13th India-U.S. Track II Dialogue on Climate Change and Energy

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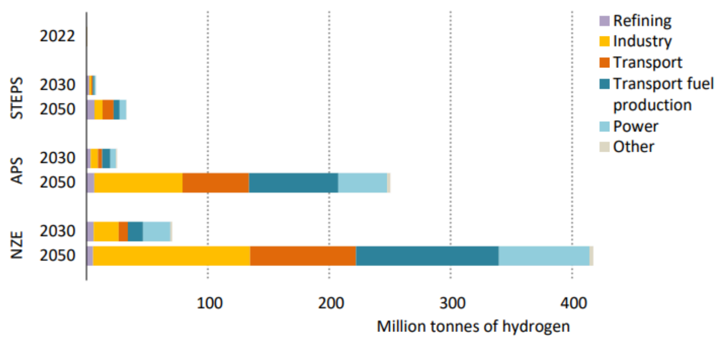
WORKING GROUP PAPER: GREEN HYDROGEN

Background

Over the last several years, hydrogen has been touted as "a critical pillar in the transition to net-zero" for its potential to decarbonize hard-to-abate industries, mobility, and power generation.[1] In November 2022, the International Renewable Energy Association (IRENA) reported that the G7's net-zero pledges will drive up hydrogen demand seven times by 2050.[2] However, in its latest World Energy Outlook issued in October 2023, the International Energy Agency (IEA) downgraded its projections on the amount of hydrogen that would be needed to meet net zero by 2030 due to an increase in confidence in direct electrification as a cost-effective alternative approach.[3]

According to IEA models, while the share of hydrogen for power generation will increase to nearly 75 million metric tons (MMT) by 2050, most hydrogen will either be used as transport fuel directly or feedstock for e-fuels.

Figure 3.36 ▷ Global hydrogen demand by sector and scenario, 2022-2050



IEA. CC BY 4.0.

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[1] https://www.weforum.org/agenda/2023/01/hydrogen-clean-energy-transition-2023/

[2] https://www.irena.org/News/pressreleases/2022/Nov/Net-Zero-Pledges-in-G7-to-Drive-Up-Global-Hydrogen-Demand-by-Up-to-7-Times

[3] https://iea.blob.core.windows.net/assets/86ede39e-4436-42d7-ba2a-edf61467e070/WorldEnergyOutlook2023.pdf

Hydrogen State-of-Play: India

India's National Green Hydrogen Mission

The National Green Hydrogen Mission (NGHM) was announced on January 4, 2023, following Union Cabinet approval of Rs. 19,744 crores. The mission has aims to achieve the following objectives by 2030: (i) produce 5 million metric tons per annum (MMTPA) of green hydrogen; (ii) avert up to 50 MMTPA CO2; (iii) add 125 GW of renewable energy for green hydrogen production, (iv) install 60-100 GW of electrolyzers; (v) create over 6 lakh new jobs; and (vi) catalyze over Rs.8 lakh cr investments. The initial budget for the Mission comprised allocations of Rs. 17,490 crores for the Strategic Interventions for Green Hydrogen Transition (SIGHT) program, Rs. 1,466 crores for pilot projects, Rs. 400 crores for Research and Development (R&D), and Rs. 388 crores for other Mission components.[4]

The mission outlines distinct components across which interventions/incentives have been proposed to enable a green hydrogen ecosystem in India. Some of these primary components include:

- Demand-side interventions: catalyzing domestic demand and export markets through demand aggregation and competitive bidding, & pilot projects across various sectors
- Supply-side interventions: SIGHT program with two distinct financial incentive mechanisms for electrolyzer manufacturing and green hydrogen production
- Development regulations, codes and standards: in line with the industry requirements for emerging technologies
- R&D and innovation through a public-private partnership framework for R&D (Strategic Hydrogen Innovation Partnership – SHIP)
- Other Components include public awareness, stakeholder outreach, and International cooperation.

Mission Implementation

India stands to gain from having one of the world's lowest costs of renewable electricity and is strategically positioning itself to export green hydrogen to nations with limited renewable energy resources or land constraints. The Government of India has showcased its commitment, as outlined in the NGHM document, to scaling up the target to 10 MMT per annum by 2030, particularly with the expansion of export markets. Ongoing discussions between India and regions such as Europe[5] and Singapore[6] highlight the country's efforts to export green hydrogen, catering to the growing demand in these areas. Over the course of 2023, numerous existing and new players in the green hydrogen sector, both from India and overseas, made various project commitments related to green hydrogen production and electrolyser manufacturing.

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[4] https://mnre.gov.in/national-green-hydrogen-mission/

[5] https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1927680

[6] https://www.reuters.com/sustainability/climate-energy/india-talks-supply-10-mln-tonnes-green-hydrogen-eu-2023-07-05/

Strategic Interventions for Green Hydrogen Transition (SIGHT)

Under the SIGHT program, two distinct incentive mechanisms are being implemented, targeting the domestic manufacturing of electrolysers and the production of green hydrogen. Bids were solicited by the Solar Energy Corporation of India (SECI) on July 10, 2023, resulting in contracts awarded to 10 companies on January 9, 2024, for a total capacity of 4,12,000 MMTPA for establishing Production Facilities for Green Hydrogen.[7]

Similarly, bids for the selection of Electrolyser Manufacturers (EM) were awarded to 8 companies on January 12, 2024, for a total capacity of 1,500 MW per annum. Scheme guidelines for SIGHT Mode 2A (aggregation model for Green Ammonia) and Mode 2B (aggregation model for Green Hydrogen) were officially notified on January 16, 2024.[8]

Green Hydrogen Standard

The Indian Green Hydrogen Standard for India was released via notification by MNRE on August 18, 2023, specifying an emission threshold of 2 kg CO2 equivalent / kg H2 as a 12-month average[9] within the parameters of both the RE-based electrolysis route and the thermochemical or biochemical-based biomass route.

Research and Development

The R&D roadmap for the Green Hydrogen Ecosystem in India underwent a public feedback process, opening on July 5th, 2023, and culminated with the release of the final version on October 13th, 2023. The roadmap aims to reduce the capital expenditure of electrolysers, enhance their efficiency, explore the integration of electrolysers with power systems, and pursue additional avenues for advancement in the field.[10]

Pilot Projects

Furthermore, scheme guidelines for the implementation of pilot projects for the utilization of Green Hydrogen in the shipping sector were issued on February 1, 2024. Similarly, scheme guidelines for the implementation of pilot projects for the utilization of Green Hydrogen in the steel sector were notified by the Ministry of New and Renewable Energy (MNRE) on February 2, 2024. Lastly, scheme guidelines for the implementation of pilot projects for the utilization of Green Hydrogen in the transport sector were notified by MNRE on February 14, 2024.

The ministry is currently in the process of formulating the scheme guidelines for the implementation of the remaining components under the NHGM.

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[7] https://www.seci.co.in/whats-new?id=new

[8] https://www.mercomindia.com/greenko-acme-reliance-winners-secis-green-hydrogen-auction

[9] https://mnre.gov.in/notice/rd-roadmap-released-by-mnre-on-the-eve-of-world-hydrogen-day/

[10] https://mnre.gov.in/notice/rd-roadmap-released-by-mnre-on-the-eve-of-world-hydrogen-day/

Hydrogen State-of-Play: United States

The U.S. Department of Energy (DOE) launched the Hydrogen Shot initiative in June 2021 which aims to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram (kg) in a decade.[11] The *Energy Earthshots Initiative*, is a larger strategic framework to “accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions” within the decade.[12]

In June of 2023, the Biden Administration released the U.S. National Clean Hydrogen Strategy and Roadmap (Strategy & Roadmap), a comprehensive framework for accelerating the production, processing, delivery, storage, and use of affordable clean hydrogen to support a net-zero carbon future and a sustainable, resilient and equitable economy.[13] The Strategy & Roadmap laid out opportunities for the domestic production of 10 MMT of clean hydrogen annually by 2030, 20 MMT annually by 2040, and 50 million MMT annually by 2050.[14] The Strategy & Roadmap identifies three key strategies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool, including:

- **Targeting strategic, high-impact uses for clean hydrogen**, which will ensure that clean hydrogen will be utilized in the highest benefit applications, where limited alternatives exist (e.g. industrial sector, heavy-duty transport, and long-duration energy storage);
- **Reducing the cost of clean hydrogen** by catalyzing innovation and scale, stimulating private sector investments, and developing the clean hydrogen supply chain; and
- **Focusing on regional networks** with large-scale clean hydrogen production and end-use in close proximity.

In August 2023, DOE announced the Hydrogen Interagency Task Force (HIT), which will implement this Strategy & Roadmap.[15] It focuses on targeting strategic, high-impact end uses, reducing the cost of clean hydrogen, and regional networks. The HIT includes experts from a broad range of agencies including Defense, Homeland Security, EPA, Transportation, National Institute of Standards and Technology, NASA, the National Science Foundation, and the Department of Agriculture. Several working groups have been established including: Supply & Demand at Scale; Infrastructure, Siting & Permitting; and Analysis & Global Competitiveness. There are two crosscutting teams as well: the Workforce, Equity and Justice team and the DOE Joint Strategy Tech Team which focuses on production, delivery, storage, conversion, application and lift off.

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

[12] https://climatemodeling.science.energy.gov/news/doe-announces-150-million-research-science-foundations-energy-earthshots

[13] https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap

[14] https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-strategy-roadmap-at-a-glancee72a84ff4e104d9e9371a16ed7203f82.pdf

[15] https://subscriber.politicopro.com/article/eenews/2023/08/21/white-house-launches-task-force-to-boost-clean-hydrogen-00111870

Clean hydrogen production standard and draft guidelines for 45V

In December 2023, the U.S. Department of the Treasury and the Internal Revenue Service issued a proposed rule clarifying how to claim the 45V Clean Hydrogen Production Tax Credit (PTC) under the Inflation Reduction Act §45V (45V Rule).[16] The Clean Hydrogen PTC creates a 10-year incentive, setting a varying, four-tier incentive in the form of emissions-based tax credits depending on the life-cycle greenhouse gas emissions of hydrogen production and whether the project meets prevailing wage and apprenticeship requirements. A Rhodium Group study predicts that under a medium-growth scenario for clean hydrogen, emissions could fall by 14-45 million metric tons from 2024 to 2035.[17] Currently, natural gas-derived hydrogen costs $1-$1.50/kg, while most estimates put the cost of green hydrogen at $4-$6/kg, although depending on location and other factors, some estimates are as low as $3/kg. These prices make green hydrogen that meets the $3/kg tax credit competitive with conventional, natural gas-derived hydrogen. The Treasury Department accepted comments on the 45V Rule throughFebruary 2024 with final rule to follow at a future, unspecified date.

There has been significant debate about how hydrogen producers can use energy attribute certificates (EACs) to claim to be using clean electricity, and thereby qualify for the 45V tax credit. This concern has led the Administration to require that, for EACs to comply with 45V, credits must fulfill the “three pillars”: (1) additionality (or “incrementality” in the language of the proposed regulations), (2) temporal matching, and (3) geographic correlation (or “deliverability” in the language of the proposed regulations).[18]

Under the proposed 45 V Rule, standards for power used in clean hydrogen production are:

- To meet the additionality/incrementality requirement, EACs must be sourced from power facilities that began commercial operations no more than 36 months before the hydrogen plant was placed in service;
- To meet the temporal matching requirement, EACs must be matched with the clean power generation hourly starting January 1, 2028, and annually before then; and
- To meet the geographic correlation/deliverability requirement, EACs must be sourced from clean electricity generation that comes from the same region as the hydrogen production facility that buys those EACs.

The proposed 45V rule reflects a policy decision from the Biden Administration to enforce strict limits on section 45V credit availability to hydrogen producers using grid power, limiting the ability of the hydrogen industry to use existing clean power sources to produce clean hydrogen in hopes that when hydrogen producers purchase EACs that follow these three requirements, emissions will be lower than in a scenario in which the EACs are

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[16] https://www.federalregister.gov/documents/2023/12/26/2023-28359/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen

[17] https://rhg.com/research/clean-hydrogen-45v-tax-guidance/

[18] https://www.resources.org/common-resources/unpacking-the-proposed-guidance-on-the-45v-tax-credit-for-clean-hydrogen/

unrestricted.[19] However, some are concerned that this will stymie clean hydrogen production in the early years because of added costs; there is disagreement between modelers who find fewer cumbersome economic impacts than many project developers expect.[20] It is therefore likely that the final guidance will provide flexibility with a transition from annual matching of renewable supply and demand initially to hourly matching over a period of 5-7 years.

Life Cycle Assessment to Determine Eligibility for Federal Incentives

Under the proposed 45V rule, hydrogen's carbon-intensity is measured through a life cycle assessment (LCA), which sums the emissions from extraction, processing, and transport of feedstock, hydrogen production, and end-use. Typically, hydrogen's end-use emissions are considered negligible because its end uses, whether as a feedstock or a fuel, do not produce non-water greenhouse gas emissions. Thus, LCAs and conversations around hydrogen's carbon-intensity focus on feedstocks and production. Today's conventional hydrogen production is estimated to produce between 9-12 kg of CO_2-equivalent per kg of hydrogen ($kgCO_{2e}/kgH_2$).[21]

The main clean hydrogen incentives in the U.S. are the Hydrogen Hubs program and the 45V Hydrogen PTC. Additionally, the 45Q tax credit for carbon sequestration is an incentive for carbon capture on steam methane formers. While 45V and the Hydrogen Hubs program administer funds differently, they nearly align on their carbon intensity thresholds and what is included within required LCAs. The Hubs program establishes a $4kgCO_{2e}/kgH_2$ target for its Clean Hydrogen Production Standard, while 45V has a tiered crediting system, shown below.

Carbon Intensity ($kgCO_{2e}/kgH_2$)	Max Hydrogen PTC Credit (\$/kg H_2)
0-0.45	\$3.00
0.45-1.5	\$1.00
1.5-2.5	\$0.75
2.5-4	\$0.60

In October 2023, DOE announced its investment of \$7 billion to launch seven Regional Clean Hydrogen Hubs (H2Hubs) across the nation and accelerate the commercial-scale deployment of low-cost, clean hydrogen. Each of the selected hubs, which are geographically dispersed among seven U.S. regions (Pacific Northwest, California, Heartland, Midwest, Appalachia, Mid-Atlantic, and Gulf Coast), are unique with some relying on renewables and others fossil fuels.

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[19] https://www.resources.org/common-resources/unpacking-the-proposed-guidance-on-the-45v-tax-credit-for-clean-hydrogen/

[20] https://www.bakerbotts.com/thought-leadership/publications/2023/december/section-45v-clean-hydrogen-production-tax-credit-irs-releases-proposed-regulations

[21] https://industrialinnovation.org/wp-content/uploads/2023/05/The-Landscape-of-Clean-Hydrogen.pdf

Each project provides a potentially unique lesson, e.g., the Mid-Atlantic hub is touted as repurposing historic oil infrastructure and using existing rights-of-way.

Federal incentives for clean hydrogen production in the U.S. are mostly technology agnostic, which means that hydrogen from either electrolysis or fossil feedstocks are eligible for funding if they can prove their LCAs fall within the clean hydrogen emission threshold of, at most, 4kgCO_{2e}/kgH_2. A caveat for 45V is that any production processes not currently accounted for in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model require that a petition is submitted and must be approved to receive tax credits. This excludes at least temporarily, hydrogen derived via methane pyrolysis, and the separation of H2 from H2S by several processes, for example.

Grid-based electrolysis and potential emissions

The cleanest way to produce hydrogen from an emissions standpoint is by splitting water into hydrogen and oxygen using renewable or zero-carbon electricity (e.g., nuclear fission, or fusion). For example, building a new solar farm and connecting it to a new electrolysis plant ensures that only electricity generated from solar energy is used to produce hydrogen, making the hydrogen's LCA effectively zero, but at high cost due to low-capacity utilization. Many hydrogen producers, therefore, are seeking to build electrolysis plants that would connect to the existing electricity grid. That hydrogen's carbon-intensity would reflect the carbon-intensity of the grid, wherein grids powered by fossil energy would send carbon-intensive electricity to the electrolysis plant and increase the LCA emissions. Until the grid is substantially decarbonized, this trade-off in cost and life cycle emissions (and the provisions of 45 V) will be an important consideration for investors.

The impact depends on how much fossil energy is used on that grid, but it can be severe; electrolysis emissions can be substantially greater than conventional fossil-based hydrogen if using a fossil-heavy grid.[22] Inversely, a grid exclusively powered by zero-carbon energy sources would not produce emissions. However, the use of fossil fuels can only be avoided if there is enough zero-carbon energy to meet existing demand and new demand from electrolysis. If zero-carbon energy supply is deficient, fossil energy would be used to meet that electricity demand and incur indirect emissions.

The proposed 45V Rule recognizes and seeks to set stringent requirements on projects with grid-connected electrolysis, requiring them to be met with new clean energy supply, verify their grid-emissions (i.e., clean energy) on an hourly basis, and use electricity generated within the same region, i.e., the three pillars described above.[23] Utilities and H2 project developers argue that the downside of applying such a rule is that the rate at which electrolyzer capacity will be

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[22] https://iopscience.iop.org/article/10.1088/1748-9326/acacb5/meta

[23] https://www.federalregister.gov/documents/2023/12/26/2023-28359/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen

built initially will be paced by solar and wind interconnection times – which are as long as 4 years in some jurisdictions.

Fossil-based H2 with CCS (i.e., blue hydrogen or methane pyrolysis)

The most common method for producing hydrogen in the U.S. is using natural gas and processing it via steam methane reforming (SMR) and increasingly, Autothermal Reforming (ATR), which is more efficient. Approximately 95% of the 10 MT of U.S. hydrogen is produced through SMR. According to the EPA, this produced 43 MMT of CO_2 in 2022. These emissions derive from separating hydrogen and carbon from methane, with the resulting carbon dioxide vented into the atmosphere as emissions, along with emissions incurred to produce the electricity and heat for the process. Additionally, a full LCA would consider methane that leaks along the natural gas infrastructure.[24]

Natural gas-based hydrogen emissions can be reduced through two methods: carbon capture and storage (CCS) and methane pyrolysis. Of the two, CCS is favored because it accommodates current SMR plants, and entails capturing the CO_2 emissions from the process and storing them underground. Methane pyrolysis, a thermochemical process, upon separation yields a hydrogen gas and solid carbon, rather than CO_2. One review of published LCAs of SMR with CCS and electrolysis found that the per kgH_2 emission range was between .2-8$kgCO_2$ for SMR and 0-3$kgCO_2$ for electrolysis. As discussed above, this range greatly depends on where and how energy is sourced, CCS capture rates, and upstream methane leakage.

Common Considerations

Role of biomethane

Biogas, and in turn biomethane, can be produced from many different sources, including landfills, wastewater treatment plants, and livestock farms. This can be used as a feedstock for hydrogen production through either SMR or electrolysis. In some cases, capturing this biogas for hydrogen production can offer an important methane mitigation opportunity, e.g., where the methane would have otherwise been released into the atmosphere.

However, incorporating this methane as a hydrogen feedstock does introduce risks around fugitive methane emissions and management of anaerobic digester effluent. For example, methane leakage from biogas production and upgrading facilities is frequently on the order of 2-4% but can be as high as 15%,[25] while methane leakage from transmission and distribution of natural gas is estimated to be in the range of 0.4-0.9%.[26] When the organic material being digested would otherwise not produce methane or if the methane is being diverted from a flare, methane loss rates as low as 2.5% are likely to negate the benefits of offsetting fossil fuels.[27] In addition, the creation of biomethane from manure (through anaerobic digesters)

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[24] https://onlinelibrary.wiley.com/doi/10.1002/ese3.956

[25] https://iopscience.iop.org/article/10.1088/1748-9326/ab9335

[26] https://www.wri.org/research/production-and-use-waste-derived-renewable-natural-gas-climate-strategy-united-states

[27] https://iopscience.iop.org/article/10.1088/1748-9326/ab9335

creates ammonia, which impacts public health due to PM 2.5 releases and has the potential for water contamination.[28] Best practices should be followed around the management of digestate and associated ammonia, air pollutants, and pathogen transport to minimize health and environmental harms.

Livestock biomethane is also seen by some hydrogen producers as a potential offsetting mechanism for more carbon-intensive fossil methane feedstocks, given that this type of biomethane can receive very low and even negative emissions-intensity scores in certain models (e.g., California's LCFS).[29] Carbon negative offsetting would allow a high-emitting blue hydrogen facility to artificially reduce its carbon intensity score by purchasing a small share of biomethane credits, while doing nothing to change the underlying production technologies or processes. Meanwhile, book-and-claim accounting systems for biomethane credits in the U.S. are relatively nascent, and several instances of fraud have been documented in the Renewable Fuel Standard and California LCFS programs, including transactions of invalid or fraudulent credits.[30,31] The M-RETS credit tracking system for renewable fuel credits launched in 2020, while M-RETS has been tracking clean energy generation credits for many more years. The Center for Resource Solutions just launched a voluntary third-party certification program for biomethane in 2021, while its equivalent certification for clean energy generation has been available since 1997. Continued challenges with the administration of U.S. EPA's Renewable Fuel Standard[32] demonstrate the need to strengthen the regulatory program's oversight of the (Renewable Identification Number) RIN market, as well as the importance of external checks on the validity of biomethane environmental attributes beyond the existing regulatory compliance framework.

Leakage

The climate impact of hydrogen does not just depend on carbon dioxide emissions, but methane and hydrogen emissions, as well.

Methane Emissions

Natural gas, the primary feedstock in reforming, is composed primarily of methane. Methane is both a direct and indirect greenhouse gas in that it absorbs infrared radiation but also affects atmospheric chemistry in ways that increase other GHGs (mostly tropospheric ozone and stratospheric water vapor). Compared with carbon dioxide of equal mass, fossil fuel methane's

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[28] https://www.sciencedirect.com/science/article/pii/S0301479722018588?via%3Dihub

[29] Cyrs et al. (2020), "Climate Strategy: Guidance for State Policymakers," WRI, https://www.wri.org/research/renewable-natural-gas-climate-strategy-guidance-state-policymakers

[30] U.S. EPA, Civil Enforcement of the Renewable Fuel Standard Program, https://www.epa.gov/enforcement/civil-enforcement-renewable-fuel-standard-program (last updated Oct. 18, 2023).

[31] California's Air Resources Board has pursued enforcement actions for violations of LCFS program standards, recording 14 settlement agreements since 2017. See California Air Resources Board, LCFS Enforcement Activities, https://ww2.arb.ca.gov/resources/documents/lcfs-enforcement.

[32] A recent EPA Office of Inspector General report identified several weaknesses in the current program and documented significant levels of RIN fraud. See U.S. EPA Office of Inspector General, *The EPA Must Improve Controls and Integrate Its Information System to Manage Fraud Potential in the Renewable Fuel Standard Program*, Report No. 23-P-0032 (Sept. 19, 2023), https://www.epaoig.gov/sites/default/files/reports/2023-09/_epaoig_20230919-23-p-0032.pdf

warming potential is 83 times higher over a 20-year period and 30 times higher over a 100-year period.[33]

For fossil-based hydrogen systems, feedstock methane emissions are one of the largest contributors to its lifecycle greenhouse gas emissions, and studies show that high methane leak rates, combined with hydrogen leakage, can make blue hydrogen applications worse for the climate in the near-term than fossil fuel alternatives.[34] Methane leakage rates can vary substantially by basin and distribution system – for example, the methane intensity of oil and gas production ranges from zero in Norway to 1.36 kg methane/GJ in Turkmenistan.[35] Life cycle assessments of fossil-based hydrogen should accurately reflect the basin-specific methane leakage rates to further incentivize methane mitigation efforts.

Hydrogen Emissions

Hydrogen itself is an indirect GHG, and it contributes to global warming along with other GHGs like carbon dioxide and methane. In fact, the latest science suggests that hydrogen has 30-40 times the warming power of carbon dioxide over the first 20 years,[36] and 8-12 times the warming power over a 100-year period.[37] Around 30% of molecular hydrogen emitted into the atmosphere chemically reacts with the naturally occurring hydroxyl radical after a few years. This reaction ultimately increases the amounts of short-lived GHGs including methane, tropospheric ozone, and stratospheric water vapor.

Hydrogen is also a small molecule that easily leaks into the atmosphere throughout the hydrogen production lifecycle – and in many cases, large volumes are intentionally vented, purged, or flared. In the absence of direct measurements, several studies have estimated emissions from venting, purging, and leakage at various stages of the value chain and in total, finding a wide range in emissions anywhere from <1% to 20%.[38] While hydrogen emissions are not currently a problem, as the hydrogen economy ramps up, there is a significant risk related to emissions of hydrogen.

The climate impact of these fugitive and intentional hydrogen emissions should be factored into LCAs for all hydrogen pathways to generate an accurate picture of climate impact. Hydrogen emissions should also be managed through leak detection and mitigation plans. High-precision, high-frequency sensors (e.g., ppb level and 1 Hz) are beginning to achieve commercialization levels in the U.S., supported by public sector funding opportunities over the last few years. These sensors will make it possible to detect even small levels of fugitive emissions that have significant climate impacts in the aggregate. Moreover, there are many operational best practices hydrogen companies can adopt to mitigate leakage, such as adequately insulating

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[33] IPCC, WG 1, The Physical Science Basis, at 7-125.

[34] https://acp.copernicus.org/articles/22/9349/2022/

[35] IEA (2022), Global Methane Tracker

[36] Warwick et al. 2023; Sand et al. 2023; Hauglustaine et al. 2022

[37] Warwick et al. (2023); Sand et al. (2023); Derwent et al. (2023); Hauglustaine et al. (2022)

[38] Esquivel-Elizondo et al. 2023

pipes, installing vapor recovery units to capture boil-off, recovering vented hydrogen, and installing control devices on storage tanks.[39]

Demand creation/hydrogen markets

Developments aimed at supporting the offtake of clean hydrogen

Lack of demand for clean hydrogen continues to be a challenge to project development and to the growth of the clean hydrogen market generally in the U.S., India, and elsewhere. While the U.S. has passed landmark supply-side policies to support clean hydrogen development, it became increasingly clear over the course of 2023, that without additional policy support for offtake, the catalytic impact the hydrogen PTC and hydrogen hubs programs were meant to have would be muted.

The U.S. regional clean hydrogen hubs selection process in particular provided DOE with evidence of the price and offtake challenges faced by the nascent clean hydrogen market, and in 2023, the agency began to explore using $1B held in reserve from the hydrogen hubs program to provide demand-side support in some way. In January 2024, DOE announced the selection of a coalition of organizations, led by the Energy Futures Initiative in collaboration with S&P Global, MIT, ICE and others, to design a mechanism to provide offtake support.

There are similar efforts being deployed in other countries as well to address the challenge presented by the lack of secured offtake. One notable example is the H2Global Instrument, an organization which makes use of the “Contracts for Difference” approach and government and philanthropic dollars to close the bankability gap for hydrogen project developers.[40]

To be successful in supporting offtake, the design developed for use in the U.S. will need to take into account the limited level of demand-side funding available, the attributes of the different end-use sectors that will be involved in offtake, regional differences in the hubs, and the unique environment created by the other incentives available at the federal, state, and local levels.

To encourage hydrogen production internationally, India, the U.S., and other countries interested in encouraging hydrogen production could develop agreements that ensure that green hydrogen and ammonia trade freely (i.e., without tariffs) to encourage the creation of a vibrant international low-carbon hydrogen market with high production in countries with low cost production potential. This would encourage investment where low-cost production is the most feasible.

Role of ammonia as an alternative to hydrogen

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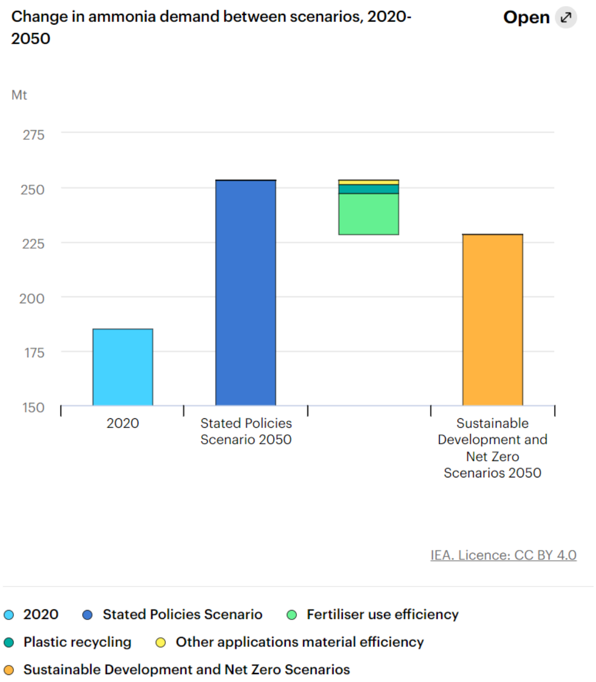
[39] https://www.edf.org/sites/default/files/documents/H2%20Emissions%20Mitigation%20Factsheet_08MAY2023.pdf

[40] “Based on a mechanism in analogy to the Contracts for Difference (CfD) approach, the difference between supply prices (production and transport) and demand prices will be compensated by grants from a public or philanthropic funding body.” https://www.h2-global.de/project/h2g-mechanism



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While 70% of ammonia is used for fertilizers, the rest is used for industrial applications.[41] And, there is a growing interest in the potential of green ammonia as a sustainable fuel given its low carbon impact and as a safe hydrogen-carrying energy vector due to its low reactivity and ability to be decomposed onsite into hydrogen through catalytic processes.[42] Ammonia is easier and cheaper to store and transport than hydrogen, even taking into account reconversion.[43] Further, ammonia has the potential to replace fossil fuels in industrial processes and electricity generation, e.g., it may provide a long-term way of storing and transporting energy from renewable sources. Researchers are making the case that ammonia is preferable to pure hydrogen from economic, environmental, and technological perspectives.[44] The IEA predicts significant increases in ammonia demand.[45]

While ammonia has attractive characteristics as a carbon-free energy vector, it still presents some safety risks due to its corrosiveness and toxicity.[46] While it is not a GHG, when combusted, ammonia gives rise to emissions of N20, which is, as well as NOx which is associated with atmospheric fine particulate formation.

Green vs. Blue Ammonia

In order to ratchet up production of either or both green and blue ammonia, the lack of a proper definition, certification, and a specific market creates a challenge. For green ammonia, there are specific challenges including the state of electrolyzer technology development and the renewable energy needs. A significant amount of renewable power would be required. Current ammonia production alone would consume 70% of the global renewable non-hydro power production.[47] Renewable power load variability is a problem for the synthesis loop, and the bigger the plant the more important the problem. For blue ammonia, additional challenges

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[41] https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary

[42] https://www.weforum.org/agenda/2023/11/green-ammonia-climate-change-energy-transition/ , https://www.sciencedirect.com/science/article/abs/pii/S0959652621007824

[43] https://www.hydrogeninsight.com/innovation/iea-ammonia-and-lohc-will-be-cheaper-options-for-shipping-hydrogen-than-liquefied-h2-even-with-reconversion-costs/2-1-1387346

[44] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf

[45] https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary

[46] https://www.sciencedirect.com/science/article/pii/S2589004223014669

[47] https://www.energy.gov/sites/default/files/2021-08/15-green-blue-ammonia.pdf

include the lack of CCUS infrastructure, particularly regarding the transportation and sequestration of CO2. (These are some of the same issues facing blue hydrogen).

A report considered a set of case studies evaluating the feasibility of producing green and blue ammonia.[48] The assessments have shown that green ammonia production can be cost-competitive with fossil fuel-based ammonia production under certain conditions. To make green ammonia competitive, the production process must be optimized to maximize efficiency and reduce costs. Researchers recommend the use of artificial intelligence and advanced manufacturing to achieve this. Another study concluded that "[w]hile green ammonia can better mitigate climate change impacts on a per kg ammonia basis, blue ammonia might offer an immediate solution for mitigating the environmental impacts of ammonia production under limited renewable electricity availability, as long as natural gas supply chain leakage rates are monitored and maintained low."[49]

Which uses of hydrogen are most relevant?

While hydrogen can be used as a fuel or a feedstock for decarbonizing across various sectors, some of its best uses lie in decarbonizing industrial processes. Currently, hydrogen production can be emissions-intensive, clean production processes are expensive, and there is an availability of a myriad of other options, such as electrification, in the short-term to decarbonize many parts of the economy. Demand must ramp up but with a higher priority for clean hydrogen uptake given to parts of the industrial sector that have relatively few other pathways to decarbonize. Some of the key sectors for clean hydrogen offtakes for the U.S. are steel manufacturing, fertilizer and ammonia manufacturing, crude oil refining, and shipping.[50] In other countries where there is no access to cheap natural gas (such as India), hydrogen is expected to be used as a fuel in thermal combustion engines as well as power plants.

While the largest current demand of hydrogen is in refining and the production of ammonia and methanol, nearly all the hydrogen used is gray and brown hydrogen i.e. produced with unabated fossil fuels.[51] And there are concerns that future clean hydrogen is not being directed toward the process that most need it.[52] For example, the U.S. Hydrogen Hubs program is channeling $7 billion towards various sectors, including buildings and power plants, which are not considered the best applications of clean hydrogen.[53] This challenge is further complicated by the nascency of decarbonization processes involving clean hydrogen for best-use sectors like steelmaking.

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[48] https://www.mdpi.com/2076-3417/13/15/8711

[49] https://www.sciencedirect.com/science/article/pii/S2589004223014669

[50] https://www.catf.us/resource/hydrogen-for-decarbonization-a-realistic-assessment/

[51] https://www.iea.org/energy-system/low-emission-fuels/hydrogen

[52] https://www.canarymedia.com/articles/hydrogen/us-hydrogen-hub-plan-may-push-clean-hydrogen-to-the-wrong-users

[53] https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0 , https://www.catf.us/resource/hydrogen-for-decarbonization-a-realistic-assessment/

Steel decarbonization using clean hydrogen: Steel manufacturing, a heavy industry sector that causes 9% of global anthropogenic CO2 emissions, is an increasingly critical sector that will need clean hydrogen to decarbonize.[54] There are two main production routes for steelmaking: primary production which involves converting iron ore into iron and then steel; and secondary steel production which involves recycling steel scrap into steel. The global average emissions intensity of steel is 1.9 tons CO2e per ton steel.[55]

Primary steel production is emissions-intensive mainly because of the process of melting iron ore into iron, typically carried out in a blast furnace using coke (made by heating coal) and high temperatures (>1200°C) with an emissions intensity of 2.3 tons CO2e per ton steel.[56] Secondary steel production is carried out in electric arc furnaces (EAF) with an emissions intensity of 0.7 tons CO2e per ton steel.[57] While secondary steel accounts for around 70% of U.S. and 57% of Indian steel production, primary steel will continue to be in demand.[58]

Another pathway for primary steel production is direct reduced iron (DRI) carried out in a shaft furnace. These furnaces use natural gas or hydrogen instead of coke to reduce pelletized iron ore at 800°C. Compared to blast furnaces, pairing hydrogen with DRI (H2-DRI) has the potential to reduce GHG emissions from the steelmaking process by up to 90%.[59]

According to the IEA, H2-DRI using electrolytic hydrogen will account for 15% of global primary steel production with a total use of 12 million tons.[60] India is set to take the center stage by 2050, with H2-DRI set to account for 22% of steel production in the country with a demand of 4.5 million tons of electrolytic hydrogen per year.[61] At current prices, using clean hydrogen instead of coal will lead to a 30% increase in the price of steel.[62] To close this gap incentives are needed for low-carbon steel production as well as demand-side mechanisms for hydrogen to rapidly scale steel decarbonization.

Given the common goals shared by the two countries to shift to hydrogen-based DRI-EAF steel production, India and the U.S. can create an important partnership that would hasten the

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[54] https://worldsteel.org/publications/policy-papers/climate-change-policy-paper/

[55] https://worldsteel.org/steel-topics/sustainability/sustainability-indicators-2023-report/#co2-emissions-and-energy-intensity

[56] Ibid.

[57] Ibid.

[58] https://rmi.org/forging-a-clean-steel-economy-in-the-united-states/#:~:text=Roughly%2070%20percent%20of%20the,between%2080%20and%2090%20percent. , https://www.business-standard.com/article/economy-policy/57-share-in-national-output-yet-secondary-steel-makers-voice-is-unheard-118032600647_1.html

[59] https://www.cell.com/joule/fulltext/S2542-4351(24)00026-6#tbl3

[60] https://www.iea.org/reports/iron-and-steel-technology-roadmap , https://worldsteel.org/wp-content/uploads/Fact-sheet-Hydrogen-H2-based-ironmaking.pdf

[61] https://www.iea.org/reports/iron-and-steel-technology-roadmap , https://worldsteel.org/wp-content/uploads/Fact-sheet-Hydrogen-H2-based-ironmaking.pdf

[62] https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf

transition to green steel, which would decarbonize the industry and provide demand for green hydrogen. This demand would lead to scaling of green hydrogen production and cost reductions of both green hydrogen and green steel production. As countries are establishing low-emissions steel partnerships, India and the U.S. should focus on building a clean steel research partnership.

The partnership would identify collaborative opportunities such as: using hydrogen as an alternative input to pulverized coal injection, piloting of natural gas-based DRI plants that have capabilities to rapidly transition to run on 100% hydrogen,alternative energy sources such as biomass or electric heaters for heating the reducing gas[63], coupling of DRI process with EAF powered by renewables, and also ensuring hydrogen supply security through low-carbon hydrogen production infrastructure. A partnership focused on collaboration to address these key issues would set the stage for primary steel production to be increasingly reliant on green hydrogen in both countries and around the world.

Storage & Transport – Connective Infrastructure

Storage and transport options, costs, trade offs

Because hydrogen is the smallest molecule in the universe, it requires highly specific infrastructure to transport or store to reduce leakage and material corrosion. It can be transported in a pipeline as compressed gas or in pressurized cylinders on freight or truck as a very low-temperature liquid; the compression and or liquefaction processes require significant energy, however, more so than similar measures for natural gas. Liquefaction consumes up to 40% of the delivered energy while compression consumes about 10%.[64]

Truck or freight transport require less infrastructure than pipelines but are only ideal for transporting volumes less than 10 miles. At longer distances, pipelines become more economical. However, hydrogen pipelines cost more than other commonly transported energy carriers like natural gas and oil due to factors like high pipeline standards that can resist corrosion and mitigate leakage risks and a smaller experienced workforce.[65] Because of these transport difficulties, some projects seek to blend hydrogen into existing natural gas pipelines or convert hydrogen to other carriers like ammonia, methanol, or synthetic methane.

Hubs vs Distributed Hydrogen

The tradeoffs with these proposals is that hydrogen can only be safely blended volumetrically with natural gas in existing infrastructure up to about 15%, while converting hydrogen to carriers like ammonia and methanol and then potentially reconverting carries enormous efficiency losses. Storing pure hydrogen as a gas or liquid avoids some of the losses that

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[63] Hall, W., Millner, R., Rothberger, J., and Singh, A., Shah, C.K. 2021. Green Steel through Hydrogen Direct Reduction: A study on the role of hydrogen in the Indian iron and steel sector. New Delhi: The Energy and Resources Institute (TERI).

[64] Feldmann, J. Byrum, Z., and Cyrs, T. 2023. "Clean Hydrogen: Outlook for freight transport in the United States." Clean Hydrogen: Outlook for Freight Transport in the United States

[65] DeSantis, D., et al. 2021. "Cost of long-distance energy transmission by different energy carriers." *iScience*. https://doi.org/10.1016/j.isci.2021.103495

naturally occur over long-distance transport, but still require large equipment and some energy to pressurize and liquify; storing hydrogen underground in salt caverns is seen as a way to avoid constructing large tanks and using energy to maintain pressure conditions, with a major DOE loan having been provided to one such project in Utah as part of a greater clean energy hub.[66]

Such energy or industrial hubs— such as the U.S. Hydrogen Hubs program—are strategically important ways to avoid large infrastructure build outs and to potentially avoid energy losses, energy expenditure, and leakage. They also provide dedicated clusters of industrial activity that can foster economies of scale, reducing the cost of emission reductions for sectors and technologies within the hub. Indeed, concentrated activity can also reduce the frictions associated with siting, constructing, and monitoring sprawling infrastructure. Although leaked hydrogen disperses more quickly than, for example, methane or carbon dioxide, it is still an odorless, flammable gas that poses explosion risks. Access to personnel trained in handling hydrogen infrastructure and potential leaks and fires would be more likely in hubs than remote locations.

Hydrogen Safety Regulations

Today, U.S. states approve pipeline projects while the Pipeline and Hazardous Materials Safety Administration (PHMSA), an agency operating under the auspices of the Department of Transportation, establishes and monitors safety standards. Because there is no federal siting authority for hydrogen pipelines, unlike natural gas and petroleum, states negotiate interstate pipeline systems. It is possible that demand for hydrogen could outpace supply and infrastructure capabilities if production and consumption are not contained within centralized clusters. Thus, U.S. policymakers have begun considering potential federal frameworks to avoid potential transport bottlenecks.

Although hydrogen infrastructure works with rules to ensure safety, it is still a niche market relative to other energy carriers. Given the energy needed to produce, convert, and transport hydrogen, co-locating production and consumption might frequently be the most efficient way system design. But policies that guide long- and short-distance transport must still ensure that materials, leaks, and emergency response mechanisms are all tailored to hydrogen’s unique qualities.

Geologic hydrogen

During 2023, interest in naturally occurring subsurface stores of hydrogen grew substantially due to the potential for this type of resource to become a widely accessible, low carbon source of hydrogen globally. Natural occurrences of hydrogen underground, referred to as *natural*

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[66] https://www.powermag.com/aces-deltas-giant-utah-salt-cavern-hydrogen-storage-project-gets-504m-conditional-doe-loan-guarantee/

hydrogen, *geologic hydrogen*, *or white hydrogen* have been observed for decades[67] though the potential to harness this resource has largely been overlooked by the broader community due to previously insufficient data around scale, volume, and accessibility.

Geologic hydrogen is produced naturally by several mechanisms, including a rapid process where iron-rich rocks react with water known as serpentinization. In fact, the U.S. Geological Survey (USGS) recently estimated that potentially trillions of tons exist globally, which is many times more than the current demand of 100 million metric tons per year.[68] However, it is uncertain how much of that is viable for extraction, with some estimates as low as just a few percentage points. Nevertheless, even just 5% of one trillion (50 billion) would be enough to meet estimates of hydrogen demand in 2050.[69] Large, economically interesting, trapped reserves of hydrogen have been identified in multiple locations using traditional oil and gas data collection and analysis processes. In addition to a focus on identifying existing reserves, several academic and private entities are developing approaches to stimulate greater rates of production either down-hole or in dedicated surface reactors.[70] [71] The array of potential production options, combined with the geologic diversity at play, could make it possible to tune production to ensure that hydrogen is as clean and low cost as possible. Initial estimates of the carbon footprint of geologic hydrogen production indicates an ability to achieve as low as 0.4 kg CO2/kg H2.[72]

The viability of geologic hydrogen production has significant implications for the clean hydrogen market and decarbonization. Because geologic hydrogen production has the potential to leverage existing, mature technologies, it is possible that geologic hydrogen could provide a pathway for developing a clean hydrogen market more quickly than would otherwise be possible. Further, depending upon the process by which the geologic hydrogen is produced, hydrogen could be generated along with valuable co-products, while ensuring that carbon-containing fossil gasses are not emitted.

Some initial investigations[73] have indicated that geologic hydrogen reserves are being replenished via ongoing serpentinization reactions, unlike the finite nature of oil and gas reserves. Perhaps most importantly, because of the above, some suggest that clean geologic hydrogen could be produced at a pressurized well-head at a cost close to or below $1/kg. Reaching this cost per unit could fundamentally shift the value proposition associated with clean hydrogen use, making it more economical to use clean hydrogen in more of the highest

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[67] Zgonnik, V. The occurrence and geoscience of natural hydrogen: A comprehensive review. Earth-Science Reviews, Volume 203, 2020, 103140. ISSN 0012-8252. https://doi.org/10.1016/j.earscirev.2020.103140.

[68] Hidden Hydrogen: Does Earth hold vast stores of a renewable, carbon-free fuel? Science, Volume 379, 6633. Hidden hydrogen: Earth may hold vast stores of a renewable, carbon-free fuel | Science | AAAS

[69] https://www.iea.org/reports/net-zero-by-2050

[70] Osselin, F., et al. Nature Geoscience. 15: 765 (2022).

[71] ARPA-E Exploratory Funding (2023) https://arpa-e.energy.gov/technologies/exploratory-topics/geologic-hydrogen

[72] Brandt, A. Joule. 7:8 (2023)

[73] Prinzhoffer, Hydrogen Energy 2018; Maiga, Omar et al (2023). Scientific Reports. 13:11876; Prinzhoffer, Hydrogen Energy 2023; Osselin, F, et al. Nature Geoscience. 15: 765 (2022).

priority applications for climate mitigation. This could be meaningful given that hydrogen is expected to be constrained to specific applications depending upon its cost and the efficiency of using hydrogen instead of electrifying.[74] The co-availability of electrolyzer and geologic hydrogen technology provides the greatest theoretical geographic coverage as the two technologies are likely to have different optimal locations.

At this time, there are still many important unknowns that must be better understood before anything can be concluded about the potential that geologic hydrogen production actually holds for global decarbonization. One is the accessibility of the available resources. In the United States, the USGS has been developing a detailed geo-resource model that will serve as a preliminary map showing where geologic resources may exist in the country, likely to be publicly released at some point in 2024. Many other countries are in the earlier stages of national data gathering. Other important factors include the validation of carbon footprint, costs, and extractability of individual reserves, which will vary depending on production method, geography, and other aspects specific to each operation. Many companies in the field are in the early stages of prospecting and development, and the outcome of their efforts will further clarify the opportunity geologic hydrogen holds. Finally, once extracted, geologic hydrogen will face the same barriers to viability as a climate mitigation tool that other forms of clean hydrogen do, including considerations about hydrogen emissions impacts, access to midstream infrastructure for transport, and hurdles associated with siting and permitting.

Policies intended to enable clean hydrogen market liftoff should be developed keeping geologic hydrogen resources in mind, and with an eye towards the innovative approaches that may be available for producing it. Such policies should ensure that any geologic resources developed are as low emissions as possible and comport with existing standards for clean hydrogen production. Additionally, it is important to integrate geologic hydrogen production methods into the standards and definitions governing clean hydrogen trade, as well as into policies and regulatory frameworks concerning the infrastructure for transportation and storage. Anticipating and addressing future permitting and siting challenges faced by geologic hydrogen producers is also crucial. Finally, policies should consider and potentially incentivize producers for any demonstrated co-benefits that may arise from geologic hydrogen production.

Opportunities for US-India Collaboration

Technical standards harmonization will enable trade and export

To enable trade of clean hydrogen between the U.S. and India, policymakers should work to harmonize standards and requirements being developed in each country. This work should build upon the efforts to align definitions of clean hydrogen in each country, which provide a foundation for trade by ensuring that both countries have a clear threshold for distinguishing clean hydrogen from carbon intensive hydrogen.

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[74] Evolved Energy Research. Hydrogen Competition in the 2022 Annual Decarbonization Perspective. Jan 2023. [Hydrogen Competition in the 2022 ADP (evolved.energy)]()

Complementary Incentives

Since clean hydrogen trade does not yet exist, the trade dynamics are expected to be significantly influenced by the incentives offered by individual countries, and how these incentives affect the cost along the hydrogen value chain. Incentives in each country should be aligned such that they are complementary to one another and cover relevant parts of the value chain based on the type of trade that the U.S. and India seek to enable with one another. For instance, because of the U.S. PTC and the SIGHT program incentives in India, both countries are in a position to become a global exporter of clean hydrogen. Pairing supply-side incentives in the exporting country with demand-side incentives in importing countries would enable trade.

Consistent standards & MRV

It is also important for importing and exporting countries to coordinate and provide clear information about what requirements should be met by producers to ensure they comply with the definition of clean hydrogen in both places. Both India and the U.S. have formulated their own definitions for clean or green hydrogen. The intensity threshold for the definition for both countries is the same at <=2kg CO_2/ kg H_2. Notably, the U.S. definition is not limited to green hydrogen whereas the Indian definition is so limited. Nonetheless, the definitions are quite similar for the green hydrogen pathway and hence both countries can formulate a mutually acceptable MRV system. This will ensure that the emissions intensity quoted by any producer can be interpreted by the market on a standardized basis and subsequently place differential premiums based on the GHG emissions associated with hydrogen production.

A robust MRV system will provide guarantees of origin for green fuels and provide assurance that the fuel is green to the extent claimed. Developing such an MRV system that is acceptable to all parties needs coordinated actions from all countries in the ecosystem. The MRV protocols should clearly lay out the requirements for auditors, specifically on the technical capabilities.

Joint development of a Price Index

Currently, the price of clean hydrogen is being set through mostly bilateral deals. The general market has no visibility of the prices, and hence achieving competitiveness in the market will take time. Also, trading in green hydrogen will be difficult without something to peg the price against. Lowering the price of green hydrogen is essential to achieve scale, and better price discovery is possible through the indexing of prices in the global markets, similar to Henry Hub (U.S.) or National Balance Point (UK) for natural gas. A price index can be region-specific to reflect the renewable resources and economic conditions.

Standards to incentives clean hydrogen end use

Both countries should coordinate on setting standards for and incentivizing the adoption of clean hydrogen in end uses where it is the best way of decarbonizing emissions.[75] This could be accomplished by aligning on climate goals and hydrogen-related targets for each end-use sector,

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[75] Evolved Energy Research. Hydrogen Competition in the 2022 Annual Decarbonization Perspective. Jan 2023. Hydrogen Competition in the 2022 ADP (evolved.energy)

by establishing a coordinated approach to demand-side market support, and through coordinating on certifications and standards related to adoption in end-uses and the "cleanliness" of those sectors.[76] Engaging private sector stakeholders from both countries in these discussions can provide valuable insights and foster a collaborative environment that accelerates progress towards shared goals.[77]

Shipping: support Paris-aligned targets for shipping decarbonization

Decarbonization of the maritime sector, which currently produces approximately 3% of global GHG emissions, can and should play a key part in driving demand for green hydrogen, primarily through its demand for green hydrogen-derived fuels, such as ammonia and methanol.

Shipping currently uses heavy fuel oil, and it is expected that green hydrogen or green hydrogen-based compounds such as ammonia or methanol will play a big role in decarbonizing the sector.[78] Shipping is often identified as the largest single predicted demand sector for green hydrogen in the future. One study estimates approximately 130 million tonnes of hydrogen demand for shipping by 2050, whereas in the same study steel and chemicals in combination account for 170 million tonnes of annual offtake. In order for this potential to materialize, however, strong policy signals are needed to assure the green hydrogen production sector that there will be strong demand for green hydrogen products in the shipping sector. Currently the discussion is fragmented: shipping interests worry that there will not be enough green hydrogen and derived fuels to meet ambitious decarbonization targets if they set them, while at the same time green hydrogen producers are concerned about adequate demand. National and international incentives such as targets for green hydrogen use and production in the sector or support mechanisms are needed.

India-US Hydrogen Task Force

The India-US Hydrogen Task Force is a high-level bilateral collaboration between the Indian MNRE and the U.S. DOE, in coordination with the U.S.-India Strategic Partnership Forum (USISPF).[79] The Hydrogen Task Force focuses on strengthening cooperation on hydrogen between industry and institutions from both countries. The task force has the following objectives:

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[76] The Value of Green Hydrogen Trade for Europe - RMI

[77] Ambitious Coalition Launches to Enable First Clean Hydrogen Shipment Across Atlantic by 2026 - Transatlantic Clean Hydrogen Trade Coalition - Hydrogen Central (hydrogen-central.com)

[78] NITI Aayog, & RMI. (2022). *Harnessing Green Hydrogen*. RMI. https://rmi.org/insight/harnessing-green-hydrogen/#%3A~%3Atext%3DIn%20this%20report%2C%20NITI%20Aayog%2Cin%202050%20could%20be%20green

[79] US India Hydrogen Taskforce: https://usispf.org/us-india-hydrogen-task-force/

- To energize the Government of India’s hydrogen economy vision through policy and regulatory recommendations;
- To encourage cutting-edge technology development, assistance & deployment of current technologies across the hydrogen value chain; and
- To conceptualize pilots and scale them for adoption.

The following working groups were created under the auspices of the Task Force and have participation from industry and government from both countries: (i) Hydrogen Production; (ii) Hydrogen Finance; (iii) Mobility; (iv) Renewable Energy Storage; (v) Industrial Hydrogen.

Based on these objectives and structure of the working groups within the Task Force, potential areas of future collaboration have been highlighted below:

- Joint research and development of hydrogen and fuel cell technologies like high-efficiency electrolyzers; Green Hydrogen production through conversion of sustainable biomass; Hydrogen safety, storage, usage and transportation;
- Co-development of advanced technologies for producing derivatives such Green Ammonia/methanol, green steel etc. at affordable cost and at scale;
- Technology demonstrations through pilot projects to accelerate scaling up and commercial deployment;
- Harmonization of regulations, standards, safety codes, and procedures across the hydrogen value chain including for hydrogen production, storage, transportation, dispensing stations, and vehicles;
- Exchange of testing and technology validation methodologies and joint testing, in accordance with relevant requirements, to evaluate new product prototypes;
- Development of Green Hydrogen Hubs;
- Information exchanges on lessons learned and best practices regarding hydrogen policies, costs, performance, safety, and infrastructure supply chain optimization;
- Public-private partnerships through structured dialogue and collaboration on hydrogen technologies;
- In-depth, analytic collaboration with DOE national laboratories on rigorous, clean energy development pathway modeling;
- Development of technology incubators for development and commercialization of advanced hydrogen technologies.