ARCHES H2

White Paper Overview

2024

Alliance for Renewable Clean Hydrogen Energy Systems

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Preface

The Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) has evolved from a concept born in 2021 into a formally organized alliance of over 400 members, now positioned to work with all interested stakeholders to organize and catalyze California's clean and renewable hydrogen ecosystem. To date, ARCHES has placed its focus on two core efforts.

1. **DOE Funding**. ARCHES has successfully negotiated an historic agreement with the DOE that dedicates $12.6 billion, including up to $1.2 billion in federal funding. These funds will be used to catalyze a clean, renewable hydrogen ecosystem across the State of California that supports environmental and energy justice and equity, improved quality of life for communities, and quality careers for workers.

2. **Market Insights**. ARCHES has acquired and organized insights from market participants to help advance shared understanding of the hydrogen market and overall ecosystem.

The purpose of this white paper overview is to summarize sector insights from the following ARCHES Working Groups: production, transportation, power, ports, maritime and aviation. In the coming months, more detailed white papers will be released from these same Working Groups to provide deeper insights and collectively serve as a strong foundation for California's forthcoming Hydrogen Market Development Strategy.

ARCHES plans to develop white papers on additional topics such as hydrogen derivatives, biohydrogen, codes and standards, and workforce development. All of these lean heavily on experts from public and private industry, communities, government, academia, and labor. ARCHES fully acknowledges that successfully building a new ecosystem and marketplace is an iterative process; feedback will always be welcome.

Overview of Cross Cutting Challenges and Opportunities

Creating a strong hydrogen ecosystem and marketplace requires a common vision supported by long term, consistent commitment. In developing the white papers summarized in this document, all sectors identified the following fundamentals that, when addressed, will further a singular vision and capture the benefits to which all parties are committed.

Technology: On the demand side, products using fuel cells and hydrogen are well-developed for some sectors, and less so for others. Even for those sectors where products are currently entering the market at scale, further **technology development** will enable better performance, longer lifetimes, and lower costs. Similarly, ongoing research and development grants and pilot projects are necessary to help advance the state of the art and support continuous technology improvement for renewable, clean hydrogen-production technologies.

Economics: Costs associated with new technologies are higher than the incumbent technologies. Hydrogen—*renewable, clean* hydrogen, in particular--is currently more expensive than fossil fuels such as diesel, gasoline, and natural gas. Additionally, fuel-cell electric vehicles (FCEVs) are more expensive than conventional internal combustion vehicles. Consistent incentives and innovative economic support mechanisms, such as the clean energy tax credits enabled by the Inflation Reduction Act (IRA), infrastructure investments in the Infrastructure Investments and Jobs Act (IIJA), and State vehicle, refueling infrastructure, and low carbon fuel incentives, are needed to help manufacturers, producers and end-users choose to develop and deploy these new technologies.

Policy: California government agencies have a long successful history of working closely together to support implementation of zero-emission and renewable energy technologies to meet the State's overarching climate, energy and air quality goals. It has become increasingly clear that for any new technology to achieve meaningful market liftoff, **regulatory frameworks and definitions** must be well-coordinated and consistent across different agencies and must be integrated with federal and local policies to the greatest extent possible. This is also true for supporting the nascent market for hydrogen and its various end uses. ARCHES believes that the forthcoming Hydrogen Market Development Strategy document will help with this alignment. Additionally, targeted mechanisms, such as incentives, research and development investments, and long-term offtake agreements to enable large-scale production, will also be critical policy tools to achieve necessary economies of scale.

Workforce and education: Demand for technicians and engineers across many trades and professions could outstrip near-term supply of resources necessary to support immediate and emerging hydrogen projects. Clean energy technology and manufacturing, including electrolyzers, fuel cells, equipment, and production facilities, offers significant opportunities for the California **workforce** of the future at all levels. These are opportunities that ARCHES is uniquely positioned to enable given its foundational partnership with organized labor and the University of California system.

Community benefits: Many businesses and communities are not fully aware of renewable clean hydrogen technologies and applications, especially those related to depollution and decarbonization—benefits that should be of particular interest to communities near ports and freight corridors. There are others who may be aware of hydrogen and its positive impacts, but are not first adopters; rather, they want to see the technology perform in the market before supporting the transition. Others want to witness hydrogen infrastructure and fuel price reductions before they accept the new technology and participate in the market. In short, there is a rich opportunity to increase awareness through pilot projects that showcase hydrogen's benefits and to establish a foundation for the outreach, education, and continued dialogue that will be essential as hydrogen technology matures in each sector.

Hydrogen and fuel-cell technologies perform very well where they are deployed if these key fundamentals are addressed—and when there is access to a reliable and affordable fuel supply. These are things ARCHES is designed to monitor and address directly. Ultimate success will hinge on investment of resources, funding, **education and training,** organized under a shared vision that ensures project deployment success, while benefiting **impacted communities, improving air quality, reducing the climate impact, and creating tangible economic benefits and leadership.** ARCHES and its partners are well-positioned to scale and deliver those tangible results.

Production

The following short summary outlines top findings by the ARCHES Clean Hydrogen Production, Distribution, and Storage Work Group, identifying the opportunities, challenges, and recommended policy actions related to transitioning the state from an economy largely reliant on fossil fuels.

Opportunities

California's Leadership

California is home to the second largest hydrogen economy in the United States, a predominately fossil based system which has been in place for more than 60 years. California's leading international agribusiness uses hydrogen and its derivatives, specifically ammonia, to supply essential fertilizers for a variety of crops. When California's breakthrough clean vehicle and fuels rules were adopted by the California Air Resources Board (CARB) in the 1980s and 1990s, hydrogen supply, storage, liquefaction and delivery systems (pipelines and delivery fleets) were developed to add hydrogen to fuel production processes, which was needed to meet these new clean air requirements.

Today, the pace and magnitude of the needed transition is unprecedented. The 2022 CARB Scoping Plan, calls for a 1,700-fold increase in the production and use of hydrogen to meet our climate, clean air, community protection, petroleum phase-out, and economic growth goals.[1] The opportunities and challenges to scaling renewable clean hydrogen production as well as the accompanying delivery and storage requirements (or "supply-side") to serve the state's growing demand are many. While federal funding will serve as the catalyst to mobilize an avalanche of projects and investments to follow, market signals from the state and statewide strategies must also be implemented.

[1] CARB*2022 Scoping Plan for Achieving Carbon Neutrality*,, December 2022, p.9, https://ww2.arb.ca.gov/sites/default/files/2022-11/2022-sp.pdf

An Unprecedented Transition Away from Fossil Fuels

Renewable, clean hydrogen will play a key role in enabling California's ambitious clean air and climate targets by facilitating the transition from traditional petroleum fuels to a feasible clean energy alternative. Renewable clean hydrogen will also accelerate health and economic benefits to frontline communities that historically have been impacted by heavy industry and goods transportation while helping to attain ambient air quality standards across California. Hydrogen can replace diesel and liquid petroleum in hard-to-decarbonize sectors such as medium and heavy-duty transportation, agriculture, industry, and heavy equipment. Over time, it can also facilitate the transition of critical thermal electric assets needed for grid reliability away from fossil natural gas. Skilled workers from traditional energy jobs can transition to new renewable clean hydrogen jobs requiring similar capabilities.

Similar to the various end uses for hydrogen, hydrogen can be produced through various means.[2] We need to ensure that renewable, clean hydrogen is being produced, which complements other California energy goals such as the Renewable Portfolio Standard and decarbonizing the electricity grid. Electrolysis is one of the most promising areas for renewable, clean hydrogen production although alternatives such as using biogenic feedstocks are also viable. Technology improvements in electrolyzers and balance of plant systems, as well as achieving large-scale manufacturing, will continue to drive down costs. The opportunities for hydrogen production, especially in traditionally disadvantaged and rural communities, are grounded in the need for domestic hydrogen production that can be utilized for the various end-use applications.

Challenges and How to Address Them

While California is poised to rapidly deploy renewable clean hydrogen production, key challenges need to be addressed through more specific market signals, technology advances, and new infrastructure to larger customers not captured by building and vehicle electrification initiatives.

Reducing Renewable Clean Hydrogen Cost

Renewable clean hydrogen production may reach price parity with conventional fuels in the next few years in line with the DOE EarthShot™ production target of $2/kg hydrogen by 2026 and $1/kg by 2031.[3] This is faster than national projections from only a few years ago but does require technology innovation and subsequent adoption. Policy levers at the state level can support achieving these ambitious goals by:

- Reducing project taxes and fees for early developers, similar to the solar tax discount;

[2] Ahmet Kusoglu 2021 *Electrochem. Soc. Interface* 30 44

[3] Hydrogen Shot | Department of Energy

- Adopting electric rate structures specific to transmission-connected renewable fuels production facilities (e.g., electrolyzers and liquefaction facilities), including wholesale power market access and reduced and reasonable transmission charges;
- Developing new electric price tariff and new ancillary services or demand-side product options for electrolyzers operating in the CAISO market; and
- Creating incentives for renewable hydrogen fuel production and electric grid integration through new demand-side management products, and access to low, zero cost energy during an over generation event at the CAISO;
- Enabling payments for electrolyzers that perform grid balancing services;
- Creating a green resource adequacy (RA) product option for the RA markets to enable merchant generators with the system ability to convert from a fossil RA service provider to a green RA service provider, with an added financial incentive for green attributes;
- Establishing clear regulatory pathways for biogenic based hydrogen projects to access feedstocks;
- Promoting access to financial instruments of support that attract private capital, such as loan guarantees and access to CAEATFA low-cost project financing;
- Expanding electricity market rules for renewable, clean hydrogen, e.g., procurement orders for electric load-serving entities to include hydrogen in storage and firm zero carbon resource in procurement opportunities.

Demand for Long-term Offtake

There needs to be demand for consistent, long term off-take of hydrogen in order to provide the certainty industry needs to invest in new projects. This demand can be facilitated by:

- Expanding the hydrogen refueling station network and improving station reliability and customer experience to facilitate long-term public adoption
- Incentivizing diesel drayage and cargo handlers at ports and rail yards, including incentives for on-site fueling and mobile fuelers for terminal operators to support 24/7 operations
- Creating new incentives for clean renewable hydrogen used to produce ammonia for agricultural use; and
- Facilitating long-term contractual commitments for clean renewable hydrogen supply for new hydrogen capable technologies in power, maritime, and industrial sectors.

Transportation

The use of hydrogen and hydrogen fuel-cell technology in California's transportation sector will be crucial to achieve the zero-emission transportation goals of the State of California, along with federal goals to reduce transportation emissions.[4] The following short summary outlines top findings by the ARCHES Transportation Working Group, identifying the opportunities, challenges, and recommended policy actions related to achieving a mature hydrogen transportation market in California with a primary focus on the medium- and heavy-duty (MDHD) fuel cell electric vehicle (FCEV) market.

Opportunities

Alignment with State Priorities

FCEVs provide a pathway to zero-emissions for the medium- and heavy-duty transportation sector where batteries alone may fall short.[5] FCEVs can achieve this while still supporting vital truck and bus operational requirements such as driving range, payloads equivalent to diesel trucks, refueling time, and continued operations during grid outages. Replacing diesel trucks with zero-emission fuel-cell electric trucks (FCETs) will dramatically cut criteria pollutant emissions in disadvantaged communities (DACs), reducing one of the biggest sources of negative health impacts to DACs from conventional transportation and energy systems.[6]

[4] *White House Fact Sheet*, April 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/12/fact-sheet-biden-harris-administration-proposes-new-standards-to-protect-public-health-that-will-save-consumers-money-and-increase-energy-security/

[5] CALSTART, *Roadmap to Fuel Cell Electric Truck Commercialization*, March 2023, https://calstart.org/wp-content/uploads/2023/03/Roadmap-to-FCET-Commercialization.pdf

[6] ARCHES Health Model, LBNL, April 2023, projects $2.95B in annual health savings, mostly driven by replacing 5500 Class 6-8 Trucks and 1000 CNG buses with hydrogen fuel cells trucks and buses.

Cost of Ownership Parity

Matching hydrogen FCEVs to diesel vehicles on total cost of ownership can happen once clean hydrogen cost targets are met, and FCEV purchase costs begin to match conventional vehicles as production and supply chain volumes expand. A wide range of manufacturers have launched or are preparing to launch heavy duty FCEV models at commercial scale, particularly Class 7 and 8 heavy-duty trucks. Transit agencies are recognizing that fuel-cell electric buses (FCEBs) can be cost competitive with the potential to replace conventional internal combustion engine buses one-for-one without sacrificing performance and operational efficiencies. New FCEB models available in 2025 will provide 350 miles or more of driving range. More options for end-users mean greater competition among manufacturers and more robust and mature supply chains, which can drive down costs.

Driving Demand

Medium- and heavy-duty FCEV market development will greatly expand demand for hydrogen production, efficient distribution, storage and supply, and refueling infrastructure. Infrastructure investments and knowledge gained through developing these vehicles and stations can be further leveraged for other transportation applications, such as rail, heavy-use urban vehicles such as refuse trucks, off-road heavy equipment at ports and airports, aviation, and maritime applications. This should also promote growth in the light duty FCEV market and accelerate station technology improvements across vehicle classes.

Challenges and How to Address Them

Timeline and Incentives

To support widespread adoption, FCEBs and FCETs must become cost-competitive with conventional trucks and buses in the next few years, including both upfront capital and ongoing operational costs (i.e., similar total cost of ownership). Until cost targets are met, policies supporting cost reduction are needed. To build confidence throughout the transition to these new technologies, fleets require incentives that are predictable, easy to access, and focused on areas that accelerate adoption. This will build market certainty for manufacturers to invest in large-scale production and establish service centers, ultimately leading to a robust secondary market. Establishing the Medium- and Heavy-Duty Zero-Emission Vehicle Fleet Purchasing Assistance Program, mandated in SB 372 (2021), would help reduce upfront costs and financing hurdles for FCETs, as would reducing or eliminating sales tax for zero-emission trucks and buses, and advocating for a national exemption of the 12% Federal Excise Tax on zero-emission trucks.

Furthermore, a program to guarantee the residual value of a FCET would: remove a write-down risk for the large fleet that purchases the new vehicle; provide access to secondary market vehicles that could be resold by dealers to smaller fleets and independent operators; and, benefit those smaller operators with a the lower price tag of a used FCET. Bulk purchases of standardized FCEBs, e.g. via state contract pricing, would ensure larger production volumes for manufacturers and better supply-chain pricing. Until the overall federal allocations are increased, the cost gap between FCEBs and conventional internal combustion engine buses will require additional funds.

Bringing Down the Cost of Hydrogen

To achieve operational costs for FCETs and FCEBs that are comparable with diesel, hydrogen fuel retail price needs to reach $5-6/kg or less.[7] Federal and state incentives, such as the IRS 45V tax credit, combined with a hydrogen marketplace, can help fleets feel confident they will have a consistent and affordable hydrogen supply as they make a commitment to purchase FCETs and FCEBs. Allowing Hydrogen Refueling Infrastructure (HRI) credits under CARB's Low Carbon Fuel Standard for stations that serve MDHD FCEVs and adopting EPA RINS credits for hydrogen would lower fuel costs to customers. Mechanisms that build transparency, longevity, consistency, and adaptability into hydrogen production pricing incentive programs will encourage sustained investment and support market development. Establishing statewide vehicle, station, clean hydrogen supply, and pricing goals for 2031, e.g. through the SB 643 report and the Hydrogen Market Development Strategy, would help build certainty among manufacturers, fuel producers, and end users. Creating a fuel supply exchange, managed by ARCHES, could match producers with price incentives and enable fleet operators and station providers to obtain the lowest price possible for their fuel while maintaining a robust and sustainable supply.

Refueling Infrastructure

Fleets that operate "over the road" trucks need to access sufficient fuel for their FCETs in convenient locations and in a timely manner to maintain operational efficiency. Freight infrastructure roadmap efforts, such as the California Transportation Commission SB 671 Working Group and the National Zero-Emission Freight Corridor Strategy, must be aligned and projects implemented promptly. The CEC's Energy Infrastructure Incentives for Zero-Emission (EnergIIZE) Commercial Vehicles and U.S. DOT's Infrastructure Investment and Jobs Act (IIJA) Alternative Fuels Corridor Funding should focus on priority projects identified in these roadmaps.

Station planning, permitting, and construction need to be streamlined to dramatically reduce station implementation timelines, similar to what has been done in California for electric vehicle charging stations. Much of this work is underway: the California Public Utilities Commission (CPUC) has an energization timelines rulemaking, the Governor's Office of Business & Economic Development (GO-Biz) plans to update its Hydrogen Station Permitting Guidebook to reflect new legislation and lessons learned, and the Governor's Infrastructure Strike Team is focusing

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[7] DOE, *National Clean Strategy and Roadmap (Draft)*, September 2022
https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-strategy-roadmap.pdf?Status=Master

administration efforts on getting projects in the ground.[8,9,10] Success of these and other initiatives hinges on contributions from groups building the infrastructure. Along similar lines, all hydrogen refueling stations and vehicle systems must be widely compatible, both within and outside California, and able to handle peak dispensing demands. Mobile refueling can serve as a bridge technology to encourage early adoption of heavy-duty FCEVs while permanent refueling stations are being built. Hydrogen fueling and fuel quality standards must be fully-integrated into existing regulatory oversight structures to protect end-users and ensure a level playing field in the nascent hydrogen market.

Achieving Economies of Scale

Heavy-duty vehicle manufacturers need to produce vehicles at volume to achieve economies of scale and reduce costs to customers. Fleets must have a variety of models available to meet different operational needs. Government mechanisms to assure incentives will be available for a minimum number of vehicles, e.g. at least 5000 FCETs and 1000 FCEBs in California, with other markets developing around the country, should help companies invest in the manufacturing infrastructure and supply chain contracts necessary to build volume and diversify their product offerings. Clustering deployments of 100 to 500 trucks regionally within corridors would enable vehicle and station manufacturers to focus fueling, maintenance, and repair services effectively, thereby reducing costs. Increasing road related weight limits for FCETs, which currently weigh more than diesel vehicles, would enable them to carry the same loads as diesel vehicles, improving profitability and encouraging sales.

[8] CPUC Energization Timeline Rulemaking: https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/energization
[9] Hydrogen Readiness - California Governor’s Office of Business and Economic Development
[10] https://build.ca.gov/

Power

The following short summary outlines top findings by the ARCHES Power Working Group, identifying the opportunities, challenges, and recommended policy actions related to decarbonizing California's power sector.

Opportunities

Resilient and Decarbonized Power Grid

Renewable clean hydrogen is an important solution for helping to decarbonize California's power sector to advance the state's climate, clean electricity, resilience, and equity goals. As California reaches high percentages of renewable primary energy, hydrogen can offer many advantages to ensure electric grid resilience and reliability, including lower cost and increased efficiency of long-duration energy storage. Repowering of required dispatchable power plants with clean renewable hydrogen also provides a large and consistent early demand that will help lower hydrogen costs for other applications.

Current Uses

Several initiatives and projects are in various stages of planning or implementation to advance the use of hydrogen in the power sector in California, including projects being developed by the Los Angeles Department of Water and Power (LADWP), the Northern California Power Agency (NCPA), Sacramento Municipal Utility District (SMUD), and others. In addition, there are opportunities to use hydrogen in smaller-scale distributed energy for resiliency and backup solutions at the local level (e.g., microgrids at ports or in communities). Hydrogen fuel cell technologies can replace smaller widely used fossil-powered distributed gensets (e.g., systems that are below 5 megawatts).

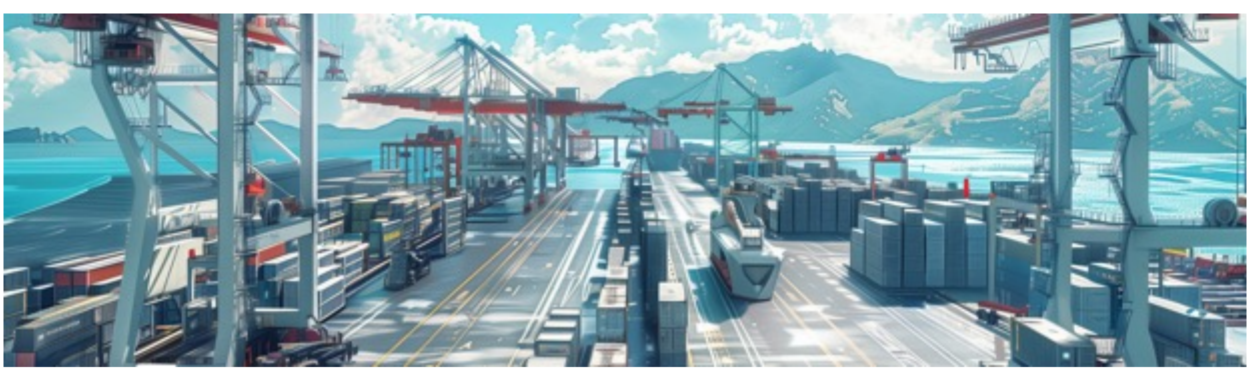
Challenges and How to Address Them

Expanding the use of hydrogen to achieve its full potential within the power sector will require ongoing research and development and significant infrastructure investments for producing, storing, and delivering hydrogen in the quantities needed in a cost-competitive market.

California will need long-duration energy storage facilities, hydrogen pipelines, hydrogen gas turbines with low-NOx emissions, and large-scale stationary fuel cells.

Actions that can help advance hydrogen use in the power sector include:

- Defining renewable clean hydrogen in a manner that is consistent with state and federal policies, and establishing standards for greenhouse gasses and criteria air pollutants;
- Establishing a procurement standard for clean hydrogen that is analogous to procurement standards for renewable and zero carbon electricity, and creating jurisdictionally consistent import/export standards for clean hydrogen;
- Leveraging forecasts for daily and annual excess renewable generation to encourage using excess renewable electricity for hydrogen production, and providing wholesale electricity market access with reasonable tariffs to dispatchable hydrogen production facilities;
- Characterizing and mitigating NO_x emissions from turbines operating on varying levels of hydrogen blended into natural gas up to 100%, and understand the performance characteristics when operated in a highly dynamic fashion to complement an electric grid system with high use of renewable sun and wind power;
- Evaluating the potential for geological storage of hydrogen in depleted oil and gas fields and in underground aquifers that exist throughout the state; and
- Streamlining the permitting process for zero-emission combined cycle or peaker power plants, as well as distributed microgrids.



Ports

The use of hydrogen and hydrogen fuel-cell technology in California's marine ports sector is an emerging concept that can dramatically reduce air pollution and climate impacts from port operations near frontline communities. The following short summary outlines top findings by the ARCHES Ports Working Group (PWG), identifying the opportunities, challenges, and recommended policy actions related to advancing the use of hydrogen and fuel cells in this important sector, with a primary focus on cargo-handling equipment and drayage truck operations.

Opportunities

Improved Health for Local Communities

Seaports around the world are primary hubs for global commerce. Three of the ten largest container ports in the U.S. are located in California, including the Port of Los Angeles, the Port of Long Beach, and the Port of Oakland. Additional major California seaports include the Port of San Diego, the Port of Hueneme, the Port of San Francisco, and the Port of Stockton. Seaports use a wide variety of mechanical equipment for various essential operations. These include top and side loaders for moving shipping containers, rubber tire gantry cranes for related operations, off-road trucks that operate on port terminals, large forklifts, rail cars, and drayage trucks that move cargo from ports to warehouses, rail lines, and other destinations.

Moving to zero-emission technologies will translate directly into improved health outcomes for residents in close proximity to ports by eliminating criteria air pollutants and alleviating the heavy pollution burden currently impacting port areas.

Current Uses

Some seaports around the world, including in California, are demonstrating hydrogen fuel cell technologies for port operations, most notably fuel cell-powered drayage trucks that collect port containers and take them to inland destinations. These are currently in prototype/pilot testing and early commercialization, including at the Ports of Los Angeles, Long Beach, and Oakland. Multiple OEMs intend to fully commercialize these vehicles by the end of 2024. Other classes of hydrogen-powered port equipment are at an earlier commercialization phase, including top/side loaders for transferring cargo between trucks and container stacks, heavy-duty forklifts, rubber-tire gantry cranes that can move containers between container stacks and yard trucks or drayage trucks, tugboats, and stationary fuel cells for shore power and backup power.

Drayage Truck

Heavy-Duty Forklifts

Top Handlers

Yard Tractor

RTG Crane

Challenges and How to Address Them

Seaports are complex sites that include a wide variety of facilities and equipment, as well as complicated operational, ownership, and oversight structures. Ports vary in size and focus. Some ports offer a wide range of operations and bring in all types of cargo, while others are more specialized, focusing for example on bulk goods or automobile off-loading operations. Hydrogen fuel cell equipment and vehicles do not yet have a long track record to build confidence among diverse seaport tenant organizations. Further technical development is needed in most categories to reach full commercial readiness. Space constraints at busy port locations may make hydrogen fueling difficult for drayage trucks in particular, requiring this to occur off-site, which precipitates additional transport and delivery costs.

These challenges can be overcome by:

- Continued technology advancement and investment in demonstrations and deployments;
- Developing mechanisms for information sharing and lessons learned amongst ports within the U.S. and internationally;
- Building on California's 2020 Hydrogen Station Permitting Guidelines document and extending to additional sectors and applications such as ports and port equipment;
- Further building trust and engaging transparently with frontline communities near ports;
- Using incentives and grants including funds to incentivize the purchase of hydrogen fuel, the high cost of which is currently a primary barrier to ongoing operations of hydrogen equipment;

- Including port equipment and hydrogen as options in California Air Resources Board (CARB) programs such as the Low-Carbon Fuel Standard, cargo-handling equipment regulations, and the Heavy-Duty Vehicle Incentive Program (HVIP); and
- Leveraging hydrogen mobile fueling, which mirrors how diesel-powered cargo handling equipment is fueled today and that as is already being applied in top-loader demonstrations.

Maritime

Low- and zero-emission marine fuels derived from hydrogen are widely regarded by energy system experts as a high-priority end-use for clean hydrogen.[11] The recent adoption of the International Maritime Organization (IMO) greenhouse gas (GHG) reduction strategy, which strives for a 30% emissions reduction by 2030 (relative to 2008 emissions), an 80% emissions reduction by 2040, and net-zero emissions by 2050, is evidence of significant global ambitions and urgency around decarbonization of marine fuel this decade. The following short summary outlines top findings by the ARCHES Maritime Working Group, identifying the opportunities, challenges, and recommended policy actions related to advancing the use of hydrogen on harbor craft vessels and in the protection of coastal waters.

Opportunities

California a Prime Candidate

Large shares of U.S. imports and exports move through California ports, making California a prime candidate for realizing significant emissions reductions through the early adoption of low-emission fuels by ocean-going vessels. Additionally, California has already implemented ambitious zero-emission regulations on certain harbor craft vessels, and the state has long led the country in efforts to reduce emissions of criteria pollutants at ports and in coastal waters. Now is the time to catalyze hydrogen and hydrogen-derived fuel adoption in California's maritime sector, allowing California to play a leading role in shipping decarbonization and to reap its associated economic and public health benefits.

The scale of hydrogen demand in the maritime sector is large enough to underpin California's overall hydrogen strategy, catalyzing hydrogen production and transport projects necessary for other end-use sectors. Analysis conducted for this white paper finds that the scale of demand for a single transpacific green shipping corridor is significant enough to provide offtake for large-scale production—more than 100,000 tonnes of hydrogen per year before 2035. For

[11] For the purposes of the forthcoming white paper, "low-emissions fuels," refers to any shipping fuel that can reduce lifecycle GHG emissions by at least 90% compared to incumbent low-sulfur fuel oil (LSFO).

context, 100,000 tonnes of hydrogen is roughly equivalent to the annual fuel demand of approximately 20,000 hydrogen FCETs (long-haul class 6 to 8 trucks).[12]

The Ports of Los Angeles and Long Beach have initiated three transpacific green corridor partnerships with East Asian trading partners, and potential shipping demand for hydrogen could exceed several hundred thousand tonnes per year before 2035. Unlocking this potential requires concerted collaboration between public and private stakeholders to implement the policy and market frameworks required to accelerate maritime offtake of hydrogen.

Challenges and How to Address Them

The working group considered two broad categories of vessels—ocean going vessels (OGV) and commercial harbor craft (CHC)—each of which has distinct fuel-switching pathways, challenges, and priority actions for advancing hydrogen and derivative fuel adoption.

Ocean Going Vessels

General consensus exists among industry first-movers and research organizations that the use of low-emission fuels derived from hydrogen are necessary to decarbonize shipping. The volumes required will be significant. As mentioned above, hydrogen demand (as a feedstock for low-emission fuel production) on a single transpacific Green Shipping Corridor connecting Los Angeles to East Asia could exceed 100,000 tonnes per year by the early 2030s; the ports of Los Angeles and Long Beach have established green corridor partnerships with three East Asian trading partners. The maritime fuel transition has begun; given recent policy and market pressures—including an IMO target to meet 10% of international shipping's energy needs with zero or near-zero emission fuels by 2030—the timeline on which significant hydrogen demand in the sector is expected to materialize has accelerated.[13]

To meet the challenge, California must evaluate how new and existing policy tools can be leveraged to assist in the development of the low-emission fuel supply chains and infrastructure necessary to introduce alternative fuel vessels on specific routes; satisfying near-term California demand will likely require low-emission fuel production near California ports. Potential policy pathways for catalyzing low-emission fuel production include:

- Bringing incumbent bunker fuels and alternative marine fuels into California's Low Carbon Fuel Standard (LCFS) program;
- Regulating GHG-emissions from OGVs in California waters; and
- Creating port-specific incentive programs (e.g., akin to the current Environmental Ship Index Program) for alternative marine fuel vessels operating on green corridors in California.

[12] Assuming annual VMT of 65,000 miles and Class 8 hydrogen fuel cell fuel efficiency of 12.5kg H2/mile
[13] IMO, "2023 Strategy on Reduction of GHG Emissions from Ships," MEPC 80/WP.12 Annex 1, page 6. 2023.

Commercial Harbor Craft

Decarbonizing CHC vessels will likely require a mix of battery electric vessels (BEVs), hydrogen fuel cell electric vessels (FCEVs), and hybrid vessels, to account for diverse operational requirements, and port-specific considerations related to each technology pathway. When comparing BEVs and FCEVs for CHC applications today, BEVs are typically lower cost, technologically more mature, and face less regulatory uncertainty around vessel design and approval. FCEV competitiveness today is driven primarily by vessel duty-cycle and range requirements, faster refueling, and the ability to fuel with mobile fuelers–avoiding the need to build out stationary infrastructure. Capital costs for FCEVs are currently 2-3x greater than for diesel incumbents. The two hydrogen vessels currently under construction in California's CHC sector are funded in part by state grants and undertaken by entities able to prioritize decarbonization at substantial cost. Additional incentives for such programs will support continued innovation and cost reductions. Once costs for fuel cell vessels become more competitive, annual hydrogen demand for California's CHC subsector is expected to be in the tens-of-thousands of tonnes by 2040, even in conservative forecasts in which hydrogen fuel constitutes a small percentage (≈10%) of the total CHC fleet's energy use. Hydrogen production near ports will be important for reducing the cost of delivered hydrogen, as the cost of transporting hydrogen can easily exceed hydrogen production costs.

Aviation

The California aviation industry currently uses hydrogen in small quantities, notably for ground transportation and as an input to produce renewable diesel fuel from hydroprocessed esters and fatty acids. As of January 2023, California indirectly consumed up to 1,600 tonnes of hydrogen annually–representing 0.2% of in-state total hydrogen production capacity. The following short summary outlines top findings by the ARCHES Aviation Working Group, identifying the opportunities, challenges, and policy needs to support the transition to clean hydrogen within the aviation industries.

Opportunities

Current Uses

Hydrogen use in aircraft is still in the early stages of development, with several prototypes undergoing testing in recent years. Future market demand for hydrogen fuel as a power source for aviation varies widely, as it is still unclear what the payload and range capabilities of hydrogen-powered aircraft will be, when commercial aircraft will be available, and how quickly such aircraft can be delivered to customers. In 2035, airport ground support equipment and ground fleets could require 14 metric tonnes per day (MTPD) of hydrogen statewide. Projections for hydrogen demand for direct use in aircraft vary from 11 metric tonnes per day to power 32 aircraft across 10 California airports to 47 MTPD to power 132 aircraft across 26 California airports by 2035.

Figure 1: *Joby's hydrogen-electric, vertical take-off and landing demonstrator aircraft completed a landmark 523 mile flight in July 2024.*[14]

Figure 2: *Project Acorn, a pioneering airside hydrogen refueling trial led by easyJet and supported by Jacobs and cross-industry partners, successfully completed at Bristol Airport, marking the first trial of its kind at a major U.K. airport.*[15]
Photo Credit: *Jacobs*

Figure 3: *ZeroAvia Dornier 228 on takeoff during 10th flight test of prototype ZA600 hydrogen-electric engine.*[16]

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[14] https://www.jobyaviation.com/news/joby-demonstrates-potential-regional-journeys-landmark-hydrogen-electric-flight/
[15] Jacobs, Jacobs Supports Ground-breaking Airport Hydrogen Trial in the UK (April 11, 2024), available at https://www.jacobs.com/newsroom/news/jacobs-supports-ground-breaking-airport-hydrogen-trial-uk
[16] ZeroAvia, ZeroAvia Successfully Completes Initial Dornier 228 Flight Test Campaign (July 19, 2023), https://zeroavia.com/complete-flight-test/

Zero-emission Jet Fuel

Due to its high energy density, hydrogen could be well-suited to the demands of aviation. Hydrogen can power aircraft in various ways; it can be used directly in fuel cells to generate electricity, providing a clean and efficient power source. Additionally, hydrogen can be utilized as a key ingredient in the production of synthetic e-fuels, which can be used in existing jet engines with minimal modifications. When produced via renewable pathways, hydrogen has the potential to offer a zero-emission alternative to kerosene-based fossil jet fuel. Hydrogen-powered aviation could improve air quality and reduce noise pollution, benefitting surrounding communities. Furthermore, hydrogen has the potential to provide airports with an avenue for both energy resilience as a backup power generating source including as mobile charging units for electric vehicles and reduced emissions from fuel-cell powered ground support equipment (GSE) and other ground transportation. Hydrogen production could be located at airports, and may prove to be a less costly and carbon-free alternative to conventional fossil jet fuel and biomass-derived sustainable aviation fuel (SAF).

Challenges and How to Address Them

Broader use of hydrogen in airports faces several challenges, including the current high production costs of hydrogen, current lack of production, distribution, and storage infrastructure and standards, and safety standards that may vary according to the use case.

In the near term, the state could encourage the development of hydrogen clusters at select airports such as Long Beach to fuel ground-support equipment, public transportation, and off-highway ground transportation with infrastructure to produce and store hydrogen fuel on-site. Such clusters could expand to fuel hydrogen powered aircraft as they become commercially viable in the coming years. Other supportive actions that could catalyze investment in hydrogen for aviation include:

- Incentivizing the use of low-carbon hydrogen as an input to liquid SAF production or other chemical/industrial processes, as well as for direct consumption by aircraft;
- Collaboration with federal and international standards organizations to develop and adopt relevant standards and policies for aircraft and ground support equipment;
- State-level leadership to encourage all California airports to include a focus on hydrogen infrastructure in their planning processes and coordination to pursue federal funding via existing grant programs like the Federal Aviation Administration’s Fueling Aviation’s Sustainable Transition via Sustainable Aviation Fuels (FAST-SAF) and Low-Emission Aviation Technologies (FAST-Tech) grants;
- Collaboration among airports and airport equipment manufacturers with airport-proximal enterprises and transit agencies that have an interest in hydrogen offtake,

developing regional entities of sufficient scale to achieve enough demand to enable at-pump cost of $3/kg of hydrogen; and

- Taking a cross-sectoral approach to standardization and regulations, especially in the context of hydrogen at airports.

Conclusion

As we consider the role renewable, clean hydrogen can play in each sector, it is important to remember the role of hydrogen in our broad pursuit of zero-emissions and carbon neutrality: **California is pursuing hydrogen to end dependence on fossil fuels**. Every hydrogen fuel-cell truck and piece of fuel-cell cargo handling equipment deployed displaces diesel, every bus and power plant displaces natural gas, every plane displaces kerosene-based fossil jet fuel, every maritime vessel displaces low-sulfur fuel oil, and renewable clean hydrogen production–done as ARCHES plans–will increase renewable energy market penetration, alongside and complementary to other clean and renewable energy enabling technologies.

The road ahead is filled with some challenges and many opportunities, much of which will be cataloged in detail in our forthcoming ARCHES white papers. We know there will be bumps in the road, but we also know that we need renewable, clean hydrogen to succeed to reach carbon neutrality by 2045. And it's clear that California is perhaps the best place in the world to create a thriving, economically viable renewable, clean hydrogen market and integrated ecosystem that can lay the foundation for market liftoff across other regions of the country and the world.