ADVANCED POWER & ENERGY PROGRAM

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Renewable Hydrogen Production

ROADMAP FOR CALIFORNIA

#RH2@APEP

RENEWABLE HYDROGEN

UCI ADVANCED POWER AND ENERGY PROGRAM

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ACKNOWLEDGEMENTS

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PURPOSE AND OVERVIEW

Purpose of the Roadmap

The purpose of this roadmap is to provide guidance to state policy makers and industry participants on policies, programs and collective action needed to ensure the successful build- out of a robust renewable hydrogen sector in California serving transportation and other energy needs as a key part of the zero-carbon economy. The roadmap also serves as a source of information for the public and interested stakeholders. As depicted in the diagram below (Figure 1), hydrogen (in blue) can form an important element of the future, integrated, zero-carbon energy and transportation sectors. The roadmap seeks to support successful evolution toward this future through rigorous analysis of evolving demand, technologies needed to serve that demand and options for effective policy support. This roadmap builds on the extensive body of work that has been developed on optimal hydrogen refueling station network deployment by addressing the supply side of the hydrogen value chain as well as assessing additional sources of future demand such as refining, ammonia production and renewables firming.

Building on Global Action

Many regional and national governmental organizations including the European Union, Japan, Australia, Korea and China have articulated clear visions and policy frameworks embracing zero-carbon hydrogen as a foundation of their long-term energy strategies.[1] Major international corporations have done the same. Hydrogen Council, an association of more than 8 major international companies, has committed to the bold goal of achieving 100% zero-carbon hydrogen by 2030 as part of a comprehensive vision for the future of hydrogen providing nearly 20% of primary energy in 2050.[2] Global auto manufacturers Toyota, Honda and Hyundai have launched hydrogen-fueled vehicles, China has deployed more than 50 hydrogen transit buses and Nikola, Toyota, Kenworth, and Cummins are developing hydrogen-fueled heavy-duty trucks. At the national level, the U.S. Department of Energy has established a major initiative to pursue hydrogen solutions across the economy through its hydrogen at scale (H2@Scale) initiative.

Progress in California

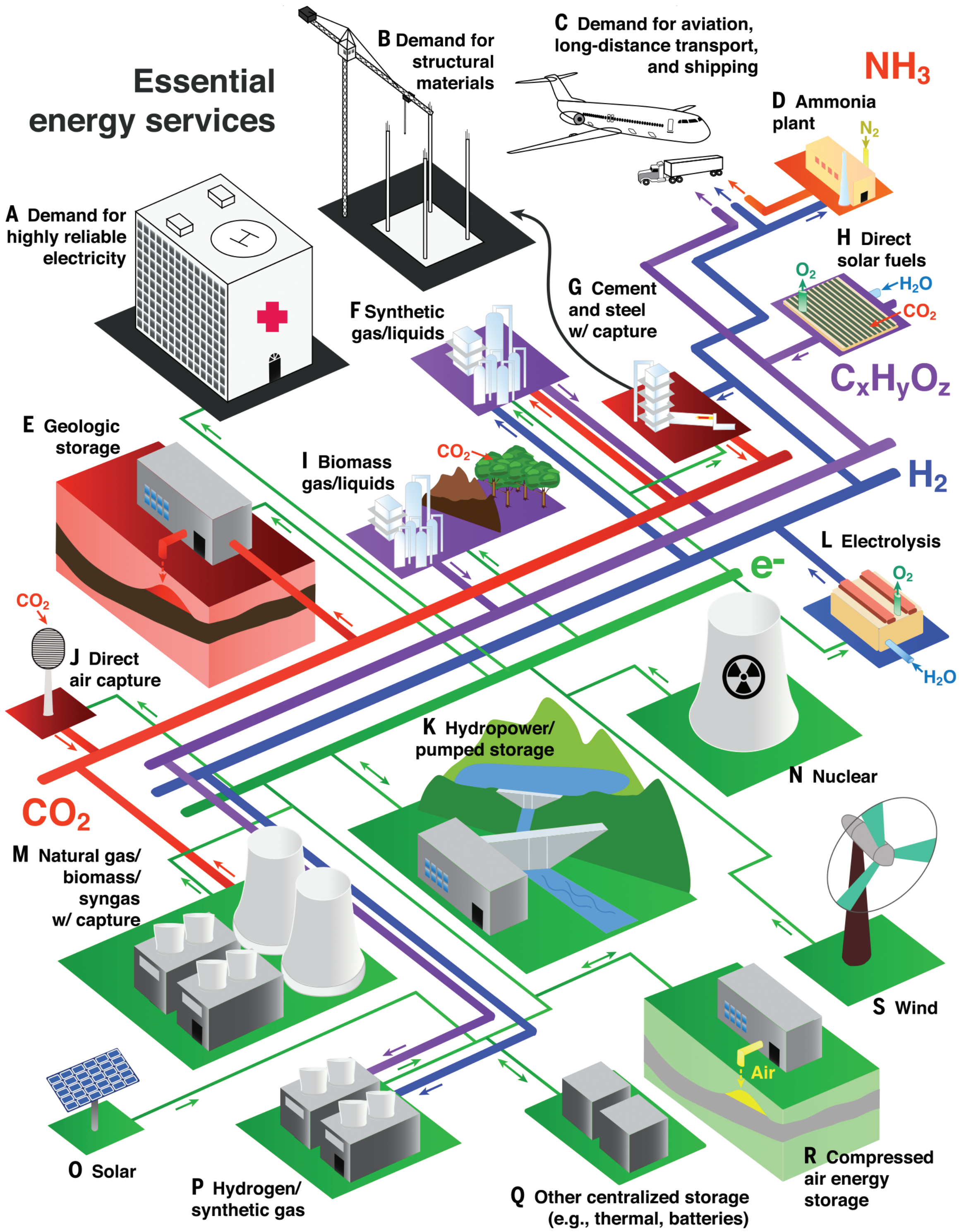
Going back as far as Governor Schwarzenegger's hydrogen highway vision in 2004[3], California has been the national leader in embracing hydrogen as part of the transportation and energy future. California is now the global leader in launching and scaling the light-duty hydrogen fuel-cell electric sector with over 40 hydrogen fueling stations in operation, nearly 30 under construction and plans to grow the network to 1000 stations by 2030. California now has nearly 7,000 hydrogen vehicles on the road and will reach 50,000 in less than five years, and as many as 1,000,000 by 2030. Through a combination of private capital and Energy Commission funding, nearly 50 tonnes per day of new renewable hydrogen production capacity has been announced to serve the California market, enough to supply over 60,000 hydrogen vehicles. The state has established through Assembly Bill 8, a program administered by the Energy Commission to fund 100 hydrogen fueling stations as a foundation for a network of up to 1000 stations by 2030 (Figure 2). California is once again demonstrating its global leadership in advancing clean energy and transportation solutions.

1 https://www.fch.europa.eu/news/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition ; https://www.meti.go.jp/english/press/2019/0312_002.html ; https://www.csiro.au/en/Do-business/Futures/Reports/Hydrogen-Roadmap ; https://www.koreatimes.co.kr/www/tech/2019/01/419_262238.html ; www.ihfca.org.cn/file/FCV%20Tech%20Roadmap.pdf

2 www.hydrogencouncil.com

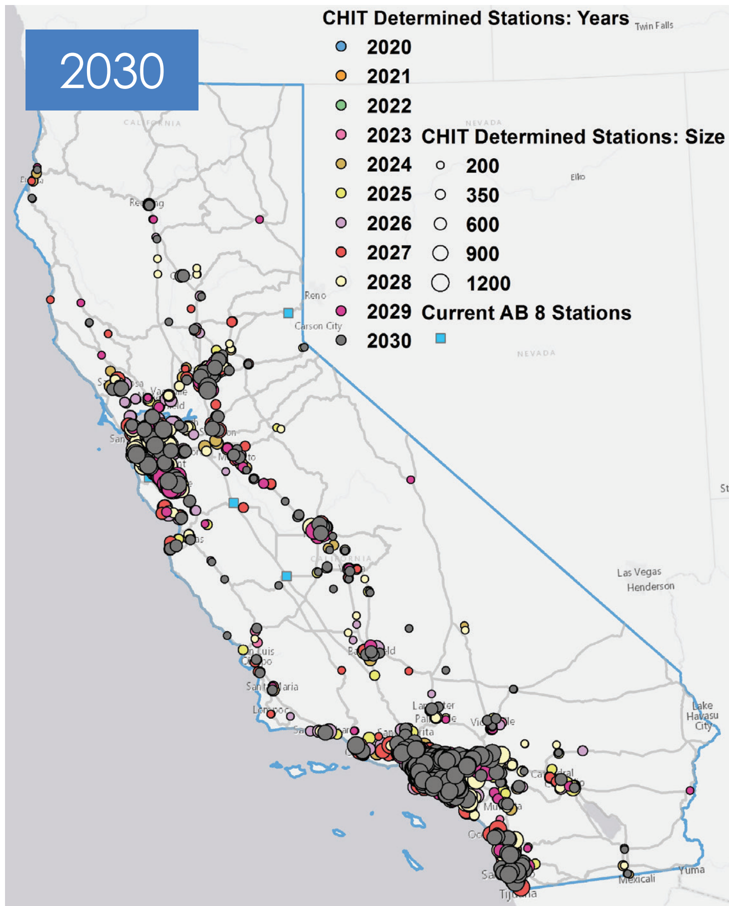
3 Executive Order (EO) S-07-04

Figure 1. The Future Energy and Transportation Ecosystem



Source: From Davis et al., Science 360, 1419 (2018)

Figure 2. California Hydrogen Refueling Station Build-out Scenario



Source: California Air Resources Board 2018 AB 8 Report

A principal conclusion of the roadmap analysis is that, with continued policy support, the renewable hydrogen sector can achieve fuel-economy adjusted price parity with conventional fuel by the mid 2020’s and can ultimately reach a dispensed price of $5/kg or below with plant-gate hydrogen cost below $2/kg. The projected pump price evolution is shown in Figure 3.

Figure 3. Cost of Dispensed Renewable Hydrogen

Source: UCI APEP

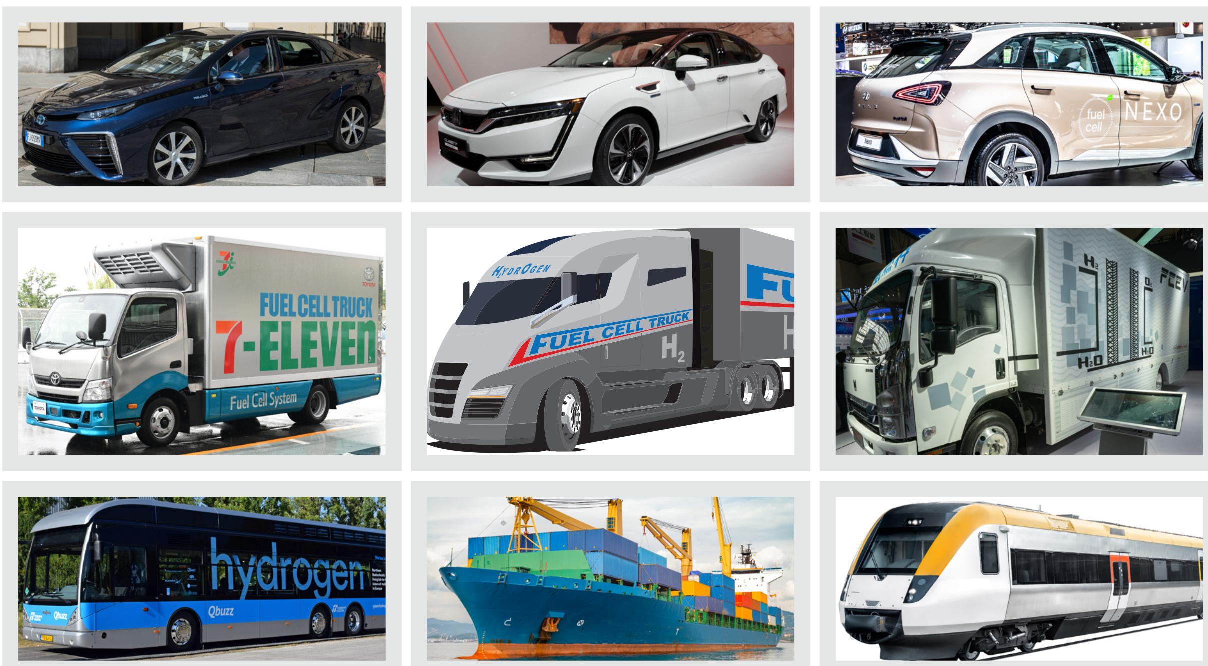
The state has established through Assembly Bill 8, a program administered by the Energy Commission to fund 100 hydrogen fueling stations as a foundation for a network of up to 1000 stations by 2030 (Figure 2).

California is once again demonstrating its global leadership in advancing clean energy and transportation solutions.

THE OPPORTUNITY

Hydrogen can serve as a critical foundation to electrification as a decarbonization strategy. Renewable electricity from solar and wind is an energy source. Hydrogen is an energy carrier that is energy dense and easily storable for indefinite periods. Hydrogen can fill an indispensable and complementary role to pure battery solutions and is particularly well suited for long-duration storage and transportation applications requiring long range or heavy payloads necessitating large amounts of on-board energy storage. Transportation will be the primary source of demand for renewable hydrogen (Figure 4) but beyond its potential role in transportation, hydrogen can provide firm renewable power and serves as a primary input to fertilizer manufacture, refining, industrial processes and next-generation steel making.

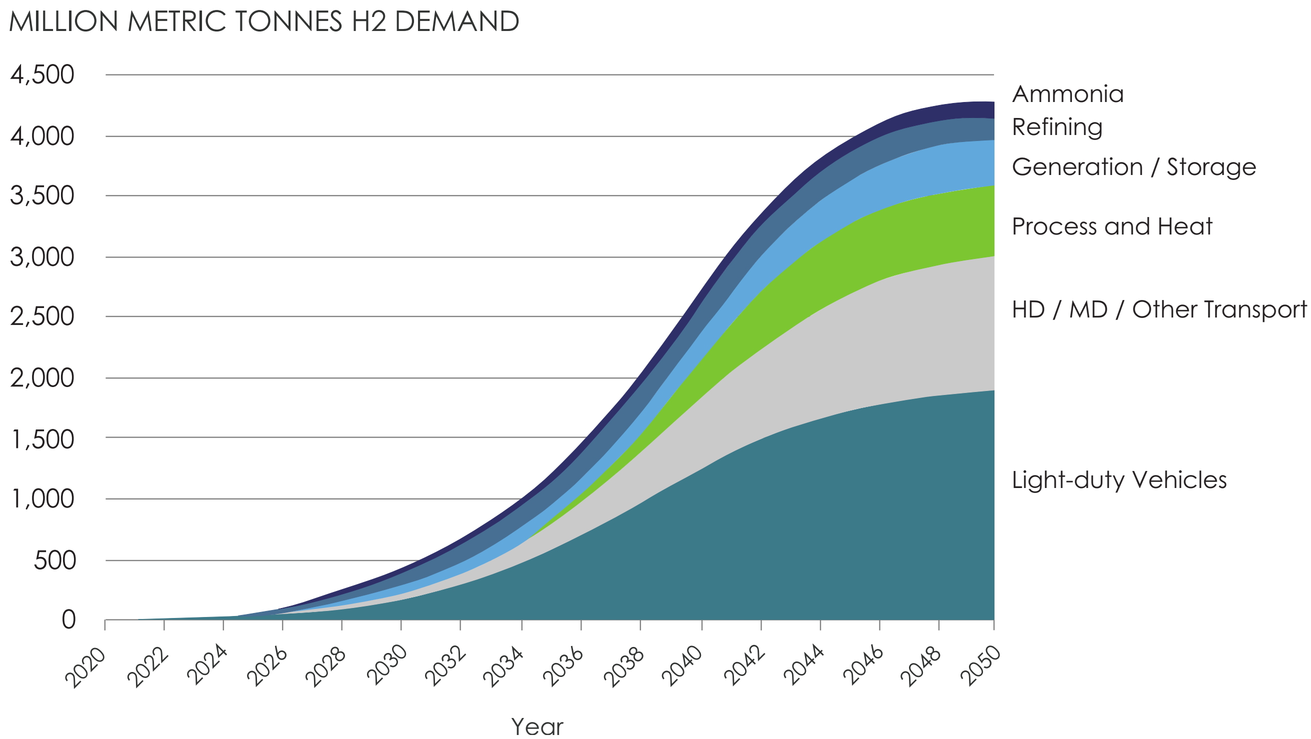
Figure 4. Hydrogen in Transportation

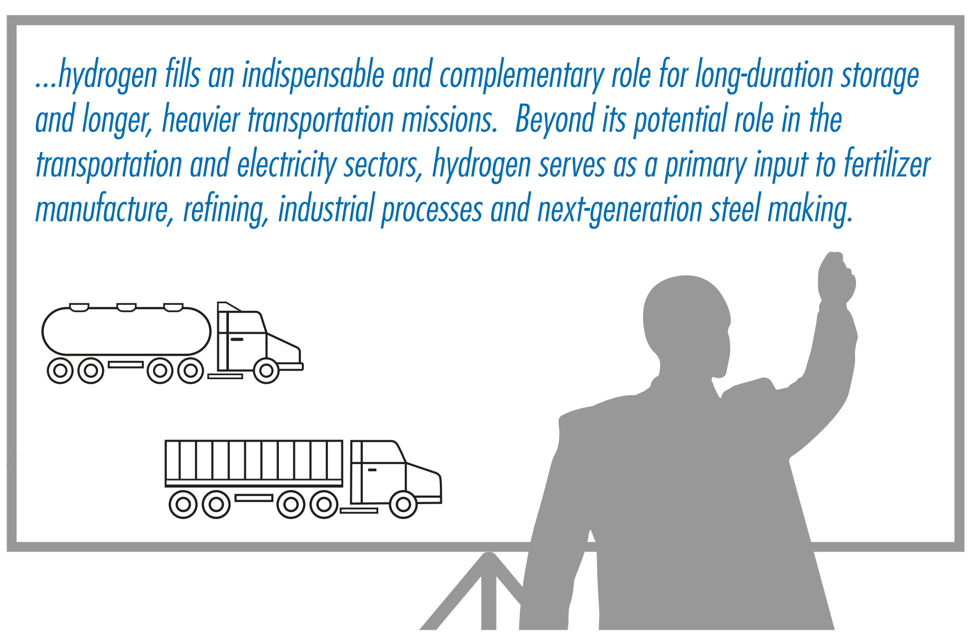


So how big an opportunity does the hydrogen economy represent for California? Assuming continued policy support and consumer adoption, renewable hydrogen demand in California could reach 4.2 billion metric tonnes annually (Figure 5) and could contribute nearly $2B to the California economy by 2030 and $18B by 2050, providing approximately 15% of California's energy consumption across all sectors[4]. Not only will this create tens of thousands of green energy jobs but it will ensure continued progress on reducing air pollution which disproportionately impacts our most vulnerable and disadvantaged communities. Renewable hydrogen will play critical, arguably indispensable, role in enabling California to go the last mile and reach 100% zero-carbon energy. The state needs to maintain its early momentum and scale up its efforts to make this a reality.

4 Assuming California ultimate energy consumption in 2050 of 2.8 exajoules (estimate from E3 "Deep Decarbonization" report CEC-500-2018-012)

Figure 5. Potential California Renewable Hydrogen Demand Growth

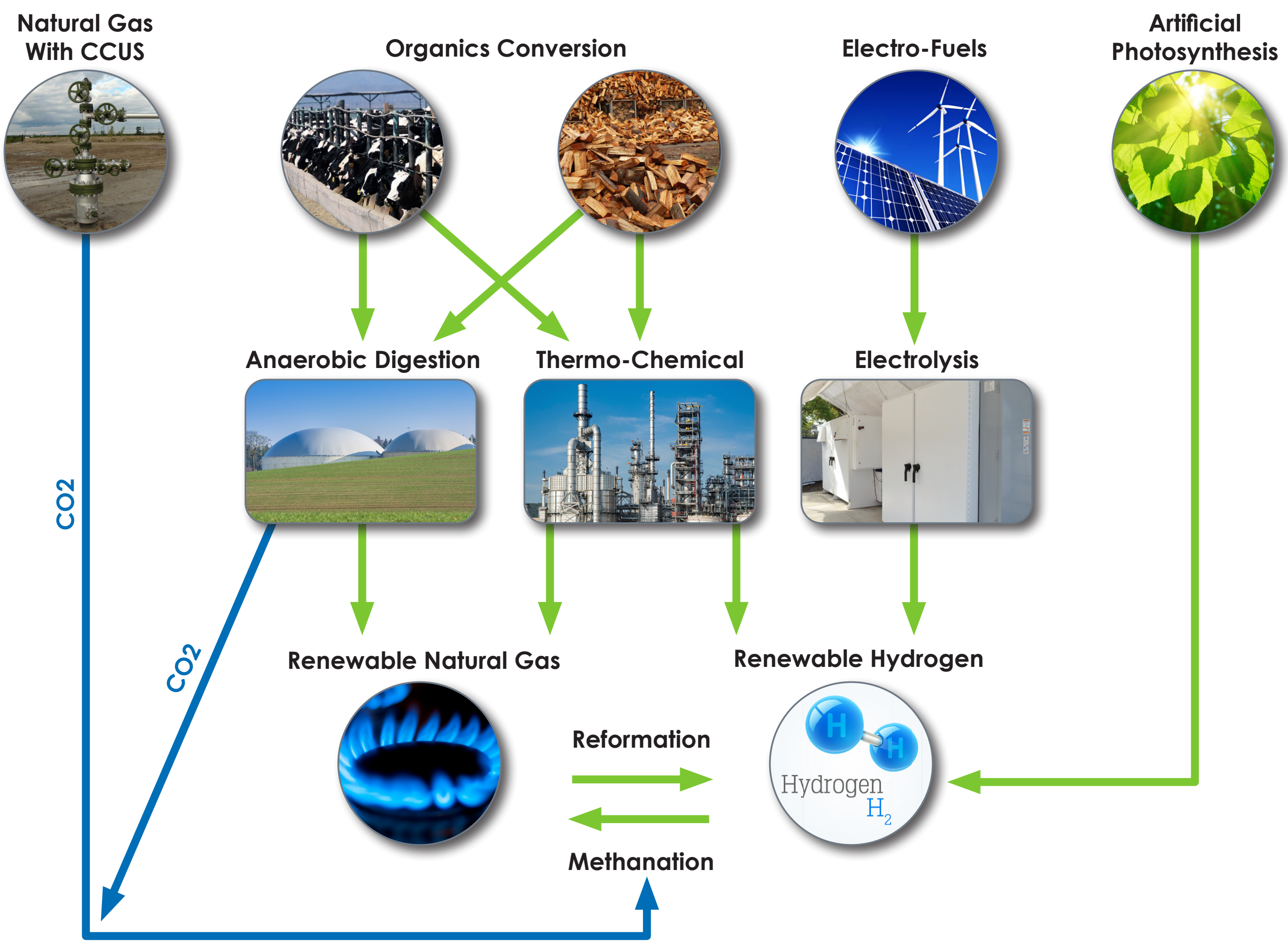




SOURCES OF SUPPLY

Renewable hydrogen (hydrogen from 100% renewable inputs) can be produced in a variety of ways (Figure 6). In basic terms, the primary methods are: 1) "splitting water" – taking H2O and splitting it into hydrogen and oxygen – using renewable energy; and 2) extracting the hydrogen content from biomass organic material (which does not produce net carbon because of its continuous growth and regrowth cycle) by chemical or thermal processes. California has abundant resources to produce hydrogen from both these pathways. Longer term, it may be feasible to split water directly in a process referred to as artificial photo synthesis. Zero-carbon hydrogen can also be created from natural gas if technology to sequester the resultant carbon emissions or bind the carbon into useful solid is included in the process. Although there are limits on the amount of renewable electricity or biomass resources that can be developed in California, the in-state resource potential is vast and is more than adequate to serve foreseeable demand.

Figure 6. Renewable Hydrogen Production Pathways



Source: UCI APEP

Today, nearly 55,000 kilograms per day of conventional merchant hydrogen production capacity (which is capacity not integrated into refinery operations) is in operation in California. The largest facilities are the Praxair plant in Ontario and the Air Products facility in Sacramento[5]. The current capacity serves the non-transportation, conventional merchant hydrogen market and is not considered renewable hydrogen supply capacity for this analysis. Six new projects targeting the California hydrogen transportation market and capable of producing or processing renewable hydrogen have been announced since 2017:

- Air Liquide—30,000 kilogram per day capacity steam methane reformer and liquefaction plant that will be capable of processing pipeline biomethane into renewable hydrogen.[6]
- Air Products—second liquefaction unit (capacity not announced).[7]
- Fuel Cell Energy and Toyota—1,200 kilogram-per-day Trigen facility at the Port of Long Beach.[8]
- Stratos Fuels—5,000 kilogram-per-day nameplate electrolytic hydrogen production facility powered by renewable electricity made primarily from wind turbines, with funding support from the CEC.[9]
- H2B2—1,000 kilogram-per-day electrolytic hydrogen production facility powered by renewable electricity from solar photovoltaic panels, with funding support from the CEC.[10]
- Sunline Transit – 900 kg per day electrolytic hydrogen production facility.[11]

The future buildout of renewable hydrogen facilities in California will be driven largely by cost and availability of feedstock (biomass and renewable electricity). Figure 7 shows the primary development areas for the various production technologies and feedstocks. Several buildout scenarios were developed for the roadmap based on varying assumptions regarding demand and relative progress of technologies. Figures 8 through 10 show the buildout under the high-demand scenario. Meeting the high-case demand scenario requires over 1,000 metric tonnes per day of new renewable hydrogen production capacity by 2030 and nearly 12,000 metric tonnes per day of capacity by 2050.

5 U.S. Department of Energy cited in the EIN Renewable Hydrogen Roadmap https://einow.org/rh2roadmap

6 Air Liquide Press Release https://energies.airliquide.com/air-liquide-build-first-world-scale-liquid-hydrogen-production-plant-dedicated-supply-hydrogen%20

7 Air Products Press Release www.airproducts.com/Company/news-center/2019/01/0107-air-products-to-build-second-liquid-hydrogen-productions-facility-in-california.aspx%20

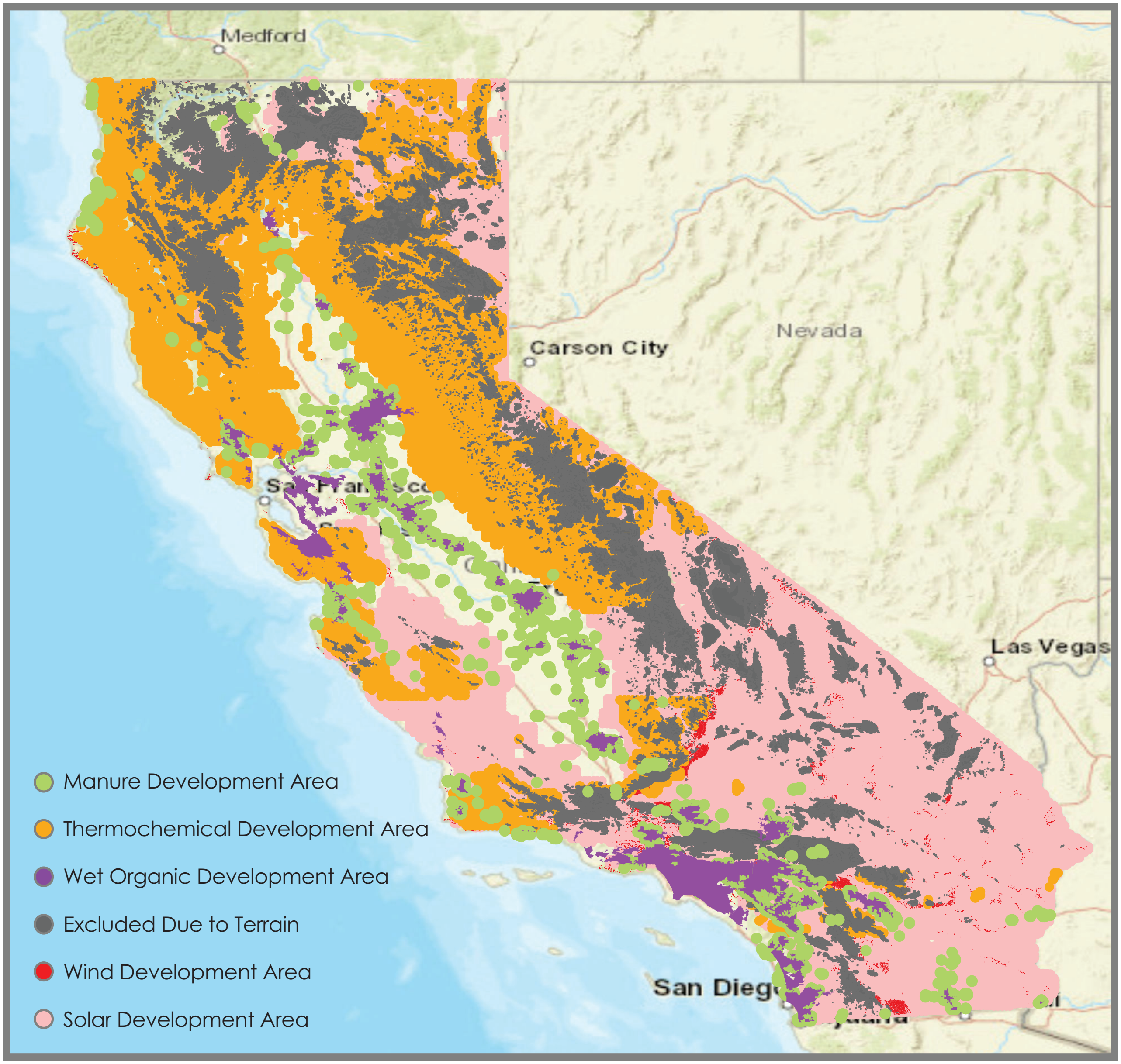
8 Greentech Media Article on Toyota Hydrogen Facility https://www.greentechmedia.com/articles/read/toyota-fuelcell-energy-renewable-power-hydrogen-plant

9 GFO-17-602 Revised NOPA https://www.energy.ca.gov/sites/default/files/2019-05/GFO-17-602_NOPA_revised.pdf

10 Ibid.

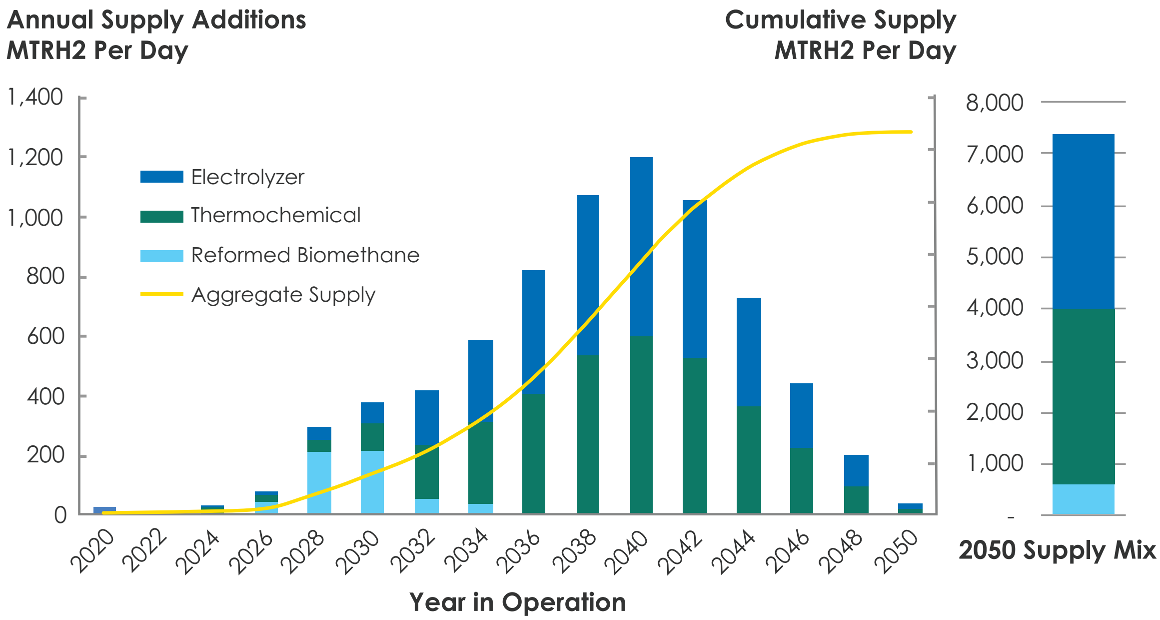
11 NEL Hydrogen Press Release https://nelhydrogen.com/press-release/nel-asa-awarded-usd-8-3-million-hydrogen-electrolyser-fueling-station-contract

Figure 7. Primary Resource Areas for Renewable Hydrogen Production and Conversion



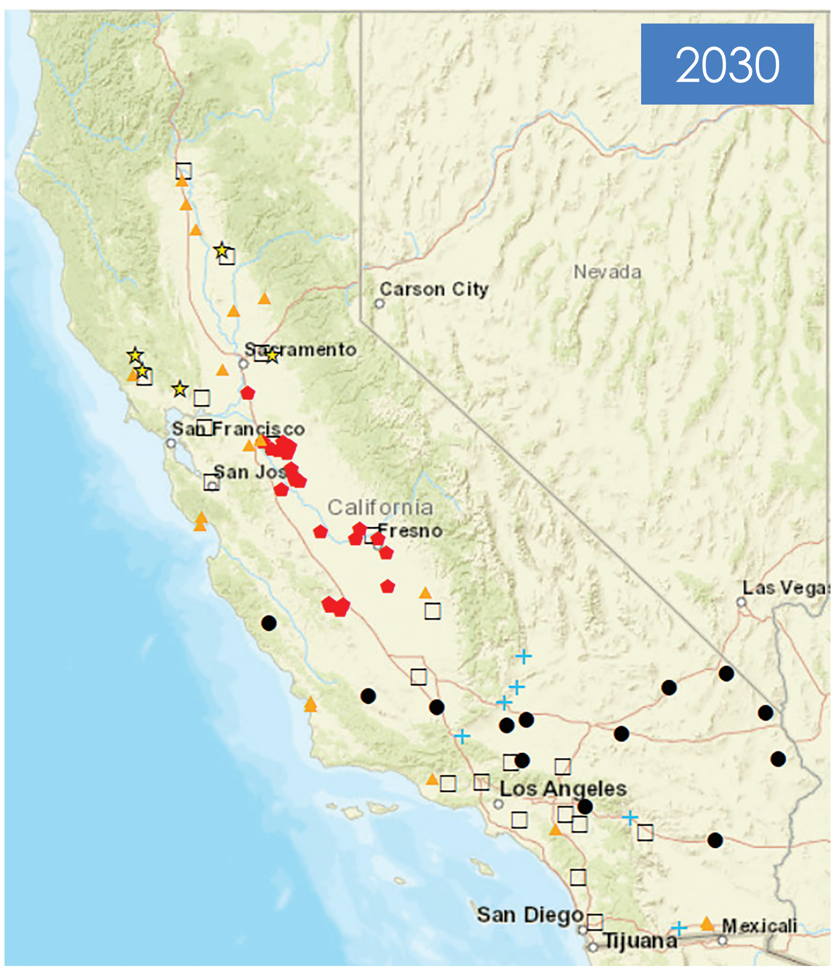
Source: UCI APEP from multiple US EPA, US DOE and California agency datasets.

Figure 8. Representative Buildout of California Renewable Hydrogen Supply



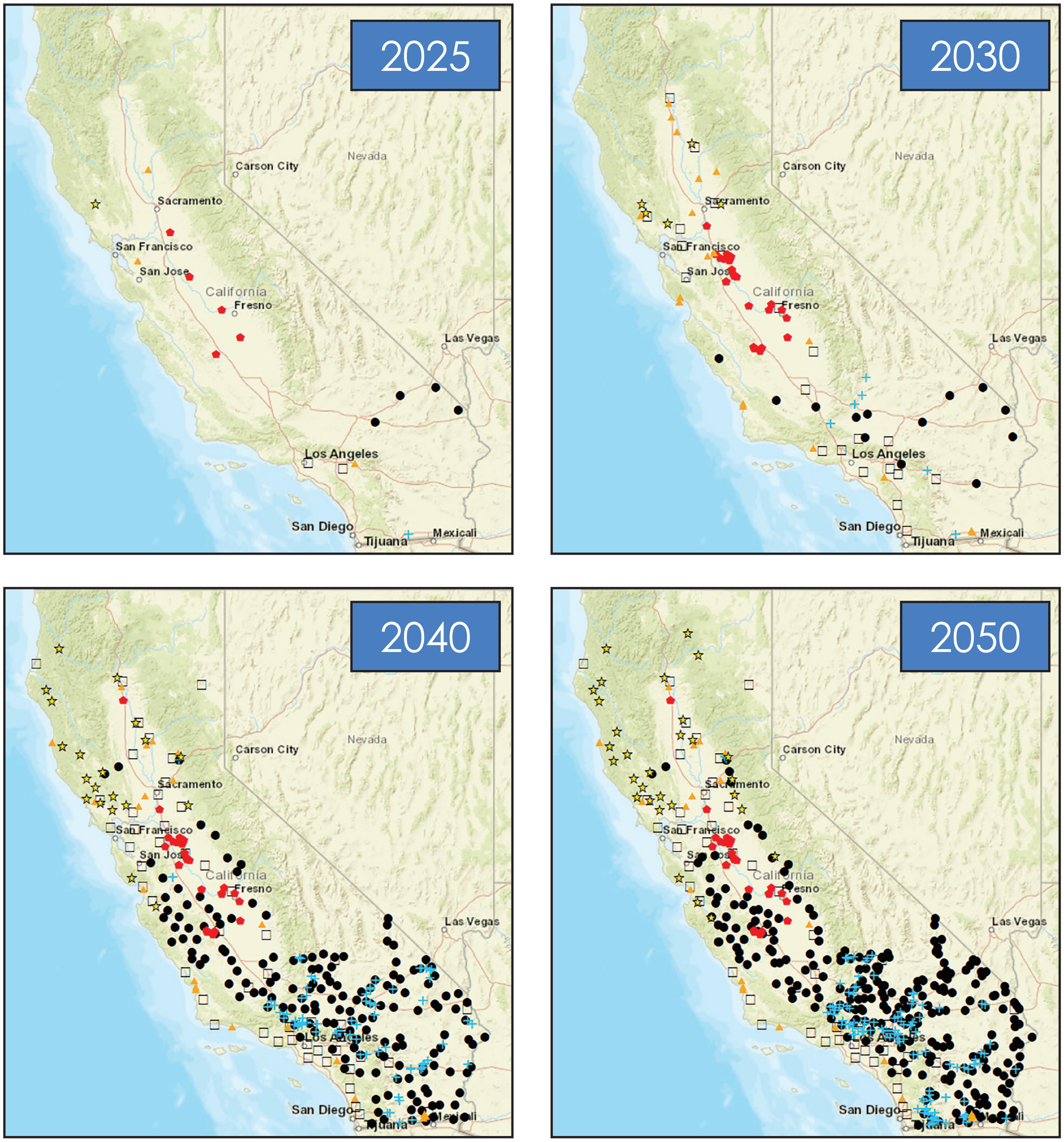
Source: UCI APEP

Figure 9. 2030 Spatial Detail



Source: UCI APEP

Figure 10. Representative Spatial Buildout Progression



Technology Count by Year	2025	2030	2040	2050
Electrolyzer Solar	4	13	169	265
Electrolyzer WInd	1	6	72	113
Thermochemical	1	5	20	30
Dairy	5	24	28	28
Organic MSW	3	19	21	21
SMR	2	21	51	51

Source: UCI APEP

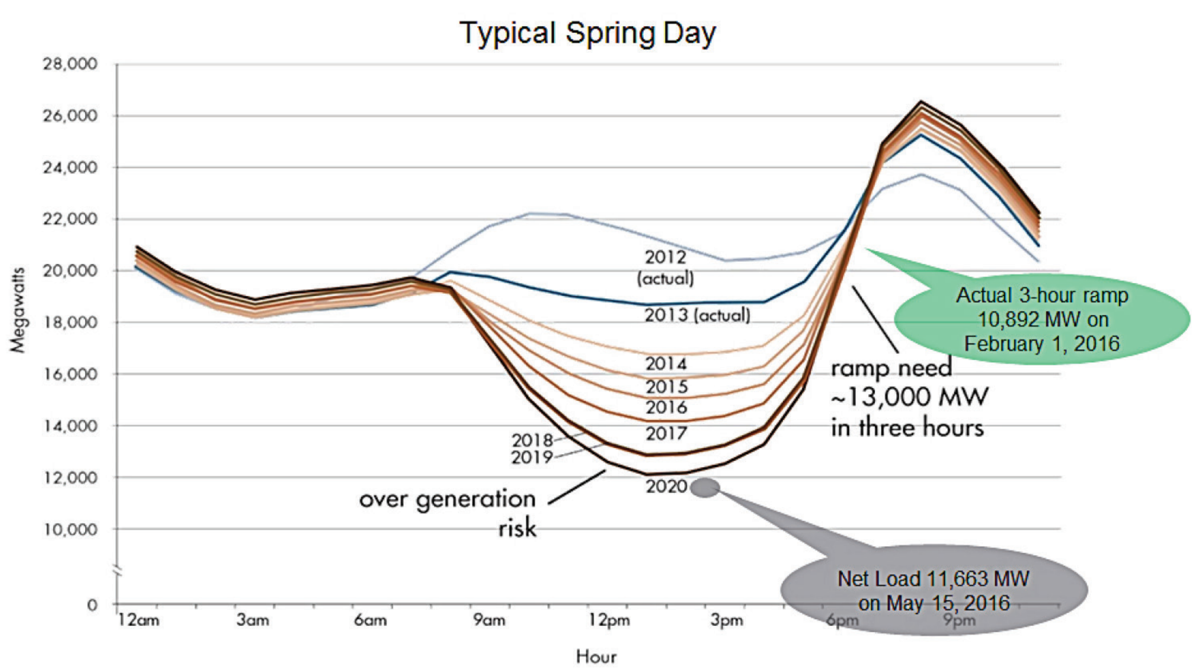
HYDROGEN, THE DUCK CURVE AND THE SEASONS

Hydrogen produced through electrolysis can play an important role in promoting the integration of a high fraction of solar and wind on the electric grid. Electrolyzers can be envisioned as a controllable load to help manage the peaks and valleys in solar and wind production by producing renewable fuel as a form of stored electrical energy. The concept is sometimes referred to as power-to-gas.

Solar and wind energy form the foundation of any strategy for the clean energy future. These resources are abundant and can provide more than enough energy to serve all current and future needs of California. (Solar and wind resource potential is more than 70 times the current annual demand in California.[12]) However, one major "catch" crops up. The timing of energy produced from wind and solar resources does not match the daily 24-hour demand for energy. Both types of resources also produce varying amounts of energy over each day, week, and season. The daily production pattern of renewable resources leads to an electricity production-relative-to-load profile that has become known as the "duck curve" (Figure 11).

This name comes from the shape of the power-supply curve that must come from nonintermittent (dispatchable) resources. The net load shape is determined primarily by the production profile of solar resources with high solar production during the middle of the day and no solar production during nighttime hours. This phenomenon can lead to excess solar power production during the middle of the day—power produced with no demand to serve. This excess power can be significant during some days (Figure 12). Using this overproduction of renewable power to produce renewable hydrogen is a promising solution to this issue.

Figure 11. The Duck Curve

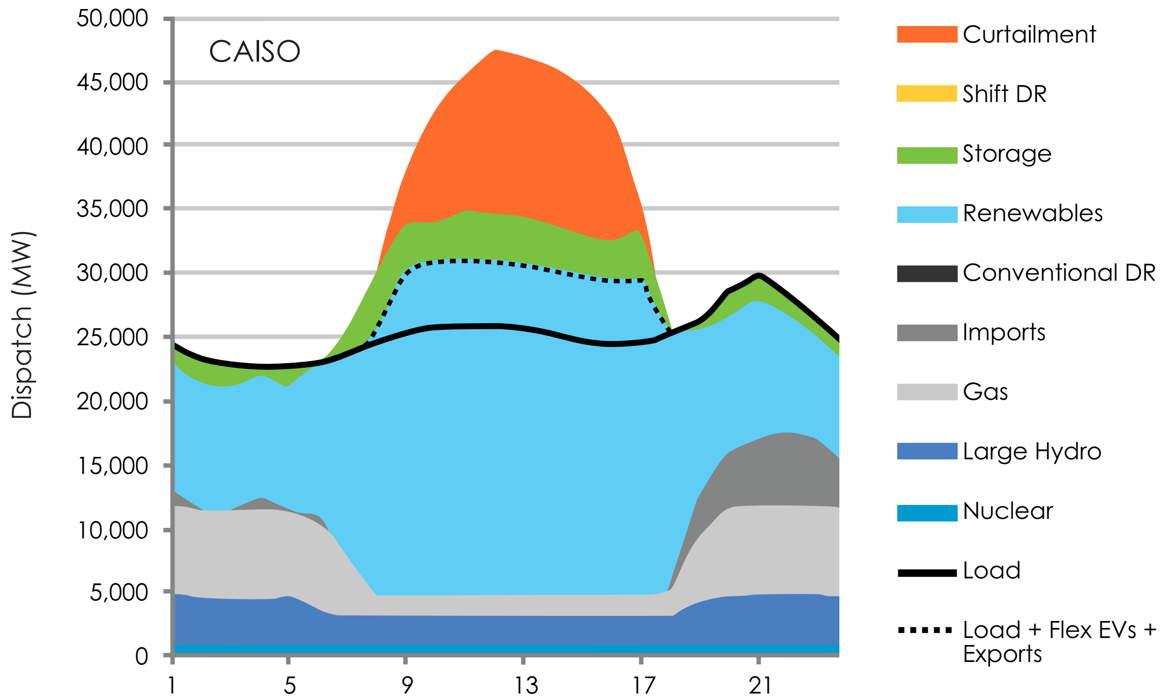


Source: California Independent System Operator.
https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

12 A. Lopez et. al. 2012. U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. National Renewable Energy Laboratory Technical Report NREL/TP-6A20-51946 and California demand form Energy Information Administration.

What about variations in solar and wind production across daily, weekly and seasonal weather patterns? As can be seen in Figure 13, seasonal variation in solar and wind production are substantial with a monthly underproduction of nearly 50% in January and overproduction of around 30% in May for a supply portfolio sized to meet average demand. Lithium-ion batteries are an excellent resource for storing power for durations of up to 4 or even 8 hours. For batteries, storage cost increases at the same rate as added duration (twice the duration equal twice the cost) and becomes cost-prohibitive at longer durations. In contrast, hydrogen energy storage system costs increase very little as the amount of stored energy increases when geological storage is used. Existing natural gas storage resources receiving hydrogen as a blend stock or gas storage converted to pure hydrogen are ideal for this purpose. These features make hydrogen energy storage ideal for day-to-night, daily, weekly and seasonal storage – any storage requirement greater than around 8 hours.

Figure 12. Excess Renewable Power Production on a High-solar Day in 2030



Source: RESOLVE Case 42mmt_Ref_20180416_2017_IEPR
https://www.cpuc.ca.gov/General.aspx?id=6442457210

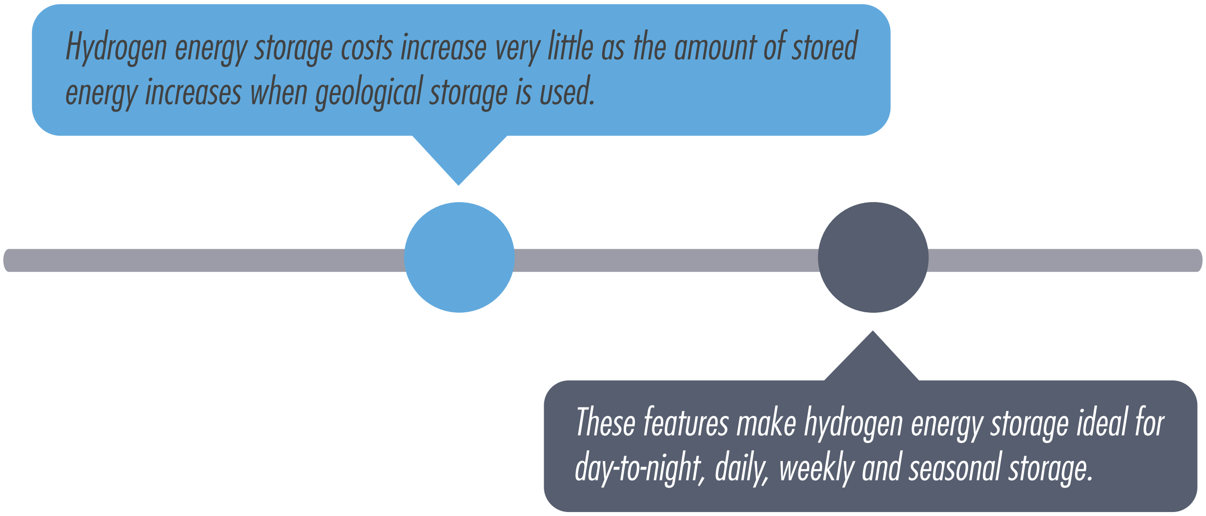
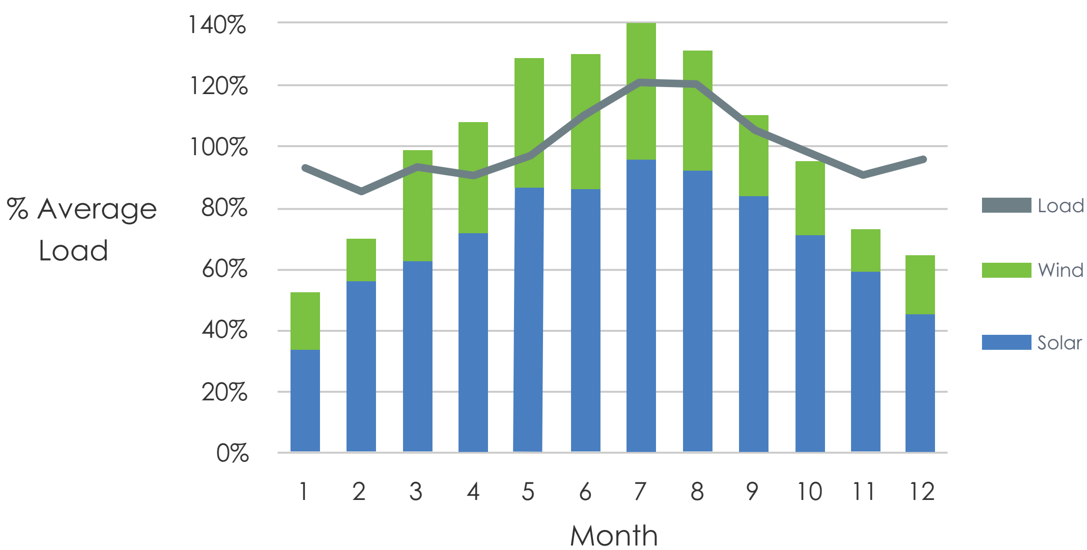


Figure 13. Monthly Average Load vs. Wind and Solar Production at 100% Renewable Fraction



Source: UCI APEP. Load and production profiles from CAISO 2016 actuals with wind and solar scaled to 100% of demand.

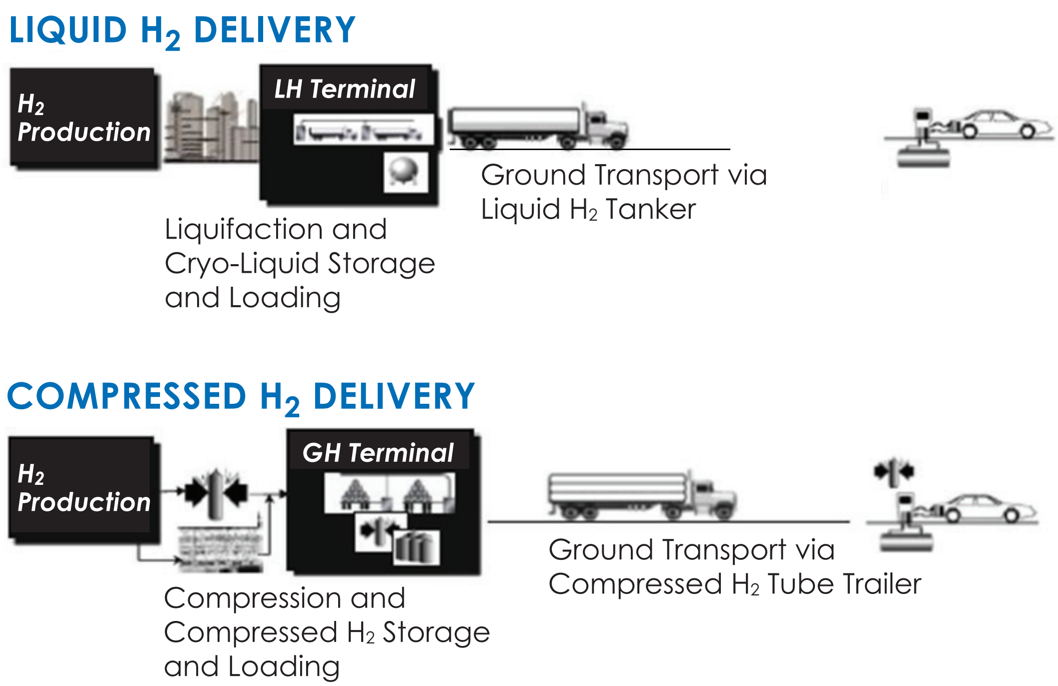
GETTING RENEWABLE HYDROGEN TO WHERE IT'S NEEDED

Unlike natural gas, an existing network of pipelines and geological storage to store and move hydrogen around is not in place. Such infrastructure may evolve beyond 2030 when demand for renewable hydrogen grows to the point that dedicated infrastructure is economically viable. In the meantime, other approaches to hydrogen transport and storage must be used. Figure 14 shows the two primary approaches in use in California:

1) Compressing the hydrogen to increase density and move it in tube trailers, tanker trucks, or rail cars to the point of use and using high-pressure tanks for storage.
2) Cooling the hydrogen to the point at which it becomes liquid and transporting the liquid via truck or rail using liquid-hydrogen tankers and employing cryogenic storage tanks for storage.

Compression and liquefaction technologies are fully mature commercially but need additional research, development, and deployment scale to reduce cost. Cost reduction is important because the plant-gate-to-station elements constitute about one-third of the dispensed cost of hydrogen based on the cost analysis done for this roadmap developed using the DOE HDSAM tool.

Figure 14. Hydrogen Delivery Chain



Source: UCI APEP adapted from DOE H2A Delivery Scenario Analysis Model Version 3.0 (HDSAM 3.0) User's Manual

Pipeline transport may be the low-cost approach in the future, as has proven to be the case for natural gas. A small hydrogen pipeline system serving the refineries in Southern California is in place and is used to supply one hydrogen station. However, significant expansion of hydrogen pipeline infrastructure is not likely to evolve until beyond 2030, when demand for renewable hydrogen grows to the point that dedicated infrastructure is economically viable. The technology is well proven, however, and more than 2,000 miles of dedicated hydrogen pipelines for serving refinery applications in the Gulf Coast are in operation. In addition, the western United States has numerous geologic formations that could be used for hydrogen storage, such as existing natural gas storage facilities, depleted oil fields, and salt caverns in nearby western states. The reliability and safety of these operations is well established.

Blending hydrogen into the natural gas system is another transport and storage approach suitable for some applications (such as any application that would otherwise use biomethane). Most use cases do not recover pure hydrogen at the point of use but rather use the methane hydrogen blend directly. Hydrogen separation is an option although additional cost is incurred. The natural gas utilities in California are investigating standards for hydrogen blending within the natural gas system. If the CPUC establishes the necessary standards, the natural gas utilities may begin, over the next few years, to provide low-cost transport and storage for applications that can take advantage of this pathway.

Several steps in the supply chain are eliminated by production of hydrogen at the point of use. Station-scale electrolysis and reformation at the fueling location produce hydrogen locally. Primary energy for electrolysis is drawn from the electric grid, and reformers use directed biomethane delivered via the natural gas grid. While this approach eliminates terminal and road transport costs, local (also called "forecourt") production is uncommon because economies of scale make that approach more expensive than alternatives. Forecourt solutions also require additional space on site, which may not be available at many locations. Future cost reduction through technology advances and expected increases in station size may lead to greater use of this approach, particularly for medium- and heavy-duty stations and larger stations in areas of lower development density.

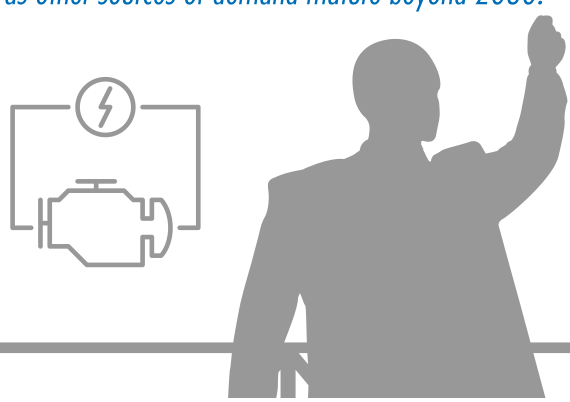
Blending on the natural gas system will likely begin over the next few years to provide low-cost transport for applications that can take advantage of this pathway.

...there are already over 2,000 miles of dedicated hydrogen pipelines for refinery applications in the gulf coast...

SELF-SUSTAINABILITY – ACHIEVING ABUNDANT, UBIQUITOUS AND AFFORDABLE RH2 SUPPLY

A self-sustainable renewable hydrogen sector can be defined as one in which growing, consumer-driven demand is supplied by a steady flow of private investment across the supply and delivery chain adequate to serve that demand. On the demand side, policies to support decarbonization and pollution reductions for transportation, energy production, commercial and industrial uses and homes are the key provided that such policies provide balanced support across all avenues to reduce pollution and carbon. On the supply side, cost reduction and greater production and delivery capacity must be achieved for the potential demand to be.

Transportation will be the primary driver of renewable hydrogen demand through 2030 and will likely remain the largest use of renewable hydrogen as other sources of demand mature beyond 2030.



Transportation will be the primary driver of renewable hydrogen demand through 2030 and will likely remain the largest use of renewable hydrogen as other sources of demand mature beyond 2030. The cost of dispensed hydrogen vehicle fuel in California today, with an average renewable fraction of 40%, averages around $16 per kilogram (roughly the energy equivalent of 1 gallon of gasoline and the cost equivalent of $6.40 per gallon when adjusted for the higher fuel economy of hydrogen vehicles). The cost of 100% renewable hydrogen would be approximately $0.60/kg higher.

This price is high relative to a near-term target of $6.00 to $8.00 per kilogram for dispensed hydrogen and a long-term goal of $4.00 per gallon. However, it should be kept in mind that solar and wind technologies have seen more dramatic cost reductions. A comprehensive analysis of potential cost reduction for dispensed renewable hydrogen based on scale economies, learning effects and innovation leads to a projection of potential cost reduction across the renewable hydrogen production and supply chain of 40% to 60% by 2030 tracking toward the $4 to $6 per kilogram target by 2050 (Figure 15)[13]. Reaching these targets will require targeted policy support and incentives to bridge the current nascent sector to a self- sustaining one by the mid to late 2020's. And such support will be needed across the entire production and supply chain. At the same time, vehicle manufacturers must cut the gap in purchase price between fuel cell vehicles relative to conventional and battery-electric solutions.

13 Renewable Hydrogen Production Technology Characterization (Interim Report). California Energy Commission contract 600-17-008. Posted at Energy Commission docket HYD-17-01. https://efiling.energy.ca.gov/Lists/DocketLog.aspx?docketnumber=17-HYD-01

A comprehensive analysis of potential cost reduction for dispensed renewable hydrogen...leads to a projection of potential cost reduction across the renewable hydrogen production and supply chain of 40% to 60% by 2030...

Reaching these targets will require targeted policy support and incentives...

Figure 15. Cost of Dispensed Renewable Hydrogen

Source: UCI APEP

1 Extend hydrogen infrastructure support to the entire supply chain

The CEC's Clean Transportation Program has funded 64 hydrogen refueling stations[14]. In addition, the CEC has sponsored a substantial amount of research on hydrogen for transportation and awarded funding for two projects with a total production capacity of 6,000 kg/day of 100 percent renewable hydrogen. However, additional support is needed for commercial, dedicated renewable hydrogen production projects and emerging technologies across the supply chain. In general, dual-purpose facilities such as steam methane reformers, which can serve both conventional and renewable hydrogen markets, and biomethane projects, which can serve both hydrogen and CNG markets, are financially viable without additional state support. However, as described below, electrolytic hydrogen and gasification have unique features that necessitate additional support, as do emerging technologies across the supply chain such as small-scale reformers and liquid carriers.

Like reformers, electrolyzers can produce either renewable or conventional hydrogen, depending on the source of the electricity used in the process. However, electrolytic hydrogen produced from non-renewable grid electricity is several times more costly than hydrogen produced from natural gas through steam-methane reformation. As a result, investments in electrolyzers dedicated to producing renewable hydrogen for a relatively new and growing market like hydrogen refueling stations represent more of a financial risk than conventional systems that supply hydrogen to established industries. For this reason, incentives may be needed to stimulate investment. Gasification is a promising renewable hydrogen production technology but requires full-scale commercial demonstration before wide-scale deployment can occur. Next-generation reformation and liquefaction technologies have the potential to significantly reduce the cost of dispensed renewable hydrogen and should receive support.

The form of financial support for renewable hydrogen production and related facilities could take any of several forms. These include a capacity credit program similar to the Low Carbon Fuel Standard (LCFS) Hydrogen Refueling Infrastructure (HRI) credits (with a requirement that eligible feedstocks and renewable electricity be used), capital grants, and loan guarantees. The amount of financial support needed for the renewable hydrogen production sector to reach self-sustainability depends on several factors, including the form of support.

The research team developed two support scenarios to scope the magnitude of support required. One uses only capital grants, and the other uses loan guarantees for the gasification projects. Both assume that anaerobic digestion projects are commercially viable without incremental support.[15] The first scenario assumes the state provides grants during the market launch phase of 50 percent of capital cost for five electrolyzer projects of 5,000-kilogram-per-day nameplate capacity stepping down to 25 percent for an additional two projects 10,000-kilogram-per-day nameplate capacity and 50 percent grants to two commercial-pilot gasification projects of 25,000-kilogram-per-day nameplate capacity. The project sizes are less than ideal but large enough to serve as commercial references for future financing. The cost of this program of support would be nearly $120 million and would ensure adequate renewable hydrogen capacity through the mid-2020s. If the gasification projects were to be supported with loan guarantees rather than grants, the program cost would be reduced to $80 million, estimating the cost of the guarantee at 20 percent of project cost.[16]

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14 Baronas, Jean, Gerhard Achtelik, et al. 2018. Joint Agency Staff Report on Assembly Bill 8: 2018 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California. California Energy Commission and California Air Resources Board. Publication Number: CEC-600-2018-008.

15 Landfill gas is the lowest cost resource and is commercially mature. Dairy projects receive support under the California Department of Food and Agriculture grant program, as well as subsidies mandated through SB 1383 and generate the most LCFS credits of any pathway. Landfill diversion projects receive tipping fees adequate to make such projects commercially viable.

16 The ability to secure commercial financing via loan guarantees is not certain but a 20 percent guarantee cost is conservative relative to the loss experience rate and actuarial estimates of default rate for loans to energy project guaranteed under the DOE Loan Guarantee Program (LGP) program. The upper estimate reported in the 2016 General Accounting Office report on the program was a credit subsidy cost of 15 percent of the loan amount. This would be 12 percent of project cost for an 80 percent loan.

2 Take steps to support a smooth expansion of production capacity that keeps pace with demand

The state has created a well-functioning program to support hydrogen station development through Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) to carefully plan, encourage through incentives, and track station buildout and operating performance. The competitive award of incentives, mandatory reporting, and active incorporation of learning has led to a successful public-private partnership. In addition to helping ensure adequate availability of fueling infrastructure to serve the early FCEV market, the program has helped shed light on areas for improvement to promote cost reduction with each generation of stations.

A key collateral feature of the program is that planning transparency and management of incentives have enabled a smooth build cycle for the station sector in which adequate new station capacity is being added without needing a dynamic wherein short supply pushes up prices to attract new capacity. No corresponding program is currently in place for the renewable hydrogen production and supply chain. Although the ability of renewable hydrogen production facilities to use nonrenewable feedstock to serve conventional merchant hydrogen markets reduces demand risk to some degree, the overall demand risk is substantial, and programmatic intervention to enable a smooth buildout of supply is likely necessary. Incentives tuned to capacity expansion and technology progress targets can serve this role.

3 Focus on forms of support that attract private capital and support development of robust competitive markets

In addition to state support during the launch phase as discussed above, the timely buildout of facilities and infrastructure needed to enable wide-scale adoption of hydrogen as an energy and transportation solution will require a steady flow of private capital into the sector. Realizing the necessary capital flow will require that prospective investors foresee the opportunity to achieve an acceptable return on investment while accounting for risk and uncertainty. In addition, transparent and well-functioning markets are critical to the long-term success of the sector for investors and consumers. Factors that enable this include a broad and diverse array of market participants, low barriers to entry, ready access to market information such as pricing, and an effective mechanism for connecting buyers and sellers across the value chain (such as commodity exchanges and procurement platforms). Although the private sector must play a primary role in achieving these goals, the state can also play an important role.

State policies and programs should be designed to ensure that the renewable hydrogen sector can attract private capital sufficient to meet capital needs in a well-functioning and established renewable hydrogen market structure by the mid- to late 2020s. Financeability requires successful operating history for the relevant technologies, relative certainty of feedstock availability, and relative certainty of a secure stream of revenue from renewable hydrogen sales. The current status of the financeability of key renewable hydrogen production technologies is summarized in Figure 16.

The renewable electricity and the battery-electric vehicle sectors have addressed the commercial lending gap largely through public-utility-sponsored procurement and investment programs. These programs use the creditworthiness of the host utility either through direct utility financing or through long-term revenue contracts to finance investment. Other approaches are needed to serve a similar role in launching and scaling the renewable hydrogen production and supply sector. The Clean Transportation Program hydrogen refueling station grant funding program and the recently approved LCFS HRI capacity credits support the refueling station part of the supply chain, but additional program elements are needed for renewable hydrogen production and capital-intensive elements of the supply chain.

Several elements should be considered in developing programs to support renewable hydrogen supply expansion by addressing the financing gap or otherwise supporting market development or both.

- Transparent and widely communicated information on expected demand growth and planned production and supply capacity additions can help private investors in planning development to match market demand. The Clean Transportation Program hydrogen refueling station build program has been very successful in this regard through vehicle population surveys of the vehicle manufacturers and detailed planning analysis for new hydrogen station additions by CARB and CEC. Such efforts should be expanded to include renewable hydrogen production and additional sources of demand, particularly for medium- and heavy-duty applications.

- Incentive eligibility should continue and extend the selection factors employed in the hydrogen refueling station program and the initial renewable hydrogen production solicitation (GFO-602) including:

  - Match funding.
  - Strength of the project commercial plan and track record of the applicant.
  - Technology diversity and encouragement of new entrants.
  - Disadvantaged community impacts.
  - Carbon reduction.

Figure 16. Commercial Financeability of Key Renewable Hydrogen Technologies

	COMMERCIALLY FINANCEABLE?	COMMENTS
Hydrogen Refueling Station	Close	LCFS price risk is the only gap.
SMR	Yes	100% financeable. Proven commercial technology with ability to secure revenue through conventional hydrogen production.
Liquefaction Facility	Yes	100% financeable. Proven commercial technology with ability to secure revenue through conventional hydrogen production.
Anaerobic Digester	Close	SB 1383 provides mandates that will make dairy projects suitable for commercial lending AD projects using landfill diverted feedstock receive contracted tipping fees; LCFS price support mechanism may be needed for full financeability.
Electrolyzer	No	Capital costs declining but currently above levels required for cost competitiveness and long-term off-take agreements for RH2 are scarce.
Gasifier	No	Technology is not fully commercial, requires high capital investment ($100M+) and long-term off-take agreements for RH2 are scarce.

Source: UCI APEP

- LCFS credits are an important source of value for the entire renewable (and conventional) hydrogen production and supply chain, but uncertainty of future credit value reduces introduces significant investment risk. An LCFS credit price support mechanism was proposed during the most recent legislative session in response to the requirements of SB 1383.[17] Should such a mechanism be put in place, it is important that it apply to hydrogen and not only dairy biomethane, as originally proposed.

- The state should also consider developing incentive programs such as grants, capacity credits, or loan guarantees specifically allocated to renewable hydrogen production and related high-capital-cost facilities, the availability of which should be tied to optimal buildout strategies. Because loan guarantee programs typically require similar documentation and credit risk assessment to conventional project finance, such programs can provide a smooth evolution to pure commercial financing. In addition, in contrast to grant programs, such programs have the potential to return borrowed funds to the sponsor. Examples of such programs include the U.S. DOE loan guarantee program[18] and the green bond program proposed by former California state Treasurer John Chiang.[19]

- Agencies providing grants or incentives can promote price transparency in the renewable hydrogen market by publishing anonymized pricing and related data on contracts for the purchase or sale of renewable hydrogen from projects receiving state support. The LCFS program and the Clean Transportation Program hydrogen refueling station program already require reporting of key data on costs, quantities, and other operational elements. However, unbundled (separate) price or cost of renewable hydrogen and associated volumes is not among the publicly reported data.

- Operational reporting requirements for funded projects should be developed in consultation with project financing entities, such as banks currently lending to energy and transportation infrastructure projects, to ensure that reported metrics address the information needs of future prospective private lenders.

- State agencies, in collaboration with stakeholders, should systematically identify market barriers in assessing the development of the renewable hydrogen production and supply sector and include supplier diversity (number and demographics) in incentive, environmental credit, and grant program award criteria.

- The market for biomass feedstock is not well formed, and secure long-term feedstock agreements will be necessary for commercial viability of projects using biomass. State agencies should convene a stakeholder process to explore approaches to addressing this issue such as establishing an exchange or clearing house.

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17 AB 1156 (Garcia, 2018) LCFS Price Support Mechanism https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201920200AB1156 reported in the 2016 General Accounting Office report on the program was a credit subsidy cost of 15 percent of the loan amount. This would be 12 percent of project cost for an 80 percent loan.

18 DOE Loan Program Office page https://www.energy.gov/lpo/loan-programs-office ; GAO DOE Loan Program Report https://www.gao.gov/assets/680/675595.pdf.

19 California Treasurer Green Bond Report https://www.treasurer.ca.gov/greenbonds/publications/reports/green_bond_market_01.pdf.

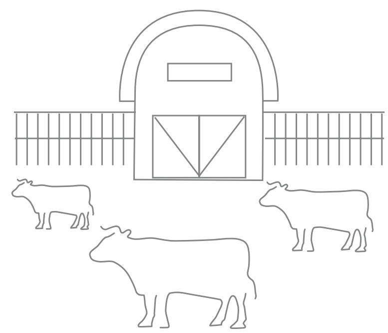
4 Reduce barriers to development in California

The development of infrastructure projects can be challenging. Impediments cited by developers include onerous CEQA requirements for some types of projects, prevalence of local opposition to new development often based on misperceptions about impacts of proposed projects, high labor rates, differing requirements across local jurisdictions, high utility rates and high tax rates. Some of these issues, such as wage rates and general state tax rates, are likely issues that will remain facts of life in California. However, state agencies can act to enable project development through efforts to harmonize local requirements, streamline permitting processes and approval of programmatic environmental impact reports. Incentives that encourage development in California should continue.

LESSONS LEARNED FROM THE DAIRY SECTOR

Driven by the push in the California Short-lived Climate Pollutant Strategy (SLCP) and industry action, the state has undertaken important steps to streamline permitting for dairy biomethane projects:

- Program Environmental Impact Report (PEIR) to relieve much of the burden on individual projects to develop environmental impact reports required under the California Environmental Quality Act (CEQA).[20]
- Consolidated permitting process spearheaded by the California Environmental Protection Agency has been established to assist project developers in navigating the permitting process.[21]



5 Establish design programs and incentives holistically across fuel types

In designing programs to provide support for renewable hydrogen production, consideration should be given to other programs that may provide support to some pathways. For example, all the organic feedstocks that are candidates for hydrogen production can also be used to produce biomethane (which itself is a primary potential feedstock for renewable hydrogen). Biomethane projects receive support developed in response to Senate Bill 1383 for which electrolytic and thermochemical hydrogen production systems do not currently qualify.

In addition, some primary organic feedstocks are currently subject to, and others are likely to become subject to, mandates that will affect the price of that feedstock for fuel production. For example, current state law directs that regulations be adopted requiring the diversion of 75 percent of the organic material that would otherwise be disposed of in landfill by 2025.[22] Dairies are not currently under mandate to capture methane emissions, but the California Air Resources Board has stated the intent in its Short-Lived Climate Pollutant (SLCP) strategy to

20 Cal EPA has led such an effort for dairy projects. See Cal EPA Dairy Program Site https://tinyurl.com/y7gcfbel

21 The Energy Commission and Go-Biz have been assisting with local permitting issues for stations for several years. This approach should be extended to the entire production and delivery chain. https://www.epa.gov/agstar/guidelines-and-permitting-livestock-anaerobic-digesters https://businessportal.ca.gov/zero-emission-vehicle-program/zev-resources

22 Senate Bill 1383 (Lara, Chapter 395, Statutes of 2016) Link to bill text https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB1383.

mandate capture in the future.[23] The pressing need for forest management to reduce wildfire risk raises the strong potential for mandates for forest thinning and other measures to gather and remove combustible material from forests.[24] Such organic waste mandates may lead to payments (known as "tipping fees," which are disposal payments) by feedstock sources. This is currently the case with landfill-diverted food waste. Potential tipping fee revenue should be considered in any feedstock or technology-differentiated project support programs when assessing the amount of support needed.

In considering appropriate levels of support for hydrogen infrastructure and ways in which the requirements compare to battery-electric vehicle infrastructure, policy makers should compare support levels across the full deployment cycle (notionally, at least 10 years of deployment) and should consider all sources of effective subsidy.

6 Establish electricity tariffs reflecting the unique benefits of electrolyzers as grid resources

Electrolyzers consuming grid electricity currently pay retail rates on tariff schedules that depend on the voltage level at which the electrolyzer interconnects. An electrolyzer receiving service on a standard commercial or industrial rate in California would pay an average of about $0.11 to $0.14 per kilowatt-hour for grid electricity[25], which currently has a renewable fraction approaching 35%.[26] For electrolyzers interconnected at the transmission level, time-of-use rates provide a relatively close proxy to wholesale electricity rates but require the consumer to receive the grid-average blend of renewable and conventional energy and do not convey ownership of renewable energy credits to the consumer. In contrast, an electrolyzer using self-generated wind or solar energy would incur cost of about $0.03 per kilowatt hour for 100% renewable energy – albeit with much less siting flexibility and a lower capacity factor.

To optimize their revenue generation through LCFS credit strategies, electrolytic hydrogen producers must have the ability to source their own wholesale electricity. In the absence of electric tariffs that provide this capability, electrolytic hydrogen producers must either accept the limitation of current tariff structures, or produce their own electricity from dedicated, co-located renewable generation facilities. Such limitations constrain the ability to optimally site electrolyzers in relation to the renewable hydrogen distribution network.

Electrolyzers can also provide grid services such as frequency support, voltage support and ramping. There is currently a knowledge gap regarding the future value of such serves and the revenue streams that might be available to electrolytic hydrogen production facilities. Additional state-funded research, or inclusion of value analysis of these functions in the electric utility integrated resource planning process, would facilitate revenue forecasting for electrolyzer project developers.

Utility-sponsored programs such as real-time rates (the rate charged tracks the wholesale market price in real time) with optional renewable-only tariff provisions (an ability for a customer to specifically buy renewable electricity and not the average mix) and dispatchable load tariffs (program allowing the utility to control a load) compensating electrolyzers for providing grid support would create easy access to electricity markets and would be particularly valuable for smaller projects not positioned to interact directly with wholesale markets. For larger or more sophisticated projects, direct access programs under which electrolyzer owners could procure

23 ARB Short-Lived Climate Pollutant Final Report https://www.arb.ca.gov/cc/shortlived/meetings/03142017/final_slcp_report.pdf.

24 Wildfire Mitigation Report. Dead Tree Utilization Assessment, The Beck Group for Calfire and the California Tree Mortality Task Force. 2017.

25 EIA Table F Retail Electric Rates; https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a.

26 CEC RPS Tracking Report; https://www.cpuc.ca.gov/RPS_Reports_Data

their own power, pay transmission access charges, and interact directly with the wholesale market for grid services, might be most effective. Regulatory proceedings under the authority of the California Public Utilities Commission and, possibly, the California Independent System Operator are needed to address these issues.

7 Facilitate access to the natural gas system for renewable hydrogen transport and storage

Renewable hydrogen produced through reformation of biomethane generally uses the natural gas system for storage and delivery of the biomethane feedstock to the reformation facility. This is the most common pathway used for renewable hydrogen production under the LCFS program today. State programs instituted under mandates contained in Senate Bill 1383 (Lara 2016) have defined standards for pipeline injection and provided subsidies for interconnection for biomethane producers. No similar programs are currently in place for methane produced from electrolytic hydrogen or for hydrogen directly injected onto the natural gas system as a blend stock. Senate Bill 1369 (Skinner 2018) directs state agencies, including the California Public Utility Commission (CPUC) to consider uses of green electrolytic hydrogen but specific action by the CPUC has not yet been initiated. Expanding existing programs and tariffs to include electrolytic methane and hydrogen is necessary to ensure a level playing field for electrolytic hydrogen and methane.

Gasifiers generally produce both methane and hydrogen. Clarity on permissible hydrogen fraction for pipeline injected biomethane is important for developers of gasification projects wishing to access the natural gas system to properly design their gas processing and conditioning systems.

Although there is substantial evidence to suggest that hydrogen fractions as high as 20% can be safely permitted in the natural gas supply.[27] California has yet to establish hydrogen blending limits. Timely action is needed to ensure that renewable hydrogen fuel producers receive the same open access to the common-carrier pipeline system as other fuel types.

8 Take steps to ensure that a mixed gas / liquid supply chain does not create barriers to market access

The hydrogen supply chain is developing as a mix of gaseous and liquid transport and storage, with 17 stations employing liquid storage and the remainder using compressed gas, according to the CARB 2018 AB 8 report. Stakeholders report different perspectives on whether the future supply chain will be dominated by liquid or compressed gaseous transport and storage. It is likely that the future network will include substantial fractions of both cryo-liquid and compressed-gas stations. Other transport and storage approaches are also under development, such as liquid organic hydrogen carriers, ammonia, DME, and others that may enter the supply mix in the future. These too would need to be integrated into the production and supply network.

Economic principles would suggest that, in a fully mature market, competitive forces will likely be adequate to ensure that the sector evolves to the most cost-effective production and supply chain configurations. However, in the early market, policy interventions may be required to ensure that otherwise promising technologies and business models have appropriate access to the supply chain. For example, one of the benefits of electrolyzer systems is that they are

27 See, for example, Oney, F., T.N. Veziroglu, and Z. Dulger, 1994, "Evaluation of Pipeline Transportation of Hydrogen and Natural Gas Mixtures," International Journal of Hydrogen Energy 19(10):813–822.

modular and can be deployed at modest scale without major diseconomies of scale. However, integration into the liquid hydrogen supply chain may pose a challenge. Liquefaction facilities show strong economies of scale and, as a result, dedicated liquefaction facilities collocated with electrolytic production facilities face a cost barrier. At the same time, accessing remote liquefaction facilities incurs cost for transport, new facilities to receive hydrogen via truck or rail, and requires access to available liquefaction capacity. This creates a potential barrier to accessing the liquid hydrogen supply chain. Other emerging technologies may face similar barriers.

Where barriers exist, state policy makers may wish to consider some form of incentives to promote market access for new entrants and emerging technologies. Potential approaches include additional incentives for projects facing supply-chain access barriers or incentives for critical supply-chain access points (such as liquefaction facilities) to provide capacity to third parties.

9 Ensure that renewable hydrogen development advances Social Justice

The buildout of the renewable hydrogen sector offers many potential benefits to disadvantaged communities through the creation of high quality, green-energy jobs, and by supporting the transition to zero-emission transportation solutions, displacing fossil fuels and their associated emissions that disproportionately impact disadvantaged communities. However, depending on the technology and supply chain model, they may also create additional truck traffic from feedstock supply and/or outbound trucking of renewable hydrogen. Noise and visual impact can also be of concern. It is recommended that state programs providing support for renewable hydrogen production and related facilities apply a social justice screen with a scoring rubric designed in consultation with stakeholders from the relevant communities. The objective of such a scoring system would be to assess net community benefits, with local economic development and clean-technology deployment weighed against potential negative impacts such as congestion, noise, and aesthetics.

10 Act to ensure that program eligibility, environmental accounting and lack of definitions are not barriers to renewable hydrogen development

As programs are developed to support the transition to clean transportation and clean energy solutions, eligibility requirements relying on specific definitions must be developed. For example, the California Renewables Portfolio Standard relies upon specific definitions for qualifying resources, as does the CPUC storage procurement mandate. The federal renewable fuel standard provides renewable identification number (RIN) credits of varying types (and values) for specific qualifying fuels.[28] Senate Bill 100 (De León, Chapter 312, Statutes of 2018) mandates that California reach 100 percent zero-carbon electricity by 2045. These programs, and other similar current and future programs, ensure environmental integrity and achievement of goals by clearly defined standards and eligibility requirements. However, these provisions can also have the effect of excluding or disadvantaging technologies or use cases not envisioned at program inception. As discussed below, these effects can create unnecessary barriers to the evolution of the renewable hydrogen production (and supply) sectors.

Federal RIN credits provide a significant subsidy for eligible fuels. D3 (cellulosic biofuel) RIN credits are trading at roughly $2 per diesel gallon equivalent.[29] Hydrogen derived from renewable

28 EPA Renewable Fuel Standard Page; https://www.epa.gov/renewable-fuel-standard-program.

29 EPA RIN Price and Volumes Page; https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information.

feedstocks is not currently eligible to generate RINs, whereas several biomethane pathways are. Three RIN pathway applications for renewable hydrogen from biomethane are pending but not approved.[30] This difference in eligibility tends to skew biomethane supply toward compressed natural gas as an end fuel, placing renewable hydrogen at a relative disadvantage. It is recommended that interested stakeholders take collective action, for example, through their trade organizations, to secure RIN pathway approval for renewable hydrogen.

In current state rulemakings and regulatory proceedings, terms such as "renewable gas," "renewable methane," and "green electrolytic hydrogen" have been used in discussion of scope and applicability of various programs and regulations. At present, no consistent definitions of the terms renewable or zero-carbon hydrogen have been established. To the extent that mandates or incentive programs or both rely on such definitions (which, by necessity, they will), it is critical for fuel producers and purchasers to have clarity on definitions to support investment and purchasing decisions. This clarity is critical to the buildout and scaling of the renewable hydrogen sector. Some working definitions are provided in Figure 17 below. Low-carbon, netzero-carbon and zero-carbon are also terms that have or may appear in legislation and/or regulation that need to be clearly defined.

Figure 17. Renewable Fuel Working Definitions

Term	Definition
Biogas (CPUC adopted definition)	Mixture of methane (major constituent) and CO_2 (typically 20% to 40% CO_2 by volume) and minor constituents derived from bio sources – cannot be introduced onto the common carrier natural gas system without cleanup
Biomethane (CPUC adopted definition)	Biogas that has been conditioned (cleaned and purified) to meet pipeline standards composed primarily of methane with small remaining amounts of CO_2
Biosyngas	Hydrogen rich gas (with high fraction of carbon monoxide, CO) produced through gasification of biomass, from which (near) pure hydrogen or methane (with additional CO_2) can be synthesized
Renewable Methane	Methane formed by combining hydrogen (generally from electrolysis) with CO_2 – it is renewable if the feedstock for the hydrogen is renewable and if the CO_2 is biogenic or captured from the atmosphere or other source of CO_2 certified to be climate-neutral
Renewable Natural Gas	While generally used interchangeably with biomethane, includes as well renewable electrolytic methane
Renewable or Green Hydrogen	Hydrogen produced using only renewable feedstock including renewable electricity, biomass or other forms of renewable energy such as solar energy
Renewable Gas	All the above

Source: UCI APEP with Stakeholder Input

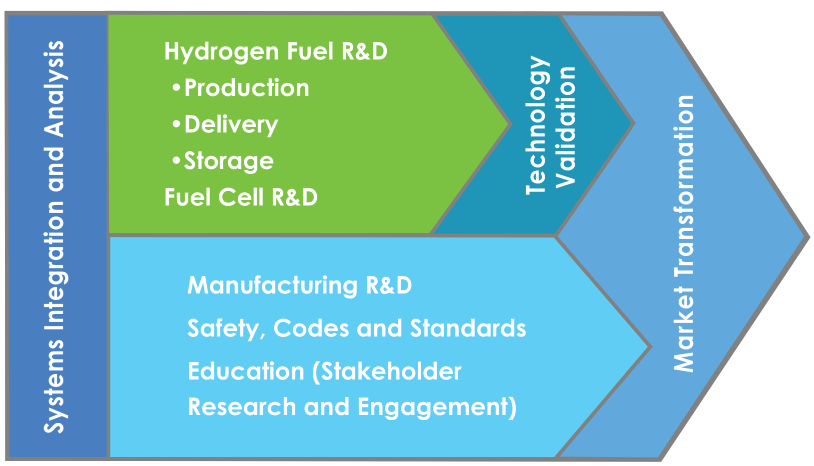
30 EPA Rnewable Fuels Pending Applications; https://www.epa.gov/renewable-fuel-standard-program/pending-petitions-renewable-fuel-pathways.

Carbon intensity provides a consistent framework that has worked well in the LCFS program. Program eligibility based on feedstock or source, as in the federal renewable fuel standard program, is another viable approach, provided that the addition of new feedstocks is explicitly provided for in program design. Technology or process-specific incentives to support nascent technologies or processes of high potential with defined expiration provisions can play an important role in advancing the sector. However, standards and or eligibility based on technology or process should be used with great caution to avoid conveyance of inappropriate market advantages or disadvantages. Renewable hydrogen market participants and trade organizations must act proactively to ensure that statutes and regulations do not directly or indirectly disadvantage renewable hydrogen.

11 Increase state RD&D investment in high-impact areas and maximize leverage of federal RD&D

Realizing the substantial (40% to 60%) cost reduction potential across the renewable hydrogen production and supply chain requires sustained international policy support to achieve global scale and drive learning effects. Also needed are sustained research, development, and demonstration programs to augment scale effects with fundamental improvements. The United States Department of Energy (U.S. DOE) within its Fuel Cell Technology Office (FCTO) is sponsoring a robust program of research under the hydrogen-at-scale (H2@Scale) cross-lab initiative and manages a broad program of research as shown in Figure 18.[31]

Figure 18. Hydrogen and Fuel Cell RD&D Organizing Framework



Source: After DOE Fuel Cell Technologies Office

31 DOE H2@Scale Home Page https://www.energy.gov/eere/fuelcells/h2scale.

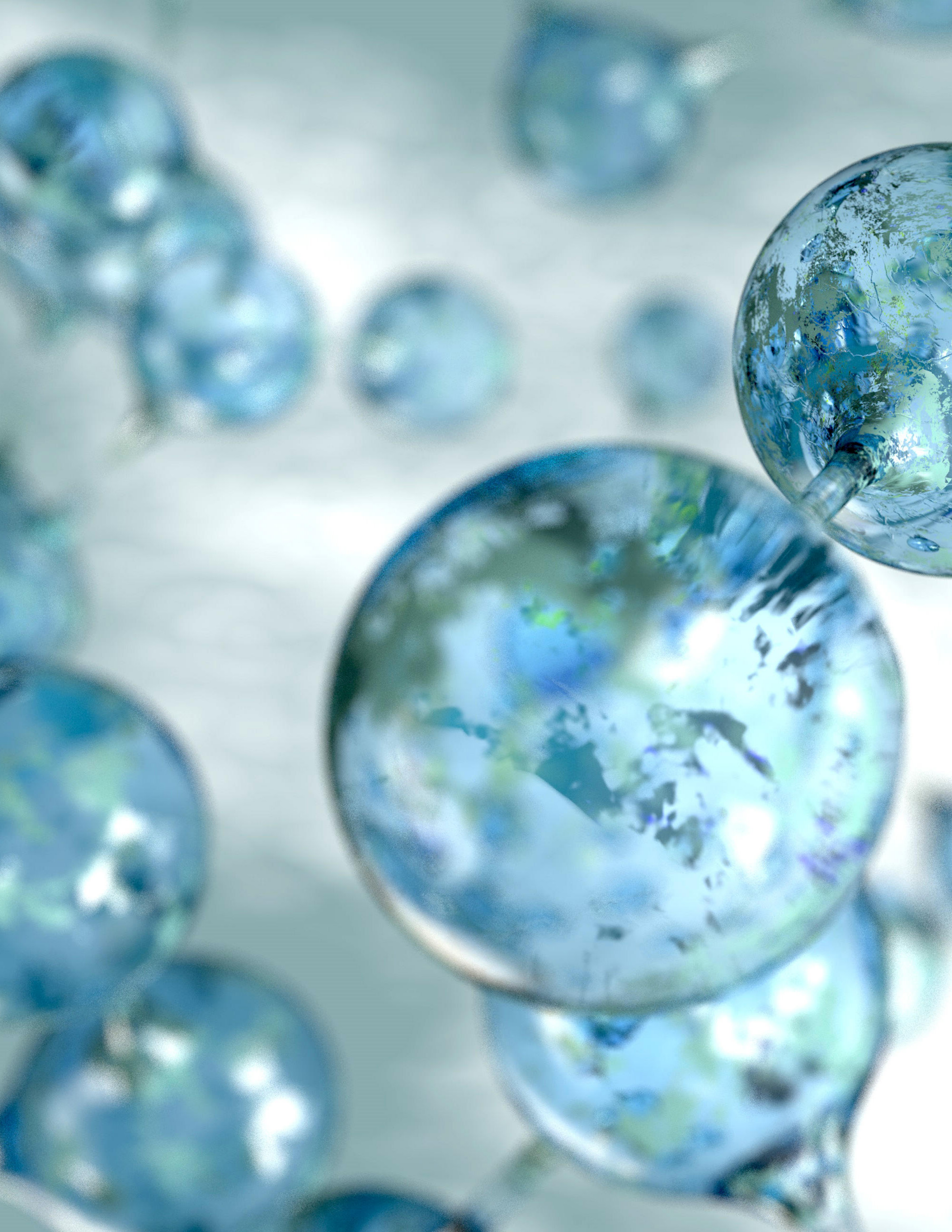
The H2@Scale program features focused research at the materials, components, and systems levels in hydrogen production, storage, and systems. California can augment this program of research to address issues of specific priority to California and bridge U.S. DOE research through technology-to-market activities such as full-scale commercial demonstration programs. Notably, the H2@Scale program does not place specific focus on renewable hydrogen production, which amplifies the importance of California RD&D activities specific to renewable hydrogen. Some specific areas of RD&D that are of specific importance to California include:

- Cost and performance tracking and market forecasting of renewable hydrogen production and supply chain infrastructure to guide investor and policy-maker decisions.
- Full-scale commercial demonstration of high-impact-potential technologies such as gasification, and novel technologies across the production and supply chain, particularly those supporting production and storage at the station scale.
- Quantification of the value of joint benefits enabled by renewable hydrogen between the transportation, electric, and natural gas systems (sometime referred to as “sector coupling”).
- Development of optimal electric and gas rate structures and market designs as they relate to renewable hydrogen.

The H2@Scale program features focused research at the materials, components and systems levels in hydrogen production, storage, and systems. California can augment this program of research to address issues of specific priority to California and to bridge DOE research through technology-to-market activities such as full-scale commercial demonstration programs.

CONCLUSIONS

Renewable hydrogen has the potential to play a significant role in the California zero-carbon economy. While transportation, particularly in longer-range and high-fuel-consumption applications, will likely be the primary application area, opportunities for the use of renewable hydrogen exist across the entire economy. With continued State policy and program support, the renewable hydrogen production sector can become self-sustaining within the next decade. This new sector of the economy will not only play a key role in decarbonizing transportation and energy but has the potential to create hundreds of thousands of high-quality, green jobs.



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RENEWABLE HYDROGEN

UCI ADVANCED POWER AND ENERGY PROGRAM

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