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Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

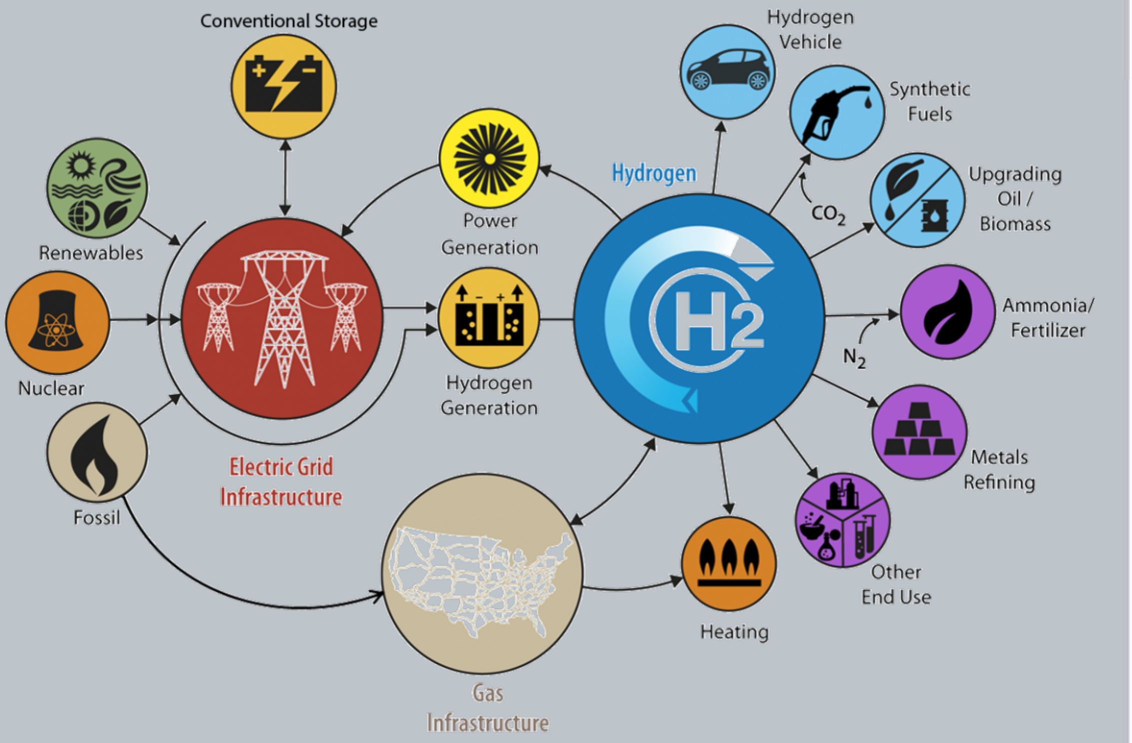
2017 H2@Scale Workshop Report

Fuel Cell Seminar and Exposition

November 7, 2017

Long Beach Convention Center

Long Beach, CA



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List of Acronyms

AB	Assembly Bill
BBB	California Independent System Operator
CRADA	Cooperative Research and Development Agreement
DOE	U. S. Department of Energy
EERE	Energy Efficiency and Renewable Energy
ESDER	Energy Storage & Distributed Energy Resources
FCEV	Fuel Cell Electric Vehicles
FCTO	Fuel Cell Technologies Office
ISO	Independent System Operator's
IRP	Integrated Resource Plans
NREL	National Renewable Energy Laboratory
PUC	Public Utilities Commissions
SOC	State-of-Charge
RD&D	Research, Development, and Demonstration
ZEV	Zero Emission Vehicle

Executive Summary

H2@Scale is a U.S. Department of Energy (DOE) initiative bringing together stakeholders to advance affordable wide scale hydrogen production, transport, storage, and utilization to unlock revenue potential and value across sectors. It is a framework through which stakeholders can work together with national laboratories through government co-funded projects as well as industry partnerships to accelerate the research, development and demonstration of applicable technologies.[1] In November of 2017, the DOE's Fuel Cell Technologies Office (FCTO) within the Office of Energy Efficiency and Renewable Energy (EERE) hosted a session on H2@Scale at the Fuel Cell Seminar in Long Beach, California. This session was one in a series of activities to solicit feedback from industry, academia, national labs, end users, and a broad group of stakeholders to inform the DOE program and further develop a framework for the H2@Scale initiative. The event drew over 300 participants from across North America as well as multiple other regions around the world, including Japan, South Korea, Europe, South Africa, and the Middle East. Information regarding these activities and prior workshops can be found on the H2@Scale website at: https://www.energy.gov/eere/fuelcells/h2-scale.

Current and emerging hydrogen production technologies utilize diverse energy feedstocks, including natural gas, water, electricity, high-temperature heat, and sunlight. The flexibility and performance capabilities of these technologies create the potential for their dynamic integration with power generators and the electricity grid, as well as their use in capturing remote energy feedstocks that are distant from electricity transmission. Use of hydrogen production in this fashion can mitigate power curtailment, enhance grid reliability, and increase the use of domestic energy resources. The resulting growth in hydrogen production could be anchored by emerging domestic industries, such as fuel cell vehicles, along with existing large-scale hydrogen consumers, such as petroleum refineries and ammonia producers. Such diverse end uses of hydrogen crosscut sectors and position hydrogen as one of an 'all of the above' portfolio strategy that enables synergies across all domestic fuels (coal, nuclear, natural gas, renewables) as well as multiple applications, including transportation, the chemical and manufacturing industries, and power generation. However, a number of technical and cost challenges remain, which makes the H2@Scale initiative an appropriate area for research and development through a federal program in conjunction with industry, academia and national laboratories.

The H2@Scale session covered the DOE's early-stage research efforts, as well as perspectives of key external stakeholders. Key conclusions from the session include:

Federal Research Activities and Partnerships

- FCTO's H2@Scale Research, Development, and Demonstration (RD&D) Consortium provides a framework for leveraging the private sector and engaging industry in appropriate roles to complement the federal role of early stage R&D. The H2@Scale Consortium currently comprises four working groups: 1) Hydrogen Quantitative Performance Analysis and Operation R&D, 2) Hydrogen Distribution Component Development R&D, 3) Advanced Hydrogen Production Concepts R&D, and 4) Hydrogen Integration with Energy Generation R&D. The initial working group members will be awardees from a call for Cooperative Research and Development Agreement (CRADA) proposals held by the National Renewable Energy Laboratory (NREL) in 2017 to advance the H2@Scale concept. CRADAs are a standard mechanism used by DOE to enable partnerships and joint projects with DOE National Laboratories. Thus far, 24 proposals were selected through the 2017 CRADA call to fund National Laboratories. The selected projects totaled over $7M in value, with over 40% of the funding coming from external stakeholders, and the remainder from FCTO. These projects will have

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[1] For more information, please see: https://energy.gov/eere/fuelcells/h2-scale.

access to state-of-the-art and unique National Laboratory facilities and expertise to address critical challenges and advance the H2@Scale vision.

- In 2017, a multi-laboratory techno-economic analysis project led by the National Renewable Energy Laboratory was initiated to evaluate the technical and economic potential of the H2@Scale concept. In preliminary analysis, the technical potential of hydrogen demand has characterized as 90 million metric tonnes/year, and economic potential has been characterized as 20-30 million metric tonnes/year. Further details are provided in the report.

Feedback from stakeholders on key issues and observations are summarized below.

Hydrogen Production

- Expected growth in hydrogen demand for fuel cell vehicles in California, along with the state's mandate for renewable hydrogen use in transportation will require new production capacity in the near- to mid-term. In February 2018, the California Energy Commission issued a grant funding opportunity for renewable hydrogen production facilities at least 1,000 kg/day in capacity. Growth of both production and distribution infrastructure will require collaboration, front-loaded spending and policies that incentivize private investments while giving state governments an exit strategy.
- Determination of the appropriate scale of hydrogen production plants in a given region considers the cost of capital, electricity, as well as cost of infrastructure to reach various demand scenarios. Capital cost of balance-of-plant equipment, such as power electronics, is significant, and requires research for cost reduction.
- Approaches that are not currently being considered in the "renewable' definition of hydrogen include the use of by-product streams, such as methane from landfills (which can be reformed into hydrogen) or hydrogen from petrochemical cracking.

Energy Production and Transmission

- Key trends in Southern California that will affect energy markets include are an increase in energy efficiency and rapid electrification, a decline in personal vehicle prices, as well as a decline in natural gas prices.
- California has over 20,000 MW of utility-scale renewable capacity, and installation of another 12,000–16,000 MW will be required for the state to meet its goal to derive 50% of its electricity from renewable sources by 2030; renewable sources of electricity already account for approximately 30% of California's electricity generation.[2] Wind power currently has the lowest levelized cost of all power generation sources being considered in California.[3] The aggressive growth that is expected in both utility-scale and distributed renewable generation will require technologies to manage grid stability and facilitate large-scale energy storage. Approaches being considered include distributed energy systems, energy exports, digitization to couple renewables and storage, and technologies that can leverage existing natural gas or electricity grid infrastructure. Hydrogen can play many roles in California's future energy system.
- Utility companies typically make investment decisions looking 20–40 years in the future. Utilities are also incorporating fuel flexibility into their plans, to remain resilient to fluctuations in prices of individual fuels.

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[2] http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf
[3] http://www.energy.ca.gov/2014publications/CEC-200-2014-003/CEC-200-2014-003-SF.pdf

- Utilities are considering several different methods of electrical and thermal energy storage today, including batteries, molten sulfur, and hydrogen.
- Analysis is necessary to determine the conditions in which it is more economical to transport energy as a chemical (e.g. hydrogen) than via electrical transmission lines.

Hydrogen Infrastructure Delivery

- In California, auto manufacturers anticipate deploying up to 37,400 fuel cell electric vehicles (FCEVs) by 2023. Hydrogen fueling station utilization is already growing rapidly; in California, the average station is on track to reach full utilization in 5 years. Additional fueling stations (beyond those currently funded) are expected to be necessary in the Southern California and Bay Area regions to meet anticipated growth in hydrogen demand. It is estimated that future stations will need to have double the capacity of those that are currently open.
- The National Renewable Energy Laboratory and Argonne National Laboratory are currently experimentally assessing the performance of a station integration strategy developed by Argonne in 2014 to reduce capital costs. The patented pressure consolidation strategy[4] has potential to reduce the capital costs of hydrogen fueling stations by 30-40% through intelligent, dynamic integration of station compressors and tube trailers. This innovative approach is receiving increased interest by industry as an opportunity to decrease cost, and is one example of the H2@Scale initiative addressing specific infrastructure challenges faced by the private sector.
- A significant barrier to reductions in the cost of fueling infrastructure is the lack of a supply chain. Many components only have one supplier, or were not originally designed for hydrogen use. Increased research and competition within the market (e.g. in the areas of dispensers, nozzles, hoses, and seals) would reduce costs.

More detailed information is provided within this report. FCTO intends to use the feedback as it coordinates across relevant DOE offices, National Labs and the private sector to further the H2@Scale concept and update Program planning and roadmap documents during the coming year.

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[4] https://patents.justia.com/patent/20150090364

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Plenary Session

Overview of Hydrogen and Fuel Cells Technology Status

Dr. Sunita Satyapal, U.S. Department of Energy Fuel Cell Technologies Office

Dr. Satyapal opened the workshop by explaining how the H2@Scale initiative can integrate early-stage R&D led by federal agencies with later-stage demonstration, deployment, and commercialization efforts led by industry. The premise of H2@Scale is that hydrogen is a unique energy carrier that can connect the electricity grid as well as stranded sources of power with a host of end uses, including transportation and petrochemicals. Hydrogen production from water splitting can leverage electricity that would otherwise be curtailed from the grid, electricity from remote power generators that are distant from transmission lines, heat from baseload generators (e.g. coal or nuclear) that may otherwise be offline due to falling natural gas prices and growth in intermittent generation, as well as hydrocarbon feedstock, such as natural gas or biogas. The value proposition of H2@Scale is strengthened by growing global interest in hydrogen uses. The market growth of fuel cells in the last year included 500 MW deployed for stationary and transportation applications in 2016, over 60,000 fuel cell units shipped worldwide in 2016, and announcements of new markets, such as the planned deployment of a couple thousand fuel cell buses in China in the near future.

In 2017, the national laboratories evaluated the technical potential of the H2@Scale concept by characterizing the total hydrogen supply achievable in the U.S. through water splitting with renewable sources of power, as well as the consumption of hydrogen achievable in the following sectors: transportation, petroleum refining, ammonia production, and blending of hydrogen into natural gas infrastructure (e.g. for heating or power generation applications). Preliminary analysis indicates that all regions of the U.S. either have the technical potential to satisfy local demand, or are in close proximity to regions with potential surplus supply. The next steps from this regional analysis are to characterize the economic potential achievable in the near- to mid-term by pursuing the following questions:

- In what regions of the U.S. does hydrogen demand currently exceed supply?
- What are the regional and national outlooks for hydrogen supply and demand?
- In what regions and industries does hydrogen production or utilization have a value proposition?
- How can hydrogen demands be bundled to reduce costs?

In 2017, the Fuel Cell Technologies Office (FCTO) launched the H2@Scale Consortium to facilitate collaboration between industry and the U.S. Department of Energy's national laboratories on priority areas of research. The Consortium assembles national laboratory capabilities in several areas of R&D, including:

- Hydrogen Materials Compatibility R&D
- Grid simulation and testing R&D
- Technoeconomic modeling and analysis
- Safety R&D.

The Consortium engages external stakeholders through Cooperative Research and Development Agreements (CRADAs). Stakeholders can submit CRADA proposals to utilize Consortium capabilities on R&D projects that advance H2@Scale concepts. Of the proposals that are selected, FCTO and the applicant will co-fund the R&D conducted by the H2@Scale Consortium, pending appropriations. For example, federal funding for industry-led projects will cover 50% of the R&D conducted by the Consortium. Awardees will gain:

- Access to the Consortium’s world-class R&D capabilities for the proposed project(s).
- Cost matching from FCTO for R&D conducted by the H2@Scale Consortium.
- Access to Consortium Working Groups, which facilitate collaboration with other relevant stakeholders.

Twenty-four applications were selected from the 2017 round of the H2@Scale CRADA Call. Future rounds may be held in the coming year, pending appropriations and alignment with federal priorities. Each awardee is being given access to at least one of the Consortium’s four Working Groups:

1. Hydrogen Quantitative Performance Analysis and Operation R&D
2. Hydrogen Distribution Component Development RD
3. Advanced Hydrogen Production Concepts R&D
4. Hydrogen Integration with Energy Generation R&D.

The Groups will meet quarterly to: 1) keep members informed of cutting-edge R&D developments in their fields, 2) collaborate on common pre-competitive R&D challenges, and 3) provide members independent technical feedback from expert stakeholders, and 4) identify priority areas for future R&D.

Dr. Satyapal concluded the overview by announcing that FCTO’s 2018 Annual Merit Review will take place from June 13–15 in Washington, D.C. The event will include hydrogen and fuel cell activities across all DOE Offices as well as other U.S. Agencies (such as the National Aeronautics and Space Administration [NASA], the Department of Transportation, and the Department of Defense). With up to 1,000 participants anticipated, those interested were encouraged to register early (see https://www.annualmeritreview.energy.gov/registration.html).

Neha Rustagi, Hydrogen Delivery Lead Technology Manager, from FCTO moderated the remainder of the session and served as lead facilitator for the workshop.

Overview of H2@Scale Concept

Bryan Pivovar, National Renewable Energy Laboratory

Dr. Pivovar described the role hydrogen can play in grid resiliency, energy storage, and emissions reductions. Each of these challenges is particularly relevant in California, where:

- Several cities have some of the highest levels of ozone and particulate matter in the U.S.
- Aggressive growth in renewable power generation is expected to create a “duck curve”[5] in the near future, creating a need to address the mismatch between power demand and the availability of solar and wind power.

California currently has several policies to address these concerns, including:

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[5] The “duck curve” is the phenomenon wherein renewables are unable to meet power demand during certain hours of the day (e.g. the afternoon), and require alternative generators to rapidly ramp up their supply. Approaches to managing the duck curve include the use of natural gas turbines that can rapidly fluctuate output, demand response programs wherein technologies can rapidly increase or decrease their power intake to match the grid’s supply, and/or energy storage (e.g. batteries).

- California's Renewable Portfolio Standard, which requires that retail sellers and publicly owned utilities obtain 50% of their electricity from renewable sources by 2030.
- The Zero Emission Vehicle (ZEV) Action Plan, which identifies state activities to promote adoption of ZEVs in light-, medium-, and heavy-duty transportation.
- The Renewable Gas Standard, which aims to incentivize use of renewable gases, such as biogas, to reduce the carbon intensity of California's gas supply, and reduce California's dependence on energy resources from other states.

Dr. Pivovar concluded by explaining that hydrogen can help address these goals due to its versatility. Hydrogen can be used to generate power across a range of scales and applications, from fuel cells that power vehicles to combustion turbines that burn hydrogen to provide stationary power. Hydrogen can additionally be produced from diverse domestic resources and technologies, including water, natural gas, electricity, and heat. As a result, hydrogen production can be dynamically integrated with power generators in manners that enhance the overall economics of energy systems. H2@Scale envisions hydrogen as a large-scale, clean, cross-sector energy carrier that connects electricity transmission, industry, and transportation.

Evolution in California Energy Generation and Transmission

Angelina Galiteva, California Independent System Operator (CAISO)

Ms. Galiteva began her presentation by sharing that the electric industry is in the midst of unprecedented changes, driven by a number of interrelated issues: Requirements for grid modernization, increased engagements of consumers in power generation and retail markets, collaboration across regions in power supply, and more. The independent system operator's (ISO) role is to manage the dispatch of power generators on the grid, to ensure that supply matches demand, and that competitive markets for power are efficient and fair. CAISO manages markets for electricity that is sold a day before it is generated (day-ahead markets), electricity that is sold within minutes of its dispatch (real-time markets), and ancillary services that are dispatched at 4-second intervals to buffer differences between power supply and demand. CAISO also manages expansions of the transmission grid, and integrations of the grid with other regions of the country.

As a result of state policies, renewables are growing rapidly in California. Currently, renewables account for 20,000 MW of installed capacity in California. Another 12,000-16,000 MW will be required to meet California's goal for 50% renewables by 2030. Due to this growth, curtailments and the impacts of the duck curve are becoming an increasing concern. During afternoon hours, "net load" on the grid (i.e. power generation that is dispatchable, such as natural gas turbines) is already commonly required to ramp up by >3,000 MW/hour. The profiles of both net and gross load are being further influenced by recent growth in rooftop solar power in California. Rooftop solar power is not accounted for in California's RPS targets, and is decreasing the demand for grid electricity during afternoon hours. As renewable penetration continues to grow in California and throughout the U.S., energy storage will become an increasingly necessary part of the portfolio of solutions to manage grid stability.

CAISO is implementing policies to support integration of resources with the grid that can enhance the flexibility of transmission and distribution. One of the challenges that distributed resources can face in accessing wholesale markets is that their capacities (e.g. power or state of charge) may be below the ISO's requirements. CAISO's Energy Storage & Distributed Energy Resources (ESDER) initiative implemented regulations in 2016 that eased state-of-charge (SOC) requirements; for example, resources are now able to submit their SOC to CAISO when they bid in to day-ahead markets, rather than the ISO assuming that the SOC is 50%. Similarly, CAISO's rules for "distributed energy resource providers" allow for entities to pool distributed resources to meet CAISO's minimum power capacity requirements to participate in wholesale markets.

The California Energy Commission is now conducting research in numerous types of energy storage, including compressed air, batteries, flywheels, and electric vehicles. Hydrogen needs to fit into this matrix, and the hydrogen community is encouraged to conduct more outreach regarding its merits for energy storage.

CAISO manages markets for wholesale power (e.g. the day-ahead market, real-time market, and imbalance markets—ancillary services). Specific activities include: 1) increasing integration of the transmission grid with other regions of the country, 2) directing the interaction of regulatory services (a category of ancillary services) with the grid at 4-second intervals to buffer differences between power supply and demand, 3) operating the market for wholesale electricity and several categories of reserves, 4) managing new resources and interconnections, and 5) planning grid expansions. CAISO is making progress toward achieving 50% penetration of renewables by 2020.

The existing storage infrastructure in California is 96% pumped hydro, and hydrogen needs to be fit into this matrix if it is to become viable. Key priorities of technologies that address problems of oversupply and ramping should be to decarbonize, decentralize, and deregionalize. Forty percent of green-house gas emissions in California come from the transportation sector.

There is a steady growth of renewables in California, with solar and wind being the cheapest resources on the grid. Modelling studies have shown that baseload will diminish in California by 2030 due to over-generation of solar energy. As a result, distributed energy systems, storage, and export or curtailment solutions will be necessary. Digitalization of technology will also be important to enable coupling of renewables and storage. California is moving forward and hydrogen can play many roles in the future.

Expansion of Hydrogen Infrastructure in California

Andrew Martinez, California Air Resources Board

Mr. Martinez began his presentation by noting that the growth of hydrogen in California can be traced to Assembly Bill (AB) 8. AB 8 was signed in 2013 and required the California Energy Commission to allocate $20M annually for hydrogen fueling stations until at least 100 hydrogen fueling stations are publicly available in California. AB8 also requires the California Air Resources Board to annually report on the number of existing and projected fuel cell vehicles in California, as well as the coverage and capacity of fueling stations. In his presentation, Mr. Martinez provided an overview of the material covered in the January 2018 AB8 report. The California hydrogen fueling network currently includes 34 open retail stations, 2 non-retail stations being upgraded to retail (in Burbank and Emeryville), and 1 non-retail station without plans for upgrade (in Newport Beach). Twenty-nine other stations are currently in development. These stations are geographically spread across northern California (San Francisco region) to southern California (Los Angeles region), with several connector stations planned in between.

Auto manufacturers anticipate deploying up to 37,400 fuel cell electric vehicles (FCEVs) by 2023, which will require rapid station deployments in the near-term. Hydrogen fueling station utilization is also growing swiftly; utilization of station capacity in California grew from about 2% to 11% within 2016. A few well-utilized stations have even required two deliveries of hydrogen by tube trailer a day. An increase in both fueling capacity, and hydrogen supply will be necessary to prevent deficits in hydrogen by 2023. The majority of the hydrogen produced in California and the U.S. as a whole is for oil applications. Approximately half of the hydrogen produced in California is "merchant" (i.e. produced in a centralized facility and sold to customers), while about half is produced at refineries for use onsite. Due to California's Senate Bill 1505, at least 33% of the hydrogen dispensed by stations receiving State funds must be renewable. Once the quantity of fuel the

State dispenses exceeds 3.5 million kilograms over 1 year, all of the stations will be required to meet the 33% requirement, regardless of whether they received state funding; this threshold is expected to be reached by 2020.

In February 2018, the California Energy Commission issued a grant funding opportunity for renewable hydrogen production facilities at least 1,000 kg/day in capacity. Mr. Martinez concluded by remarking that H2@Scale concepts are central to California's path forward in both renewables and use of hydrogen in new applications, such as medium- and heavy-duty transportation.

Fireside Chats on Impacts of H2@Scale

Alignment of H2@Scale with Energy Storage and Resiliency

Panelists discussed the relevance of hydrogen to current and future needs of energy systems, including grid stability and energy storage. The panel included Noah Meeks **(Southern Company)**, Ron Kent **(SoCal Gas)**, Daniel Dedrick **(NRG**[6]**)**, and Matthew Pellow **(Electric Power Research Institute)**. The panel was moderated by Frank Novachek **(Xcel Energy)**.

Question 1 – How are you currently preparing for the evolution of the market and how does hydrogen fit in?

- Technologies that reduce carbon emissions within the energy system are a future priority, and hydrogen is essential to this portfolio. SoCal Gas is pioneering a method to make solid carbon during hydrogen production from natural gas. The carbon can then be converted to valuable products, such as carbon fibers used in building materials, airplanes, and vehicles.
- Key trends in Southern California that will affect energy markets are a decline in personal vehicle prices, a decline in gas prices, and an increase in energy efficiency and rapid electrification. The future of transportation is electric, although it is unclear what the fuel choice will be; hydrogen may play a role in this evolution. Hydrogen also has a value proposition in long-duration energy storage, as it is very scalable. It is important to bear in mind that any new storage technologies will have to be competitive with natural gas combustion turbines to succeed.
- NRG is one of the largest independent power producers in the United States. Many utility-scale assets associated with retired gas power plants are being replaced with renewable solar power generating facilities. The emerging "duck curve"[7] in high renewables markets makes management and integration of storage a priority for these new utility-scale assets. In the near term, storage will be large-scale lithium ion, but other storage technologies (e.g. hydrogen) will have potential in the long term. Continued low Power Purchase Agreement prices (well below $40/MWh for the foreseeable future), may provide an opportunity to produce cost-effective renewable hydrogen at large scale. However, growth of large-scale hydrogen energy storage will require policies that develop markets around renewable hydrogen.
- EPRI is a nonprofit research institute working with the utility industry. The industry's most pressing issue is the evolution of electricity markets, as electricity becomes a larger share of energy use in applications. EPRI is looking forward to see how the energy sector will evolve and H2@Scale aligns well.

Question 2 – What time frame do you consider for energy markets?

- Utility companies make investment decisions looking 20–30 years into the future, but policy changes are more rapid and stress traditional approaches to doing business. Changes in wholesale electricity

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[6] On February 6, 2018, GIP entered into a purchase and sale agreement with NRG for the acquisition of NRG's full ownership interest in NRG Yield and NRG's renewable energy development and operations platform consisting of a robust pipeline of over 6.4 GW of backlog and development projects, as well as operational oversight of 2.4 GW across 17 states. The Transaction is subject to certain closing conditions, including customary legal and regulatory approvals. NRG Yield expects the Transaction to close in the second half of 2018. From: http://investors.nrg.com/phoenix.zhtml?c=121544&p=irol-newsArticle&ID=2330859.

[7] The "duck-curve" refers to the shape of the net electric load minus wind and solar generation for a typical high-renewables penetration day. The "neck of the duck" represents largest demand for dispatchable generation to service load as non-dispatchable renewables ramp down.

markets are slow, while changes to ancillary markets happen more quickly. The focus of change is currently shifting to distribution markets.

- The design life of utility-scale power plants extends out 35 years with 10–20 year off-take contracts, thus providing a defined timeline for technology introduction. For specific assets, a 4–5 year window exists on the front-end of a project for technology decisions due to the characteristic development timelines for utility-scale generating facilities.
- Southern Company typically plans 40 years out, and considers potential costs of carbon and fluctuations in the cost of natural gas in planning. They plan for fuel flexibility to account for price volatility.
- The state of California has established plans for timeframes of 2030 and 2050. SoCal Gas determines what it has to do today in order to meet those goals. The two challenges they currently face are: 1) an energy storage problem—wind suppliers are investing in other states to avoid curtailment, and 2) leveraging and integrating the natural gas/electricity grid to optimize their value.

Question 3 – Hydrogen has opportunities to help with these problems. Is anyone looking at hydrogen now? If not, why?

- Most of NRG's current thinking is around analysis and research, although there's no reason not to work with parties interested in large-scale hydrogen production. The developments of power plants must focus on "bankable" off-take and technologies, as financing can be a challenge otherwise. Hydrogen is on their roadmap, but it requires continued focus to make sure the technology is ready when the market is ready.
- Southern Company is focusing on analysis and is not currently incorporating hydrogen in their integrated resource plans (IRPs).[8]

Question 4 – Is hydrogen an adjunct of the electricity grid, or is the opposite true? When will we start planning for a hydrogen pipeline? What is the role that collaboration with national laboratory facilities, such as the Energy Systems Integration Facility at NREL, can play in enabling hydrogen integration with the grid?

- Policy making needs to be based on models, not on narratives. The national labs may be the country's greatest asset and the industry should use national labs more often.
- The future fuel infrastructure could be based in hydrogen or ammonia, just as today's infrastructure is based in both natural gas fuel and electricity. Ultimately, the success of any form of energy is dependent on energy density; transporting hydrogen through ammonia could be a great option. It is also important to assess the conditions in which it is cheaper to move energy via wire than it is via a gas (e.g. hydrogen) pipeline.
- EPRI has had productive conversations with NREL about identifying aggregate value in integrating hydrogen with the electricity grid.

Question 5 – Why is biomass not considered in the hydrogen economy? Biomass is a baseload option that has many benefits, and is being studied at DOE national laboratories.

- SoCal Gas has 4–5 projects right now pursuing the conversion of biomass to methane, including the conversion of undigestibles, and a plan to refurbish an old incineration plant to gasify woodchips. Further growth is a matter of cost.

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[8] IRPs detail a utility's plans to meet their projected demand in the coming decades, using both supply- and demand-side resources (e.g. power generation, ancillary grid services, demand response, energy storage, etc.) States often require utilities to develop IRPs, and submit them to public utilities commissions (PUCs) for review.

- There are multiple utilities trying to determine where conversion of biomass to hydrogen fits into their business model, but there is significant uncertainty. The technology pathway is there; the next step is to minimize risk.
- Southern Company operates the largest biomass plant in the country at 100 MW. The challenge to the industry is energy density and the ability to compete with natural gas prices.
- Xcel was forced to accept biomass through legislation. It introduced a lot of new operations and maintenance issues, and clean up was difficult. The whole biomass pathway does deserve another look.

Question 6 – How should we deal with the duck curve and thermal storage?

- There are customer products available now for customer side thermal storage. There are also bulk thermal storage options available.
- Storage will be a mix of energy sources. The big winners will be ones that can scale to very large sizes.
- The key criteria in storage are energy density and energy efficiency; hydrogen is a winner in the former but a loser in the latter. It has to become commercially viable today, to be a part of deals today.
- SoCal Gas is working with UCLA on molten sulfur thermal storage. Utility scale molten salts are often very expensive, but sulfur has potential to meet the requirements of high-temperature storage at low cost. The heat captured can then be used to produce hydrogen.

Question 7 (comment) – Hydrogen technologies need a "shiny object" to hook customers, as well as a definition for a modular design that investors can wrap their hands around.

Innovation Example: Consolidation Strategy for Fueling Station Cost Reductions

Amgad Elgowainy, Argonne National Laboratory

Dr. Elgowainy provided an overview of an operation strategy that can reduce the cost of compression at hydrogen fueling stations by 30%–40% through innovative integration of station compression and storage. Dr. Elgowainy first explained the role that FCEVs can play in driving hydrogen demand. Vehicle choice models show that 25–40 million FCEVs could be deployed in the U.S. if fueling costs reached $5/kg by 2050. Currently in California, hydrogen cost at the dispenser is $13–$16/kg. Of this overall cost, refueling accounts for $6–$8/kg, delivery accounts for $4–$6/kg, and production accounts for $2/kg. The compressor accounts for nearly half of refueling costs, and is often oversized and underutilized during peak hours of the day. A reduction in the costs of hydrogen compressors can therefore play an essential role in driving national hydrogen demand.

In 2014, Argonne used their thermodynamic and flow dynamics modeling capabilities to conduct early-stage simulations of fueling stations, which led to the development of the pressure consolidation strategy. The premises of the strategy are that: 1) at stations supplied by tube trailers, the compressor draws its hydrogen directly from the tubes within the trailer, 2) a compressor's capacity (kilograms/hour) increases as the pressure as its suction increases, 3) an increase in suction pressure reduces the motor power required for compression, 4) a reduction in a compressor's motor size reduces its price, and 5) at a typical hydrogen fueling station the compressor currently idles during many hours of the day when station demand is low. Pressure consolidation involves use of the compressor during off-peak times of the day to transfer hydrogen from tubes that are emptying (in a tube trailer) to tubes that are at higher pressure. This "consolidation" of hydrogen results in certain tubes of the trailer having a higher pressure than would otherwise be the case. During hours of peak station demand, the compressor can therefore draw hydrogen from these high-pressure tubes to achieve a higher capacity than otherwise possible. As a result, a station can utilize a smaller compressor to achieve its peak demand than possible under conventional operation.

The strategy is currently being experimentally tested at NREL to establish proof-of-concept. A commercial demonstration is being planned with a recent award from DOE's Technology Commercialization Fund, in partnership with PDC Machines.

Alignment of H2@Scale with National Scale Hydrogen Infrastructure Growth

Panelists discussed expected evolutions of hydrogen infrastructure, including liquefaction plants and terminals, pipelines, and diversity of hydrogen feedstock. The panel included Al Burgunder **(Praxair)**, David Edwards **(Air Liquide)**, and Michael Beckman **(Linde)**. The panel was moderated by Steve Ellis **(Honda)**.

Question 1 – What shifts do you expect to see in hydrogen infrastructure (capacities of stations, pipelines, terminals, liquefiers) in near to mid-term?

- As demand increases, liquid hydrogen will play a bigger role. It's more economical, and the low density of gas is difficult to manage.
- Hydrogen is not an easy molecule to access, and we need to include approaches based on fossil fuels (e.g. methane reformation) in our thinking. With the low cost of electricity, electrolysis is also a good option. We also need to consider accessing hydrogen streams produced as a by-product of industrial processes, such as petrochemical cracking (e.g. ethylene production). Pipelines are the most sensible approach to deliver hydrogen in areas of dense demand, but not necessarily for distribution to small consumers that are long distances apart.
- Leveraging current available technology is important. Hydrogen will have a lot of local decisions in the near term. For the near-term, industry needs to optimize the efficiency of technologies we already have.

Question 2 – What would be a more effective method of hydrogen delivery?

- A more efficient method would be to cryo-pump hydrogen into pipelines. The hydrogen could then reach stations as a higher pressure gas, minimizing the need for compression at each station.
- Cryo-pumping of hydrogen occurs at large forklift installations today, with ¼" tubing. However, moving such piping into neighborhoods is challenging.
- Air Liquide already has pipelines serving oil refineries today, but the source and demand ports are very limited. The distribution network is very different from hydrogen stations.

Question 3 – What do you think will be some of the largest drivers in the pathways of hydrogen delivery in the future?

- Currently, the limiting source is the hydrogen molecule, which stations source primarily from small scale renewable electrolysis or large scale steam methane reforming. Five years from now, investments will lead to more distributed and renewable solutions.
- We need to advocate diverse use of hydrogen, including other fleet vehicles, such as bus depots and freight trucks.
- There will be a bigger push for hydrogen use in medium and heavy-duty vehicles. However, it is a challenge to compete with gasoline's one hundred year history. An added challenge is demand for hydrogen to be cheaper and greener.

Question 4 – Should medium-duty/heavy-duty vehicles share fueling infrastructure with light-duty vehicles?

- This would make a lot of sense. A liquid pump is the way to economically get a lot of flow at high pressure—the energy cost is lower than for gaseous compressors, and less maintenance is required. Liquid stations are also very scalable.
- Fleets can support the large-scale rollout of hundreds of stations by driving utilization.
- In the CNG industry, fleet vehicles used to have their own dedicated filling locations.

Question 5 – What do you see as the largest barrier to the growth of large scale hydrogen infrastructure?

- Investment in large-scale liquefaction plants is challenging when demand is not stable.
- California has a mandate for percentages of hydrogen fuel to be produced from renewable sources, which is a barrier for the expansion of hydrogen. Low-emissions approaches that are not being sufficiently considered in the "renewable" definition include the use of methane from landfills. Landfill gas can be reformed for low-cost hydrogen production. States should redefine renewable hydrogen pathways to make their goals easier to achieve.
- The demand for FCEVs that people want to buy needs to be higher. Fueling stations will also need to have a reasonable price point for consumers. There also need to be policies in place that reduce the cost of hydrogen. Once the market is established, the supply can be diversified to include renewables, facilitate grid resiliency, etc.
- How do we get to a point where green molecules can come from anywhere and then be tapped off anywhere?
- When policy requirements come into effect, something will have to give, although it's not clear what that will be. There are existing requirements on purity for landfill gas.
- Station costs are currently really high and might need to be focused on first.

Question 6 – In what areas of R&D would government support be valuable?

- Government can help industry to understand how this market might develop and how to best support. DOE's current research is valuable. The labs are evaluating critical components, such as hoses, and supplying information to manufacturers. Manufacturers do not have the resources to research many of the components that the labs study.
- There are limited suppliers of components, which is still a challenge. Industry needs better, lower-cost components, such as cryogenic valves that last for hundreds of thousands of fills.
- Currently, Air Liquide is in the process of proving the market and the business model, not the technology. We've gotten where we are today using existing technology. Work needs to move towards reliability and efficiency improvements—the focus should be less on research and more on development.

Question 7 – How big of a challenge is fuel quality?

- Fuel cells need to become more flexible in terms of the purity of hydrogen they can accept. As the industry grows, we will have more sources of hydrogen, and thus more contaminants; the standards currently reflect the purity of liquid hydrogen, which is high because the liquefaction process removes many contaminants. Praxair's goal is to ramp up supply quickly, which may require fuel cells to be more robust.
- Currently, Air Liquide uses many pathways of hydrogen supply. These will be streamlined in the future, which will enable more standard definitions of common contaminants.

Question 8 – What is the thinking about liquid hydrogen carriers, such as ammonia?

- Liquid hydrogen carriers are very much in the R&D state, and are a medium- or long-term concept. Air Liquide looked at ammonia, but has not decided to invest at this time.

- The concept is interesting, but there is concern about the economics and the purity.
- The time it takes to get hydrogen out of the carriers (dehydrogenation) is difficult for high demand stations.

Question 9 – How do you determine the scales of production plants (e.g. 100 tonne/day vs. 5 tonne/day)?

- Production is very centralized today with long transportation distances. The issues to optimize are capital costs of large-volume production, as well as of distribution.
- Praxair's experience is limited in this area and the efficiency of larger plants is unknown. The data suggests they might be more efficient but only at full utilization.
- Air Liquide looks at how to optimize the costs of power and distribution, considering the location.

Question 10 – Is liquid hydrogen even relevant in the near term, considering the amount of demand, cost, complexity, etc.?

- Linde is presupposing that the demand for hydrogen will develop sufficiently to justify the costs of liquid delivery. A pipeline costs $1-2 million/mile, which can be a barrier to gaseous delivery.
- Currently, some companies are pursuing "mobile pipelines" (i.e. high-pressure, high-capacity tube trailers to deliver gaseous hydrogen cost-effectively). At some point, liquid delivery will be a better solution.

Question 11 – What specific commitments would you like to see from stakeholders (state, partner) that would allow you to commit to new production?

- In order for large companies to invest, dedicated demand and a solid business case are necessary.
- There has been a lot of investment by the state of California into fueling stations, but little investment into delivery infrastructure to transport hydrogen.
- We need policies or partnerships that guarantee demand.

Alignment of H2@Scale with Hydrogen Infrastructure Needs for FCEVs

Panelists discussed cross-cutting R&D needs to enable growth of hydrogen fueling stations. The panel included Bill Elrick **(California Fuel Cell Partnership)**, Ghassan Sleiman **(FirstElement Fuel)**, and Steve Szymanski **(Proton Onsite)**. The panel was moderated by Danny Terlip **(National Renewable Energy Laboratory)**.

Question 1 – As demand for hydrogen increases, what types of infrastructure do we need to meet demand?

- Electrolysis is already at technological maturity to be ready for scale up, but it needs to be done in a cost effective way. Distributed installations of large-scale electrolysis to meet regional demands has potential, in lieu of on-site electrolysis at fueling stations. Very few stations in California have electrolyzers, primarily due to the cost of installation, and sometime due to the cost of electricity.
- In the short term, liquid hydrogen would need to be delivered to a site. In the medium term, there may be different solutions. Liquid hydrogen has the advantage of reducing energy consumption onsite, but the disadvantage of increasing energy consumption upstream.
- Stations must double in capacity. Additionally, infrastructure to support California's renewable hydrogen mandate is necessary.

Question 2 – There has been a lot of variability in hydrogen stations lately. Would retrofits be possible in the future?

- Retrofitting can be very expensive if stations are not initially built for growth. Building larger stations now to account for future demand may be a better approach.
- There is merit in coming up with balance-of-plant designs that can accommodate retrofits
- An analysis of the costs of retrofits would be beneficial to the market.

Question 3 – Can you speak a bit about how high-volume delivery infrastructure is being aligned with future plans for station deployment?

- CAFCP is developing a new 2030 Roadmap to guide coordination of next steps. Growth will require collaboration and front-loaded spending
- This is certainly a gap in the market today.

Question 4 – In what time frame do you think investments in large-scale infrastructure (e.g. liquefiers and pipelines) will be needed to meet demand for FCEVs?

- Six months ago would have been ideal. There are not enough hydrogen stations to support the expected growth in vehicles in the next five years. Development of stations takes a lot of time, and we therefore need to start planning and financing large-scale infrastructure now. In the short term, hydrogen needs to be cost competitive with gasoline, and in the long term, it needs to be produced renewably.
- Planning for rapid scale up in demand needs to start immediately, including increases in capacity for liquefaction.

Question 5 – What are the key R&D areas to enable hydrogen infrastructure?

- A significant driver of the cost of renewable hydrogen production is the cost of electrolysis. Capital cost is another significant cost driver; research should focus on reducing the costs of balance-of-plant components, such as power electronics.
- There are not enough suppliers for fueling station components—there is only one dispenser manufacturer in the world, one nozzle manufacturer, etc. Many components have not been designed for hydrogen specifically. Components that were originally designed for other industries (e.g. valves designed for use in natural gas) and are now being engineered for hydrogen use can be more expensive than necessary. Further development of the supply chain would drive competition and decrease costs.
- Investments are needed to enable progress in the U.S. Other countries like Denmark, Canada, Germany, Japan and Norway are supplying most of the components for stations being installed in the US over the next 2 years.
- In order to drive reductions in the cost of hydrogen, CAFCP is working on approaches to increase infrastructure scale rapidly, drive investment into technology improvements, and increase components manufacturers.

Question 6 – Are there specific infrastructure components you would like to see more R&D on?

- Dispensers, nozzles, hoses, and O-rings for gaseous stations.
- Most reliability issues occur in the wintertime because seals, compressors, and valves have failed in cold weather. We need more research to drive robustness in cold weather. We need to focus on issues that transcend California, such as issues in the Northeast.

Closing Remarks

Mark Ruth, National Renewable Energy Laboratory

Mr. Ruth summarized the workshop by reiterating the challenges and opportunities identified in the discussions. He urged the attendees to continue to think "outside the box" and look for additional opportunities where hydrogen can be generated while supporting other components of the energy system, and where hydrogen can be used as a clean feedstock or energy source. He also urged attendees to think about how hydrogen can meet user needs in unique ways that are not commonly considered. Mr. Ruth is leading the H2@Scale techno-economic analysis project characterizing the technical and economic potential of hydrogen supply and demand in the U.S. In preliminary results, the project has defined the technical potential of hydrogen demand as 151 million metric tonnes/year. The project team has determined that this potential can be met independently from diverse domestic resources, including solar, wind, biomass, and nuclear power, as well as natural gas and coal feedstocks. The economic potential of hydrogen has preliminarily been characterized as 22–45 million metric tonnes/year, depending heavily on the prices of natural gas and the portfolio of power generators on the grid. This project along with others, with a focus on early stage R&D to address key challenges, will continue as part of DOE's H2@Scale activities.

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