RESEARCH REPORT

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Moving Beyond the Colors: The Full Life-Cycle Emissions of Hydrogen Production Pathways for California

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16. Abstract
There is growing interest in the use of hydrogen as a transportation fuel but the environmental benefits of using hydrogen depend critically on how it is produced and distributed. Leading alternatives to using fossil natural gas to make hydrogen through the conventional method of steam methane reforming include using electrolyzers to split water into hydrogen and oxygen, and the use of biogas as an alternative feedstock to fossil natural gas. This report examines the latest carbon intensity (CI) estimates for these and various other hydrogen production processes, adding important nuances to the general "colors of hydrogen" scheme that has been used in recent years. CI values for hydrogen production can vary widely both within and across hydrogen production pathways. The lowest CI pathways use biomass or biogas as a feedstock, and solar or wind power. The report also analyses jobs creation from new hydrogen production facilities and shows that these benefits can be significant for large-scale facilities based on either future biomass/biogas-to-hydrogen or solar-hydrogen production technologies. Recommendations include setting stricter goals for the state's Low Carbon Fuel Standard (LCFS) program to continue to reduce the carbon footprint of California's transportation fuels.

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The California Resilient and Innovative Mobility Initiative (RIMI) serves as a living laboratory, bringing together university experts from across the four UC ITS campuses, policymakers, public agencies, industry stakeholders, and community leaders to inform the state transportation system's immediate COVID-19 response and recovery needs, while establishing a long-term vision and pathway for directing innovative mobility to develop sustainable and resilient transportation in California. RIMI is organized around three core research pillars: Carbon Neutral Transportation, Emerging Transportation Technology, and Public Transit and Shared Mobility. Equity and high-road jobs serve as cross-cutting themes that are integrated across the three pillars.

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Disclaimer

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Important Definitions

Concept	Definition used
LCA	Life Cycle Assessment: According to ISO14040:2006: *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (International Organization for Standardization 2006).
Fuel Pathway Carbon Intensity (CI)	The California Air Resources Board (CARB) defines the fuel pathway carbon intensity (CI) as *"the sum of the greenhouse gases emitted throughout each stage of a fuel's production and use, also known as the "well-to-wheels" or "life cycle" analysis for the fuel. CI is expressed as the amount of life cycle greenhouse gas emissions per unit of fuel energy ... (gCO_2e/MJ). CIs include the direct effects of producing and using this fuel, as well as indirect effects that may be associated with how the fuel affects other products and markets."* (CARB 2022a).
Feedstock	Main source of energy or mass used to produce a fuel (e.g., hydrogen). Feedstocks may be biomass, natural gas, renewable energies, among others and the viability of a particular feedstock depends on the hydrogen (H_2) production process.
SMR	Steam Methane Reforming: Thermochemical hydrogen production method. The process relies on the decomposition of natural gas using water and heat to generate H_2 and carbon dioxide (CO_2) emissions.
Electrolysis	Electrochemical hydrogen production method. The process splits water (H_2O) into oxygen (O_2) and hydrogen (H_2), using electricity as feedstock.
GWP	Global Warming Potential. A characterization factor used to convert a non-CO_2 GHG into CO_2-equivalent (CO_2e) based on the relative cumulative radiative forcing effect over a time period, typically 100 years (as used in this report).

Executive Summary

Executive Summary

There is growing interest in the use of hydrogen as a transportation fuel, particularly in the context of the recently awarded, multi-year U.S. Department of Energy "Hydrogen Hubs." The environmental benefits of using hydrogen depend critically on how it is produced and distributed. Leading alternatives to using fossil natural gas to make hydrogen through the conventional method of steam methane reforming include using electrolyzers to split water into hydrogen and oxygen, and using biogas as an alternative feedstock to fossil natural gas. Additional potential pathways include those based on pyrolysis of biomass, biomass fermentation and algal growth processes, production from fossil fuels using carbon capture and sequestration, nuclear power-assisted pathways, and direct photo-electrochemical hydrogen production. This report examines the latest carbon intensity (CI) estimates for various hydrogen production processes, adding important nuances to the general "colors of hydrogen" scheme that has been used in recent years.

Key findings from this analysis include that the CI values for hydrogen production can vary widely both within and across hydrogen production pathways. The lowest CI pathways use biomass or biogas as a feedstock where in some cases CI values can be strongly negative,[1] at least in the near term where methane emissions are being allowed to be directly admitted to the atmosphere, and solar or wind power to hydrogen where CI values can approach zero. Additionally, an analysis of jobs creation impacts from new hydrogen production facilities shows that these benefits can be significant for large-scale facilities based on either future biomass/biogas-to-hydrogen or solar-hydrogen production technologies.

Key areas for policy action and associated continued research include:

1) Include biomass/biogas pathways in legislative and policy definitions of "green" or low-carbon intensity hydrogen where they can be clearly shown to have low or negative CI;
2) Ensure that program rules allow incentive program benefits including both federal and state programs, to be combined or "stacked" to provide incentives for low-CI hydrogen production and use while these programs are in place;
3) CARB should consider setting stricter goals for the Low Carbon Fuel Standard (LCFS) program to continue to reduce the CI of California's transportation fuels and improve the economics of production and use of the lowest CI fuels including renewable hydrogen; and
4) Allow curtailed renewable sources of electricity to count toward any additionality requirements for renewable hydrogen production as they would otherwise go unused.[2]

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[1] Note: CI values are positive if a fuel production pathway contributes net carbon-dioxide equivalent emissions to the atmosphere, negative if they effectively reduce emissions that would otherwise occur, and 0 if they have no net effect.
[2] Note: Additionality requirements stipulate that renewable energy systems must be newly developed in conjunction with a fuel production pathway, versus taking advantage of existing production facilities that are already in use.

Careful tracking of the environmental impacts of hydrogen production and use will continue to be important for both policy/regulatory purposes such as participation in LCFS and Production Tax Credit programs, as well as for broader analysis around state climate and other environmental goals. California was recently awarded funding for a Hydrogen Hub project for the U.S. Department of Energy under a consortium named the Alliance for Renewable and Clean Hydrogen Energy Systems (ARCHES). This program is intended to dramatically increase the production and use of hydrogen in California for various end uses including transportation, with a focus on very low CI and renewable hydrogen production systems. This will necessitate considerable analysis to measure and verify the performance of these systems relative to Department of Energy goals and targets, taking into consideration many of the aspects discussed in this report.

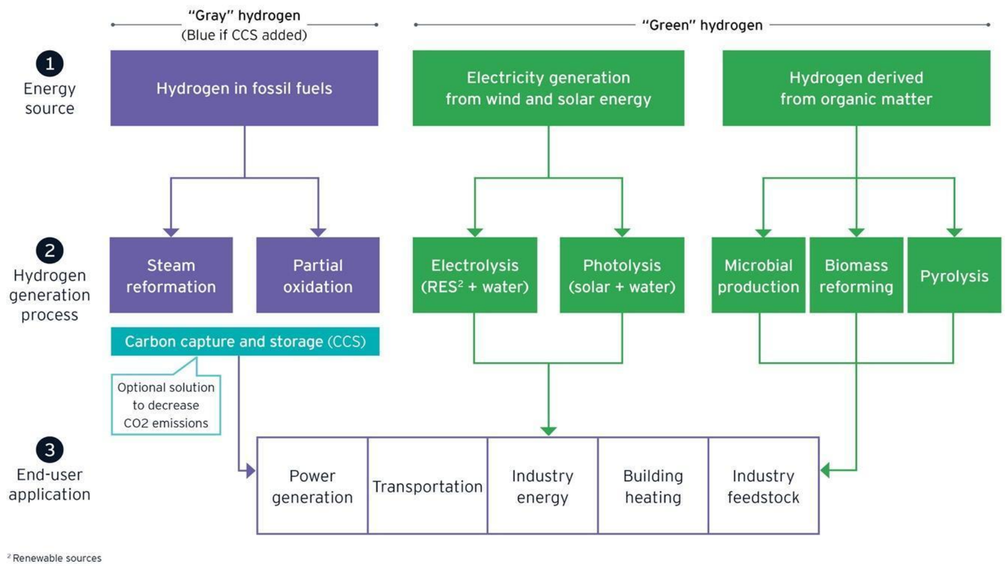
Contents

Introduction

As interest in hydrogen as an energy as a transportation fuel has increased, concern has focused on the various ways that hydrogen is made and whether they are environmentally conscious. Those processes are categorized as “green,” “blue,” “gray,” and other colors in relation to their means of production and environmental impact. As described further below, green hydrogen uses renewable feedstocks and often has very low or even negative carbon-intensity (CI), while blue and grey hydrogen pathways are defined as using fossil fuels as feedstocks and where the blue pathways use carbon captures and sequestration (CCS) to reduce carbon emissions and CI scores. While these categorizations are somewhat useful to indicate the environmental and climate change impacts of different production pathways, they are not especially useful for policy making or industry decision-making purposes because they are subjective. Most important is that hydrogen as a vehicle fuel can have a much lower carbon footprint—measured by the amount carbon dioxide emitted per unit of energy produced — than fossil fuels (even 0 or negative CI in terms of overall emissions) but that depends strongly on how the hydrogen is produced and distributed. A CI of 0 represents carbon neutrality, and the higher the score the worse the impact on the environment. The CI score for a pathway can be negative if the pathway results in a net reduction in overall greenhouse gas (GHG) emissions, for example if methane (a potent GHG) that otherwise would be released to the atmosphere is instead converted to hydrogen and carbon dioxide (a much weaker GHG).

Hydrogen can be produced in a variety of ways, often described as “pathways.” Green hydrogen pathways are considered the cleanest as they can result in production without significant GHG emissions. Most definitions of green pathways for hydrogen production only include electrolysis from renewable electricity sources; however, Figure 1 indicates additional production pathways. Some of these additional pathways can have near-zero or even negative greenhouse gas (GHG) emissions as well as low or no other emissions of concern. Hydrogen produced from natural gas is classified as “grey” or “blue.”

Figure 1. Example Schematic of Hydrogen Production Pathway Classifications

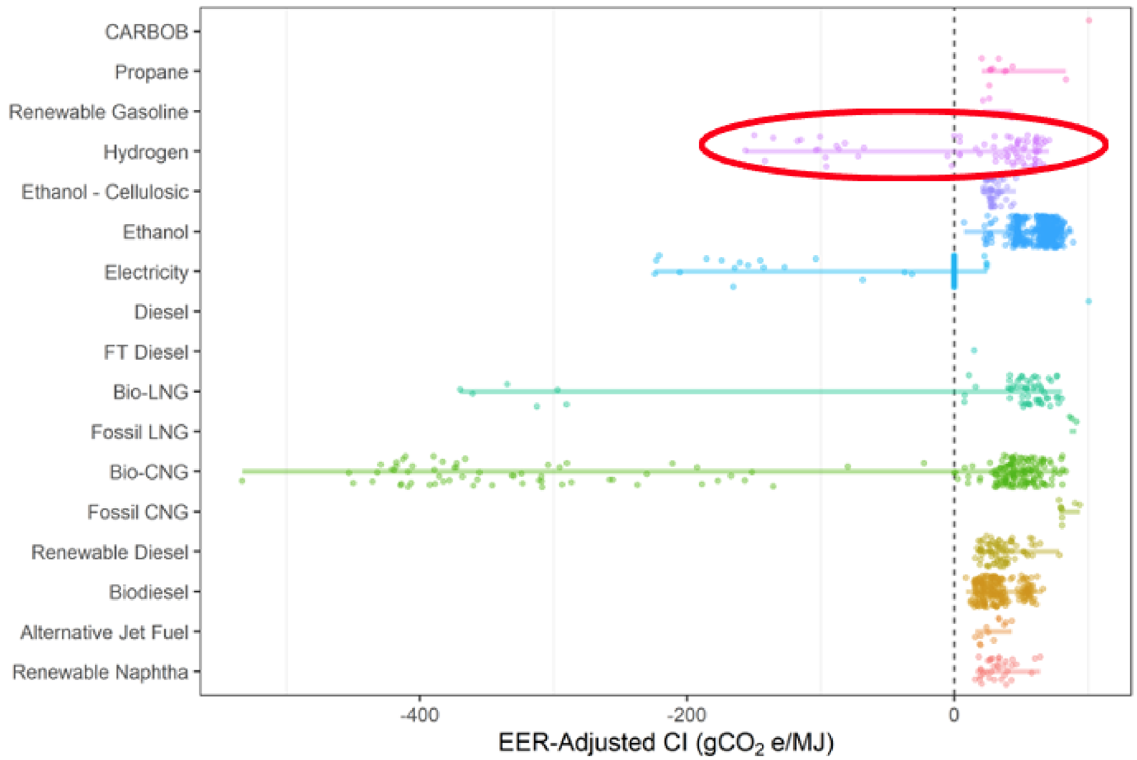


Source: EY - Global

It is important to remember that hydrogen is not an inherently low-carbon fuel. Hydrogen is carbon-free at the point of use, but there are upstream considerations. How hydrogen is produced, along with how it is transported and used across different sectors, greatly affects its overall carbon footprint. For example, hydrogen produced from electrolysis using renewable electricity that is generated nearby could have near-zero GHG emissions. Meanwhile, hydrogen produced from fossil natural gas through steam methane reforming (SMR)—a process involving heating methane from natural gas to produce carbon monoxide and hydrogen—that is then liquefied, transported long distances, and used in fuel cell vehicles could have overall life cycle GHG emissions similar to those from gasoline used in a comparatively sized modern vehicle.

California's Low Carbon Fuel Standard (LCFS) takes a life-cycle approach (LCA) when calculating the CI of various transportation fuels. In the LCFS, CI is measured in grams of carbon-dioxide equivalents (gCO_2e) per megajoule (MJ, an energy unit) and indicates the GHG emissions from the production, transportation, and use of a fuel. Carbon dioxide equivalents combine various GHG emissions (e.g., methane and nitrous oxide in addition to CO_2) into a single measure by multiplying the impact of each gas by its estimated global warming potential compared to CO_2 over a given time horizon (e.g., 100 years). An "energy economy ratio" (EER) adjustment is applied to account for the greater efficiency of fuel-cell electric vehicle drivetrains when hydrogen is used for transportation applications. As shown in Figure 2, hydrogen pathways have varying CI scores, ranging from somewhat lower than the California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) baseline to 0 or even less than zero when using certain biofuel pathways. In the figure, each dot represents a specific certified pathway within the broad categories shown on the y-axis.

Figure 2. CI of Different Transportation Fuel Pathways as Defined in California's Low Carbon Fuel Standard Program



Source: California Air Resources Board

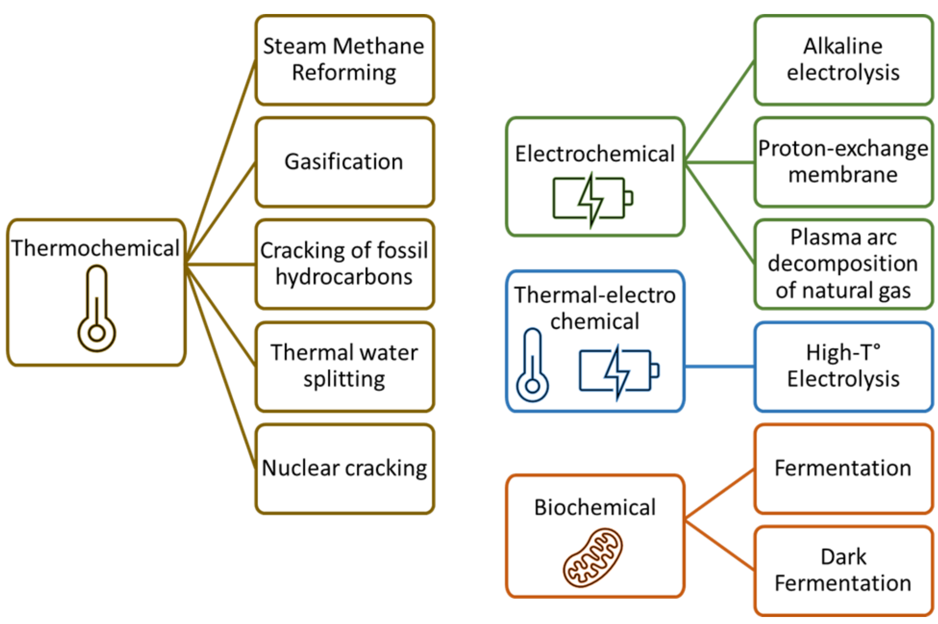
Note: CARBOB is the gasoline used in California and stands for California Reformulated Gasoline Blendstock for Oxygenate Blending; CNG is compressed natural gas; EER is energy economy ratio where the relative drivetrain efficiencies of battery electric, fuel cell electric, and conventional drivetrains are accounted for; FT is Fischer-Tropsch process; LNG is liquified natural gas.

Hydrogen Production Pathway Overview

In hydrogen production pathways, input energy and other materials (e.g., electricity, natural gas, biomass, water, etc.) are converted to hydrogen, potentially through an intermediate product such as "synthesis gas" (syngas, a mix of gases mainly including hydrogen and carbon monoxide) that is then further converted to hydrogen at some desired purity level as a final product. LCA techniques can be used to assess the full impacts of these production methods on one or more environmental indicators such as GHG emissions, criteria pollutant emissions, water use, etc.

Primary production methods for hydrogen include SMR, coal gasification, electrolysis of water, biomass gasification or pyrolysis, and methane cracking. There are also several emerging methods including photo-electrochemical, solar thermo-chemical, algae-based methods, and others. The production methods can be classified according to the nature of the chemical reaction that generates the hydrogen, including thermochemical, electrochemical, thermo-electrochemical, and biochemical (see Figure 3). The production pathways are dependent on the raw materials, or feedstocks, used for the reaction, and the feedstocks have a large influence on the carbon intensity of the overall process. Typical feedstocks include natural gas or biogas (methane), steam or water, and electricity.

Figure 3. Classification of Hydrogen Production Pathways



Source: Adapted from classifications proposed in (Rinawati et al. 2022)

Thermochemical Hydrogen Production Pathways

The SMR process decomposes methane (CH_4) contained in natural gas or biogas to produce hydrogen (H_2) using water and heat. A byproduct of this reaction is carbon monoxide (CO), which can then be used in a subsequent reaction to produce CO_2 and additional hydrogen (see Equations 1 and 2). Several studies have analyzed the carbon footprint of the SMR method (Lewis et al. 2022; Sun et al. 2019). SMR is currently the primary method used to produce hydrogen in the United States (Lampert et al. 2015).

Steam-methane reforming and water-gas shift reactions:

$$CH_4 + H_2O + heat \rightarrow CO + 3H_2 \quad \text{(Eq. 1)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 + heat \quad \text{(Eq. 2)}$$

$$\textit{Overall: } CH_4 + 2\,H_2O \rightarrow CO_2 + 4\,H_2 \quad \text{(Eq. 3)}$$

Another thermochemical process known as gasification uses a device known as a gasifier to process any of a number of feedstocks to produce syngas that can then be converted to hydrogen. There are a variety of different types of gasifiers, using either air or oxygen to react with a bed of fuel, either a fixed bed of the updraft or downdraft type,[3] or a fluidized bed consisting of a mixture of suspended fuel and air. Gasifiers can operate on coal (Midilli et al. 2021), petroleum, or biomass (Chang et al. 2011) as feedstocks. The chemical reaction between the heated air and fuel converts the organic fuel to syngas, rich in hydrogen, CO, and CO_2. The carbon monoxide can be further converted to hydrogen using the water-gas shift reaction, similar to SMR (see Equation 2). A related thermochemical process known as pyrolysis can produce hydrogen in an oxygen-limited environment, with somewhat different gas compositions but then utilizes similar hydrogen separation and clean-up processes as other thermochemical systems.

Less commonly used methods of thermochemical hydrogen production include thermochemical decomposition of water using nuclear or solar energy (Rosen 2010) as well as methane cracking. Methane cracking produces hydrogen by decomposing the feedstock using the thermochemical process of pyrolysis without the presence of steam (or oxygen), thereby reducing the amounts of CO and CO_2 generated as by-products (Banu and Bicer 2021). The pyrolysis reactions require a higher temperature than SMR (above 1,200 °C), rendering it a more energy-intensive production pathway.

[3] In downdraft gasifiers both fuel and gas move downward, and the gas is drawn off the bottom. In updraft gasifiers fuel moves downward and gas moves upward and is drawn off the top. The two processes differ in the types of fuel they can accommodate, and their efficiency and level of emissions produced.

Electrochemical Hydrogen Production Pathways

Electrolysis is a production method that relies on splitting water (H_2O) into hydrogen and oxygen (O_2), using a cathode and anode (see Equations 2 and 3) in an electrochemical cell. The reaction requires electricity that can be provided by different sources such as the electricity grid or renewable sources such as solar and wind. Three main electrolysis mechanisms have been studied, with varying degrees of implementation.

Alkaline electrolysis, used commercially, relies on electrolyte solutions (often potassium hydroxide—KOH) to support the electrochemical reaction but faces some limitations due to its inefficiency. Polymer electrolyte membrane electrolysis (PEM) improves the efficiency of hydrogen production compared to alkaline technology by having the ions transfer across a solid polymer electrolyte with supporting catalysts. While also a commercialized technology, PEM systems require rare and therefore expensive materials including platinum and iridium in the catalyst layers. Solid oxide electrolysis is a newer technology that shows good potential but under somewhat different conditions as it relies on high temperatures of at least several hundred degrees Celsius to achieve greater energy efficiencies (Holladay et al. 2009).

Biochemical Hydrogen Production Pathways

Biochemical processes primarily use the process of fermentation, where biological microorganisms consume organic matter and release hydrogen as a product (Dai et al. 2016). Various pre-treatment steps are used to prepare the material for chemical reaction, depending on the nature of the feedstock. Potential feedstocks include but are not limited to lignocellulosic biomass, refined sugars, or wastewater. When undertaken in the absence of light, the process is called dark fermentation.

Renewable Hydrogen Production Pathway Overview

Renewable hydrogen depends on the feedstocks to produce it being renewable, meaning that they are not being depleted in an overall sense by producing hydrogen. Other pathways can be low carbon but not renewable. Examples of low carbon but non-renewable hydrogen production include fossil pathways that have robust carbon capture and storage (CCS), and electrolysis using nuclear power. Renewable pathways fall into two broad categories: water electrolysis with wind and/or solar power, or biomass-fueled production though pyrolysis or gasification.

Water Electrolysis

Electrochemical hydrogen production pathways from splitting water into its component elements have been key processes for so-called “green” hydrogen due to their capacity for carbon-free operation. This assumes that the electricity supplied to the system is from a carbon-free source such as solar or wind. Water splitting has the additional benefit of producing pure hydrogen that does not require additional purification and treatment steps. When it comes to methods of water electrolysis there are three main types of systems: Alkaline, PEM, and high-temperature solid oxide.

Alkaline electrolysis is a well-established technology that utilizes an alkaline electrolyte such as KOH or sodium hydroxide (NaOH) in water to support the electrical conductivity needed to separate water into its hydrogen and O_2 products. The limitations with alkaline systems are low levels of current density, which require an increased surface area of electrodes, and low operating pressure which requires bulky stack design. The liquid electrolyte must also be isolated from air containing CO or carbonate reactions will form that impede the chemical conversion process.

Anode Reaction:

$$4OH^- \rightarrow O_2 + 2H_2O \quad \text{(Eq .4)}$$

Cathode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad \text{(Eq. 5)}$$

PEM is another mature technology that utilizes a polymer electrolyte material to support the water conversion process. Use of this material gained interest due to the solid electrolyte design that improves some of the challenges of alkaline electrolysis. The cell construction allows for highly pure hydrogen that does not require additional energy for purification before storage and distribution. The PEM system’s operation, however, includes acidic conditions, which when combined with the high voltage necessary for water splitting, requires highly stable materials that are not susceptible to corrosion. Platinum and iridium are among the most widely utilized materials in these cells. The high cost of these rare metals in turn limits the potential for PEM electrolyzers to be scaled up to meet demand for widespread hydrogen production.

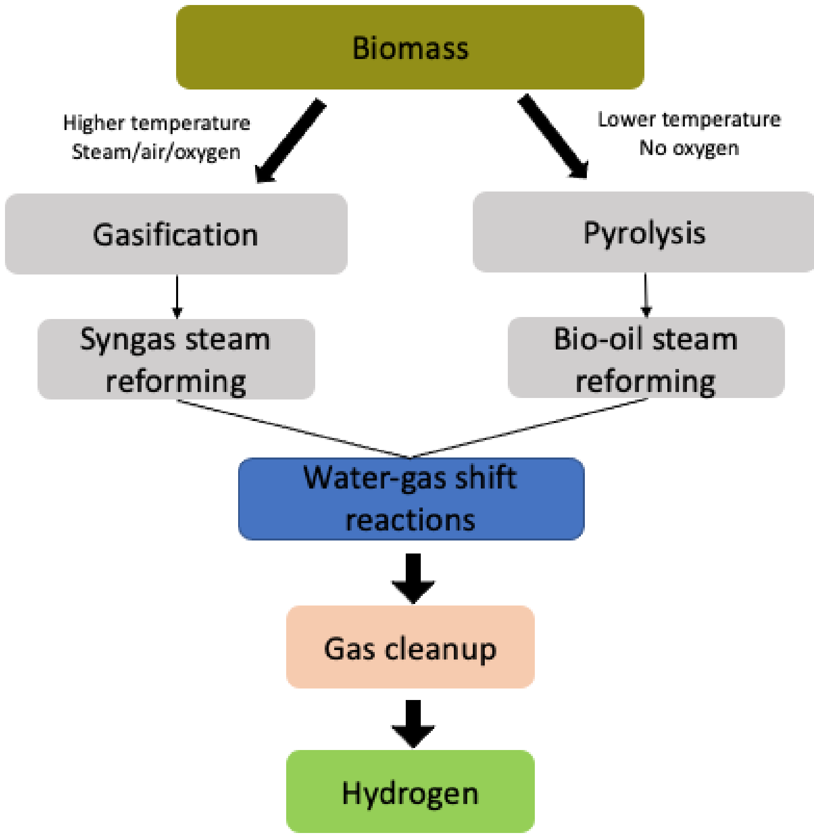
Solid oxide electrolysis is a newer technology still undergoing laboratory development but shows promise for addressing the challenges of alkaline and PEM electrolysis processes. These systems improve upon electrolyzer efficiency by using higher temperatures to improve activity, while simultaneously replacing much of the necessary electrical energy input with heat energy. They behave similar to alkaline systems except that a solid electrolyte does not have corrosiveness of liquid KOH solutions (Holladay et al. 2009). While these materials continue to be studied, they can function in both solid oxide fuel cells and electrolyzers, therefore increasing their potential utility (Laguna-Bercero 2012).

Biogas, Biofuels, and Waste Conversion

Multiple biological pathways for hydrogen production exist, with thermochemical pathways being the most fully developed. In gasification, the source (biomass) is heated to high temperatures and combined with a gas stream to produce hydrogen, as well as carbon monoxide, and carbon dioxide. This process mimics that of fossil fuel gasification but utilizes existing feedstock that may otherwise go to waste. Just like in fossil fuel gasification, additional units of hydrogen can be produced from the water-gas shift reaction, further oxidizing CO to CO_2. Conversely, pyrolysis occurs at lower temperatures than gasification, and can take place in the absence of oxygen while primarily producing liquid or solid products.

Biomass gasification is challenging to optimize due to the inherent variability in the feedstock. The quantity and quality of hydrogen produced, and the efficiency of production, can depend on the water content and chemical composition of the feedstock, as well as the particle size and reaction temperature. With water being the primary source of hydrogen for the reaction, moist feedstock is preferable as it can reduce the amount of additional water required for conversion. There is an upper limit however (40% by weight), where increased water lowers the reaction temperature and thus reduces the efficiency of production (Cao et al. 2020).

Figure 4. Schematic of Biomass-Based Hydrogen Production Pathways

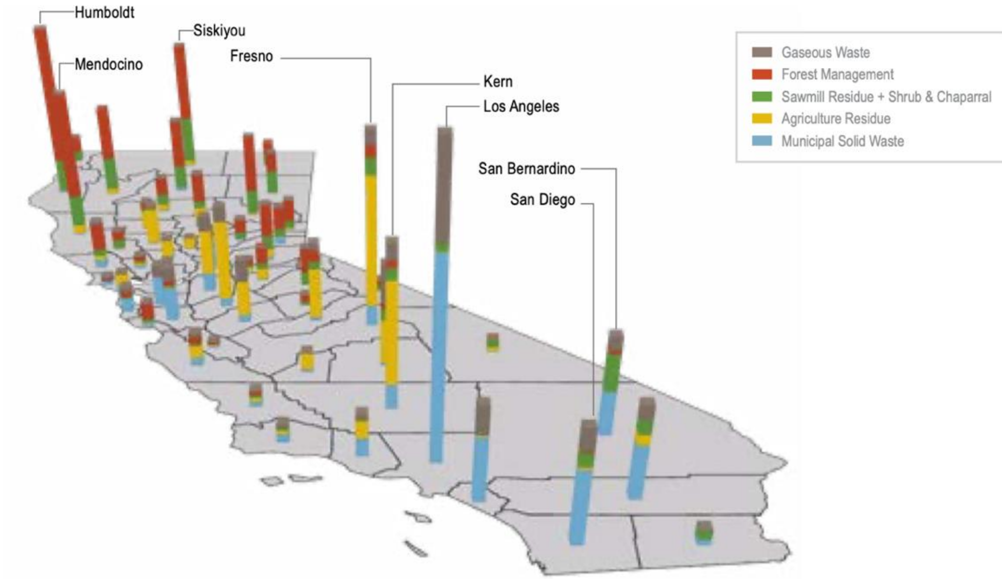


Source: Adapted from Cao et al. 2020

In all biomass processes the purity of the hydrogen produced must be considered. At the end of the production line, hydrogen must be effectively separated completely from the output gas stream to achieve the purity needed for end use. This involves using pressure or temperature swing adsorption processes already in use for SMR. The technology thus is available but introduces system complexities compared to the process of electrolysis.

There is a potentially large supply of biomass/biogas feedstocks for low CI hydrogen production in California. An estimated 56 million dry tons of waste biomass could be available by 2045 and could potentially produce up to five million tons of hydrogen per year (Baker et al. 2020). A recent estimate of the state's available biomass resources for biogas and/or hydrogen production (Figure 5) identifies feedstock source availability by region. Southern California production resources are dominated by municipal waste and other gaseous waste sources. Central California has a mix of those sources as well as agricultural residues and forest waste. Northern California sources come mostly from wood waste, forest management, and sawmill residues.

Figure 5. Biomass and Waste Feedstock Availability Estimate for California



Source: Lawrence Livermore National Laboratory (Baker et al. 2020)

Concept of Carbon Intensity of Fuels and the California LCFS Program

LCA is a well-established and comprehensive method to assess and quantify multiple environmental impacts across the life cycle of a product or service (International Organization for Standardization 2006). It is essential for estimating a fuel production pathway CI, but as described below, a full-scale LCA includes multiple impact categories. LCA, and especially its narrow application for CI estimation, has been widely used in the assessment of renewable and low-carbon fuels, especially given the relative importance of upstream emissions for these fuels.

Life Cycle Assessment

LCA typically has three primary steps: 1) goal and scope definition; 2) life cycle inventory; and 3) impact assessment. The goal and scope definition requires the determination of the system boundaries (i.e., what processes will be included or excluded from the LCA) and the functional unit (the unit by which the service provided by the system is measured), among others. Both choices can determine the comparability of LCA findings across studies. In the life cycle inventory step, all direct and indirect inputs and outputs are assessed. A useful distinction in this step is between the foreground and background systems. The foreground system consists of the processes modeled or measured directly by the LCA practitioner (for example a techno-engineering model of producing hydrogen by gasification or a factory producing hydrogen by gasification from which data will be collected), while the background systems consist of the industrial systems upon which the foreground system depends (e.g., the electricity grid). Much of the background data used in LCA are reference life cycle inventory datasets, often derived from public or commercial databases such as Ecoinvent (Wernet et al. 2016). Once a life cycle inventory is completed, impact assessment is used to calculate indicators related to impacts on humans, ecosystems, and resources. This is mostly done by applying characterization factors to inventory flows to calculate an impact indicator. Different impact categories can be assessed, and in LCA a suite of impact categories should be assessed; however, the most common impact category used (whether alone or in a suite) is global warming.

To combine the emissions of various GHGs into a single measure, LCA uses global warming potentials (GWPs) of each studied gas to convert non-CO_2 GHGs into carbon dioxide equivalents (CO_2e). The GWP is an estimated magnitude of the cumulative effect over a given time horizon (e.g., 100 years) of each gas relative to CO_2. By definition, CO_2 is the reference gas and has a GWP value equal to 1. GWPs are published by the Intergovernmental Panel on Climate Change (IPCC) in their assessment report based on the latest scientific understanding of the radiative forcing effect of the different GHGs. The fifth IPCC report, AR5, reports GWP values of 25 for CH_4 and 298 for nitrous oxide for 100 years (IPCC 2014).

California Low Carbon Fuel Standard (LCFS)

Various fuels employed for transport, electricity production, and other uses can have widely different life cycle or "wells to wheels" GHG emissions. The California LCFS program evaluates the CI of transport fuels in units of grams of carbon dioxide equivalents per megajoule (gCO_2e/MJ) of the final fuel produced. The main goal of the LCFS program is to reduce GHG emissions from transportation fuels in California (CARB n.d.).

The program complements the state's Cap-and-Trade program and employs a market-based approach to efficiently reduce the CI for transport fuels in California. The market-based approach consists of setting a weighted average fuel carbon emissions standard per energy output that decreases over time. Fuel suppliers with a CI below the standard can sell their "surplus" credits in the market, and fuel suppliers above the standard can purchase those credits to meet the standard. The market approach incentivizes every agent in the market to achieve the standard cost-effectively, as opposed to imposing a uniform emissions limit for each fuel produced. As of 2021, the CI benchmark for CARBOB gasoline is set at 90.74 gCO_2e/MJ, and 79.55 gCO_2e/MJ for 2030 and beyond (CARB n.d.).

Currently, hydrogen represents a small fraction of the total fuels transacted in the LCFS program. In 2021, a total of 1,931,358 GGE (gasoline gallon equivalent) of hydrogen were transacted in the program, or 0.07 percent of the total (CARB 2022a). Despite the present low level of hydrogen consumption, it has the potential to represent an important future share of the fuel used in the transportation sector in California (Schoenung and Keller 2017).

The fuels with the most volume transacted in 2021 were renewable diesel (39%) and ethanol (32%). Renewable diesel can be used directly in place of petroleum diesel, and ethanol is typically blended in gasoline either at low levels for use in conventional gasoline vehicles or at higher blends in flex-fuel vehicles. Hydrogen-fueled vehicles use an entirely different powertrain from internal combustion vehicles, namely a fuel cell powertrain coupled with an electric motor.

California Low Carbon Fuel Standard Application Process

The application process for the LCFS program and carbon credits require the company that produces the fuel (e.g., hydrogen) to undergo an LCA to estimate the CI associated with their pathway. CARB provides a default set of values for the most common fuel production methods with various categories in the life cycle stages. The CI for these pathways is estimated using the CA-GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) 3.0 model (CARB 2018).

The company may use these CI figures if their production process conditions and characteristics are similar. If the company produces a next-generation fuel, such as hydrogen, with a different production method or with different parameters (e.g., transport distance, efficiency, among others), they need to apply for their own Tier 2 pathway. In the application process, they must provide evidence of the estimated CI using the CA-GREET 3.0

model. All the application and annual verification process is administered by CARB. The information contained in Tier 2 applications provides a rationale for any variations of carbon intensity within the same production method of hydrogen.

California GREET Model Overview

Different software tools for LCA have been developed that include pathways for hydrogen production using default or industry data parameters. The GREET model developed at Argonne National Laboratory assesses the life cycle energy use and emissions derived from fuel production and vehicle use (Wang 1999) and has been used extensively to analyze the emissions associated with transport options, including hydrogen pathways (Liu et al. 2020). CA-GREET 3.0 (CARB 2018) is an adapted version of the GREET model) using California industry data to model the existing pathways from the original GREET model. CARB developed this model to support the state's Low Carbon Fuel Standard. Other LCA tools include commercial software such as GaBi and SimaPro, which have LCA modeling capability in addition to hosting commercial reference life cycle inventory databases, such as Ecoinvent and GaBi Professional These commercial reference life cycle inventories contain a much larger set of materials extraction and processing flows from regions around the world and allow for the calculation of many impact categories.

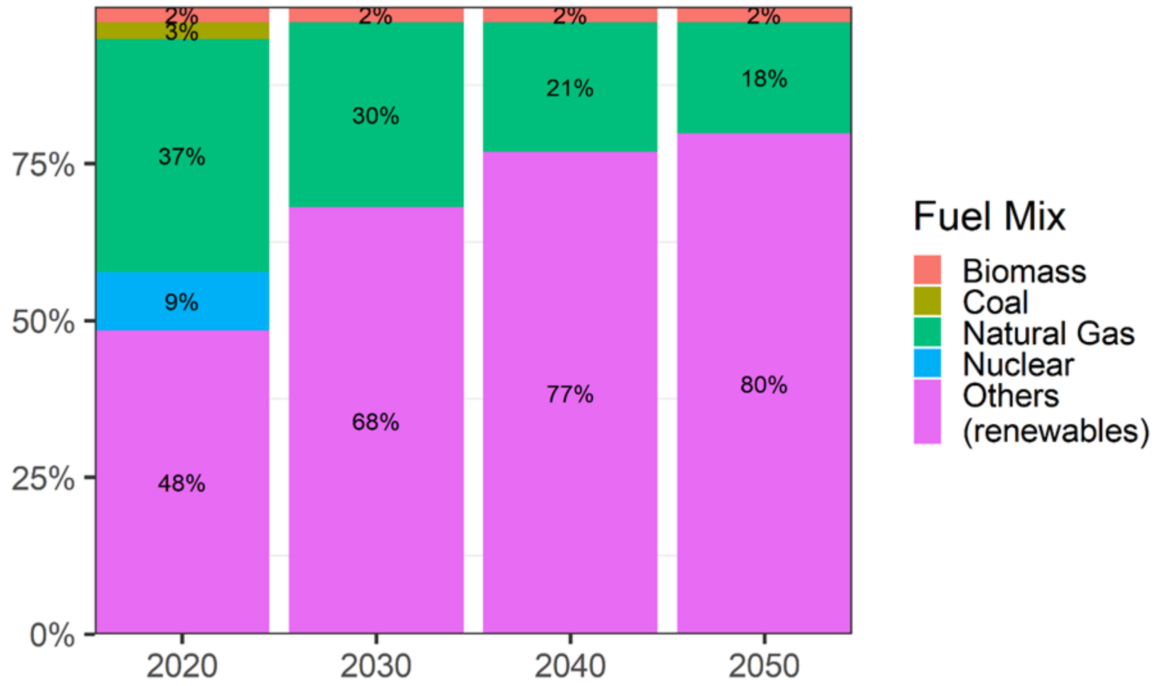
While the GREET model and its spin-offs specifically focus on life cycle GHG and criteria air emissions from transportation-related vehicles and fuels, GaBi and similar software were created for conducting LCAs of any product or system. In addition, GREET is regionally focused on the U.S. or California. Significant advantages of GREET, however, are that it is free, and far more transparent on multiple levels including its modeling assumptions, scope of analysis, and default parameters used to characterize each pathway.

Modeled Hydrogen Production Pathways

Our research team compared the CI of different hydrogen production pathways: steam reforming from natural gas, renewable natural gas, and biomass; gasification from coal, pet coke, and biomass; electrolysis with different energy sources; and integrated fermentation from biomass. We used the most updated version of the GREET model from October 2021 (general model features described in Wang 1999), using the standard parameters in the already modeled hydrogen production pathways.

However, we varied one modeling feature to understand the different effects it has on each pathway. Every pathway uses electricity as part of the production method, with different relative influences on the resulting hydrogen CI. We recalculated the CI values for all the hydrogen production pathways using different average electricity grid mixes for California. For the year 2020, we used historical data (California Energy Commission 2021), and for 2030 and 2040 we used projections according to planned policy actions (Ambrose et al. 2020). Over the period assessed, the projected grid for California will increase the share of renewable energy while reducing natural gas, coal, and nuclear sources (see Figure 6).

Figure 6. California Grid Electricity Mix – Year 2020 and Projected Through 2050



Source: 2020 electricity mix comes from historical data (California Energy Commission 2024). Electricity mix projections were obtained from Ambrose et al. (2020).

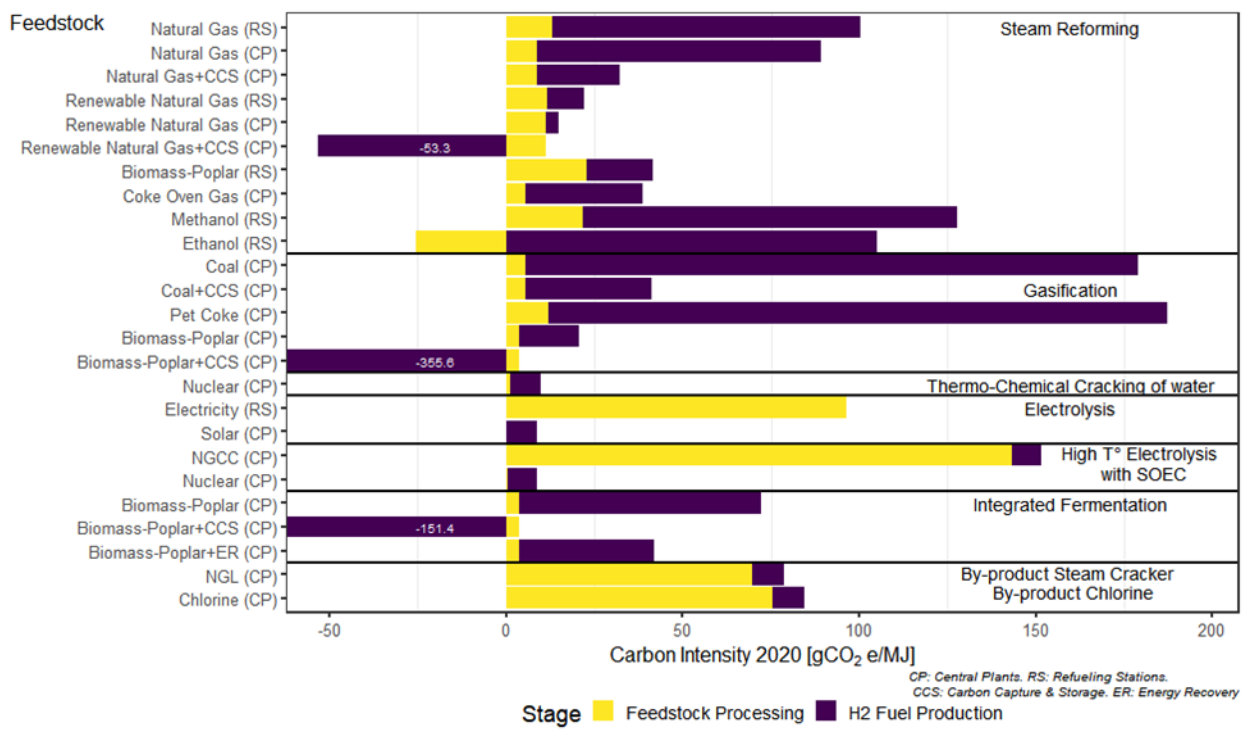
Carbon Intensity for Different Hydrogen Production Pathways

The hydrogen production pathways contained in the GREET model show important differences in their CI (see Figure 7). Under current conditions, gasification of fossil fuels has a higher CI than SMR and electrolysis with average grid electricity demand of a similar magnitude. Pathways with renewable feedstocks have a low CI, below 25 gCO_2e/MJ, similar to SMR with renewable natural gas and biomass gasification.

Pathways with the lowest emissions are electrolysis from low-carbon energy sources such as solar or nuclear, or from thermo-chemical cracking of water using nuclear energy. Steam reforming or gasification production methods with biomass as feedstock show a low CI value in the range of 50 gCO_2e/MJ. Including a carbon capture and sequestration step (CCS) considerably reduces the CI of SMR, coal gasification, and biomass gasification, even allowing biomass pathways to obtain negative CIs. However, CCS technologies are still being proven and entail considerable implementation costs.

For almost every production method, except electrolysis or by-products, the hydrogen production stage is the most emission intensive. In general, refueling station pathways (where hydrogen is produced at a small scale at the refueling station site) have higher emissions than production at central plants.

Figure 7. Hydrogen Production Pathway Carbon Intensity Included in the GREET Model

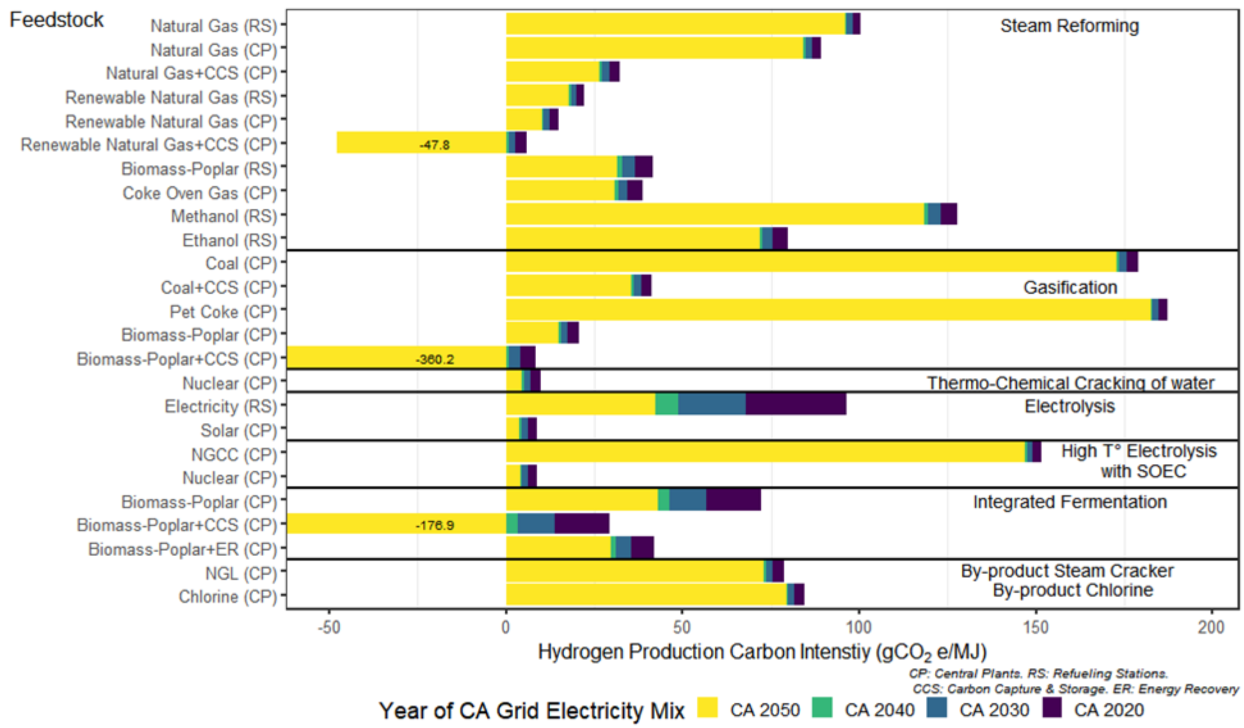


Source: GREET Model (Wang 1999). 2020 electricity mix was obtained from historical data (California Energy Commission 2024)

For projected grid-electricity mixes that have lower carbon emissions per unit of electricity, every pathway CI decreases over time. Figure 8 shows the decrease per period by visually removing the extra stacked color in the bar graphs. The higher reduction occurs in the electrolysis with grid-electricity pathway and the fermentation methods, due to their strong reliance on electricity. Steam reforming pathways show marginal reductions in CI, as the main source of carbon emissions are the chemical reactions that release CO_2, not from the use of electricity.

By 2050, with a cleaner grid electricity mix, the pathways with the lowest CI are still thermo-chemical cracking using nuclear energy and electrolysis using renewable energy. Excluding pathways that use unproven CCS technology, these are followed steam reforming of renewable natural gas, steam reforming or gasification of woody biomass, electrolysis using grid power, and integrated fermentation of woody biomass. Steam reforming of natural gas, currently the most common production method, still has relatively high carbon emissions compared to most other production technologies.

Figure 8. Projection of Gaseous Hydrogen Production Pathways CI Included in the GREET Model



Source: GREET Model (Wang 1999). The 2020 electricity mix was obtained from historical data (California Energy Commission 2021). Electricity mix projections are performed using the projections by Ambrose, et al. (2020).

Note: The yellow bars represent the lower carbon intensity grid values for 2050. The green bars represent the additional values as estimated in 2040, the blue bars represent the additional emission values in 2030, and the purple bars represent the additional emission values in 2020. Overall, all pathways reduce their CI due to the reduction of carbon emissions by the California electricity mix from 2020-2050.

Established LCFS Pathways for Hydrogen Production

CARB, following LCFS Regulation 95488.8(d), has published all the available pathways and their respective carbon intensity (CI) (CARB 2022a). From the available data, up to July 2022, there were 82 approved pathways (LCFS Pathway Certified Carbon Intensities) related to hydrogen as a fuel category. Fifty-two of these records were Tier 2 applications, which we used to analyze the variation among the same production pathways.

We reviewed each application to determine the type of hydrogen produced (gaseous or liquid) and the production method: SMR, electrolysis, or methane cracking. Additionally, the application documents were reviewed to characterize their estimated CI with life-cycle stage detail. Some of the applications contained confidential information not available publicly. We replicated the calculations of new values for CI pathways with the most current version of the CA-GREET model (CARB 2022b).

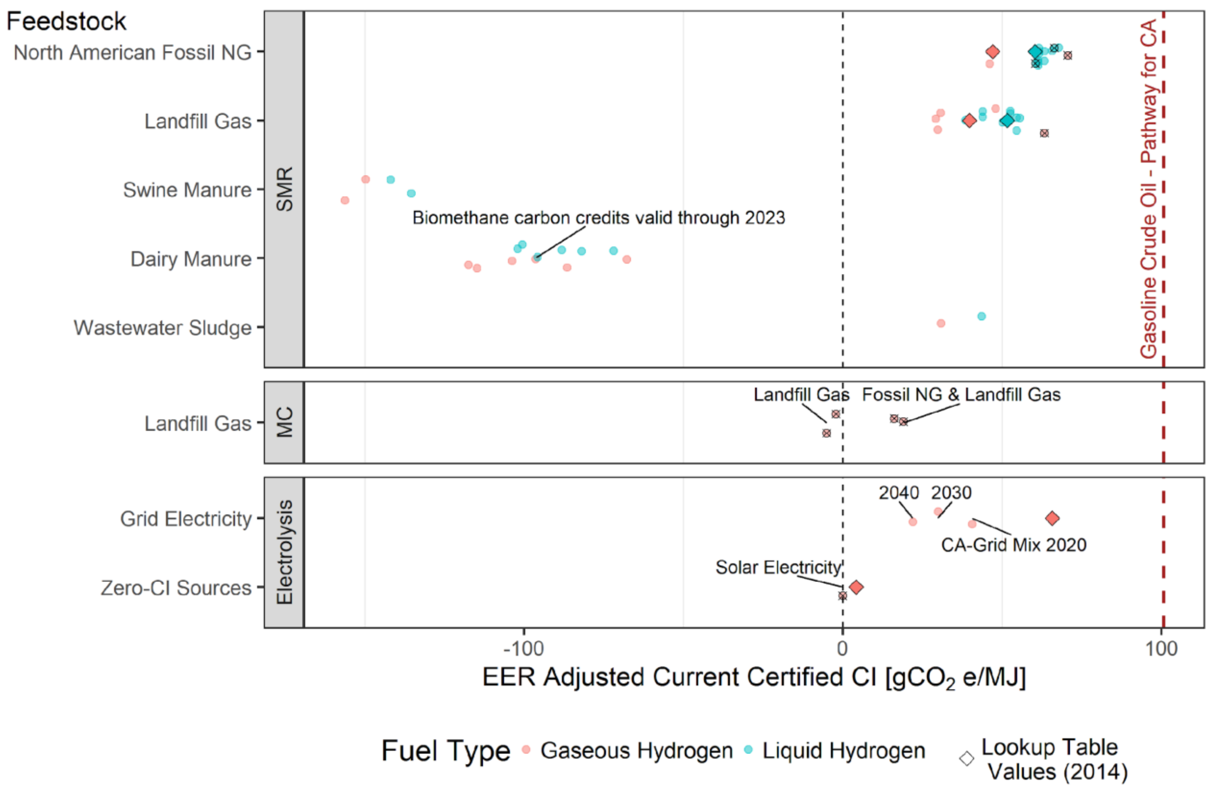
Carbon Intensity of LCFS Pathways for Hydrogen Production

The CI of hydrogen pathways varies widely in the LCFS pathways, as in the GREET estimated pathways discussed above. In the LCFS calculations, the GHG emissions of these pathways vary not just by the overall process used to produce hydrogen, but by additional details including the feedstock used (e.g., natural gas, biogas, biomass, or electricity and water); how the feedstock is pre-processed (if needed); process efficiency that can be dependent on the scale and technology type; the transport distance from where hydrogen is produced to where it is used; and other factors such as the CI of any electricity used for hydrogen production and compression. Figure 9 shows a more nuanced view of CI scores for the main hydrogen production pathways, which vary between and within production types. All values shown in the figure were obtained from publicly available information provided by CARB.

The very low (negative) CI scores of some biogas pathways are especially noteworthy; however, the most accessible of these pathways are limited by feedstock availability. Also noteworthy is the projected reduction in CI for grid electrolysis from 2020 through 2040 based on California's commitments to a clean power grid. In turn, renewable electrolysis could be greatly expanded over time; however, water availability may be a concern in desert areas.

Some hydrogen production pathways have the lowest CI scores available of any fuel type. Pathways for producing hydrogen based on water electrolysis and the use of renewable electricity (mainly solar and wind) can have near-zero CI scores. Some biogas pathways can have negative CI scores—at least in the near term—because they receive carbon credits for preventing methane (a potent GHG emission) from otherwise being released directly into the atmosphere. However, other hydrogen production pathways deliver only modest CI reduction benefits. Pathways based on conventional SMR without CO_2 sequestration reduce CI scores by less than 50 percent relative to gasoline, especially when hydrogen is compressed and transported as a liquid.

Figure 9. CI Scores of Main Hydrogen Production Pathways as Used in Transportation Applications

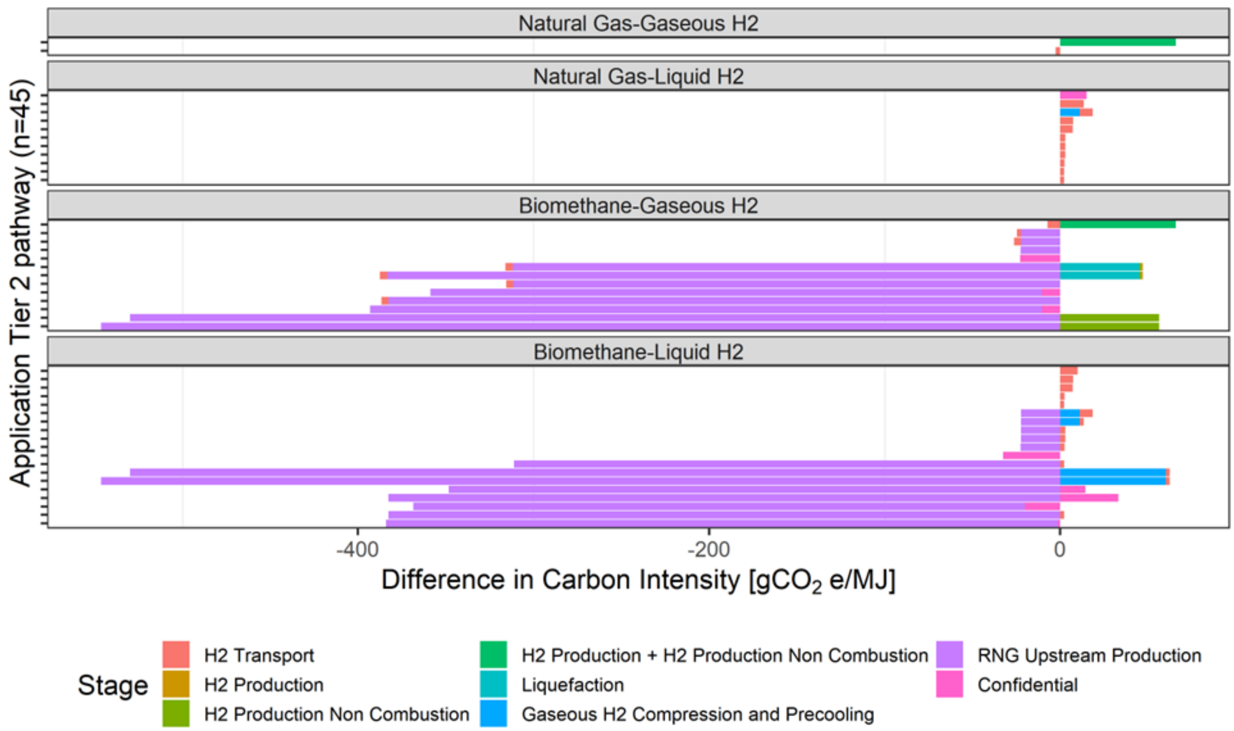


Source: Compiled by UC ITS from CARB June 2022 data.

Notes: EER is energy economy ratio (2.5x for light-duty and 1.9x for heavy-duty hydrogen vehicles); MC is methane cracking; NG is natural gas; SMR is steam methane reforming. Carbon intensity values are from: ww2.arb.ca.gov/es/resources/documents/lcfs-pathway-certified-carbon-intensities. Tier 2 pathways are newer fuel production pathways than the more well-established Tier 1 pathways in the LCFS program.

The research team also analyzed each application package of the Tier 2 pathways to retrieve more detailed information on the source of differences relative to the baseline Lookup Table values. These are presented in Figure 10 below. As shown, the manner in which renewable natural gas is produced can have a very large impact on overall CI, where other differences in production pathways relative to the standard lookup table values have a more subtle impact.

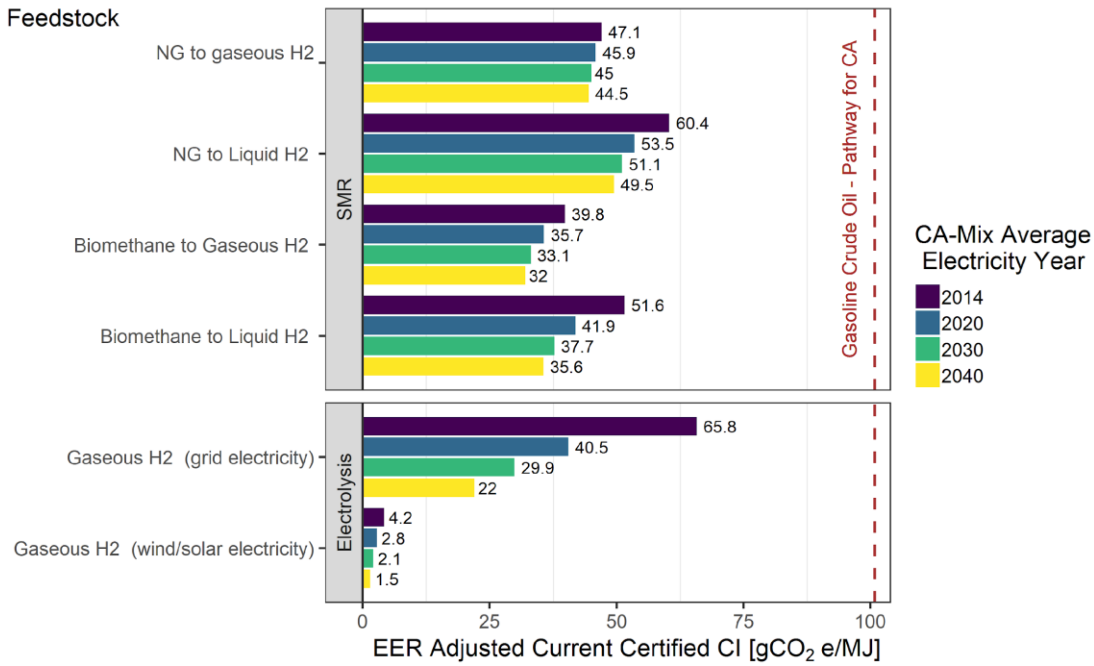
Figure 10. Difference In Carbon Intensity of 44 Tier 2 Pathways with Respect to Their Lookup Table Pathway Counterpart



Note: Each horizontal bar is an individual Tier 2 application.
Source: Individual applications are available at CARB LCFS Pathways Applications (CARB 2022d).

Over time, hydrogen produced from grid-based electrolysis will get even cleaner. The CI of hydrogen produced from grid-based electrolysis will drop because California law (Senate Bill 100, DeLeón) requires the state's electricity grid to steadily reduce emissions and reach carbon neutrality by 2045. Figure 11 shows the CI scores for the primary hydrogen production methods based on specific assumptions for each pathway and the impact that the production year has on those scores. Similar to the GREET pathway analysis shown above, improvements in the California grid over time will reduce the CI of all pathways, especially for grid-based electrolysis.

Figure 11. Hydrogen Production Pathway CI Values with Evolution of California Grid



Note: H2 = hydrogen; NG = natural gas; SMR = steam methane reforming

Source: Compiled by UC ITS from CARB June 2022 data.

Hydrogen for Transportation Applications and Energy Economy Ratio Adjustments

In addition to determining the CI from energy added to a vehicle (gasoline, other liquid fuel, electricity, natural gas, hydrogen, etc.) the LCA requires an additional step, namely estimating how much energy is needed to supply power to the wheels through the vehicle's combustion engine or electric motor, which depending on its technology and design, can be better or worse at converting a unit of input energy to mechanical power that drives the wheels, and this therefore necessitates an estimate of that conversion efficiency.

In the LCFS program, the conversion efficiency is called the Energy Economy Ratio (EER). Since electric drivetrains are more efficient than combustion engine drivetrains, the EER for battery electric, hybrid electric, and hydrogen fuel cell vehicles will be greater than 1, where 1 is the baseline gasoline vehicle EER. For hydrogen fuel cell vehicles, the EERs have been estimated to be 2.5 for light-duty vehicles and 1.9 for heavy-duty vehicles, as noted in Figure 6 above. This means that on a per energy unit basis, a hydrogen-powered vehicle will cover between 1.5 to 2.5 times the distance of an internal combustion vehicle. This energy performance makes hydrogen vehicle drivetrains enticing, especially for heavy-duty vehicles such as trucks and trailer rigs, and trains, that lose efficiency with heavy loads. These larger vehicles also have additional space to carry the high volume of hydrogen needed.

The EER adjustment is critical for transportation applications. Analyzing the CI of hydrogen production relative to other transportation fuels does not tell the full story without the EER adjustment. Hydrogen fuel cell vehicles can typically go at least twice as far on a unit of energy as their gasoline and diesel fuel counterparts. The EER adjustment is critical, therefore, for an apples-to-apples comparison.

Review of U.S. and International Studies for Renewable Hydrogen Production

To provide context on life cycle assessment studies in hydrogen production we surveyed the literature to see how academic studies and other standardized methods compare to the pathways presented in the LCFS and the CA GREET model. Many submissions to LCFS certification rely on the Lookup Table pathways that provide a template LCA for hydrogen production. This means they are not finely tuned to a specific set of parameters in use by the submitter. This varies from academic studies that, while not having data sourced directly from companies, often explicitly model the inputs around material production, plant operation, and end-of-life based on specific regional considerations (Bareiß et al. 2019; Terlouw et al. 2022).

These differences stem from the primary difference in system boundaries being used for GREET Lookup Table pathways and specialized models. Literature on the environmental impact of hydrogen production focuses most often on well-to-gate systems, neglecting the distribution component of the fuel because the main interest up to this point has been how to effectively produce low-carbon hydrogen. The GREET pathways are evaluated at a well-to-wheels level to determine the carbon intensity of the fuel up to the point of use.

In many of the studies reviewed for this report, we note that it is common to include impacts from the production of the electrolysis stack or solar panels such that even wind and solar energy used for water electrolysis contribute some degree of carbon emissions to the overall process (Schropp et al. 2022; Zhao et al. 2020). This is in addition to the emissions associated with hydrogen production itself when grid electricity is used for various control systems at a production plant, even though renewable feedstocks like wind and solar are used in production. These values may be small in the context of the overall fuel production pathway emissions, but such discrepancies require being aware of the inconsistencies in units as well as system boundaries, as different studies may not be readily comparable.

In addition to the academic studies evaluating hydrogen production emissions, we also reviewed standardized modeling approaches for the carbon intensity of hydrogen beyond GREET and CA-GREET. The PRIMES (price-induced market equilibrium system) model developed by the European Commission (EC) stands out. PRIMES is a comprehensive model that incorporates micro-economic principles with behavioral modeling, and engineering with energy systems. The complex model produces outputs of energy supply and demand and prices, in addition to trade, emissions, costs, and investment. This relies on a robust network of sub-modules that address each of these components. Among these sub-modules is one that evaluates the supply chain of fuel production including hydrogen and estimates CO_2 emissions from combustion and process-related emissions, as well as atmospheric pollutants. It is this module that relates most closely to the life-cycle emissions determined by GREET.

The PRIMES model presents a similar approach to GREET concerning emissions as the emissions are assessed only for fuel combustion either at the point of use or in upstream processes. Scope 3 (indirect) emissions from equipment manufacture are not included. We note that this model, published in 2018, is limited as the only hydrogen production pathway considered is water electrolysis from low-carbon or renewable electricity. Biomass pathways and more conventional means of hydrogen production are mentioned but not assessed in detail. Of relevance here is that in 2023 the EC drafted new regulations explicitly detailing production standards based on the principle of "additionality" and set emission calculation guidelines for renewable transport fuels (European Commission 2023a). Additionality refers to the need to develop new renewable resources to provide power for these types of facilities, versus drawing on (diverting) existing renewable facilities that are currently feeding the grid.

The EC regulation details methodology specifying the components to be evaluated in analyzing emissions, time frames for determining emissions, and how to allocate emissions for co-products from hydrogen production such as excess steam or biochar. While this differs in structure from both the PRIMES and GREET models mentioned above, it provides a framework for establishing robust emissions accounting for renewable fuels like hydrogen. The emission calculation specifically includes emissions from static and elastic (time varying) inputs in addition to emissions from processing (compressing or liquefying), transport and distribution, and combustion at the point-of-use (minus emissions from carbon capture and storage as applicable that do not apply to renewable hydrogen as directly implemented).

Electricity use as a feedstock is relevant to this calculation and, unlike GREET, there are special stipulations for attributing emissions to grid electricity that are not considered fully renewable according to European Union (EU) Directive 2018/2001. These stipulations require accounting for electricity under one of three methods: 1) using calculations provided in the appendix of the regulation; 2) attribution of emissions based on the full load hours of fuel operation; or 3) using the emission factor of the marginal electricity in the utility market region if available. The regulation also provides standardized values for use in the emissions calculation if proprietary information is not publicly available. This creates a standardized process for determining the carbon intensity of renewable fuels even if a localized tool such as GREET is not available. It thus serves as a unifying framework to enable the comparison of different production pathways so that companies in the EU can make informed investment decisions (European Commission 2023b).

Hydrogen Storage for End-Use Applications

Hydrogen storage is an issue being addressed at many levels depending on the end use of the hydrogen. The principal issue is that hydrogen is a very light gas that requires a large volume for containment under atmospheric conditions. The primary methods for reducing the space needed for containing hydrogen currently are compression and liquefaction. High-pressure conditions ranging from 5,000 to 10,000 psi (pounds per square inch) are required for compressed storage, while cryogenic cooling is required for liquified storage. Novel storage processes are being developed and include the storage of hydrogen as a gas inside porous materials, as well as chemically binding hydrogen in ammonia, methanol, and metal hydrides (Preuster et al. 2017).

The best storage mechanisms for hydrogen depend on the end use. This can include anything from how much space is available for storage—light-duty vehicles have less space for tanks than trucks and trains for example. In the case of chemical storage, hydrogen is stored as a liquid or solid which improves the size and stability of the storage needed. The challenge, however, comes from the need for hydrogen to be released from the compound which requires extra processing steps. With each technology comes additional economic implications, so the context for use is crucial (Andersson and Gronkvist 2019).

For use as fuel in on-road transportation, hydrogen is primarily stored as a compressed gas at 700 bar of pressure, and this involves storage in specially designed pressure vessels. Liquid and cryo-compressed storage are being evaluated now as potentially more cost-effective solutions due to lower cost tanks, and higher density hydrogen storage. The tradeoff, as shown in Figure 11 (above), is that liquid hydrogen will have a higher CI due to the additional energy inputs required in production compared to equivalent processes for gaseous hydrogen production. Aviation and maritime transportation may use alternative forms of hydrogen and therefore have different storage needs (Ayvali et al. 2021).

Jobs Creation and Training Aspects of the Emerging Hydrogen Economy

The UCLA Luskin Center for Innovation used economic input/output (I/O) modeling to estimate the job creation potential of hydrogen fueling station construction as part of this study. The analysis includes estimates of per-station job creation based on on-site hydrogen production technology, as well as figures for general construction and operations. The analysis relies on capital cost estimates to model job impacts for stations utilizing biomass-based production (with and without carbon capture) and varying types and scales of solar to hydrogen pathways. The analysis also includes breakdowns of the highest-growth occupations in each area, with a discussion of job quality metrics and equity implications.

For biomass-based hydrogen production using gasification technologies, the study uses capital cost estimates from Salkuyeh et al. (2018). For solar to hydrogen pathways, it considers the potential for medium and large-scale hydrogen production using an advanced solar photo-electrochemical hydrogen production pathway based on capital cost estimates in Pinaud et al. (2013). The analysis examines four different system designs (Types 1-4) and production scales of 1 and 10 metric tons of hydrogen per day.

High-level findings from the job creation analysis for hydrogen production were as follows:

- The job creation potential of *biomass* hydrogen production plants is very high, estimated at approximately 319 full-time equivalent jobs (FTEs) per facility without carbon capture. Integrating carbon capture technology into biomass hydrogen fueling stations increases labor needs significantly, to approximately 588 FTEs/station.
    - The key factor driving high modeled job creation estimates for biomass production facilities is very high capital costs—approximately $647 million and $852 million for stations without and with carbon capture, respectively.
- The labor impact of solar-hydrogen production is significantly lower than biomass, ranging from 3.37 FTEs/facility at the low end to approximately 272 FTEs/facility at the high end, varying by solar-hydrogen type and throughput across a range of 1-10 metric tons per day.
    - Due largely to lower capital costs and low (1.8%) local purchase percentage for reactor assembly—a large cost component—electrolysis facilities have notably lower labor impacts than biomass ones.
- Ongoing hydrogen fuel production is estimated to create between 30.9 and 99.5 FTEs annually, based on estimates of fuel throughput and varying by production facility type.
- When examining the most heavily represented industries among directly and indirectly created jobs, manufacturing jobs across various industries dominate the highest-growth occupations, both in ongoing production-related jobs and those associated with hydrogen production technology. High-

growth occupations are mixed in terms of job quality, though average wages in most areas are generally high.

Table 1. Job Creation Potential from Capital Expenditures of Biomass-Based Hydrogen Production Facilities

Biomass Facility Type	Per Facility Capital Expenditures	FTEs by Type			
		Total	Direct	Indirect	Induced
No carbon capture	$647 million	319.06	153.12	80.61	85.32
With carbon capture	$852 million	588.30	275.14	153.05	160.11

Table 2. Construction Job Creation from Solar-Hydrogen Production Facilities by Type and Size and Job Type

Electrolysis Station Type and Size	FTEs by Type			
	Total	Direct	Indirect	Induced
Type 1 – 1 MT	3.37	2.11	0.45	0.81
Type 2 – 1 MT	5.33	3.33	0.71	1.28
Type 3 – 1 MT	30.19	18.88	4.03	7.28
Type 4 – 1 MT	10.87	6.80	1.45	2.62
Type 1 – 10 MT	10.73	6.71	1.43	2.59
Type 2 – 10 MT	33.29	20.82	4.44	8.03
Type 3 – 10 MT	272.14	170.22	36.29	65.64
Type 4 – 10 MT	103.22	64.56	13.76	24.90

Note: MT is metric tons per day of hydrogen production

Background and Limitations

The job creation estimates in this study were created using economic input/output (IO) modeling. I/O models map the interrelationships among different industrial sectors, allowing users to track how the effects of money spent in one area stimulate activity throughout the supply chain and the economy as a whole. For instance, capital expenditures for hardware for a hydrogen production and fueling station support jobs directly involved in the manufacturing of that hardware, but also support jobs in the supply chain for that hardware (e.g., sub-component manufacturing, raw material extraction and refining). The model also estimates generalized job creation benefits across the broader economy—jobs involved in the provision of the various goods and services on which workers spend money. The model outputs are thus categorized into three types of jobs:

- *Direct jobs* are created in the immediate industry of interest (e.g., hydrogen production plant hardware manufacturing workers).
- *Indirect jobs* are created in supporting industries throughout the supply chain (e.g., refined metals workers).
- *Induced jobs* are miscellaneous positions throughout the economy supported by the expenditures of workers filling direct and indirect jobs (e.g., healthcare workers, grocery store personnel, barbers, etc.).

The model provides outputs in the form of FTEs with one FTE being equivalent to the labor activity of one worker employed full time for one year. That does not necessarily mean that every FTE takes that form; one FTE could represent two workers employed full time for six months, one worker employed at half time for two years, or any other combinations.

Some fundamental limitations of I/O models, that should be taken into account when interpreting these results, include:

- *Static relationships*: The inter-industry relationships used by the model are a snapshot of a point in time. This analysis utilized the IMPLAN software 2022 California State Total data package. The model outputs therefore reflect 2022 conditions and do not account for changes in economic conditions that may occur over time (for instance, between the time of analysis and the construction of a hydrogen production facility).
- *Linear scaling*: The model assumed that expenditures in a given sector create jobs using a constant relationship of money to jobs, not taking into account any variation caused by fixed labor needs or economies of scale. Spending $10 million on fabricated metals, for instance, will produce exactly 10 times the labor impacts as spending $1 million on fabricated metals.
- *Impact Timing*: The model aggregated job creation regardless of when each job will be created. In other words, the job creation potential attributed to a given station type will not necessarily be realized by the time the station is completed. While some jobs will inherently be created at the time of construction (such as those directly involved in construction), others will require time for the stimulating effects of station construction to ripple throughout the economy.
- *Granularity*: I/O models are best suited to high-level, macroeconomic analysis. As the scale of economic activities under study decreases, the uncertainty of results increases. This is true, in part, due to the

relative effects of linear scaling (see above) increasing. It is also especially important when examining job creation at the industry level. Model outputs can be broken down to identify industries where job growth is expected to be highest, but even these are still high-level jobs, with a variety of different worker types within them. The smaller the scale, the greater the likelihood that real-world conditions will noticeably vary from the generic industry jobs profile, creating greater uncertainty when attempting to characterize job quality for created jobs.

Methods

I/O modeling relies on translating expenditures, in dollars, to jobs based on the industry or industries in which money is spent and the model's internal calculations on how many jobs are created. Job creation figures vary, in large part, based on the labor intensity of a given sector—that is, how many jobs (in FTEs) are created for a given expenditure. Labor intensity varies based on the inner workings of the industrial sector. Wages can also affect results. All other factors equal, equivalent spending in two different sectors would create more jobs in the one where average worker wages are lower.

This analysis begins with capital cost estimates by station type, broken down by the material and hardware components necessary for station construction. These cost estimates do not account for construction labor costs, which vary significantly depending on geographic location, geological conditions, proximity to and state of supporting infrastructure, and other factors. For this reason, the study uses a simplistic estimate of construction labor costs, assessing them as 30 percent of capital expenditure costs. In the case of biomass stations we also include lower construction cost estimates as the 30 percent estimate may be somewhat excessive given the high capital cost of these facilities.

Ongoing jobs from hydrogen fuel production from these renewable facilities are calculated under the assumption of 100 percent local production and based on reference figures (1 and 10 metric tons per day) for daily production of hydrogen. These were used to estimate the total annual value of produced hydrogen fuel, which was converted into numbers of jobs based on the U.S. national average for FTEs/$1 million of output for the industrial gas production industry. This means that ongoing job estimates may not reflect California-specific conditions, and that exactly how costs are incurred during the production phase may influence the actual labor impact. For instance, the results show slightly higher job creation potential for hydrogen production from biomass facilities using carbon capture versus those without carbon capture because per-kg costs are higher for the former. However, it is uncertain to what degree these costs are incurred for additional labor expenses.

To examine the types of jobs that will be created in greater detail, the Luskin Center used the model to break out job creation figures for the highest-growth direct and indirect jobs. We then used "bridging" data provided by IMPLAN to match industry designations to codes within the North American Industry Classification System (NAICS)—a system used to classify industries and businesses for economic analysis purposes, primarily by federal agencies. NAICS codes and industrial categories for the top five direct and indirect occupations are used to obtain estimates of worker wages, access to healthcare benefits, and unionization rates from the U.S.

Department of Labor's Bureau of Labor Statistics. These measures form the basis for a discussion of job quality and potential policy choices that may impact California workers in these areas. Further details of this job creation analysis are provided in Appendix A.

Recommendations and Conclusions

As work to develop the hydrogen economy continues, there are many issues to consider. These include the prominent environmental impact issues considered here, as well as additional technical, economic, and social justice aspects related to the development of hydrogen production, transport/storage, and end-use projects.

Concerning GHG emissions and broader environmental aspects, renewable hydrogen production relies on abundant feedstock availability, which presently includes water and biomass (along with process electricity), as well as specialized materials required for electrolyzer stacks. Scaling up to meet the desired demand for hydrogen vehicles and industry use (including ammonia use for agriculture) requires close monitoring and allocation of resources. Water is a scarce resource under the current conditions, and while research is showing promising developments for seawater electrolysis (Loomba et al. 2023), commercially available technologies rely on desalinated, deionized water. Meanwhile, biomass resources are abundant in California but consist of many different types and are broadly distributed, with more located in remote areas of the state away from areas where the demand for hydrogen is highest. This raises issues of how to collect and process feedstocks in an efficient and economically advantageous manner, as well as challenges delivering hydrogen fuel products to end users.

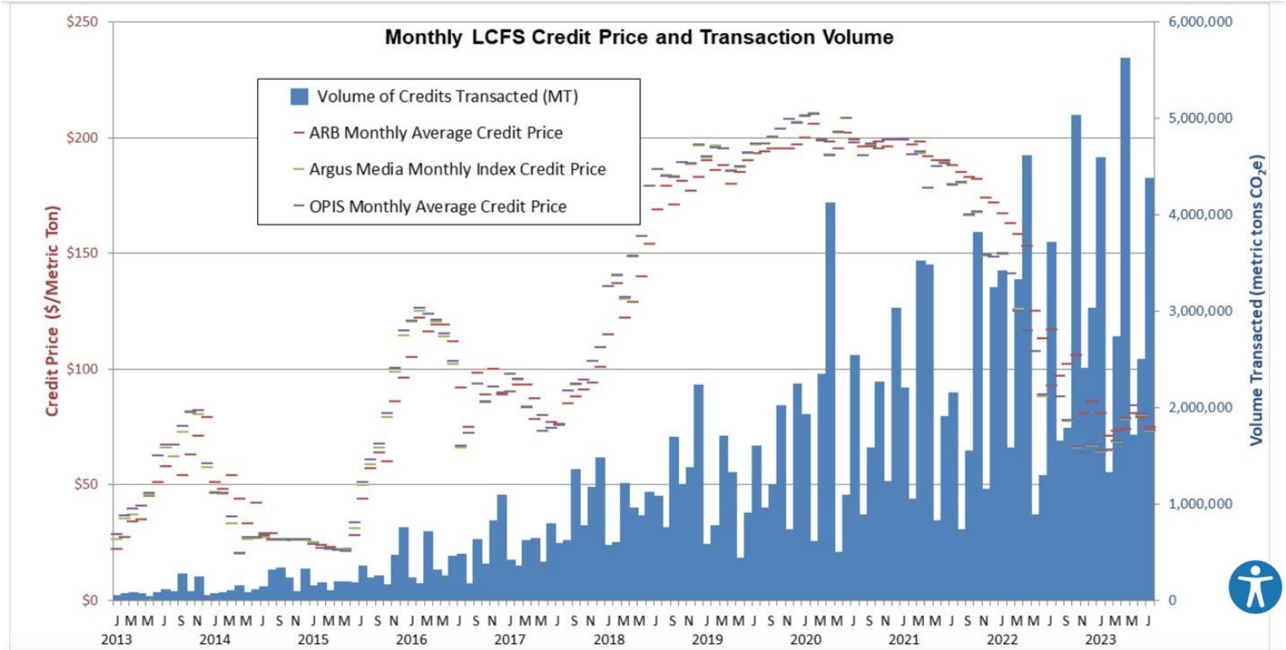
There is reason to believe that the cost of hydrogen production may be reduced by marketing secondary products created in the manufacture of hydrogen. . One example of this is presented by Wu et al. (2016) where the residues from waste plastics used to produce hydrogen through pyrolysis, formed carbon nanotubes could be produced and sold. Furthermore, aligning economic and environmental considerations may provide a pathway for lower-cost hydrogen production in the market. This can be done through the use of such coproducts and government incentives such as the Production Tax Credit from the Inflation Reduction Act. Future research may include developing methods to align economic and environmental considerations in hydrogen production pathways, as well as evaluating air quality impacts as well as GHG emissions.

Based on the results of our study of the full life-cycle costs of hydrogen as a transportation fuel, we provide the following recommendations. First, we recommend that “green” hydrogen be defined to including low CI biomass-based hydrogen production pathways along with the widely accepted method of producing hydrogen though the electrolysis of water using renewable sources of electricity. As discussed above these pathways can have very low (0 or lower) CI values. Biomass/biogas production plants may cause local emissions of air pollutants depending on their type, but these can be tightly controlled through appropriately specified regulations.

Second, we recommend that federal and state credit programs be combined or “stacked” where appropriate to encourage the cleanest and lowest CI sources of production. This includes, for example, combining credits from the state LCFS with the latest federal production tax credit (PTC). The final PTC guidelines for meeting specified levels of carbon emissions have not yet been issued, however the proposed PTC value of $3 per kilogram for achieving the lowest level of life cycle emissions of 0.45 kg of CO2-equivalents per kilogram of hydrogen produced is a potential “game changer” in the market for very low CI hydrogen.

Third, we recommend that CARB consider setting stricter LCFS goals to increase credit values and stimulate the production of the lowest CI transportation fuels. A significant amount of renewable diesel fuel has been produced for the California market in recent years, generating a large number of credits and depressing the credit prices in the market. As shown in Figure 12 below, credit prices dropped from the $180-200 level from 2018 through mid-2021 to about $75 per credit in recent months. This has undermined the economics of hydrogen and other clean fuels, reducing producer interest as well as consumer interest in hydrogen fuel cell vehicles.

Figure 12. Low Carbon Fuel Standard Credit Prices and Volumes - 2013-2023



Fourth, concerning regulations requiring hydrogen production through renewable electrolysis, we recommend that the state allow excess (curtailed) solar and wind power to count towards any “additionality” requirements. In the long term, as the California grid becomes more fully decarbonized, we believe that any additionality requirements should no longer be necessary, and the electricity needs for hydrogen production plants can figure directly into utility integrated resource planning.

In conclusion, careful tracking of the environmental impacts of hydrogen production and use will continue to be important for both policy/regulatory purposes such as in LCFS and PTC programs, as well as for broader analysis around state climate and other environmental goals. California was recently awarded funding for a “Hydrogen Hub” project for the U.S. Department of Energy (DOE) under a consortium called the Alliance for

Renewable and Clean Hydrogen Energy Systems (ARCHES). This program is intended to dramatically increase the production and use of hydrogen in California for various end uses including transportation, with a focus on very low CI and renewable hydrogen production systems. This will necessitate considerable analysis to measure and verify the performance of these systems relative to DOE goals and targets, taking into consideration many of the aspects discussed in this report.

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Appendix A: Further Details of Hydrogen Production Pathways Labor Analysis

Additional details of the hydrogen production pathway labor analysis are provided below, including the full set of job creation results.

Model Results

We estimate that capital expenditures for a single biomass-based hydrogen production facility as described above will generate approximately 319 FTEs without carbon capture integration, or approximately 588 FTEs with carbon capture (Table A-1). Direct jobs account for nearly half of the FTEs generated in both cases, with the remainder divided almost evenly between indirect and induced jobs.

Table A-1: Job Creation Potential of Capital Expenditures from Biomass-Based Hydrogen Production Facilities

Biomass Facility Type	Per Facility Capital Expenditures	FTEs by Type			
		Total	Direct	Indirect	Induced
No carbon capture	$647 million	319.06	153.12	80.61	85.32
With carbon capture	$852 million	588.30	275.14	153.05	160.11

Modeled estimates of construction labor jobs created from biomass-based stations are anomalously high, driven (as discussed above) by the methodological link between capital expenditures and rough construction labor cost estimates. Thus, we include alternative estimates that assume lower construction labor costs as a percentage of capital expenditures that are, in our judgment, more reasonable. Unfortunately, more accurate evaluations of construction labor impacts would require accounting for numerous factors that vary based on individual station construction sites and more complex methods that are beyond the scope of this study.

Based on estimates of construction labor costs, we calculate FTEs based on labor intensity coefficients for direct, indirect, and induced jobs from the IMPLAN model (see Table A-3). These figures are identical for construction labor used for both biomass and electrolysis production stations.

Table A-2: Labor Intensity Coefficients for Construction Labor by Job Type, FTEs/$1 Million

Total	Direct	Indirect	Induced
10.50	6.57	1.40	2.53

Table A-3: Construction Job Creation from Biomass-Based Hydrogen Production Stations by Job Type and Labor as a Percentage of Capital Expenditure Scenario

Labor Cost (% of capital cost)	Biomass Station Type	FTEs by Type			
		Total	Direct	Indirect	Induced
30%	No carbon capture	2,038.83	1,275.21	271.86	491.76
	With carbon capture	2,684.82	1,679.25	357.99	647.57
10%	No carbon capture	679.61	425.07	90.62	163.92
	With carbon capture	894.94	559.75	119.33	215.86
5%	No carbon capture	339.80	212.53	45.31	81.96
	With carbon capture	447.47	279.88	59.67	107.93

We model annual ongoing FTEs associated with hydrogen fuel production from biomass stations based on an assumed daily production of 18,900 kg with 100 percent uptime (see Table A-4).

Table A-4: Ongoing Jobs from Biomass-Based Hydrogen Fuel Production Per Station

Biomass Station Type	Production Cost	Annual H_2 Production Value	FTEs/Year by Type			
			Total	Direct	Indirect	Induced
No carbon capture	$3.10/kg	$21.38 M	57.42	15.86	23.85	17.72
With carbon capture	$3.44/kg	$23.74 M	63.74	17.60	26.47	19.67

With respect to electrolysis systems, we estimate that capital expenditures for the construction of a single site will generate between 0.55 FTEs and 4.26 FTEs, a significantly lower figure than biomass-based sites. As iterated in the key findings above, a key driving factor in these results is the fact that reactor assembly makes up a large portion of capital expenditures. This area has a small impact on in-state employment, with a local purchase percentage figure of 1.8 percent. Job creation potential varies by production facility type and size (see Table A-5). Four types of reference solar energy to hydrogen systems are assessed of varying types and sizes. These are not specific commercial systems but rather reference future medium and large-scale photo-electrochemical type systems based on analysis conducted in Pinaud, et al. (2013).

Table A-5: Job Creation Potential of Capital Expenditures on Solar-Hydrogen Production Stations Per Station

Electrolysis Station Type and Size	Per Facility Capital Expenditures	FTEs by Type			
		Total	Direct	Indirect	Induced
Type 1 – 1 MT	$1,070,484	1.26	0.56	0.35	0.36
Type 2 – 1 MT	$1,690,414	0.94	0.42	0.26	0.27
Type 3 – 1 MT	$9,580,545	2.58	1.20	0.67	0.71
Type 4 – 1 MT	$3,448,754	0.55	0.26	0.14	0.15
Type 1 – 10 MT	$3,406,105	1.46	0.66	0.39	0.41
Type 2 – 10 MT	$10,563,671	3.26	1.39	0.90	0.96
Type 3 – 10 MT	$86,361,841	4.26	1.91	1.14	1.21
Type 4 – 10 MT	$32,756,436	3.50	1.76	0.83	0.91

As aforementioned, construction labor costs for electrolysis systems are estimated at roughly 30 percent of capital expenditures, with construction jobs calculated therefrom. Expectedly, larger facilities and particular types (especially Types 3 and 4) are predicted to generate more construction jobs. This may vary from real-world conditions depending on exactly to what degree capital costs translate to increased construction labor costs and how those labor costs are incurred (e.g., what types of workers).

As with biomass-based stations, ongoing hydrogen production jobs are estimated using national industry standards based on output value. We assume a daily output of 50,000 kg with 100 percent uptime, providing job estimates by electrolysis facility type (see Tables A-6 and A-7).

Table A-6: Construction Job Creation from Solar-Hydrogen Production Facilities by Type, Size, and Job Type

Electrolysis Station Type and Size	FTEs by Type			
	Total	Direct	Indirect	Induced
Type 1 – 1 MT	3.37	2.11	0.45	0.81
Type 2 – 1 MT	5.33	3.33	0.71	1.28
Type 3 – 1 MT	30.19	18.88	4.03	7.28
Type 4 – 1 MT	10.87	6.80	1.45	2.62
Type 1 – 10 MT	10.73	6.71	1.43	2.59
Type 2 – 10 MT	33.29	20.82	4.44	8.03
Type 3 – 10 MT	272.14	170.22	36.29	65.64
Type 4 – 10 MT	103.22	64.56	13.76	24.90

Table A-7: Ongoing Jobs from Electrolysis Hydrogen Fuel Production Per Facility and by Type

Electrolysis Station Type	Production Cost	Annual H_2 Production Value	FTEs/Year by Type			
			Total	Direct	Indirect	Induced
Type 1	$0.63/kg	$11.50 M	30.87	8.52	12.82	9.53
Type 2	$0.93/kg	$16.97 M	45.57	12.58	18.93	14.07
Type 3	$2.03/kg	$37.05 M	99.48	27.47	41.31	30.70
Type 4	$1.19/kg	$21.72 M	58.32	16.10	24.22	18.00

To provide further detail on the types of jobs that will be created through hydrogen production facility construction and operation, we identified the five direct and indirect industries in which modeled growth was the highest for capital expenditures, construction, and operation. While there is some variation across station types, certain industries (e.g., valve and fittings manufacturing) are consistently heavily represented among those linked to capital expenditures. Directly created jobs in this space are dominated by manufacturing sectors, while indirect jobs tend more towards administrative and sales jobs, along with positions related to transportation and machine shops.

Direct jobs consistently account for greater growth than indirect jobs, and the highest-growth occupations typically see at least an order of magnitude greater growth than the fourth- or fifth-highest growth occupations. See Tables A-8 through A-11 for a full breakdown.

We do not provide separate industry-level growth figures for different facility sizes. Because of the previously mentioned model linearity, relative job growth among different industries would remain the same across different-sized stations of the same type. Only the magnitude of jobs generated per station would fluctuate in the model results.

Jobs related to construction and operation of stations are a simpler picture, the former represented by a single industry (an IMPLAN-specific categorization, “Construction of new manufacturing structures”) and the latter with only two manufacturing industries in play (see Table A-10).

Table A-8: Top 5 Direct and Indirect Growth Occupations from Biomass-Based Hydrogen Production Facility Capital Expenditures

Station Type	IMPLAN Occupation	NAICS Code	FTEs/Station
	Direct		
No carbon capture	1. Valve and fittings, other than plumbing, manufacturing	3329	66.95

Station Type	IMPLAN Occupation	NAICS Code	FTEs/Station
	2. Metal tank (heavy gauge) manufacturing	332420	62.12
	3. Power boiler and heat exchanger manufacturing	332410	14.73
	4. Other fabricated metal manufacturing	332999	1.29
	5. Sheet metal work manufacturing	332322	1.28
	Indirect		
	1. Wholesale – Other durable goods merchant wholesalers	423	7.82
	2. Employment services	5613	6.50
	3. Truck transportation	484	3.81
	4. Management of companies and enterprises	55111	3.58
	5. Machine shops	332710	3.12
	Direct		
With carbon capture	1. Valve and fittings, other than plumbing, manufacturing	3329	167.48
	2. Metal tank (heavy gauge) manufacturing	332420	77.19
	3. Power boiler and heat exchanger manufacturing	332410	14.91
	4. Industrial process variable instruments manufacturing	334513	2.68
	5. Fluid power pump and motor manufacturing	333996	1.60
	Indirect		
	1. Wholesale – Other durable goods merchant wholesalers	423	14.90
	2. Employment services	5613	12.16
	3. Truck transportation	484	7.07
	4. Management of companies and enterprises	55111	6.71
	5. Machine shops	332710	6.03

Table A-9: Top 5 Direct and Indirect Growth Occupations from 10 MT Solar-Hydrogen Production Facility Capital Expenditures by Type

Station Type	IMPLAN Occupation	NAICS Code	FTEs/Station
	Direct		
Type 1	1. Valve and fittings, other than plumbing, manufacturing	33291	0.48
	2. Power boiler and heat exchanger manufacturing	332410	0.10
	3. Industrial process variable instruments manufacturing	334513	0.05
	4. Metal tank (heavy gauge) manufacturing	332420	0.008
	5. Fluid power pump and motor manufacturing	333996	0.005
	Indirect		
	1. Wholesale – Other durable goods merchant wholesalers	423	0.036
	2. Employment services	5613	0.027
	3. Management of companies and enterprises	55111	0.020
	4. Machine shops	332710	0.018
	5. Truck transportation	484	0.017
	Direct		
Type 2	1. Industrial process variable instruments manufacturing	334513	1.03
	2. Valve and fittings, other than plumbing, manufacturing	33291	0.26
	3. Power boiler and heat exchanger manufacturing	332410	0.04
	4. Electricity and signal testing instruments manufacturing	334515	0.020
	5. Analytical laboratory instrument manufacturing	334516	0.017
	Indirect		
	1. Management of companies and enterprises	55111	0.131
	2. Custom computer programming services	541511	0.104

Station Type	IMPLAN Occupation	NAICS Code	FTEs/Station
	3. Warehousing and storage	4931	0.053
	4. Employment services	5613	0.044
	5. Machine shops	332710	0.035
	Direct		
Type 3	1. Industrial process variable instruments manufacturing	334513	0.75
	2. Valve and fittings, other than plumbing, manufacturing	33291	0.65
	3. Power boiler and heat exchanger manufacturing	332410	0.38
	4. Metal tank (heavy gauge) manufacturing	332420	0.030
	5. Heating equipment (except warm air furnaces) manufacturing	333414	0.014
	Indirect		
	1. Management of companies and enterprises	55111	0.118
	2. Custom computer programming services	541511	0.081
	3. Wholesale – Other durable goods merchant wholesalers	423	0.071
	4. Employment services	5613	0.044
	5. Machine shops	332710	0.035
	Direct		
Type 4	1. Power boiler and heat exchanger manufacturing	332410	1.44
	2. Metal tank (heavy gauge) manufacturing	332420	0.11
	3. Industrial process variable instruments manufacturing	334513	0.065
	4. Heating equipment (except warm air furnaces) manufacturing	333414	0.054
	5. Crown and closure manufacturing and metal stamping	332119	0.026
	Indirect		
	1. Wholesale – Other durable goods merchant wholesalers	423	0.078
	2. Machine shops	332710	0.061

Station Type	IMPLAN Occupation	NAICS Code	FTEs/Station
	3. Management of companies and enterprises	55111	0.048
	4. Truck transportation	484	0.043
	5. Employment services	5613	0.034

Table A-10: Top 5 Direct and Indirect Growth Occupations from Hydrogen Production Facility Construction Labor

IMPLAN Occupation	NAICS Code	FTEs/$1 million
Direct		
1. Construction of new manufacturing structures	N/A*	6.57
Indirect		
1. Truck transportation	484	0.098
2. Wholesale – Other durable goods merchant wholesalers	423	0.091
3. Employment services	5613	0.089
4. Other real estate	531	0.073
5. Wholesale – Machinery, equipment, and supplies	4238	0.064

* These occupational areas are customized, specific to IMPLAN, without a directly matched NAICS code.

Table A-11: Top 5 Direct and Indirect Growth Occupations from Ongoing Hydrogen Production

IMPLAN Occupation	NAICS Code	FTEs/$1 million
Direct		
1. Industrial gas manufacturing	325120	0.716
2. Plastics material and resin manufacturing	325211	0.013
Indirect		
1. Management of companies and enterprises	55111	0.110
2. Services to buildings	5617	0.066
3. Employment services	5613	0.057
4. Truck transportation	484	0.057
5. Wholesale – Other nondurable goods merchant wholesalers	424	0.049

Job Quality and Equity Implications

The aim of this analysis is to characterize the most impactful types of jobs using salient metrics of quality, such that policymakers can anticipate areas where state action should be taken to support worker-friendly environments, healthy wages, and quality benefits in newly created green jobs. Understanding job quality in these areas will help policymakers anticipate the fiscal and security benefits of hydrogen fueling station construction for the California workers building and operating them, and how policy action can proactively address shortcomings. To assess job quality, we examine the occupations with the most FTEs generated on a per-station or per one million dollars basis. We do not exhaustively examine all affected occupations and do not delve deeply into the many other measures of job quality that exist. We recommend this area be considered in future research, along with factors such as transferability of skills from fossil gas workers to the nascent hydrogen industry.

Among the high-growth occupations identified above, we prioritized occupations among the top 5 for biomass-based facilities, given the greater per-station job potential modeled resulting from larger capital expenditures. Many of these overlap with occupations related to electrolysis stations, making them occupations of interest. We also include some of the consistently represented indirect jobs and the highest-growth direct occupations related to construction and operation of stations. Therefore, occupations considered for job quality analysis are:

1. Valve and fittings, other than plumbing, manufacturing
2. Metal tank (heavy gauge) manufacturing
3. Power boiler and heat exchanger manufacturing
4. Wholesale−Other durable goods merchant wholesalers
5. Employment services
6. Truck transportation
7. Management of companies and enterprises
8. Machine shops
9. Industrial process variable instruments manufacturing
10. Construction of new manufacturing structures
11. Industrial gas manufacturing

We use three metrics to assess job quality for these occupations: annual wages, access to healthcare benefits, and portion of the workforce represented by a union. The data sources for each metric vary somewhat in terms of how accurately it describes the occupation of interest (as opposed to a more generic industry that includes the occupation) and recency:

- Annual wage data from the U.S. Bureau of Labor Statistics (BLS) quarterly census of employment and wages is accessed using the Employment and Wages Data Viewer.[4] We utilize 2022 annual averages for private sector industries for the NAICS code of interest. Results are filtered by California counties. We

[4] See https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=Tables.

calculate average annual wages per employee across all California counties for which data is provided, weighted by annual average employment for each county.

- Healthcare benefit access data is available at the industry level from the BLS National Compensation Survey: Employee Benefits in the United States, March 2022.[5] As indicated in the title, this is a national dataset, and therefore does not capture how conditions in California may vary from the national average. We utilize the figure for Access within Incidence of healthcare benefits for private industries within which the occupations of interest fall.
- Workforce percentage represented by a union data is taken from the BLS January 2023 economic news release, Table 3: Union affiliation of employed wage and salary workers by occupation and industry, 2021-2022 annual averages.[6] We use the 2022 percent of employed figure for workers represented by unions (as opposed to members of unions) for the occupation or industry within which our occupations of interest fall.

[5] See https://www.bls.gov/ebs/publications/september-2022-landing-page-employee-benefits-in-the-united-states-march-2022.htm.
[6] See https://www.bls.gov/news.release/union2.t03.htm.

Table A-12: Job Quality Metrics for 11 Highest-Growth Occupations

Occupation	NAICS Code	*California, NAICS-level*	*National, Industry/Occupation Group-Level*	
		Annual Wages	**Access to Healthcare Benefits**** (% of industry workers)	**Representation by Unions**** (% of employed)
Valve and fittings, other than plumbing, manufacturing	33291	$93,135	90%	8.9%
Metal tank (heavy gauge) manufacturing	332420	$77,406	90%	8.9%
Power boiler and heat exchanger manufacturing	332410	$80,168	90%	8.9%
Wholesale–Other durable goods merchant wholesalers	423	$103,695	89%	3.9%
Employment services	5613	$59,563	54%	9.5%
Truck transportation	484	$63,116	85%	15.5%
Management of companies and enterprises	55111	$158,662	96%	4.8%
Machine shops	332710	$67,808	90%	8.9%
Industrial process variable instruments manufacturing	334513	$99,378	90%	8.9%
Construction of new manufacturing structures	236210*	$113,003	75%	12.4%
Industrial gas manufacturing	325120	$120,417	90%	8.1%

*Because the IMPLAN occupation does not have a direct NAICS analogue, we utilize NAICS 236210: industrial building construction as an approximate match for calculating wage data.
**For clarification on which industries or occupations healthcare access and union representation data is derived from, see Appendix B.

As Table A-12 shows, the selected job quality metrics present a mixed picture of quality among the highest-growth occupations. Additionally, there are some important caveats to the information conveyed by these metrics, most notably that they are aggregate figures that do not accurately describe every type of worker within a NAICS code. For instance, production occupations within fabricated metal product manufacturing (which includes valve and fittings and metal tank manufacturing) make up a large portion of the workers (approximately 57% nationally) with wages substantially below the average ($46,110 versus an average of about $57,000 nationally), per the BLS Occupational Employment and Wage Statistics (OEWS) May 2022 dataset.[7]

This shortcoming is even more pronounced with the figures for access to healthcare benefits and representation by unions, as these are high-level industry figures (hence why many of the above percentages for these metrics are identical across various durable goods manufacturing industries). A more nuanced and detailed discussion of job quality would necessitate a much more in-depth analysis of worker data, which is beyond the scope of this study. However, we would encourage labor-focused research efforts in this area in the future.

These limitations aside, this first-step analysis shows that, on average, the highest-growth jobs related to hydrogen production stations generally pay well and have good access to benefits and unionization rates that, while low compared to many other developed economies, equal or exceed the prevailing national rate (6% for all industries in 2022, per Statista[8]). There are some notable exceptions to this characterization. Employment services, truck transportation, and machine shops all have significantly lower wages than other high-growth occupations, and employment services and construction workers' access to healthcare benefits are also low outliers. There are some occupations where unionization rates are noticeably lower than others, but these (Wholesale–Other durable goods merchant wholesalers and management of companies and enterprises) tend to be high-paying employment areas (both have California-weighted annual average wages above $100,000).

These data do not capture some relevant context and real-world conditions. For example, the analysis does not assess how generous those benefits are, nor what administrative or structural barriers may prevent workers from taking advantage of them. The data also does not reflect some elements of job quality, such as workplace safety or the prevalence of business practices that exploit workers (e.g., misclassification of workers and shunting of costs within the trucking industry).[9]

Comparing unionization rates among occupations of interest to the national rate is also overly simplistic, as it does not consider the decades-long decline of organized labor in the United States—a trend fomented, in large part, by government action empowering business over workers. The strength of organized labor in the U.S. currently lags behind many other developed nations. In 2019, the Organization for Economic Co-operation and Development (OECD) pegged trade union density in the U.S. at 9.9 percent, a figure on par with Turkey and

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[7] See https://www.bls.gov/oes/current/naics4_3320A1.htm.

[8] See https://www.statista.com/statistics/1376233/union-membership-rate-manufacturing-industry-us/.

[9] Murphy, Brett (2017). Retail giants enable trucker exploitation. *USA Today.* Accessed Sep 22, 2023. https://www.usatoday.com/pages/interactives/news/rigged-retail-giants-enable-trucker-exploitation/.

Lithuania and well behind nations such as the United Kingdom, Canada, Italy, and numerous Scandinavian nations.

Given the breadth and complexity of these issues, a point-by-point plan for ensuring job quality is beyond the scope of this study. As a general approach, we recommend that as policymakers take action to revivify organized labor and empower California workers in the green job economy they look to other countries for standards and best practices. Robust organized labor can be a vehicle for negotiating for better wages and benefits for workers while addressing complex, workplace-specific conditions and concerns. In particular, we recommend that any support through the use of state funds for hydrogen production station construction stipulate minimum standards for workers. Given that most of the forecasted job generation will occur through manufacturing of components, it will be important that these requirements extend to procurement, not just on-site construction, and ongoing operation.

Appendix B: Industry and Occupation Data Matching for Healthcare Benefit Access and Union Representation Figures

Table B-1: Healthcare Benefit and Union Representation Classifications

IMPLAN Occupation	Healthcare Benefit Access Classification*	Union Representation Classification**
Valve and fittings, other than plumbing, manufacturing	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Durable goods
Metal tank (heavy gauge) manufacturing	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Durable goods
Power boiler and heat exchanger manufacturing	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Durable goods
Wholesale – Other durable goods merchant wholesalers	Service-providing industries → Trade, transportation, and utilities → Wholesale trade	Nonagricultural industries → Wholesale and retail trade → Wholesale trade
Employment services	Service-providing industries → Professional and business services → Administrative and waste services	Sales and office occupations → Office and administrative support occupations
Truck transportation	Trade, transportation, and utilities → Transportation and warehousing	Nonagricultural industries → Transportation and utilities → Transportation and warehousing
Management of companies and enterprises	Management, professional, and related → Management, business, and financial	Management, professional, and related occupations → Management, business, and financial operations occupations → Management occupations
Machine shops	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Durable goods
Industrial process variable instruments manufacturing	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Durable goods
Construction of new manufacturing structures	Goods-producing industries → Construction	Nonagricultural industries → Construction
Industrial gas manufacturing	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Nondurable goods

*From BLS National Compensation Survey: Employee Benefits in the United States, March 2022. Private industry workers by industry group or occupational group.

**From BLS January 2023 economic news release, Table 3: Union affiliation of employed wage and salary workers by occupation and industry, 2021-2022 annual averages.