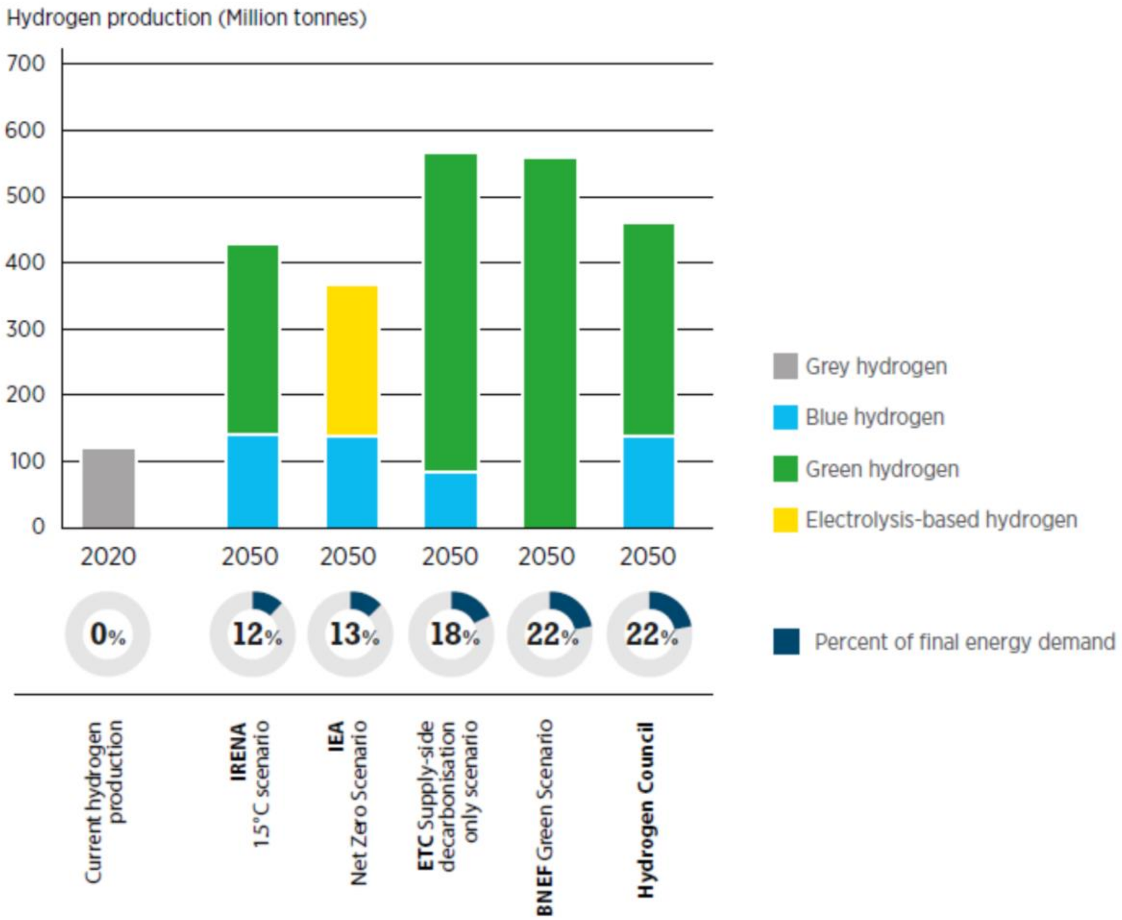

Figure 1: Estimates for Global Hydrogen Demand in 2050. Source: International Renewable Energy Agency.[7]

Notably, the various global and domestic analyses show that the bulk of hydrogen demand in 2030 and beyond is linked to applications that are not yet commercially mature and require focused RDD&D. Those include the use of hydrogen—or hydrogen-based fuels-- in steelmaking, maritime shipping, aviation, and as a seasonal form of electricity storage. Accordingly, hydrogen has become a central piece

[6] Princeton University, "Net-Zero America Project," December 2020, https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/; National Academies of Science, "Accelerating Decarbonization of the U.S. Energy System," 2021, https://www.nap.edu/download/25932# ; Energy Innovation, "A 1.5°C NDC for Climate Leadership by the United States," April 2021, https://energyinnovation.org/wp-content/uploads/2021/04/A-1.5-C-Pathway-to-Climate-Leadership-for-The-United-States_NDC-update-2.pdf ;

[7] International Renewable Energy Agency, "Geopolitics of the Energy Transformation The Hydrogen Factor," 2022, https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

of global innovation efforts, with proliferating initiatives and commitments aimed at catalyzing cost reductions and technology advancement. Those include the global Green Hydrogen Catapult initiative which targets significant cost reductions in green hydrogen production by 2026, the Breakthrough Catalyst program launched at COP26, which places hydrogen technology advancement at its core, and the First Movers Coalition and Mission Possible Partnership initiatives aiming to supercharge the advancement of solutions for the hardest-to-abate sectors in this decade.[8] It is therefore critical for the U.S. to bolster targeted hydrogen RDD&D in this decade to advance its deployment in the hardest-to-abate sectors of our economy and rise to the global challenge to cut emissions.

Hydrogen production and use is inefficient; outside of the narrow set of hard-to-abate sectors with limited alternatives, its untargeted deployment may stall climate progress and increase costs for Americans.

It is critical to keep in mind that while hydrogen is a versatile resource that can be theoretically used across a wide range of applications, it does not follow that harnessing its full versatility is beneficial for America. In fact, hydrogen is an energy intensive solution relative to alternatives like direct electrification, where those alternatives exist and are reliable.[9] The production, transport, storage and use of hydrogen typically involve a series of energy conversions that incur high efficiency losses. For instance, between 20 and 50 percent of energy is lost in the production of hydrogen. Additionally, hydrogen equipment and appliances, such as fuel cell cars and boilers, are generally much less efficient than electric alternatives.[10] (Figure 2) These losses make hydrogen a relatively costly option for many applications that can be feasibly served by more efficient solutions like direct electrification. Those performance limitations relative to other solutions have led to the European coinage "the champagne of the energy transition" in reference to hydrogen, to convey the importance of deploying it sparingly and in a targeted manner. In other words, hydrogen is best left for special occasions.

[8] Green Hydrogen Catapult, https://greenh2catapult.com/ ; The Breakthrough Catalyst Program, https://www.breakthroughenergy.org/scaling-innovation/catalyst ; The First Movers Coalition, https://www.state.gov/launching-the-first-movers-coalition-at-the-2021-un-climate-change-conference/ ; Mission Possible Partnership, https://missionpossiblepartnership.org/about/

[9] Direct electrification means replacing the direct use of fossil fuels with the direct use of electricity (e.g., switching from an oil-powered car to an electric car)

[10] Electric alternatives include battery electric cars and heat pumps.

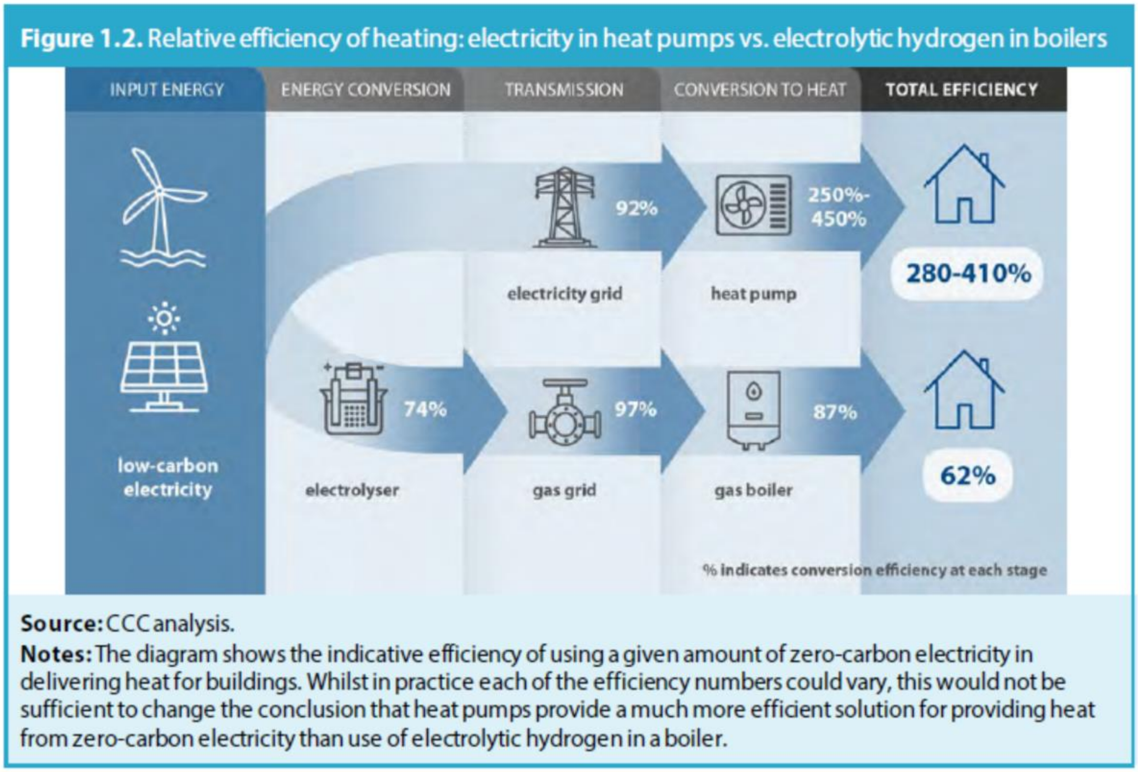

Figure 1.2. Relative efficiency of heating: electricity in heat pumps vs. electrolytic hydrogen in boilers

Source: CCC analysis.
Notes: The diagram shows the indicative efficiency of using a given amount of zero-carbon electricity in delivering heat for buildings. Whilst in practice each of the efficiency numbers could vary, this would not be sufficient to change the conclusion that heat pumps provide a much more efficient solution for providing heat from zero-carbon electricity than use of electrolytic hydrogen in a boiler.

Figure 2: Relative Efficiency of Heating Electricity in Heat Pumps vs. Electrolytic Hydrogen in Boilers- Pulled from the study conducted by the U.K. Climate Change Committee[11]

Buildings and passenger cars generally constitute two particularly poor widespread applications for hydrogen, with a strong evidence base supporting this notion.[12] Hydrogen boilers can be up to 4 times less efficient than electric heat pumps, and a number of studies estimate that it could require 5 to 6 times more renewable electricity to heat a home with hydrogen than to do so with an efficient heat pump.[13] Due to this wide efficiency differential, abounding independent studies conclude that hydrogen use for home heating is a markedly costly option relative to alternatives- notably heat pumps.[14] The European consumer

---

[11] UK Climate Change Committee, "Hydrogen in a low-carbon economy," November 2018, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/ . The CCC is an independent, non-departmental public body, formed to advise the UK and devolved Governments and Parliaments on tackling and preparing for climate change.

[12] It bears noting that there may be limited applications where hydrogen-heated buildings and hydrogen fuel cell passenger cars are the most feasible and cost-effective options. However, the niche status should be reflected in a lower rung of RD&D priorities.

[13] International Energy Agency, "Global Hydrogen Review 2021," (page 87), 2021, https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf ; Recharge News, "Why using clean hydrogen for heating will be too difficult, expensive and inefficient: report, " February 2021, https://www.rechargenews.com/markets/why-using-clean-hydrogen-for-heating-will-be-too-difficult-expensive-and-inefficient-report/2-1-960777 ; Jan Rosenow, "Heating homes with hydrogen: Are we being sold a pup?," 2021, https://www.raponline.org/blog/heating-homes-with-hydrogen-are-we-being-sold-a-pup/

[14] Jan Rosenow, Collection of Hydrogen Heating Studies, https://www.linkedin.com/posts/janrosenow_hydrogen-heating-studies-activity-6893841727841464320-SC6l/ ; International Council on Clean Transportation (ICCT), "Hydrogen for heating? Decarbonization options for households in the European Union in 2050," March 2021, https://theicct.org/wp-content/uploads/2021/06/Hydrogen-heating-eu-feb2021.pdf

organization BEUC estimates that electric heat pumps are the cheapest clean heating option for consumers and that hydrogen boilers will very unlikely outcompete them. The BEUC study finds that the annual costs of heating a home with a hydrogen boiler can be as high as 60 to 140 percent more than using a heat pump, depending on the country evaluated.[15] Further, a diverse group of European stakeholders have urged their governments to steer clear of pursuing hydrogen as a widespread solution in buildings on account of those critical limitations.[16]

Similarly, it could require up to 3 times more electricity to power a hydrogen fuel cell passenger car than a battery electric car.[17] This stark efficiency differential has led a number of automakers and experts to submit that hydrogen is better suited for heavy, long-range trucks than passenger cars.[18] For instance, the DOE recognizes that hydrogen fuel cell vehicles have a higher value proposition in medium and heavy duty trucks- as opposed to passenger cars- where they may offer more range and shorter refueling times relative to battery electric vehicles.[19]

Hydrogen's efficiency challenges reveal the importance of targeting the technology to those applications where it is best suited for the task to avoid saddling Americans with unnecessary costs linked to wasteful solutions. A study by the European Climate Foundation illustrates the pressure that an untargeted deployment of hydrogen may exert on the scale of energy infrastructure buildout, on account of its inefficiencies. Researchers found that while the widespread deployment of hydrogen in buildings and on-road transportation may deliver a degree of savings on electric network infrastructure –relative to a case where homes and vehicles are mostly electrified-- those savings would be much smaller than the increased costs in renewable projects, electrolyzers, and storage facilities to produce and store green hydrogen, and in the upkeep and refurbishing of the gas network to transport the hydrogen (Figure 3). This energy infrastructure "supersizing", as the study coins it, sharply increases energy system costs and household energy bills relative to high electrification cases.

---

[15] BEUC, The European Consumer Organisation, "Goodbye gas: heat pumps will be the cheapest green heating option for consumers," November 2021, https://www.beuc.eu/publications/goodbye-gas-heat-pumps-will-be-cheapest-green-heating-option-consumers/html

[16] Euractiv, "Avoid hydrogen for heating homes, urges energy efficiency coalition," January 2021, https://www.euractiv.com/section/energy/news/avoid-hydrogen-for-heating-homes-urges-energy-efficiency-coalition/

[17] Transport & Environment, "Electrofuels? Yes, we can … if we're efficient," December 2020, https://www.transportenvironment.org/wp-content/uploads/2020/12/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf ; Princeton University, *Net-Zero America Project*, December 2020, https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/ ;Lexology, "Battery electric vs hydrogen — which is the future for electric vehicles?," September 2021, https://www.lexology.com/library/detail.aspx?g=1bf1cbf0-ac2f-4b39-a3de-2df77a9a515e#:~:text=The%20fuel%20cell%20process%20of,than%20three%20times%20as%20much.

[18] Green Car Reports, "Battery-electric car or hydrogen fuel cell? VW lays out why one is the winner," April 2020, https://www.greencarreports.com/news/1127660_battery-electric-or-hydrogen-fuel-cell-vw-lays-out-why-one-is-the-winner#:~:text=Put%20simply%2C%20batteries%20are%20far,chemical%20reaction%20in%20the%20cells.

[19] Argonne National Laboratory, "Assessment of Potential Future Demands for Hydrogen in the United States," October 2020, https://greet.es.anl.gov/publication-us_future_h2

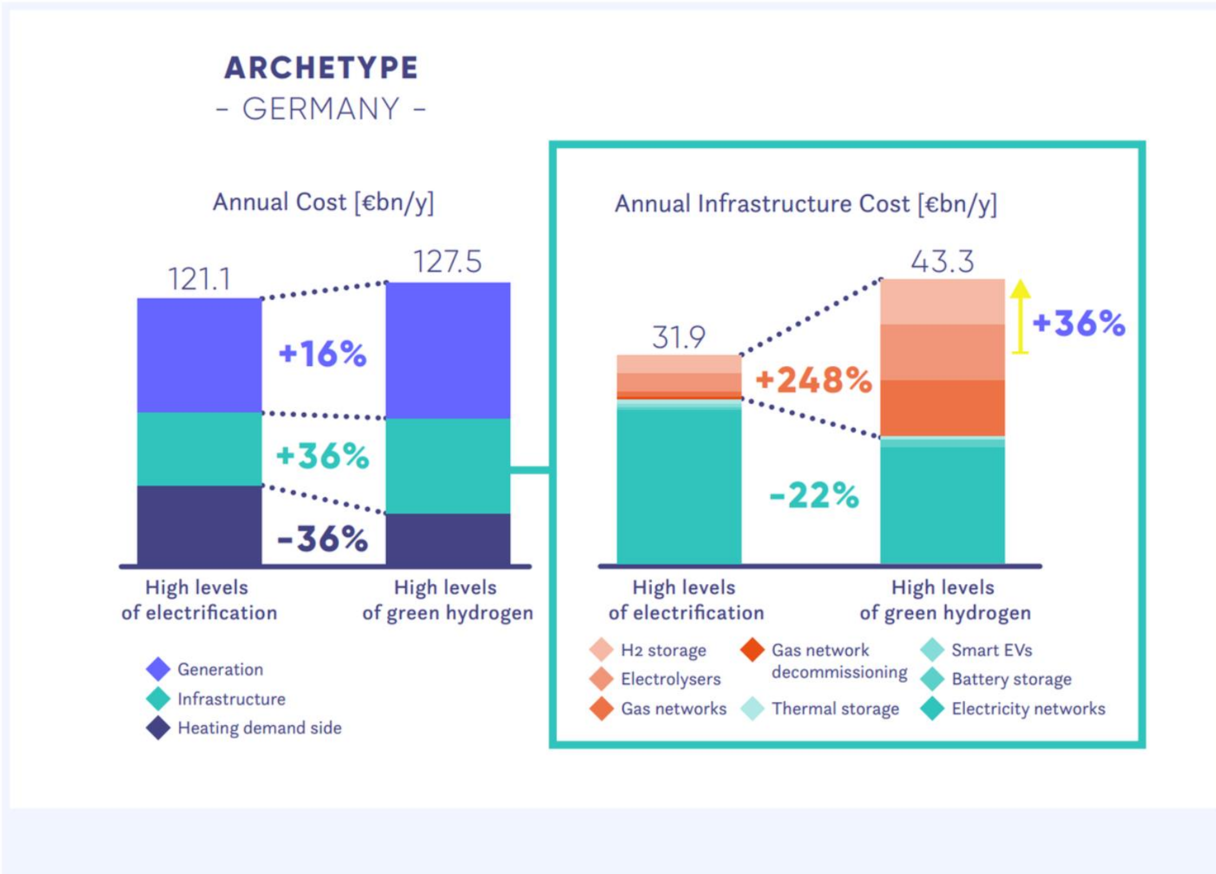

Figure 3: Infrastructure investments and associated costs, Germany example. Source: European Climate Foundation.[20] *The high hydrogen case reflects more expanded hydrogen use and moderate electrification in both buildings and transportation. The study estimates a net 36 percent increase in infrastructure costs in the high hydrogen case. The 22 percent reduction in electricity network investments is largely outweighed by the 248 percent increase in expenses on electrolyzers, storage facilities, and refurbishing gas networks. The study also estimates a 16 percent increase in investments in renewable energy projects in the high hydrogen case.*

Accordingly, there is now strong consensus around the ranking of hydrogen end-uses based on efficiency and cost-effectiveness relative to other solutions (Figure 4).

[20] European Climate Foundation, "Towards Fossil-Free Energy in 2050," 2019. https://europeanclimate.org/wp-content/uploads/2019/03/Towards-Fossil-Free-Energy-in-2050.pdf

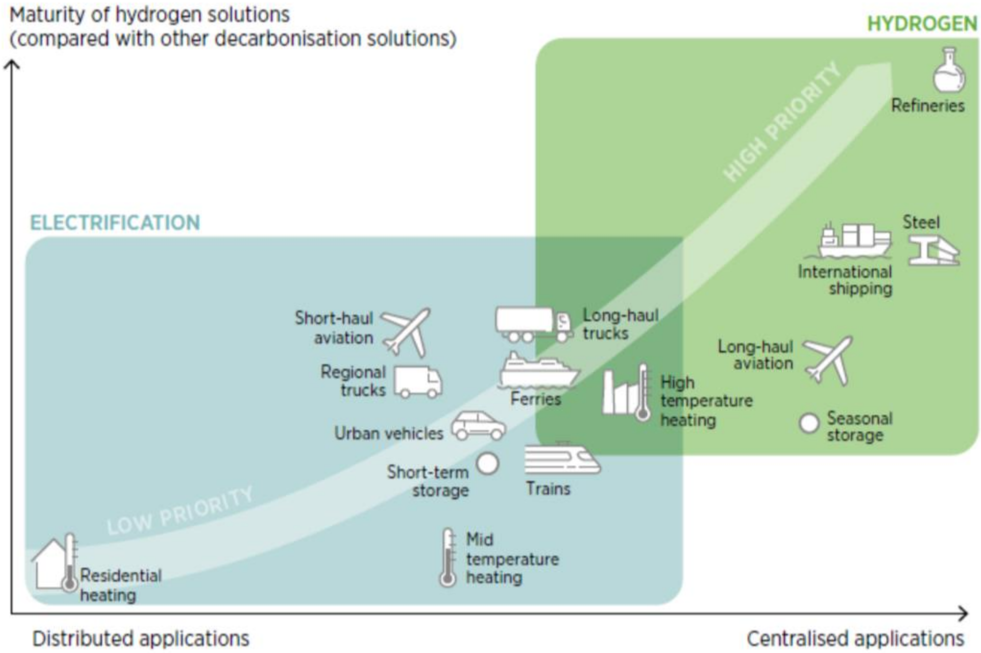

Figure 4: Clean hydrogen policy priorities. Source: International Renewable Energy Agency.[21] *Refineries are labeled as a "high priority" application given that they already use large amounts of hydrogen; replacing that highly polluting hydrogen with cleaner forms is thereby a priority. It also bears noting that this figure is added for illustration purposes and does not necessarily reflect NRDC's views on the most appropriate ranking of applications.*

In order to identify its highest value applications and prioritize DOE RDD&D efforts accordingly, hydrogen should not be investigated in an atomized fashion, but rather in conjunction with other climate solutions like direct electrification and energy efficiency in efficient pathways to net-zero emissions by 2050. The DOE's Hydrogen and Fuel Cells Technologies Office should be directed to periodically conduct a similar holistic assessment to tease out hydrogen's highest value applications, in collaboration with other relevant technology offices (this is further discussed in the Recommendations section).

RDD&D to advance zero-emission, green hydrogen should be the only pathway prioritized relative to alternatives owing to its cost-effectiveness, unique benefits, and higher standards of climate and public health integrity.

More than 95 percent of all hydrogen used in the U.S. today is produced from methane gas in a process called steam methane reformation (SMR).[22] This is now generally referred to as "gray" hydrogen. In this process, methane gas is both used as the source of hydrogen and combusted at high temperatures to provide the energy that drives the process. SMR is a major source of climate pollution in the U.S. as well

[21] International Renewable Energy Agency, "Geopolitics of the Energy Transformation The Hydrogen Factor," 2022, https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen
[22] U.S. Department of Energy, *Fact of the Month May 2018: 10 Million Metric Tons of Hydrogen Produced Annually in the United States*, May 2018, https://www.energy.gov/eere/fuelcells/fact-month-may-2018-10-million-metric-tons-hydrogen-produced-annually-united-states

as large amounts of health-damaging air pollutants such as nitrogen oxides, volatile organic compounds and particulate matter.[23] The use of hydrogen as a tool for deep decarbonization is therefore premised on eliminating carbon emissions arising from its production process. To date, various alternatives to gray hydrogen have been proposed. Those receiving the most attention and interest include electrolysis, gas-based pathways with carbon capture, and biomass-based pathways.

In the electrolysis process, water is used as the hydrogen feedstock, rather than methane gas. Electricity is used to split water into its constituents, hydrogen, and oxygen, and to the extent that the electricity is generated by a renewable resource such as wind, solar or hydro, the hydrogen is zero-carbon and air pollution-free. Hydrogen produced in this manner is often referred to as "green hydrogen." Alternatively, the gas-based SMR process can be equipped with carbon capture to produce "blue hydrogen."[24,25] Biomass-based production pathways constitute a third category--which remains in pre-commercial stage--whereby dry biomass resources can be gasified to produce hydrogen, and to the extent that the carbon produced in the process is captured, the hydrogen can potentially have a negative emissions profile. Those production pathways vary materially in cost projections, scalability, and climate and public health impacts. Zero emissions, green hydrogen offers the most compelling value proposition relative to other resources and would enable Americans to capture the full range of benefits that hydrogen offers.

a. Green Hydrogen Offers the Largest Potential for Cost Reductions

Today, green hydrogen is more expensive than both gray and blue hydrogen. However, relative economics are poised to markedly evolve over the next decade and beyond in favor of green hydrogen. It offers the largest potential for cost reductions (Figure 5). This is owing to the projected plummeting in the costs of electrolyzers--the equipment where the water splitting occurs-- driven by increased deployment and virtuous learning effects, as well as projected further cost reductions in renewable electricity. Owing to this potential, a number of expert projections, including those by Bloomberg New Energy Finance (BNEF), the International Renewable Energy Agency, McKinsey & Company and others, estimate that green hydrogen may start competing with gray hydrogen by as early as 2030 under favorable conditions and outcompete it before 2050, even absent climate policy to bolster its economics relative to fossil-based resources.[26] These green hydrogen cost reductions, however, are preconditioned on meaningful policy and deployment-driven support; this highlights the importance of strongly channeling public and private

---

[23] Pingping Sun, Ben Young, Amgad Elgowainy, Zifeng Lu, Michael Wang, Ben Morelli, and Troy Hawkins, *Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities*, ACS Publications, April 2018, https://pubs.acs.org/doi/10.1021/acs.est.8b06197

[24] Blue hydrogen can also be produced via Autothermal Reformation (ATR), a process not yet commercially mature. ATR can achieve higher carbon capture rates than a "regular" SMR plant coupled with carbon capture but would unlikely achieve 100% carbon capture.

[25] This color-based nomenclature is an oversimplification of the various technologies. Hydrogen production pathways can be far more complicated in terms of associated greenhouse gas emissions and public health impacts, and hydrogen production is thereby more of a gradient than discrete colors (as coined by Rhodium Group in its note "Clean Hydrogen: A Versatile Tool for Decarbonization"). I resort to the simplistic color scheme in this testimony both as a shorthand and to plug into today's deliberations on hydrogen.

[26] BNEF, "Blue Hydrogen Could Become the White Elephant on Your Balance Sheet," December 2021, https://www.bloomberg.com/news/articles/2021-12-16/market-risks-white-elephant-in-push-for-blue-hydrogen-bnef-view; IRENA, "Making Green Hydrogen a Cost-Competitive Climate Solution," December 2020, https://www.irena.org/newsroom/pressreleases/2020/Dec/Making-Green-Hydrogen-a-Cost-Competitive-Climate-Solution ; Hydrogen Council, McKinsey & Company, "Hydrogen Insights 2021," 2021, https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

support towards green hydrogen development, relative to other sources. Efforts that hold promise include DOE's Hydrogen Shot initiative– which targets an 80 percent reduction in the costs of clean hydrogen by 2030– and the global Green Hydrogen Catapult initiative which targets green hydrogen costs below $2 per kilogram by 2026 (the scale and speed of possible green hydrogen cost reductions have exceeded expectations, prompting the Catapult to nearly double electrolyzer deployment ambition by 2027– from a 25 gigawatt electrolyzer commitment announced in 2020 to a 45 gigawatt commitment announced in 2021).[27]

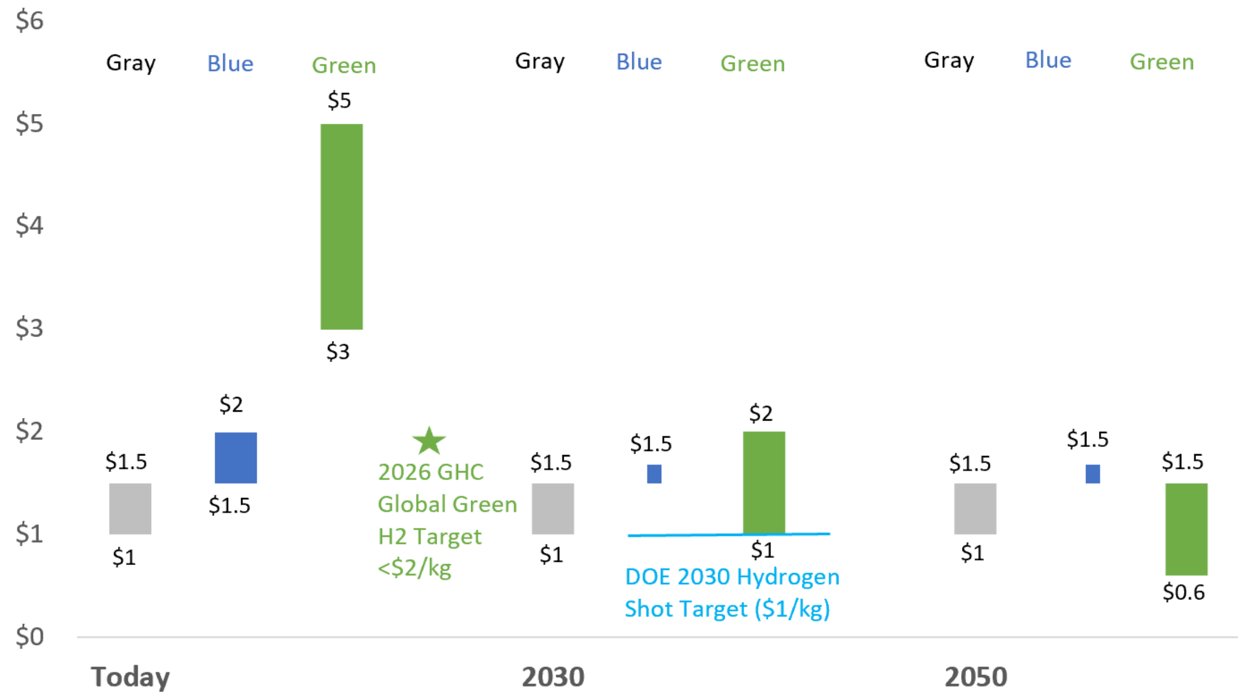

Figure 5: Estimates of U.S. Hydrogen Production Costs, Current and Projected ($ per kilogram of hydrogen produced). GHC= Green Hydrogen Catapult. Green hydrogen cost reductions assume steady reductions in electrolyzer costs and access to low-cost renewable energy. Gray and blue hydrogen costs assume continued low gas prices and no climate policy constraints, such that their 2050 costs are likely underestimated. Data sourced from and built on various resources, including U.S. DOE, BNEF, Resources for the Future, McKinsey & Company, and Rhodium Group[28].

[27] The Green Hydrogen Catapult is a global initiative launched in 2020 with the convening support of the UN's High-Level Climate Action Champions and Rocky Mountain Institute, with the goal of driving significant green hydrogen scale-up by 2026 and production costs below $2 per kilogram, https://greenh2catapult.com/

[28] National Renewable Energy Laboratory, The Technical and Economic Potential of the H2@Scale Concept within the United States, October 2020, https://www.nrel.gov/docs/fy21osti/77610.pdf; BloombergNEF, *'Green' Hydrogen to Outcompete 'Blue' Everywhere by 203*0, May 2021, https://about.bnef.com/blog/green-hydrogen-to-outcompete-blue-everywhere-by-2030/ ; US Department of Energy, *Secretary Granholm Launches Hydrogen Energy Earthshot to Accelerate Breakthroughs Toward a Net-Zero Economy*; Jay Bartlett and Alan Krupnick, *Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions* , December 2020, Resources for the Future , https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/; Galen Hiltbrand, Whitney Herndon, Eric G. O'Rear, and John Larsen, September 2021, Clean Hydrogen: A Versatile Tool for

In contrast, gas-based pathways equipped with carbon capture inherently offer fewer cost reduction opportunities as the process will always remain more onerous, and therefore likely more costly, than uncontrolled gas-based hydrogen (gray hydrogen) on account of the costs and infrastructure involved in the capture, transport, and storage of the carbon. In addition, the SMR technology is largely mature—offering fewer opportunities for cost reductions—even if the carbon capture technology is not. In fact, BNEF estimates that with aggressive cost reductions--in line with those targeted by the DOE's Hydrogen Shot– green hydrogen may outcompete blue hydrogen in many places in the U.S. by as early as 2030, with economics decidedly in favor of green hydrogen after 2030 (Figure 4 above). BNEF projects favorable economics for green hydrogen relative to blue hydrogen even in Middle Eastern petrostates, where gas is abundant and low cost (Figure 6). BNEF further notes: "Imagine you have a billion-dollar asset, but its market is permanently undercut by a new and cheaper technology. Such could be the fate of "blue" hydrogen investors […]. This technology is set to be permanently undercut by cheaper "green" hydrogen from renewables, except in markets with generous support". DOE's own analysis corroborates this trend, projecting a predominantly green hydrogen pathway in the U.S. should cost reductions in electrolyzers and access to cheap renewable electricity materialize (Figure 7).

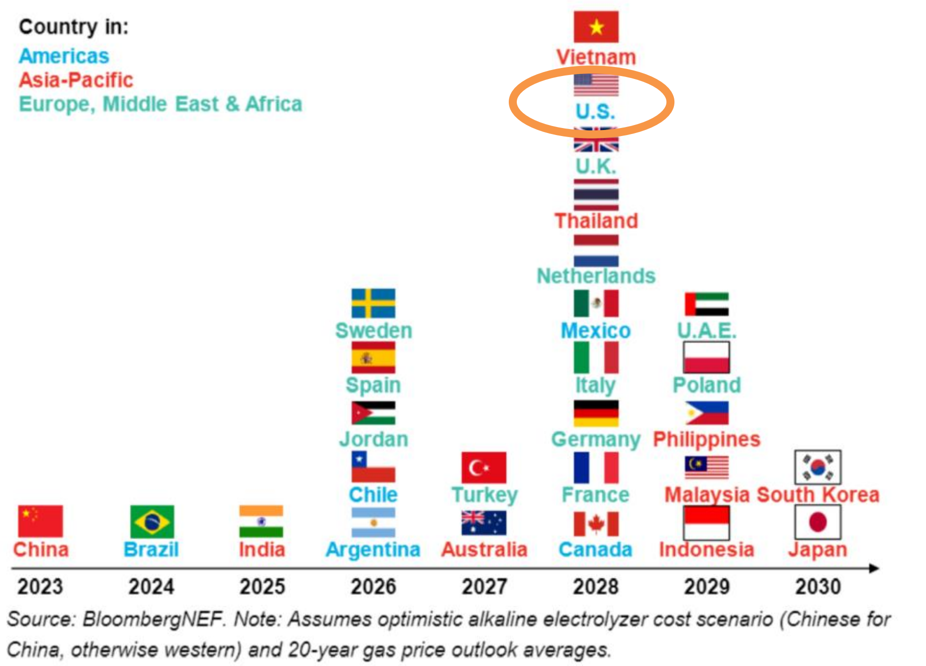

Figure 6: Year When Hydrogen from New Green Plants Undercuts New Blue Production. Source:BNEF[29]

Decarbonization, Rhodium Group, https://rhg.com/research/clean-hydrogen-decarbonization/ ; Hydrogen Council, McKinsey & Company, "Hydrogen Insights 2021," 2021, https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

[29] Bloomberg New Energy Finance, "Hydrogen: 10 Predictions for 2022," January 2022

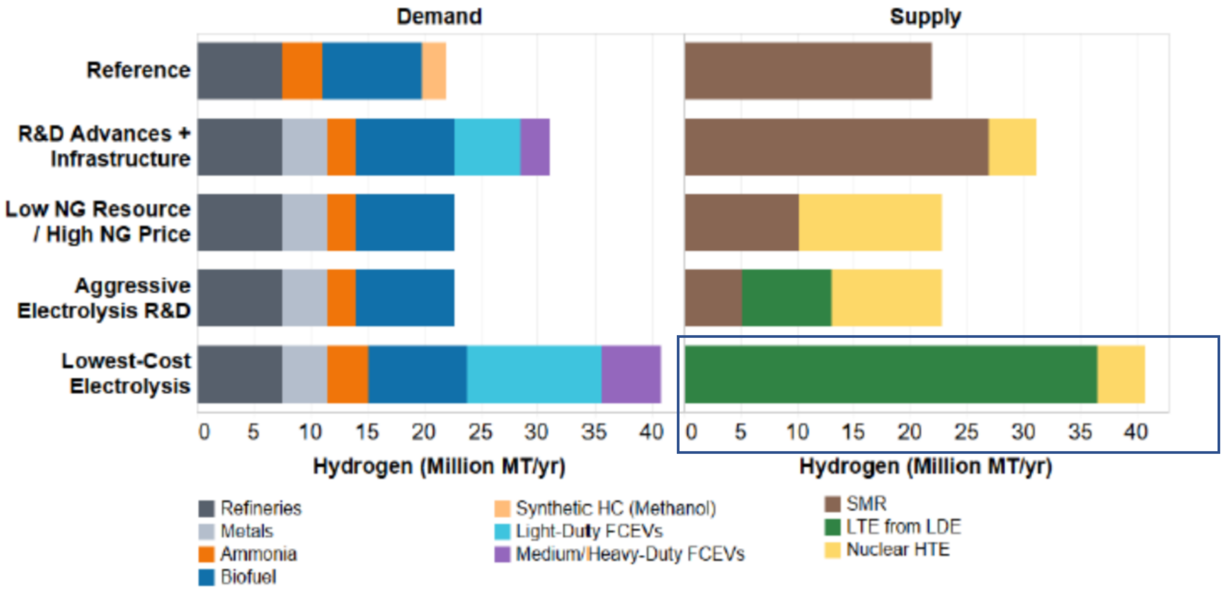

Figure 7: Hydrogen Supply Sources and Demand Applications. Source: U.S. DOE.[30] The Lowest-Cost Electrolysis scenario reflects electrolyzer cost reductions in line with those projected to be potentially delivered by current domestic and global policies, in addition to an assumption that electricity markets would allow electrolyzers to monetize the energy and grid services that they can provide. The "Reference", "R&D Advances + Infrastructure" and "Low NG Resource/High NG Price" scenarios assume electrolyzer costs in line with today's high costs and are therefore not relevant to the discussion at hand.

It bears noting that some experts have come out in criticism of projections that green hydrogen may outcompete blue hydrogen by 2030. But those criticisms tend to overlook the fact that medium and long-term cost projections are the more important metric, as opposed to near-term cost comparisons. This is due to the fact hydrogen investments are generally long-lived assets, with lifetimes exceeding 20 years, and as good investors, we must therefore prioritize investments that offer the better medium and long-term economic outlook, as opposed to a more favorable outlook solely over the next 5 or so years. Plus, the bulk of new hydrogen demand for decarbonization will likely occur after 2030, underscoring the need to lay more emphasis on the medium to long-term cost projections. As noted above, the economics of green hydrogen in the medium to long-term are decidedly more favorable than blue hydrogen, further highlighting that green hydrogen is a more sound investment for both near-term deployment and as an area of focus for RD&D.

Further, blue hydrogen projects are inherently more risky investments relative to green hydrogen given their exposure to the volatility of gas prices, which may be heightened by climate-related regulations (as I discuss in b. below, blue hydrogen's lesser compatibility with net-zero goals constitutes another layer of risk for investors).[31]

[30] National Renewable Energy Laboratory, "The Technical and Economic Potential of the H2@Scale Concept within the United States," 2020, https://www.nrel.gov/docs/fy21osti/77610.pdf

[31] The ongoing European energy crisis offers a useful illustration of the price risks to which gas-based assets are exposed.

b. Green hydrogen is the resource most strictly aligned with U.S. long-term climate targets and the goal of protecting the health of our communities; but safeguards are necessary

While blue and electrolytic hydrogen can emit less emissions than today's gray hydrogen, they may still be linked to dangerous climate pollution absent safeguards (Figure 8). In fact, if the electrolysis process is powered by today's average U.S. electricity grid- as opposed to clean electricity- the resulting hydrogen can have worse emissions than gray hydrogen.[32] Similarly, unchecked methane leakage in the case of blue hydrogen (further discussed below) could pose a serious climate threat; it would also run counter to the clarion call issued by climate scientists who cite rapidly slashing methane emissions in this decade as the most powerful tool to curb the alarming rate of climate warming. It is therefore imperative that DOE impose a strict hydrogen production standard based on the lifecycle carbon intensity of production on all its hydrogen demonstration and deployment investments. However, while a rigorous carbon intensity threshold is critical, it is not sufficient as it does not capture non-greenhouse gas emissions factors, including the compatibility with long-term climate goals and public health impacts of the various hydrogen resources.

Green hydrogen powered by verifiably 100 percent renewable electricity is the resource most strictly aligned with the U.S. and global long-term climate goals owing to its zero-carbon status. However, safeguards are critical to ensure that the electricity powering the process is clean, or else, electrolytic hydrogen may emit more carbon relative to other hydrogen sources.

In contrast, while blue hydrogen can achieve low-carbon status, it is unlikely to achieve zero-carbon status and may be linked to detrimental health impacts (as noted below). It should therefore not be considered "clean". First, the efficiency of carbon capture has not been demonstrated beyond 90 to 95 percent, so the SMR process will likely result in a certain amount of residual emissions. Second, there will be methane emissions from leakage during the production of methane gas and its transport to the SMR facility.[33] There remain important challenges with the rigorous measurement and reporting of methane leakage in addition to uncertainties concerning the potential for leakage to be reduced to near zero. Investments in blue hydrogen thereby extend the present challenge of methane leakage, and absent strong regulations to measure and reduce leaks, blue hydrogen projects may have detrimental climate impacts.[34] Blue hydrogen is therefore less compatible with a pathway to net-zero greenhouse gas emissions – even assuming low levels of methane leakage- and constitutes a riskier investment than green hydrogen, with a potential for asset stranding.[35] This shortcoming is manifested in reputable and independent studies showing a much lesser amount of blue hydrogen deployment in most pathways to net-zero relative to other clean hydrogen sources.[36]

---

[32] However, emissions linked to electrolysis-based hydrogen will drop in lock-step with the decarbonization of the electricity grid.

[33] Dennis Y.C. Leunga, Giorgio Caramannab M. Mercedes, Maroto-Valerb, An overview of current status of carbon dioxide capture and storage technologies, November 2014, Science Direct, https://www.sciencedirect.com/science/article/pii/S1364032114005450

[34] Euractiv, "German government disavows blue hydrogen," January 2022, https://www.euractiv.com/section/energy/news/avoid-hydrogen-for-heating-homes-urges-energy-efficiency-coalition/

[35] Stranded assets refer to assets that are no longer financially viable, prior to the end of their economic life, typically as a result of a change in the market and/or regulatory environment.

[36] James H. Williams, Ryan A. Jones, Ben Haley, Gabe Kwok, Jeremy Hargreaves, Jamil Farbes, Margaret S. Torn , Carbon-Neutral Pathways for the United States, January 2021,

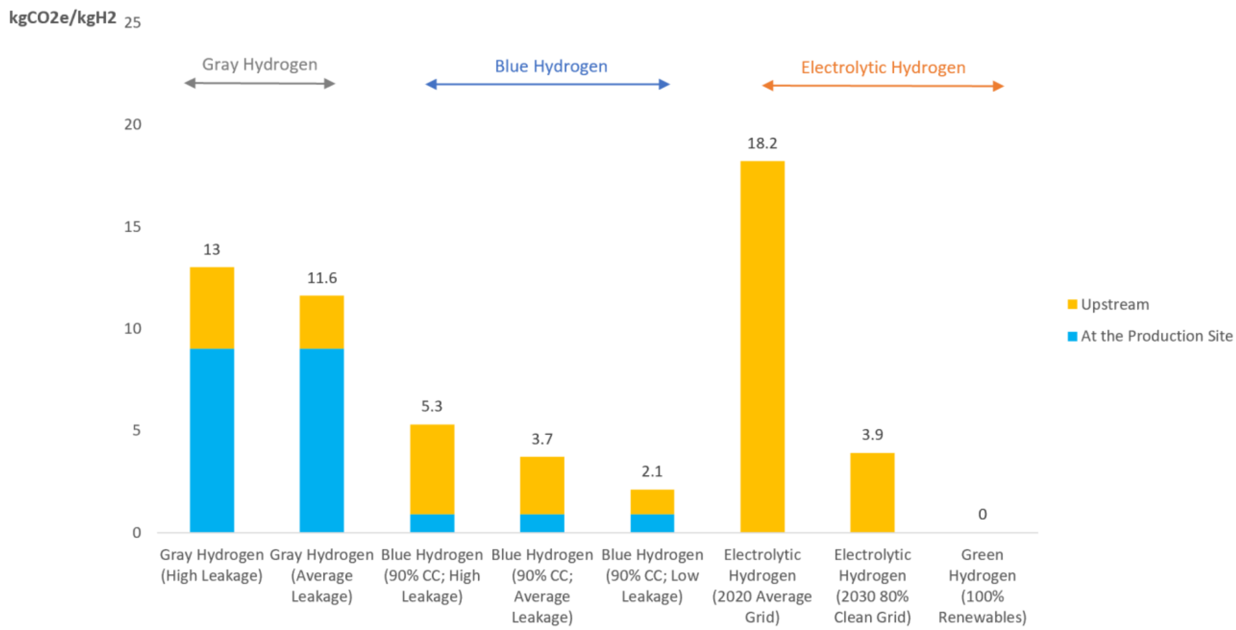

Figure 8: Estimates of the Carbon Intensity of Various Hydrogen Production Pathways (kilograms of carbon-dioxide equivalent per kilogram of hydrogen produced). The carbon intensity encompasses greenhouse gas emissions arising both at the site of production and upstream of production. CC = carbon capture; High methane leakage assumes a 3.7 percent rate, national average assumes a 2.3 percent rate, and low leakage assumes a 1 percent rate. Estimates lowball blue hydrogen emissions as they assume 1) that zero-emissions electricity powers the carbon capture process; and 2) the 100-year global warming potential of methane, which significantly reduces the magnitude of upstream methane emissions (in carbon-dioxide equivalent terms) relative to the 20-year estimate. The carbon intensity of an 80 percent clean grid by 2030 reflects analysis by the Analysis Group which examines pathways towards achieving President Biden's goal of a 100 percent clean power sector by 2035.[37]

Additionally, and importantly, green hydrogen is more conducive to protecting the health of our communities. Blue hydrogen involves the extraction, delivery and use of gas, which can dangerously pollute people's air and water and negatively impact the health of our communities.[38]

---

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284 ; Princeton University, "Net-Zero America Project," December 2020, https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/; Sustainable Development Solutions Network, "America's Zero Carbon Action Plan," November 2020, https://www.unsdsn.org/Zero-Carbon-Action-Plan

[37] Analysis Group, "Economic Impact of a Clean Electricity Payment Program," September 2021, https://www.analysisgroup.com/globalassets/insights/publishing/2021-Economic-Impact-of-a-Clean-Electricity-Payment-Program.pdf

[38] The Union of Concerned Scientists, "Unveiling the Public Health Burden of Natural Gas," 2021, https://blog.ucsusa.org/science-blogger/public-health-burden-natural-gas/

c. Green hydrogen can uniquely bolster the resilience and affordability of a highly renewable electric grid

Zero-carbon, renewables-based hydrogen could also bolster the reliability and cost-effectiveness of a highly clean electric grid. A strong evidence base shows a wind and solar- dominated electricity system is a highly effective mechanism for achieving economy-wide decarbonization.[39] As the share of renewables on the grid continues to increase, green hydrogen may be one of the few technologies that can help the grid ride through the variable nature of wind and solar generation. First, green hydrogen is a promising form of seasonal electricity storage. It can be produced when there is excess renewable energy, especially in the fall and spring, stored for several months and then used to generate electricity when wind and solar output is low. By helping the electricity grid ride through the seasonal differences in renewables performance, green hydrogen could meaningfully bolster the reliability and resiliency of a very high renewable grid. Additionally, by making use of excess renewable electricity that would otherwise be wasted, green hydrogen could lower costs for consumers given that renewable power projects would need to recoup less of their investment from the non-hydrogen electricity customers. DOE recognizes that those services will become increasingly valuable as the electric grid incorporates higher levels of renewable energy, and as such, DOE explains that electrolysis technology "has inherent advantages over SMR". [40]

d. Biomass-based hydrogen faces scalability challenges

While biomass-based hydrogen is garnering some interest owing to its potential negative emissions profile, a number of factors beset its widespread deployment. Biomass resources pose complex sustainability challenges, as a range of feedstocks may generate a net increase in carbon emissions and therefore result in dangerous climate impacts.[41] It is therefore critical that all types of biomass-based resources be subject to rigorous accounting of their climate impacts.[42] A robust evidence base demonstrates that the supply of *truly sustainable, low carbon* biomass is limited. Further, it is expected that the limited supply will be subject to competition arising from a range of hard-to-abate applications with limited alternatives for decarbonization, including heavy industry applications and aviation.[43] Those feedstock limitations bear on the scalability of biomass-based hydrogen. In fact, and on account of the limited potential biomass availability for hydrogen production, DOE only considers biomass-based

---

[39] James H. Williams, Ryan A. Jones, Ben Haley, Gabe Kwok, Jeremy Hargreaves, Jamil Farbes, Margaret S. Torn , Carbon-Neutral Pathways for the United States, January 2021, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284 ; Princeton University, *Net-Zero America Project*, December 2020, https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/; Sustainable Development Solutions Network, *America's Zero Carbon Action Plan*, November 2020, https://www.unsdsn.org/Zero-Carbon-Action-Plan

[40] National Renewable Energy Laboratory, The Technical and Economic Potential of the H2@Scale Concept within the United States, October 2020, https://www.nrel.gov/docs/fy21osti/77610.pdf

[41] Thomas Buchholz, *et al*., "A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies," GCB Bioenergy, (2016). https://doi.org/10.1111/gcbb.12245; Bentsen, N.S., "Carbon debt and payback time – Lost in the forest?," Renew. Sustain. Energy Rev., (2017). doi:10.1016/j.rser.2017.02.004

[42] Alessandro Jacopo, et al., "Carbon accounting of forest bioenergy - conclusions and recommendations from a critical literature review," Joint Research Centre, European Commission, 2014, http://publications.jrc.ec.europa.eu/repository/bitstream/JRC70663/eur25354en_online.pdf

[43] Energy Transitions Commission, "Bioresources Within a Net-Zero Emissions Economy," July 2021. https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf

hydrogen as a resource in a side scenario in a recent analysis, leaving it out of its central hydrogen economic potential scenarios.[44]

e. Relative employment impacts of the various hydrogen resources remain uncertain

The relative employment impacts of the various production pathways are not well understood, on account of the emerging and/or pre-commercial status of some of the technologies and their lack of widespread deployment. However, emerging assessments indicate that green hydrogen *may* offer larger potential for job creation relative to blue hydrogen, linked to both the construction, materials, and equipment required to build the green hydrogen facility and the renewable energy projects that power the electrolyzers.[45] A better understanding of the relative employment impacts will likely be achieved as hydrogen deployment ramps up in the U.S. and globally.

For all of these reasons – larger potential for enduring cost reductions, better compatibility with long-term climate goals, lesser harm for public health, and unique grid reliability benefits – DOE should prioritize green hydrogen in its RDD&D efforts to ensure wise stewardship of taxpayers' dollars. Further, where blue or biomass-based hydrogen investment does occur – such as in the Infrastructure Investment and Jobs Act (IIJA) – DOE should be directed to implement robust safeguards on account of their climate and public health risks; notably, DOE should apply a rigorous and ambitious carbon intensity standard for its investments in hydrogen production, so as to minimize detrimental climate and public health impacts (I discuss this in greater detail in the Recommendations section below).[46]

Hydrogen transport and delivery infrastructure warrants caution and further assessment

Hydrogen is a fundamentally different gas relative to methane gas, and when it comes to transporting it, requires either a full conversion of existing gas pipelines to accommodate large shares of hydrogen or entirely new hydrogen-compatible pipelines. DOE's hydrogen RD&D program currently focuses on advancing various ways to transport hydrogen, including both new hydrogen pipelines and converted gas pipelines (as well as other alternatives)[47]. Recent legislative proposals – including the hydrogen title in IIJA- direct the Department to examine the opportunities and barriers to building pipeline infrastructure and converting existing gas pipelines.

However, the current RD&D and legislative landscape fail to recognize critical gaps and risks that warrant further investigation. Hydrogen pipelines entail large investments in long-lived assets that require a clear business case in the near, mid, and long-term. This is largely lacking today, due to the nascency of

---

[44] National Renewable Energy Laboratory, "The Technical and Economic Potential of the H2@Scale Concept within the United States," 2020, https://www.nrel.gov/docs/fy21osti/77610.pdf

[45] Rhodium Group, "Clean Hydrogen: A Versatile Tool for Decarbonization," September 2021, https://rhg.com/research/clean-hydrogen-decarbonization/ ; Energy Monitor, "Hydrogen tests climate policymakers with its job potential," October 2021, https://www.energymonitor.ai/tech/hydrogen/hydrogen-tests-climate-policymakers-with-its-job-potential

[46] Infrastructure Investment and Jobs Act, as passed in November 2021. https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf

[47] Other alternatives include transport by truck and in the form of chemical carriers.

the hydrogen market as a decarbonization tool, and such investments thereby remain fairly premature--a case of putting the cart before the horse. In particular, there remain many uncertainties in relation to the extent of hydrogen's future role in the economy and the mid and long-term landscape of its supply and demand centers.[48] There also remains significant uncertainties concerning the tradeoffs between a more decentralized hydrogen system--less reliant on transport infrastructure owing to a closer proximity between supply and demand centers--and a more centralized system. A near-term leap into hydrogen transport infrastructure thereby risks imposing unnecessary costs on Americans and creating stranded assets.[49] Recognizing these risks, an increasing number of stakeholders across Europe are now arguing for holding off on large-scale investments in hydrogen pipelines until a clear demand pattern has emerged.[50] In a similar vein, other groups have proposed to future-proof near-term investments in hydrogen pipelines or repurposing efforts by focusing on a small-scale buildout of pipelines around what are expected to be secure long-term hydrogen demand centers – for example, steel manufacturing clusters- and gradually expanding networks if and when an economic and climate case for such an expansion emerges.[51] Experts also agree that an expedient way of catalyzing hydrogen scale-up in the near to medium-term is by developing hydrogen clusters – a set of hydrogen producers and users in close proximity– that would require no to little transport infrastructure.[52]

Additionally, there remain important knowledge gaps concerning the climate impacts of hydrogen leakage arising from transport and storage infrastructure, including pipelines, warranting caution and further study (I discuss this in the following section).

Considering the risks and uncertainties, it is judicious for the DOE to target the advancement of green hydrogen use in clusters--or a cohort of hydrogen suppliers and users situated in close proximity such that widespread hydrogen transport infrastructure is unnecessary. In parallel, the DOE should conduct transparent and periodic assessments investigating where new hydrogen pipeline networks or conversion measures would be secure investments – i.e., servicing hydrogen demand centers with a high likelihood of materializing-- and that are consistent with the goal of achieving net-zero emissions by 2050 (in line with the European proposal noted earlier).

---

[48] Camilla Naschert, Hydrogen lobbying sets wrong priorities, says BloombergNEF founder, S&P Global, May 2021, https://platform.marketintelligence.spglobal.com/web/client?auth=inherit#news/article?KeyProductLinkType=2&id=64534120 ; Evans et. al, *In-Depth Q&A: Does the World Need Hydrogen to Solve Climate Change*, CarbonBrief

[49] Stranded assets refer to assets that are no longer financially viable, prior to the end of their economic life, typically as a result of a change in the market and/or regulatory environment.

[50] Camilla Naschert, Hydrogen lobbying sets wrong priorities, says BloombergNEF founder, S&P Global

[51] Agora Energiewende, *No-Regret Hydrogen*, February 2021, https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf; Climate Action Network Europe, *CAN Europe's Position on Hydrogen*, February 2021, https://caneurope.org/content/uploads/2021/02/CAN-Europe_position-on-hydrogen_February-2021.pdf

[52] Hydrogen Council, McKinsey & Company, "Hydrogen Insights 2021," 2021, https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

The climate and public health impacts of some hydrogen transport and use patterns remain uncertain, warranting further investigation.

Applications that involve hydrogen combustion--such as turbines to generate electricity and boilers to generate heat--carry air pollution risks. While burning hydrogen produces no carbon dioxide, it can generate high levels of nitrogen oxides--a health-damaging criteria air pollutant--and the extent to which those emissions could be mitigated remains to some degree uncertain. In fact, due to hydrogen's chemical characteristics, blends of hydrogen and methane may even yield higher emissions of nitrogen oxides than methane alone, if not managed.[53] The DOE recognizes this issue and argues for the need to develop new controls to drive air pollutant emissions to de minimis levels.[54] As a critical prerequisite to investments in hydrogen turbine technology, the Department should be directed to further investigate the air pollution impacts of hydrogen combustion, especially on impacted communities, and the feasibility of developing proper emissions controls

Hydrogen is a small molecule that is prone to leakage along its supply chain. It is a short-lived, indirect greenhouse gas that can warm the Earth by increasing the amounts of other greenhouse gasses in the atmosphere.[55] Emerging science suggests that the climate impact of hydrogen leakage may be larger than previously thought. The Environmental Defense Fund is currently leading an effort to improve our understanding of the climate consequences of hydrogen leakage. Preliminary findings suggest that the climate impacts of hydrogen applications relative to their fossil fuel counterparts depend strongly on the leakage rate and the time period of interest. For example, if leak rates are high, we could have more warming over the following decade from the hydrogen applications relative to the fossil fuel systems they are replacing — though as the decades pass, the prevention of a build-up of carbon dioxide in the atmosphere leads to less warming from the hydrogen applications even with high leakage. The bottom line is that even the cleanest forms of hydrogen are not necessarily climate neutral, and if left unmanaged, hydrogen leakage could undermine its climate benefits over the near-to-medium term. Currently, the total amount of leakage in hydrogen systems remains unknown— heightening the importance of developing technologies and systems to rigorously measure, report, and verify hydrogen leakage rates. Given the level of interest around hydrogen as a decarbonization pathway, additional research and analysis is needed to better understand hydrogen's full climate impact in different applications and at different stages of the supply chain.

---

[53] Prepared direct testimony of Kevin Woo, David Mcquilling, and Kevin Lang on behalf of Southern California gas Company, San Diego Gas & Electric Company, Pacific Gas and Electric Company, and Southwest Gas Corporation, November 2020, https://www.socalgas.com/sites/default/files/2020-11/H2_Application-Chapter_4-Technical.pdf ; UPROSE, THE POINT CDC, New York City Environmental Justice Alliance, New York Lawyers for the Public Interest, Clean Energy Group, Chhaya CDC, Sierra Club, and Earthjustice. "RE: State Environmental Quality Review Act Final Scoping Document Astoria Replacement Project Astoria Gas Turbine Power LLC." November 6, 2020. https://www.cleanegroup.org/ceg-resources/resource/peak-coalition-letter-astoria-replacement-project/.; NYS Department of Environmental Conservation, SEQR Lead Agency. "State Environmental Quality Review Act Final Scoping Document: Astoria Replacement Project." Astoria Gas Turbine Power LLC, September 2020. https://www.nrg.com/assets/documents/legal/astoria/09-18-20AstoriaFinalScope.pdf.

[54] U.S. DOE, Hydrogen Program Plan, November 2020, https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[55] Hydrogen is an indirect greenhouse gas including because when emitted, it interferes with the global chemical reactions which control the concentration of methane and the formation of ozone, both of which are major greenhouse gasses.

II. Areas of Improvement in the DOE's Hydrogen RD&D Focus and Structure

The DOE hydrogen innovation agenda is marked by a series of commendable successes reflective of the Department's state-of-the-art RD&D capabilities.[56] However, hydrogen technology's shifting role both nationally and globally, in conjunction with the incredible advancement in clean energy solutions like electrification, efficiency, and renewable energy, warrant a reexamination of DOE's hydrogen RDD&D portfolio and a reshuffling of priorities. Below are key areas requiring necessary improvements with fuller recommendations for addressing the shortcomings in the subsequent section.

1. **Hydrogen's unique value proposition can be better evaluated:** There is strong consensus that clean energy technologies such as renewable energy, energy efficiency, electric vehicles, high-efficiency heat pumps, and energy storage batteries are now able to meet much of the nation's energy needs affordably and reliably.[57] It is therefore critical that DOE's hydrogen program tease out hydrogen's unique value proposition in relation to those readily available climate solutions to guide RD&D priorities and set program goals. Until recently, the Department has largely assessed the potential for U.S. hydrogen deployment and use in a fairly isolated manner, without fully considering the potential widespread deployment of more efficient clean energy solutions and the implications on hydrogen's highest value applications. However, we recognize that the Department– notably, the Hydrogen and Fuel Cell Technologies Office (HFTO)-- is increasingly adopting a more holistic and cross-technology lens to identify hydrogen's most compelling potential. This direction should be strongly encouraged and supported.

2. **DOE's hydrogen RD&D agenda adopts an expansive approach to hydrogen production pathways, overlooking their different value propositions:** DOE's portfolio currently spans the advancement of all production pathways, with the work apportioned to the Hydrogen and Fuel Cell Technologies Office; Office of Fossil Energy and Carbon Management; the Office of Nuclear Energy; and the Bioenergy Technologies Office based on their energy source or feedstock of focus. However, as noted previously, the various hydrogen production pathways are characterized by different cost, benefits. public health, climate, and risk profiles. This warrants prioritization of production pathways offering the greatest value to America and the achievement of long-term climate goals.

3. **DOE's hydrogen portfolio retains an expansive approach to hydrogen end-uses:** A strong evidence base demonstrates that hydrogen's highest value applications include the hardest-to-electrify sectors of the economy. While DOE's most recent Hydrogen Program Plan indicates a stronger orientation toward those end-uses, the Department's innovation work still lays emphasis on hydrogen applications that are projected to remain largely outcompeted by alternative clean energy technologies, e.g., passenger cars. Further, recent Congressional direction – notably, statutory language in IIJA--directs DOE to advance hydrogen use in buildings for heat, which as noted earlier would be a poor use of taxpayers' dollars and should thereby be deprioritized.

---

[56] U.S. DOE, "2021 Annual Merit Review Awards," https://www.hydrogen.energy.gov/annual-review/annual_review21_awards.html

[57] National Academies of Science, *Accelerating Decarbonization of the U.S. Energy System*, 2021, https://www.nap.edu/catalog/25932/accelerating-decarbonization-of-the-us-energy-system; Princeton University, *Net Zero America Project*, 2020, https://netzeroamerica.princeton.edu/the-report; James H. Williams et al., *Carbon-Neutral Pathways for the United States,* AGU Advances 2, no. 1, January 2021, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

III. NRDC Recommendations for a Revised Orientation of DOE's Hydrogen RDD&D Portfolio to Maximize Benefits to America and the Global Climate Fight

The points made earlier can be distilled into a set of guiding principles and actionable recommendations enabling DOE's hydrogen RD&D portfolio, as well as current and future legislative hydrogen proposals, to better bolster the technology's climate, public health, and economic value, and mitigate the risks. DOE's current focus on a wide range of end-uses and production pathways is incommensurate with hydrogen's most unique value-- which lies chiefly in its targeted use in the hardest-to-abate sectors and when produced in a manner that adheres to the highest standards of climate and public health integrity. It is therefore advisable for the DOE's integrated hydrogen work to prioritize the advancement of *targeted* hydrogen use cases and production pathways.

DOE should prioritize investments in no-regret and targeted hydrogen RDD&D opportunities and, concurrently, bridge the knowledge gaps arising from the novel nature of hydrogen's expansion beyond its current niche industrial role by way of rigorous and transparent assessments.

1. **DOE's hydrogen RDD&D portfolio should be guided by a holistic and periodic assessment, conducted across DOE offices, of hydrogen's unique role in relation to other readily available clean energy solutions in the most efficient pathways to net-zero greenhouse gas emissions by 2050.**

Owing to hydrogen's potential cross-sectoral reach, the Hydrogen and Fuel Cells Technologies Office (HFTO) should be directed to collaborate with other DOE offices- including the Office of Policy, the Advanced Manufacturing Office (AMO), the Vehicle Technologies Office (VTO), the Office of Electricity (OE), and others--to conduct a periodic assessment of hydrogen's highest value applications and most expedient role in relation to other clean energy solutions, assuming best available technology projections for the latter, in efficient pathways to net-zero greenhouse gas emissions by 2050. This would build on HFTO's current efforts to conduct an assessment of this nature under the auspices of the Systems Analysis sub-program. [58] HFTO should be encouraged and supported to continue this effort, with a direction to closely collaborate with the other offices noted above and be guided by the holistic economy-wide analyses conducted by the Office of Policy. HFTO should then set hydrogen RDD&D priorities on this basis. In fact, the identification of hydrogen's unique value proposition should be the bedrock on which investments in both early-stage R&D and large-scale deployment and demonstration projects are predicated and would foster optimal stewardship of public money in the short time window to 2050. This is a key foundational step to mitigate the risks of misguided hydrogen investments that cannibalize and reshuffle priorities away from other more efficient and cost-effective clean energy solutions, stalling climate progress and placing undue burdens on U.S. households and businesses in the transition to a net-zero emissions economy.

[58] U.S. DOE, Systems Analysis Overview, June 2021, https://www.hydrogen.energy.gov/pdfs/review21/plenary11_rustagi_2021_o.pdf

2. **DOE's hydrogen investments should be targeted at the hardest-to-abate sectors of the economy, placing the U.S. at the vanguard of global clean energy innovation efforts**

In efficient pathways to net-zero emissions, in both domestic and global assessments, the bulk of projected new hydrogen demand in 2030 and beyond is linked to applications that are not yet commercially mature. Those include the use of hydrogen-based fuels in maritime shipping and aviation, hydrogen as a chemical feedstock in steelmaking, and hydrogen as a long-duration storage of electricity. IEA reports that to reach net-zero emissions by 2050, $90 billion of global public money should be funneled into R&D by 2030, around half of which should be allocated to hydrogen-related technology. IEA also reports that innovation gaps are notably found in end-use industrial applications, heavy road transport, shipping, and aviation.[59] It is therefore critical that DOE's hydrogen activities be plainly focused on advancing the technology in those hard-to-abate applications to ready them for broad commercialization in 2030 onward, when the imperative to decarbonize them becomes ever more urgent.

Congress should direct HFTO to collaborate with other offices in delivering on this vision. Further, Congress should direct offices to develop criteria and guidance to limit funding to technologies and sectors compatible with net-zero emissions by 2050, as well as clear metrics and goals to facilitate tangible progress. Congress should also appropriate dedicated funding for these cross-cutting activities, so that programs have shared budgets for collaboration, associated with appropriate milestones and reporting requirements to ensure strong DOE and congressional oversight of these activities.[60]

- HFTO should be directed to collaborate with AMO on advancing hydrogen use in heavy industrial applications, notably in new steel plants, commensurate with ongoing efforts to expand the domestic steel industry. [61]
- HFTO should collaborate with OE to investigate the potential for hydrogen as a long-duration storage of electricity, as well as the grid behavior and benefits of electrolyzers.[62] Relatedly, HFTO should collaborate with relevant DOE offices to assess the technological barriers and solutions to enabling the long-duration storage of hydrogen in geologic formations.
- HFTO should be directed to explore and advance the use of hydrogen-based fuels in aviation, expanding aviation-related innovation activities beyond the predominant purview of BETO, as is currently structured. Both offices should collaborate on this task.
- HFTO should be directed to collaborate with the Department of Transportation to assess and advance the use of hydrogen-based fuels in maritime shipping, notably in deep-sea vessels.

---

[59] International Energy Agency, "Global Hydrogen Review 2021," 2021, https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf

[60] This builds on the hydrogen cross-cut that DOE included in its FY22 budget request, https://www.energy.gov/sites/default/files/2021-06/doe-fy2022-budget-volume-2-v3.pdf

[61] The global 2030 Breakthroughs campaign launched by the UN High Level Climate Champions defines the tipping point in the technology trajectory as it relates to decarbonizing steelmaking to be when 20 zero-carbon, commercial-scale steel facilities (producing more than 1 million tons of steel per annum) are operational by 2030. https://racetozero.unfccc.int/wp-content/uploads/2021/09/2030-breakthroughs-upgrading-our-systems-together.pdf ; Bellona, "Hydrogen in steel production: what is happening in Europe – part two," May 2021, https://bellona.org/news/industrial-pollution/2021-05-hydrogen-in-steel-production-what-is-happening-in-europe-part-two

[62] This would build on the DOE's hydrogen program's involvement in workshops and analyses through the Energy Storage Grand Challenge initiative.

This is particularly critical in light of the series of commitments that the U.S. has made to help create green shipping corridors by 2030 and accelerate the sector's decarbonization. Notable initiatives include the COP26 Clydebank Declaration, shipping commitments made during the 2021 Quad Leaders' Summit, and recent announcement by the Ports of Shanghai and LA to establish the first transpacific green shipping corridor. [63]

- HFTO should be directed to phase down or deprioritize work on hydrogen applications that will largely be outcompeted by more efficient and cost-effective options, notably passenger cars and buildings heat.

The H2@Scale initiative which targets the cross-sectoral and integrated deployment of hydrogen, would mirror this Office-level targeted vision in its technical assessments and activities.

Further, focusing DOE's hydrogen innovation efforts on the hardest-to-electrify sectors would facilitate the rise of the U.S. to the vanguard of global clean energy innovation, and bolster American economic and technological competitiveness in an increasingly climate-aware global economy. The global Breakthrough Energy Catalyst program launched at COP26 aims to rapidly commercialize emerging technologies deemed key to meeting climate goals, including long-duration energy storage and sustainable aviation fuels. Similarly, the global Green Hydrogen Catapult initiative aims to mobilize and accelerate hydrogen applications in the hardest-to-abate sectors, including steelmaking and maritime shipping. And the U.S. played a central role in launching the First Movers Coalition, which targets ambitious private sector procurement by 2030 of clean technologies in steel, shipping, trucking and aviation.[64] With its leading energy innovation capacities and track record, the U.S. thereby stands to rise to the forefront of solving the most intractable global climate innovation challenges and bolster the U.S. competitive edge in the global race to clean energy innovation.

3. **The DOE should only prioritize the advancement of zero-emitting, green hydrogen as the pathway with the largest potential for cost reductions and safeguarding public health, most strictly aligned with long-term climate goals, and offering unique benefits to the electric grid.**

Hydrogen production is energy intensive, and even resources touted as "clean" may emit high levels of greenhouse gas emissions absent critical safeguards (as discussed above). It is therefore imperative that the DOE impose a rigorous and verifiable carbon intensity limit on all its investments in hydrogen projects – a limit that should encompass emissions arising both at the site of production and

[63] The Clydebank Declaration launched at COP26 commits signatories from Europe, the U.S., Africa, Asia, and Oceania to establish at least six green corridors by the middle of this decade, https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors; The Quad agreement signed in September 2021, announced the formation of green shipping corridors by 2030 between the U.S., Japan, India, and Australia, https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/24/fact-sheet-quad-leaders-summit/; C40 Cities, *Port of Los Angeles, Port of Shanghai, and C40 Cities announce partnership to create world's first transpacific green shipping corridor between ports in the United States and China,* January 2022, https://www.c40.org/news/la-shanghai-green-shipping-corridor/

[64] Green Hydrogen Catapult, https://greenh2catapult.com/ ; The Breakthrough Catalyst Program, https://www.breakthroughenergy.org/scaling-innovation/catalyst ; The First Movers Coalition, https://www.state.gov/launching-the-first-movers-coalition-at-the-2021-un-climate-change-conference/ ; Mission Possible Partnership, https://missionpossiblepartnership.org/about/

upstream of production.[65] DOE should also establish standards that protect community public health and natural resources as it relates to hydrogen deployment.

In addition to a strict carbon intensity limit, DOE should foster optimal stewardship of taxpayers' dollars by prioritizing zero-emitting, green hydrogen in its RD&D and deployment initiatives. The latter's higher climate and public health integrity relative to other production pathways, coupled with its potential to deliver the most cost reductions and unique grid reliability benefits, render it a more appropriate public investment. Investing significantly in blue hydrogen risks expending limited public funds on technologies not well positioned to play a major role in decarbonizing our economy, given blue hydrogen's generally unfavorable economics relative to green hydrogen and the possibility that it will be beset by residual emissions (both upstream methane leakage – even if this is significantly reduced– and emissions arising onsite as carbon capture technology is unlikely to economically achieve 100 percent efficiency).

Accordingly, the DOE should center its hydrogen RDD&D portfolio on improving the various aspects of electrolysis technology, including the costs, efficiency, durability, and dependence on freshwater resources. Similarly, hydrogen deployment initiatives-- notably, DOE's Hydrogen Shot initiative and hydrogen hubs program pursuant to IIJA--should prioritize green hydrogen to robustly position the technology on the declining cost curve and maximize benefits to Americans.

Further, a predominant focus on green hydrogen RDD&D may bolster U.S. ambitions to become a hydrogen exporter, as countries are displaying strong inclination toward exclusively sourcing the cleanest sources of hydrogen. In fact, the UN global hydrogen principles advise future importing countries to favor certifiable, zero-carbon hydrogen resources.[66] It is therefore likely that climate-aware countries and future hydrogen import centers like Europe will prefer zero-emitting green hydrogen over fossil-sourced hydrogen.

4. As a pre-requisite to supporting hydrogen pipeline projects, DOE should be directed to periodically assess the future landscape of pipelines linked to hydrogen supply and demand centers with a high likelihood of materializing in efficient pathways to net-zero by 2050.

Hydrogen transport infrastructure requires further reflection and technical investigation, on account of the long asset lifetimes as well as the range of uncertainties that still permeate the future clean hydrogen industry. DOE can play a unique and critical role in charting a sound course for investments in gas pipeline conversions and new hydrogen pipelines, and it should use caution in doing so. DOE should periodically assess the future geographical landscape of potentially secure hydrogen supply and demand centers in efficient pathways to net-zero greenhouse gas emissions by 2050, guided by the holistic decarbonization assessment detailed in our first recommendation in this section[67]. This

[65] IIJA directs DOE to publish a carbon intensity threshold for hydrogen deemed "clean" by May 2022, with room to revise it no less than 5 years from publication. This threshold will guide DOE's hydrogen investments as they relate to the IIJA-directed hydrogen hubs and beyond.

[66] UN High Level Climate Champions, "UN Climate Champions launch 'guiding principles' for climate-aligned hydrogen," October 2021, https://racetozero.unfccc.int/un-climate-champions-launch-guiding-principles-for-climate-aligned-hydrogen/

[67] This would build on and constitute a refinement to the H2@Scale assessment published in October 2020, National Renewable Energy Laboratory, "The Technical and Economic Potential of the H2@Scale Concept within the United States," October 2020, https://www.nrel.gov/docs/fy21osti/77610.pdf;

exercise is critical to identify regions of focus for hydrogen transport infrastructure, guide public and private investments in a direction aligned with long-term climate goals and mitigate premature or misguidedly expansive investments in pipelines. Further, DOE should conduct an add-on analysis identifying a set of pipeline corridors that are robust against a range of hydrogen futures and supply and demand centers. This builds on the European study by the expert group Agora Energiewende which identifies a set of "no-regret" pipelines around future hydrogen demand hubs deemed highly likely to materialize.[68] The study was conducted with a view towards countering a stakeholder push to make widespread investments in both the conversion of gas pipelines to carry hydrogen and new dedicated hydrogen networks. The introduced "Hydrogen Infrastructure Finance and Innovation Act" by senators Coons and Cornyn includes a sample directive for DOE to conduct a similar assessment.[69]

5. DOE should bridge critical knowledge gaps concerning hydrogen's climate and public health impacts.

DOE bears responsibility to ensure that hydrogen policy and deployment is not detrimental to public health or the climate. The Department should be directed to investigate the air pollution impacts of hydrogen use--a directive consistent with the Department's own assessment of the current knowledge gap as it relates to hydrogen combustion-- and develop the requisite technology solutions to achieve de minimis criteria air pollution levels linked to use. Investments in combustion applications such as turbines and boilers should be treated with caution absent appropriate technology solutions.

DOE should also engage in research and discussions around the full climate impacts associated with hydrogen use in different applications and at different stages of the supply chain and include hydrogen leakage risk in their assessments and solutions going forward.

6. DOE must engage in proactive, transparent and inclusive stakeholder engagement.

The plethora of work within the purview of DOE's hydrogen program– RD&D efforts as well as investments in deployment linked to the Hydrogen Shot Initiative and hydrogen subtitle pursuant to IIJA– will meaningfully shape the trajectory of our nation's emerging clean hydrogen industry. It is therefore imperative that DOE be directed to engage in proactive and transparent dialogue with a wide range of stakeholders with diverse views. There should be a clear, accessible, and inclusive stakeholder engagement process. Notably, the Department should be directed to proactively engage with community and environmental justice groups who may be affected by hydrogen deployment, to ensure that harm is avoided, and benefits are maximized. As part of stakeholder engagement, it should also be clear how comments are being incorporated and decisions are being made.

---

[68] Agora Energiewende, "No Regret Green Hydrogen," 2021, https://static.agora-energiewende.de/fileadmin/Success_Stories/PW/PW_EU_Green-H2/A-E_241_Succ_Stor_Pathways_EU_H2_hubs_WEB.pdf

[69] "Hydrogen Infrastructure Finance and Innovation Act," https://www.coons.senate.gov/imo/media/doc/text_hii_hifia.pdf

We look forward to working with you and other stakeholders on these issues. There is much we need to learn from each other and many important questions which need to be resolved. Thank you for your careful attention to this input and the opportunity to testify.