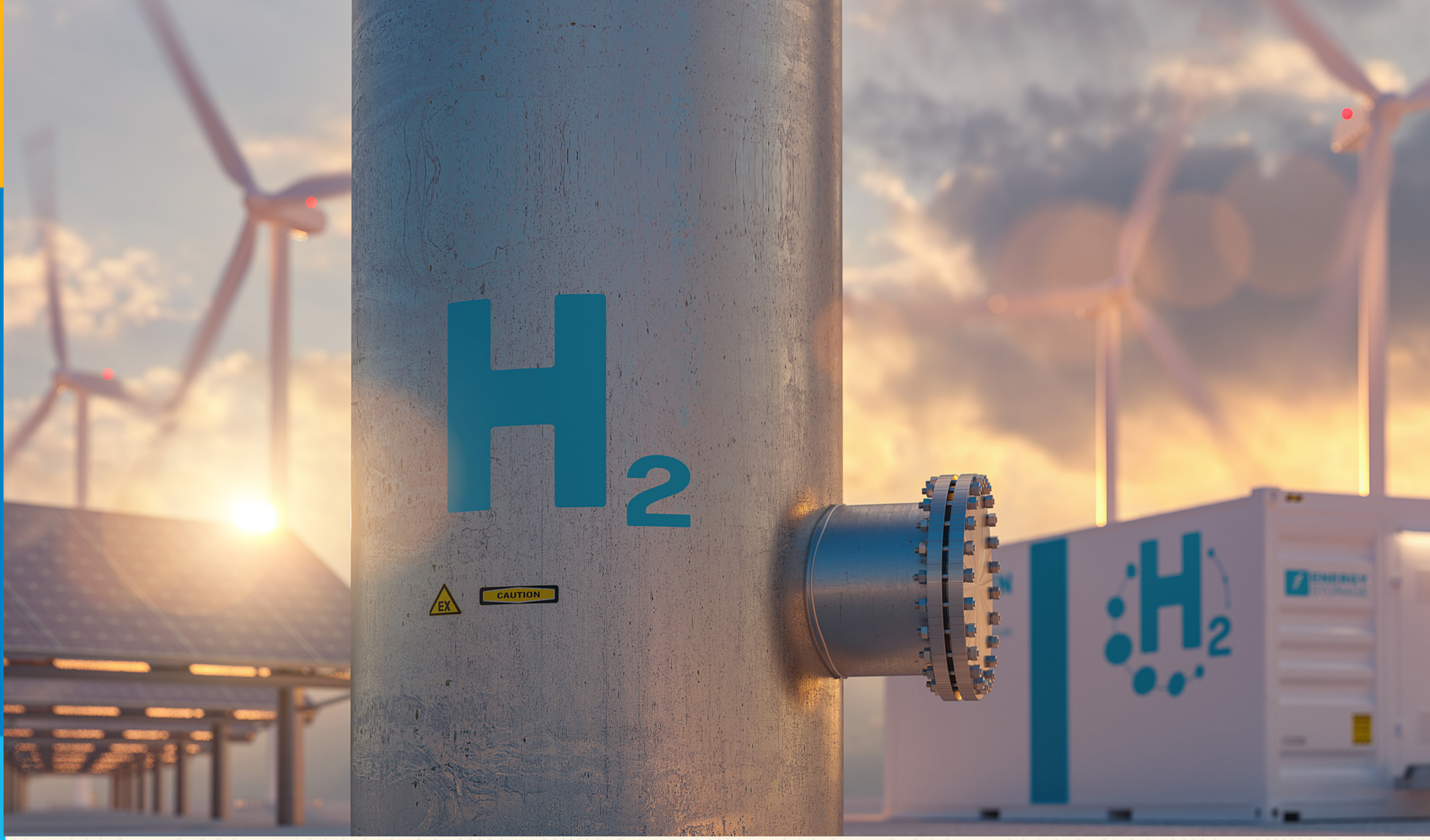

August 2023

Hydrogen Policy Brief

Guidance for policymakers on appropriate limited production, delivery, and applications of renewable energy-based electrolytic hydrogen

the climate center

The Climate Center, August 2023

Hydrogen Policy Brief
The Climate Center Policy Guidance Document

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Findings and Guidance – Summary

Hydrogen Production

- Green hydrogen is defined and referred to in this guidance as renewable energy-based electrolytic hydrogen: hydrogen produced electrolytically[1] via solar, wind, geothermal, hydroelectricity, and — in some limited cases — with certain kinds of biomass.[2]
- Green hydrogen production projects should be carried out with robust public participation as well as meaningful community and other stakeholder engagement, especially with any communities of concern that may be impacted by a new or converted hydrogen production facility.
- Renewable energy generation capacity that supports hydrogen production must be expanded commensurate with expanded hydrogen production capacity. This is necessary in order to ensure that energy demand from hydrogen production does not displace existing renewables and force the increased use of fossil fuels to meet the demand.
- The Climate Center supports:
  - California's efforts to improve green hydrogen production technology and bring down the cost of green hydrogen production.
  - With California's electricity grid on a trajectory toward 100 percent renewable, low-carbon power, The Climate Center does not oppose the use of grid power for electrolysis-based hydrogen production. However, hydrogen produced via grid electricity cannot be characterized as "green" unless a direct pathway can be shown from a proximate point of generation to the electrolysis facility via the distribution grid.
- The Climate Center is opposed to:
  - Any method of hydrogen production based on fossil fuels, including those with carbon capture.
  - The use of most biomass feedstocks for large-scale hydrogen production intended for offsite use.
- Unresolved:
  - Smaller-scale, biomass-based hydrogen production for onsite use and/or municipal sewage energy conversion or landfill gas to energy may make sense for some facilities with a consistent feedstock, but community and environmental impact problems emerge when this practice is scaled up. In order to generate the quantities of hydrogen needed to make a biomass-based production facility economically viable, the scale required would result in negative impacts, as outlined in The Climate Center's 2021 report on forest biomass.[3]

Policy guidance: State investments in hydrogen production should be limited to advancing renewable energy-based electrolytic hydrogen production, with new renewable energy

[1] Hydrogen produced by running an electric current through water, splitting the hydrogen and oxygen.
[2] Large-scale, woody waste biomass, biomass feedstocks that displace food crops, and bioenergy from confined animal feedlots are not included in the definition.
[3] https://theclimatecenter.org/fossil-fuels/should-california-support-forest-sourced-bioenergy-considerations-for-wildfire-climate-and-environmental-justice/

sources developed in tandem with new hydrogen production, and with community and environmental safeguards, using solar, wind, geothermal, and hydropower. We do not support state investments in hydrogen production from large-scale, manure-to-energy projects at confined animal feedlots.

Hydrogen Delivery

- The Climate Center supports:
  - Prioritizing renewable, energy-based hydrogen facilities that produce and consume hydrogen onsite, or export production to adjacent properties within a limited, prescribed locality. Community, neighborhood, or utility-scale seasonal storage for resilience purposes — where 100 percent green hydrogen is piped to a local, small-scale generating facility with appropriate community engagement — may offer more benefits than burdens.
- The Climate Center is opposed to:
  - Proposals to pipe hydrogen in order to be blended with fossil gas or in its pure form for use in residential and most business purposes. The state should cease investments aimed at blending hydrogen into existing gas lines and/or creating new hydrogen gas lines for residential purposes. A clear path exists for building electrification with no need for piped gas of any kind, eliminating combustion in the home and its inherent health and safety issues.
- Unresolved:
  - There may be use cases for small to mid-scale green hydrogen production for use in stationary fuel cells for residential and non-residential resilience purposes.
  - In cases where solar-hydrogen production is inadequate to meet a given onsite need, piping hydrogen should be limited to difficult-to-electrify industrial sectors and other limited applications, such as steel-making, cement manufacturing, plate glass, aviation, seasonal energy storage, and other high energy need applications.
  - To the extent that hydrogen is transported via truck, such trucks should be clean emission battery electric or fuel cell electric vehicles at the earliest possible date.

Policy Guidance: As a best practice, hydrogen end-use deployments should be colocated with green hydrogen production. Piping, trucking, and other delivery methods should be avoided, absent substantive technological improvements that ensure community safety.

Hydrogen Applications

- A clear pathway exists for the electrification of transportation with battery electric vehicles (EVs), especially in the light-duty category. The state should reconsider its investment of public dollars in hydrogen fueling infrastructure for light-duty service.
- Expansion of hydrogen fueling infrastructure should be strictly focused on supporting heavy-duty fuel-cell,[4] long-haul vehicle fleets using only green hydrogen. Such vehicles should also feature energy export capabilities similar to bidirectional battery electric vehicles as a dispatchable generation resource.
- The Climate Center supports:
    - Efforts to advance green hydrogen in hard-to-electrify sectors — such as the rail, marine, and aviation sectors — where they are powered by fuel cells and do not require pipelines.
    - Efforts to apply green hydrogen in other hard-to-electrify sectors — such as steelmaking, plate glass manufacturing, and cement production — with the caveat that there may be alternatives to traditional cement or concrete that can obviate the need for conventional cement production with carbon capture for the process emissions.
    - Efforts to develop green hydrogen as a seasonal (very long-duration) energy storage method.

Policy guidance: Use of green hydrogen should be limited to applications where direct electrification is not feasible.

[4] Heavy-duty refers to class 7 and 8 vehicles in excess of 26,000 pounds. Details: https://afdc.energy.gov/data/10380

Introduction

The latest climate science indicates that global temperatures will likely surpass the 2015 Paris Agreement 1.5 degrees Celsius threshold of warming as soon as 2030 or earlier.[5] As outlined in the United Nations Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (2022),[6] we must act immediately to avert catastrophic climatic change by cutting emissions in half by 2030 *and* removing hundreds of billions of tons of climate pollution from the atmosphere.

The Climate Center is a climate and energy policy nonprofit working to rapidly reduce climate pollution at scale, starting in California. Our strategic goal is for California to enact a suite of policies that will accelerate equity-centered climate action, achieving net-negative emissions and resilient, healthy communities by 2030, inspiring the nation and the world to greater climate action. All of The Climate Center's work is guided by three principles: follow the science, prioritize climate justice for frontline communities, and secure a just transition for workers. This is the lens through which we address the question of how hydrogen fits into, or doesn't fit into, the suite of policies that will achieve a stabilized global climate.

The hydrogen debate — based on efficiency costs, climate pollution, health and safety, and environmental impacts — is complex and has ebbed and flowed over the past several decades. It has reemerged over the past few years as a hot topic in energy policy circles and elsewhere.

Some advocates paint hydrogen as a panacea that will solve most, if not all, of our energy and climate problems. Some detractors condemn hydrogen as a false climate solution or dead end. The reality is that hydrogen is neither a panacea, nor categorically a false solution. It is, like most other energy options, a technology that — when planned carefully with meaningful safeguards and appropriate climate-friendly production methods and applications — could present opportunities in special circumstances with net benefits for communities and the environment. Most importantly, the strategic location of electrolytic hydrogen production as an offtaker of excess renewable energy generation enables the full optimization of an area's distributed generation capacity, creating flexible local energy systems that deliver maximum resilience to communities under a wide range of environmental and grid-related conditions. A small-scale example of this dynamic exists at the Stone Edge Farm Microgrid near Sonoma, California, whose "hydrogen park" includes fuel cell hives, a hydrogen storage and fueling station, and an electrolyzer.[7]

This current cycle of heightened attention is different for at least three reasons. 1) Substantial federal and state funding allocations are being made to advance hydrogen technology and commercialization. 2) The cost of renewable energy and electrolyzers (using clean electricity to break water into hydrogen and oxygen)[8] has dropped to a point where green hydrogen is

[5] Yangyang Xu, Veerabhadran Ramanathan and David G. Victor.. Global warming will happen faster than we think. Nature. December 5, 2018. https://www.nature.com/articles/d41586-018-07586-5; IPCC, 2021; and Zeke Hausfather. Analysis: What the new IPCC report says about when world may pass 1.5C and 2C. Carbon Brief. October 8, 2021. https://www.carbonbrief.org/analysis-what-the-new-ipcc-report-says-about-when-world-may-pass-1-5c-and-2c
[6] https://www.ipcc.ch/assessment-report/ar6/
[7] "Stone Edge Farm Microgrid Tour – Hydrogen Park," https://sefmicrogrid.com/overview/tour/
[8] For a good primer on how electrolyzers work, see: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis#

beginning to make economic sense. 3) The urgency of the climate crisis is causing some countries and industries to look to green hydrogen as a viable part of the response.

It is important to evaluate the prospects for hydrogen. The IPCC's Sixth Assessment Report states that 100 percent renewable energy systems would likely need to include fuels such as hydrogen.[9] Many organizations have asserted that green hydrogen is an essential component of a future low-carbon economy, including the International Renewable Energy Agency, the International Energy Agency, and the World Energy Council. Several countries have published standalone hydrogen strategies, including the Netherlands, Germany, Portugal, France, Japan, and Australia. And according to the Rocky Mountain Institute, for certain high energy intensity industries and other applications, hydrogen may be the only viable option for decarbonization.[10]

Current hydrogen production from fossil fuels is harmful to communities and the environment. In the 20th century, an extremely carbon-intensive hydrogen industry grew alongside oil refining. Refiners bond hydrogen with hydrocarbons in crude oil to make lighter combustion fuels, and with impurities to be removed from the crude to protect process catalysts and meet fuel specifications. Refiners make additional hydrogen for these purposes via a process that burns fossil fuels for energy to strip hydrogen from hydrocarbon gases. As of 2023, these "steam reforming" hydrogen production plants account for more than 95 percent of hydrogen production capacity in California, and refining accounts for nearly all statewide hydrogen use. The technology and carbon intensity of this already-built hydrogen production are described in the next section. The challenge this already-built fossil fuel hydrogen industry poses to renewable hydrogen development in California further underlines the need for clear guidance toward climate-friendly hydrogen policy. For health and safety problems linked to hydrogen use in oil refining, see Appendix 2: Oil Refining — A Hazardous Use of Hydrogen.

In this guidance, we assess and share some fundamental principles regarding hydrogen as a potential climate solution. For the purposes of this guidance, we define green hydrogen as hydrogen produced via the electrolysis of water to split the water to obtain the hydrogen, powered exclusively by renewables such as solar, wind, geothermal, and hydroelectricity. There are significant problems associated with most biomass-based production methods, so biomass is not categorically included in the definition of green hydrogen in this guidance. There are three main categories to consider regarding hydrogen: production, delivery, and applications.

[9] https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_06.pdf (see chapter six, page four)
[10] https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf

Hydrogen Production

Renewable energy-based electrolytic hydrogen (green hydrogen)

Hydrogen can be produced by using any source of electricity to run a current through water to split the water molecule to produce oxygen and hydrogen gas. Electrolysis may be considered clean or “green” only if based on energy sources that do not emit greenhouse gases or other pollutants, and that don’t strain or displace scarce resources or cause other community hazards or environmental harms.

To make the entire system green, renewable, low-carbon energy would also need to be used to compress the gas to pressures that enable it to be stored and transported safely and efficiently, without leaks that can be detrimental to the health of communities and the environment.

Making this method of hydrogen production economically viable is the first order of business in making hydrogen a helpful response to the climate crisis. In this guidance, we use the term “green hydrogen” to refer to renewable energy-based electrolytic hydrogen produced via solar, wind, hydro, and geothermal power. Biomass-based is complicated. Most biomass-based systems pose community and environmental impacts beyond greenhouse gas emissions considerations. Grid power may be used for electrolysis, but until the grid is nearing 100 percent low-greenhouse gas and/or renewable energy around the clock, such hydrogen should not be characterized as green or renewable energy-based.

It is also critically important that new green hydrogen production be developed only in tandem with new renewable energy resources commensurate with the new hydrogen production capacity demand. This co-location of new renewable generation with hydrogen production is necessary in order to avoid displacing more efficient use of renewable energy for direct electrification and to avoid firing up fossil fuel peaker plants in order to meet demand for hydrogen production. This would be an unintended consequence directly counter to climate and community interests. Furthermore, local generation resources dedicated to hydrogen production during normal operations could be redirected to serve critical loads in the wider community during power outages through temporary electrolysis curtailment until grid power is restored.

It is important to note that the efficiency of all end use applications is critically important and is the true first order of business in a systems approach. Maximizing the efficiency of end uses reduces the primary energy source capacity required to produce hydrogen to serve the end use.

Policy guidance: California budget investments should be limited to advancing green hydrogen, with community and environmental safeguards integrated as a top priority.

Steam reformation of natural gas

In order for applications of hydrogen to make sense as a climate solution, the production of hydrogen must not exacerbate climate change. Currently, roughly 95 percent of hydrogen production is made by applying high temperature steam to methane gas (the main component of fossil or natural gas) in what is called steam reformation.[11] Methane reacts with the steam to produce hydrogen, carbon monoxide, and carbon dioxide.

Steam reformation emits approximately 9.15 to 10.25 tons of carbon dioxide (CO_2) per 1 million standard cubic feet (SCF) of hydrogen produced.[12,13,14] This method of hydrogen production does not result in a climate-friendly fuel, as it releases significant CO_2 pollution, equivalent to roughly ten times the mass of hydrogen produced, during production alone (not including the significant release of methane during transport through leaking pipes).[15]

Policy guidance: Steam reformation of fossil gas is not a hydrogen production method that serves the state's climate goals. This method of hydrogen production, and the petroleum refineries where most of it is produced, should be placed on a track for managed phaseout as part of California's overarching decarbonization policy.

Biomass-based

Modeling in the IPCC's Sixth Assessment Report projects scenarios where 101 exajoules[16] of energy will need to be sourced from biomass globally by 2060 in order to stay within 1.5 degrees Celsius of warming.[17] This is one of the more complex, difficult, and controversial energy sources. There are numerous forms of biomass, such as municipal sewage, the organic fraction of landfills, plant-derived oils, and woody biomass. There are also several methods of energy conversion of biomass feedstock to usable energy of liquid fuel. In many cases, especially when scaled up, biomass systems pose significant community and environmental risks. Conversion of petroleum refineries to biofuel refining can prolong impacts to communities of concern that have suffered for decades from petroleum refining. Crops grown for fuel can displace food crops. Facilities established to process woody biomass can create demand for more feedstock, which induces counterproductive destruction of forests for energy generation.

In the case of hydrogen, biomass feedstocks like agricultural wastes can be processed in anaerobic digesters[18] that produce methane (CH_4) gas.[19] The methane can then be reformed into hydrogen and CO_2 via the steam reformation process. When such systems are kept at a very small scale and completely sealed with no leaks, the impacts to nearby communities and

[11] https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics
[12] https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/
[13] Sun et al, Criteria air pollutants and GHG emissions from hydrogen production in U.S. steam methane reforming facilities. Env. Sci. Technol. 2019 (53): 7103–7113. https://pubs.acs.org/doi/10.1021/acs.est.8b06197
[14] Changing Hydrocarbons Midstream (Chapter 3); www.energy-re-source.com/publications
[15] https://www.npr.org/2022/02/03/1077392791/a-satellite-finds-massive-methane-leaks-from-gas-pipelines
[16] An exajoule equals 277,778 gigawatt-hours
[17] See figure TS.11 Global energy use, 2060, Scenario IMP-REN-2.0 on pages 92 and 93 in the IPCC's AR6 WGIII report: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf
[18] https://www.epa.gov/agstar/how-does-anaerobic-digestion-work
[19] https://scied.ucar.edu/learning-zone/how-climate-works/methane#

the environment are minimal. At a larger scale, there are myriad problems, including negative impacts (including but not limited to noise, smell, and air pollution) to local communities and the environment.

In “The False Promises of Biogas: Why Biogas Is an Environmental Justice Issue”[20] published in May 2021, the authors found that “manure-to-energy projects have the potential to be helpful for small farms (not large-scale, confined animal feedlot operations [CAFO’s]) if the biogas produced on the farm is reused only at that farm. When manure-to-energy projects are installed on factory farms, the processing of the methane produced for the power grid or for the transportation sector releases CO_2 and hazardous air pollutants and requires the installation of gas pipelines and other infrastructure that leak tremendous volumes of methane. Biomethane production burdens and poisons local communities while degrading our planet's health and sustainability. Manure-to-energy projects are not a sustainable solution to the problems caused by CAFO’s because they entrench an already polluting facility with more contamination mechanisms. Local, state, and national governmental entities need to stop promoting and incentivizing CAFO manure-to-energy projects at the expense of the environment and rural communities.”

A potential moral hazard is also created if excessive biogas program incentives become a greater profit center than the original business model, resulting in larger livestock facilities with even greater methane emissions.[21] Factory farm-scale or any large-scale, biomass-based hydrogen production[22] is not a viable option from a climate or climate justice perspective, and should not be labeled as clean, green, or renewable hydrogen.[23]

Policy guidance: Biomass-based hydrogen production should not be scaled up for utility-scale electricity generation or hydrogen production for vehicle fuel to be marketed offsite. Biomass-based hydrogen production, if deployed at all, should be limited to smaller scale, onsite production and use in instances where there is a known, consistent feedstock, such as municipal sewage or landfill gas. Such deployments should not require or catalyze an expansion of feedstock.

The color code

Many in the hydrogen industry use color codes to try to clarify the several methods of hydrogen production. Apart from the use of green hydrogen as defined, in this guidance we do not refer to the various forms of hydrogen production in terms of colors. Not all stakeholders agree on definitions for each color and the code sows confusion instead of clarity for many. The definition

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[20] https://www.liebertpub.com/doi/10.1089/env.2021.0025
[21] https://www.visaliatimesdelta.com/story/news/2023/05/18/californias-methane-climate-solution-rewards-dairy-gas/70223176007/
[22] There are two main types of biomass-based hydrogen production: gasification (https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification), and steam reformation of biomethane (see Exec. Summary: https://www.nrel.gov/docs/fy14osti/60283.pdf)
[23] Many environmental justice organizations including the Central California Asthma Collaborative, CEJA, Leadership Counsel for Justice and Accountability, Central California Environmental Justice Network, Center on Race, Poverty and the Environment, and others, reject biomass as a “green” energy or climate solution.

of “green” hydrogen is a main point of contention.[24] Ninety-five percent of hydrogen today is “gray,” produced in a polluting process using fossil gas.[25]

The table below is an attempt to capture most of the agreed-upon color designations.

Hydrogen Production Method Color Codes*			
Color	Feedstock	Primary Energy Source	Production Process
Green✧	Water	Solar, Wind, Geothermal, Hydro	Electrolysis
Gray	Methane	Combustion of hydrocarbons	Steam reformation or gasification
Brown (in some versions Black)	Coal	Combustion of hydrocarbons	Steam reformation or gasification
Blue	Methane	Combustion of hydrocarbons	Steam reformation or gasification with carbon capture
Pink (in some versions yellow)	Uranium and Water	Nuclear power	Electrolysis

* Note: color codes vary; to avoid confusion, it is best to simply indicate what kind of production method you are talking about when you are talking about it. Carbon intensity of any given production method is a more meaningful way to assess production methods from a climate perspective, but environmental and social impacts must be considered.

✧ Note: Some define green hydrogen to include steam reformation of biogas. Scaled up biogas production has many non-green problems and is not included as green in this table.

Source: multiple sources; Image credit: W. Hastings

After eliminating production methods based on fossil fuels, a more meaningful and helpful way to address various methods of hydrogen production is to assess any given production method for its carbon dioxide emissions intensity.[26] However, carbon intensity alone is not enough. Although it is necessary to assess the climate emissions from any given method, low-greenhouse gas methods that may create or exacerbate localized community or environmental impacts must be taken into account.

Another confusing aspect of trying to categorize hydrogen according to colors is that the production method, whatever color it may be, does not address how the hydrogen is delivered and used. Delivery and end use may have social and/or environmental impacts unrelated to the production method.

Policy guidance: The color code is not something that is universally agreed upon and can sow more confusion than clarity. It is best to avoid trying to refer to hydrogen production methods by color, but refer to them in the longer set of terms that describe the process at hand.

[24] The Green Hydrogen Coalition includes biomass-based hydrogen in its definition of green: “produced from non-fossil-fuel feedstocks and emits zero or de minimis greenhouse gas emissions on a lifecycle basis.”
[25] https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics
[26] Carbon intensity is a measure of how low or high a given system or process is in terms of greenhouse gas emissions. It refers to how many grams of carbon dioxide are released to produce a unit of electricity or product.

Hydrogen Delivery

Truck and rail

Hydrogen can be transported by truck or rail, but it must be compressed or liquified, both of which require significant energy use. Then there is the fuel/energy use for the truck or train. Risks of accidents and leakage are problems that may never be fully resolved.[27] Advancing systems where hydrogen is produced and used onsite is a better approach.

Policy Guidance: Avoid and/or minimize transporting hydrogen by truck or rail, limiting such transport to within a prescribed distance from hydrogen hubs or other production centers.

Pipelines

“Blending” hydrogen into existing pipelines designed for methane is fundamentally problematic. Hydrogen is well-known to cause embrittlement of pipeline materials. Precisely the kind of thing one would not want to see in a system that needs to have tight fittings and no cracks to prevent gases from escaping.

A University of California Riverside hydrogen blending study[28] produced for the California Public Utilities Commission (CPUC) found that hydrogen pipeline injection "becomes concerning" as the blend approaches 5 percent hydrogen by volume. Due to low density, this is less than 2 percent by energy content. Even so, gas utilities are engaged in efforts to add hydrogen to existing gas lines as a means of “decarbonizing” the gas pipeline system. This notion is fraught with technical and other difficulties.[29]

Energy Innovation’s March 2022 report “Assessing the Viability of Hydrogen Proposals” found that “using hydrogen in buildings creates major challenges and safety risks throughout the existing natural gas infrastructure system because of the difference in chemical properties between hydrogen and methane. Hydrogen cannot be readily swapped for methane for use in heating or consumer appliances above a 5 to 20 percent blend with natural gas without enormous costs and disruption, and low blends achieve very few greenhouse gas emissions reductions while increasing nitrogen oxide (NOx) pollution.”[30]

Hydrogen has characteristics that make it safer than other fuels in some respects, but in the case of pipelines to buildings, there is no upside. Hydrogen is a “slippery” gas that can escape through minute seams or cracks in pipelines more easily than fossil gas. And as with any combustion fuel, there is a risk of unintended ignition or explosion. Fortunately, there is a clear

[27] https://www.energy.gov/eere/fuelcells/hydrogen-delivery
[28] https://www.cert.ucr.edu/hydrogen-impacts-study
[29] https://www.canarymedia.com/articles/hydrogen/experts-say-blending-hydrogen-into-gas-pipelines-wont-work
[30] https://energyinnovation.org/publication/assessing-the-viability-of-hydrogen-proposals-considerations-for-state-utility-regulators-and-policymakers/

path to residential electrification with no need for gas infrastructure of any kind. With electric heat pump space heating and cooling, water heaters, and induction cooktop stoves emerging as practical and affordable means of eliminating the need for gas appliances, there isn't any objective justification for injecting hydrogen into residential fossil gas lines.

Onsite green hydrogen production is always the best model, and off-grid systems that use solar to power stationary fuel cells may have a future. But piping hydrogen, with strict design and leak detection applied, must be reserved for applications and industrial purposes where electrification is not an option, such as cement, steel, and plate glass manufacturing. Pipeline technologies are being developed that proactively manage hydrogen leakage.[31] Such technologies should be further developed in connection with the creation of hydrogen hubs in areas zoned for heavy industry. That said, any existing pipelines designed for fossil gas, not specifically designed for piping hydrogen, must not be used to deliver hydrogen, even at low blending concentrations.

Policy guidance: Restrict the development of hydrogen pipelines to cases where there is no other alternative. In no cases should hydrogen be introduced in pipelines not specifically designed to carry hydrogen.

Green ammonia

The chemical formula for ammonia is NH_3: one nitrogen atom and three hydrogen atoms. Hydrogen is inherently difficult to store and transport. Recent technology advances in "green" ammonia production[32] may make this compound a contender as a storage and transport medium for hydrogen.[33] Although there are no commercial-scale green ammonia plants in existence today, this prospect should not be ignored. Hydrogen boils at negative 423 degrees Fahrenheit. Ammonia boils at negative 28 degrees Fahrenheit, making it far less energy-intensive to condense and transport. If green ammonia can advance to commercialization, it could make green hydrogen distribution more practical. As in any energy conversion, the process of producing green ammonia and then converting it again to hydrogen has an efficiency cost.

As anyone who has ever used ammonia as a cleaning solvent knows, ammonia poses an inhalation hazard. In the event of accidental releases of ammonia, which would be at much higher and far more dangerous concentrations than household cleaners should ammonia be used to store or transport hydrogen, there is a significant risk to public safety. Additionally, production facilities and/or application scenarios for in-state use of ammonia for this purpose might pose disparate exposure risks to low-income communities of color.

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[31] H2 Clipper, "Safety Pipe Technology," https://www.h2clipper.com/solutions/safety-pipe.

[32] One way of making green ammonia is by using hydrogen from water electrolysis and nitrogen separated from the air. These are then fed into the Haber process (also known as Haber-Bosch), all powered by sustainable electricity. In the Haber process, hydrogen and nitrogen are reacted together at high temperatures and pressures to produce ammonia. https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

[33] https://www.sciencedaily.com/releases/2020/11/201118141718.htm

Policy guidance: Further research on the efficacy and public safety dimensions of ammonia in this context is needed.

Green Hydrogen Applications

Green hydrogen is defined in this guidance as being produced via electrolysis of water using solar, wind, hydro, or geothermal energy sources (renewable energy-based electrolytic hydrogen).

Applications efficiency

As noted briefly in the section on hydrogen production, the energy efficiency of any end-use applications for hydrogen should always be maximized. It makes no sense to build more expensive energy generation capacity and hydrogen infrastructure than is truly needed in order to power inefficient end-uses.

Onsite production and use

Hydrogen can be produced and used onsite. This is a highest and best-use deployment scenario. It doesn't necessarily need to be trucked or piped. Green hydrogen can be produced wherever there is abundant sunshine, wind, geothermal resources, or hydroelectric power. In cases where applications can be colocated with the production facility, the need to deliver the hydrogen via pipeline or any other method is eliminated.

Policy guidance: Colocation of production and use is the preferred deployment model.

Electricity generation

Existing law, SB 100 (De León, 2018)[34] establishes as a policy of the state to achieve net zero greenhouse gas emissions as soon as possible, but no later than 2045, and to achieve and maintain net negative greenhouse gas emissions thereafter and to ensure that, by 2045, statewide anthropogenic greenhouse gas emissions are reduced at least 85 percent below the statewide greenhouse gas emissions levels in 1990. In order to achieve this goal in the electricity sector, green hydrogen may be required to provide a clean resource for times when variable resources such as solar and wind are not adequate.

There are two ways to generate electricity using hydrogen: stationary fuel cell stacks and combustion.

Stationary fuel cell stacks: One method is to feed green hydrogen into stationary fuel cell stacks that produce electricity, with water vapor as the only emission. Fuel cells themselves are

[34] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100

efficient in terms of energy conversion, but when taking all of the factors for getting green hydrogen to a fuel cell stack, including compression and storage, inefficiencies emerge. There are several other longstanding challenges to the widespread use of fuel cells for this purpose, including high initial investment costs, maintenance, and replacement, as current fuel cell technology operating life is limited. Efforts have been underway for many years to address all of these issues.

Combustion: The less expensive method is to combust hydrogen in turbines designed for hydrogen. The problem in this case is that hydrogen combustion is not without emissions consequences. Although mostly water vapor with no CO_2 emissions, hydrogen combustion also produces significant quantities of nitrogen oxide (NOx), a well-known criteria pollutant,[35] lung irritant, and smog precursor. Burning hydrogen can emit up to six times as much NOx emissions as that of methane combustion.[36]

Policy guidance: Combustion of hydrogen for electricity generation should not be pursued as a climate solution. Electricity generation as an application for hydrogen should be limited to use of stationary fuel cells for smaller scale uses for very long-duration (seasonal scale) for resilience purposes (see seasonal energy storage below). We support continued research and development to bring down the costs of fuel cells.

Light-duty vehicles

Over the past ten years, battery electric vehicles (EVs) have decisively “won the race” to become the mainstream replacement for gasoline-powered light-duty vehicles, or passenger cars. Although hydrogen fuel cell electric vehicle (FCEV) technology has been amply demonstrated, cost, technical, and deployment logistical problems have rendered that option less than promising. There are more than 1 million EVs registered in California and only about 12,000 FCEVs.[37] The majority of auto manufacturers are producing or plan to produce battery EVs, and more than 80 makes and models are currently available in California, with more being introduced each year.

Significant challenges remain with the electrification of light-duty vehicles, such as providing charging infrastructure for residents of multi-unit dwellings and integration with an electric grid that has the capacity to support them. These challenges are not insurmountable and state resources should continue to be focused on resolving them.

Policy guidance: We do not support further state investments in hydrogen fueling for light-duty passenger vehicles. Overcoming the challenges of electrifying the light-duty vehicle sector should be prioritized over supporting competing technologies.

[35] https://www.epa.gov/criteria-air-pollutants
[36] https://earthjustice.org/wp-content/uploads/hydrogen_earthjustice_2021.pdf
[37] https://www.canarymedia.com/articles/hydrogen/why-is-california-wasting-millions-on-hydrogen-fuel-pumps

Long-haul, heavy-duty vehicles

The heavy-duty vehicle classification refers to vehicles in excess of 26,000 pounds. In the case of Class 7 vehicles, this equals 26,000 to 33,000 pounds and in the case of Class 8 vehicles, in excess of 33,000 pounds.[38] Given the unique needs of these vehicles, there are reasons why it makes sense to pursue hydrogen fuel cell electric technology for this sector. Heavy-duty vehicles, especially long-haul, heavy-duty vehicles, need a long range between refueling. They carry heavy payloads. They require fast refueling. Several manufacturers have emerged that produce fuel cell heavy-duty vehicles.

Infrastructure required to serve the charging needs of heavy-duty vehicles is far more limited in scope than the light-medium duty sector. Long-haul, heavy-duty vehicles refuel at freeway truck stops and, in some cases, centralized fleet service yards.[39]

Even in the long-haul, heavy-duty vehicle sector, the jury may still be out. Battery electric semis (Class 8) are in development. Battery electric, heavy-duty infrastructure developers may design a system along major trucking routes that use cheap peak solar and/or wind power that might otherwise be curtailed to charge batteries that heavy-duty vehicle drivers could swap out quickly. The superior efficiency of such a system would likely prevail over less efficient FCEV trucks.

However, given their strenuous duty cycle and need for quick refueling, long-haul transport providers should weigh the pros and cons of each technology to determine the market size and nature of the long-haul sector. There may be an opportunity to hybridize these technologies, with primary use of batteries supplemented with a fuel-cell range extender.

Policy guidance: Although the window appears to be closing, with long-haul, battery electric, heavy-duty vehicles in development, there may still be a role for green hydrogen in the long-haul, heavy-duty vehicle sector.

Stationary fuel cells

There is a role for green hydrogen to play in stationary fuel cell stacks[40] for power supply, electric system integration, and energy resilience. Solid oxide fuel cells[41] offer high heat cogeneration that can boost overall efficiency or supply thermal-intensive operations. However, many of the proposals in this sector articulate scenarios that use fossil gas in the near term and make varying commitments to shift to green hydrogen over time (e.g. Bloom, MainSpring, industry in general). Some have time horizons to go full green hydrogen by 2045 and some have no timeline at all. Some also don’t specify use of green hydrogen, just hydrogen produced by any means. A market and policy strategy is needed to ensure that the industries that want to

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[38] For more detail see: https://afdc.energy.gov/data/10380
[39] https://www.mckinsey.com/capabilities/operations/our-insights/global-infrastructure-initiative/voices/unlocking-hydrogens-power-for-long-haul-freight-transport
[40] For a good primer on what a fuel cell is, see: https://www.energy.gov/eere/fuelcells/fuel-cells
[41] https://www.energy.gov/fecm/solid-oxide-fuel-cells

transition to green hydrogen are not dragging their feet hanging on to fossil gas, while using the promise of green hydrogen as a marketing ploy. The market and policy efforts need to establish timelines and interim target dates along the lines of the California Renewable Portfolio Standard and set a goal for full green hydrogen much earlier than 2045.

Policy guidance: Stationary fuel cell applications should accelerate adoption of green hydrogen and should be limited to serving critical facilities and applications where energy resilience is the purpose and the losses in cost and efficiency are acceptable, given the overriding need.

Seasonal energy storage (very long-duration)

Chemical battery technology has advanced dramatically over the past 15 years and costs have plummeted. This is all good news and we see the results in applications all around us every day, but there is one instance where chemical batteries still fall short — seasonal energy storage. This is storage measured in weeks and months, not days and hours, and is meant to address what the Germans call the *dunkelflaute*, that extended period of time in the winter when the sun isn't shining and the wind isn't blowing.[42]

A 2020 analysis by the National Renewable Energy Lab found that, without any kind of new effort to accelerate this use, it will take until 2050 for hydrogen energy storage to be cost-competitive with other, more limited long-duration storage options, such as pumped storage.[43]

An ideal storage solution for hydrogen and the grid would be to use otherwise curtailed wind and/or solar power to produce hydrogen that is then stored for later export back into that same region on the grid when needed via stationary fuel cells (or if available, heavy/medium-duty FCEVs with energy export features) that convert the stored hydrogen back into electricity. Though cost-prohibitive at this time, this is a path worth pursuing, especially when considering avoidance of NOx emissions from the combustion of stored hydrogen.

Another study reports on the development of a new water-splitting process and material that maximize the efficiency of producing green hydrogen, making it an affordable and accessible option for conversion of green hydrogen for renewable energy storage.[44] A program to accelerate the advancement of green hydrogen-based, long-duration storage should be considered a policy priority for California. California's 2022-2023 budget includes $380 million in the general fund over two years to invest in long-duration storage projects throughout the state to support grid reliability.[45] This may include green hydrogen-based storage.

Policy guidance: Very long-duration (seasonal) energy storage and electricity generation is a deployment model that is worthy of ongoing evaluation.

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[42] https://qz.com/can-europe-survive-the-dreaded-dunkelflaute-1849886529
[43] https://www.nrel.gov/news/program/2020/answer-to-energy-storage-problem-could-be-hydrogen.html
[44] https://www.sciencedaily.com/releases/2022/01/220114153429.htm
[45] https://www.ebudget.ca.gov/2022-23/pdf/BudgetSummary/ClimateChange.pdf

Rail

The first hydrogen-powered train made its debut in 2018 in Germany.[46] Diesel heavy rail is a good candidate for a transition to hydrogen. Weight is not as much of an obstacle, they have substantially more unused space that can be employed for fuel storage and they can refuel in multiple locations, since they tend to travel to more locations and trainyards where centralized fuel storage can be located. They are also modular, so the fuel can be stored incrementally depending on the length of a train. As such, hydrogen power in rail is scalable.

Policy guidance: Green hydrogen applied to rail is an application that is worthy of continuing evaluation.

Marine

Most shipping and other marine transportation is still fueled almost entirely by fossil fuels. Ships can burn hydrogen directly in combustion engines producing primarily water vapor as exhaust along with some oxides of nitrogen (NOx), or they could more efficiently use fuel cells to run electric motors. One of the first demonstrations of the latter just launched in early 2022 in the San Francisco Bay Area, a fuel cell ferry.[47]

Policy guidance: Green hydrogen applied to marine transportation is an application that is worthy of continuing evaluation.

Aviation

Aviation is a hard-to-electrify sector. Battery electric aircraft have been demonstrated and so-called “sustainable aviation fuels” based on biomass have proponents, but scalability issues and impacts from the feedstock supply chain (as discussed above) remain significant barriers to widespread adoption. Hydrogen fuel cell electric aircraft technology has been demonstrated[48] and several companies are in the process of developing fuel cell electric planes. However, significant technological obstacles remain, chief among them the fact that the fuel density on aircraft would require that liquid hydrogen be used. This presents the same energy intensity issue that any liquid hydrogen system presents.

Green hydrogen production should be colocated at airports to avoid the need for delivery.

Additionally, as referenced in the section in this paper on hydrogen safety, there are emerging findings on the indirect effects of free hydrogen release in the atmosphere. Hydrogen use in aviation presents a unique question. We don’t know yet whether hydrogen leaks at high altitude might have a different or greater indirect effect on climate warming gases.

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[46] https://www.aa.com.tr/en/energy/projects/worlds-1st-hydrogen-powered-train-launches-in-germany/21657#
[47] https://ww2.arb.ca.gov/lcti-zero-emission-hydrogen-ferry-demonstration-project
[48] https://www.rechargenews.com/energy-transition/hydrogen-powered-electric-plane-makes-first-flight-between-two-commercial-airports/2-1-1202977

Policy guidance: Green hydrogen applied to the aviation sector is an application that is worthy of continuing evaluation.

High energy intensity industrial uses

Steel manufacture

Steel-making is a highly energy-intensive process with significant greenhouse gas emissions. In fact, more greenhouse gases are formed by weight in the process than the steel produced. The average CO_2 emissions from steel production is about 1.85 tons of CO_2 per ton of steel produced.[49] If the steel industry were a country, its CO_2 emissions would rank in the top ten.

The most recent California Air Resources Board report on mandatory greenhouse gas reporting shows that there are no facilities in California engaged in primary steelmaking from ore.[50] However, there are nearly two dozen facilities that alloy, forge, smelt or shape purchased steel or other metals but do not actually make steel from ore. Green hydrogen in this sector is relevant as these processes are also highly energy-intensive and difficult to electrify.

Theoretically, green hydrogen could serve as a basis for completely eliminating fossil fuels from the high energy input needed for producing steel.[51] A leading case study in this regard is the HYBRIT project aimed at making fossil-free steel in Sweden.[52] California should consider requiring that any new steel-making in the state use onsite green hydrogen for energy, while ensuring no negative impacts on nearby communities or the environment.

Policy guidance: Green hydrogen applied to the steel-making industry is an application that is worthy of continuing evaluation.

Cement manufacture

The cement/concrete industry presents a complicated problem in terms of addressing climate impacts. Although cement-making is an energy-intensive process, energy inputs are not the only sources of emissions. The greenhouse gas emissions from making cement are approximately 40 percent from energy use for heating and driving the processing and 60 percent from the chemical reaction that occurs when limestone is heated at high temperatures to make cement, known as "process emissions."[53]

Cement alone accounts for 1.8 percent of California's greenhouse gas emissions and 8 percent of CO_2 emissions worldwide.[54] It is considered to be one of the most difficult-to-mitigate industrial sectors. According to a February 2019 report by Global Efficiency Intelligence, California's cement factories are the largest consumers of coal and petroleum coke in the state.

49 https://www.carbonclean.com/blog/steel-co2-emissions
50 https://ww2.arb.ca.gov/mrr-data
51 https://cen.acs.org/environment/green-chemistry/steel-hydrogen-low-co2-startups/99/i22
52 https://www.hybritdevelopment.se/en/
53 https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_1_Cement_Production.pdf
54 https://www.fastcompany.com/90699145/cement-is-responsible-for-8-of-global-emissions-but-it-doesnt-have-to-be

California's aging and inefficient cement production facilities are substantially dirtier than new facilities in other countries.

The opportunity to clean up California's cement industry is significant and green hydrogen can play a role on the energy side of the equation. Some form of carbon capture and storage (which is itself controversial)[55] will be needed for the process emissions[56] when limestone is used. Legislation was enacted in the state in 2022 to address this facet of cement production.[57] All of the above could be obviated if low or no greenhouse gas alternatives to cement, of which there are several, get beyond the technology demonstration phase rapidly.[58]

Policy guidance: California should make greenhouse gas reduction in the cement industry a high priority, pursuing both green hydrogen in conventional cement manufacturing as well as investing in research and development of alternatives to conventional cement and/or concrete.

Plate glass manufacture

Plate glass manufacture is a very energy-intensive industry,[59] in which electrification is not an option and there are no process emissions, so all greenhouse gas reduction is a product of the energy inputs. California is home to several plate glass manufacturers. A world's first project in Liverpool, United Kingdom has used hydrogen to replace fossil gas in the process.[60] The mission going forward is to use green hydrogen for plate glass manufacturing in California.

Policy guidance: Green hydrogen applied to some industrial applications where electrification and alternative products are not an option, and where there is no prolonging of fossil fuel refining or use, are applications that are worthy of further evaluation.

Environmental and Social Considerations

Public participation, equity, and environmental justice

All green hydrogen production, delivery, and end use deployments should be carried out with robust public participation and with meaningful community and other stakeholder engagement, especially with any communities of concern that may be impacted by a new or converted hydrogen production facility.

Section 65040.12 of the California Government Code[61] defines environmental justice to mean "the fair treatment and meaningful involvement of people of all races, cultures, incomes, and

[55] https://theclimatecenter.org/our-work/research/carbon-capture-and-storage-policy-brief
[56] Process emissions are emissions not related to energy demand, but are the result of a chemical reaction
[57] https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB905
[58] https://www.sciencedaily.com/releases/2021/08/210818083918.htm
[59] https://spectrum.ieee.org/float-glass
[60] https://www.powerengineeringint.com/hydrogen/world-first-as-hydrogen-used-to-manufacture-glass/
[61] https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?sectionNum=65040.12.&lawCode=GOV

national origins, with respect to the development, adoption, implementation, and enforcement of environmental laws, regulations, and policies."

The Climate Center is in alignment with the state's definition and with the principles developed by the California Environmental Justice Alliance.[62] In particular, we agree that meaningful engagement with communities means that decisions are informed by residents of environmental justice communities.

Decision-makers must be proactive and culturally relevant when soliciting input. This kind of engagement is a necessary prerequisite when developing actions that are meant to safeguard community health and safety. Decision-makers must be responsive to community concerns, transparent in their work, and must ensure that engagement and accountability for decisions is ongoing for any given project.

Policy guidance: All green hydrogen production, delivery, and application/deployment activities should include robust, meaningful community engagement and participation in decision-making.

Labor and the role of green hydrogen in a truly just transition

The U.S. market for green hydrogen was estimated to be about $1 billion in 2021 and is projected to grow to between $60 and $72 billionby 2030.[63,64] Some analysts see a tipping point coming soon for green hydrogen.[65] This means that there is enormous potential for the labor community in the green hydrogen sector in the coming decade and beyond. On the supply side, jobs in the green hydrogen sector will include those in the renewable energy-based electrolytic production of hydrogen and in electrolyzer manufacture. On the supply side there will be everything from stationary and mobile fuel cell manufacture, to jobs in all of the sectors where green hydrogen will be used.

There are job prospects in the hydrogen sector where green hydrogen is not the chosen fuel type, and in applications of green hydrogen that are counterproductive to climate goals. Examples include blending of hydrogen into residential fossil gas lines or fossil gas electricity generation plants, as these applications have the effect of prolonging fossil gas use beyond the point where it might be terminated altogether. Therefore, not all job creation in the sector will be supported.

Policy guidance: Green hydrogen production and application offers a lot of opportunity for job creation. However, not all jobs in the emerging green hydrogen sector should be considered part of an appropriate response to the climate crisis.

[62] https://ceja-action.org/ej-decision-maker/ej-principles/
[63] https://www.prnewswire.com/news-releases/green-hydrogen-market-to-be-worth-60-56-billion-by-2030-grand-view-research-inc-301624094.html
[64] https://www.globenewswire.com/en/news-release/2022/06/29/2471419/0/en/Green-Hydrogen-Market-Size-is-projected-to-reach-USD-72-Billion-by-2030-growing-at-a-CAGR-of-55-Straits-Research.html
[65] https://rmi.org/green-hydrogen-fast-beneficial-and-inevitable/

Water use in hydrogen production

It takes between nine and 25 kilograms of fresh water to produce one kilogram of hydrogen via electrolysis.[66] If California, which is in a multidecadal drought, aims to scale up electrolysis-based hydrogen production, then water use must be assessed[67] and compared to other uses. Although water consumed for hydrogen production purposes is not returned directly to the body of water from which it was removed, it is not removed from the hydrocycle, as combusting it or using it in a fuel cell recombines hydrogen with oxygen to produce water vapor in an equal volume to the quantity of water consumed in its production.

It is necessary to note that enormous quantities of water are used in fossil fuel extraction[68] and refining.[69] Water is used to drill and refine oil, hydraulically fracture (frack) wells and process gas, as well as produce electricity in some natural gas power plants. Large quantities of highly contaminated water must be dealt with as a result of these uses. There is no contamination of water from beginning to end in hydrogen systems based on electrolysis, whether the end use is combustion or use in a fuel cell.[70]

In a February 2023 brief “Exposing a New Threat to Our Water,” Food and Water Watch found that if the U.S. Department of Energy’s projections for renewable energy-based hydrogen production are met, the water requirement would be equal to the consumption of about 34 million people.[71]

Policy guidance: Full-cycle analyses of the impacts of hydrogen production and use that includes water use should be continued to assess the social and environmental impacts of scaling up hydrogen production and use prior to investments in public dollars for scaled up hydrogen production and infrastructure development.

Energy efficiency

Energy inefficiency is the Achilles’ heel of hydrogen. With current technology, green hydrogen efficiency from initial production to compression to delivery to end use is about 30 percent at best, which means more than 70 percent of the renewable energy used to produce green hydrogen is lost across the full cycle.

Renewable energy resources are precious. Electricity generated via clean renewables should be prioritized for use directly in beneficially electrified applications. Hydrogen, even green hydrogen, must not delay or supplant electrification when electrification is feasible.

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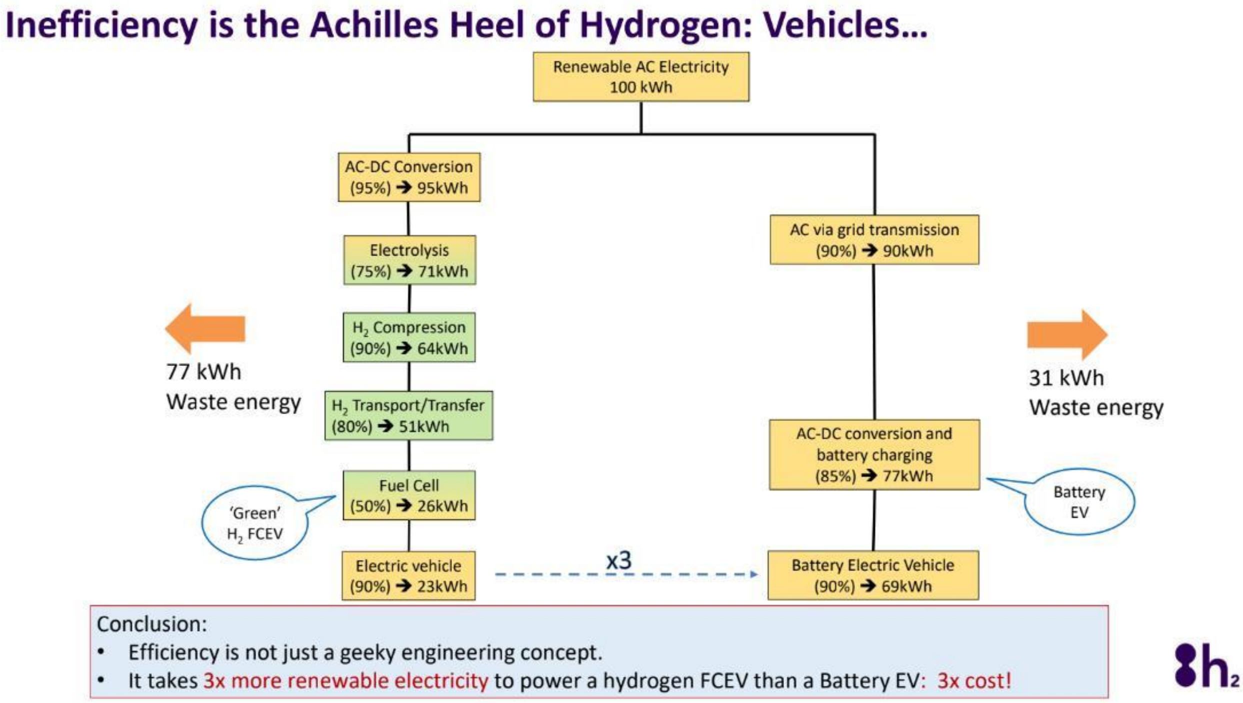
[66] https://pubs.acs.org/doi/10.1021/acsenergylett.1c01375
[67] https://www.natlawreview.com/article/water-resource-considerations-hydrogen-economy
[68] https://www.fractracker.org/2021/11/oil-and-gas-companies-use-a-lot-of-water-to-extract-oil-in-drought-stricken-california/
[69] https://www.sciencedirect.com/science/article/pii/S0016236117309511
[70] There is no contamination of water in the process of electrolyzing (splitting the hydrogen molecule from the oxygen) then recombining in a fuel cell the hydrogen molecule and oxygen to produce water molecules in vapor form. Overview: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis
[71] https://www.foodandwaterwatch.org/2023/02/07/hydrogen-water-use/

The figure below illustrates the difference in energy efficiency between battery electric vehicles and fuel cell electric vehicles. Overall, fuel cell vehicles require about two to three times the energy input compared to battery electrics.



Source: David Cebon, Professor of Mechanical Engineering, University of Cambridge, England (used with permission) (https://h2sciencecoalition.com/members/david-cebon/)

Hydrogen critics point to the fact that, with renewable energy-based hydrogen, there are substantial efficiency losses in the process of producing, compressing, and recombining hydrogen with oxygen in a fuel cell. This is indeed true, however, energy inefficiencies are not necessarily a reason to discard the technology. Many systems that have been in use for decades have huge efficiency losses. We choose to use inefficient technologies due to the overriding real or perceived non-energy benefits of the technology.

Two other things to take into account are that the purpose of using hydrogen can override inefficiency in cases, like community resilience or manufacturing essential materials. Further, efficiency doesn't matter as much in instances where hydrogen can be produced cleanly via solar and wind power that is otherwise "curtailed" at times when sun and wind are abundant and the demand load is low. If approached correctly, hydrogen production facilities with dedicated renewable generation offer additional capacity which can be redirected to serve local critical loads during an outage or other emergency. At this time, the prime indicator of progress in decarbonization revolves around building local energy systems that fully use the energy landscape to optimize GHG-free generation potential.

Policy guidance: Due to the unavoidable efficiency cost that translates directly into cost in dollars, green hydrogen applications should be limited to those where electrification is not an option, or is not enough on its own, such as in deployments meant to serve critical facilities and resilience purposes.

Hydrogen fuel safety

Every fuel has some degree of inherent risk. Fuels are fuels because they contain energy in a concentrated form. There are several characteristics of hydrogen that make it safer than other fuels. Given that it is 14 times lighter than air, when gaseous hydrogen is released, it dissipates and rises rapidly. It does not pool or stick to anything and it is not toxic. Although hydrogen is combustible, it is far less explosive than traditional fossil fuels[72] and can be managed safely using established ventilation protocols.[73]

However, hydrogen gas, composed of diatomic hydrogen (H2, two bonded hydrogen atoms) is a very tiny molecule that is prone to leakage and is very combustible. Strict leak detection must be required wherever it is deployed. Hydrogen has a very broad flammability range from 4 to 74 percent concentration in air. Even with proper safety precautions, there will always be risk of fire or explosions with hydrogen.[74]

For more on the safety of hydrogen as fuel, see the U.S. Department of Energy's "Safe Use of Hydrogen"[75] and NRDC's "Hydrogen Safety: Let's Clear the Air."[76] Apart from its use as a fuel, using hydrogen as a chemical process reactant can create serious hazards. See Appendix 2 "Oil Refining — A Hazardous Use of Hydrogen."

Policy guidance: Although there are several characteristics of hydrogen gas that make it safer than other fuels, hazards remain due to its tendency to leak and its flammability. For these reasons, hydrogen deployments should be limited to those where no other option is available, and where strict leak detection and other safety measures have been implemented and are strictly enforced.

Hydrogen as a greenhouse gas

Hydrogen is generally not considered to be a greenhouse gas. But because hydrogen reacts with compounds in the troposphere, emissions of hydrogen can affect the dynamics and concentrations of methane and other high-intensity greenhouse gases. Therefore, it can be considered an *indirect* greenhouse gas. Indeed, several recent analyses have begun to explore this dimension of hydrogen's role as an indirect greenhouse gas.[77, 78, 79, 80] In particular,

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72 https://www.powermag.com/lessons-learned-from-a-hydrogen-explosion/ "Hydrogen can be explosive at concentrations of 18.3% to 59%. Although this range is wide, it is important to remember that gasoline can present a greater danger than hydrogen because the potential for explosion occurs with gasoline at much lower concentrations: 1.1% to 3.3%."
73 Hydrogen Tools – Ventilation, https://h2tools.org/bestpractices/ventilation
74 See page two: https://www.nasa.gov/pdf/513855main_ASK_41s_explosive.pdf
75 https://www.energy.gov/eere/fuelcells/safe-use-hydrogen
76 https://www.nrdc.org/experts/christian-tae/hydrogen-safety-lets-clear-air
77 https://acp.copernicus.org/articles/22/9349/2022/acp-22-9349-2022.pdf
78 Warwick et al. (2022) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067144/atmospheric-implications-of-increased-hydrogen-use.pdf
79 Bertagni et al. (2022) https://www.nature.com/articles/s41467-022-35419-7
80 Ocko and Hamburg (2022) https://acp.copernicus.org/articles/22/9349/2022/acp-22-9349-2022.pdf

hydrogen leaks could help the potent greenhouse gas methane to remain in and build up in the atmosphere. A future hydrogen economy would therefore have greenhouse consequences and would not be negligible. Although the climate impacts of a 100 percent green hydrogen economy would likely be far less than the current fossil-based economy, if the full climate benefits are to be realized in a future green hydrogen economy, careful attention must be paid to minimize leakage of hydrogen in production, storage, and end use. Placing leakage minimization as a top priority has safety, efficiency, and climate benefits and must be resolved for hydrogen to be considered a climate solution.[81]

Policy guidance: Hydrogen's role as an indirect greenhouse gas presents a challenge to any thought of a massive, economy-wide scale-up of hydrogen, or a notion of a "hydrogen economy." The more ubiquitous hydrogen becomes, the more the risk of leakage becomes significant. Hydrogen production and use should be limited to purposes where no other option is available.

Conclusion

On the application side, green hydrogen should only be considered in cases where electrification is not an option. No hydrogen deployment models should have the consequence of extending the operating life of fossil fuel refining or other infrastructure. No hydrogen deployment model should replace or delay direct electrification in cases where direct electrification is feasible, and when properly implemented, integration of hydrogen production into local energy systems should increase available renewable generation capacity.

There is a viable path toward electrification in most sectors as a climate solution, assuming rapid decarbonization of energy sources for electricity generation. Electricity infrastructure is already in place and is ubiquitous. The main caveat in this regard is the all-eggs-in-one-basket risk. Therefore, a carefully planned green hydrogen sector can play a role in offering a climate-friendly option when electricity is unavailable.

Standing up a green hydrogen-based system requires enormous public investment in new infrastructure. Electric infrastructure is ubiquitous and electrification in most sectors is practical, increasingly affordable, available, and reliable. Due to longstanding and unresolved problems including efficiency, cost, and safety, the narrow pool of valid production, delivery, and application models for hydrogen is shrinking. Investment of public funds should be limited to advancing renewable energy-based electrolytic hydrogen with community and environmental safeguards on the production side. Absent the development of adequate safety systems, hydrogen pipeline and other delivery systems should be minimized and hydrogen production should be colocated with applications.

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[81] https://www.edf.org/blog/2022/03/07/hydrogen-climate-solution-leaks-must-be-tackled

Appendix 1: Resources

Case studies

The following case studies are presented for informational purposes only and their inclusion in this guidance does not imply an endorsement on the part of The Climate Center.

- **ARCHES** (https://archesh2.org/)
  The Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) is California's public-private hydrogen hub consortium to accelerate the development and deployment of clean, renewable hydrogen projects and infrastructure. Clean hydrogen can supplement renewable energy sources to reduce greenhouse gas emissions and advance a zero-carbon economy. The U.S. Department of Energy will award $8 billion to up to 10 regional hydrogen hubs to build self-sustaining hydrogen economies of producers, infrastructure, and users. In partnership with the Governor's Office of Business and Economic Development (GO-Biz), ARCHES unites key public and private stakeholders to build the framework for a California renewable, clean hydrogen hub. For a statement on caveats and guardrails around hydrogen hubs, see The Promise and Perils of Hydrogen Hubs.

- **HyBuild**[82]
  HyBuild Los Angeles is the Green Hydrogen Coalition's initiative to create the first scaled ecosystem for "green" hydrogen in North America, targeting under $2.00/kg delivered "green" hydrogen in the Los Angeles Basin.

- **Intermountain Power Agency Renewed**
  https://www.ipautah.com/ipp-renewed/
  New fossil gas-generating units will be designed to utilize 30 percent hydrogen fuel at start-up, transitioning to 100 percent hydrogen fuel by 2045.

- **Lancaster, California**
  https://hydrogen-central.com/green-hydrogen-plant-lancaster-one-california-largest/
  Plans to produce 20,000 tons of renewable hydrogen annually and supply users throughout the Los Angeles area when it opens in 2025.

- **Clean Air Now/Xerox Technology Demonstration Project**
  Hydrogen can be produced and used onsite. It doesn't necessarily need to be trucked or piped. This was one of the key prospects of hydrogen demonstrated by the Clean Air Now Solar Hydrogen Vehicle Project[83] at Xerox Corporation, El Segundo, California. This $2.5 million demonstration project was the first fully permitted, commercially dedicated facility of its kind in the United States. All aspects of the renewable hydrogen

[82] https://www.ghcoalition.org/hybuild-la
[83] http://www.clean-air-now.com/CAN-XeroxIEAReport2000.pdf

economy were incorporated into the facility by design, from renewable hydrogen generation and hydrogen storage and dispensing, to end-use technology practically applied at a private corporation. The facility demonstrated fully independent hydrogen fuel production and use, creating a virtually pollution-free transportation system. After its ribbon-cutting in 1995, the project resulted in refinements in codes and standards for hydrogen fueling and resulted in several hydrogen-related spin-off projects and programs at municipalities, transit agencies, and academic institutions.

There were several challenges identified by the project. One is capacity. The system produced about 1,800 standard cubic feet (SCF) of green hydrogen per day in the summer and roughly 1,200 SCF of green hydrogen per day in the winter months. This was enough fuel to provide ranges of not much more than 100 miles per vehicle in the project. Capacity limitations of solar/hydrogen still pose a barrier to scaling for transit fleets and other large scale operations. Another challenge is the power to compress the hydrogen. In the Clean Air Now project, the compression used grid power. Significant challenges remain to make onsite green hydrogen production and use generally deployable.

- **AC Transit**
  Alameda County Transit (AC Transit) is one of the most advanced agencies in terms of adoption of hydrogen-powered, heavy-duty vehicles. Unfortunately, AC Transit produces no hydrogen onsite and has it trucked in from Southern California. This demonstrates how hydrogen for a scaled-up hydrogen fleet can't be produced reliably and cleanly onsite via solar at the volume needed for a transit agency with existing technology.[84]

- **Valley Link**
  https://www.valleylinkrail.com/valleylink-project (East SF Bay)
  Hydrogen-powered vehicles have been identified as being highly-effective in meeting Board Sustainability Policy guidance.

- **Zero-Emission Hydrogen Ferry Demonstration Project**
  https://ww2.arb.ca.gov/lcti-zero-emission-hydrogen-ferry-demonstration-project
  California Air Resources Board $3 million grant to build the first hydrogen fuel cell passenger ferry in the United States

Governmental projects and programs

- U.S. Department of Energy EarthShot program: The first Energy Earthshot, launched June 7, 2021 — Hydrogen Shot — seeks to reduce the cost of clean hydrogen by 80 percent to $1 per 1 kilogram in one decade.
  https://www.energy.gov/eere/fuelcells/hydrogen-shot
- Hydrogen Hubs ($8 billion): A nationwide network of regional hydrogen hubs intended to create good-paying jobs and jumpstart America's clean hydrogen economy.

[84] https://www.actransit.org/zeb

https://www.energy.gov/articles/doe-launches-bipartisan-infrastructure-laws-8-billion-program-clean-hydrogen-hubs-across

- National Renewable Energy Lab (NREL): https://www.nrel.gov/hydrogen/
- California Fuel Cell Partnership: https://cafcp.org/
- California Air Resources Board H2 Fueling Infrastructure Program: https://ww2.arb.ca.gov/our-work/programs/hydrogen-fueling-infrastructure
- Hydrogen-related laws and incentives in California (Alternative Fuels Data Center): https://afdc.energy.gov/fuels/laws/HY?state=CA

Non-governmental organizations

- California Hydrogen Business Council: https://www.californiahydrogen.org/
- Green Hydrogen Coalition: https://www.ghcoalition.org/
- California Stationary Fuel Cell Collaborative: http://stationaryfuelcells.org
- U.S. Fuel Cell Council: http://www.usfcc.com/
- Physicians for Social Responsibility: https://www.psr.org/wp-content/uploads/2022/06/hydrogen-pipe-dreams.pdf
- Rocky Mountain Institute: https://rmi.org/we-need-hydrogen-but-not-for-everything/

Academic papers and studies

- UC Davis Institute of Transportation Studies: Current Hydrogen/Fuel Cell Projects
- UCLA Engineering Department:
    - UCLA Announces Study that Could Reduce Cost of Fuel Cells
    - UCLA-led study could be step toward cheaper hydrogen-based energy

Other reports and papers

- The Future of Hydrogen (International Energy Agency): https://www.iea.org/reports/the-future-of-hydrogen
- Reclaiming Hydrogen for a Renewable Future (EarthJustice): https://earthjustice.org/wp-content/uploads/hydrogen_earthjustice_2021.pdf
- Five Reasons to Be Concerned About Green Hydrogen (Clean Energy Group): https://www.cleanegroup.org/wp-content/uploads/Five-Reasons-to-be-Concerned-About-Green-Hydrogen.pdf
- Hydrogen Reality Check: We Need Hydrogen — But Not for Everything (Rocky Mountain Institute): https://rmi.org/we-need-hydrogen-but-not-for-everything/
- Hydrogen's Decarbonization Impact for Industry: Near-term Challenges and Long-term Potential (Rocky Mountain Institute): https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf
- IPCC report: 'Clean hydrogen needed for net zero, but only where green electric solutions not feasible' (All 193 UN nations sign off on document that casts doubt on

widespread use of hydrogen for heating and cars, while pointing out the many challenges the sector must overcome): https://www.rechargenews.com/energy-transition/ipcc-report-clean-hydrogen-needed-for-net-zero-but-only-where-green-electric-solutions-not-feasible/2-1-1197644

- Green Hydrogen: A Guide to Policy Making (International Renewable Energy Agency): https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf
- Hydrogen Safety: Let's Clear the Air (Natural Resources Defense Council): https://www.nrdc.org/bio/christian-tae/hydrogen-safety-lets-clear-air
- Environmental Justice and Environmental Principles Regarding the Buildout of Hydrogen in California (letter to the Governor and other state leaders, March 2023): https://theclimatecenter.org/wp-content/uploads/2023/03/EJ-and-Enviro-Hydrogen-Principles-3.23.23.pdf

Appendix 2: Oil Refining — A Hazardous Use of Hydrogen

Petroleum refining relies on hydrogen as a chemical reactant rather than as a fuel. Refiners bond hydrogen with hydrocarbons in their oil streams to make lighter fuels from heavier crude oils and bond it with contaminants to remove them from the oil in order to protect process catalysts and meet fuel specifications. In California, oil refining has been the predominant use of hydrogen for many decades through to the present.

Toxic byproducts

In addition to enabling high-emitting fossil fuel combustion, this use of hydrogen creates serious health and safety hazards for refinery workers and nearby communities due to toxic byproducts of refining processes. Examples include:

- Hydrogen sulfide (H_2S), a toxic gas that forms during the use of hydrogen to remove sulfur from crude oil. H_2S is noxious, a corrosion hazard at typical refining process temperatures, a toxicity hazard at low air concentrations in chronic exposures, and deadly in acute exposures at high concentrations.
- Hydrogen fluoride (HF), a catalyst used by some refiners in gasoline production, is so toxic in acute exposures that sudden release of HF is a mass-casualty hazard in refining.
- Hydrogen cyanide (HCN), which forms as a byproduct of catalytic cracking in refineries, is a potent cancer risk.

Refinery explosions and fires

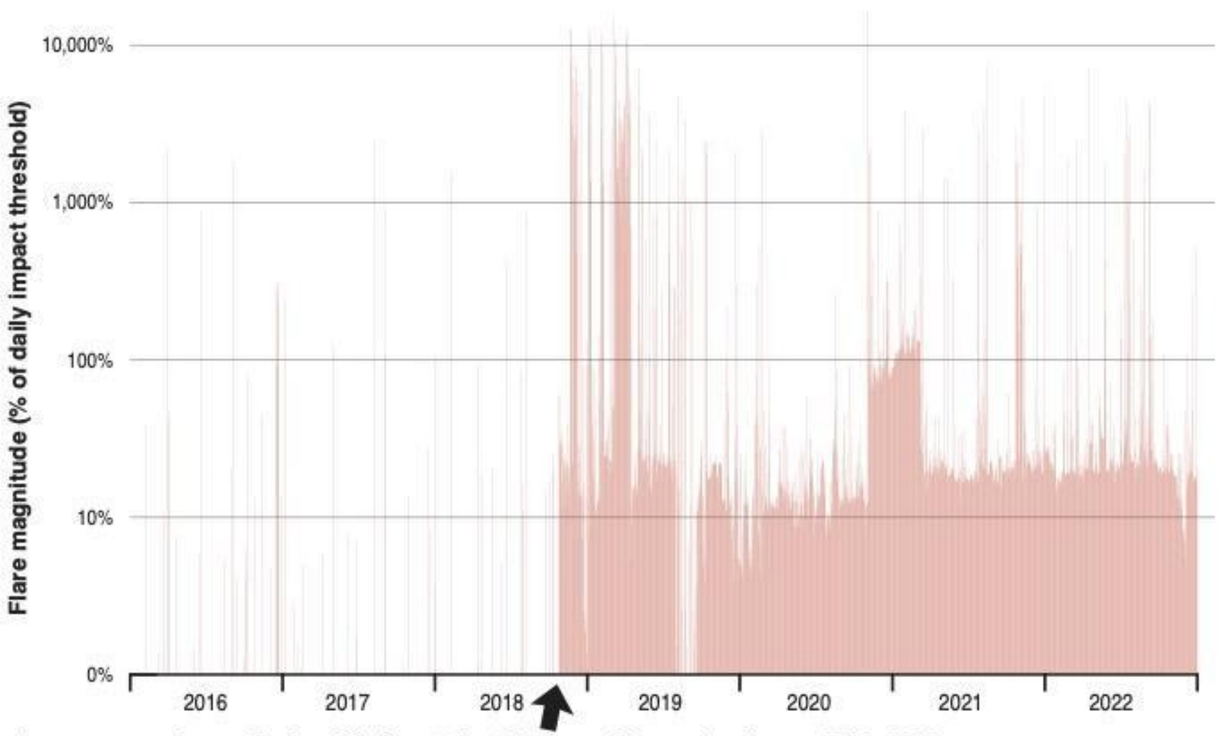
Specific hazards associated with hydrogen in oil refining include sulfidic corrosion of carbon steel by H_2S, embrittlement “cracking” of metallic equipment, and runaway reaction heat increases. Hydrogen reacts with carbon, sulfur, nitrogen, or oxygen from the oil processed at high pressure in refinery reactors to generate its own reaction heat. The reactions feed on themselves: the hotter they get, the faster they get hot. Runaway hydrogen processing reactions have burned holes in the seven-inch-thick stainless steel walls of hydrocracking reactors. At least ten catastrophic refinery explosions or fires involving hydrogen have been reported since 1987, five of which occurred in California. In one example, a refinery worker was killed and 46 others were injured in a 1997 hydrocracker explosion and fire in Martinez, California.

Flaring

Safeguards that refiners employ to mitigate hydrogen-related hazards are only partially effective and cause their own health and safety hazards. Importantly, one indication of the overall safety problem is that refinery hydrocracking, hydrotreating, and hydrogen production reactor vessels are designed to be rapidly depressurized to flares as a way to avoid explosions and fires.

Flaring is uncontrolled open air combustion. It causes acute exposures to the flared pollutants in nearby communities. Bay Area air officials set a flaring significance threshold in 2005 and 2006: half a million cubic feet of process gas flared per day, or 500 pounds of sulfur dioxide emitted per day. Hydrogen-related flaring incidents at two Bay Area refineries exceeded this impact threshold 100 times over a ten-year period. After expanding its hydrogen production in late 2018, hydrogen-related flaring at a third Bay Area refinery increased to near-daily frequency and exceeded this impact threshold by ten to 100 times repeatedly through 2022.[85,86] See the graph below.

Policy guidance: The state should accelerate a managed decline of combustion fuel refining and no hydrogen application should be permitted to operate with hydrogen produced via steam methane reformation at petroleum refineries.



Frequency and magnitude of flaring at the Chevron Richmond refinery, 2016–2022.
Frequency shown ranges from 0–31 days per month. Magnitude shown as percentage of BAAQMD cause analysis threshold; 0.5 million cubic feet of vent gas flared or 500 pounds of SO_2 emitted per day (criteria triggering flare incident causal analysis from BAAQMD Rule 12-12). Arrow: approximate date the refinery commissioned a new and larger fossil fueled hydrogen plant.
Data: BAAQMD Rules 12-11 and 12-12 public reports.

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The graph above shows that, after expanding its hydrogen production in late 2018, hydrogen-related flaring at a third Bay Area refinery increased to near-daily frequency and exceeded the allowable impact threshold by ten to 100 times repeatedly through 2022.

[85] For details on hydrogen-related hazards in oil refining see Chapter 3 in Changing Hydrocarbons Midstream https://www.energy-re-source.com/publications

[86] Data reported from the Chevron Richmond Refinery by the Bay Area Air Quality Management District pursuant to its rules 12-11 and 12-12: www.baaqmd.gov/about-air-quality/research-and-data/flare-data; and www.baaqmd.gov/about-air-quality/research-and-data/flare-data/flare-causal-reports

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