Renewable Hydrogen Roadmap

energy independence now

Mission

Energy Independence Now (EIN) is the only nonprofit organization dedicated to advancing fuel cell electric vehicles (FCEVs) and the hydrogen-fueling infrastructure required to catalyze a rapid transition to a clean energy and transportation economy. EIN engages in comprehensive research, strategic policy advocacy and public outreach to promote the widespread adoption of fuel cell electric vehicles and renewable hydrogen (RH_2) as a key part of a zero-emission transport future.

Philosophy

EIN believes that the urgency and massive scale of climate change, petroleum dependence and air-quality challenges warrant solutions that are immediate, diverse and far-reaching. EIN believes that any and all vehicle technologies and alternative fuels that hold the promise of addressing these challenges should be actively pursued. Our organization advocates for both the deployment of immediate, near-term solutions as well as longer-term solutions that will help us achieve California's climate and air quality goals.

Leadership

EXECUTIVE DIRECTOR - BRIAN GOLDSTEIN
DEPUTY DIRECTOR - JUSTO ROBLES

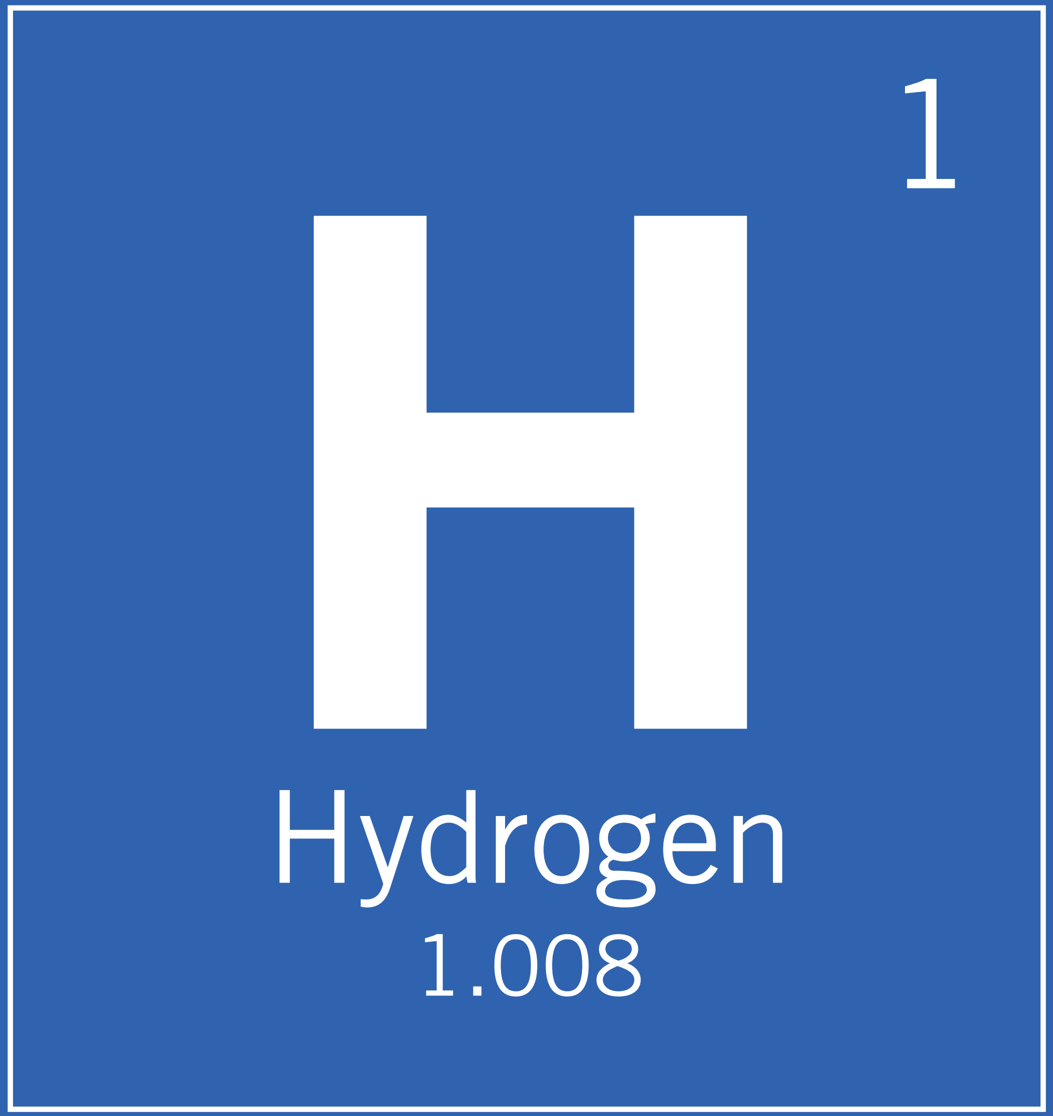
A SPECIAL THANKS TO THE

California Hydrogen Business Council

The California Hydrogen Business Council (CHBC) is comprised of over 100 companies, agencies and individuals involved in the business of hydrogen. Its mission is to advance the commercialization of hydrogen in the energy sector, including transportation, goods movement and stationary power systems to reduce emissions and dependence on oil. More information is available at www.californiahydrogen.org.

The vision of the CHBC is to reinforce California's position as the most advanced clean energy state in the US, expanding the sustainable use of its precious natural and renewable resources and providing clean air to its citizens, by adopting hydrogen and fuel cell technologies in transportation, power and goods movement markets.

EIN thanks the CHBC for helping to obtain sponsorship for this roadmap within its membership and for the support of its Renewable Hydrogen and Hydrogen Energy Storage Sector Action Groups as well as CHBC staff and members that reviewed drafts of this roadmap.



A SPECIAL THANKS TO THE

Leonardo DiCaprio Foundation

The Leonardo DiCaprio Foundation (LDF) is dedicated to the long-term health and wellbeing of all Earth's inhabitants. LDF supports projects around the world that build climate resiliency, protect vulnerable wildlife, and restore balance to threatened ecosystems and communities.

Through grant-making, public campaigns and media initiatives, LDF brings attention and needed funding to six program areas – Wildlands Conservation, Oceans Conservation, Climate Change, Indigenous Rights, Transforming California and Innovative Solutions.

EIN is grateful for the support of LDF, which has provided grant funding in support of EIN's ongoing research, advocacy and outreach to promote the widespread adoption of fuel cell electric vehicles and renewable hydrogen.

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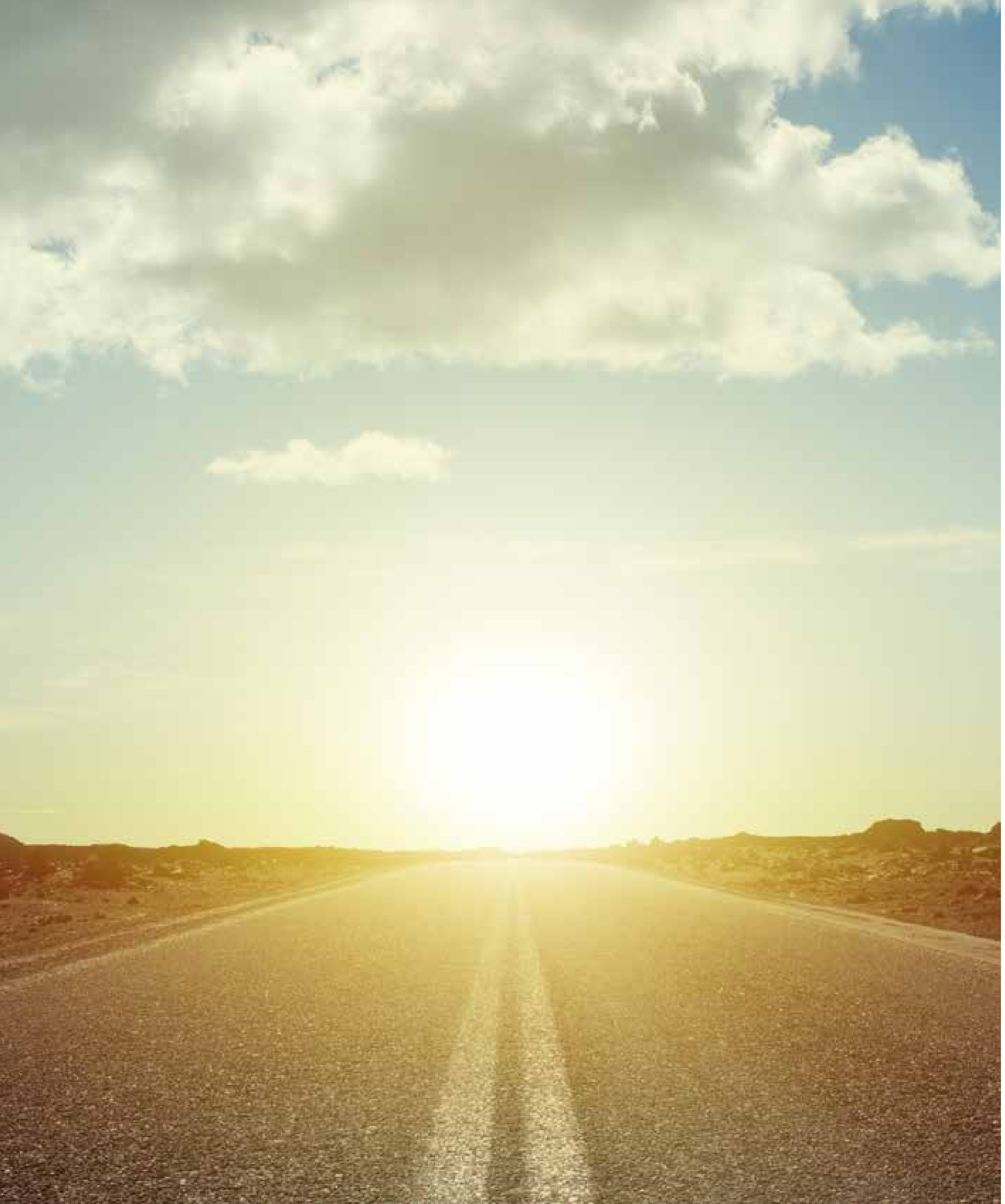
FOUNDATION



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Contents

Acronyms

ARFVTP	Alternative and Renewable Fuel Vehicle Technology Program
ARRA	American Recovery and Reinvestment Act
CARB	California Air Resources Board
CEC	California Energy Commission
CH_4	Chemical Formula for Methane
CHBC	California Hydrogen Business Council
CI	Carbon Intensity
CNG	Compressed Natural Gas
CO_2	Chemical Formula for Carbon Dioxide
CPUC	California Public Utilities Commission
CSD	Compression, Storage and Delivery
DME	Dimethyl Ether
DOE	Department of Energy
ECR	Enhanced Community Renewables
EIN	Energy Independence Now
EPA	Environmental Protection Agency
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions & Energy Use in Transportation
GTSR	Green Tariff Shared Renewables Program
H_2	Chemical Formula for Hydrogen
H2NIP	Hydrogen Network Investment Plan
H_2O	Chemical Formula for Water
HFI	Hydrogen Fuel Initiative
IGC	Industrial Gas Company
IOU	Investor-Owned Utility
LCFS	Low Carbon Fuel Standard
LDF	Leonardo DiCaprio Foundation
LFG	Landfill Gas
LMOP	Landfill Methane Outreach Program
LNG	Liquefied Natural Gas
MHE	Material Handling Equipment
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
PEM	Polymer Electrolyte Membrane
PEV	Plug-in Electric Vehicle
PPA	Power Purchase Agreement
PV	Photovoltaic
R&D	Research and Development
RH_2	Renewable Hydrogen
REC	Renewable Energy Certificate
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
RPS	Renewable Portfolio Standard
SCAQMD	South Coast Air Quality Management District
SMR	Steam Methane Reforming
TOU	Time-of-Use
WREGIS	Western Renewable Energy Generation Information System
WWTP	Wastewater Treatment Plant
ZEV	Zero-Emission Vehicle

Introduction to Hydrogen and Definition of Renewable Hydrogen (RH_2)

Hydrogen is the lightest, smallest and most abundant element in the universe. It naturally carries a very high amount of energy relative to its weight. Hydrogen is a necessary component for large-scale industrial processes such as oil refining and ammonia production but its use as a transportation fuel, industrial heating feedstock and storage medium for renewable electricity is growing.

Naturally-occurring, pure hydrogen readily combines with other elements to form molecules such as water (H_2O) or methane (CH_4). Hydrogen must therefore be isolated or "produced" by breaking the chemical bonds in the molecules that form these substances. While most hydrogen is currently produced from natural gas, it can also be produced without the carbon byproduct of fossil fuels.

It is this central theme of decarbonized or carbon-free hydrogen production that this paper will explore, primarily through the lens of California's zero-emission transportation goals and its Renewables Portfolio Standard. In that capacity, **renewable hydrogen can be defined as any hydrogen produced using renewable energy or electricity derived from renewable sources as defined and accepted by California policy.**[1]

Eligible renewable hydrogen energy sources in California currently include facilities using "biomass, solar thermal, photovoltaic, wind, geothermal, fuel cells using renewable fuels, small hydroelectric generation of 30 megawatts or less, digester gas, municipal solid waste conversion, landfill gas, ocean wave, ocean thermal, or tidal current, and any additions or enhancements to the facility using that technology."[2]

Executive Summary

Primarily using the lens of the transportation market in California, this roadmap identifies the opportunities and challenges for renewable hydrogen to provide zero-emission or even carbon-negative transportation fuel as well as critical energy storage for renewables. It considers the many aspects of the current hydrogen ecosystem and identifies the steps and policy decisions that are necessary to stimulate growth in the renewable hydrogen marketplace and clean energy economy.

As clean energy technologies achieve economies of scale and become universally accessible, constraints on sustainable energy production and storage are beginning to emerge. California experiences periods of high energy demand when renewables aren't available, as well as periods of substantial overproduction of renewable electricity. The latter scenario is already forcing the state to curtail renewables at unprecedented rates. These circumstances highlight the need for energy storage mediums that enable grid flexibility and allow consumers to utilize renewables on demand.

Hydrogen has the unique potential to connect the clean energy systems of the future by allowing storage of renewable energy that can be used to fuel transportation, generate heat for industrial processes and send electricity to the grid. California already leads the world in adopting hydrogen as an alternative fuel source for transportation and bipartisan leaders are committed to building 200 hydrogen fueling stations as part of the state's implementation of the "California Hydrogen Highway". California policymakers are collaborating with automakers to bring zero-emission Fuel Cell Electric Vehicles (FCEVs) to market and they have already adopted mandates requiring that 33.3% of the hydrogen used to fuel those vehicles at publicly funded stations must be produced from renewable sources.

Increasing the production of renewable hydrogen is necessary in order for California to achieve its current and emerging clean energy goals. SB 350, passed into law in 2015, already mandates 50% renewable energy by 2030 and Governor Brown has set a state goal of 5 million zero-emission vehicles (ZEVs) during the same time frame. In addition, the California Legislature is currently considering SB 100, which would establish an overall state target of 100% clean energy for California by 2045, while accelerating the interim benchmarks of 50% by 2026 and 60% by 2030. Due to the intermittent nature of wind and solar, the state simply cannot reach 100% renewable without energy storage. Similarly, due to the range, size and recharging limitations of battery electric vehicles, FCEVs are a necessary component of the state's ZEV goal.

Renewable hydrogen presents a near best-case scenario for clean energy storage and zero-emission transportation. Today in California and across the world, hydrogen is already produced at scale for industrial processes like oil refining and ammonia production. Industrial hydrogen is commonly produced through the reformation of natural gas but there are many ways to produce hydrogen renewably. This roadmap explores those that are currently most cost-effective and scalable – including production technologies and feedstocks.

The following series of eight high-priority recommendations for policymakers and stakeholders will help California catalyze the renewable hydrogen marketplace and achieve its ambitious economic and environmental goals:

1. **Begin the Journey to 100% Renewable Hydrogen Now**
2. **Fund Scalable Projects for 100% Renewable Hydrogen Production**
3. **Improve Low Carbon Fuel Standard (LCFS) Incentives**
4. **Promote Tools to Lower the Cost of Electricity for Renewable Hydrogen Producers**
5. **Address Hydrogen Distribution and Storage Challenges**
6. **Expand the US EPA's Renewable Fuel Standard (RFS) Program**
7. **Incentivize Consumers and Stakeholders**
8. **Broaden the Hydrogen Community Through Education & Outreach**

Introduction

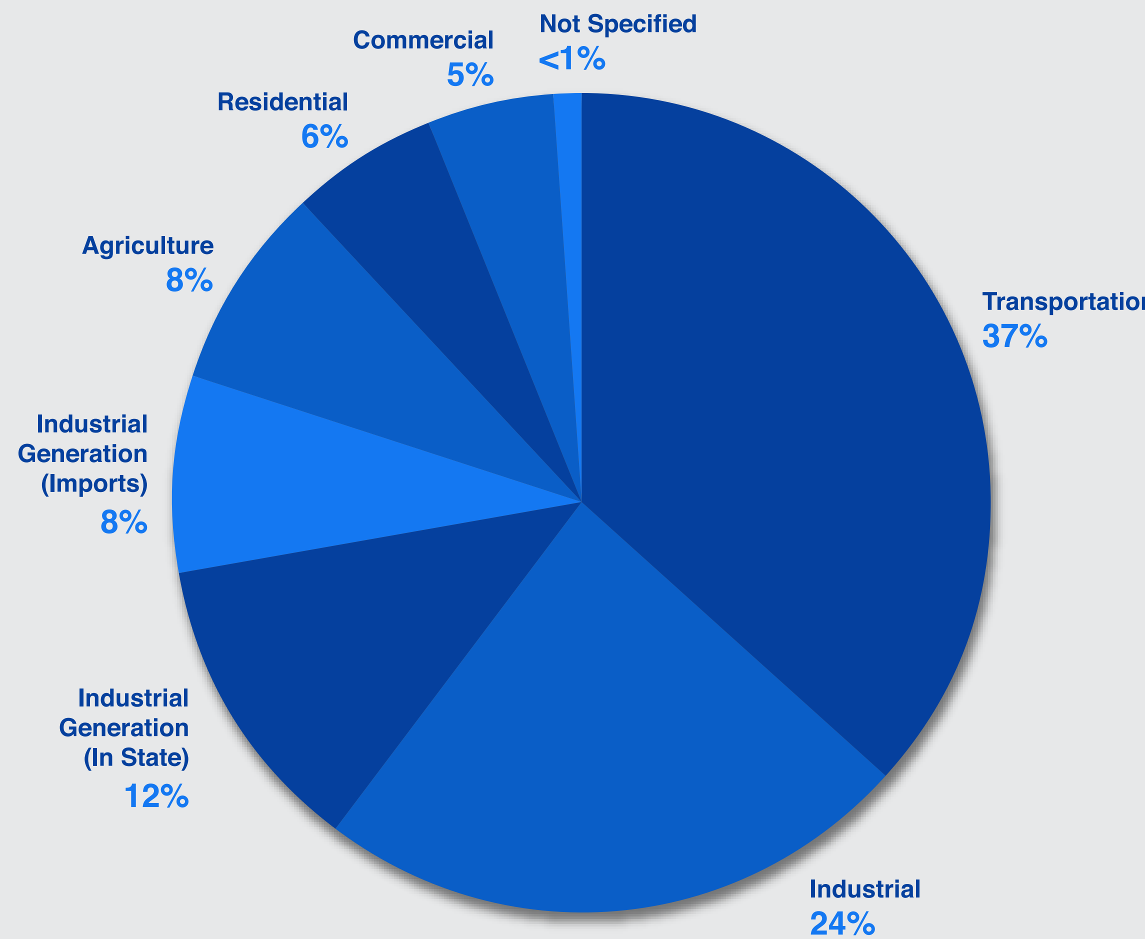
Renewable hydrogen is hydrogen that is produced, isolated or captured without the use of fossil fuels. When used within a fuel cell, hydrogen is part of a catalytic process that generates electricity without combustion, thereby eliminating the emission of greenhouse gases (GHGs) and criteria pollutants. It is used widely throughout the US for transportation, industrial enterprises (such as oil refining and ammonia production) and electricity generation.

Hydrogen, however, does not naturally exist alone in its pure state and must be isolated through chemical processing, which requires energy inputs. Therefore, a feedstock like methane or an energy source like wind or solar is necessary to support this process. Renewable hydrogen can be produced through multiple methods, commonly using renewable electricity or renewable biogas to generate a carbon-neutral (and sometimes carbon negative) fuel or energy carrier.

The transportation sector is by far the largest source of GHG emissions in California, generating 37% of the state's GHGs or 163 million tons of carbon dioxide equivalent (CO_2e) emissions in 2014 alone.[3] California already has aggressive GHG reduction targets that require cutting petroleum use in half by 2030[4] and cutting GHG emissions by 40% (below 1990 levels) by 2030.[5] To meet these goals, California is pursuing a ZEV (Zero Emission Vehicle) action plan proposed by Governor Jerry Brown. In 2012, Governor Brown issued an executive order calling for 1.5 million ZEVs by 2025.[6] He followed this action with a 2018 Executive Order updating that goal to 5 million ZEVs by 2030. FCEVs are a vital component of California's zero-emission future because their range and refueling time are comparable to conventional combustion vehicles and their only emission is water vapor. While FCEVs emit zero tailpipe emissions, the hydrogen that fuels them should be produced renewably in order to achieve a true zero-emission "well-to-wheels" transportation solution.

This zero-emission approach puts California on track to achieve its GHG goals and significantly reduce pollution levels. Californians will benefit from cleaner air and reductions in pollution-related health issues while

Figure 1. California Greenhouse Gas Emission Profile by Sector



***Source:** California Greenhouse Gas Emission Inventory – 2016 Edition* combatting climate change, catalyzing innovation and creating new economic opportunities.

Per SB 1505, hydrogen stations receiving state funding must meet the 33.3% renewable requirement, while CARB will be requiring all stations in California to meet the renewable requirement once the total hydrogen fuel dispensed for transportation in California exceeds 3.5 million kilograms over a 12-month period. As of 2017, however, very little renewable hydrogen was actually being produced in California. Rather than dispensing renewable hydrogen, most fuel suppliers are meeting the 33.3% renewable requirement by offsetting hydrogen sales with renewable energy certificates (RECs). RECs are tradable certificates that represent power that is verifiably produced from renewable energy projects that are not included in commodity electricity generation.

Currently, the only California policy tool that is advancing the production of renewable hydrogen is the Low Carbon Fuel Standard (LCFS) program, administered by CARB. Hydrogen producers can apply for LCFS pathway certification for qualifying renewable projects and then begin generating valuable credits, which can then be sold or traded to help recover production costs.

California has been instrumental in building the market for hydrogen as a transportation fuel by incentivizing the production and adoption of FCEVs and by directly investing in hydrogen fueling infrastructure. Here are some of the important steps along the way:

2004/2005

The state adopted the California Hydrogen Highway Blueprint Plan as a framework for creating the infrastructure to support FCEVs.

2006

California Senate Bill 1505 (SB 1505) established the Air Resources Board as the authority to regulate the emissions and renewable content of hydrogen produced to fuel FCEVs (as part of an overarching effort to reduce vehicular GHG pollution, criteria air pollutants and toxic air contaminants).[7] SB 1505 mandated that 33.3% of the hydrogen supplied through the state's fueling infrastructure be made from "eligible renewable energy resources" as deemed by the Public Utilities Code.

2007

California Assembly Bill 118 (AB 118) created the California Energy Commission's Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP). The bill directed the California Energy Commission (CEC) "to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the State's climate change policies."[8]

2007

California Governor's Executive Order S-01-07 created the LCFS program, directing CARB to meet a target of at least 10% reduction in the carbon intensity (CI) of California's transportation fuels by 2020.[9]

2013

Energy Independence Now published the Hydrogen Network Investment Plan (H2NIP) to address the challenges facing the development of hydrogen fueling infrastructure in California. CEC adopted Operations & Maintenance program funding as proposed by EIN in H2NIP.

2013

California Assembly Bill 8 (AB 8) pledged $20 million in annual funding to support the construction of 100 hydrogen-fueling stations.

2018

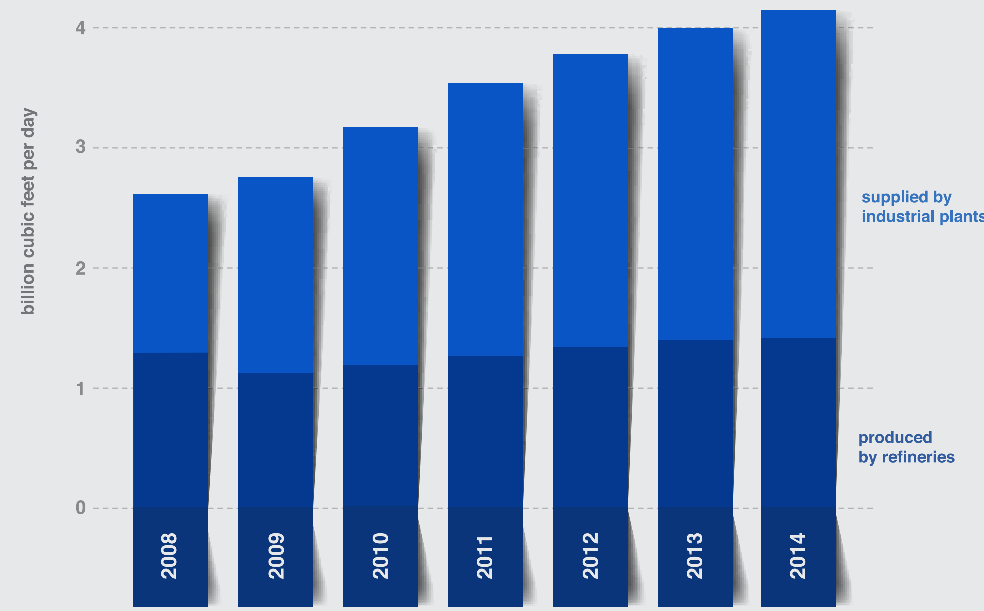
California Governor's Executive Order B-48-18 doubled the State's construction goal for hydrogen stations, establishing new targets of 200 stations and 5 million total zero-emission vehicles on California roads by 2030.

Global Hydrogen Market

Most of the hydrogen produced globally, 65 billion kg per year,[10] is used in chemical and refining industries and is produced with fossil fuels. Steam Methane Reformation (SMR) is the most prevalent technology from which hydrogen is produced, using natural gas, refinery and chemical plant off-gases as feedstock. The US currently produces about 10 billion kilograms of hydrogen annually, about 15% of global hydrogen production.[11] End-use of hydrogen in the US is primarily for oil refining, ammonia production, food processing, metals treatment and other chemical processes such as fertilizer production.

As shown in Figure 2, the petroleum industry has increased its consumption of hydrogen as a means to lower the sulfur content of gasoline and meet stricter environmental standards.[12] Increasingly, hydrogen used by refineries is being supplied by industrial gas companies (IGCs) - Figure 3. These gas companies primarily use SMR to produce hydrogen, but also source hydrogen produced as a by-product in chemical plants. Networks of hydrogen gas pipelines, concentrated around refineries in areas such as California and the Gulf Coast, allow industrial gas companies to transport high volumes of hydrogen economically.[13]

Figure 2. US Historical Refinery Demand for Hydrogen



Source: *Energy Information Administration (EIA)*

Figure 3. Major Industrial Gas Companies

Industrial Gas Companies	Market Capitalization
The Linde Group (LIN–Frankfurt)	$42 billion
Air Liquide (AI:FP–Paris)	$57 billion
Praxair (PX–New York)	$46 billion
Air Products (APD–New York)	$37 billion

Source: *Annual reports, Google Finance and Yahoo Finance Forbes website: https://www.forbes.com*

California Hydrogen Market

Figure 4. California Hydrogen Production Facilities (as of January 2016)

Producer	City	Technology	Capacity (kg/day)	Industry
Air Products	Sacramento	SMR	5,542	Multiple
Praxair	Ontario	SMR	20,483	Multiple
Air Liquide	El Segundo	SMR	207,240	Oil Refining
Air Liquide	Rodeo	SMR	289,172	Oil Refining
Air Products	Carson	SMR	240,976	Oil Refining
Air Products	Martinez	SMR	212,059	Oil Refining
Air Products	Martinez	SMR	84,342	Oil Refining
Air Products	Sacramento	SMR	unknown	Food
Air Products	Wilmington	RFG SMR	385,562	Oil Refining
Praxair	Ontario	SMR	28,917	Multiple
Praxair	Richmond	SMR	626,539	Oil Refining
Total			**2,100,832**	

Source: *Hydrogen Analysis Resource Center, U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, accessed at: http://hydrogen.pnl.gov/hydrogen-data/hydrogen-production*

A significant amount of hydrogen is produced in California to supply the oil refineries (over 2 million kg per day) while additional hydrogen is largely consumed by the food and metals industries. Figure 4 provides data on levels of hydrogen produced by IGCs to supply oil refineries.

As California continues the rollout of hydrogen stations and infrastructure development to support FCEVs, demand for hydrogen by the transportation sector will increase. CARB projects that by 2019 there will be 13,500 FCEVs on the road, and by 2022 there may be as many as 43,600 FCEVs. Using a "business-as-usual" scenario, the CARB projects that by 2022 the capacity of the statewide hydrogen station network will be 16,580 kg/day (assuming 180kg/day station capacity for new stations). However, CARB created an "expected" scenario that assumes lower station costs, higher station capacity and private investment not assumed in the "business-as-usual" scenario. The expected scenario splits stations into two groups: those receiving state funding to meet the AB 8 goal of 100 stations and additional stations funded privately or funded by a new state program. For the first expected scenario, the capacity of stations needed to meet demand would increase to 18,473 kg/day, a nearly 2,000 kg/day increase.[14] For the second expected scenario, the station capacity would need to increase to 46,550kg/day.

Using the "business-as-usual" scenario, the most conservative of CARB's projections, California FCEV drivers will consume over 6 million kilograms of hydrogen annually. Of that figure, over 2 million kg will need to be produced renewably in order to meet the SB 1505 requirement. While this is only a fraction of California's current overall hydrogen production, California currently produces very little renewable hydrogen without the use of offsetting renewable energy certificates RECs to provide a renewable designation.[15]

Hydrogen Production Technologies & Pathways

As of this writing, hydrogen is produced primarily from two technologies: Steam Methane Reforming (SMR) and Electrolysis. A third technology, Tri-generation, uses natural gas or biogas as a feedstock to produce electricity, heat and hydrogen. A brief overview of the three technologies provides a baseline for how the market operates today, and a review of the renewable opportunities available through each production technology.

Hydrogen can also be produced using direct solar water-splitting and biological processes, however, these processes are in early stages of research or commercialization. More information on these hydrogen production processes is available through the Department of Energy’s Fuel Cell Technologies Office.

Steam Methane Reformation

Ninety-five percent of the hydrogen currently produced in the US is generated through a chemical catalytic process called steam methane reforming (SMR).[16] SMR is a process that moves stored chemical energy to hydrogen. The hydrogen is generally produced at large centralized plants using natural gas as the primary feedstock. SMR deploys high-temperature steam in the presence of a catalyst to produce hydrogen from a methane (CH_4) source, such as natural gas. Other feedstocks include ethanol, biogas, propane and gasoline.[17]

While it's true that FCEVs do not emit harmful greenhouse gases, a carbon footprint nevertheless exists from the natural gas feedstock and SMR process used to produce hydrogen. The well-to-wheels carbon footprint of FCEVs can be further reduced, however, by using renewable feedstock as the input for SMR-produced hydrogen.

Biogas is one such input. It is produced from organic material such as landfill or dairy waste, using anaerobic bacteria. As the bacteria decompose the waste in an oxygen-free environment, the resulting slurry emits a gas containing methane. Wastewater treatment plants use a similar digestion method to process waste and generate methane gas. In California, methane emissions must be captured and eliminated.

Thanks to its high methane content (and thus hydrogen), biogas can be used as a feedstock to produce electricity or to power vehicles. The potential for biogas-produced hydrogen is significant: the Sacramento region alone could produce 93,300 tons of hydrogen annually from local biogas, enough to power 527,000 FCEVs for a year.[18]

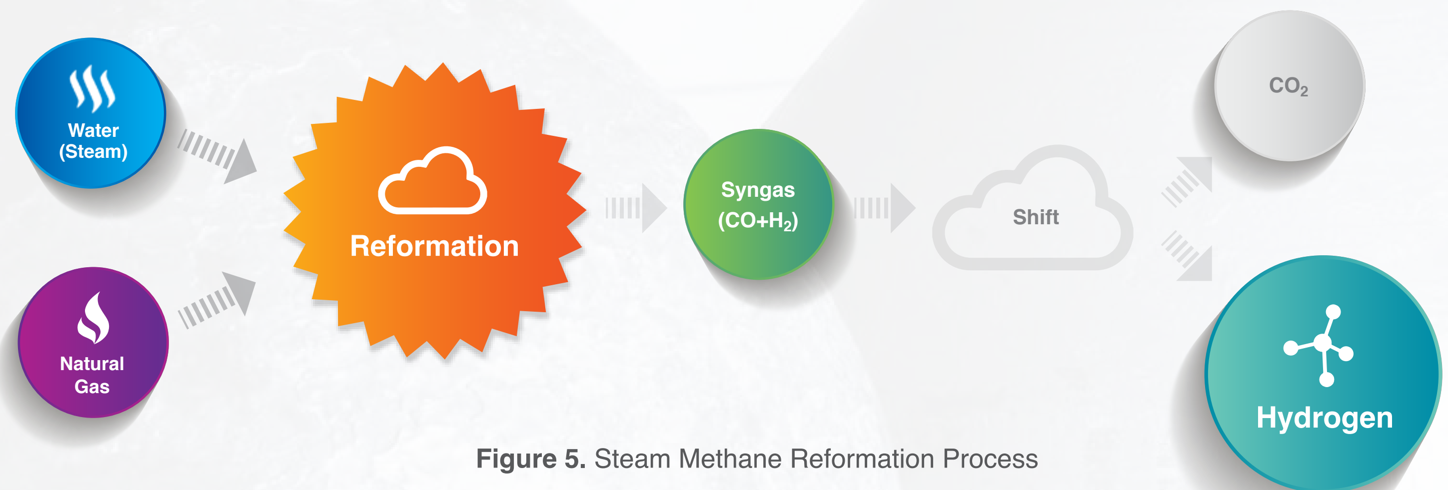


Figure 5. Steam Methane Reformation Process

Challenges

RIN Ineligibility. Biogas-derived hydrogen projects are eligible for LCFS credits but not for Renewable Identification Number (RIN) credits under the federal Renewable Fuel Standard Program (RFS). Renewable natural gas (RNG) producers generate valuable RIN credits that inflate prices for biogas, while hydrogen producers who use the same biogas as a feedstock are not eligible to collect the same RIN credits. This creates a disproportionate advantage for RNG producers. If hydrogen were an approved fuel pathway, producers could generate RIN credits, which would significantly offset the cost of developing renewable hydrogen projects using biogas and renewable electricity feedstocks.

Transportation Costs. Transportation of biogas-derived hydrogen is an added cost, largely because hydrogen cannot be injected into gas pipelines due to regulatory stipulations. Thus, FCEV-quality hydrogen produced from biogas would have to be trucked to retail fueling stations. For biogas-to-hydrogen projects situated near urban areas (such as landfills or WWTPs), the added cost of trucking is not prohibitive (in the range of $1-2/kg).[19] For dairy digester projects in rural areas, however, the added transportation cost can be significant.

Biogas to RH_2 from Landfills

Biogas generated from landfills can be reformed and processed into renewable hydrogen and used in fuel cells to generate electricity and power FCEVs. The largest amount of available biogas in the US is concentrated in landfills, which produce about 10.6 million tonnes of methane annually. Not including the landfill methane already being captured in current projects, another 2.5 million tonnes is available, which could be converted to approximately 648,000 tonnes of hydrogen annually.[20] Per the EPA's Landfill Methane Outreach Program (LMOP), 314 unique landfills exist in California, with 81 operational projects using biogas.

Landfill gas (LFG) is generated by organic landfill waste decomposing in the absence of oxygen. The process of LFG generation typically occurs underground, where pressure is higher. Collecting the resulting gas requires a system of pipes and blowers.[21] Once collected, LFG needs to undergo a cleanup process to remove undesirable components such as siloxanes. After cleanup, the gas can be upgraded and purified to 100% methane, which can then be used in a number of ways, including transportation fuel, direct pipeline injection, on-site power generation and thermal applications.[22] Approximately a quarter of US landfills are collecting and processing LFG for electricity generation or direct use, leaving approximately 75% as an untapped resource.[23]

A joint project between the US DOE and a BMW manufacturing site in South Carolina successfully demonstrated a landfill-to-hydrogen project that produced hydrogen on-site for fuel cell-powered material handling equipment (MHE). The hydrogen was produced using small-scale SMR at the 500kg/day level. The resulting feasibility study estimated the 10-year levelized cost of hydrogen at $5.46/kg, which was cost-competitive with delivered hydrogen. This cost did not include some initial gas clean-up processing, collection, compression, storage or dispensing costs.[24]

Challenges

Sources. LFG projects are excluded from CEC funding due to legislation that aims to reduce the amount of solid and organic waste distributed to landfills. AB 341 requires that 75% of the solid waste stream be reduced through recycling or composting by 2020, and SB 1383 mandates a 50% reduction in the statewide disposal of organic waste from the 2014 level by 2020 and a 75% reduction by 2025. As a result of these policy changes, landfills would begin to produce less methane due to the proposed reduction in the amount of decomposing organic matter.

Scale. The US DOE-sponsored LFG-to-hydrogen project demonstrated that very small-scale (around 50kg/day) SMR hydrogen production from LFG is not economical. When the scale is larger, however (500kg/day and above), the small-scale SMR can be economically viable. This result points to the need for further research on small-scale SMR to reduce capital costs.

Gas Clean-Up. LFG is a mix of methane and carbon dioxide gas that contains additional components, including water, siloxanes, nitrogen and oxygen. These components must be removed or reduced down to parts-per-billion levels before the gas can be used in SMR equipment. In order to remove the contaminants, multiple gas cleanup processes are utilized, requiring additional equipment and increased cost. Additional R&D could target the reduction of capital costs and the increase of efficiencies in gas clean-up processing for small-scale SMR applications.

Biogas to RH_2 from Dairies

California has approximately 1,400 dairies, producing roughly 20% of the nation's milk supply.[25] Dairies produce a significant amount of animal waste, which is typically stored in open lagoons that generate methane gas and release it into the atmosphere. These open lagoons can be covered and the gas can be captured and used to generate electricity or upgraded to RNG or hydrogen. Other dairy digester technologies are available to reduce methane emissions and allow for electricity or fuel generation.

California's agriculture industry, dominated by dairies, is responsible for almost 60% of the state's methane emissions.[26] According to the EPA, methane has a 25 times greater impact on climate change than carbon dioxide. Recently, California enacted legislation to address the challenge of controlling these emissions. In September 2016, Governor Brown signed into law SB 1383, which requires a methane reduction of 40% below 2013 levels by 2030.[27] AB 1613 directs $50 million from the State's cap and trade funds to support the State's methane emission reduction goals. In addition, the California Department of Food and Agriculture's Dairy Digester Research & Development Program has disseminated $12 million in grants to foster the installation of dairy digesters throughout the state.[28] Despite these incentives and grant assistance, only 13 digesters currently operate in the state, with another three under construction.[29] Today, no dairy digester projects generate hydrogen from biogas in California. The current projects use biogas to generate electricity, or for combined heat and power generation.

Obtaining cost data is difficult, because biogas-to-hydrogen dairy digester projects currently do not exist in California. A 2010 analysis by the National Renewable Energy Laboratory (NREL) estimated that it would cost approximately $6/kg to generate biomethane from a dairy's covered lagoon using anaerobic digestion.[30] This estimate does not include the cost of upgrading the biomethane to hydrogen.

NREL calculates that 486,000 tonnes of hydrogen could be generated annually from dairy digesters throughout the US, not including existing systems. Further analysis shows that 8 of the top 14 counties in the U.S. with the highest hydrogen production potential from animal manure are in California and could generate 72,300 tons of hydrogen annually.[31]

Challenges

Cost. The dairy industry cites cost as the major barrier to large-scale adoption of dairy digesters, but economies of scale[32] have been identified as a way for dairies to lower these costs. Dairies with at least 1,000 cows straddle the tipping point where digester and energy generation is profitable. Multiple dairies in close proximity could improve the economics by combining their waste streams and generating biomethane at a central digester.

Regulations and Geography. Most dairies are dispersed in rural areas, which makes aggregating waste to achieve economies of scale difficult. Dairy digester projects also must comply with environmental regulatory standards regarding compliance, permitting and issues connecting to pipelines or to the grid. Selling power to the grid through net metering or providing RNG to pipelines can be a source of income to support dairy digester projects once these barriers are addressed.

Biogas to RH_2 from Wastewater Treatment Plants

Wastewater treatment plants (WWTPs) process wastewater generated in urban areas through the sewer system. The wastewater undergoes several treatment processes (to clean and disinfect) before being returned to the water stream. The waste sludge byproduct can produce biogas using anaerobic digesters. This raw biogas must be cleaned in order to be converted to biomethane (which can be used to generate electricity and heat or upgraded to CNG or LNG) or further upgraded into renewable hydrogen using SMR technology. The raw biogas produced from the wastewater treatment process contains GHGs and air-polluting emissions such as carbon dioxide, methane and nitrous oxide.[33] These emissions are vented into the air unless they can be captured and used.

An NREL report on the potential for hydrogen production from biogas showed that, across the nation, the potential annual hydrogen generation from WWTPs is 509,000 metric tons. Some of the top counties for hydrogen potential from WWTPs are in California. Combining the counties of Los Angeles, Orange County and San Diego alone, the total untapped annual hydrogen potential is 17,300 metric tons.[34]

WWTPs are ideal for hydrogen generation projects, because most are located in or near urban areas, where hydrogen fuel demand is highest. In addition, many (if not most) already use anaerobic digesters to produce biogas, which could be upgraded or used for SMR without the added cost of digester capital investment.[35]

Challenges

Cleaning. Biogas derived from anaerobic digestion of waste sludge in WWTPs requires cleaning to remove impurities such as siloxanes, which can damage equipment used to combust biomethane or hydrogen. The additional cleaning and upgrading needed to get from raw biogas to high-purity hydrogen for use in FCEVs or tri-generation is expensive.

Incentives. WWTPs need incentives to sell biogas to hydrogen producers in order to compete with RNG producers. Hydrogen does not currently qualify for RIN credits from the federal RFS program, which makes biogas more valuable for RNG producers and edges hydrogen producers out of the market.

Tri-Generation

Tri-generation is a technology that uses molten carbonate fuel cells to produce hydrogen, electricity, heat and water from natural gas or biogas. Like SMR, Tri-generation systems produce hydrogen through the reforming process but they do not require additional hydrocarbon fuel to create heat and steam. Instead, this technology uses the heat and steam by-product or waste energy from power production occurring within the same system. Thus, tri-generation is more efficient than SMR in terms of the amount of fuel input required to power the reformation process, which in turn yields significantly less GHG emissions.

Tri-generation systems are noteworthy in the context of the early commercialization of FCEVs because operators/investors can leverage multiple revenue drivers to mitigate variable demand for hydrogen as the market for vehicles and stations continues to evolve. For example, Fuel Cell Energy's flagship tri-generation plant can produce 1,200 kg of hydrogen per day while simultaneously generating approximately 2,350 kW of electricity, which can be sold or consumed on-site. Waste heat produced in the fuel cell can also be used externally for other industrial processes. Finally, the system produces about 600,000 gal/year of water, which can be used for multiple purposes. The cost of producing hydrogen is thus reduced by the co-production of power, heat and water from these fuel cell systems.

Tri-generation systems are small relative to SMR plants and can be sited near industrial hydrogen consumers or FCEV filling stations, eliminating the need to transport hydrogen long distances and further reducing the well-to-wheels emission profile of hydrogen production. They can also be sited near renewable fuel sources, such as wastewater treatment plants and dairy farms to produce renewable hydrogen. In fact, renewable hydrogen produced from dairy biogas via tri-generation and used in FCEVs has a CI substantially less than zero, largely because of the methane emissions that the process diverts and recycles. This process serves to clean the air by mitigating GHG emissions from multiple sources (agriculture and transportation) and has the potential to be one of the most impactful alternative fuel pathways.

Fuel Cell Energy successfully demonstrated the first tri-generation power station in California, producing heat, hydrogen and electricity at the Orange County Sanitation District's wastewater treatment plant in Fountain Valley, California. The system used biogas from the wastewater treatment plant as feedstock to produce heat, electricity and hydrogen for an on-site fueling station that supported 25-50 FCEVs per day.[36]

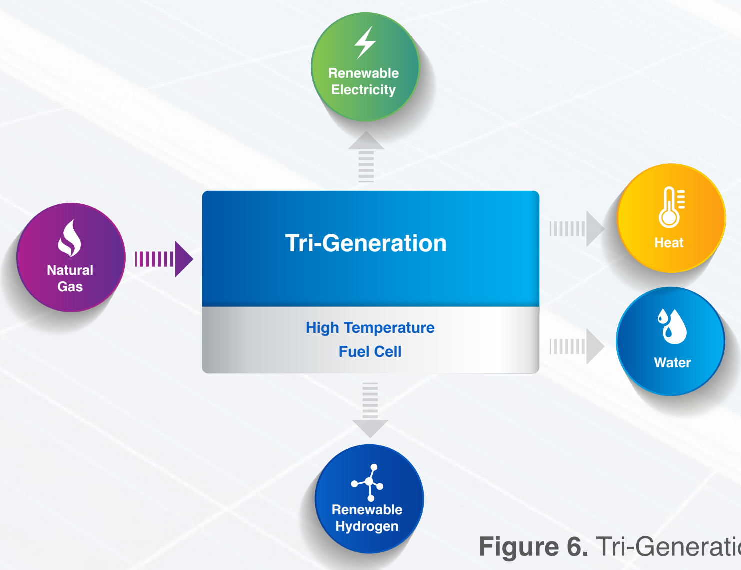


Figure 6. Tri-Generation Process

Challenges

RIN Ineligibility. Biogas-derived hydrogen is eligible for LCFS credits but not for RIN credits under the federal RFS program. Tri-generation hydrogen producers compete with RNG producers, who generate valuable RIN credits for their fuel and can thus pay higher prices for biogas feedstock.

The last amendment to the RFS program (EPA Pathways II) directly states that adding pathways from biogas to hydrogen is beyond the scope of the rule: "We also received comments on adding pathways for biogas to transportation fuels other than CNG/LNG and electricity. These other fuel types included dimethyl ether (DME) and hydrogen (H). However, assessing emissions associated with these production processes is also beyond the scope of this rule."[37]

Electrolysis

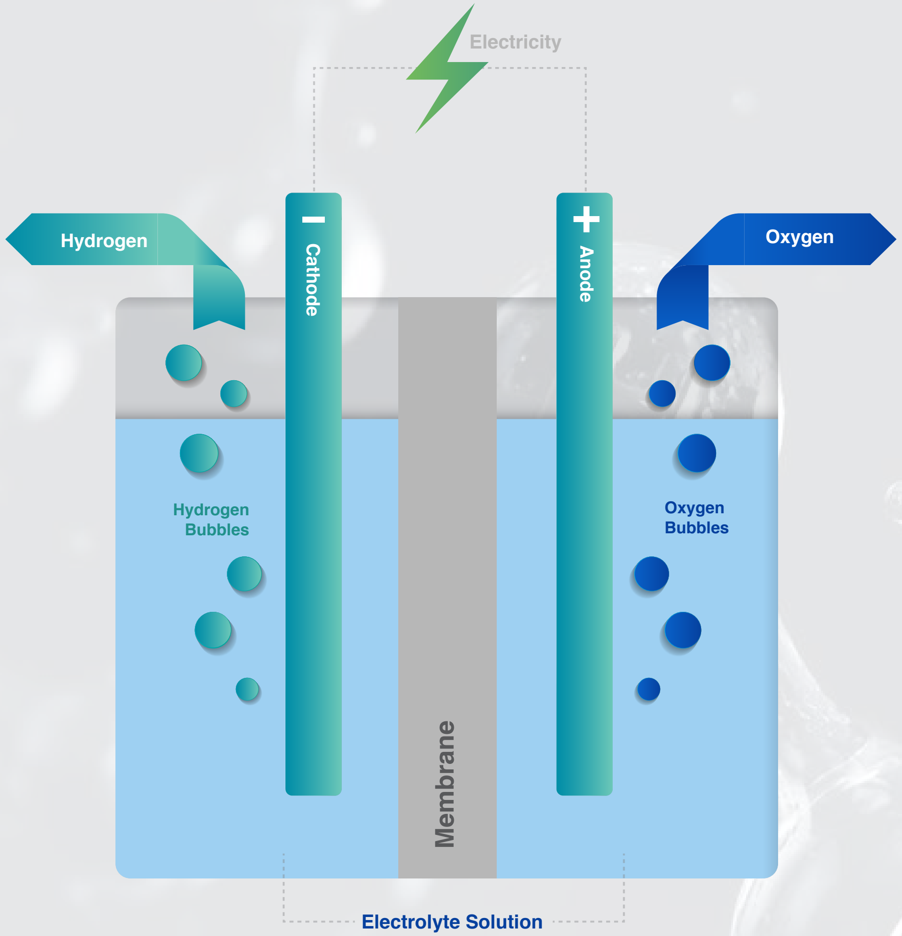
Electrolysis is a process that utilizes electricity to break the H_2O bond in a piece of equipment called an electrolyzer by separating water molecules into hydrogen and oxygen. Electrolysis has many industrial uses, including as a fuel and oxygen source aboard submarines[38] and spacecraft.[39]

Electrolyzers come in various sizes, from a compact unit the size of a household dishwasher to versions for use in large-scale industrial plants. They generally employ one of the following three technologies:[40]

- **Alkaline** – a liquid alkaline electrolyte solution of sodium or potassium hydroxide
- **Polymer Electrolyte Membranes (PEM)** – the electrolyte is made of a polymer material
- **Solid Oxide Membranes** – the electrolyte is made of a solid ceramic material

Developed in the 1800's, alkaline electrolyzer technology is the most mature and, until recently, the one best suited for large-scale hydrogen generation (up to 50,000 kg/day).

Figure 7. Electrolysis Process



The advent of PEM technology is more recent, starting in the 1960s and advancing over the last few decades to commercial scale. PEM electrolyzers are commercially available and have historically been smaller than alkaline electrolyzers (up to 1-2MW or approximately 500-1000 kg/day), although economies of scale and technological advances are driving increased production capacity with PEM electrolyzers. Solid Oxide Membrane technology is commercially used for power generation but is still in the R&D/demonstration phase for electrolyzers.

Electrolysis systems can be centralized or distributed, but currently there are no large centralized electrolysis projects under development in California for hydrogen production. Distributed electrolysis systems, however, are smaller (up to 1500 kg) and more easily located on-site or near hydrogen fueling stations. There are currently three on-site electrolysis hydrogen stations that are operational in California and another five are under development, as listed in Figure 8.

Figure 8. List of State-Funded On-site Electrolysis Hydrogen Stations as of January 2018

Station Address
1100 Seminary Avenue Oakland, CA 94621 (transit bus only)
8095 Lincoln Avenue Riverside, CA 92504
17287 Skyline Boulevard Woodside, CA 94062
12600 East End Avenue Chino, CA 91710
1850 Holt Boulevard Ontario, CA 91761
1172 45th St Emeryville, California 94608

Source: *California Governor's Office of Business and Economic Development*

Electrolyzers consume a significant amount of electricity as an input, which, in addition to the capital cost of the equipment itself, makes it generally more expensive than SMR. However, one of the greatest attributes of electrolyzer technology is the flexible nature of the equipment, some of which can adjust to variable renewable generation loads and can help minimize the cost of electrical inputs during periods of peak pricing. Electrolyzer operators can produce and store hydrogen during times of high or excessive electricity generation and low demand/prices, while decreasing hydrogen production as renewable generation decreases and electrical demand stresses the grid. Thus, electrolyzer systems can rapidly take advantage of low electrical pricing and support energy storage mechanisms to help avoid curtailment of intermittent renewable power sources, such as wind and solar. The resulting 100% renewable hydrogen can be used for transportation or converted back into electricity and returned to the grid, effectively supplying solar or wind power when the sun is not shining and the wind is not blowing.

Figure 10 shows the cost of hydrogen as a function of electricity prices.

Challenges

Cost of Electricity. The fluctuating long-term cost of electricity makes it challenging to model the lifetime cost of operating the electrolyzer.

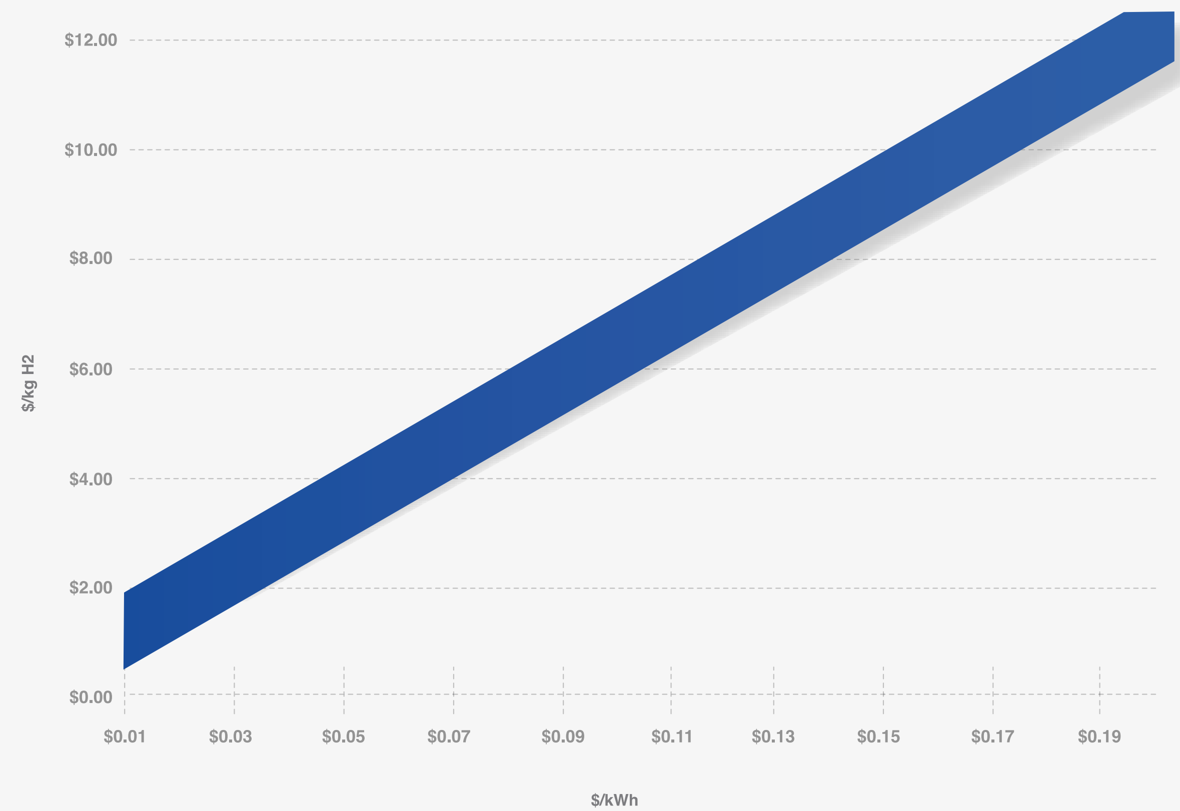
Hydrogen Not Recognized by RFS. The RFS program does not recognize hydrogen produced through electrolysis as a pathway, barring it from generating valuable RIN credits.

Figure 9. Major Electrolyzer Firms

Electrolyzer Companies	Market Cap (January 2018)
Nel Hydrogen (NEL–Oslo)	$438M
Hydrogenics (HYG—Toronto)	$171M
ITM Power (ITM–London)	$179M

Source: *Bloomberg Markets*

Figure 10. Cost of Hydrogen Produced by Electrolysis as a Function of Electricity Prices



Source: *ProtonOnsite - 2 MW PEM Electrolyzer at 2107 Costs*

Renewable Distributed Electrolysis

Distributed electrolysis systems, commonly sized at 1,500 kg/day or less, are small and sufficiently modular to be located on site at a hydrogen station, which eliminates the cost and emissions associated with trucking hydrogen from centralized production sites. Only a small portion of existing/planned hydrogen stations in California, however, include on-site (or distributed) production. Of those, an even smaller portion are coupled with on-site renewable power generation. Station sites in urban areas simply do not have enough space to co-locate enough power generation equipment with hydrogen production, storage and dispensing equipment. They can, however, still be connected to solar photovoltaic (PV) installations to utilize renewable electricity and reduce demand charges.

The market will likely reach the point, as the technology shrinks in size and cost and becomes more efficient over the long term, where distributed generation can feasibly be coupled with on-site production. It remains to be determined if that can be achieved before grid electricity reaches 100% renewable.

In the meantime, California's current Renewable Portfolio Standard (RPS) penetration for retail electricity stands at 27%.[41] Though it reduces the CI of the overall pathway, exclusive use of grid power with a distributed electrolysis system is not yet a 100% renewable pathway and producers currently are not permitted to claim even prorated renewable content from grid sources without purchasing the accompanying RECs.

The cost of producing hydrogen with a 1MW electrolyzer co-located with a 1MW PV system (approximately 2.5 acres of PV panels), which also uses flexible demand-response utility programs to reduce energy costs, is about $8.77/kg.[42] The resulting hydrogen would be roughly 32% renewable and generates credits from the LCFS program, which offset some of the production costs. Presently, the only ways to increase the renewable content are by purchasing RECs to offset non-renewable electricity costs or by increasing the size of the PV system.

Challenges

Costs. Electrolyzers have high capital and operating costs, which result in higher-priced hydrogen compared to SMR technology. Specifically, high electricity prices in California make electrolyzer- produced hydrogen more expensive than in other parts of the country where electricity is cheaper. Producing hydrogen using SMR technology and buying biogas credits to meet the 33.3% renewable requirement is cheaper than electrolyzer-produced hydrogen using current REC pricing.

Hydrogen Not Recognized by RFS. Currently the EPA's RFS program does not recognize hydrogen produced through electrolysis as a pathway for credits, which would help offset the higher cost of the technology.

Renewable Central Electrolysis

Centralized electrolysis systems produce hydrogen for multiple distribution points and are not necessarily co-located with fueling stations. Station capacities will quickly grow well beyond the 180kg/day that the early network grants required. Stakeholder conversations about future capacity now begin around 300 kg/day and stretch upward to 1000 kg/day. Thus, in order to serve multiple stations, centralized electrolysis production facilities would need to produce 1,500 kg/day or more. The main cost drivers for electrolysis systems are the price of electricity, the efficiency of the electrolyzer and the capital cost of the system.

Advances in R&D and competition for market share are driving up electrolyzer efficiencies and helping manufacturers leverage economies of scale to reduce capital costs. This leaves electricity prices as the primary variable that impacts the economic viability of hydrogen production through electrolysis.

Several mechanisms can drive down the price of electricity, including demand-response rate programs, renewable integration and preferential, discounted or subsidized utility rates.

Demand-response programs use reduced rates or credits to reward customers that respond to peak grid periods by varying electrical demand to help balance pressure on the grid.

On-site renewable electricity generation helps producers avoid peak grid pricing, lowering production costs and the environmental impact of the end product. While it is possible to co-locate large-scale, centralized electrolysis installations with renewable generation facilities without grid connectivity, this type of project is significantly more expensive than utilizing grid-connected facilities. The intermittent generation characteristics of wind and solar, for example, can leave electrolyzers idle for extended periods of time, reducing productivity and limiting market opportunity. Increased storage capacity (of hydrogen or electricity) is then necessary to minimize downtime, which adds considerable expense.[43] Furthermore, 100% on-site renewable penetration requires 3 to 3.5 times more PV or wind capacity relative to the size of the electrolyzer, which would only be economically practical if the project is co-located with a facility that can take on the additional load or if the California net-metering program is expanded to include installations larger than 1MW.[44] Even with the ability to produce 100% renewable hydrogen with on-site PV or wind, grid connectivity is still necessary to stabilize energy loads and to mitigate downtime for equipment, which is especially relevant to alkaline electrolyzers because they are not able to easily respond to power fluctuations.

The recent NREL study, "California Power-to-Gas and Power-to-Hydrogen Near-Term Business Case Evaluation," highlighted a pathway in which a large central electrolysis system utilized 95% renewable electricity from PV for delivery to refineries. The resulting hydrogen price is $10.68/kg, assuming pipeline delivery and LCFS values for gasoline vehicles rather than FCEVs. Adjusting this figure to reflect average compression, storage and delivery (CSD) costs for truck delivery in California ($3.45)[45] and a 0 gCO_2e/MJ CI score (with an LCFS credit value of $125) yields an approximate cost of $9.80/kg for 95% renewable hydrogen delivered to a station for use in FCEVs.

Challenges

Delivery Costs. Centralized production requires delivery to hydrogen stations, which can be very expensive (averaging $3.45/kg for trucking to the San Francisco, San Diego and Los Angeles areas, including compression and storage). Pipeline delivery of hydrogen is less polluting than truck delivery; however, the installation of pipeline infrastructure requires high upfront costs and presents logistical and geographic challenges.

Siting. 100% on-site renewable penetration requires 3 to 3.5 times more PV or wind capacity relative to the size of the electrolyzer, which is only economically practical if the project is co-located with a facility that can take on the additional load or if the California net-metering program is expanded to include installations larger than 1MW.

Grid Connectivity. Centralized hydrogen production facilities still need to be grid connected in order to stabilize energy loads and balance the intermittent renewable production characteristics of wind and solar. Alkaline electrolyzers are currently the most scalable electrolyzer technology but offer reduced flexibility managing variable electrical loads, necessitating grid connectivity or large and expensive storage equipment.

Hydrogen Not Recognized by RFS. Currently the EPA's RFS program does not recognize hydrogen produced through electrolysis as a pathway for credits, which would help offset the higher cost of the technology.

Green Tariff/Shared Renewables Electrolysis

In 2015, California implemented the Green Tariff Shared Renewables Program (GTSR), legislated through SB 43. The GTSR has two components that allow customers of the state's three investor-owned utilities[46] (IOUs) to purchase renewable energy:

1) Green Tariff – Customers may elect to purchase up to 100% of their electricity from solar generation. Customers then pay a different rate for renewable electricity (tariff) or an extra fee (rider) on top of standard electricity rates.

2) Enhanced Community Renewables (ECR) – Customers may purchase a portion of a solar project, directly from a developer, to cover 25% to 100% of their monthly electricity demand. Customers then receive a credit from the utility relative to the level of their renewable purchase.

Customers can participate in either one of the programs, but not both and the load must not exceed 2MW. This would likely mean that only smaller, distributed hydrogen projects would be eligible.

The GTSR program would, in theory, allow a distributed electrolysis project to purchase 100% renewable electricity and thereby produce 100% renewable hydrogen.

Challenges

GTSR Exclusivity. The GTSR program is only available in California markets that are covered by the IOUs. This exclusivity can impact distributed electrolysis projects that are trying to establish LCFS pathways using as much renewable energy as possible. One such project is in the city of Riverside, which is not covered by the IOUs and therefore does not meet the requirements of the GTSR program. The only way for that project to purchase renewable energy is through RECs, which are not recognized by LCFS as reducing the CI score of a project.

The Economics of Renewable Hydrogen

Ultimately, in order to sway consumers, renewable hydrogen needs to be cost competitive with gasoline (and conventional hydrogen) on a per-mile basis.

Until consumers are either forced to shoulder the indirect costs of fossil fuels (or dramatic increases in oil prices) and/or policymakers increase incentives for alternative fuels, hydrogen must be priced comparably to gasoline to achieve rapid market growth as a transportation fuel.

While a kg of hydrogen has roughly the same energy content as a gallon of gasoline, FCEVs are twice as efficient, so a kilogram of hydrogen can cost about twice the price of a gallon of gasoline and remain competitive on a per mile basis. A gallon of gasoline currently costs between $3-$4 in California, thus a comparable target for renewable hydrogen is about $8/kg at the dispenser.

Cost Drivers: The cost of renewable hydrogen can vary widely depending on production and distribution components such as feedstock pricing, compression/storage/delivery (CSD) costs, price of equipment, operations and maintenance requirements, etc. The production technologies and renewable feedstocks identified in this roadmap yield an approximate price range of $2/kg to $15/kg before CSD.

Rather than modeling the various inputs for each individual technology type, which would require access to proprietary data from equipment providers, this roadmap utilizes a series of US Department of Energy economic studies conducted through the Fuel Cell Technologies Office and the National Renewable Energy Laboratory. **Figure 11 summarizes data from these reports to illustrate approximate cost ranges for the pathways examined in this roadmap.**

It is important to note that the cost of CSD of gaseous hydrogen is a significant component of the end cost to consumers.

Figure 11. Costs of Production for Renewable Hydrogen Pathways (Does Not Include CSD)

Pathway	Renewable Level	Technology	Input	Plant Capacity	Levelized Cost of Production ($/kg)
Solar PV + CA Grid to H2 - 1MW	32%	PEM Electrolysis	Grid and Solar Electricity, Water	398kg/day	$8.02
100% Solar PV Generation to H2 - 1MW	100%	PEM Electrolysis	Grid Electricity, Water	126kg/day	$15.43
Biogas to H2	100%	SMR	Landfill, Wastewater or Dairy Biogas	1500kg/day	$2.94
Tri-Generation Biogas to H2	100%	Tri-Generation	Biogas	1500kg/day	$5.99
Natural Gas to Hydrogen	0	SMR	Natural Gas	398kg/day	$2.17

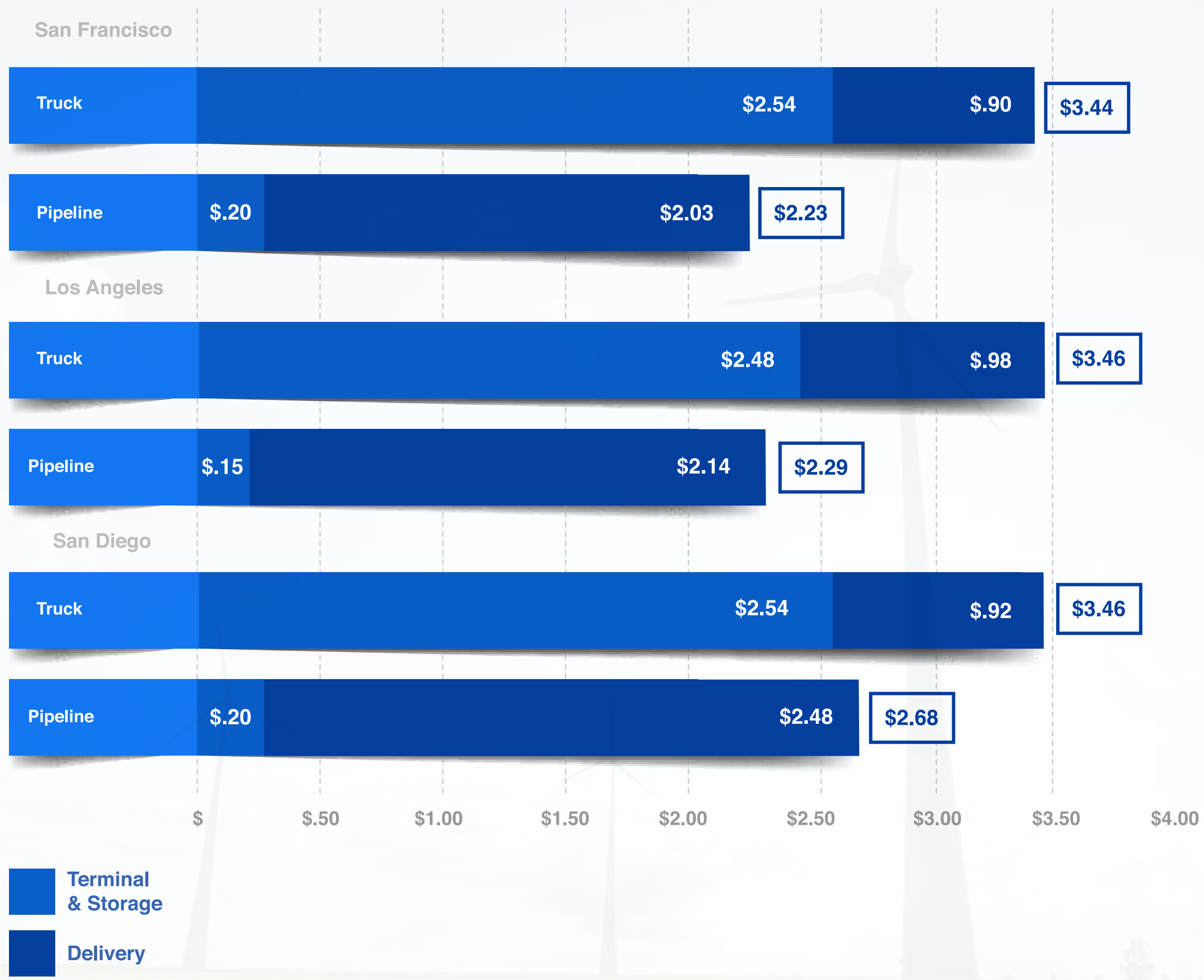
Source: *Levelized Cost of Production Calculated by EIN using data from "California Power-to-Gas and Power-to-Hydrogen Near-Term Business Case Evaluation" Eichman, Josh, Flores-Espino, Francisco, National Renewable Energy Laboratory, December 2016*

Figure 12 illustrates CSD costs for gaseous hydrogen delivery via truck and pipeline to San Francisco, Los Angeles and San Diego.

This roadmap focuses primarily on renewable hydrogen production methods coupled with gaseous delivery by truck or pipeline because gaseous storage, delivery and fueling dominate the current hydrogen ecosystem in California. Liquid hydrogen, however, offers both benefits and challenges that impact CSD costs as well as the cost and capacity of FCEV fueling stations. For example, delivery trucks can carry significantly more liquid hydrogen (lowering the cost and environmental impact of trucking) but the cost of liquefaction combined with trucking equipment and on-site liquid hydrogen storage is significantly higher. The high cost of liquefaction equipment is generally only economical when combined with large-scale centralized production facilities.

For now, it seems that gaseous hydrogen will continue to dominate the FCEV marketplace, but the growing need for higher storage capacity at stations and lower distribution costs may create a stronger case for liquid hydrogen. Whether liquid or gaseous hydrogen is utilized, growth in centralized production will require efficient distribution networks to transport hydrogen throughout the state, likely generating the need for pipeline investments and increased trucking capacity.

Figure 12. Hydrogen CSD Costs



Source: *"California Power-to-Gas and Power-to-Hydrogen Near-Term Business Case Evaluation" Eichman, Josh, Flores-Espino, Francisco, National Renewable Energy Laboratory, December 2016*

Revenue Drivers: As of late 2017 there were approximately 3,500 light duty FCEVs in California and 31 publicly accessible hydrogen fueling stations in the state, compared to approximately 25 million total registered automobiles and about 10,000 gas stations. The market for FCEVs and hydrogen fuel is in its infancy and near-term consumer demand for renewable hydrogen likely will not be enough to make an economic case for developers to invest in renewable production infrastructure. California policymakers have recognized this fact and, in response, introduced market incentives that promote fuels that help reduce GHG emissions in the transportation sector.

Currently, the SB 1505 33.3% renewable requirement, coupled with LCFS credits and emerging consumer demand for hydrogen fuel are the only revenue drivers for renewable hydrogen in the transportation market.

The LCFS was enacted through AB 32 with the goal of reducing the CI of transportation fuels in California by 10% by 2020. The LCFS program is a key component of the hydrogen sector because it establishes an additional revenue driver for producers while showcasing the reductions in pollution that the hydrogen economy will generate. LCFS program administrators evaluate individual production methods and assign CI scores that ultimately determine the value of the end credit. CI scores are calculated by evaluating the amount of carbon used in the fuel production process. The lower the CI of a production method, the higher the value of the credit.

LCFS credits are calculated using this equation:

Credits = (CIstandard – CIHydrogen/EER) × Energy Density × EER × Hydrogen (in kg) × 10–6

Energy Economy Ratio (EER) represents "the efficiency of a fuel as used in a powertrain as compared to a reference fuel."[47] The value for the energy density of hydrogen is 120 MJ/kg.

An example of the credit values is shown in Figure 13, using a CI of 113.38 gCO_2e/MJ (grams of carbon dioxide equivalent per megajoule of energy) which represents non-renewable hydrogen created through SMR, with natural gas as a feedstock in a central large-scale plant.

Hydrogen producers are not required to participate in LCFS, but they can "opt-in" and provide data on life-cycle emissions in order to establish a CI score. Opting into the program allows a producer to generate LCFS credits, which can then be sold to regulated parties (such as refineries) to offset GHG emissions. LCFS program administrators have certified five hydrogen pathways, documented one proposed pathway, and provided guidelines that can be used by producers to apply for a CI score.

Figure 14 provides a list of the approved hydrogen pathways and several others for comparison, including dairy gas to CNG and the score calculated by Fuel Cell Energy for the waste water treatment plant to hydrogen demonstration project at the Orange County Sanitation District facility in Southern California.

Figure 13. LCFS Credit Revenues for Natural Gas to SMR Hydrogen Used in FCEVs

Vehicle Type	EER	Credit Revenues (kg) per LCFS Credit Price		
		$50	$100	$150
Light/Medium FCEV	2.5	$0.75	$1.49	$2.24

Source: *LCFS CARB Credit Price Calculator*

Figure 14. LCFS Approved Hydrogen Pathways

Pathway	Company	CI Score	LCFS Credit Price at $100
Landfill gas to hydrogen via methane cracking using tube trailer transport	LytEn	-5.28	$2.91
Landfill gas and natural gas to hydrogen via methane cracking using tube trailer transport	LytEn	47.73	$2.28
Landfill gas and natural gas to hydrogen via methane cracking onsite	LytEn	40.36	$2.37
Landfill gas to hydrogen via methane cracking onsite	LytEn	-12.65	$3.00
Hydrogen production via electrolysis using solar electicity	AC Transit	0	$2.85
Dairy biogas to CNG	California Bioenergy LLC	-272.97	$6.13
WWTP biogas to hydrogen (prospective pathway)	Fuel Cell Energy	-0.82	$2.84

Source: *CARB LCFS Pathway Certified Carbon Intensities and LCFS CARB Credit Price Calculator*

The LCFS-approved hydrogen pathways include four pathways for a proprietary methane cracking technology created by LytEn LLC. LytEn proposes using landfill gas or a combination of natural gas and landfill gas in each pathway. AC Transit has the fifth approved pathway for a hydrogen refueling station in Emeryville, California that utilizes two solar installations totaling just under 1MW with an on-site electrolyzer to produce up to 64kg/day of renewable hydrogen. Since the solar generation offsets the electricity required to produce and compress hydrogen from the electrolyzer, LCFS administrators have awarded AC Transit a certified CI score of 0 gCO_{2e}/MJ.

LCFS administrators also provide lookup table pathways that allow producers to expedite certification by applying for a pathway with minimal operational data reporting.

The five hydrogen pathways and one gasoline pathway (for reference) in the LCFS lookup table are listed in Figure 15.

In December 2016, LCFS officials announced plans to condense this table to four pathways for SMR and to add four additional pathways for electrolysis.[48]

Program administrators are also working to increase the number of applications from hydrogen producers by streamlining data collection processes and exploring ways to account for renewable electricity content in hydrogen production. LCFS currently does not account for the use of RECs toward CI scores but officials are considering allowing fuel producers to apply traceable renewable power investments.

Renewable hydrogen demand will increase as the 33.3% standard is enforced and the number of hydrogen stations and FCEVs continue to grow. Initially, this demand will be met utilizing a variety of sources including the purchase of biogas, investment in indirect renewable generation and on-site renewable hydrogen generation at stations. The supply of renewable hydrogen will increase as market barriers diminish and policy incentives grow beyond the SB 1505 renewable requirement. California policymakers clearly recognize their role in this process and have taken yet another leadership position by allocating nearly $4m in grant funding through the California Energy Commission's Grant Funding Opportunity 17-602 to fund the state's first 1000/kg per day 100% renewable hydrogen production facility.

Figure 15. LCFS Lookup Table Pathways

Existing Lookup Table Pathways	CI (gCO_{2e}/MJ)
Compressed H2 from central reforming of NG (includes liquefaction and re-gasification steps)	151
Liquid H2 from central reforming of NG	144
Compressed H2 from central reforming of NG (no liquefaction and re-gasification steps)	106
Compressed H2 from on-site reforming of NG	105
Compressed H2 from on-site reforming with 33% renewable feedstocks	88
CARBOB - based on the average crude oil supplied to California refineries and average California refinery efficiencies	100

Source: *Hydrogen in LCFS*

Economic Impact of Renewable Hydrogen: With a GDP of $2.5 trillion, California hosts the 6th largest economy in the world,[49] growing at a rate of 3.29% in 2015 and creating more jobs (483,000)[50] than any other state. California is well known for its progressive approach toward climate change and the environment. Many of California's policies follow suit, including the most recent GHG emissions reduction goal of 40% below 1990 levels by 2030, put in place by Governor Jerry Brown in 2016 (SB 32).

As part of its efforts to eliminate pollution and protect against climate change, California has committed to developing a hydrogen economy. The California Energy Commission committed $20 million/year for 10 years to build the initial network of 100 hydrogen fueling stations and recently committed approximately $4 million in additional funding to support development of renewable hydrogen production. In January 2018 Governor Brown increased the State's commitment to 200 stations.

California has helped create a new hydrogen economy for transportation, which has spurred investment activity from the private sector. More than a dozen developers applied for the most recent station grant solicitation, submitting more than 100 applications. Electrolysis firms previously working outside California are now establishing a presence within the state and companies that supply hydrogen tube-trailer trucks and certified drivers are now in demand to transport gaseous hydrogen to stations.

The American Recovery and Investment Act (ARRA) of 2009 established metrics that help estimate job creation based on infrastructure spending. Through this model:

- $92,000 of investment spending creates one job-year
- 64% percent of the job-years can be captured as direct and indirect job creation
- 36% of the job-years are induced effects

Direct jobs are those created specifically at the funded organization while indirect jobs relate to third parties such as suppliers and service-providers. Induced jobs are created elsewhere in the economy as increase in income lead to additional spending by companies and workers. This methodology suggests that California's original $200 million hydrogen infrastructure investment under AB 8 is creating over 2,000 new jobs and that Governor Brown's 2018 Executive Order will double that number (see Figure 16).

In 2008, the Department of Energy conducted economic analysis specific to the hydrogen transportation economy, submitting a report to Congress titled "Effects of a Transition to a Hydrogen Economy on Employment in the United States". The report analyzed two scenarios, one that assumed the success of President George W. Bush's Hydrogen Fuel Initiative (HFI) and a less-aggressive scenario. The HFI scenario assumed 96% light-duty market penetration of FCEVs by 2050 while the less-aggressive scenario assumed 38.2%. The projected impact on jobs was massive, suggesting that the HFI scenario would increase US employment by 675,000 jobs while the less-aggressive scenario would create 361,000 new jobs.

Additional research conducted by the Bay Area Council Economic Institute concludes that every $1 billion in infrastructure investment creates approximately 13,500 new jobs or about 24% more than the ARRA methodology.[51] Estimates of the total number of green jobs in California vary, but 2015 estimates published by the California Center for Jobs & the Economy indicate that the number was above 200,000 at the time, accounting for roughly 2% of total jobs in the state.[52]

To estimate job growth resulting from the development of new renewable hydrogen production facilities would require collection of CAPEX data relative to multiple production pathways, combined with feedstock and CSD development costs. Much of this data is proprietary and challenging to collect. Alternatively, perhaps the California Energy Commission solicitation for renewable hydrogen production can provide a glimpse of this potential job growth opportunity. The $4m solicitation covers up to 75% of total project cost, requires a minimum daily production capacity of 1,000/kg or about 1/30th of the daily transportation demand for hydrogen that CARB anticipates by 2022. Thus, a roughly $120m investment would be necessary to fully meet FCEV fuel demand in this short time frame. Without including CSD and feedstock development, this investment would create approximately 1,725 jobs in the next 5 years using ARRA methodology, or approximately 1,620 jobs using the methodology of the Bay Area Council Economic Institute.

Figure 16. Job Creation Estimation from California Hydrogen Station Investment

	(100 Stations)	(200 Stations)
CA H2 Station Investment	**$200,000,000**	**$400,000,000**
Job Years ($92,000)	**2,174**	**4,348**
Direct and Indirect Jobs (64% of a job year)	**1,391**	**2,782**
Induced Jobs (36% of a job year)	**783**	**1,566**
Total Jobs from Station Investment	**2,174**	**4,348**

Source: *Calculated by EIN Using ARRA Methodology*

Recommendations

Hydrogen is already a critical component of the global economy, serving as a necessary input for many industrial processes, including oil refining and fertilizer production. It is also poised to contribute to the sustainable energy economy and clean air future well beyond its use as a transportation fuel. The most abundant substance on earth, hydrogen is uniquely versatile and holds enormous potential as a fuel and energy carrier for materials handling, goods movement, energy storage, grid management and power production.

The fundamental challenges impeding the growth and adoption of renewable hydrogen are primarily economic. Production technology is already well-established and sustainable feedstocks such as biogas and renewable electricity are amply available in California.

This roadmap identifies key issues that have the greatest potential to stimulate the successful integration of renewable hydrogen into our clean transportation and sustainable energy future. The following are designed to provide a framework to help guide the priorities and investments of policymakers, regulators, consumers and business leaders.

1. Begin the Journey to 100% Renewable Hydrogen Now

2. Fund Scalable Projects for 100% Renewable Hydrogen Production

3. Improve Low Carbon Fuel Standard (LCFS) Incentives

4. Promote Tools to Lower the Cost of Electricity for Renewable Hydrogen Producers

5. Address Hydrogen Distribution and Storage Challenges

6. Expand the US EPA’s Renewable Fuel Standard (RFS) Program

7. Incentivize Consumers and Stakeholders

8. Broaden the Hydrogen Community Through Education & Outreach

1. Begin the Journey to 100% Renewable Hydrogen Now

Hydrogen is an elegant solution to the challenge of cleaning up the transportation system, but it would be short-sighted to focus solely on promoting vehicle adoption and building retail distribution capabilities without pursuing 100% renewable hydrogen production methods. As of January 2018, there were 31 hydrogen stations and approximately 3,800 FCEVs in California. There is no better time to begin developing the final component, 100% renewable fuel production, to support a complete zero-emission well-to-wheel transportation solution. This small quantity of stations and vehicles could have feasibly been supplied by as few as 2 modestly-sized (1,000kg/day) renewable production facilities – if the hydrogen community had only begun development 2 years ago.

While FCEV rollout plans and the supporting station framework have been evolving for years, renewable hydrogen production efforts are only now gathering momentum. Projects that commence now likely will take 2 years to develop, at which point CARB is projecting 13,500 FCEVs and 60+ stations. In order to even have a chance of catching up to the point where renewable production can meet demand in the near-to-medium term (even at 33.3%), policymakers and the hydrogen stakeholder community should immediately support renewable production projects that are scalable well beyond one station. In doing so, the hydrogen community will be in a position to "catch up" to the point where there is enough renewable fuel supply to fill demand while lowering FCEV well-to-wheel emissions profiles even further, proving the concept to industries beyond transportation and boosting the California economy along the way. Otherwise, the FCEV community could easily grow beyond the point where renewable hydrogen production would be able to catch up, even in a 10-year time frame, because producers likely would still have to begin with modest (1,000kg/day) facilities due to investment risk, feedstock constraints, etc. Even waiting 3 years to initiate the development of renewable hydrogen production, assuming a 2-year commissioning process, California would need to start with 10 production facilities (1,000kg/day) just to meet the 33.3% requirement by 2022 and up to 30 production facilities, at the same time, to achieve a 100% renewable hydrogen fuel supply in 2022.[53]

2. Fund Scalable Projects for 100% Renewable Hydrogen Production

California taxpayers have invested in the infrastructure to establish retail distribution of hydrogen for transportation—largely because Californians want to combat climate change by reducing GHG emissions and improve air quality by mitigating harmful criteria pollutants that lead to serious health issues. ZEV adoption is a huge step toward cleaning up the transportation sector, but the vehicles can only be as clean as the sources of their fuel.

Policymakers and hydrogen stakeholders, right now, have the rare opportunity to create a 100% renewable and sustainable transportation system while the FCEV market and supporting infrastructure are still in their infancy. Each additional year that it takes to initiate renewable production projects will result in multi-year shortages of renewable hydrogen for FCEVs due to rapid growth in vehicle adoption and station openings. If the hydrogen stakeholder community waits only 3 years to begin developing renewable production, it could take an additional 10-20 years to catch up to the point where demand for even 33.3% renewable hydrogen content can be met without offsets from other markets.

In 2017, the California Energy Commission recognized this challenge and responded by issuing a competitive grant solicitation for almost $4m to support renewable hydrogen production for FCEVs. This is a powerful signal from California that will serve to jump-start the market. Policymakers should monitor this project and build from the momentum in order to begin scaling up this critical area.

Steep upfront costs and early market risk will continue to deter market investment in renewable hydrogen production. To offset these costs and to jump-start the renewable hydrogen marketplace, policymakers should develop strategy to catalyze investment in production projects that increase in scale and utilize various feedstocks such as biogas and curtailed renewables. This will instill investor confidence, signal California's long-term commitment to the FCEV market and serve to increase the role of renewable hydrogen in industrial processes and energy storage.

These projects will generate valuable data on cost, scalability and challenges while educating the public about the role of renewable hydrogen in achieving zero-emission transportation and energy systems. They can also serve to focus on individual challenges within the energy system such as feedstock development, scrubbing technologies, pipeline injection, etc.

3. Improve Low Carbon Fuel Standard (LCFS) Incentives

LCFS credits are a vital market incentive, establishing a critical revenue driver for fuel producers while the market for FCEVs is in its infancy. Station and fuel developers must be able to predict basic cash flow in order to justify capital investments to support FCEVs. LCFS credit revenue helps bolster cash flow for investors but the market is volatile due to volume fluctuations and uncertainty about the duration of the overall program.

Extend the LCFS Program for 10+ Years

Developers need long-term certainty in order to make capital investments in a nascent industry. Extending the LCFS credit market for 10 years or longer would provide a significant level of stability and bankability for investors as a support mechanism for a hydrogen market that could take decades to mature. Developers of hydrogen stations and production facilities could model revenue from LCFS credits through a significant portion of the lifetime of their equipment rather than just a few short years, reducing investment risk and making projects more attractive. This would also incentivize production of renewable hydrogen while lowering prices to consumers because LCFS credit values increase along with the level of renewable content in the fuel.

Establish a Market Floor

The LCFS credit market is subject to a cap in credit values, limiting the maximum value of credits for fuel producers, but the program does not have a floor to ensure a minimum value for credits. A minimum value for LCFS credits would provide stability and confidence in the credit market, allowing investors to more accurately project revenue and mitigate the risk of financing new projects. Advocating for the LCFS floor is a step that stakeholders can take by educating policymakers and LCFS administrators about the challenges the sector faces, and how a floor would help promote new projects.

Establish New Pathways for Renewable Hydrogen

LCFS program administrators evaluate individual production methods and assign carbon intensity (CI) scores that reflect the amount of carbon used in the fuel production process. The lower the CI of a production method, the higher the value of the credit. Currently, five LCFS-certified hydrogen production pathways exist, but many more production methods (or variations of approved methods) have yet to be analyzed. The stakeholder community would benefit from certifying as many LCFS pathways as possible, so that these valuable credits can be modeled into investment profiles <u>before</u> developers attempt to finance renewable hydrogen production processes. This would help alleviate investor uncertainty and improve developer access to financing by demonstrating that investors can rely on a consistent LCFS marketplace.

Consider Existing Pathways that Currently Do Not Qualify for LCFS Credits

While renewable grid content contributes to LCFS credit values for plug-in electric vehicles, renewable hydrogen producers do not receive LCFS credits for the same electricity. This puts hydrogen producers at a disadvantage by disregarding the actual renewable content of the fuel and forcing them to look elsewhere for renewable feedstocks. Policymakers should seek to create a fair market for LCFS credits by holding fuel producers to the same standards.

Policymakers should also consider allowing renewable hydrogen project developers to leverage existing landfill gas production in California as an eligible feedstock to meet SB 1505 requirements and to qualify for LCFS credits at least in the near term. California is phasing organic waste out of landfills and limiting new landfill gas projects but existing landfill gas projects have the potential to help bridge the gap in renewable hydrogen production while new facilities emerge using different feedstocks.

4. Promote Tools to Lower the Cost of Electricity for Renewable Hydrogen Producers

The cost of producing hydrogen is largely a function of the cost of the energy sources or feedstocks that fuel the production process. Electrolysis (splitting water molecules into hydrogen and oxygen using electricity) holds enormous potential for renewable hydrogen production because the technology is mature and access to renewable electricity is growing rapidly.

In fact, due to variable consumer demand and variable wind/solar energy production, California utilities are already forced to curtail significant amounts of electricity during periods of over-production. Electrolyzers offer unparalleled grid management capabilities, allowing excess renewable energy that would otherwise be wasted to be stored in the form of hydrogen, which can be used for transportation fuel or returned to the grid through fuel cells. In 2017 alone, California curtailed enough electricity to fuel approximately 50,000 FCEVs for the entire year.

While curtailed renewable electricity can be cheap, free or even generate revenue (utilities often have to compensate third parties to take the excess electricity), developers cannot predict the availability of this feedstock. Electrolyzers must operate consistently and produce enough hydrogen to cover capital costs as well as ongoing operations and maintenance expenses. Thus, operators must have access to a continuous supply of electricity, putting them at the mercy of fluctuating energy prices.

As is the case with any business investment, electrolyzer operators must be able to project future revenue and profits despite fluctuating energy prices that account for approximately two-thirds of operating costs. For this process to be financially sustainable, operators must secure access to long-term, low-cost electricity commonly in the range of $.05 - $.06 per kilowatt-hour.

Renewable hydrogen stakeholders and advocates should organize their efforts through a strategic action plan that focuses on developing long-term rate management strategies such as:

- **Maximizing and expanding Time-of-Use (TOU) incentives.**
- **Negotiating access to wholesale rates or preferential pricing (common for refineries and increasingly for EV charging).**
- **Increasing LCFS electrolyzer pathway allowances to include renewable content from the grid (rather than just direct renewable use or content that is offset by credits).**
- **Identifying relevant proceedings and events for stakeholders to provide comments and advocacy for preferential or wholesale electricity rates.**
- **Coordinating electrolyzer firms, utilities, utility commission representatives, California Energy Commission leaders and other relevant parties to discuss challenges and explore potential resolutions.**
- **Creating and distributing outreach materials to help inform and update stakeholders, consumers and the general public.**
- **Researching how to maximize Green Tariff and Shared Renewables (GTSR) impacts on the price of electricity and the levelized cost of hydrogen for electrolyzer projects.**
- **Researching how GTSR interacts with other demand/response utility programs such as time-of-use (TOU) rates.**
- **Researching how GTSR can positively impact LCFS pathways and procurement of LCFS credits.**

5. Address Hydrogen Distribution and Storage Challenges

Hydrogen storage and distribution can be expensive, in some cases costing more than production including operating expenses and renewable feedstocks (see Figure 12). Hydrogen fuel for the transportation sector is primarily stored in a gaseous state and trucked using heavy duty vehicles. Compressors, however, require substantial energy inputs and trucking commonly produces greenhouse gas emissions and criteria pollutants.

While much of this roadmap analyzes renewable hydrogen in the context of a transportation fuel, the scale of renewable hydrogen as an energy storage mechanism or as a clean industrial feedstock is massive. For example, the average daily volume of California hydrogen stations in Q3 2017 was 1,291 kg/day. Earlier that year, in April 2017, California ISO reported energy curtailment of more than 87GWh or enough to produce and store approximately 48,000 kg of hydrogen per day. In fact, current research shows that there is plenty of curtailed PV available to produce enough renewable hydrogen to fuel FCEVs in the base CARB scenario well past 2050.[54] Figure 4 indicates that current hydrogen production for industrial purposes in California is about 2,100,832 kg/day. Hydrogen in these volumes simply must be consumed at the site of production or distributed via pipeline.

In order to maximize the potential of renewable hydrogen, stakeholders must explore ways to lower the cost of storage and distribution, focusing on the following areas:

Fund Research & Development for Hydrogen Storage Technologies.
One of the major benefits of hydrogen as an energy carrier is that it can be transported and stored in gaseous or liquid form. Other storage mediums such as liquid hydrogen organic carriers (LOHC) and hydrides are in the R&D phase but not yet commercial. Currently, gaseous storage, delivery and fueling dominate the hydrogen ecosystem in California. Gaseous hydrogen is less expensive to transport and store at lower volumes, but the lower volumes require more frequent re-filling. Liquid hydrogen, however, offers both benefits and challenges that will impact storage and distribution costs as well as the cost and capacity of FCEV fueling stations. For example, delivery trucks can carry significantly more liquid hydrogen (lowering the cost and environmental impact of trucking) but the cost of liquefaction combined with trucking equipment and on-site liquid hydrogen storage are higher. The high cost of liquefaction equipment is generally only economical when combined with large-scale centralized production facilities. Further analysis into the costs and opportunities for a storage network is needed to fully understand how the industry can plan for, and implement, a long-term storage solution for hydrogen.

Fund Studies and Demonstration Projects Focusing on Increasing Levels of Hydrogen in Existing Natural Gas Pipelines and Support Increased Hydrogen Injection Standards.
The California Energy Commission, Public Utility Commission and gas utilities are natural stakeholders in this endeavor and should collaborate to investigate the effects of increasing permissible levels of hydrogen in existing natural gas pipelines. Canada, Japan and several European countries already allow significantly more hydrogen to be injected into pipelines and there are many international demonstration projects that highlight potential in this area. Currently, there is one demonstration project in the US, at the University of California, Irvine. This project successfully demonstrates an important way to capture clean energy that would otherwise be wasted. Policymakers should use this information to guide new injection standards and to promote additional research that will drive progress in this area.

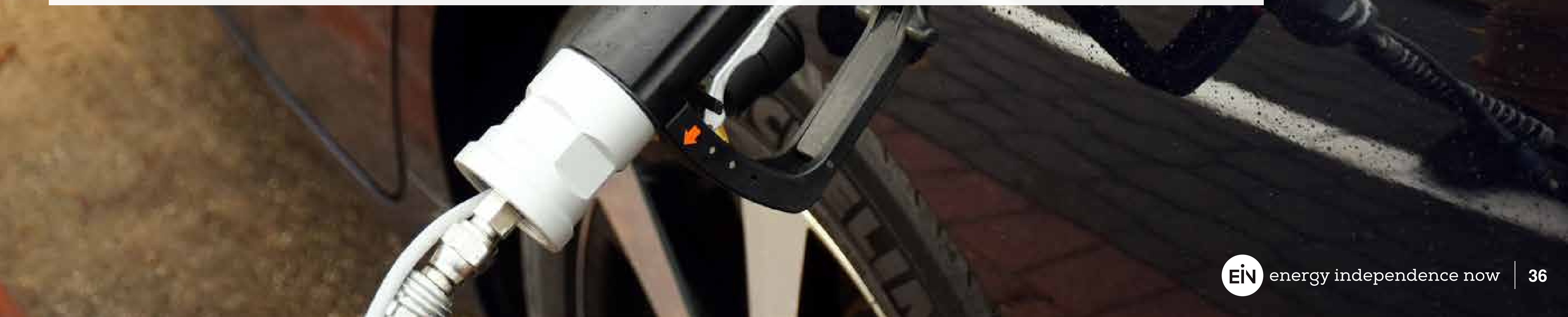
Support Dedicated Hydrogen Pipelines.
Eventually, hydrogen should have dedicated pipeline systems that can support retail and industrial customers. This will help reduce the cost of hydrogen and provide a storage and distribution resource that will promote increased use of renewables from biogas and stranded or excess wind & solar.

6. Expand the US EPA's Renewable Fuel Standard (RFS) Program

Add Hydrogen as a Pathway to the RFS Program, Making RIN Credits Available to Renewable Hydrogen Producers. The US Congress created the RFS Program to reduce GHG emissions, expand the US renewable fuel sector and reduce US dependence on imported oil. Under the RFS program, the US Environmental Protection Agency assigns RINs to approved renewable fuels. RINs function as the currency of the RFS program, adding a valuable revenue driver for some renewable fuel producers, who can sell them as credits to regulated parties such as oil refineries.

RNG, an important feedstock for renewable hydrogen, is currently an approved RFS pathway that generates valuable RIN credits. However, hydrogen is not an approved RFS pathway even when producers use RNG as a feedstock. Thus, RNG producers generate valuable RIN credits that inflate prices for biogas, while hydrogen producers that use the same biogas as a feedstock are not eligible to collect the same RIN credits. This creates an unfair financial advantage for RNG producers and a distinct competitive disadvantage for renewable hydrogen producers.
This flaw in the RFS program penalizes renewable hydrogen producers that utilize biogas feedstock because they pay more for RNG, effectively forcing them to buy RIN credits that they don't need and that they cannot recover through the sale of renewable hydrogen fuel (which has a lower GHG profile than RNG because hydrogen is not combusted in FCEVs).

The EPA's RFS program should incorporate the production of renewable hydrogen as an approved pathway and allow hydrogen producers to generate RIN credits. This will lower the cost of hydrogen fuel for consumers and offset the expense of developing renewable hydrogen production projects that use biogas or renewable electricity feedstocks.



7. Incentivize Consumers and Stakeholders

Reward Consumers. Direct and indirect incentives have helped drive the FCEV market and thus, the consumer market for hydrogen fuel. FCEV customers currently benefit from financial incentives, including a $5,000 rebate from the State of California and another $1,500 rebate for low-income adopters, as well as indirect incentives such as access to carpool lanes and free metered parking in some cities. Additionally, automakers are commonly offering three years of free fueling, offsetting up to $15,000 of fuel costs. Unfortunately, a federal tax credit of up to $8,000 for FCEV customers expired on December 31st, 2016. The loss of the federal tax credit is clearly a blow to the FCEV industry and stakeholder groups should actively pursue replacing or reinstating this incentive. Consumers should be rewarded for making the choice to drive clean-air vehicles and for doing their part in reducing pollution from transportation. Rewarding consumers can come in a variety of ways, each of which can be explored and piloted in the short term to gauge effectiveness, but these incentives must remain in place for more than five years in order to allow enough time for consumer awareness to build and to allow the automotive industry the necessary time to ramp up development, production and marketing efforts for the vehicles.

Look Beyond the FCEV Community. California policymakers should encourage the use of renewable hydrogen for energy storage and industrial applications by generating awareness and incentives that reach beyond the FCEV community. Outreach campaigns should target new users while leveraging the massive existing community of hydrogen consumers to reduce costs of renewable production and distribution technologies through economies of scale. Such opportunities include: (1) incentivize petroleum refineries to use renewable hydrogen to meet a portion of their current demand (hydrogen is widely used by refineries to produce petroleum distillate fuels); (2) encourage the use of renewable hydrogen in ammonia production; (3) explore incentives to utilize renewable hydrogen for industrial heating that currently relies upon natural gas; and (4) increase industrial end uses of renewable hydrogen in processes such as food production.

8. Broaden the Hydrogen Community Through Education & Outreach

Now that FCEVs are available to consumers and hydrogen stations are open to the public, the FCEV industry needs advocates to help educate drivers, decision-makers and thought leaders. Stakeholders should provide an objective non-partisan voice of support to raise awareness about the emerging FCEV marketplace throughout California and the rest of the country. The hydrogen stakeholder community must make a coordinated effort to reach out to state and local government representatives to provide informational materials and briefings. EIN proposes the development and dissemination of a strategic action plan with the following recommendations:

- **Identify officials in positions of influence related to the hydrogen sector.**
- **Identify the most effective policy actions for the sector and ensure that the hydrogen community is prepared, responsive and present. This should include participation in public meetings on issues such as changes to LCFS or RFS and responding to requests for public comment on all issues that impact the hydrogen community, such as CPUC storage proceedings.**
- **Target policymakers with outreach materials that illustrate the benefits of renewable hydrogen, background information on the sector and key issues.**

Conclusion

EIN's goal is to promote – through research, advocacy, outreach and market engagement – the goal of achieving 100% renewable and decarbonized hydrogen production and consumption. EIN plans to follow this roadmap with a quantitative assessment of the renewable hydrogen ecosystem in order to highlight relevant economic opportunities and to promote investment in this critical area. Once renewable hydrogen projects begin to scale, we expect the market to find cost reduction mechanisms that will support additional development, eventually meeting all of the transportation sector's demand (including light, medium and heavy-duty vehicles as well as materials handling and goods movement).

Eventually, the entire fuel supply powering FCEVs (and Plug-in Electric Vehicles) needs to be generated renewably. It is EIN's opinion that with a nascent market for renewable and sustainable fuels emerging in California, and with economies of scale developing over time, 100% renewable hydrogen is a feasible goal.

This roadmap illustrates the case for renewable hydrogen through the lens of transportation but it truly transcends the entire energy sector – enveloping agriculture, waste management and urban planning. Even with the projected number of FCEVs in California surpassing 40,000 by 2022,[55] hydrogen demand by the transportation sector will still only amount to roughly 1% of California's overall need for this vital energy carrier. If all the hydrogen in the state — approximately 550 million kg annually — were produced renewably, it would have a truly massive economic and environmental impact.

While California has helped promote renewable hydrogen as part of the zero-emission transportation future, much work remains to be done. Several additional policy mechanisms are necessary to push the renewable hydrogen sector forward, as well as relatively minor changes to existing programs such as RFS and LCFS. Through these efforts, and the others outlined in this roadmap, we are confident that renewable hydrogen projects will rapidly come on line.

EIN envisions a future with clean air and a stable climate. We see hydrogen fueling stations with on-site renewable hydrogen generation using electrolysis with solar. We see renewable hydrogen production using tri-generation at wastewater treatment plants and landfills. Down the road, we see large-scale renewable hydrogen production plants co-located with large-scale wind, solar and other renewable electricity generation sites. We see chains of dairy digesters generating large amounts of biogas as feedstock for steam reformation or tri-generation. All of this is possible because these technologies are mature, available today and already in use worldwide.

We see a future in which renewable hydrogen fuels our lives, our economy and our world. For transportation, agriculture and industry. For energy storage. For a cleaner, healthier and more energy-efficient way of life.

All it takes is for someone to lead the way – and who better than California?

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