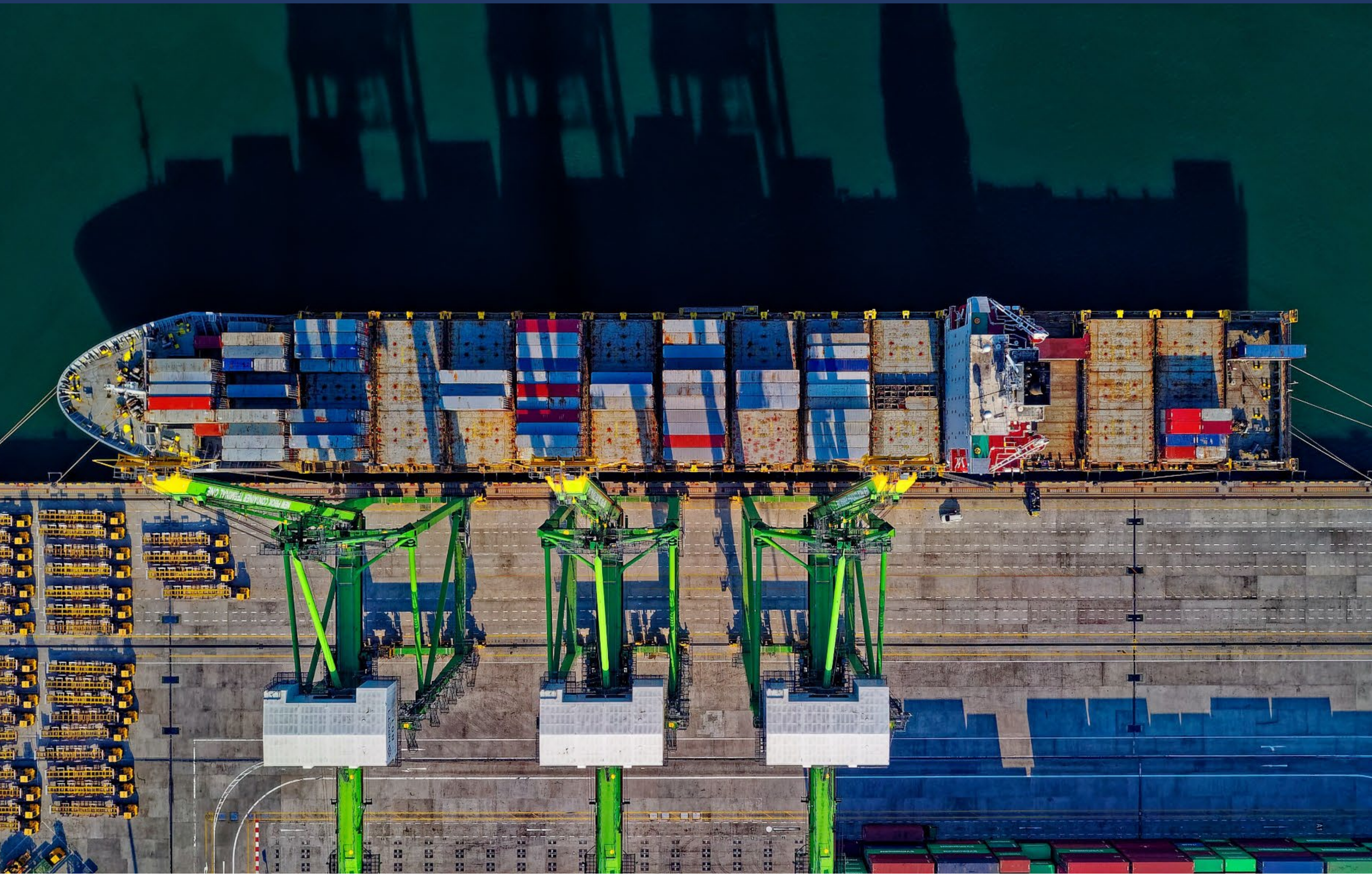

ENERGY INNOVATION
POLICY & TECHNOLOGY LLC®

HYDROGEN POLICY'S NARROW PATH

DELUSIONS & SOLUTIONS

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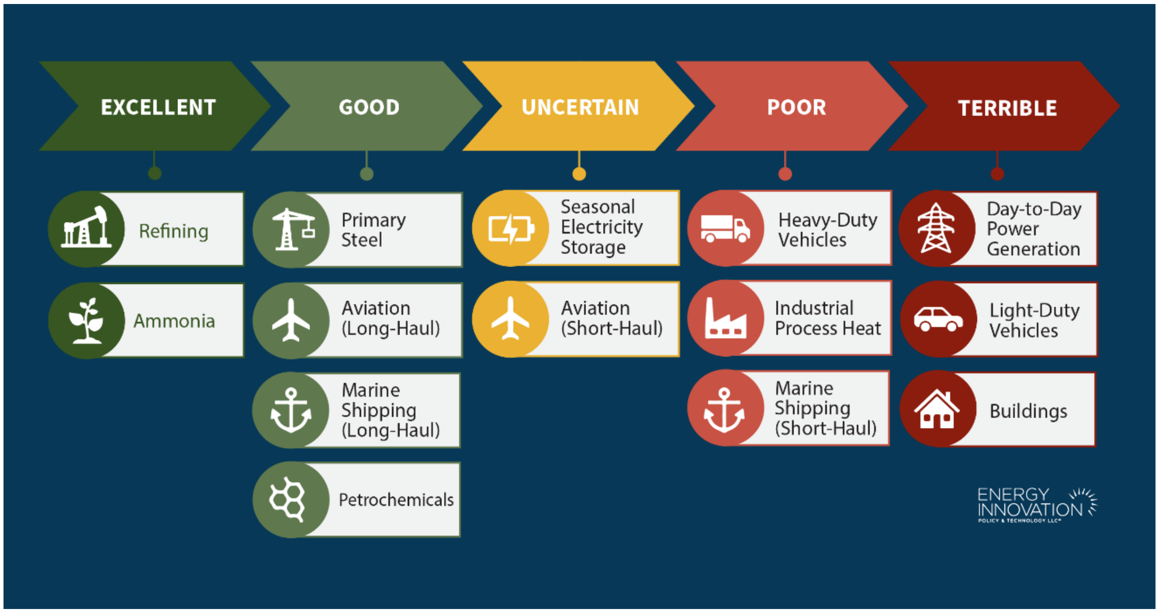
EXECUTIVE SUMMARY

Hydrogen excitement has taken the world by storm. Long considered a technology that is decades away from financial viability, clean hydrogen has recently captured policymakers' imagination as an energy carrier and chemical feedstock that *can* be produced without emitting climate pollution and *can* be used in place of fossil fuels in all economic sectors. This has led to a frenzy of activity to jump-start the nascent clean hydrogen industry, both to set up pathways for deep decarbonization and to seize the promised economic benefits for early adopters that can attract new investment and jobs. However, the hydrogen goldrush is fraught with unintended consequences—and charging full speed ahead without careful navigation risks doing more harm than good. That is, ostensibly "clean" hydrogen production can increase reliance on fossil fuels, and some hydrogen uses can displace cheaper technologies and worsen inequity.

Hydrogen will be important for achieving our climate goals, but it can do so if and only if it is truly zero-carbon and directed to appropriate applications. Straying from this narrow path can reverse, delay, or raise the costs of emissions reductions.

This paper aims to focus hydrogen policy to advance an efficient, cost-optimal, climate-friendly future. It does not comprehensively consider all hydrogen production methods or potential uses, nor does it explore every niche case or short-term solution. Instead, it aims to illuminate just enough trees to see the forest—without losing the forest for the trees. It uses the United States as a lens, though its conclusions are applicable globally.

Figure 1. Hydrogen's competitive prospects for decarbonization by end-use sector



The paper's core analysis assesses hydrogen's competitive prospects for decarbonizing 12 end-use sectors. Low-value uses are defined as applications where hydrogen is likely to be outcompeted by alternative clean energy technologies, meaning public support for hydrogen in these domains will likely raise costs and set back the clean energy transition. High-value uses are defined as applications where hydrogen can eventually compete with alternatives on a level playing field, or where no alternatives exist.

This study assumes the use of hydrogen from electrolysis, which splits hydrogen from water molecules using electricity. Electrolysis is the lone known pathway capable of achieving truly zero-carbon hydrogen production at scale and at lower cost than today's dirty production methods. Other options may have roles to play but face issues that make them less desirable for serving as the backbone of a clean hydrogen industry.

This paper includes two-page summaries of each of the 12 end-use sectors, covering hydrogen's potential to reduce emissions, infrastructure requirements for its use, its social impacts, and the relative strengths or weaknesses of competing technologies.

KEY TAKEAWAYS

The key insights from this analysis of hydrogen's role in a clean economy include:

- **Hydrogen's low-value uses are all when used for energy, while its high-value uses are all when used as a feedstock.** There are generally far more efficient ways to decarbonize the provision of energy—due in part to rapid advances in battery technologies—while there are few alternatives for cleaning up chemical feedstocks.
- **Hydrogen's low-value uses are much more dependent on the development of sprawling hydrogen pipelines and end-use equipment than its high-value uses.** While new infrastructure will be important to enabling hydrogen's growth, these investments likely can be focused on tight industrial clusters rather than distributed and intertwined throughout the economy.
- **Hydrogen's low-value uses often increase the risk of social harms and inequitable outcomes, while its high-value uses generally do the opposite.** Proactively directing hydrogen away from low-value uses and into high-value ones can help it advance rather than set back environmental justice and equity goals.
- **Electrolytic hydrogen that relies on fossil fuel power would fail to reduce net climate pollution across all end uses, with steel as the lone potential exception.** Hydrogen would almost universally do more harm than good if its production isn't subject to strict guardrails (i.e., requiring electrolyzers to draw from new, deliverable, hourly matched clean energy) that prevent it from increasing fossil fuel power plant electricity generation—even after accounting for its use downstream.
- **In the U.S., hydrogen's market potential for high-value uses exceeds clean hydrogen production goals—meaning any hydrogen flowing to low-value uses cuts into decarbonizing high-value sectors on the necessary timeline.** At the same time, hydrogen's low-value uses imply a demand more than four times greater than its high-value uses, which may give the false impression that hydrogen must grow at breakneck speed with little regard to how it is produced or used.

- **Hydrogen's uptake in high-value uses will require targeted demand-side policies—supply-side subsidies alone will not ensure this outcome (and may make better alternatives for low-value uses look worse).** Institutional barriers, market failures, and sheer momentum all favor hydrogen's uptake in low-value uses and suggest policymakers need to intervene to set the industry on the right course.

POLICY RECOMMENDATIONS

This paper focuses on the core options that policymakers should consider to drive the hydrogen industry in the right direction and protect the public—and climate—from unintended outcomes. The following lists provide high-level, demand-side policy recommendations—that is, policies that can boost clean hydrogen's uptake in high-value uses or minimize risks associated with its adoption in low-value uses. Where possible, technology-neutral policy designs (e.g., targeting the development of low- or zero-carbon products like clean steel or sustainable aviation fuels) can support hydrogen where it's best suited rather than presupposing it as the right solution.

Policy tools to boost hydrogen's uptake in high-value uses include the following:

- **Advance market commitments (AMCs)** are guarantees to buy a certain volume of a product that has yet to reach commercialization. Policymakers should consider AMCs for products whose development and deployment they want to quickly scale.
- **Contracts for difference (CfDs)** are arrangements where one party ensures an established offtake price for the product of another party (by paying any premium relative to the market sale price), without the former having to be the buyer. Policymakers should consider CfDs to support first-mover developers whose clean products may be more expensive than existing products or those of later entrants.
- **Reverse auctions** are a mechanism by which a buyer for a product sets the parameters of a procurement and then allows private actors to bid against each other to provide the product at the lowest price. Policymakers should consider reverse auctions when they want to purchase (or encourage the purchase of) a product that is commercially available but has low price transparency.
- **Subsidies for end-use equipment or utilization** in pre-selected high-value hydrogen uses (e.g., steelmaking) can incentivize developers to invest in these uses, such as by covering some percentage of capital costs or paying developers per kilogram of clean hydrogen they procure. Policymakers should consider such subsidies when they can provide the needed boost to push some projects into profitability, and when they want to make such support available to all potential high-value uses rather than choosing winners within this set.
- **Research and development (R&D) support for emerging technologies** involves providing grants for research labs, academia, private firms, and industry to test new, unproven technologies. Policymakers should consider R&D support for high-value hydrogen uses that have no proven technology ready to scale.
- **Performance standards** involve setting a benchmark for an entire industry to achieve, often becoming gradually more stringent over time (e.g., a percentage uptake of clean fuels, feedstocks, or products). Policymakers should consider performance standards as a complement to financial incentives, as the former

ensures continuous progress toward a defined goal while the latter eases any cost impacts and provides motivation for surpassing such goals.

Recommendations for minimizing the risks of hydrogen's low-value uses include:

- **Focus midstream infrastructure on tight industrial clusters.** Dedicated hydrogen pipelines and storage sites will be critical to enabling the industry's growth, but they likely can be concentrated in regions with strong renewable resource quality and co-located with high-value hydrogen users, with derivative products like steel and sustainable aviation fuels then transported using existing infrastructure. This approach can help prevent the siphoning of limited, valuable hydrogen by entities pursuing more dispersed low-value uses like vehicle fueling stations and buildings.
- **Hedge bets on hydrogen infrastructure investments.** If policymakers do choose to support some low-value hydrogen uses, they should try to ensure these investments will still have some value if the primary purpose fails. For example, policymakers could prioritize hydrogen vehicle fueling stations at ports that could serve multiple potential users (e.g., container handlers, tractor-trailers), making them more durable if one or more uses fail to achieve long-term viability. They could also require fueling stations to have a minimum ratio of electric vehicle chargers to fuel pumps to strength stations' viability if all hydrogen applications fail.
- **Require a high burden of proof of value and community benefits agreements.** Regulators and policymakers should subject hydrogen projects to a high burden of proof of their benefits and long-term viability before approving any public subsidy, such as grants or utility cost recovery via rates. This can allow private actors to explore low-value hydrogen uses without shifting financial risks to the public or captive consumers. Policymakers should also require developers to negotiate community benefits agreements with affected communities while taking steps to ensure they fulfill their intended purpose.
- **Set rigorous health and safety standards.** As several low-value hydrogen uses involve combustion, regulators should establish rigorous pollution standards for nitrogen oxide (NOx) emissions, including for home appliances and industrial equipment. Policymakers should also establish thorough standards around hydrogen safety and leakage across the hydrogen value chain.

INTRODUCTION

Hydrogen (H_2) is a molecule that *can* be produced without emitting greenhouse gases (GHGs) and *can* be used in place of fossil fuels across all economic sectors. Interest in hydrogen has skyrocketed given the urgent imperative to cut climate-warming pollution. In theory, a large, interconnected clean hydrogen economy could be a silver bullet—with vast financial gain for developers and governments that are first to adopt this technology.

However, hydrogen's versatility as an agent of decarbonization comes with a catch: if not carefully managed, its production, transport, and use can actually *increase* net GHG emissions and further harm pollution-burdened communities. Hydrogen holds real value as a tool to cut emissions from economic sectors still heavily reliant on fossil fuels and with few alternatives to replace those fuels, like steelmaking and aviation. However, policymakers must adopt holistic policies that ensure truly clean hydrogen production and must proactively direct hydrogen toward the highest-value end uses to help realize this vision and avoid a wide range of unintended consequences—including a net increase in climate pollution and retreating from environmental justice goals.

This paper assesses hydrogen's role in a clean energy economy through the lens of the U.S. However, its lessons and policy recommendations apply globally.

HYDROGEN BASICS

The conventional hydrogen industry has been around for many years. Today, the U.S. produces 10 million metric tons (MMT) of hydrogen per year, almost exclusively via a process using fossil fuels called steam methane reformation (SMR). Making hydrogen from natural gas-based SMR emits approximately 10 kilograms (kg) of CO_2e per kilogram of hydrogen, with all domestic production contributing 1-2 percent of U.S. climate pollution. This hydrogen is primarily used to refine crude oil (55 percent) and to make ammonia and methanol (35 percent).[1]

Hydrogen production can also be carbon-free. The gold standard is electrolysis, which splits water molecules into hydrogen and oxygen using electricity. This process can be zero-emissions if and only if it does not increase fossil fuel power generation, whether:[2]

- Directly by using electricity from fossil fuel power plants; or
- Indirectly by using clean, zero-carbon electricity that was previously serving another purpose, thereby causing fossil fuel facilities to ramp up to fill in for the lost power.

It is also technically possible to use hydrogen in a far wider range of applications than are conventional today. Hydrogen can be used as a feedstock or for energy. Hydrogen-as-a-feedstock involves its use as a physical molecule, such as to refine and purify other substances or to build more complex chemicals. Hydrogen-for-energy involves burning hydrogen for heat (including for power generation) or using it in a fuel cell to generate electricity.

RECENT DEVELOPMENTS

Electrolyzers, fuel cells, and other hydrogen technologies have been under development for decades, with researchers forecasting the need for various amounts of clean hydrogen by the 2040s to meet global climate emissions reduction targets.[3] However, several trends and policy decisions have accelerated hydrogen's relevance in recent years, propelling a once-obscure technology into the spotlight. For example:

- Electric and gas utilities have been **proposing plans to blend hydrogen with natural gas** for use in buildings and power plants in order to meet (or get ahead of potential) legislative requirements for decarbonizing their operations.[4] This involves an existential question of gas utilities' role in a zero-carbon energy future.
- The U.S. Infrastructure Investment and Jobs Act (IIJA) of November 2021 includes $9.5 billion for clean hydrogen research, development, and demonstration projects. Most notable is its requirement to create **hydrogen hubs**, intended to test different ways of making and using hydrogen while building infrastructure clusters to enable longer-term growth. In October 2023, the U.S. Department of Energy (DOE) made its initial selection of seven hubs (totaling $7 billion in federal funds), though it may take 8-12 years for the hubs to reach full commercial operations.[5]
- The U.S. Inflation Reduction Act (IRA) of August 2022 includes the "Section 45V" **Clean Hydrogen Production Tax Credit**—a highly lucrative, long-term, uncapped subsidy that advanced clean hydrogen's financial viability by 10-20 years overnight. The U.S. Treasury has yet to release final rules for how developers can earn the credit, with the forthcoming decision set to establish whether 45V will be limited to truly clean hydrogen production (and support the growth of a successful industry) or allow far dirtier hydrogen to qualify (and risk derailing its long-term viability).[6]
- **Russia's invasion of Ukraine** in February 2022 amplified European Union concerns regarding its dependence on natural gas imports and increased urgency around diversifying to other energy sources. While the EU had a hydrogen strategy in place well before then, this event accelerated policy support for hydrogen.[7]

The sudden injection of public funding for hydrogen has fueled hype around where it *can* be used, with less attention paid to where it *ought* to be used to support a rapid, equitable, and cost-effective clean energy transition. In particular, U.S. hydrogen policy is heavily weighted toward supply-side subsidies, making hydrogen a hammer such that every potential application looks like a nail. Similarly, states and countries are eager to position themselves as leaders in the budding industry, aiming to attract investment and jobs and become an exporter of hydrogen technology or commodities. These actions risk a race to the bottom, indiscriminately subsidizing hydrogen while losing focus that it is a means to an end in decarbonization rather than a worthy end in itself.

THE NEED FOR A MEASURED APPROACH

Hydrogen is unfortunately not a miracle technology. In fact, unlike most other clean energy technologies, hydrogen risks *worsening* climate pollution and other social outcomes if not approached with care.[8]

In particular, electrolytic hydrogen production is highly energy intensive. This means it can emit 1.5-5 times more GHGs than the conventional natural gas-based SMR process if it causes fossil fuel power plants to ramp up—and it can raise *net* GHG emissions even after the hydrogen displaces fossil fuels downstream.[9] It also means hydrogen requires far more electricity to accomplish the same goal than clean alternatives like electric vehicles and electric heat pumps, so hydrogen's use can lead to wasting limited clean energy and to underinvestment in fundamentally more competitive technologies.

Hydrogen also has unique chemical properties that make it much trickier to manage. As the smallest molecule in the universe, it is especially prone to leakage. This characteristic makes hydrogen a safety risk, as it has no odor, is highly flammable, and can exacerbate cracks in steel pipelines;[10] it also makes hydrogen a climate risk, as it has approximately a 12 times greater warming impact than CO_2 over a 100-year period.[11] If hydrogen is combusted for heat, it can worsen emissions of NOx—a pollutant that harms the respiratory system—relative to natural gas.[12] Hydrogen's faster flame speed also increases the risk of "flashback," which can damage equipment.[13]

While subsidies can rapidly scale clean hydrogen production, there are practical limits to its growth. Trying to take shortcuts—such as building electrolyzers without bringing new, deliverable, time-matched clean energy online in parallel—would set the industry up for failure.[14] (We discuss this in depth in our separate paper on building a robust, truly clean electrolytic hydrogen industry positioned for long-term viability.)[15]

Ultimately, hydrogen holds a lot of promise as a climate solution, but **there is a narrow path forward** to ensuring it delivers on its value. Blind subsidization of the hydrogen industry across its value chain risks reversing or delaying decarbonization; worsening public health, safety, equity, and consumer cost outcomes; and standing up infrastructure

HYDROGEN COMPETITORS

Hydrogen *can* replace fossil fuels in just about any application—but that doesn't mean it should. In most cases, another technology can fulfill the same role more efficiently and with fewer risks to health, safety, climate, and consumer costs. The two main competitors are direct electrification and bioenergy.

Electrification is better suited than hydrogen in most cases where the latter would be used for energy—especially where energy density and storage requirements are low. Electric equipment is generally far more efficient, can allow for more gradual changes that make use of an existing network (i.e., the power grid), and produces no harmful emissions when using clean electricity.

Bioenergy is often preferable to hydrogen in cases where the latter is needed for its high energy density or as a feedstock. However, competition for arable land limits bioenergy supply and means there are consequences (e.g., for crop prices) from pushing too hard on this lever.

Separately, energy and material efficiency measures should be pursued to their fullest extents; these can shrink (but will not eliminate) the need for clean technologies.

and jobs that will be stranded if hydrogen ever must compete on an even playing field with more cost-effective technologies. Yet falling short on hydrogen risks missing critical milestones for achieving a clean economy, failing to abate fossil fuel pollution that hydrogen is uniquely suited to eliminate, and ceding leadership on a new industry to other states or countries.

Figure 2. Hydrogen policy's narrow path forward

This paper assesses hydrogen's prospects for decarbonizing 12 end-use sectors. It seeks to clarify where hydrogen is very likely to outcompete other clean technologies for most or all of a market, and where it is highly unlikely to ever be cost-effective relative to alternatives (at least without a substantial and uninterrupted subsidy advantage). As part of this analysis, the paper examines infrastructure requirements for and social impacts of using hydrogen for given applications. With an improved understanding of hydrogen's role in a clean energy transition, policymakers can pair well-designed production subsidies with targeted demand-side measures that help direct hydrogen toward where it is most needed and away from its most risky or counterproductive ventures.

The rest of this paper describes the methodology and results of our analysis examining hydrogen's viability across 12 end-use sectors; discusses common themes and lessons from the analysis; and provides policy recommendations for developing a hydrogen industry that supports—rather than hinders—a rapid, equitable, and cost-effective clean energy transition. The paper is accompanied by a technical appendix that details the assumptions and calculations used in our analysis.

END-USE ANALYSIS

In general, it's best to have technology-neutral policies that aim to achieve a set of goals rather than pick winners and losers. However, hydrogen requires the consideration of massive long-term investments, and policies are already providing hydrogen-specific support (e.g., 45V tax credit, U.S. hydrogen hubs). Thus, policymakers should have a directional sense of where it's worth directing public funds to the research, development, demonstration, and deployment of hydrogen-using technologies and hydrogen-enabling infrastructure to guide the industry toward successful growth.

This end-use analysis examines 12 sectors in which hydrogen could be used as a means for decarbonization. These 12 sectors include the largest potential markets most frequently cited as likely uses for hydrogen (but are not exhaustive). This study does not consider other relatively niche applications that may be well suited (e.g., remote construction or mining equipment) or a bad fit (e.g., metro trains) for hydrogen.

APPROACH

Our analysis produced four categories of findings:

- **A qualitative score conveying hydrogen's competitive prospects for decarbonization.** Scores express the degree to which hydrogen can cost-effectively clean up a given end use relative to existing and emerging alternative technologies. They do not uniformly describe all possible uses of hydrogen within each category; instead, they are heuristics for how to think about hydrogen's potential in each case.
    - **"Terrible"** uses for hydrogen are unlikely to be competitive with alternatives on cost and performance in just about every instance. Like using champagne to water a lawn, hydrogen's "terrible" uses mean wasting an expensive product to provide a lower-quality service where far better alternatives exist.
    - **"Poor"** uses for hydrogen may have viable niches, but competing technologies are likely to capture most of the market. Public support should identify and target these exceptions, but most proposed investments in this category would likely fail to achieve their promised value and deserve high scrutiny up front.
    - **"Uncertain"** uses for hydrogen are those that have too much technological uncertainty on cost and performance to have confidence about its ultimate role in serving a market. Policies should pursue hydrogen's potential without fully committing to it as a solution that is certain to outcompete alternatives.
    - **"Good"** uses for hydrogen will likely serve a large part of the market but may not be the exclusive winner. In general, hydrogen will compete with biofuels (which have limited sustainable availability) and less-mature electric technologies, neither of which are likely to crowd out hydrogen before mid-century (if ever).
    - **"Excellent"** uses for hydrogen are those which hydrogen alone can serve. Other factors may influence the absolute size of the market, but the market itself will almost certainly be completely captured by hydrogen.

- **Hydrogen's GHG emissions abatement potential in $kgCO_2e/kgH_2$ when serving a role in place of the incumbent fossil fuel.** These values assume the use of zero-carbon electrolytic hydrogen with no leakage between its production and use. They also assume that the use of hydrogen abates fossil fuels' upstream production emissions. For comparison, natural gas-based SMR hydrogen emits 10 $kgCO_2e/kgH_2$, and electrolytic hydrogen that directly or indirectly causes natural gas power plants to ramp up (due to electrolyzers' operations) emits 20 $kgCO_2e/kgH_2$.
- **Hydrogen's demand potential in MMT of H_2 if it were used as the *exclusive technology* for replacing fossil fuels in part or all of today's U.S. end-use market.** These estimates use the latest available data for the U.S. and generally assume full market coverage (i.e., that hydrogen would replace all fossil fuels serving the end use). The study's scope aims to capture most of a market (based on readily available data) without assessing every edge case. This analysis is not a forecast but instead uses recent historical data to give a sense of relative scale; it also does not attempt to estimate a "reasonable" share of hydrogen use in each case.[i] For comparison, the U.S. currently produces 10 MMT of SMR hydrogen and has a goal of producing 50 MMT of clean hydrogen by 2050 (vs. today's negligible production).
- **Hydrogen's breakeven price vs. the incumbent fossil fuel in $\$/kgH_2$,** which is pulled exclusively from the DOE.[16] These values are defined as the *delivered* price of hydrogen that would be competitive with the incumbent fossil fuel, *without* consideration of alternative clean technologies like electrification or bioenergy. For comparison, SMR hydrogen sells for approximately $1/kg in the U.S. (fluctuating with natural gas prices), with electrolytic hydrogen costs varying widely (but generally several times more expensive today pre-subsidy).[17]

Given this paper's focus on pointing hydrogen policy toward an optimal future of a clean economy, the analysis here focuses strictly on electrolytic hydrogen. Electrolysis is technologically proven, does not require fossil fuels, and can become cheaper than SMR hydrogen even without subsidies (with low-cost electrolyzers and electricity).

This paper does *not* consider "blue" hydrogen produced via SMR with carbon capture and sequestration, which perpetuates reliance on fossil fuel infrastructure and requires uninterrupted subsidies for financial viability (as adding and operating carbon capture systems will always be more expensive than not doing so).[18] If blue hydrogen does gain traction, it is unlikely to last, as forecasts suggest electrolysis will soon eclipse it in cost.[19]

This paper also does not consider geologic hydrogen, given there is no guarantee that economically recoverable hydrogen deposits will be found in meaningful quantities.[20] However, such discoveries could change the dynamics of this analysis—though some factors (e.g., NOx emissions from hydrogen combustion) remain applicable.

Figure 3 shows the core finding of this analysis, clarifying where electrolytic hydrogen is likely or unlikely to be competitive with alternative decarbonization technologies. Hydrogen's high-value uses are those that fall in the "excellent" and "good" categories, while its low-value uses are those that fall in the "terrible" and "poor" categories.

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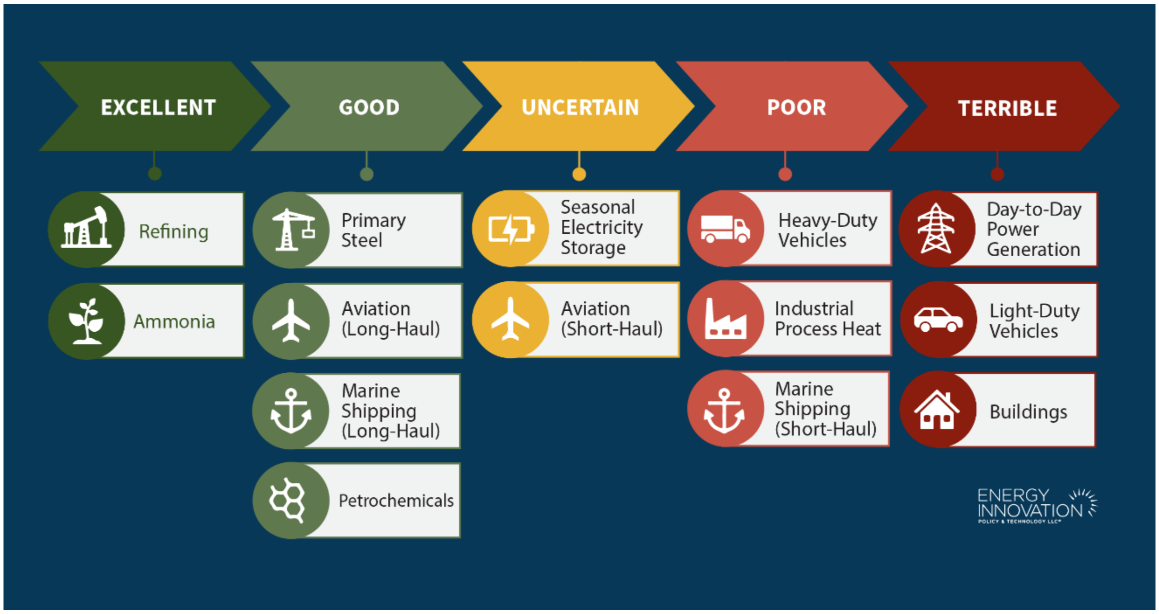
[i] The end of this section includes a reading list of rigorous forecasts conducted by other organizations.

Figure 3. Hydrogen's competitive prospects for decarbonization by end-use sector



The two "short-haul" applications do not have their own dedicated end-use overview sections and are instead discussed in their related "long-haul" sections.

The following hydrogen end-use overviews are designed to stand alone—that is, the reader need not review them in order. Each overview includes:

- **Top-line findings** about hydrogen's prospects, GHG abatement potential, demand potential, and breakeven price vs. the incumbent fossil fuel.
- **Context** covering why hydrogen is being considered for serving a given application.
- The **scope** of our analysis for estimating the values reported in the top-line findings (with more detail in the accompanying technical appendix).
- **Infrastructure needs** if hydrogen is to play a significant role in decarbonizing the sector, occasionally compared with the infrastructure requirements of the leading alternative clean energy technologies.
- **Social impacts** of using hydrogen to serve this role, including coverage of the main risks and benefits to public health, safety, climate, equity, and consumer costs.
- **Competing technologies** that are likely to capture at least a small share of the sector's market, with detail about their relative advantages and disadvantages; notably, this section does *not* consider carbon offsets, direct air capture, or energy and material efficiency to be "competing technologies"—though efficiency should be maximized wherever possible.
- The **takeaway** summarizing what policymakers should know about the end use.
- A list of recommendations for **further reading**, which are targeted toward readers who want to learn much more about hydrogen's or competing technologies' role in helping to decarbonize the end use—including a **featured story** that focuses on considerations related to environmental justice, equity, labor, or innovation.

BUILDINGS

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
TERRIBLE	**6-8** $kgCO_2e/kgH_2$	**78** MMT H_2	**0.4-0.5** $\$/kgH_2$

Hydrogen has at best a negligible role to play in decarbonizing buildings.

CONTEXT: U.S. gas utilities have announced at least 22 proposals to blend hydrogen with natural gas in their pipelines, aiming to deliver lower-carbon fuels to homes and businesses for space heating, hot water, cooking, and clothes drying.[21] Concepts for net-zero gas delivery vary from switching to a "clean fuels" portfolio—consisting of hydrogen, renewable natural gas (RNG), and synthetic natural gas—to enabling a 100 percent hydrogen system.[22] Utilities find such approaches compelling for meeting (or anticipating potential) legislative requirements for decarbonizing their operations while continuing to use and invest in their gas delivery systems; however, superior alternatives exist that generally obviate the need for hydrogen.

SCOPE: The top-line metrics assume that hydrogen replaces all natural gas used in the U.S. residential and commercial sectors in 2022 and that all hydrogen-burning appliances and equipment (e.g., furnaces, stoves) are as efficient as their natural gas-burning counterparts.

INFRASTRUCTURE NEEDS: Today's pipelines and end-use appliances are not suited to handle a blend of more than 20 percent hydrogen by volume with natural gas.[23] Even this may be an optimistic upper limit, requiring careful testing and targeted pipeline and appliance retrofits to lessen leakage and explosion risks.[24] Exceeding a 20 percent blend carries extreme logistical and cost challenges, such as replacing all pipelines and appliances on a distribution system.[25]

Gas utilities would also need to increase pipelines' size or pressure to provide similar service with hydrogen as natural gas, which would be costly or dangerous, respectively. Hydrogen carries about a third of the energy of natural gas by volume.[26] This means any use of hydrogen would result in less delivered energy (e.g., a longer wait to boil water) with today's pipelines.

SOCIAL IMPACTS: Burning hydrogen in buildings carries risks related to public health, safety, climate, and consumer costs. Hydrogen burns hotter than natural gas, which can worsen emissions of nitrogen oxide—a pollutant that harms the respiratory system.[27] Hydrogen's faster flame speed also increases the risk of "flashback," which can damage appliances.[28]

As the smallest molecule, hydrogen leaks much more readily than natural gas, including through cracks that odorants (such as what is added to natural gas so leaks can be smelled) cannot travel through. This raises explosion risks, particularly since hydrogen is much more flammable than natural gas. It also worsens climate change, as hydrogen has approximately a 12 times greater warming impact than CO_2 over a 100-year period.[29] In fact, leakage of hydrogen from its use in buildings can eliminate its climate benefits.[30] Even assuming zero-carbon hydrogen and no leaks, a 20-80 blend of hydrogen and natural gas by volume would only cut climate pollution by 7 percent at most, due to its lower volumetric energy density.

Hydrogen's use in buildings poses a substantial risk of increasing consumer energy bills. Gas utilities would need to source hydrogen below approximately \$0.50/kg to break even with natural gas—an extremely low price that will rarely be possible without never-ending policy support.[31] In the near term, hydrogen might look attractive due to steep federal subsidies, but costs could skyrocket once those expire. However, some gas utilities may be given authorization to recover these higher costs from their customers absent sufficient regulatory oversight. Any hydrogen use will also require tests and pipeline upgrades, adding more costs.

These cost impacts could be further worsened if hydrogen is part of a broader "clean fuels" strategy. RNG is scarce and will be needed to decarbonize other sectors, which will boost its price.[32] Synthetic natural gas requires making methane (CH_4) from hydrogen and a net-zero source of captured carbon (e.g., from direct air capture)—an extremely expensive proposition.[33]

Collectively, these risks are very likely to worsen equity outcomes. Rising energy costs from the use of hydrogen will compel higher-income households to switch to electric appliances (which have higher up-front costs but lower lifetime costs than gas-fired counterparts), thereby increasing the share of gas system costs borne by remaining lower-income customers.[34]

COMPETING TECHS: Electric appliances are the clear winner over hydrogen for cutting emissions in buildings.[35] **Electric heat pumps** use clean electricity three to six times more efficiently than electrolyzing hydrogen and burning it in a furnace, achieving this by moving—rather than producing—heat. New modern heat pumps also perform well in very cold weather.[36] Similarly, **induction stoves** use clean electricity three times more efficiently than electrolyzing hydrogen and burning it in a gas stove. They can also boil water much faster than natural gas (and especially hydrogen) stoves and have better temperature control.

Unlike gaseous fuels, electric appliances have no adverse health, safety, or climate impacts. It is also far easier to gradually install electric appliances building by building relative to having to replace all pipelines and appliances before being able to achieve higher hydrogen blends.

Another competing technology is **thermal energy networks**, which use pipelines to exchange heat between buildings and the earth.[37] These networks are highly efficient and can be especially helpful in colder climates where electrification may be relatively more expensive.

TAKEAWAY: Regulators should deny hydrogen-blending requests given their generally worse climate, health, safety, and cost outcomes relative to alternatives.[38] Legislators should similarly avoid supporting hydrogen blending. A review of 54 independent studies finds that "at best hydrogen will play a niche role for heating buildings," such as to back up electric heat pumps in extremely cold climates.[39] The prevalence of gas utility hydrogen blending proposals does not imply value as a climate solution—instead, these proposals allow gas utilities to profit from new infrastructure investments while delaying meaningful emissions reduction efforts.

FURTHER READING:

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DAY-TO-DAY POWER GENERATION

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
TERRIBLE	**7-8** $kgCO_2e/kgH_2$	**83** MMT H_2	**0.7-1.5** $\$/kgH_2$

Hydrogen can’t compete with direct clean energy use or batteries for daily power needs.

NOTE: *This should be compared with the “Seasonal Electricity Storage” overview.*

CONTEXT: Electric utilities and independent power producers (IPPs) in at least 18 U.S. states have proposed “hydrogen-ready” power plants, aiming to co-fire natural gas and hydrogen to gradually reduce these facilities’ carbon intensity.[40] The U.S. Environmental Protection Agency (EPA) also issued rules in April 2024 addressing climate pollution from existing coal- and new natural gas-fired power plants, with hydrogen co-firing being one potential compliance tool.[41]

SCOPE: The top-line metrics assume 75 percent of the total natural gas used for U.S. power generation in 2022 is replaced with hydrogen (representing the assumed share that would contribute to day-to-day power generation), with hydrogen turbines matching the heat rate (efficiency) of the natural gas turbines they’re using or replacing.

INFRASTRUCTURE NEEDS: Hydrogen is not a “drop-in” fuel replacement for natural gas; however, it is possible to design or retrofit natural gas power plants to handle some share of—and up to 100 percent—hydrogen while keeping the same “basic configuration” of the turbine.[42] Hydrogen can also be electrolyzed and stored on site; however, salt dome caverns may be the only cost-effective bulk storage option and are geographically limited.[43] Hydrogen sourced via pipeline would likely need to come from new or repurposed lines, as nearly all existing U.S. natural gas transmission pipelines are subject to embrittlement from hydrogen.[44]

A core challenge with hydrogen for power generation is controlling emissions of nitrogen oxide (NOx)—a pollutant that harms the respiratory system.[45] Standard “diffusion” combustion systems can be modified or built to use 100 percent hydrogen, but doing so could worsen NOx emissions due to hydrogen’s higher flame temperature. Newer “lean premix” combustion systems can mitigate NOx emissions by keeping temperatures low, but these systems struggle to manage natural gas’s and hydrogen’s disparate characteristics.[46] Today’s cutting-edge premix systems are limited to approximately 50 percent hydrogen co-firing by volume—a rate that would only cut climate pollution by 22 percent at most (i.e., with zero-carbon hydrogen and no hydrogen leakage) due to hydrogen’s lower volumetric energy density.[47] Separately, post-combustion emissions control technologies can further reduce (but not eliminate) NOx.[48]

SOCIAL IMPACTS: Burning hydrogen to help meet day-to-day electricity demands carries risks related to greenwashing, public health, and consumer costs. Electric utilities and IPPs often plan to test low levels of hydrogen co-firing, then gradually raise this amount over time. Such proposals can imply two benefits, neither of which tell the full story. First, the climate impact of such claims appears as if it would be the share of hydrogen being co-fired (e.g., 30 percent co-fire by volume equating to a 30 percent greenhouse gas emissions reduction), but the reality is much lower (approximately 12 percent in this example) due to hydrogen’s lower volumetric energy density. Second, this strategy suggests such facilities will eventually burn exclusively clean hydrogen; this may be the intent, but as discussed below, this is very unlikely for intermediate and baseload power generation. Ultimately, such plans may only prolong fossil fuel power plants (and their pollution in surrounding communities) with few real benefits.

Co-firing hydrogen with natural gas can worsen NOx emissions, particularly if using diffusion combustion systems.[49] This may even be allowed under current EPA rules, as emissions limits for natural gas currently do not apply equally to hydrogen.[50] While measures can be taken to reduce NOx emissions, these facilities are often in communities that have long borne the brunt of harmful air pollution, and the residual levels may still be unacceptable.

Lastly, hydrogen co-firing costs can be extreme even with federal subsidies and particularly when predicated on frequent operations.[51] The costs of fuel, facility upgrades, and stranded assets (i.e., facilities closing early because they are no longer competitive or able to comply with federal regulations) can all be passed through to customers with regulatory approval.

COMPETING TECHS: The key consideration for hydrogen in power generation is *when* the hydrogen is being used. This end-use overview looks at replacing natural gas with hydrogen for most of its current use, which is to help serve day-to-day electricity demands.

On an average day, it is cheapest to meet demand with low to zero marginal cost **clean energy resources** like wind, solar, geothermal, hydro, and nuclear power. **Lithium-ion batteries** are complementary to these clean generation resources—they can charge from excess clean energy in some parts of the day (e.g., afternoon) and discharge in other parts of the day (e.g., evening). Batteries have no emissions, can provide power instantaneously, and have round-trip efficiencies of 85 to 90 percent.[52] By contrast, electrolytic hydrogen combustion has a round-trip efficiency on the order of 24 to 35 percent (at best approaching 65 percent with technological improvements) while having operational limits and NOx emissions impacts.[53] Clean energy and batteries can collectively serve the vast majority of demand. Thus, hydrogen has no role to play in day-to-day power generation, as its use at higher frequencies would imply electrolyzing hydrogen in many of the same hours when it's being burned for power.

TAKEAWAY: Regulators should dismiss proposals to co-fire hydrogen with natural gas at existing power plants or to build new "hydrogen-ready" power plants for the purpose of serving day-to-day power generation needs. Other technologies are available today that can provide these services at lower cost (largely due to their efficiency advantages) and without adverse public health risks. These proposals risk giving electric utilities an excuse to continue operating or building fossil fuel power plants with no actionable plan for cost-effectively cleaning up their portfolio, thereby delaying the transition to a decarbonized electricity generation mix.[54]

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LIGHT-DUTY VEHICLES

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
TERRIBLE	**18-20** $kgCO_2e/kgH_2$	**74** MMT H_2	**[unavailable]** $\$/kgH_2$

Electric vehicles have insurmountable advantages over hydrogen fuel cell vehicles.

NOTE: *This should be compared with the "Heavy-Duty Vehicles" overview.*

CONTEXT: Manufacturers, governments, and researchers have spent decades developing hydrogen fuel cell electric vehicles (FCEVs) in pursuit of clean vehicles that operate similarly to internal combustion engine vehicles (ICEVs)—that is, promising long ranges and fast fueling times. However, battery electric vehicles (BEVs) have improved dramatically over this time, closing the gap on these metrics and taking off in sales and infrastructure deployment. Even so, a desire to keep all options open has kept interest in FCEVs alive. For example, California is dedicating substantial funding to FCEVs despite very low sales and a booming BEV market.[55]

SCOPE: The top-line metrics assume all gasoline use from U.S. light-duty vehicles (LDVs) in 2022 is replaced with hydrogen. They adjust for the relative efficiencies of ICEVs and FCEVs, referencing current (2025) and future (2050) forecasted fuel economies and using compact car and pickup truck vehicle classes as proxies for all LDVs.

INFRASTRUCTURE NEEDS: Supporting hydrogen LDVs at scale would require building out an expansive network of refueling stations, tanker trucks (to deliver hydrogen), and—when demand is sufficiently high—dedicated hydrogen pipelines. Given that hydrogen is a much less energy-dense (but more volatile) fuel than gasoline, refueling stations require large storage tanks, compression or liquefaction equipment, and safety systems.

As of 2023, there was a massive gap in the number of U.S. public BEV charging stations (more than 100,000) and hydrogen refueling stations (60).[56] BEVs have a clear path to growth, as they allow for recharging at home; public charging stations can also be built in a modular manner while using the existing distribution system, which can be gradually upgraded over time.

By comparison, FCEV refueling stations represent a big risk. Not long ago, policymakers were pursuing compressed natural gas (CNG) vehicles to help clean up the transportation sector; however, CNG stations peaked in 2016 and have been closing due to "high repair and operating costs, and fleets transitioning away from CNG."[57] As BEVs have taken off, CNG stations are being stranded, hurting consumers who took on the risk of buying CNG cars.[58] This same situation is likely to play out with FCEV stations—a risk consumers shouldn't have to bear.

SOCIAL IMPACTS: FCEVs are generally a net benefit for reducing local pollution, as ICEVs cause health-harming smog while fuel cells emit only water vapor.[59] However, if electrolytic hydrogen production is dirty, this benefit risks coming at the cost of communities near fossil fuel power plants that will run more often to supply the power.[60] Unlike with BEVs, dirty electrolytic hydrogen can wipe out or reverse FCEVs' climate benefits—an impact that can be worsened by the high rates of hydrogen leakage at refueling pumps, given that hydrogen has approximately a 12 times greater warming impact than CO_2 over a 100-year period.[61]

Building out a hydrogen distribution system to refuel FCEVs will also raise transportation costs for consumers (or result in two sub-par systems in FCEV and BEV infrastructure). While BEVs are taking off and have a path to self-sufficiency, FCEVs would likely only grow with heavy and sustained policy support, which would raise taxes and electricity rates (or cut support for BEVs).

COMPETING TECHS: FCEVs' key roadblock is that **battery electric vehicles** outperform them on many key metrics and are closing the gap on the others.[62] BEVs are much more efficient, requiring two to three times less clean electricity than FCEVs using electrolytic hydrogen.[63] They cost less than FCEVs—on sticker price, fuel costs, and maintenance—and this will remain true over time.[64] They have better acceleration, better handling, and more cargo space.[65]

FCEVs currently outperform BEVs on range and refueling speed. However, 96 percent of LDV trips are less than 125 miles, meaning BEVs can complete most trips on a single charge.[66] BEV ranges also continue to improve (with the latest Tesla Model S surpassing 400 miles), as do the quality and availability of fast chargers (now able to get BEVs back to "80 percent charge in 30 minutes" and with much shorter times on the horizon).[67] Further, BEVs can be charged at homes and businesses, meaning most consumers likely already spend far less idle time refueling with BEVs than with FCEVs or ICEVs.[68] This all points to a vanishingly small use case for hydrogen LDVs, making it extremely costly to build an enabling FCEV refueling network.

Markets and analysis both reveal BEVs' superiority. BEVs are already reaching cost parity with ICEVs, with 1.1 million cars sold in the U.S. in 2023—up 48 percent year-over-year and capturing 7 percent of the market.[69] Studies show current policies may see U.S. electric LDV sales rise to 56 to 67 percent by 2032, and reaching 100 percent sales by 2030 would help save $2.7 trillion through 2050.[70] By contrast, analysts expect FCEVs will remain "a very small portion" of LDV sales through 2044, and fewer than 3,000 FCEVs were sold in 2023—down from 2021's peak.[71]

TAKEAWAY: BEVs have an enormous lead in vehicle sales and charging station deployment, fundamental efficiency and performance advantages, and a clear path to mitigate range and refueling speed concerns. This reality makes hydrogen LDVs not only unnecessary for realizing a clean transportation system but also counterproductive to achieving this goal in a timely and cost-effective manner. BEVs will require significant public investment to reach maturity—including for charging stations, fleet purchases, and staff for city and highway planning. Using limited resources on duplicative hydrogen infrastructure risks raising consumer costs, leading to stranded assets, and hindering BEVs' growth. Private companies should be welcome to take risks in investing in FCEVs, but policymakers should prioritize scaling BEVs' proven success.

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HEAVY-DUTY VEHICLES

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
POOR	**13-14** $kgCO_2e/kgH_2$	**35** MMT H_2	**4.0-5.0** $/$kgH_2$

Electric trucks are cheaper than fuel cell options, with the performance gap narrowing.

NOTE: *This should be compared with the "Light-Duty Vehicles" overview.*

CONTEXT: While light-duty vehicles (LDVs) are well on their way to an electric future, hydrogen is often talked about as still having a sizable market in cleaning up heavy-duty trucks (HDTs)—and particularly long-haul tractor-trailers—due to perceived limitations with battery electric trucks (BETs). For example, six of seven federally funded hydrogen hubs have plans to build out hydrogen refueling station networks, with at least five explicitly pointing to serving HDTs.[72]

SCOPE: The top-line metrics assume all diesel use from U.S. Class 7-8 HDTs in 2022 is replaced with hydrogen.[73] They adjust for the relative efficiencies of internal combustion engine trucks (ICETs) and fuel cell electric trucks (FCETs), referencing current (2025) and future (2050) forecasted fuel economies and using Class 8 tractor-trailers as proxies for all Class 7-8 trucks. This analysis does not examine other medium- or heavy-duty vehicle classes, but Class 7-8 trucks consume a majority (approximately 68 percent) of U.S. transportation sector diesel.[74]

INFRASTRUCTURE NEEDS: Supporting hydrogen HDTs would not require as expansive of a network of refueling stations and pipelines as for hydrogen LDVs, as this infrastructure could be limited to major highways and industrial centers. However, hydrogen HDT refueling stations "require significantly more hardware and, in turn, have higher construction costs" than comparable electric HDT recharging stations.[75] Both electric and hydrogen HDTs would need substantial investments in transmission lines or pipelines, respectively, to supply their stations; however, electric HDTs' greater efficiencies would make co-located electricity generation and storage lower cost for recharging stations than co-located hydrogen electrolysis and storage.

The key infrastructure challenge for hydrogen HDTs is justifying the cost of pipelines and stations for serving a limited and contested slice of the HDT market. Nearly 90 percent of all domestic freight tonnage is moved less than 250 miles—a use case that clearly favors electric HDTs.[76] Medium-duty vehicles like buses and delivery vehicles are also well suited to go electric, even in cold weather.[77] The question then becomes whether (or to what extent) it's lower-cost to build hydrogen infrastructure to support the remaining, more challenging HDT use cases relative to fostering continually improving electric HDTs and charging solutions.

SOCIAL IMPACTS: FCETs are generally a net benefit for reducing local pollution, as ICETs are responsible for health-harming smog while fuel cells emit only water vapor.[78] However, if electrolytic hydrogen production is dirty, this benefit risks coming at the cost of communities near fossil fuel power plants that will run more often to supply the power.[79] Unlike with BETs, dirty electrolytic hydrogen can wipe out or reverse FCETs' climate benefits—an impact that can be worsened by the high rates of hydrogen leakage at refueling pumps, given that hydrogen has roughly a 12 times greater warming impact than CO_2 over a 100-year period.[80]

COMPETING TECHS: Even with long-haul tractor-trailers, **battery electric trucks** are likely to be cheaper than FCETs, limiting the latter's growth and longevity. BETs are much more efficient, requiring two to three times less clean electricity than FCETs using electrolytic hydrogen.[81] Studies find long-haul tractor-trailer BETs will be less expensive than diesel ICETs on a total cost of ownership basis by 2030 (holding true even at "very high daily mileages" and when factoring in battery size limits and electric infrastructure costs) and on sticker price by 2040.[82] These BETs will also be less expensive than hydrogen FCETs, which will "struggle" to reach parity with ICETs.[83] Other studies also show BETs' cost advantage over ICETs and FCETs.[84]

The argument in favor of hydrogen HDTs is that they are more capable of meeting companies' strict timetables due to their longer range, faster refueling, and greater cargo capacity. However, this performance gap is quickly closing due to innovations in batteries and charging.

First, batteries are rapidly improving on cost and energy density. Battery prices and energy densities have fallen 19 percent and risen 7 percent (respectively) on average with every doubling in deployment, with no signs of slowing.[85] As this trend continues, batteries will enter new markets like buses and vans, driving more deployment that fuels this virtuous cycle and expands charging infrastructure.[86] In fact, real-world tests show "big improvements in [battery] trucks and chargers" and that "truck depots can operate battery electric vehicles in large numbers in a variety of use cases," which makes weight limits much less of an issue.[87]

Second, charging innovations are boosting BETs' on-road time. New ultra-fast chargers can add 150-250 miles in just 30 minutes; paired with higher ranges, mandatory breaks and driving time limits, and charging opportunities during loading and unloading, battery tractor-trailers will soon be capable of handling most jobs.[88] Electric rate design reforms can help charging become "substantially cheaper than diesel" by setting time-varying rates and avoiding the highest-price hours. Innovations in how trucks charge may further propel battery HDTs' advantage.[89] For example, 50 percent of electric trucks sold in China in 2022 were battery-swap capable, able to pull into stations to exchange depleted batteries for full ones in minutes.[90]

TAKEAWAY: Hydrogen HDTs may have a niche market for especially difficult jobs, such as those requiring around-the-clock operations, extremely high payloads, or operations far from the grid. However, battery HDTs are increasingly capable of handling the vast majority of tasks, including in long-haul, heavy-duty trucking. Battery HDTs' fundamental efficiency advantage, favorable cost prospects, and domination of other transportation markets may leave hydrogen HDTs little room to grow and suggest policymakers should prioritize battery HDTs' success.

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INDUSTRIAL PROCESS HEAT

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
POOR	**7-9** $kgCO_2e/kgH_2$	**51** MMT H_2	**0.7-1.5** $\$/kgH_2$

Hydrogen may be limited to opportunistic retrofits for providing high-temperature heat.

CONTEXT: More than 90 percent of combustible fuel use in U.S. industry (i.e., excluding fuels used as feedstocks) is used to provide heat to alter materials or manufacture goods.[91] Different industrial processes require different temperatures of heat, categorized loosely as low (below 100-200°C), medium (from 100-200°C to 500°C), and high (above 500°C). Particularly for high-heat processes needed to make steel, cement, glass, and chemicals, industrial stakeholders often look to lower-carbon fuels like hydrogen to reduce their emissions.[92] This is because hydrogen readily achieves high temperatures and—as a fuel—is a more familiar concept that might not require as many changes to equipment and processes (relative to electrification).

SCOPE: The top-line metrics assume all natural gas used in the U.S. manufacturing sector in 2022 for non-feedstock purposes (making up approximately 81 percent of non-feedstock industrial energy use) is replaced with hydrogen. It assumes hydrogen-using technologies are equally efficient as natural gas-based counterparts. For simplicity, this analysis does not assess hydrogen for replacing coal or oil for industrial heat, though this is doable (if more complex).

INFRASTRUCTURE NEEDS: Hydrogen is not a "drop-in" fuel replacement for natural gas; equipment designed to burn fossil fuels may need modifications before it can use significant shares of (or 100 percent) hydrogen.[93] This is due to hydrogen's unique properties, including a fast flame speed (increasing the risk of "flashback" that can damage equipment), high flame temperature that increases harmful nitrogen oxide (NOx) emissions, low volumetric energy density (meaning you must burn more hydrogen than methane to get the same heat output), and small molecule size (worsening risks of leakage, explosions, and embrittlement of pipes and other equipment).[94] With the right upgrades and technological advancements, it may be possible to account for these differences, but it may also require a large investment by facility owners, whether for retrofits or replacements of equipment with very long service lives.[95]

Industrial heat—particularly at high temperatures—requires a lot of energy, whether through hydrogen or electricity. As discussed below, electric technologies own a significant efficiency advantage. Hydrogen may hold an edge for a given facility if it's easier to build pipelines to deliver fuel than an energy-equivalent amount of electric transmission, or if it's much easier to reconfigure the facility to use hydrogen. However, this may require new, dedicated hydrogen pipelines, as natural gas pipelines are not suited to handle high shares of hydrogen.[96]

SOCIAL IMPACTS: Burning hydrogen for industrial process heat primarily carries public health risks related to its potential for worsened NOx emissions. Industrial facility owners can install equipment and modify operations to mitigate these emissions—such as by premixing fuels, adjusting airflow, and using post-combustion controls—though they would not be expected to do so absent regulation.[97] Such measures can reduce NOx emissions below that of natural gas combustion, but because these facilities are often in communities that have long borne the brunt of harmful air pollution, the residual NOx may still be unacceptable.[98]

COMPETING TECHS: The main competitor to hydrogen for cleaning up industrial process heat is electric technologies, which can collectively meet any temperature requirements at higher efficiencies and with no air pollution.[99] These technologies vary in market readiness, meaning some industrial sectors can switch to electric heat today (e.g., food, paper), while others need research and development before they'll be available (e.g., cement).[100] One study finds commercialized technologies could electrify 78 percent of non-feedstock industrial energy demand in Europe, rising to 99 percent when including technologies under development.[101]

Electric technologies providing industrial heat include electric boilers, heat pumps, resistance heating, induction heating, plasma torches, electric arc furnaces, and shock-wave heating.[102] **Heat pumps** are notable for moving rather than generating heat, allowing them to use 1.5 to five times less energy to provide the same amount of heat as perfectly efficient combustion.[103] However, they are limited to lower temperatures (up to 200°C) and lose efficiency when generating higher temperature increases.[104] **Thermal batteries** convert electricity into heat (using resistance) and can store this heat for days at temperatures up to 1,700°C in a thermal storage medium (e.g., graphite blocks) surrounded by insulated casing.[105] This means electricity can be procured when it's clean and low-cost, with heat then available on demand, all while maintaining a high round-trip efficiency of around 95 percent. Other technologies are also under development that replace the need for high-temperature heat altogether, helping to clean up trickier sectors like cement production.[106]

Due to losses from electrolysis and combustion, hydrogen for industrial heat is generally far less efficient than electric alternatives, requiring on the order of 1.5 times as much clean electricity to play the same role.[107] However, electric technologies can require larger, more complex retrofits or replacements of existing equipment than hydrogen.[108] They may also require grid upgrades to permit higher power draws. While hydrogen may use more electricity overall, it may be situationally easier to deliver (via new pipelines) than electricity.

TAKEAWAY: There may be opportunities for hydrogen in a few niche high-temperature heat cases, such as in retrofitting newer combustion equipment, using hydrogen to serve multiple roles (e.g., as a feedstock), or when building hydrogen pipelines would be much less expensive than new transmission lines. However, directly electrifying industrial process heat should be prioritized wherever possible due to its higher efficiency and lack of harmful air pollution.

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SEASONAL ELECTRICITY STORAGE

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
UNCERTAIN	**7-8** $kgCO_2e/kgH_2$	**28** MMT H_2	**[unavailable]** $\$/kgH_2$

Hydrogen can serve long-duration energy storage needs but carries public health risks.

NOTE: *This should be compared with the "Day-to-Day Power Generation" overview.*

CONTEXT: Achieving a fully clean electricity system with a high share of variable renewable energy resources will require complementary long-duration energy storage (LDES) services.[109] In particular, the grid will need seasonal to multi-annual energy storage capacity, with the former primarily shifting wind and solar generation from high- to low-output months, and the latter primarily shifting hydro generation from wet to dry years. Electrolyzers can use excess clean energy to make hydrogen, which can then be stored at large volumes over long periods.

SCOPE: The top-line metrics assume 25 percent of the total natural gas used for U.S. power generation in 2022 is replaced with hydrogen (representing the assumed share that would be needed to serve in a seasonal electricity storage capacity), with hydrogen turbines matching the heat rate (efficiency) of the natural gas turbines they're using or replacing.

INFRASTRUCTURE NEEDS: Combustion turbines can burn hydrogen for power, but a core challenge is controlling emissions of nitrogen oxide (NOx)—a pollutant that harms the respiratory system.[110] Today, new or modified turbines can burn 100 percent hydrogen with high NOx emissions (conventional "diffusion" combustion) or co-fire up to 50 percent hydrogen with natural gas with lower NOx emissions (newer "lean premix" combustion).[111] However, it will be critical to achieve 100 percent hydrogen use with near-zero NOx emissions.

Hydrogen for LDES implies the use of "peaker" power plants that run infrequently but can quickly adjust their operations. Facilities predicated on running more often (e.g., combined cycles) don't make sense for hydrogen, as their frequent use would imply electrolyzing hydrogen in many of the same hours that it's being burned for power.[112] Only LDES services justify hydrogen's inefficiencies for power.[113]

Fuel cells can also use hydrogen to generate power, notably more efficiently than combustion and with no harmful emissions.[114] Cost and performance obstacles at scale currently make them better suited for distributed than centralized power, though the latter may improve with time.[115] Fuel cells can provide backup power for critical facilities (e.g., hospitals) where batteries might be too expensive for keeping large complexes online for long periods, but these cases are rare enough to refuel on-site hydrogen storage tanks via trucks rather than build pipelines.

In general, power plants are unlikely to someday gain access to readily available hydrogen via pipeline—instead, utilities should have clear plans for how hydrogen will be electrolyzed and stored, as they will likely need to provide or procure the clean power for electrolysis. Such plans may include new or repurposed hydrogen pipelines where they allow power plants to access underground storage sites like salt dome caverns, which have very large capacities and lower costs but are geographically limited.[116] Pipelines can also connect other high-value hydrogen users in tight industrial clusters. This allows for “sector coupling,” where power plants can use more hydrogen in some periods and put more hydrogen into the pool in others.[117] Flexibility by other customers in their hydrogen use can then reduce storage costs for the whole cluster.

SOCIAL IMPACTS: Hydrogen for LDES faces two main risks. First, developers may pursue “hydrogen-ready” peakers without a clear plan for switching to 100 percent clean hydrogen. Falling short can drive overinvestment in natural gas on the premise of these plants someday being clean.[118] Second, developers may fail to adequately control NOx emissions. Peakers are disproportionately located in low-income neighborhoods and communities of color, where they considerably worsen health outcomes even when emitting at permitted rates.[119]

COMPETING TECHS: Two types of competing technologies exist for this end use—other storage resources that can act as LDES, and energy resources that shrink the need for storage.

There are four classes of technologies that can provide LDES: (1) **mechanical storage** like pumped hydro or compressed air energy storage; (2) **electrochemical storage** like iron-air or flow batteries; (3) **thermal storage**; and (4) **chemical storage** like hydrogen and its derivatives (e.g., ammonia).[120] Many hold an edge over hydrogen in higher round-trip efficiency or having no risk of harmful emissions. However, hydrogen’s relative competitiveness improves at seasonal and multi-annual durations and when it can take advantage of sector coupling.[121]

Other technologies can cut the need for LDES by complementing variable renewable energy. Emerging options include **enhanced geothermal** and **advanced nuclear**, which can run around the clock or follow changes in electricity demand.[122] **Carbon capture** may also play a role, particularly if it can fully eliminate on-site emissions (e.g., Allam Cycle plants) and use biofuels.[123] However, any use of natural gas would suffer from upstream methane leakage, and biofuel combustion or gasification brings its own health-harming emissions challenges.[124]

TAKEAWAY: Regulators should require a very high burden of proof of hydrogen power plants’ value on cost, feasibility, public health, and equity metrics relative to competing technologies. Proposals should be limited to seasonal storage applications, include detailed plans for how and from where utilities will procure clean hydrogen, and ensure that power plants will be capable of using 100 percent hydrogen with ultra-low to zero NOx emissions. This will require sites with high variable renewable energy penetration (to justify the need for LDES) and low-cost geologic storage; it will also depend on the successful development of cost-effective fuel cells or low-NOx hydrogen combustion systems. In most U.S. jurisdictions, LDES needs are still many years away, meaning regulators need not make big bets on hydrogen today—especially since doing so could lock in fossil fuel infrastructure if it fails to pan out.[125]

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MARINE SHIPPING

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
GOOD	**10-12** $kgCO_2e/kgH_2$	**10** MMT H_2	**0.7-3.0** $/kgH_2

Hydrogen can be used to make two alternative fuels enabling long-distance marine trips.

NOTE: *We rate long-haul marine shipping as "good" but short-haul marine shipping as "poor." This overview does not cover marine port operations.*

CONTEXT: Marine shipping vessels primarily burn bunker fuels like heavy fuel oil or marine gas oil.[126] However, in July 2023, the International Maritime Organization's 175 member states voted unanimously to work toward net-zero marine shipping by "close to" 2050.[127] Thus, the industry has momentum to decarbonize, but it will need policy support to ensure the costs of this transition will be borne across all parties rather than harming first movers.

Hydrogen could support a clean maritime sector in several ways. For example, hydrogen can be used directly via fuel cells or combustion to power ships, which is feasible for shorter-distance trips.[128] However, hydrogen storage on board is a big challenge, and marine shipping requires high energy densities for long-haul, transoceanic voyages with large cargo capacities.

Hydrogen-derived e-fuels therefore hold greater promise for much of long-distance marine shipping. In particular, electrolytic hydrogen can be used to make clean ammonia (NH_3) using nitrogen from the air as well as clean methanol ($CH3OH$) using a net-zero source of carbon.[129] Maritime companies are already ordering vessels that can be powered by these e-fuels.[130]

SCOPE: The top-line metrics assume hydrogen, hydrogen-derived ammonia, or hydrogen-derived methanol replace all U.S. residual oil and distillate fuel oil consumption from domestic and international shipping in 2022. They use fuel cell ships for 10 percent (domestic) and ammonia or methanol ships for 90 percent (international) of marine fuel consumption.

INFRASTRUCTURE NEEDS: The direct use of hydrogen generally requires new vessels, in part to accommodate extra space required for hydrogen storage. Hydrogen must be liquefied to increase its volumetric density for storage; this requires energy-intensive cryogenic tanks to keep it at -253°C.[131] Liquefied hydrogen also suffers from evaporative "boil-off" losses, which can quickly compound over longer voyages and erode climate benefits. Hydrogen ships would require new bunkering (i.e., refueling) equipment and processes, which no port has today.[132]

Among the e-fuels, methanol is furthest along.[133] Methanol's key advantages are it being liquid at room temperature (thus not needing cryogenic tanks or pressurization) and its ability to largely use existing infrastructure; in particular, it can be used with "minor modifications" to existing vessels, with some ships running on methanol today.[134] Its key downside is its reliance on a carbon source; this can initially be sourced from fossil fuel combustion (albeit with half the climate benefit) but must eventually come from a net-zero source (e.g., biomass or the air).

Ammonia is less proven as an e-fuel, but its production is a mature process. Ammonia's key advantage is not needing a carbon source for its production, which implies a lower long-term fuel cost once enabling infrastructure is built out.[135] Its key downside is it generally requires new ships with specialized combustion equipment and cryogenic storage to cool it to -33°C—but relative to hydrogen, its liquefication uses much less energy and results in far less boil-off.[136]

SOCIAL IMPACTS: Conventional bunker fuels are highly polluting, releasing harmful sulfur oxides (particularly from heavy fuel oil but largely mitigated from marine gas oil), nitrogen oxides (NOx), and particulate matter that endanger port communities. Hydrogen and e-fuels can reduce or eliminate sulfur oxides and particulate matter, though NOx is more complicated and can remain high from hydrogen or ammonia combustion.[137] Methanol and (especially) ammonia are also toxic. Methanol spills may be less harmful for the environment and marine ecosystems relative to oil; the evidence is less clear for ammonia, which may be more damaging but over a smaller area and for a shorter period of time.[138] Supplemental power technologies—such as wind-powered sails, on-board solar, and batteries—and optimizing logistics (e.g., "just-in-time arrival") can mitigate these impacts by reducing fuel use.[139]

COMPETING TECHS: The top competitors to hydrogen and e-fuels for marine shipping are biofuels and electrification. **Biofuels** cover a wide range of products, from ones that can be directly used in today's vessels to ones that can be converted to bio-methanol (offering a hydrogen-free option for methanol-powered ships).[140] Some biofuel-derived products even require hydrogen for refining into renewable diesel.[141] Biofuels' big downside is sustainable feedstock availability, as multiple sectors will be competing for the same limited supply.[142]

Battery-powered **electric ships** are most prominently competing with hydrogen for smaller, shorter-haul vessels (e.g., ferries, tugs).[143] They face challenges for longer-haul routes due to batteries' current higher weight and space requirements per unit of energy that they provide. However, batteries' relatively high round-trip efficiencies suggest that battery-optimized vessel designs could make direct electrification cost-effective for on the order of 40 percent of global containership traffic.[144] Batteries also continue to rapidly fall in cost and improve in efficiency; paired with advances in supplemental power technologies and maritime logistics, electric ships may have the potential to serve even more of the long-haul shipping market.[145]

TAKEAWAY: Hydrogen-derived methanol and ammonia may play a big role in cleaning up long-haul marine shipping, though the relative share of these e-fuels—as well as their ultimate competitiveness with biofuels and electric ships—is less certain. Battery ships' fundamental efficiency advantage is likely to win out over hydrogen vessels for short-haul marine shipping. In all cases, decarbonized shipping is likely to mitigate local pollution risks (supported by supplemental power technologies), though electric ships are needed to eliminate these risks.

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AVIATION

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
GOOD	**9-15** $kgCO_2e/kgH_2$	**29** MMT H_2	**0.7-3.0** $/kg$H_2$

Hydrogen can be used to make sustainable aviation fuels needed for long-distance flights.

NOTE: *We rate long-haul aviation as "good" but short-haul aviation as "uncertain."*

CONTEXT: The conventional approach to reducing aviation emissions has been via sustainable aviation fuel (SAF), defined as "liquid hydrocarbon jet fuel produced from renewable or waste resources that is compatible with existing aircraft and engines."[146] SAF uptake to date has been negligible, but the U.S. SAF Grand Challenge aims to rapidly scale its use by 2050.[147]

Hydrogen could play several roles in decarbonizing aviation. Fuel cell-powered aircraft have high efficiencies but low range, while hydrogen combustion aircraft can achieve greater range but are still limited to about a third of the passenger market.[148] Ultimately, aviation requires high energy densities to support more passengers or cargo and travel longer distances.

Hydrogen-derived SAF ("e-fuels") therefore holds the greatest potential for most of the aviation sector. The Fischer-Tropsch process converts hydrogen and carbon into liquid e-fuels. Carbon can initially be sourced from fossil fuel combustion (albeit with half the climate benefit) but must eventually come from a net-zero source (e.g., biomass or the air).[149] The most promising path may be power-and-biomass-to-liquids (PBtL), in which hydrogen boosts SAF output per unit biomass by a factor of 2.4-3.75 relative to conventional, hydrogen-free biomass routes.[150]

SCOPE: The top-line metrics assume hydrogen or e-fuels replace all U.S. jet fuel consumption in 2021, including from private airlines (domestic flights and international departures) and the federal government (including military). The metrics use fuel cell aircraft for 1 percent, hydrogen combustion for 33 percent, and PBtL e-fuels for 66 percent of jet fuel replacement.

INFRASTRUCTURE NEEDS: The direct use of hydrogen requires new or retrofitted aircraft, in part to accommodate extra space for liquid hydrogen storage.[151] These aircraft would need to meet specific design standards to ensure compatibility with the same airports as today's jets.[152] Airports would also need hydrogen delivery, storage, and refueling infrastructure.

E-fuels can be used in existing aircraft with up to a 50 percent mix with conventional fuel—though work is underway to allow for 100 percent.[153] This limits the need for changes to jets or airports. Instead, e-fuels require carbon sources (e.g., carbon capture equipment, biomass) and SAF production facilities. One study finds PBtL production could be cost-effective in much of the U.S. Midwest and Great Plains by using off-grid renewables to power electrolyzers (avoiding grid interconnection costs), steel tanks to store hydrogen, and local biomass production—with e-fuels able to use existing jet fuel infrastructure rather than requiring hydrogen pipelines.[154]

SOCIAL IMPACTS: Jet fuel combustion worsens local air quality by releasing smog-forming compounds, toxins, and particulate matter, raising airport workers' and adjacent communities' risk of respiratory issues, cardiovascular disease, and cancer.[155] E-fuels can improve air quality because of their lower sulfur content and fewer impurities.[156] Hydrogen fuel cell aircraft would cause no pollution, but hydrogen combustion aircraft would still emit harmful nitrogen oxides.

Jet fuel combustion also creates contrails—created by water vapor attaching to particulate matter and freezing—that could be responsible for as much as two-thirds of aviation's climate impact.[157] E-fuels can only partially mitigate this problem (from emitting fewer particulates).[158] Hydrogen fuel cell and combustion aircraft do not emit particulates, but they do emit relatively more water vapor, which can attach to naturally present aerosols—so their impact on contrail formation and their climate warming effects are currently unclear.[159]

COMPETING TECHS: The top competitor to hydrogen for SAF production is **biomass**, with most SAF made today (and expected in the near future) coming from fats, oils, and greases—though some hydrogen is often used to treat biomass to produce SAF.[160] The U.S. Department of Energy finds there is more than enough potential biofuel supply in the U.S. to replace all jet fuel "without impacting agriculture, trade, or current uses of biomass."[161] However, other studies find this wouldn't be sufficient to also support other sectors' biofuel needs for their decarbonization or would strain land use.[162] Thus, while biomass has momentum and greater technological maturity, hydrogen-based PBtL's ability to cut biomass needs—along with its cost and emission advantages—may give it an edge to serve much of the market.[163]

The top competitor to hydrogen fuel cell and combustion aircraft for short-haul aviation is **battery electric technologies**. These aircraft have a substantial energy efficiency advantage over hydrogen alternatives but suffer from the relatively high weight of batteries, which will need dramatic improvements in energy density to access more than a tiny share of the market.[164] For example, current technologies can only achieve up to 400 miles with fewer than 10 seats.[165] By comparison, fuel cell aircraft can achieve similar ranges but with roughly five times more seats, and hydrogen combustion aircraft can reach ranges of several thousand miles and far greater capacity.[166] However, new aircraft design concepts (optimized for batteries rather than jet fuel) may be able to achieve much more range or capacity.[167] If battery aircraft find success for more short-haul trips and SAF scales quickly for long-haul trips, there may be less appetite to build infrastructure to enable a shrinking market for hydrogen aircraft.

TAKEAWAY: Hydrogen-based e-fuels hold great potential to reduce biofuel demands for cleaning up long-haul aviation, and hydrogen fuel cell and combustion aircraft will compete with battery aircraft for shorter-range trips. However, SAF does little to solve local air pollution and climate-warming contrail issues. Thus, barring a breakthrough, it will still be important to take other measures to mitigate aviation's harms—including reducing air travel.[168]

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PETROCHEMICALS

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
GOOD	**3-4** $kgCO_2e/kgH_2$	**50** MMT H_2	**0.9-2.3** $/$kgH_2$

Hydrogen can be paired with captured carbon to build chemicals needed in everyday life.

CONTEXT: The chemicals industry produces more than 100,000 types of chemicals; however, most of them derive from a handful of building blocks: petrochemicals (which contain carbon) and ammonia (which doesn't contain carbon and is covered in a separate overview).[169] Loosely, the former include methanol, olefins, and aromatics; together, they are used to make diverse products such as plastics, pharmaceuticals, cleaning products, paints, and synthetic fibers.[170]

Petrochemicals are almost exclusively made from fossil fuels. In fact, a primary use of hydrogen today (starting from natural gas) is making methanol.[171] However, electrolytic hydrogen and captured carbon can also be used to make "e-methanol," which can in turn make most petrochemicals via methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) processes.[172]

This overview describes how electrolytic hydrogen can obviate the need for fossil fuels in making most petrochemicals.[173] It focuses on the carbon embodied in feedstocks, which get "chemically transformed and become part of the output products," rather than fuels, which are burned for heat or electricity and immediately release carbon as CO_2 (with these functions covered in separate overviews).[174] While temporarily fixed, the carbon in feedstocks eventually is released into the atmosphere (such as when plastics are incinerated); thus, the carbon must ultimately come from a net-zero source rather than fossil fuels.[175]

SCOPE: The top-line metrics assume all methanol, olefins, and aromatics production in the U.S. is replaced with hydrogen and a net-zero form of captured carbon. Specifically, the metrics estimate (1) U.S. production of these chemicals for 2022, (2) conversion ratios for hydrogen-to-methanol, MTO, and MTA, and (3) greenhouse gas emissions rates from today's chemicals production. True values either are not public, are not well defined, or range widely depending on many variables. Thus, the results of this analysis have high uncertainty.

INFRASTRUCTURE NEEDS: Today's U.S. petrochemicals are made in 312 petrochemical plants and 131 refineries (which make a substantial share of petrochemicals as byproducts from refining crude oil into more useful fuels).[176] In general, these facilities start with fossil fuels and break them into other chemicals, whereas an electrolytic hydrogen-based chemicals sector would start from component parts and use them to build more complex chemicals. Thus, much of today's chemicals infrastructure may be incompatible with this transition—though midstream and end-use assets like pipelines, tanker trucks, storage sites, and manufacturing plants could move and use the same underlying chemicals as-is.

Clean chemicals will require at least five types of facilities: hydrogen electrolyzers, carbon capture plants, e-methanol production plants, and MTO and MTA facilities. Carbon can initially be sourced from fossil fuel combustion (albeit with half the climate benefit) but must eventually come from a net-zero source (e.g., biomass or the air).[177] E-methanol plants use the same underlying technology as conventional methanol plants but with slightly different configurations; based on current projects, this appears to be enough of a change to warrant new production facilities rather than retrofitting existing ones.[178] E-methanol plants can also be smaller and more distributed, supporting better integration with renewables rather than needing to move lots of energy (or hydrogen) to these facilities.[179]

SOCIAL IMPACTS: Petrochemical facilities and refineries are extreme public health hazards, emitting various toxins and carcinogens.[180] Hotspots of these plants have led to "sacrifice zones that disproportionately harm frontline communities of color and low-income communities."[181] A move to electrolytic hydrogen-based chemicals would reduce health risks associated with fossil fuel production and combustion—and could lower the need for refineries when paired with transportation electrification. However, it might not directly mitigate risks associated with synthesizing more complex chemicals from these net-zero building blocks. The transition could make chemicals production more dispersed since it would not have to be clustered in regions of high fossil fuel extraction or ports, thereby relieving pressure from today's hotspots. However, regulations targeting air pollution would be needed to address the biggest risks.[182]

COMPETING TECHS: Two technology classes can also help reduce the need for fossil fuel-derived petrochemicals. First, **biomass** (as a net-zero hydrocarbon) can take less energy to transform into other chemicals relative to making hydrogen, capturing carbon, and building things from the ground up.[183] For example, Brazil makes ethanol from sugarcane and then uses it to produce ethylene (an olefin); the U.S. currently makes an enormous amount of ethanol from corn for blending in gasoline, but this could instead be used to make ethylene—especially as vehicle electrification advances.[184] Biomass can also be symbiotic with hydrogen: biomass gasification or pyrolysis can produce methanol alongside a CO_2 stream that can be paired with hydrogen to make e-methanol.[185] However, biomass faces limitations from being a more complex feedstock than natural gas or refined oil as well as a constrained supply.[186]

Second, some chemical products can be **recycled**, whether mechanically (e.g., plastics being shredded, melted down, and formed into a new product) or chemically (i.e., broken down into component molecules).[187] However, while recycling can be improved, it faces limits due to quality (e.g., mechanical recycling results in impurities), impracticality of collection, or costs.[188]

TAKEAWAY: While the petrochemicals sector is complex, hydrogen can play a large role in cleaning it up by making e-methanol (with a net-zero source of captured carbon), then further developing and using MTO and MTA processes to make most of the sector's building blocks. However, chemical production's huge hydrogen demand potential and its lasting pollution impacts suggest it will be critical to cut total demand, such as by improving material efficiency.

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PRIMARY STEEL

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
GOOD	**23-32** $kgCO_2e/kgH_2$	**2** MMT H_2	**1.25-2.3** $\$/kgH_2$

Hydrogen is the clearest path to clean up steel, though new technologies are on the way.

CONTEXT: Most primary steel (i.e., high-quality steel originating from iron ore) is made today from the combination of a blast furnace (BF), responsible for 93 percent of global ironmaking, and a basic oxygen furnace (BOF), responsible for 71 percent of global steelmaking.[189] The two processes are often integrated in a single system (BF-BOF) and rely heavily on coal.[190] A lower-emitting method involves using natural gas to purify iron ore via the direct reduced iron (DRI) process, then using electricity to make steel in an electric arc furnace (EAF).[191] Hydrogen can replace natural gas in the DRI process, providing a near-term path to fully clean primary steel.

SCOPE: The top-line metrics assume all coal-based BF-BOF crude steel production in the U.S. in 2022 is replaced with a hydrogen DRI process. The "GHG abatement" range incorporates the two major hydrogen steelmaking pathways as well as whether hydrogen gets credit for the full emissions reductions or shares credit with other changes (e.g., using electricity in the EAF).

INFRASTRUCTURE NEEDS: There are two key hydrogen-based steelmaking routes: hydrogen-based direct reduction to electric arc furnace (H2-DRI-EAF) and hydrogen-based direct reduction to smelter (H2-DRI-SMELT-BOF). Each has its own infrastructure considerations.

Modern natural gas-based DRI systems can already accept up to 30 percent hydrogen, and minor retrofits can enable the use of 100 percent hydrogen.[192] Thus, it's possible to gradually clean up steelmaking by building natural gas DRI facilities (which cut climate pollution 70 percent compared to coal-based BF-BOF) and adding hydrogen as it becomes available.[193]

DRI-EAF plants can be integrated (like BF-BOF) or separated. This means iron production can be sited where iron ore and renewable energy are abundant, with iron shipped elsewhere to produce, finish, and shape steel (making up the vast majority of jobs).[194] This also "considerably decreases" hydrogen infrastructure needs, since iron can be moved rather than hydrogen.[195]

Both hydrogen routes require relatively high-quality iron ore. However, H2-DRI-EAF is limited to the highest-quality pellets, while H2-DRI-SMELT-BOF can use a much wider range of ore.[196] Both processes also require a small amount of solid carbon to strengthen the steel, remove impurities, and increase process efficiency, but this requirement is higher for H2-DRI-SMELT-BOF.[197] Adding carbon drives some CO_2 emissions, so it must come from a net-zero source like charcoal.[198] H2-DRI-SMELT-BOF facilities also can reuse BOFs in coal-based BF-BOF plants—an option that may allow for a smoother transition for these facilities.[199]

SOCIAL IMPACTS: Hydrogen can eliminate the public health risks of the highly polluting coal-based BF-BOF process, such as factory workers' and fenceline communities' higher rates of asthma and cancer (from emissions of fine dusts and carcinogens like cadmium and arsenic).[200] Hydrogen can also reinvigorate steel communities by providing a viable path to keep plants open and competitive. For example, an analysis of the Ohio River Valley shows iron and steel jobs would fall under business as usual but increase significantly under a transition to H2-DRI-EAF, due in part to coal mine closures and rising clean steel demand, respectively.[201]

COMPETING TECHS: There are four categories of low-carbon steel: primary with hydrogen, primary with electricity, primary with fossil fuels and carbon capture and storage (CCS), and secondary with electricity and scrap. Hydrogen is best positioned to make clean primary steel in at least the near to medium term given its commercial readiness and deep emissions reductions. H2-DRI-EAF and H2-DRI-SMELT-BOF have similar cost ranges but different roles.[202]

Two technologies under development that would directly electrify steelmaking are **molten oxide electrolysis** and **alkaline electrolysis**.[203] Both processes can use relatively low-grade iron ore, allow for smaller, modular steelmaking plants, and avoid the need for hydrogen infrastructure (though molten oxide electrolysis requires a large and constant electricity supply to maintain very high temperatures).[204] Their energy requirements are also at least comparable with hydrogen processes and hold potential to become much more efficient.[205] However, they won't be commercially available until 2035-45, and they have high cost uncertainty—meaning it's too risky to wait for them to begin cleaning up steelmaking.[206]

Fossil fuel-based steelmaking with **carbon capture and storage** will not be able to compete with hydrogen.[207] This pathway involves high residual emissions (upstream from coal mining or methane leaks as well as onsite from imperfect carbon capture rates), costly CO_2 pipeline and storage investments, and risks of not qualifying as "clean" in global markets.

Lastly, 20 percent of the global steel market (and 70 percent of U.S. steel production) is **secondary steel**, made with scrap and an EAF.[208] This process uses no iron ore and uses five to seven times less energy than primary steelmaking; thus, it should be expanded wherever possible.[209] However, there are limits to scrap availability (which can be increased with higher-quality recycling and processes to remove impurities), and secondary steel is lower quality (restricting its application to uses like construction).[210] Thus, it cannot replace all primary steel.

TAKEAWAY: Nearly half of U.S. primary steel facilities will have to make major investments to continue operations.[211] Policymakers must act quickly to ensure they transition to cleaner processes (like DRI plants that can move to 100 percent clean hydrogen) to avoid locking in coal-based BF-BOF steelmaking for decades to come. As steel is a highly competitive global market, producers need policy support to ensure they'll remain profitable through such a transition.[212] Newer electric-only technologies may someday play a big role, but hydrogen-based processes are poised for immediate growth and are necessary to clean up steel on a meaningful timeline.

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REFINING

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
EXCELLENT	**9-10** $kgCO_2e/kgH_2$	**6** MMT H_2	**1.0-1.3** $/kg$H_2$

Refining demands must decline with time, but only hydrogen can clean up this process.

CONTEXT: Refineries take crude oil extracted from the ground and refine it into fuels that can be used in vehicles, aircraft, and other equipment.[213] The process of transforming and separating out other molecules also results in a variety of products that can be burned on-site for energy or sold to the chemicals industry. These petrochemicals are a small share of overall refinery output but can be a significant part of their revenue and total petrochemical output.[214]

Refineries are one of the top consumers of hydrogen today, using it to remove sulfur from crude oil and as part of other processes like breaking down complex hydrocarbons into refined fuels.[215] A transition to electric vehicles, clean fuels, and clean feedstocks will eventually remove the need for oil refineries altogether (with these sectors covered in separate overviews). In the meantime, as long as refineries exist, their emissions can be reduced by switching from dirty natural gas-based hydrogen to clean electrolytic hydrogen—a shift that is already beginning.[216]

SCOPE: The top-line metrics assume all steam methane reformation hydrogen used for refining in the U.S. in 2021 is replaced with clean hydrogen. They do not displace hydrogen produced as a byproduct of refining, since this occurs naturally and is generally used on site.

INFRASTRUCTURE NEEDS: There are 131 operable refineries in the U.S. today.[217] Reducing emissions in the refining sector while these facilities still exist relies on retrofitting existing plants (or merely swapping their hydrogen source) and reducing demand for their products.

Most hydrogen used in refineries comes from integrated steam methane reformation (SMR) facilities that make and use natural gas-based hydrogen on site (together with hydrogen produced as a byproduct from refinery processes).[218] The remainder comes from merchant hydrogen producers that may have long-term natural gas offtake contracts upstream, hydrogen offtake contracts with refineries, and privately owned hydrogen pipelines.[219] These dynamics make it difficult for electrolytic hydrogen to access the refining market on price alone (i.e., without regulatory intervention), as it may require stranding often-integrated assets, breaking contracts, or harming relationships with important oil and gas industry stakeholders.

Refineries also generally need a consistent hydrogen supply for their operations, which SMR has traditionally delivered. Moving these plants fully to electrolytic hydrogen is thus likely to require on-site storage or pipelines to smooth gaps in production, as electrolyzers should only run when clean energy is abundant and cheap (which are necessary conditions for lower-cost, zero-carbon hydrogen production).[220]

SOCIAL IMPACTS: Refineries are extreme public health hazards, emitting various toxins and carcinogens.[221] Hotspots of these facilities have led to “sacrifice zones that disproportionately harm frontline communities of color and low-income communities.”[222] A move toward clean hydrogen in refineries will reduce health risks associated with fossil fuel production and combustion. However, it will not directly mitigate risks associated with the actual refining process. Doing so requires regulations targeting air pollution and, ultimately, reducing the need for refineries.[223]

COMPETING TECHS: As hydrogen is a fundamental part of refining, there are no known alternatives to clean hydrogen for reducing emissions from this process. Instead, hydrogen's "competitors" for this market are **technologies that shrink the need for refined products**, such as electric vehicles, sustainable aviation fuels, clean fuels for marine shipping, and hydrogen-derived chemical feedstocks. However, these technologies must gain traction in parallel, as refineries are anticipating lower fuel demand (due to electrification) and are considering retrofits and process changes to emphasize chemicals production.[224]

Electrolytic hydrogen will also arguably face greater competition from SMR hydrogen with carbon capture and sequestration (often called "**blue hydrogen**") in the refining sector. Blue hydrogen perpetuates reliance on fossil fuel extraction and transportation (along with associated leakage) and dependence on subsidies or carbon pricing for its financial viability (as adding and operating a carbon capture system to an existing hydrogen production process will always be more expensive than not adding or operating it). By contrast, electrolytic hydrogen does not depend on fossil fuels and can eventually become cheaper than SMR hydrogen even without subsidies with sufficiently low-cost electrolyzers and electricity. However, in the case of refining, blue hydrogen may hold an advantage in being relatively less disruptive—that is, in newer integrated systems, it may cost less to add carbon capture equipment, as it allows for the continued use of SMR facilities and does not require breaking or restructuring natural gas contracts.[225] As electrolytic hydrogen declines in cost or refining demands wane, dependence on blue hydrogen (and its fossil fuel infrastructure) will also fall.

TAKEAWAY: Refining will be necessary to some degree until sectors reliant on its products fully switch to clean alternatives like electric vehicles, sustainable aviation fuels, and hydrogen- or biofuel-derived chemicals. During this transition, clean hydrogen can help reduce refineries' climate pollution. However, clean hydrogen is not a solution to refineries' total greenhouse gas emissions (including from fossil fuel extraction and the downstream use of refined products and chemicals), nor will it remedy refining processes' severe public health impacts. Ultimately, clean hydrogen is an important band-aid during the process of reducing oil refining—and ideally eliminating it altogether—and should be treated accordingly, rather than used as justification for an expansion or life extension of refineries.

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- **Featured story:** Adam Mahoney, "A community poisoned by oil: People living in Wilmington, California, experience higher levels of illness and ailing mental health," *High Country News*, June 22, 2022, https://www.hcn.org/issues/54-8/south-pollution-a-community-poisoned-by-oil/

AMMONIA

Prospects	GHG Abatement (using zero-carbon H_2)	H_2 Demand Potential (if replacing all fossil fuels)	H_2 Breakeven Price (vs. incumbent fossil fuel)
EXCELLENT	**9-10** $kgCO_2e/kgH_2$	**3** MMT H_2	**0.9-2.3** $\$/kgH_2$

Chemical fertilizers have inherent problems, but hydrogen can clean up their production.

CONTEXT: Ammonia production is one of the main uses of hydrogen today. The Haber process reacts hydrogen with nitrogen from the air at high temperatures and pressures with a catalyst to make ammonia.[226] Nearly 90 percent of ammonia is in turn used to make chemical fertilizers, with the remainder used to produce other compounds like explosives, plastics, and synthetic fibers.[227] Ammonia demand may grow considerably for use as a carbon-free fuel in sectors like marine shipping. However, this overview will highlight ammonia's use for fertilizer.

SCOPE: The top-line metrics assume all steam methane reformation (SMR) hydrogen used in ammonia production in the U.S. in 2021 is replaced with clean hydrogen.

INFRASTRUCTURE NEEDS: The U.S. had 35 ammonia production facilities in 2022, operated by 16 companies in 16 states. More than half of ammonia production capacity is in Louisiana, Oklahoma, and Texas due to their large natural gas reserves.[228] The U.S. has over 3,000 miles of ammonia pipelines linking the Gulf Coast with agriculture in the Midwest and Great Plains.[229]

Most hydrogen used for ammonia production comes from integrated SMR facilities that make and use natural gas-based hydrogen on-site.[230] The remainder comes from merchant SMR plants that may have long-term natural gas delivery contracts upstream, hydrogen offtake contracts with ammonia facilities, and privately owned hydrogen pipelines.[231] These dynamics make it difficult for electrolytic hydrogen to access the ammonia market on price alone (i.e., without regulatory intervention), as it may require stranding often-integrated assets, breaking contracts, or harming relationships with important partners.

Conventional ammonia production plants also generally need a consistent hydrogen supply for their operations, which SMR has traditionally delivered. Moving these plants fully to electrolytic hydrogen is thus likely to require on-site storage or pipelines to smooth gaps in production, as electrolyzers should only run when clean energy is abundant and cheap (which are necessary conditions for lower-cost, zero-carbon hydrogen production).[232] However, new technologies are enabling more flexible and modular ammonia production, allowing for start-up within hours instead of days and adjusting output rates over minutes instead of hours.[233] Building new ammonia plants at smaller sizes in renewables-rich regions would require less reliance on hydrogen midstream infrastructure—though as clean ammonia production grows in the U.S., it may be beneficial to use ammonia pipelines to access the Gulf for exports.[234]

SOCIAL IMPACTS: Cleaning up ammonia production is essential but insufficient to solve chemical fertilizers' climate and environmental problems. Most of ammonia-based fertilizer's climate emissions come from its use.[235] Only about half of chemical fertilizers' nitrogen is taken up by crops, with the rest lost to groundwater or the atmosphere.[236] This includes nitrous oxide emissions (a greenhouse gas 265 times more potent than CO_2 over a 100-year period that drives nearly half of agriculture's climate emissions), nitrogen-fueled algal blooms from runoff that create aquatic dead zones, and polluted drinking water and local air quality.[237]

Adopting clean hydrogen for ammonia production would reduce health risks associated with fossil fuel production and combustion. However, it would not mitigate risks from downstream fertilizer use; this requires improving rates of nitrogen uptake in soil, reducing fertilizer use, and relying on alternatives like organic fertilizers.[238] It also would not prevent more general risks associated with ammonia—itself a toxic substance that must be carefully managed.[239]

COMPETING TECHS: As hydrogen is a fundamental part of ammonia production, there are no known alternatives to clean hydrogen for reducing emissions from this process. Instead, hydrogen's "competitors" for this market are technologies or practices that shrink the need for ammonia. For fertilizer, these include organic fertilizers and new technologies that skip the Haber process entirely (as well as best management practices for increasing efficiency).[240]

Organic fertilizers derive from biogenic sources, such as manure, bone meal, and "digestate" (rich residual material leftover from anaerobic digestion of organic matter).[241] Relative to chemical fertilizers, they improve the structure, health, nutrient density, and water retention of soil; they also release nitrogen more gradually, thereby reducing climate emissions per unit of applied fertilizer.[242] However, they are limited in supply and have their own problems if not properly managed.[243] Nascent technologies include **plasma reactors**, which use air, water, and electricity to make fertilizer with fewer field emissions, and **genetically edited microbes**, which can be applied to soil to directly fix atmospheric nitrogen into a form plants can use.[244]

Separately, in seeking to clean up existing ammonia production facilities, electrolytic hydrogen may face greater competition from SMR hydrogen with carbon capture and sequestration (often called "**blue hydrogen**"). Blue hydrogen has its own problems in perpetuating fossil fuel infrastructure and dependence on subsidies to beat out unabated SMR hydrogen. However, in the near term for newer integrated SMR-ammonia systems, it may cost less to add carbon capture equipment than to switch to electrolysis, as it allows for the continued use of SMR facilities and does not require breaking or restructuring natural gas contracts.[245]

TAKEAWAY: Clean hydrogen is essential for climate-friendly ammonia production—the demand for which may only rise with new applications like marine shipping fuels—and can reduce emissions from fertilizer use. However, it's worth maximizing efficiencies in fertilizer application and management, as well as pursuing organic fertilizers and new technologies that reduce the need for ammonia-based fertilizers, to further reduce climate pollution (and other public health and environmental hazards) associated with chemical fertilizers.

FURTHER READING:

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- Jeffrey Rissman, *Zero-Carbon Industry: Transformative Technologies and Policies to Achieve Sustainable Prosperity*, Columbia University Press, 2024, https://zerocarbonindustry.com/#chapter-2, p.37-61
- **Featured story:** Chris Baraniuk, "Why firms are racing to produce green ammonia," BBC, February 26, 2024, https://www.bbc.com/news/business-68230697

FURTHER READING

The following publications include hydrogen end-use analyses and demand forecasts at varying levels of detail and from a range of different perspectives. The most relevant summary figure or explanatory sections are highlighted in bold.

Hydrogen end-use analyses

- Michael Liebreich, “Hydrogen Ladder Version 5.0,” Liebreich Associates, October 20, 2023, https://www.linkedin.com/pulse/hydrogen-ladder-version-50-michael-liebreich/
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- Robin Gaster, “A Realist Approach to Hydrogen,” Information Technology & Innovation Foundation, January 2024, **pages 23-39,** https://www2.itif.org/2024-hydrogen-realism.pdf
- Sasan Saadat and Sara Gersen, “Reclaiming Hydrogen for a Renewable Future: Distinguishing Oil & Gas Industry Spin from Zero-Emissions Solutions,” Earthjustice, August 2021, **Figure 6 on page 22,** https://earthjustice.org/wp-content/uploads/hydrogen_earthjustice_2021.pdf
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Hydrogen demand forecasts

- Eric Larson et al., “Net-Zero America: Potential Pathways, Infrastructure, and Impacts,” Princeton University, October 29, 2021, **Page 194,** https://netzeroamerica.princeton.edu/the-report
- Ben Haley et al., “Annual Decarbonization Perspective 2023: Carbon-Neutral Pathways for the United States,” Evolved Energy Research, 2023, **Figure 44 on page 57,** https://www.evolved.energy/_files/ugd/294abc_c5f79e16ca7a470b8168e1bbe7d98c7f.pdf
- Hannah Murdoch et al., “Pathways to Commercial Liftoff: Clean Hydrogen,” U.S. Department of Energy, March 2023, **Figure 7 on page 18,** https://harnessinghydrogen.npc.org/files/H2-CH_5-Demand_Drivers-2024-04-30.pdf
- Emily Beagle, Nathan Iyer, Sarah Ladislaw, and Alexa Thompson, “Policy Memo: Clean Hydrogen Abatement,” RMI, 2021, https://rmi.org/insight/policy-memo-clean-hydrogen-abatement/
- Stéphanie Bouckaert et al., “Net Zero by 2050: A Roadmap for the Global Energy Sector,” International Energy Agency, October 2021, **Figure 3.8 on page 109,** https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf
- National Petroleum Council, “Harnessing Hydrogen: A Key Element of the U.S. Energy Future, Chapter 5 – Demand Drivers for Low Carbon Intensity Hydrogen in the United States,” April 30, 2024, **Figure 5-3 on page 15,** https://harnessinghydrogen.npc.org/files/H2-CH_5-Demand_Drivers-2024-04-30.pdf

DISCUSSION

This section discusses key themes and lessons arising from hydrogen end-use analysis.

Hydrogen's low-value uses are all when used for energy, while its high-value uses are all when used as a feedstock.

Low-value uses are defined as applications where hydrogen is likely to be outcompeted by alternative clean energy technologies over the long term, meaning public support for hydrogen in these domains will likely lead to higher costs or longer timelines for achieving a clean economy. High-value uses are defined as applications where hydrogen can eventually become competitive on a level playing field with alternative technologies, or where there is no alternative to hydrogen for decarbonization.

In almost all cases, hydrogen-for-energy (e.g., for buildings, light- and heavy-duty vehicles, industrial process heat, and day-to-day power generation) is a low-value use. This owes to the low round-trip efficiency of using electricity to electrolyze hydrogen and then burning it for heat or using it in a fuel cell to generate power. Whenever the direct electrification of a process is possible, it generally uses much less clean energy to accomplish the same goal (even if batteries are used as an intermediary). In particular, blending hydrogen with natural gas in pipelines is almost universally a bad idea, having little impact on climate pollution while delaying real decarbonization solutions.

The potential exception is hydrogen for seasonal electricity storage. This "hydrogen-for-energy" use is differentiated by leaning on hydrogen's ability to be stored at low cost for very long durations—a role today's batteries are ill-suited to play but that emerging technologies could someday fill. However, as long as clean electricity is available (including through long-duration storage) to serve electric technologies at reasonable prices, other hydrogen-for-energy uses have little to gain from this storage capability.[ii]

By contrast, hydrogen-as-a-feedstock (e.g., for refining, ammonia, petrochemicals, steel, and e-fuels for aviation and marine shipping) is almost always a high-value use. Feedstocks generally cannot be directly electrified, and competing technologies are still in the R&D phase, rely too heavily on biofuels (with associated land use and local pollution implications), or do not exist.

Hydrogen's low-value uses are much more dependent on the development of sprawling hydrogen pipelines and end-use equipment than its high-value uses.

Several hydrogen-for-energy uses would require a substantial investment in hydrogen midstream infrastructure and end-use equipment. For example, any meaningful use of hydrogen in buildings would require pipeline upgrades and new, hydrogen-capable appliances across entire distribution systems. Hydrogen fuel cell light-duty vehicles

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[ii] Industrial process heat and heavy-duty vehicles have traditionally been seen as well-suited for hydrogen due to its storage and energy density advantages, but the advent of technologies and capabilities like thermal batteries, fast chargers, and battery-swapping make direct electrification increasingly competitive.

would require developing hydrogen pipelines and storage sites to serve a near-ubiquitous network of refueling stations on par with today's gas stations. Heavy-duty vehicles would require less sprawl if confined to major highways but might still depend on pipelines to serve regions with less favorable renewable resource quality (noting that some stations might be able to self-supply with on-site electrolysis).

By contrast, the hydrogen-as-a-feedstock uses all involve industrial facilities that take large quantities of hydrogen at single sites and make other products, which can be moved and used largely with existing infrastructure (e.g., liquid fuel pipelines, conventional aircraft). These facilities—such as steel, chemical, and e-fuel production plants—can be sited together in regions of high renewable resource quality (to enable local electrolytic clean hydrogen production). This suggests it may be more cost-effective to build tight industrial clusters with shared hydrogen storage sites and pipelines than cross-country pipeline networks or expansive distribution systems. It also would minimize the need to build new, hydrogen-specific end-use equipment, as clean steel, chemicals, and sustainable aviation fuels can generally be used as-is.[iii]

In many hydrogen-for-energy uses, electric technologies are already taking off and do not depend as much on new infrastructure upgrades. For example, individual homes can generally charge electric vehicles and install electric heat pumps with today's distribution systems. Focusing hydrogen support on its high-value uses avoids investing enormous sums of public money on duplicative infrastructure (such as hydrogen vehicle refueling stations) that is highly likely to be outcompeted by alternative technologies.

COMMUNITY ENGAGEMENT

The hydrogen industry is essentially starting from scratch (or at least reinventing itself), having the opportunity to distinguish itself from the fossil fuel industry and its fraught reputation by helping to usher in a more equitable and just energy system. Clean hydrogen will also need to grow rapidly to meet climate goals, but it will fail to do so if it faces public opposition at every juncture.

The DOE has made community engagement a focus of its hydrogen hubs program.[246] However, communities have been raising alarms around a lack of access, transparency, and genuine consideration of their concerns, calling meetings "nothing more than a sales pitch for hydrogen."[247]

Administrators and hydrogen project developers alike must ensure that engagement happens early and with real action in response to community concerns—not merely inform the public about projects and attempt to explain away points of conflict. We refer to resources drafted with community engagement at the center for further reading.[248]

[iii] The potential exception here is marine shipping, which would require retrofitted or new-build ships to accommodate ammonia or methanol as a fuel.

Hydrogen's low-value uses often increase the risk of social harms and inequitable outcomes, while its high-value uses generally do the opposite.

Hydrogen's low-value uses generally have greater potential for social harm. For example, fenceline communities near hydrogen-burning power plants and industrial facilities—and especially homes using natural gas with any blend of hydrogen—would risk exposure to higher NOx emissions.[iv] Intertwining hydrogen infrastructure and fuel with public spaces and housing would bring heightened risks of user error (e.g., leaving a hydrogen stove on with its less-visible flame and lack of odor) and leaks inherent from using an expansive network of pipes and appliances—especially if these pipes and appliances were designed for natural gas. These leaks carry safety risks from explosions alongside climate risks from hydrogen's significant climate-warming impact.

Low-value uses would also risk raising energy bills. This could occur due to having to build relatively more clean energy to power energy-intensive electrolyzers rather than efficient electric appliances. It could also occur due to monopoly utilities passing higher costs—from using hydrogen in buildings or power generation—through to customers if they could convince regulators of their necessity. In the case of gas bills from hydrogen blending, wealthier households would be able to switch to lower-cost electric appliances, leaving lower-income households with the burden of increasingly expensive fuel and gas delivery infrastructure. Lastly, hydrogen blending in any capacity risks perpetuating fossil fuel infrastructure, delaying the transition to a zero-emission economy.

By contrast, high-value uses can eliminate local harmful air pollutants, such as by switching from coal to clean hydrogen and electricity for steelmaking or replacing the traditional natural gas-based SMR process with clean electrolytic hydrogen for ammonia production and refining. In other cases, hydrogen may only mitigate local pollution (e.g., sustainable aviation fuels are slightly less harmful than jet fuel when combusted) or at least not make it worse (e.g., petrochemicals production), meaning policymakers will need to take other actions to protect affected communities. It's also easier to manage hydrogen's safety risks in industrial settings with hydrogen contained to clusters overseen by trained professionals, moved in pipes and used in equipment designed for hydrogen, and with access to advanced monitoring equipment.

Electrolytic hydrogen that relies on fossil fuel power would fail to reduce net climate pollution across all end uses, with steel as the lone potential exception.

Clean hydrogen production is possible via electrolysis if using new, deliverable, hourly matched clean electricity.[249,v] However, hydrogen production that forgoes any of these "three pillars"—such as drawing from an existing clean energy resource—would cause

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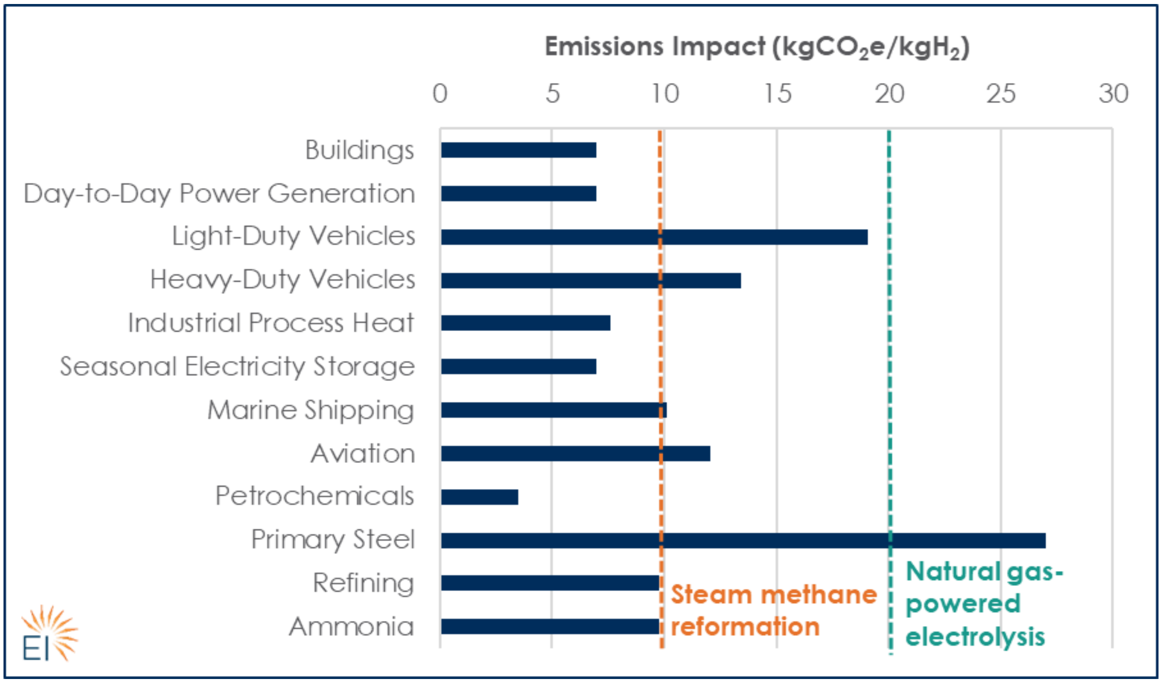
[iv] Industrial facilities can adopt more complex pre- or post-combustion pollution reduction measures than may be economically viable for distributed, more rudimentary household appliances.

[v] There are exceptions to this rule, such as using clean energy that would have otherwise gone to waste or been retired, but these are rare and often difficult to verify. See: https://energyinnovation.org/publication/45v-exemptions-need-strong-guardrails-to-protect-climate-grow-hydrogen-industry/

fossil fuel power plants to increase their operations to serve the demand previously supplied by the now-diverted clean power. The climate pollution associated with this rise in fossil fuel electricity generation must be attributed to its cause (i.e., electrolysis).

As shown in Figure 4, dirty electrolysis would drive a greater increase in GHG emissions from hydrogen production than the decrease in GHG emissions from hydrogen's displacement of fossil fuels downstream. This is fundamentally due to it taking more fossil fuels to generate electricity to make hydrogen than it does to use fossil fuels directly, such as natural gas to heat buildings or gasoline and diesel to power vehicles. The exception is using natural gas-based electrolytic hydrogen to replace coal-based steel production—though coal-based electrolysis would still drive a worse outcome.[vi]

Figure 4. Net climate pollution impact from hydrogen production and use[vii]



The blue bars represent the GHGs that would be avoided by the use of hydrogen in place of the incumbent fossil fuel for each application. The dashed lines represent the GHGs that would be emitted by today's hydrogen production (orange) and by electrolysis if not using new, deliverable, hourly matched clean power (turquoise).

This is a critical consideration due to the pending rules for the IRA's highly lucrative 45V tax credit. It's possible that the U.S. Treasury's final rules will allow dirty electrolytic

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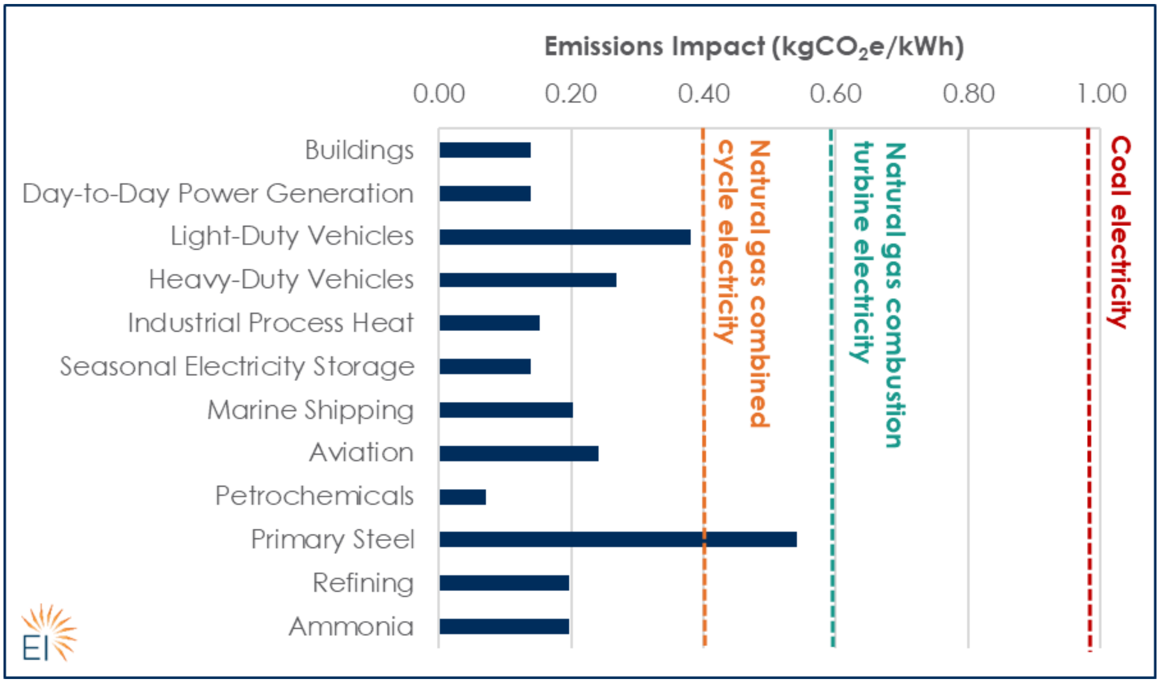
[vi] This paper uses natural gas-fired power generation (with an approximate emissions rate of 20 $kgCO_2e/kgH_2$) as the proxy for what would fill in for clean power that is diverted to electrolyzers, both to be conservative and because U.S. coal-fired power generation (with an emissions rate of 40-50 $kgCO_2e/kgH_2$) is phasing out.

[vii] Two hydrogen-for-energy uses (light- and heavy-duty vehicles) have relatively high abatement estimates; however, electric alternatives would achieve far greater efficiencies—that is, they avoid more GHG emissions per unit of clean energy than electrolytic hydrogen.

hydrogen to qualify for the full subsidy, with producers then “greenwashing” the hydrogen (i.e., advertising it as clean despite it worsening net climate pollution). In this scenario, using hydrogen would generally be detrimental unless states or companies explicitly require the use of truly clean hydrogen.[viii] Further, due in part to such rules facilitating the growth of a hydrogen industry that cannot survive without perpetual subsidy extensions, this harmful outcome would not naturally resolve itself over time.[250] In sum, realizing hydrogen’s climate benefits requires setting proper guardrails for electrolysis; otherwise, hydrogen’s use would not compensate for its upstream impact.

Relatedly, as shown in Figure 5, using clean electricity to displace fossil fuel electricity almost always does more to reduce net climate pollution than using it to electrolyze hydrogen for use in any downstream application. Thus, while it is critical to grow a robust clean electrolytic hydrogen industry to serve high-value uses in order to achieve a carbon-free economy, hydrogen policy should generally not take priority over (and certainly should not reverse progress on) efforts to clean up the power grid.

Figure 5. Net climate pollution impact from hydrogen use vs. cleaning the grid



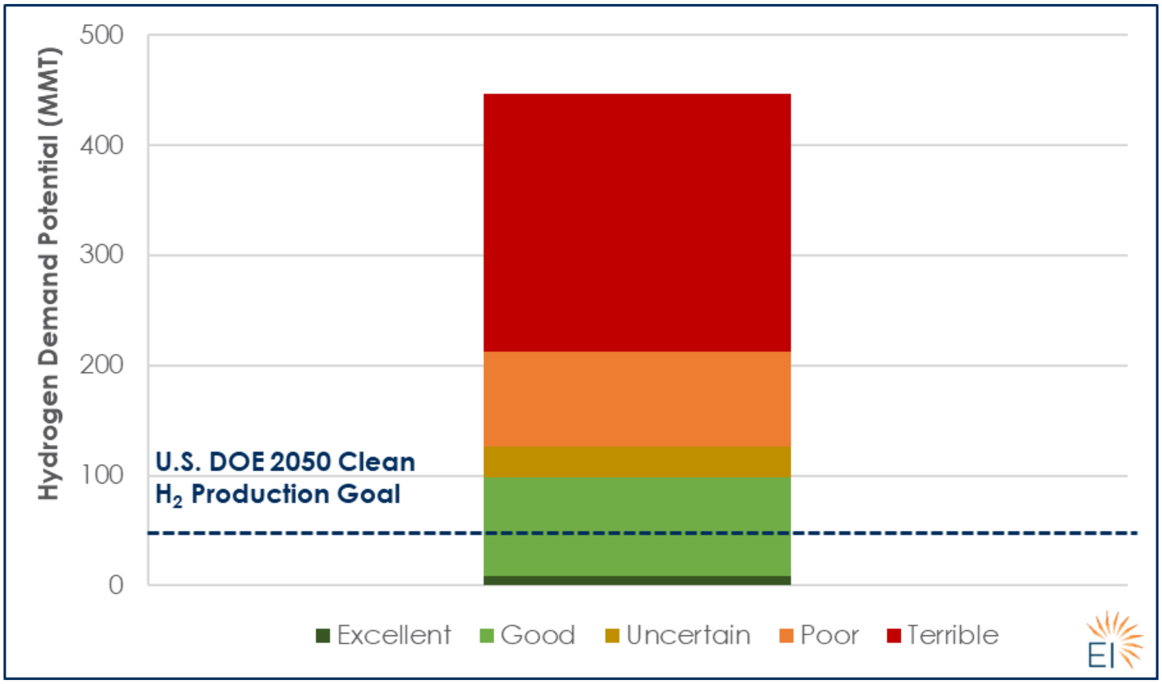
The blue bars represent the GHGs that would be avoided by the use of hydrogen in place of the incumbent fossil fuel for each application. The dashed lines represent the GHGs that would be avoided by replacing fossil fuel power with clean electricity.

[viii] By contrast, electric technologies like electric vehicles and heat pumps are so efficient that they generally reduce net climate pollution even if using dirty electricity. See: https://www.forbes.com/sites/energyinnovation/2023/12/17/hydrogen-isnt-electric-vehicles-treating-it-the-same-under-45v-tax-credit-would-be-a-mistake/

In the U.S., hydrogen's market potential for high-value uses exceeds clean hydrogen production goals—meaning any hydrogen flowing to low-value uses cuts into decarbonizing high-value sectors on the necessary timeline.

The DOE has a target of 50 MMT of clean hydrogen production by 2050—the same year by which the Intergovernmental Panel on Climate Change (IPCC) reports the need to achieve net-zero GHG emissions globally.[251] As shown in Figure 6, our hydrogen end-use analysis finds that the market potential for the combined high-value uses is approximately double this goal.

Figure 6. U.S. hydrogen demand potential by prospect category



The hydrogen demand potential for high-value uses ("excellent" and "good") is approximately double the DOE's 2050 clean hydrogen production goal—meaning achieving a net-zero economy by 2050 will likely require directing hydrogen to these high-value uses while also relying on alternatives (e.g., efficiency, biofuels).

Our analysis takes a high-level approach, roughly estimating how much hydrogen each end-use category would require to fully replace today's fossil fuel consumption. In reality, demand for these services will change over time—for example, aviation demand is expected to rise, clean fuels and chemicals should reduce the need for refining, and international trade of clean products could boost or cut domestic hydrogen needs.[252] Hydrogen also will not be the only mechanism for decarbonizing some of these end uses, as biofuels can shrink hydrogen demands in aviation, marine shipping, and petrochemicals, while some steel production may go the route of direct electrification.

However, the main idea stands: achieving a net-zero economy on the IPCC's stated timeline will require prioritizing hydrogen in high-value uses.[ix]

In the same vein, claims are often made that hydrogen is necessary to at least support cleaning up buildings, vehicles, industrial process heat, and power generation. Figure 6 shows this can imply the need for as much as four times the high-value uses' market potential. This in turn can drive hysteria around the need to grow the hydrogen industry at any cost—thus clouding the prior takeaway that dirty hydrogen production can reverse climate progress. While rapid growth of the hydrogen industry is indeed critical, it must occur in a clean manner and predominantly support high-value uses.

Lastly, these hydrogen volumes have enormous implications for the electricity system. Producing 50 MMT of clean electrolytic hydrogen would require approximately 2,500 terawatt-hours of clean energy, or more than 60 percent of U.S. electricity demand in 2022.[x] This would require roughly 1,000 gigawatts of new wind and solar resources—more than four times the volume installed in the U.S. as of the end of 2023.[253] Given limits to the pace of clean energy deployment, clean hydrogen should not be wasted on low-value uses that have more efficient alternatives for decarbonization.[254] Further, by encouraging flexible, price-responsive electrolyzers (i.e., via strong 45V rules), policy can ensure clean hydrogen production supports rather than harms grid reliability.[255]

Hydrogen's uptake in high-value uses will require targeted demand-side policies—supply-side subsidies alone will not ensure this outcome (and may make better alternatives for low-value uses look worse).

By far the most significant U.S. hydrogen policy is the 45V production tax credit, which will drive a reduction in the cost of electrolytic hydrogen. However, this will not be sufficient to ensure that hydrogen is primarily taken up in high-value uses.

One reason is that the status quo may favor hydrogen for low-value uses. For example, there is a higher willingness to pay for hydrogen in the vehicle sector relative to other uses due in part to higher gasoline and diesel prices. If policymakers support the buildout of hydrogen refueling stations, hydrogen producers may seek to sell to those stations over markets that have access to lower-cost fossil fuels. As another example, some actors are motivated to buy hydrogen for low-value uses to maintain their business models, such as gas utilities looking to blend hydrogen into their pipelines to slow progress on electrification. In particular, monopoly utilities can endure the higher cost of hydrogen in place of natural gas if they can convince regulators that doing so is necessary to meet state policy goals (and thus recover costs from their customer base).

Another reason is that the status quo may hinder hydrogen for high-value uses. For example, steel producers (or their investors) are not willing to accept the risk of switching from existing coal blast furnaces to new hydrogen direct reduced iron

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[ix] See also: https://www.agora-industry.org/fileadmin/Projekte/2021/2021-06_IND_INT_GlobalSteel/A-EW_298_GlobalSteel_Insights_WEB.pdf, pages 42-44.
[x] This estimate assumes an electrolyzer efficiency of 50 kilowatt-hours per kilogram of hydrogen.

facilities based on supply-side subsidies alone.[256] They need the assurance that comes with long-term offtake contracts for their products, which is complicated by the fact that clean hydrogen is expected to fall in cost over time such that late adopters may be able to undercut first-mover users. They also need assurance that hydrogen will remain cost-effective and available as needed throughout these facilities' decades-long lifespans. Other high-value uses face the same risks, with refineries, chemical producers, and shipping operations all requiring massive investments to switch to clean hydrogen and navigating competitive global markets with thin margins.

Separately, supply-side subsidies for hydrogen will distort markets and make hydrogen appear to be favorable in low-value uses over better-suited alternatives that are not receiving comparable financial support. This can in turn influence decision-makers to invest in hydrogen technologies where they will be incapable of continuing to compete with alternatives if public support is leveled or phased out across these options.

Targeted demand-side policies can help minimize hydrogen's uptake in low-value uses and ensure its growth in high-value uses. Such actions will build an industry that is robust (with jobs and infrastructure that will remain viable over the long term), improves social outcomes, and helps achieve climate change mitigation goals on time.

POLICY RECOMMENDATIONS

The U.S. government is headed in the right direction on hydrogen policy.[257] The U.S. Treasury's draft 45V Clean Hydrogen Production Tax Credit rules set the stage for subsidizing truly clean hydrogen production and building a durable industry.[258] The DOE has also begun implementing the IIJA's hydrogen provisions, including the $7 billion for hydrogen hubs and $1 billion for supportive demand-side initiatives.[259]

However, Treasury may still reverse course in its final 45V rules, threatening hydrogen's emissions reduction potential. The hydrogen hubs also support some low-value uses like vehicles and industrial heat, limiting the hubs' ability to uplift high-value uses. And federal funding heavily favors hydrogen production (on the order of $30 billion per year) over demand-side support.[260]

This section provides a high-level overview of demand-side policy recommendations—that is, policies that can boost clean hydrogen's uptake in high-value uses or minimize risks associated with its adoption in low-value uses. It does not discuss supply-side policies (e.g., the 45V tax credit), as we cover these in depth in separate papers, and because these policies benefit all offtakers (low- and high-value alike) by driving lower clean hydrogen prices.[261] This list is not exhaustive, though it concludes with "further reading" resources that cover more ground. Finally, it focuses primarily on the U.S.—which tends to employ more carrots than sticks—but the concepts apply globally.

BOOST UPTAKE IN HIGH-VALUE USES

The following offers a collection of policies intended to boost the near-term uptake and long-term financial viability of hydrogen in high-value uses by supporting these uses' development and deployment. The goal is not to maintain the same magnitude of policy support forever but to cover early-stage costs until these uses have advanced to become self-sufficient on their own merits, in part by advancing technologies along learning curves and building enabling infrastructure.[262]

Where possible, technology-neutral policy designs (i.e., targeting the development of low- or zero-carbon products) can support hydrogen where it's most competitive rather than presupposing it as the right solution. Policies should also include clear standards and definitions for "green" products. Any policies that involve awarding contracts should use eligibility-based processes, weighing factors such as carbon intensity or emissions reductions, the amount of funding needed to make a project viable, and the likelihood of an award leading to a project that reaches a final investment decision.

Each policy below can be enacted at the state or federal level. The following sections include a short policy description, an explanation for why the policy is effective, an indication of when to use it, and examples of how it's being used today.

Advance market commitments

An advance market commitment (AMC) is a guarantee—typically from a government—to buy a certain volume of a product that has yet to reach commercialization. It greatly reduces the risk of investing in a new product (e.g., clean fertilizer, sustainable aviation fuel) that may require substantial but uncertain cost by ensuring the developers will have at least one large offtaker, given that other buyers may be too price sensitive to make such commitments. AMCs are meant to buy down the higher costs of (and help form a market for) a new product, with the premise that costs will fall with deployment.

Policymakers should consider AMCs for nascent products whose development and deployment they want to quickly scale. For example, governments can make an AMC for zero-carbon steel to satisfy a certain percentage of their annual steel use. This would reduce risk for producers who pursue hydrogen-based steelmaking (without explicitly requiring the use of hydrogen) by guaranteeing they will have a buyer—even if prices are initially much higher than coal-based steel. Private sector coalitions can also use AMCs to drive change in their industries without any single entity assuming total risk, such as airlines collectively agreeing to buy a certain quantity of very-low-carbon sustainable aviation fuels. This would encourage the use of hydrogen over bioenergy (which hasn't achieved the same depth of emissions reductions) but not require it in case lower-cost solutions were developed.[263]

International organizations have used AMCs to support the rapid development and effective distribution of vaccines.[264] Most recently, the global health partnership Gavi organized an AMC for COVID-19, using funding from higher-income countries (as well as contributions from the private sector and philanthropists) to guarantee the purchase of billions of vaccine doses, thereby derisking their development and rapid production.[265] The AMC also allocated a substantial share of doses for lower-income countries, ultimately helping to reduce the virus's spread and saving millions of lives.[266]

Contracts for difference

A contract for difference (CfD) is an arrangement where one party (typically a public entity) ensures an established offtake price for the product of another party (typically a private actor).[267] If the actor sells their product at a market price below the CfD price, the public entity agrees to pay the difference; in a two-way CfD, selling the product above the CfD price means the private actor would pay the excess to the public entity.

Policymakers can use CfDs to support first-mover developers whose clean products may be more expensive than existing dirty products or products made by later entrants who benefit from first movers' actions (e.g., more robust supply chains, trained workforce). These contracts allow governments to serve as "risk-taking intermediaries" without requiring them to purchase products or to set a price for the entire market.[268] CfDs work best when there is an established market for the product, though they can also be designed to work with related indices (e.g., natural gas prices if a market price does not exist for SMR-based hydrogen).[269]

CfDs can be structured for clean hydrogen or clean products. The former is better where clean hydrogen can replace dirty hydrogen in existing uses (e.g., refining, ammonia), with the contracts helping to cover the initial price premium of this switch. The latter is better where hydrogen might compete with other technologies for producing a given clean product. For example, "carbon contracts for difference" help cover the cost of investing in clean technologies by paying the difference between "the actual associated emission reduction cost and the carbon price producers would pay when sticking to the conventional high-carbon production"—though this structure can also work when there is no carbon pricing scheme in place.[270]

CfDs have traditionally been used in the United Kingdom and EU to support clean energy technologies like offshore wind, which has significantly reduced projects' financing costs.[271] More recently, they have been employed in the U.K., Germany, and Japan to support clean hydrogen and industrial products.[272]

Reverse auctions

A reverse auction is a mechanism by which a buyer for a product sets the parameters of a procurement and then allows private actors to bid against each other to provide the product at the lowest price. This tool can provide de-risked, long-term contracts for the auction winners. Policymakers should consider using reverse auctions (or requiring regulated entities like utilities to use them) when they want to purchase (or encourage the purchase of) a commercially available product that has low price transparency. For example, U.S. utility Xcel Energy used a reverse auction to procure new clean energy resources and settled at record-breaking prices for solar-plus-storage systems.[273]

Subsidies for end-use equipment or utilization

Subsidies for hydrogen end-use equipment or utilization in pre-selected high-value uses (e.g., steelmaking) can incentivize developers to invest in these uses, such as by covering some percentage of capital costs or paying developers per kilogram of clean hydrogen they procure. Policymakers should consider these subsidies when they want to provide a boost to the market for the targeted end uses without necessarily having to select specific projects for awards. This approach can push otherwise-unprofitable projects into viability; however, it can also risk doing too little if these technologies need a greater degree of offtake certainty to attract investment (e.g., via a state-backed long-term contract), and it risks budgetary uncertainty if provided on an uncapped basis.

As an example, Colorado passed two laws in this category in May 2023. One provides a \$1/kgH_2 tax credit for truly clean electrolytic hydrogen (i.e., using new, deliverable, hourly matched clean electricity) that is used in “hard-to-decarbonize” applications including steelmaking and chemicals production.[274] This policy reinforces the need for clean hydrogen production (such as if Treasury weakens the final 45V federal subsidy rules) while creating an incentive to sell hydrogen to its highest-value users. The other authorizes the Colorado Energy Office to award up to \$168 million in tax credits to projects that explore or implement reductions in industrial GHG emissions.[275] These tax credits can apply to a range of industrial equipment upgrades or replacements, covering hydrogen use as well as electrification and efficiency.

R&D support for emerging technologies

Research and development (R&D) support involves providing grants for research labs, academia, private firms, and industry to invent and test new, unproven technologies. It’s generally too risky to pursue R&D initiatives otherwise—at least outside of continuously improving existing technologies (e.g., new car or phone models) or venture capital choosing to take on such risks (with no guarantee of these pursuits focusing on GHG emissions reductions). Thus, R&D support allows researchers to explore, design, and test the feasibility of new technologies free from risk of having to make their money back via successfully developing and selling a product. Technologies that do find success can then be commercialized and scaled through other policies.

Policymakers should consider R&D support for high-value hydrogen uses that have no proven technology ready to scale (e.g., processes to build complex petrochemicals from hydrogen and captured carbon). R&D support has long found success across the clean energy industry, such as through the DOE’s Advanced Research Projects Agency – Energy (ARPA-E) and more recently through the DOE Office of Clean Energy Demonstrations’ Industrial Demonstrations Program.[276]

Performance standards

Performance standards involve setting a benchmark for an entire industry to achieve, often becoming gradually more stringent over time. They may take the form of a percentage emissions reduction relative to some baseline, carbon intensity value, or percentage uptake of clean fuels, feedstocks, or products. By setting an industry standard, they ensure gradual technology improvements or fuel switching without relying on subsidies or estimates of how much public money is needed to reach a similar target. On one hand, these standards can raise the cost of consumer products or harm industry competitiveness with companies that are not subject to the policy (e.g., foreign companies with no accompanying trade policies like a carbon border adjustment mechanism). On the other, they can be paired with subsidies to ease any cost impact, and the improved clean industry can end up being lower-cost or otherwise more desirable than dirtier competitors.

Policymakers should consider performance standards as a complement to financial incentives, as the former ensures continuous progress toward a defined goal while the latter eases any cost impacts and provides motivation for surpassing such goals. For example, U.S. progress toward a cleaner electricity grid is largely due to its combination of federal investment and production tax credits paired with state renewable portfolio standards. More recently, the EU has begun applying performance standards for the targeted use of clean hydrogen, requiring 42 percent of the hydrogen used in industry to come from clean sources by 2030 (and 60 percent by 2035).[277] Notably, standards encouraging hydrogen uptake should account for upstream impacts, such as induced emissions from electrolysis and hydrogen leakage.

REDUCE RISK FROM LOW-VALUE USES

The following lays out a series of recommendations to minimize the risks of hydrogen's low-value uses. These are especially important in the presence of steep incentives for hydrogen production like the 45V tax credit in the U.S., as these may lead to hydrogen artificially beating out better-suited alternatives for low-value uses (at least during the period of hydrogen's subsidy advantage).

Focus midstream infrastructure on tight industrial clusters

Hydrogen pipelines and storage sites will be critical for the industry's success. Pipelines can move large hydrogen volumes from areas of high renewable resource quality to industrial offtakers—including existing facilities that may not have space for on-site renewables, such as refineries and ammonia production plants. Storage sites can help smooth gaps in production from electrolyzers (which need to avoid running whenever their operations would cause fossil fuel power plants to generate more power) such that offtakers can always have a consistent supply of hydrogen; this includes storage over many months or years in response to higher or lower clean energy availability. Together, pipelines and storage can reduce offtakers' hydrogen procurement costs by balancing supply and demand over more users, reducing the electrolyzer and storage capacity needed to meet the needs of any single buyer.

However, policymakers should use caution when considering the level of midstream infrastructure needed to successfully grow the hydrogen industry. The high-value hydrogen uses all rely on large industrial facilities that can be sited in regions of high renewable resource quality and transport their products via lower-cost, often-existing networks. The low-value hydrogen uses often require a much more expansive web of pipelines, such as to supply vehicle fueling stations or buildings. This dynamic suggests the top priority for hydrogen midstream infrastructure policy support should be to facilitate tight industrial clusters of pipelines and storage sites, with the potential for longer transmission pipelines if deemed preferential to separate hydrogen supply and demand in certain instances (e.g., moving hydrogen from the Great Plains to today's steelmaking communities rather than relocating that industry and its jobs).

Hedge bets on hydrogen infrastructure investments

To the degree policymakers choose to support low-value uses for hydrogen, they should seek to hedge bets such that some value can still come of investments that fall short of their intent. For example, the best first option for hydrogen vehicle fueling stations would likely be multi-purpose facilities at marine ports, capable of supplying container handlers, tractor-trailers, and other equipment. These stations would be more durable to any individual hydrogen use losing out to electric alternatives. Policymakers could also require hydrogen fueling stations that receive public funding to have a minimum ratio of electric vehicle chargers (e.g., five chargers per pump) to help ensure these facilities' continued viability if fuel cell vehicles fail to take off.

Require a high burden of proof of value and community benefits agreements

Regulators and policymakers should subject hydrogen projects to a high burden of proof of their benefits and long-term viability before approving any public subsidy, such as grants or utility cost recovery via rates. This can allow private actors to explore low-value hydrogen uses without shifting financial risks to the public or captive consumers. For example, the Massachusetts Department of Public Utilities issued an order in December 2023 that allows utilities to pursue clean hydrogen delivery arrangements with interested customers but requires all costs (including any infrastructure upgrades) to be borne strictly by these customers. It also allows utilities to assess hydrogen in their systems but makes the costs "the sole responsibility of the utility shareholders"—at least until hydrogen technologies "prove to be a viable alternative to the business-as-usual model and support the Commonwealth's climate targets."[278]

Policymakers should also require hydrogen developers to negotiate community benefits agreements with affected communities while taking steps to ensure they fulfill their intended purpose.[279] That is, such agreements must not create a rubber-stamp process that gives tacit community approval to fast-track development. Instead, they should include transparency and accountability mechanisms, center disadvantaged communities' voices and needs, and advance high-road jobs.[280] Policymakers should also ensure communities can access proper legal representation and policy knowledge to ensure that agreements are designed and implemented well. Finally, policymakers should consider how other benefit negotiation tools like project labor agreements can support equitable outcomes.

Set rigorous health and safety standards

As several low-value hydrogen uses involve combustion, regulators should establish rigorous pollution standards for harmful NOx emissions—particularly if today's rules do not hold hydrogen to at least the same standards as natural gas.[281] Such standards may include requirements around combustion techniques (e.g., keeping temperatures low to reduce or eliminate NOx), post-combustion controls, or emissions rates (such as for stoves in buildings). More generally, policymakers should establish thorough standards around hydrogen safety and leakage across the hydrogen value chain.[282]

FURTHER READING

The following resources include more information on hydrogen demand-side policies.

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CONCLUSION

Hydrogen will be essential to achieving a fully decarbonized economy. However, it will only play this role if it's produced in a truly clean manner and used in applications that require it to cut pollution. Straying from this narrow path risks bringing disastrous consequences in the form of reversing, delaying, or raising the costs of climate change mitigation efforts while worsening environmental justice outcomes.

Hydrogen policy is at a critical (if sudden) juncture. Hydrogen is alluring in promising to act as a silver bullet solution that will bring new jobs and investment—which may prompt some actors to take shortcuts to more quickly realize that vision. But this is a mirage that risks giving way to wasted funding, stranded assets, and missed emissions reduction targets, with clearer-eyed actors winning the race on more competitive technologies. By looking at hydrogen holistically, in the context of what's needed to ensure its clean production and long-term competitive prospects, policymakers can guide the industry to robust growth and sustainable success. The path exists to maximize hydrogen's potential in achieving our climate goals—we need only walk it.

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