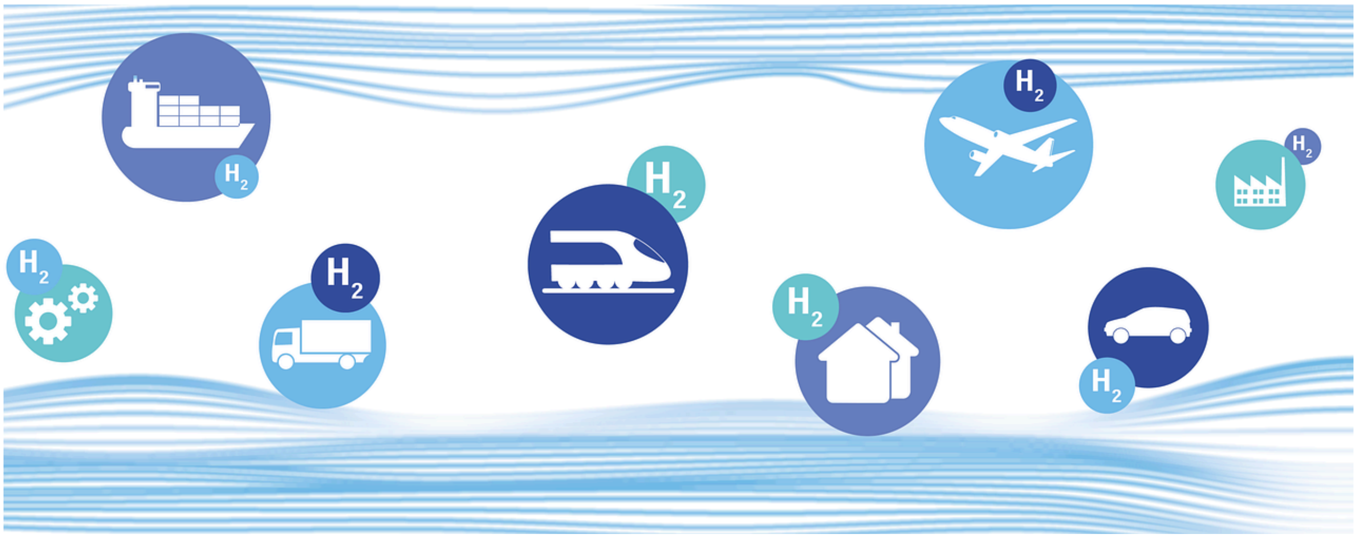

HYDROGEN LITERATURE REVIEW

Prepared for Communities for a Better Environment

JANUARY 2024

GRIDWORKS

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ACKNOWLEDGMENTS

This literature review was created on behalf of Communities for a Better Environment (CBE) as a part of the "Equity and Hydrogen Initiative." In 2023, Gridworks partnered with CBE to serve as a facilitator for 10 environmental justice organizations across California, including: Asian Pacific Environmental Network (APEN), California Environmental Justice Alliance (CEJA), Center for Community Action and Environmental Justice (CCAEJ), Center on Race, Poverty & The Environment (CPRE), Central Valley Air Quality Coalition (CVAQ), Environmental Health Coalition, Leadership Counsel for Justice and Accountability, Pacoima Beautiful, and Physicians for Social Responsibility Los Angeles (PSR-LA).

The result was the development of a shared environmental justice advocacy position on green hydrogen[1]. Our discussions, bolstered by the information from this literature review, explored hydrogen production, storage and delivery, and end-uses in an environmental justice context.

The Initiative continues in 2024 by expanding conversations to include potential allies, including labor groups, environmental organizations, Tribes, ratepayer advocates, and more. A final report and accompanying materials will follow these efforts.

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[1] Equity and Hydrogen, Communities for a Better Environment. https://www.cbecal.org/issues/equity-and-hydrogen/

WHY DOES HYDROGEN MATTER?

In efforts to accelerate the decarbonization of the economy, governments and corporations are investing in hydrogen as a low- or zero-emission fuel to replace fossil gas (also referred to as natural gas or methane gas). At the federal level, in June 2021, the U.S. Department of Energy (DOE) launched the first Energy Earthshot, which aims to reduce the cost of "clean hydrogen"[2] to $1 per kilogram (kg) in one decade so that it may contribute to addressing the climate crisis.[3] To support this goal, the Inflation Reduction Act introduces a new clean hydrogen production tax credit and broadens the existing investment tax credit to apply to hydrogen projects and standalone hydrogen storage technology.[4] Additionally, through the Bipartisan Infrastructure Law, the federal government is investing $7 billion into seven regional hydrogen hubs,[5] which is expected to catalyze more than $40 billion in private investment as well.[6]

As of July 2022, the oil refining sector dominates hydrogen use in California, consuming about 800,000 metric tons (or 800 million kilograms) of hydrogen per year to lower the sulfur content of diesel.[7] This represents about 40% of annual hydrogen demand in California (2 million tons/year).[8] Other hydrogen end uses include ammonia fertilizer, material manufacturing, steel production, power generation, and transportation.[9]

Looking forward, in California and other states across the U.S., gas utilities are looking to blend hydrogen into their respective fossil fuel mixes as one method (among others) to meet emissions reduction goals.[10, 11, 12] Additionally, California's Low Carbon Fuel Standard allows the use of hydrogen as a low carbon transportation fuel,[13] and the state has and is investing in the adoption of hydrogen fuel cell electric vehicles and buildout of hydrogen refueling infrastructure.[14] Further,

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[2] The Inflation Reduction Act defines "clean hydrogen" as hydrogen with lifecycle greenhouse gas emissions of 4 kg of CO2 equivalent or less per 1 kg of hydrogen (Inflation Reduction Act at page 120).
[3] U.S. DOE Hydrogen Shot website, accessed September 25, 2022.
[4] Cooper, Heather, September 2022, Clean Hydrogen Tax Benefits Under the Inflation Reduction Act, accessed September 25, 2022.
[5] Hydrogen hubs selected for negotiation are located in the Mid-Atlantic ($750M), Appalachia ($925M), California ($1.2B), Gulf Coast ($1.2B), Heartland ($925M), Midwest ($1B), and Pacific Northwest ($1B) (See Footnote #5).
[6] Press Release: Biden-Harris Administration Announces Regional Clean Hydrogen Hubs to Drive Clean Manufacturing and Jobs, October 13, 2023, accessed December 15, 2023.
[7] Earthjustice, July 2022, Earthjustice Comments on Hydrogen's Role in California's Clean Energy Future, TN#244040 filed in California Energy Commission Docket 21-IEPR-05, page 3.
[8] Giliani, H. and Sanchez, D., 2020, Introduction to the Hydrogen Market in California, University of California Berkeley, page 3.
[9] UC Irvine Advanced Power and Energy Program, 2020, Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California, TN#233292 in Docket 17-HYD-01, prepared for the California Energy Commission Clean Transportation Program, page 9.
[10] Southern California Gas Company (SoCalGas), ASPIRE 2045: SoCalGas Sustainability Strategy, at slides 8 and 11. See also SoCalGas' Leading Through Sustainability website.
[11] Northwest Natural, Hydrogen: The other piece of the puzzle website, accessed September 25, 2022.
[12] National Grid, December 2021, One of the US' first green hydrogen blending projects launches on Long Island, accessed September 25, 2022.
[13] California Air Resources Board (CARB), LCFS Electricity and Hydrogen Provisions website, accessed September 27, 2022.
[14] California Energy Commission (CEC), Hydrogen Vehicles & Refueling Infrastructure website, accessed September 27, 2022.

the California Energy Commission, through the Integrated Energy Policy Report, is analyzing the potential for hydrogen combustion in the power generation and transportation sectors.[15]

Although gas utilities are uplifting hydrogen as a zero-emission fuel, the reality is that 95% of hydrogen made in the U.S. today, referred to as "grey hydrogen" and described in more detail below, results in more greenhouse gas emissions than natural gas to produce the same amount of heat (Figure 1).[16] It is possible to produce hydrogen with little to no emissions, but the methods and technologies are still developing and qualifications for "clean," "renewable," and "green" hydrogen vary (this is discussed in more detail in the green hydrogen description below).

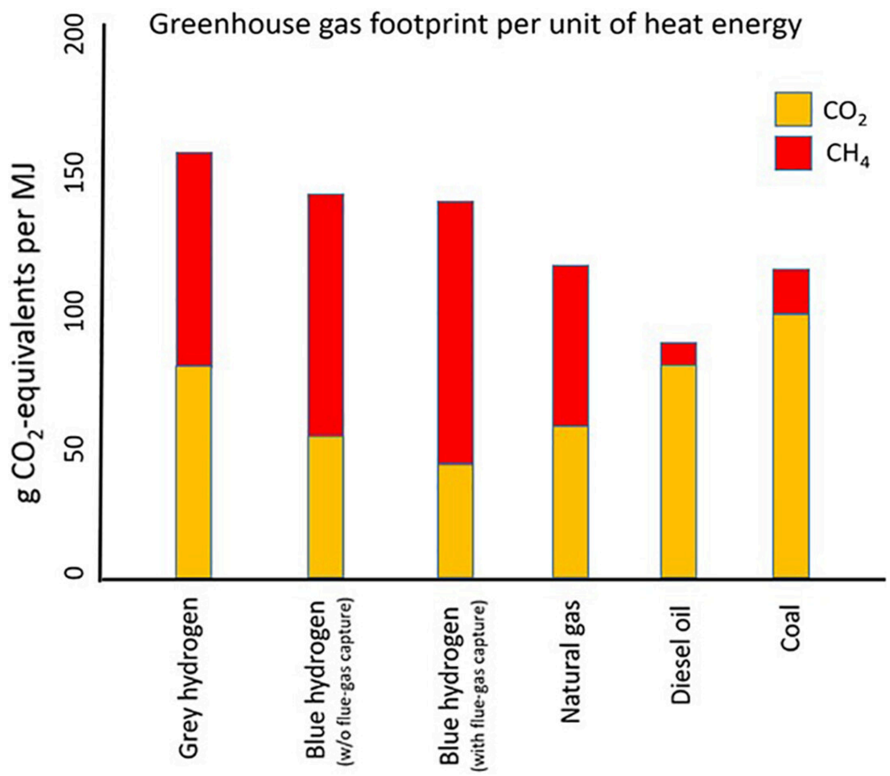

Figure 1: Carbon Intensity of Hydrogen Types Compared to Fossil Fuels[17]

Industry experts note that hydrogen has the potential to decarbonize the most carbon-intensive industries including ammonia production, oil refining, and methanol production. The same experts find that hydrogen in end uses such as trucks, buses, cement, home heating, and passenger cars has either low potential or is considered uncompetitive given the potential for alternative fuels like electricity.[18]

[15] California Energy Commission, September 11, 2023, Presentation - Hydrogen Analysis for Electricity Generation in the 2023 IEPR, filed in Docket 23-IEPR-06 (TN#252210).
[16] Howarth, Robert and Jacobson, Mark, July 2021, How green is blue hydrogen?, *Energy Science & Engineering*, 2021; 9: 1676-1687, at pages 1677 and 1683.
[17] Figure 1 of Howarth, Robert and Jacobson, Mark, July 2021, How green is blue hydrogen?, *Energy Science & Engineering*, 2021; 9: 1676-1687,
[18] Bloomberg NEF, 2022, Presentation - Hydrogen Market Growth, TN#243616 in CEC Docket 22-IEPR-05, slide 6.

Stakeholders across environmental justice, environmental, academia, utilities, and industry sectors are forming their advocacy positions regarding the role of hydrogen in California's clean energy future. This document summarizes recent literature on hydrogen production, opportunities, risks, and projects in California to help inform stakeholders so that they may develop their own perspectives and determine their advocacy positions on the role of hydrogen in California's transition to clean energy.

TYPES OF HYDROGEN PRODUCTION

"Types" of hydrogen are defined in relation to the greenhouse gas emissions associated with production. Hydrogen production is an evolving space and a whole rainbow of hydrogen types from black to pink is emerging (Figure 2). For the purposes of this paper, Gridworks discusses the three most common hydrogen types: grey, blue, and green.

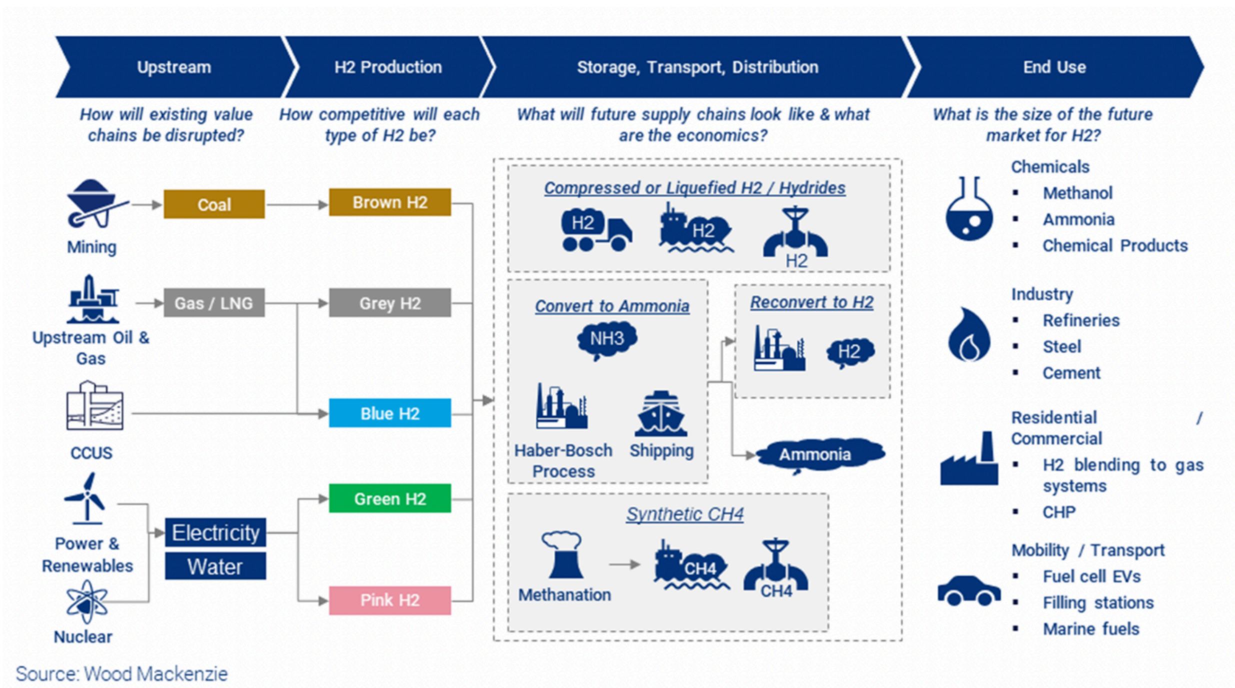

Figure 2: Hydrogen Types[19]

Grey hydrogen is made from fossil gas in a process called steam methane reformation (SMR); SMR is used to produce about 95% of hydrogen made in the U.S.[20] In California, as of 2019, grey hydrogen production capacity at (and for) oil refineries was over 1 million tons per year.[21] In the SMR process, methane in fossil gas reacts with steam to create hydrogen gas and carbon monoxide. A second reaction is then performed with additional steam, creating more hydrogen gas and carbon dioxide. The high greenhouse gas emissions associated with grey hydrogen result from using methane as the primary input (also referred to as feedstock), the fossil gas used to power the SMR process, and the leakage from the gas distribution system used to deliver the fuel

[19] van Dorsten, Bridget and De la Cruz, Flor Lucia, Decoding the hydrogen rainbow, accessed September 25, 2022.
[20] U.S. DOE, Hydrogen Production: Natural Gas Reforming website, accessed September 23, 2022.
[21] Giliani, H. and Sanchez, D., 2020, Table 4: Hydrogen Production Capacity of California Refineries in Introduction to the Hydrogen Market in California, University of California Berkeley, page 5.

to run the SMR process.[22] The exact amount of emissions resulting from grey hydrogen depends on the characteristics of the fossil gas used in the process (e.g., source, composition). Estimates of lifecycle emissions found in the literature range from ~10 to 20 kg CO_2 equivalent (CO_2eq) per 1 kg hydrogen produced.[23, 24]

Blue hydrogen is grey hydrogen combined with carbon capture and storage to reduce the release of emissions from the SMR process. However, carbon capture and storage is an energy-intensive process itself and produces additional greenhouse gas emissions. Carbon capture rates vary from 56% to less than 90% and commercial-scale long-term storage may not be feasible.[25] Recent research finds that total greenhouse gas emissions for blue hydrogen production are only 9% - 12% less than for grey hydrogen.[26]

Green hydrogen is generally defined as hydrogen produced by electrolysis directly powered by renewable electricity, consistent with the International Energy Agency.[27] Electrolysis uses electricity to split water into hydrogen and oxygen within a unit called an electrolyzer. Electrolyzers can vary in size from small, appliance-sized equipment to large-scale central production facilities.[28] Because green hydrogen production uses water as the input/feedstock and renewable electricity as the energy source, it does not result in greenhouse gas emissions (in theory).[29] Globally, less than 1% of hydrogen is produced through electrolysis, and green hydrogen represents only 0.02% of global hydrogen production.[30]

More hydrogen terminology. In some cases, California regulatory agencies use the term **"renewable hydrogen"** to describe hydrogen produced with methods where carbon emissions are offset with renewable energy credits or other means. For example, the California Energy Commission (CEC) has funded "renewable hydrogen production facilities" that produce hydrogen via gasification of rejected recycled mixed paper waste and electrolysis where carbon emissions in the electricity used are offset with the purchase of renewable energy credits.[31] Additionally, the California Air Resources Board (CARB) definition of “renewable hydrogen,” per the Low Carbon

[22] Howarth, Robert and Jacobson, Mark, July 2021, How green is blue hydrogen?, *Energy Science & Engineering*, 2021; 9: 1676-1687, at pages 1678-1679.
[23] Hydrogen Council, January 2021, Exhibit 1 in Hydrogen decarbonization pathways, at page 6.
[24] Howarth, Robert and Jacobson, Mark, July 2021, How green is blue hydrogen?, *Energy Science & Engineering*, 2021; 9: 1676-1687, at page 1679. Gridworks converted from megajoules to kilograms of hydrogen using conversion factors from the National Renewable Energy Laboratory, October 2008, Hydrogen Data Conversion Factors.
[25] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 3.
[26] Howarth, Robert and Jacobson, Mark, July 2021, How green is blue hydrogen?, *Energy Science & Engineering*, 2021; 9: 1676-1687, at page 1676.
[27] Footnote 34 of Earthjustice's paper *Reclaiming Hydrogen for a Renewable Future* states: The International Energy Agency’s definition of “green hydrogen” is consistent with the predominant approach among experts in the United States and internationally, such as the European Bank for Reconstruction and Development (“made by using clean electricity from renewable energy technologies to electrolyse water”), international energy companies like Iberdrola (“electrolysis from renewable sources”), and energy consultancies like Wood Mackenzie (“produced from water by renewables-powered electrolysis”).
[28] U.S. DOE, Hydrogen Production: Electrolysis website, accessed September 26, 2022.
[29] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page iv.
[30] Earthjustice, August 2021, Reclaiming Hydrogen for a Renewable Future, at page 7.
[31] California Air Resources Board (CARB), September 2022, 2022 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Deployment, at page 8.

Fuel Standard, includes “hydrogen produced through fossil natural gas, which is combined with carbon capture from biomethane through 'book and claim.'"[32, 33] The federal government recently defined **"clean hydrogen"** as hydrogen with lifecycle greenhouse gas emissions of 4 kg of CO_2 equivalent CO_2eq or less per 1 kg of hydrogen.[34]

In Europe and Japan, researchers and corporations are analyzing and testing the use of biomethane as a source to synthesize so-called "green hydrogen." The production process seems to mirror hydrogen produced via SMR (referred to as "grey hydrogen" above), but using biomethane rather than fossil gas as the primary input.[35, 36]

HYDROGEN STORAGE

According to some experts, "Hydrogen storage is the key enabling technology which will lead to successful deployment of hydrogen, including its economic sustainability."[37] Pure hydrogen can be stored physically in gas, liquid, or material form (Figure 3). When thinking about storage, it is important to consider the energy it takes to put hydrogen into the storage vessel in relation to the energy that the hydrogen ultimately provides. For example, when hydrogen is stored as compressed gas, the power needed to pressurize the hydrogen into tanks represents about 10% of the hydrogen's energy content.[38] Additionally, when hydrogen is stored in liquid form, the hydrogen requires extremely low cryogenic temperatures.[39] Storing hydrogen as a liquid requires significant amounts of time and energy, and about 40% of energy is lost during the liquefaction process. Currently, liquid hydrogen is reserved for special high-tech applications such as space travel, and has not yet been largely commercialized.[40]

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[32] California Energy Commission, January 2023, 2022-2023 Investment Plan Update for the Clean Transportation Program, at page 62.
[33] CARB, Low Carbon Fuel Standard (LCFS) Guidance 19-05, Reporting and Recordkeeping for Natural Gas and Book-and-Claim Accounting for Biomethane, Revised October 2019, at pages 5-6.
[34] Inflation Reduction Act at page 120.
[35] European Union Commission CORDIS, Using renewable biogas to produce green hydrogen, accessed October 4, 2023.
[36] Air Products, 2017, Biogas to Hydrogen Upgrading Shikaoi Hydrogen Farm, accessed October 4, 2023.
[37] Aziz, M. et al., June 2020, Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization, *Energies*, 13, 3062 at page 2.
[38] Hassan, I.A., et al., 2021, Hydrogen storage technologies for station and mobile applications: Review, analysis, and perspectives, Renewable and Sustainable Energy Reviews 149: 111311, at page 6.
[39] U.S. DOE, Hydrogen Storage website, accessed September 26, 2022.
[40] Yue, Meiling et. al., May 2021, Hydrogen Energy Systems: A critical review of technologies, applications, trends, and challenges, Renewable and Sustainable Energy Reviews; 146, at page 8.

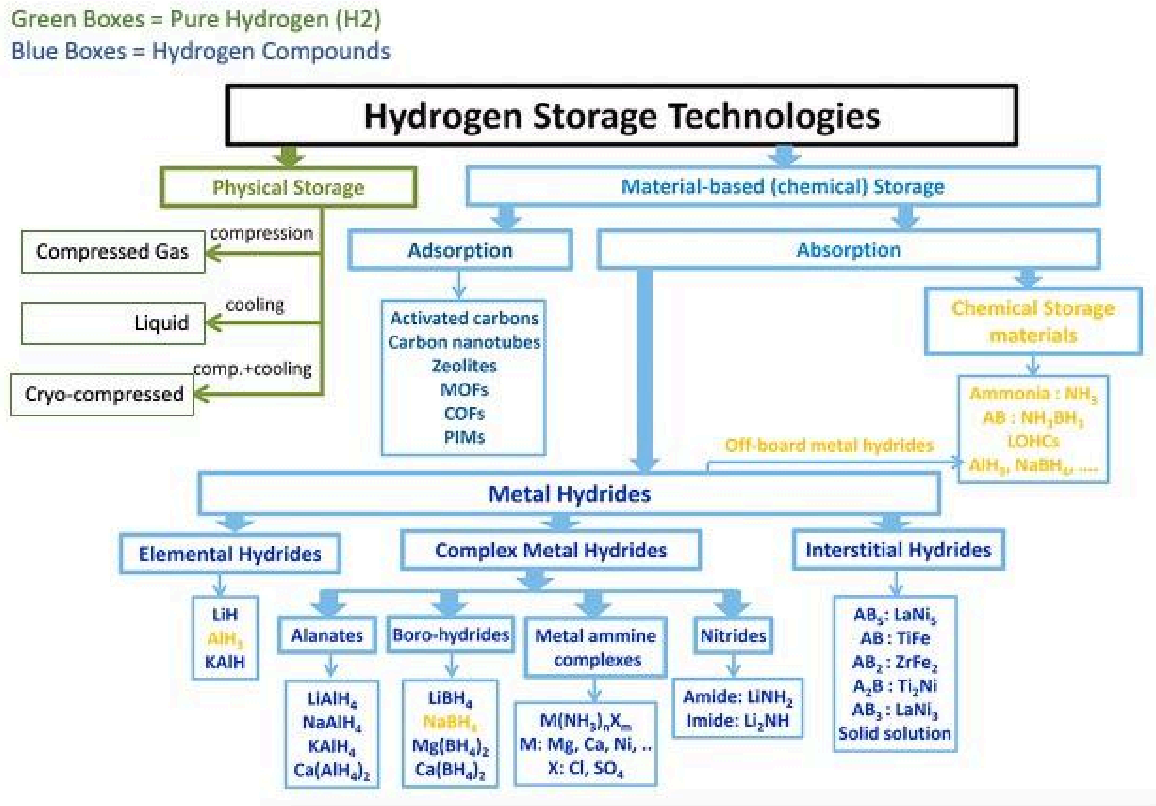

Figure 3: Hydrogen Storage Technologies[41]

Pure hydrogen is most commonly stored as compressed gas in steel gas cylinders. This is widely used when transporting and distributing hydrogen through hydrogen pipelines and hydrogen tube trailers[42] (*see Hydrogen Transportation and Distribution section below*).

For long-term storage, there is potential to store large volumes of hydrogen gas underground in places like aquifers, depleted natural gas and oil deposits, and salt caverns.[43, 44] The feasibility and costs of storing hydrogen in aquifers and depleted natural gas and oil deposits, however, still need to be proven.[45] Storage in salt caverns is the most proven method, having been used in the United States since the 1980s.[46] The Advanced Clean Energy Storage (ACES)[47] project in Delta, Utah, the largest project in the only known salt cavern in the Western U.S., won a $504.4 million loan guarantee for the development of two underground hydrogen storage salt caverns that will supply

[41] Hassan, I.A., et al., 2021, Figure 3 of Hydrogen storage technologies for station and mobile applications Review, analysis, and perspectives, Renewable and Sustainable Energy Reviews 149: 111311, at page 5.
[42] Yue, Meiling et. al., May 2021, Hydrogen Energy Systems: A critical review of technologies, applications, trends, and challenges, Renewable and Sustainable Energy Reviews; 146, at page 7.
[43] International Energy Agency Hydrogen Technical Collaboration Programme, Task 42: Underground Hydrogen Storage website, accessed September 27, 2022.
[44] U.S. DOE, Advanced Clean Energy Storage website, accessed September 27, 2022.
[45] International Energy Agency, June 2019, The Future of Hydrogen, page 70.
[46] International Energy Agency, June 2019, The Future of Hydrogen, page 69.
[47] The ACES project will support the Intermountain Power Agency's Intermountain Power Project (IPP) Renewed Project - an 840 MW hydrogen-capable gas turbine combined cycle power plant that will initially run on a blend of 30% green hydrogen and 70% natural gas starting in 2025 and incrementally expanding to 100% green hydrogen by 2045 (source, accessed December 15, 2023).

generation fuel for the Intermountain Power Plant.[48] Southern California Gas Company (SoCalGas), through a pre-feasibility study for the Angeles Link Project, has studied pipeline options to connect the Intermountain Power Plant and the ACES project to the Los Angeles Basin.[49]

In material-based scenarios, hydrogen is bonded with other elements, such as carbon, metals, or chemicals for storage. Here, again, it is important to consider the energy needed to convert the hydrogen for material-based storage, and then reconvert that stored hydrogen into a form appropriate for its end use. Box 1 takes a closer look at hydrogen stored as ammonia, because ammonia is a highly prevalent industrial material that is gaining attention across the globe as a potential direct or indirect fuel source in the energy industry.

Box 1. Does Ammonia Belong in a Clean Energy Economy?

What is ammonia? Ammonia is the second most commonly made chemical in the world (the first is sulfuric acid). Ammonia is made by combining nitrogen and hydrogen (NH_3). It is used as agricultural fertilizer, refrigerant gas, or as an input in chemical manufacturing processes. Additionally, ammonia can be directly combusted as a fuel (in a fuel cell, internal combustion engine, or gas turbine), or the hydrogen can be separated out and used as a fuel source. When hydrogen is "released" from ammonia (in a process called "cracking"), the resulting products include hydrogen (H_2), nitrogen (N_2), NOx, and N_2O (nitrous oxide).[50]

Why does ammonia matter in an energy context? Ammonia may be a more familiar industrial commodity to people than hydrogen (it's been used in large-scale fertilizer production for more than 100 years). Additionally, researchers are studying ammonia-powered engines and gas turbines for decarbonization solutions in industrial use cases like aviation and maritime shipping.[51, 52] However, the International Energy Agency states that the use of ammonia in the energy system "generally raises more health and safety considerations than hydrogen, and its use would probably need to continue to be restricted to professionally trained operators."[53]

Similar to pure hydrogen, ammonia can be stored in gas or liquid form. In liquid form, ammonia has nearly 3-times the energy density of compressed hydrogen and about 1.5-times the energy density of liquid hydrogen, meaning that there is more energy in liquid ammonia per unit stored when compared to pure hydrogen in gas and liquid states.

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[48] U.S. DOE, Advanced Clean Energy Storage website, access November 21, 2022.
[49] Paragon Partners, September 2021, Southern California Gas Company Proposed Hydrogen Pipeline Systems Study - Rev. 1, included as Appendix 5 to SPEC Services Reports, available at: https://www.socalgas.com/sustainability/hydrogen/angeles-link/technical-documents/spec-reports, accessed January 3, 2024..
[50] Johnson Matthey, November 2022, Ammonia cracker: design and safety considerations presentation, accessed December 1, 2022..
[51] Kapat, Jay and Otto, Marcel, November 16, 2022, Ammonia as a Liquid for the Future of Aviation presentation, accessed December 1, 2022.
[52] RMI, November 18, 2022, The Potential Future for Ammonia Market Nexus presentation, accessed December 1, 2022.
[53] International Energy Agency, June 2019, The Future of Hydrogen, page 35.

However, it takes 34-times more energy to extract hydrogen from liquid ammonia as it does from liquid hydrogen.[54]

*Why does ammonia matter in a **clean energy** context?* Because ammonia is already a common industrial commodity, hydrogen proponents might say "Hey, we've already got this great vehicle to store hydrogen and unlock all its economic potential. It holds more energy than hydrogen alone, we already know how to make and manage it, and we can store all the green hydrogen that we plan to make." And while it is true that green hydrogen can be stored as ammonia, this should not get twisted to presume that ammonia itself is a clean fuel or an effective contributor to a clean energy economy (though there is research underway to find a pathway to "green ammonia"[55]).

Making ammonia is an energy intensive process and ammonia itself is "highly toxic, flammable, corrosive, and escapes from leaks in gaseous forms."[56] Exhaust from using ammonia as a direct fuel source (i.e., combusting ammonia) and ammonia cracking (separating hydrogen from nitrogen) includes NOx and N_2O which are harmful to humans, public health, and the environment (See *Hydrogen Production and Use Exposes People to Pollution* section below). So while ammonia is a familiar carrier that has been widely used for ages, it may not be a good candidate for broad use in a clean energy economy, and clean energy and community advocates should watch out for a double dose of hydrogen/ammonia greenwashing.

HYDROGEN TRANSPORTATION AND DISTRIBUTION

For the 800,000 tons (800 million kilograms) of hydrogen currently produced by and for oil refineries in California, limited transportation is necessary because the production plants usually operate next to or even on refinery property.[57]

For the remaining 1.2 million tons of hydrogen consumed in California each year, hydrogen is distributed through three methods:

- **Pipelines:** Least expensive but limited capacity. Currently only about 1,600 miles of hydrogen-specific pipelines are available in the United States. These pipelines are located near large petroleum refineries and chemical plants in California, Illinois, and the Gulf Coast. Hydrogen can also be blended into the natural gas fuel mix and transported via the existing pipeline infrastructure system at rates of 5 - 20% by volume.[58]

[54] Aziz, M. et al., June 2020, Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization, *Energies*, 13, 3062 at page 6.
[55] Ostuni, R. (AEA - Phoenix), November 2022, Retrofitting Grey to Blue to Green - Making Net-zero Ammonia Possible presentation, accessed December 1, 2022.
[56] International Energy Agency, June 2019, The Future of Hydrogen, page 35.
[57] CBE's Comments to the California Air Resource Board for the Scoping REA
[58] Raju, Arun et. al., 2022, Hydrogen Blending Impacts Study prepared for the California Public Utilities Commission, University of Riverside, Agreement Number 19NS1662, at page 8.

- **High-pressure Tube Trailers:** Compressed hydrogen gas transported by truck, train, ship, or barge. This is expensive and primarily used for distances of 200 miles or less[59] (e.g., the distance from eastern California to the Los Angeles Basin)
- **Liquefied hydrogen tankers:** This process is also expensive but relatively more efficient than transport by high-pressure tube trailers. However, if the liquefied hydrogen is not used at a sufficiently high rate at the point of consumption, it will boil off or evaporate from its storage vessel.[60]

Today, hydrogen distribution primarily occurs via tube trailers. The International Energy Agency estimates that high-pressure gas tube trailers and liquid hydrogen tanks will remain the main distribution methods until 2030.[61]

The current pressure limit for compressed hydrogen gas in steel tubes limits each trailer to transporting a maximum of 280 kg of hydrogen.[62] This means that for a "green" hydrogen plant with a production capacity of 10,000 kg of hydrogen per day (such as those receiving incentives from the CEC[63]), at least 35 trailers are needed to transport just one day's worth of production.

SoCalGas has proposed the Angeles Link Project to construct a hydrogen transport system and pipelines to serve the Los Angeles Basin.[64] While the Project itself has not yet been approved, the CPUC has approved that SoCalGas may establish a specific account to track its costs related to planning the Project, which may be as high as $29.9 million.[65] The Angeles Link Project is currently conducting feasibility studies as part of Phase One.[66]

HYDROGEN FORECASTING, OVERSIGHT, AND REGULATION

Hydrogen demand forecasts and regulation of hydrogen production, transportation, storage, and use are spread across a variety of California state agencies and, in the case of the California Public Utilities Commission (CPUC), the companies that the agency regulates. This section introduces current activities and responsibilities among the CPUC, the California Energy Commission (CEC), and the California Air Resources Board (CARB); these may change as hydrogen production and use increase in California.

To achieve clean transportation goals, CARB and CEC are responsible for investing millions of dollars per year to better understand and promote the use of hydrogen in the transportation sector. Each year, CARB evaluates the need for new public hydrogen fueling stations. CARB then

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[59] U.S. DOE Alternative Fuels Data Center, Hydrogen Production and Distribution website, accessed September 26, 2022.
[60] U.S. DOE, Alternative Fuels Data Center, Hydrogen Production and Distribution website, accessed September 26, 2022.
[61] International Energy Agency, June 2019, The Future of Hydrogen, at page 80.
[62] International Energy Agency, June 2019, The Future of Hydrogen, at page 79.
[63] California Air Resources Board, September 2022, 2022 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Deployment (also referred to as the AB8 Annual Report), at page 8.
[64] Southern California Gas Company Angeles Link Website, accessed August 15, 2023.
[65] CPUC, Decision 22-12-005, Decision Approving the Angeles Link Memorandum Account to Record Phase One Costs, December 15, 2022.
[66] Southern California Gas Company, Angeles Link Quarterly Report (Phase One) For the Period April 1, 2023 through June 30, 2023.

reports to the CEC the quantity of fuel needed for existing and planned hydrogen-fueled vehicles, geographic areas where fuel will be in need, and station coverage.[67] CEC directs investments in hydrogen fueling infrastructure via the Clean Fuel Transportation Program.[68] There is, however, already a misalignment between expected demand for hydrogen fueling stations and the state's goals. When California achieves its goal of developing 200 hydrogen fuel stations (as is expected in 2027), station capacity will be more than four times vehicle manufacturers' best-case scenario for fuel-cell electric vehicles adoption in California, resulting in the potential for fueling stations to become stranded assets.[69]

The CPUC regulates pipeline safety and fuel mixes for all investor-owned utilities in California, including Southern Gas Company, SoCalGas, and Pacific Gas and Electric. Additionally, the CPUC is responsible for implementation of SB 1369, which directs the targeted use of green hydrogen in California's decarbonization strategies.[70] The CPUC may ultimately determine whether Southern California Gas Company's Angeles Link project will be approved. However, "the CPUC has not made a determination whether the hydrogen pipeline delivery services provided by investor-owned utilities would fall within the jurisdiction of the CPUC."[71]

CARB has responsibility for ensuring that California meets its statewide greenhouse gas emission reduction goals and criteria pollutant (such as NOx) emission limits. The agency's 2022 Scoping Plan, a biennial plan identifying emissions caps by sector and pathways for emissions reductions, identifies hydrogen as an important resource for achieving GHG reduction goals in aviation, ocean-going vessels, rail, chemical and allied products (pulp and paper), transportation, buildings, and industry.[72] Further, by June 1, 2024, CARB is required to prepare a report that includes, among other requirements, policy recommendations regarding the use of green hydrogen in California.[73]

The CEC is responsible for developing the IEPR, a biennial report that synthesizes assessments and forecasts of energy industry supply, production, transportation, delivery and distribution, demand, and prices. The 2023 IEPR includes an assessment of the potential for hydrogen combustion to replace methane combustion at power plants across California. The CEC's preliminary analysis found that it would take approximately 1.7 billion kg of hydrogen to replace the 216 billion cubic feet (Bcf) gas burn shown in CARB's Scoping Plan; this is estimated to require 537 electrolyzers at an estimated capital cost of $71.5B. The CEC noted a number of challenges with producing, storing, and transporting this quantity of hydrogen.[74]

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[67] CARB, September 2022, 2022 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development, Executive Summary, page ix.
[68] CEC, 2023-2024 Investment Plan Update for the Clean Transportation Program, accessed October 4, 2023.
[69] Hydrogen Vehicle Fueling Infrastructure and Fuel Production in California Frequently Asked Questions, as referenced in *Lawmakers strike $106 million deal for fueling hydrogen cars, trucks - even though hardly anyone drives one*, Alejandro Lazo (CalMatters), September 15, 2023, accessed October 4, 2023.
[70] California Public Utilities Code Section 400.3, accessed August 15, 2023.
[71] CPUC Decision 22-12-005 Approving the Angeles Link Memorandum Account to Record Phase One Costs, issued December 20, 2022, page 8, as cited in CPUC Staff Proposal on Gas Distribution Infrastructure Decommissioning Framework in Support of Climate Goals, December 21, 2022, page 15.
[72] CARB, December 2022, 2022 Scoping Plan for Achieving Carbon Neutrality, Table 2-1: Action for the Scoping Plan Scenario: AB32 GHG Inventory sectors, pages 72-79.
[73] Senate Bill 1075, Skinner, 2022, accessed August 15, 2023.
[74] California Energy Commission, September 11, 2023, Presentation - Hydrogen Analysis for Electricity Generation in the 2023 IEPR, filed in Docket 23-IEPR-06 (TN#252210).

OPPORTUNITIES TO USE HYDROGEN IN CALIFORNIA'S CLEAN ENERGY ECONOMY

California is investing significant dollars into developing a hydrogen market. For example, through the ARCHES consortium, the state has been awarded $1.2 billion in federal funds to develop a hydrogen hub that will produce, store, transport, and use hydrogen. ARCHES stated priorities include advancing clean, renewable hydrogen; focusing efforts on communities with the largest pollution burden; taking a multi-sectoral approach; developing public policy that enables early markets for private capital to scale; prioritizing the hardest to abate sectors; and creating an economically sustainable, expanding renewable hydrogen market. In compliance with the federal Justice40 Initiative, at least 40% of benefits will be directed to California's disadvantaged communities.[75] The ARCHES process is a public-private partnership that requires participants following the process to sign non-disclosure agreements in order to protect confidential industry information; it is not yet publicly clear what kinds of projects ARCHES will support, though as of early 2024 the ARCHES website indicates end-uses such as power plants may receive ARCHES funding, along with research into ammonia opportunities, among other possibilities. According to ARCHES, projected benefits realized per year are expected to include:

- $2.95B of health cost savings
- 6,900 tonnes less NOx
- 326 tonnes less PM10 and PM2.5
- 13,292 fewer days of work lost
- 2,097 fewer hospitalizations
- 48 fewer premature deaths[76]

In April, 2023, the UC Davis Institute of Transportation Studies published the *California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California, Final Synthesis Modeling Report*.[77] The report describes the findings from a two-year investigation and modeling analysis of potential future hydrogen systems in California, including demand, production capacity, facility siting, and transportation routes. According to the study, the transportation sector will be a primary driver of the hydrogen market, and by 2030, hydrogen demand in the transportation sector in California could be sufficient to support a hydrogen production system that includes 10 facilities of 25 tons of hydrogen per day and five facilities sized at 50 tons per day.[78] However, there are multiple ways that a hydrogen market could develop in California; this report may be a useful document to help guide stakeholder conversations and understanding of a carbon-neutral California that may include hydrogen.

Blending Hydrogen for Use in Gas Appliances

Hydrogen can be blended into the fossil gas fuel mix to provide energy to appliances that currently use fossil gas (e.g., space heaters, water heaters, dryers, stoves). However, the proportion

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[75] ARCHES website, https://archesh2.org/, accessed January 3, 2024.
[76] ARCHES Community Benefits Plan, available at: https://archesh2.org/community-benefits-2/, accessed January 3, 2024
[77] Fulton, Lew, June 13, 2023, Supporting California' Move to Zero-Emission Vehicles: Creating a Viable, Large-Scale Fuel-Cell Vehicle and Hydrogen System, accessed July 31, 2023.
[78] UC Davis Institute of Transportation Studies (ITS), April 2023, California Hydrogen Analysis Project, The Future Role of Hydrogen in a Carbon-Neutral California, pages 12-13.

of hydrogen cannot exceed 20% of the fuel mix without introducing safety concerns, such as overheating of appliance components and flashback (i.e., when the flame moves "upstream" back into equipment). The existing literature indicates that hydrogen can be blended into natural gas at a range between 5-20% without having a significant impact on safety and operation of end use appliances.[79] However, a 20% hydrogen blend only reduces greenhouse gas emissions by, at most, 6%.[80]

Hydrogen as a Power Source for Fuel Cells[81]

A fuel cell uses the chemical energy of hydrogen to produce electricity. Fuel cells can be stacked to increase the amount of electricity generated. A typical fuel cell stack may consist of hundreds of fuel cells, which can be used as a stationary power source for backup power or power in remote locations. Fuel cells can also be used for portable power and transportation.[82]

Hydrogen is used to power fuel cells in zero-emission vehicles, also called fuel cell electric vehicles. The energy in 1 kilogram (kg) of hydrogen gas is about the same as the energy in 1 gallon of gasoline.[83] Light duty fuel cell electric vehicles can refuel in about five minutes and have a driving range of about 300 miles.[84]

Hydrogen fueling and fuel cell electric vehicles contribute to achieving California's zero-emission transportation goals for light-, medium-, and heavy-duty vehicles. Since 2013, as required under Assembly Bill 8 (Perea, 2013), the California Energy Commission and California Air Resources Board have been collaborating on the development of hydrogen fueling stations in California. Between 2008 and 2021, the California Energy Commission invested more than $230M through the Clean Transportation Program to support hydrogen refueling infrastructure. As of October 2022, there are 61 hydrogen fueling stations in the state and California Energy Commission staff anticipate that California will meet the goal of 200 hydrogen refueling stations by 2025,[85] as adopted by Governor Brown's 2018 Executive Order B-48-18.[86] The state plans to invest at least $90 million between 2022 and 2026 on hydrogen fueling infrastructure.[87] As previously noted, California Energy Commission staff estimate that, when the network of 200 hydrogen fuel stations are constructed and fully operational, capacity will *exceed* demand by more than four times.[88]

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[79] Raju, Arun et. al., 2022, Hydrogen Blending Impacts Study prepared for the California Public Utilities Commission, University of Riverside, Agreement Number 19NS1662, at page 8.
[80] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 8.
[81] Hydrogen can also be used as a power source for some combustion engines and turbines; however this is less efficient than gas combustion engines and results in nitrogen oxides. Therefore, researchers find that fuel cells are the preferred method to use hydrogen as a power source (Yue, Meiling et. al., 2021, Hydrogen Energy Systems, at page 5).
[82] U.S. DOE, Fuel Cell Animation (Text Version) website, accessed September 28, 2022.
[83] U.S. DOE, Alternative Fuels Data Centers, Hydrogen Basics, accessed September 23, 2022.
[84] U.S. DOE, Alternative Fuels Data Center, Fuel Cell Electric Vehicles, accessed September 23, 2022.
[85] California Energy Commission, January 2023, 2022-2023 Investment Plan Update for the Clean Transportation Program, at pages 7-8.
[86] Executive Order B-48-18, January, 26, 2018.
[87] California Energy Commission, Table ES-2: Investment Plan Allocations for FY 2022-2023 and Beyond, Including Clean Transportation Program (Program), and General Funds (in Millions), January 2023, 2022-2023 Investment Plan Update for the Clean Transportation Program, at page 13.
[88] California Energy Commission, January 2023, 2022-2023 Investment Plan Update for the Clean Transportation Program, at page 61.

Industrial Applications

Almost all the hydrogen produced in the U.S. each year is used for refining petroleum, treating metals, producing fertilizer, and processing foods.[89] These use cases are likely to continue into the future, though grey hydrogen should be replaced with green hydrogen to achieve a clean energy economy.

Moving forward, industry proponents claim that green hydrogen can be used in sectors that do not have other viable decarbonization options (e.g., maritime shipping, industrial processes that require high temperatures, long-distance trucks or trains, and/or a small portion of electricity supply).[90] However, there may be few industrial use cases where hydrogen would truly be necessary over another low- to zero-carbon fuel, such as electricity (Figure 4). It should be noted that fuels identified as suitable substitutes for hydrogen, such as biogas, have historical and ongoing negative environmental and health impacts in environmental justice communities in California, particularly communities in the San Joaquin Valley.[91] The tradeoffs between clean energy fuels should be carefully studied and considered in consultation with community members to determine the appropriate use cases in California's clean energy economy.

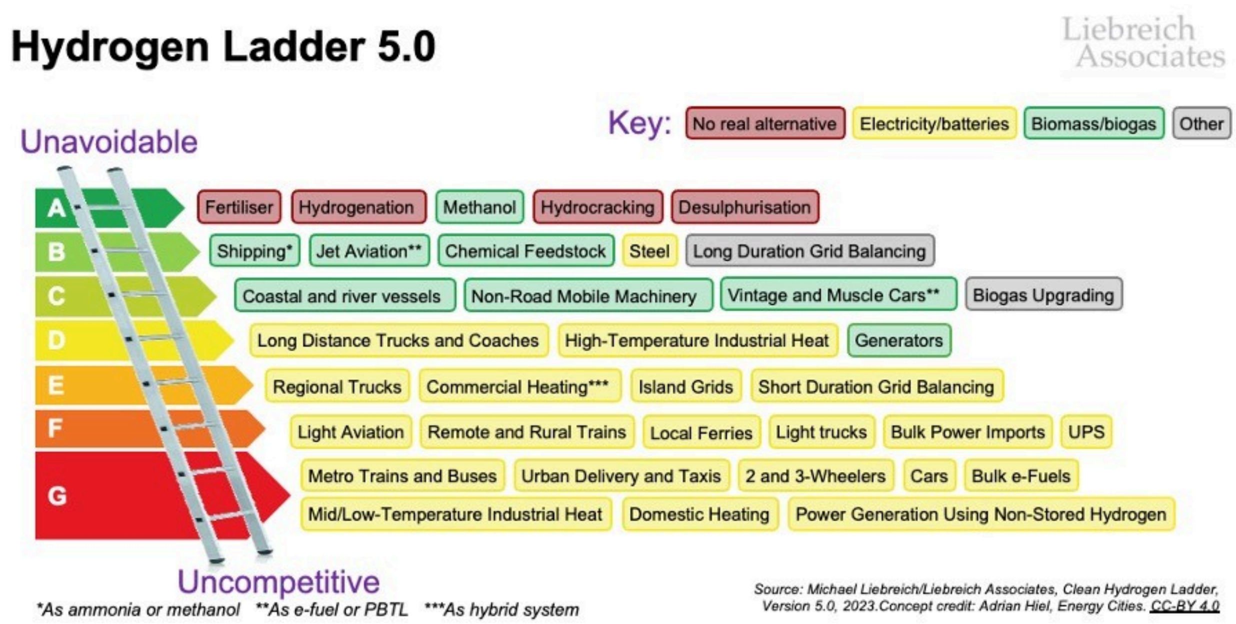

Figure 4: "Clean Hydrogen Ladder v.5.0"[92] - Industrial Hydrogen Uses Cases and Competing Fuels

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[89] U.S. DOE, Alternative Fuels Data Centers, [Hydrogen Basics](), accessed September 23, 2022.
[90] Earthjustice, August 2021, [Reclaiming Hydrogen for a Renewable Future](), at page 4.
[91] Refer to [Joint Environmental Justice Low Carbon Fuel Standard Letter (March 15, 2023)]() and [Coalition Comments on LCFS Community Workshops (June 14, 2023)]() submitted regarding the Low Carbon Fuel Standard.
[92] Liebreich Associates (Concept credit: Adrien Hiel, Energy Cities), October 2023, [The Clean Hydrogen Ladder v.5.0](), accessed December 15, 2023.

RISKS OF USING GREEN HYDROGEN AND POSSIBLE MITIGATION MEASURES

Hydrogen Emissions Contribute to Climate Change Impacts

While hydrogen's primary contributions to climate change are a result of the current production process (*see grey hydrogen description*), hydrogen emissions also contribute to climate change impacts. Hydrogen is an indirect greenhouse gas, and new research is indicating that climate impacts from hydrogen emissions are consequential with indirect effects that are twice as high as previously studied.[93]

Additionally, like methane, hydrogen's climate impacts are potent though short-lived. Near-term (10-year time frame) climate change impacts from hydrogen are 3-8 times more potent than long-term impacts (100-year time frame). That said, hydrogen's indirect effect on methane in the atmosphere leads to a longer atmospheric lifetime for methane and can affect the climate for roughly an additional decade.[94]

Further, because hydrogen can leak across the entire value chain, including electrolyzers, compressors, storage tanks, pipelines, and fueling stations, the consistent emission of hydrogen can continuously expose the environment to "short-term" effects. Put another way, because hydrogen is always leaking, the environment is consistently experiencing hydrogen's more potent climate change impacts.

The primary way to prevent these possible climate impacts seems to be ensuring that hydrogen does not leak from the gas system. This is discussed in more detail below.

Green Hydrogen is Resource Intensive

Electrolysis is an energy-intensive process and, if powered directly by renewable electricity, can divert those renewable electricity resources away from existing customers, thereby creating demand for more fossil-based electricity. Therefore, to deliver meaningful emissions reductions, green hydrogen must be made with either new renewable resources and/or surplus renewable energy.[95]

Electrolysis, by definition, is a process that requires the use of water. The amount of water used depends on the type of electrolysis technology. One study estimates that for every kilogram of hydrogen produced with electrolysis, 9 kg of water must be consumed. This is about 33% less water than currently used in fossil-based power generation and energy production.[96] Another study finds that up to 18 kg of water must be used to produce 1 kg of hydrogen (Figure 5).[97] Further, analysis by RMI found that 20-30 kg of water is needed per kg of hydrogen produced by renewable electrolysis (Figure 6). RMI asserts that the water needed to produce green hydrogen

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[93] Okco, Ilissa and Hamburg, Steven, July 2022, Climate consequences of hydrogen emissions, *Atmospheric Chemistry and Physics*; 22, 9349-9368, at page 9350.
[94] Ibid.
[95] Earthjustice, August 2021, Reclaiming Hydrogen for a Renewable Future, at page 13.
[96] Beswick, Rebecca, et. al, August 2021, Does the Green Hydrogen Economy Have a Water Problem?, American Chemistry Society Energy Letters; 6, 9, 3167-3169, accessed September 23, 2022.
[97] Mehmeti, Andi et. al, February 2018, Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies (Table 1), Environments; 5, 24.

will be "insubstantial" relative to overall demand for water and that there are commercially mature technologies that could produce the water needed for green hydrogen production.[98]

Type	Thermo-Chemical				Electrolysis	
Conversion pathway	Steam methane reforming	Coal Gasification	Biomass Gasification	Biomass Reformation	Proton exchange membrane (PEM)	Solid oxide electrolysis cells (SOEC)
Abbreviation	SMR	CG	BMG	BDL-E	E-PEM	E-SOEC
Feedstock	Natural gas	Coal	Corn Stover	Ethanol	Electricity	Electricity
Natural gas (MJ/kg H_2)	165	-	6.228	-	-	50.76
Coal (kg/kg H_2)	-	7.8	-	-	-	-
Biomass (kg/kg H_2)	-	-	13.5	6.54	-	-
Electricity (kWh/kg H_2)	1.11	1.72	0.98	0.49	54.6	36.14
Water (kg/kg H_2) [1]	21.869	2.91	305.5	30.96	18.04	9.1

Figure 5: Resource Intensity of Hydrogen Production[99]

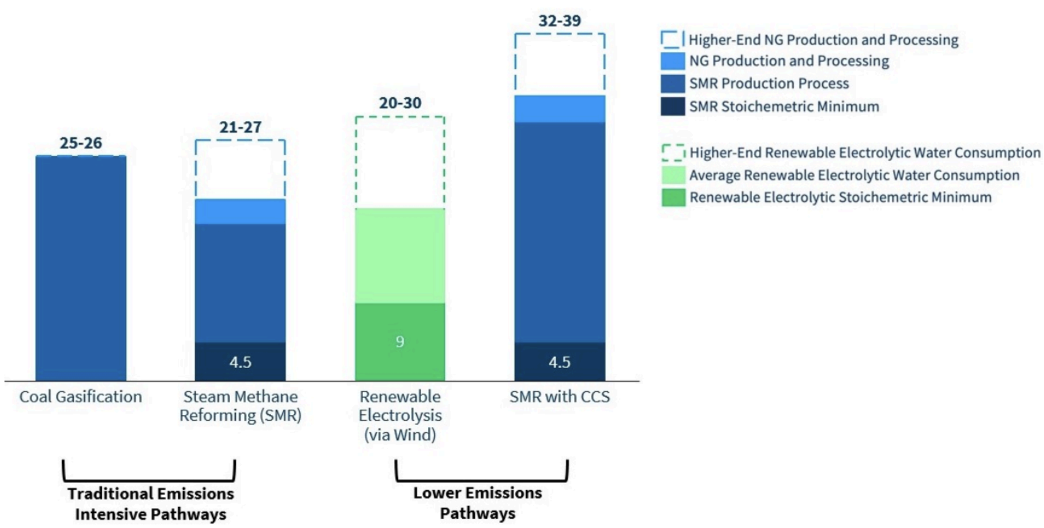

Figure 6: Water Consumption of Various Hydrogen Production Pathways (kg/kg H2)[100]

Clean Hydrogen Production Standards Can Have Limited Effect

A Clean Hydrogen Production Standard (CHPS) sets an emissions limit for the production of clean hydrogen. The Inflation Reduction Act established a CHPS of lifecycle greenhouse gas emissions of 4 kg of CO_2eq or less per 1 kg of hydrogen.[101] The same standard served as the starting point for the

[98] Ramirez, Kaitlyn, et. al. (RMI), August 2023, Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption, accessed August 15, 2023.
[99] Mehmeti, Andi et. al, February 2018, Table 1 in Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies, Environments; 5, 24.
[100] Ramirez, Kaitlyn, et. al. (RMI), August 2023, Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption, accessed August 15, 2023.
[101] Inflation Reduction Act at page 120.

U.S. DOE in implementing the Bipartisan Infrastructure Law.[102] The CHPS ultimately adopted by the DOE would not be a regulatory standard; it would serve "only to guide the DOE's hydrogen programs...[including] the Regional Clean Hydrogen Hubs Program and the Clean Hydrogen Research and Development Program."[103]

The federal CHPS of 4 kg of CO_2eq or less per 1 kg of hydrogen is not stringent enough to meaningfully reduce emissions beyond what is expected with natural technological development. The trade association, Hydrogen Council, estimates that by 2030, emissions intensities for green hydrogen will be well below 4 kg CO_2eq per kg hydrogen for several electricity generation options (Table 2). These projections indicate that a more stringent CHPS is warranted.

Table 2: 2030 Green Hydrogen Emissions Intensities[104]

Renewable Electricity Generation Resource	Emission Intensity of Green Hydrogen (per kg hydrogen)
Large Solar	1.0 kg CO_2eq
Onshore Wind	0.5 kg CO_2eq
Hydropower (run-of-river)	0.3 kg CO_2eq

Further, any CHPS that allows renewable energy credits to be counted calculating lifecycle emissions intensity accounting should be carefully designed and closely monitored to ensure that credits are real. According to joint comments recently submitted to the DOE, "It would be appropriate to allow producers to use power purchase agreements to claim that their electrolyzers are running on zero-emission electricity if:

- The producer enters an agreement with a newly constructed wind or solar facility to purchase energy bundled with RECs;
- The hydrogen producer retires the RECs and no other entity can claim the emissions benefits of the renewable energy;
- The generator is either connected to the same balancing authority as the hydrogen producer or has an agreement to dynamically transfer electricity to the producer's balancing authority; and
- The hydrogen producer uses the energy in the same hour that the electric generator delivers it to the grid."[105]

While a CHPS can be a useful tool to set minimum GHG emissions expectations for hydrogen production, to have a meaningful effect for communities and climate, the standard must be carefully designed and include strict emissions limits on GHGs, criteria pollutants, and hazardous air pollution.

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[102] U.S. DOE Clean Hydrogen Production Standard Draft Guidance, accessed December 1, 2022.
[103] U.S. DOE Clean Hydrogen Production Standard Draft Guidance, at page 2, accessed December 1, 2022.
[104] Hydrogen Council, January 2021, Hydrogen decarbonization pathways: A life-cycle assessment, at page 6.
[105] Earthjustice CHPS comments at page 15.

Hydrogen Blends Cause More Leakage from and Damage to Existing Infrastructure

Hydrogen contains only one-third of the energy of natural gas, meaning that a higher volumetric flow rate is needed to deliver the same amount of energy when compared to natural gas. This could be done by increasing the operating pressure in the pipeline, or replacing existing pipelines with larger ones. Increasing the operating pressure, however, introduces a risk of increased leakage.[106]

Hydrogen can leak at a rate between 1-10% across the entire production and distribution chain, including from electrolyzers, compressors, liquefiers, storage tanks, pipelines, trucks, trains, ships, and fueling stations. Additionally, because hydrogen is a tiny molecule, it can leak up to three times faster than methane. However, leakage detection technologies are not yet sophisticated enough to precisely measure leakage when it occurs at rates below safety thresholds.[107]

The main safety concern related to hydrogen is the higher probability of ignition related to leaks or gas accumulation in confined spaces. One risk assessment evaluating a 20% blend of hydrogen found that the number of explosions per year and risk of injuries from in-home explosions could increase by four times.[108] To reduce the safety risk, existing leak detection practices and leak repair procedures would need to be improved.[109]

Further, blending hydrogen into the fossil gas fuel mix can cause embrittlement of the steel pipes in the gas transmission and distribution systems. Embrittlement is the process of strength and ductility reduction within a metal, which makes it more brittle. Embrittlement exposes pipelines to loss of tensile strength, toughness, and fatigue resistance.[110] All of this can lead to more gas leakage in the form of new leakage of hydrogen and increased leakage of methane.[111]

To address the risk of embrittlement, a single, system-wide hydrogen blending rate (also referred to as an injection standard) would have to account for the most vulnerable metals, materials, and conditions within all of the existing infrastructure. A recent study commissioned by the California Public Utilities Commission concluded that it is only appropriate to apply a 5% hydrogen blend standard to the existing natural gas system to reduce risk of safety impacts and damage to end use appliances.[112] Recognizing that a 20% blend may only reduce greenhouse gas emissions by 6%,[113] a 5% blend rate would be expected to reduce greenhouse emissions by 1.5%.

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[106] Raju, Arun et. al., 2022, Hydrogen Blending Impacts Study prepared for the California Public Utilities Commission, University of Riverside, Agreement Number 19NS1662, at pages 8 and 12.
[107] Okco, Ilissa and Hamburg, Steven, July 2022, Climate consequences of hydrogen emissions, *Atmospheric Chemistry and Physics*; 22, 9349-9368, at page 9350-9351, 9355-9356.
[108] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 13.
[109] Raju, Arun etCommission. al., 2022, Hydrogen Blending Impacts Study prepared for the California Public Utilities , University of Riverside, Agreement Number 19NS1662, at page 7.
[110] Raju, Arun et. al., 2022, Hydrogen Blending Impacts Study prepared for the California Public Utilities Commission, University of Riverside, Agreement Number 19NS1662, at page 10.
[111] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 4.
[112] Raju, Arun et. al., 2022, Hydrogen Blending Impacts Study prepared for the California Public Utilities Commission, University of Riverside, Agreement Number 19NS1662, at pages 4 and 8.
[113] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 8.

Hydrogen Production and Use Exposes People to Pollution

Grey hydrogen production (and therefore, blue hydrogen production) typically occurs at existing oil refineries, which perpetuates exposure of neighboring communities to harmful pollutants like nitrogen oxides (NOx), fine particulate matter, carbon monoxide, and volatile organic compounds.[114] Further, without a consistent definition on what qualifies as "green" or "renewable" hydrogen, production methods could continue to emit harmful pollution into communities but be considered acceptable because the pollution is paired with carbon offsets.

Use of hydrogen in buildings may increase existing environmental injustices, as Black, Indigenous, and People of Color (BIPOC) are more likely to be exposed to indoor air pollution due to decades of discriminatory housing policies.[115] Injecting hydrogen into the existing gas system for use in buildings can increase the indoor air pollution from gas-burning stoves, furnaces, and other appliances, further endangering the health of BIPOC communities. Further, the California gas utilities have acknowledged that blends of hydrogen and methane may result in higher NOx emissions.[116] Exposure to NOx is associated with higher rates of dementia in older adults, is a likely cause of asthma, and can exacerbate asthma symptoms, leading to more emergency room visits and hospital admissions for asthma.[117]

Combustion in the industrial sector also increases NOx emissions. In addition to impacts of indoor emissions, NOx is a precursor of both ground-level ozone (smog) and fine particulate matter and can cause serious harm to air quality and public health, like increased rates of asthma and pregnancy complications.[118]

Hydrogen burns at a higher flame temperature than methane and, consequently, hydrogen combustion can produce even more NO_x pollution than methane combustion.[119] One study of industrial boilers found that combustion of pure hydrogen instead of methane would produce more than six times the NO_x emissions.[120]

Combustion of hydrogen in the electricity generation sector also poses NO_x risks, whether or not hydrogen is blended with methane gas.[121] In one study, General Electric found that NO_x emissions from gas turbines could increase by as much as 35% when burning 50% hydrogen, and 100% when burning 100% hydrogen.[122]

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[114] Earthjustice, August 2021, Reclaiming Hydrogen for a Renewable Future, at page 10.
[115] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 15.
[116] Earthjustice, August 2021, Reclaiming Hydrogen for a Renewable Future, at page 29.
[117] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at pages 15-16.
[118] U.S. Environmental Protection Agency, *Basic Information about NO2*, accessed July 25, 2022; Stephanie Lovinsky-Desir, *et al.*, 2018, Air *Pollution, Urgent Asthma Medical Visits And The Modifying Effect Of Neighborhood Asthma Prevalence*, 85 Pediatric Rsch. 36; Jun Wu, *et al.*, 2009, *Association Between Local Traffic-Generated Air Pollution and Preeclampsia and Preterm Delivery in the South Coast Air Basin*, 117 Env't Health Perspectives 1773).
[119] Mirko Bothien, *et al.*, January 2020, *Hydrogen Gas Turbines: The Path Towards a Zero-Carbon Gas Turbine*, ETN Global, at page 9.
[120] Cellek Mehmet Salih & Ali Pinarbasi, 2018, *Investigations on Performance and Emission Characteristics of an Industrial Low Swirl Burner While Burning Natural Gas, Methane, Hydrogen-Enriched Natural Gas and Hydrogen as Fuels*, 43 Int'l J. of Hydrogen Energy 1194, 1205.
[121] Bothien *et al.*, at page 77.
[122] General Electric, March 2022, *Hydrogen for power generation - Experience, requirements, and implications for use in gas turbines*, at 14.

Hydrogen Use Will Increase Gas Rates

The retail cost of hydrogen includes the costs of production, storage, transportation, and distribution. Regarding production costs, the cost of making grey or blue hydrogen will always be more than the cost of the methane from which it is produced. Additionally, green hydrogen production currently costs twice as much as grey hydrogen production (Figure 6)[123] and is not expected to be competitive with grey or blue hydrogen for 10 years."[124] Tax credits available through the Inflation Reduction Act can significantly reduce hydrogen production costs; however, the credits' impacts steadily decline after 2023 until they expire in 2032.[125] Further, when storage, transportation, and distribution costs are factored in, the total retail cost of hydrogen can be two to four times the production cost alone.[126, 127]

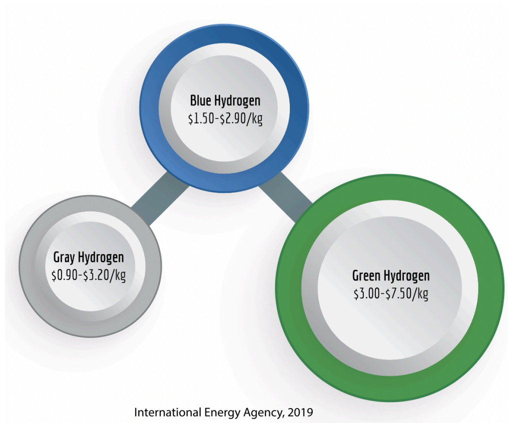

Figure 7. Costs of Hydrogen Production[128]

Given the potential for increased leakage and embrittlement, it's expected that gas utilities will need to make incremental capital expenditures to fortify gas infrastructure if hydrogen is blended into the fuel mix. These expenditures will in turn result in higher gas rates for customers. The impact to gas rates could be minimized by only using hydrogen in specific use cases for sectors without other decarbonization solutions, rather than blending it into the whole system, and ensuring that rate design follows cost causation principles.

CONCLUSION

There is a lot of research and investment in and political attention to hydrogen, and the production and use of hydrogen will be increasing as California transitions to a clean energy

[123] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 11.
[124] California Energy Commission, 2022-2023 Investment Plan updates for the Clean Transportation Program Draft Staff Report, at pages 64-65.
[125] The International Council on Clean Transportation, January 2023, Blog: Can the Inflation Reduction Act Unlock a Green Hydrogen Economy?, accessed January 3, 2024.
[126] Hassan, I.A., et al., 2021, Hydrogen storage technologies for station and mobile applications Review, analysis, and perspectives, Renewable and Sustainable Energy Reviews 149: 111311, at page 5.
[127] International Energy Agency, June 2019, The Future of Hydrogen, at page 67.
[128] Krasner, Andee and Gottleib, Barbara, June 2022, Hydrogen Pipe Dreams, Physicians for Social Responsibility (PSR), at page 11.

economy. Stakeholders have much to discuss to help form their advocacy positions. Some suggested topics include:

- What terminology and qualifications should be used for "green" hydrogen? Should this align with the federal definition for "clean" hydrogen? How would California Energy Commission and California Air Resource Board definitions for "renewable" hydrogen fit in?
- What are the use cases for hydrogen that can benefit environmental justice communities in 2025, if any? What about in 2030 and 2045 as technologies are expected to mature?
- How can stakeholders and regulatory agencies require hydrogen producers and utilities to be transparent about the amounts of water and electricity used to produce green hydrogen? Which regulatory agencies already do or should have this responsibility?
- What tradeoffs are present among the "clean" resources that can be used in industrial end uses, such as those identified in Michael Liebreich's Clean Hydrogen Ladder? Could community advocates identify criteria and/or a decision-making matrix to help policy makers and industry leaders make more informed decisions about the opportunities and risks of different emerging "clean" resources (e.g., biogas, lithium batteries for long-duration storage, hydrogen)?
- What additional research needs to be conducted to better understand the opportunities and risks of producing and using hydrogen?