Preparing for a Net-Zero Future:
An Overview of Low and No-Carbon Fuels in Arizona

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Introduction

Arizona has experienced tremendous growth in a range of new advanced manufacturing industries in recent years. Many of them are commercializing new technologies that will reduce carbon emissions across all economic sectors and support the world's transition to net zero by 2050. In Arizona, attracting the industries of the future as well as maintaining competitiveness nationally and internationally requires leveraging emerging technologies and promoting a healthy environment.

Addressing climate change requires innovation to mitigate emissions and transform how energy is generated, sited, and consumed, how people and goods are transported, and how buildings and everyday products are designed and manufactured. The convergence of public support, lower-cost clean energy, a need to meet clean air standards, and demands by businesses for clean energy and healthy communities presents an opportunity for investment and growth in Arizona industries that support sustainability.

The United States government is setting ambitious clean and renewable energy goals that include significant investments in the broad electrification of transportation and buildings. Still, there are sectors of our economy and industrial applications that generate significant carbon emissions that are not easily and reliably electrified, from shipping, heavy-duty trucking, and long-haul aviation to concrete and steel manufacturing. In a net-zero economy, many hard-to-decarbonize industries are likely to rely on alternative fuels. The development of low and no-carbon fuels (LNCF) to support industry is essential to our net-zero emissions future.

The Nature Conservancy is committed to putting Arizona on a path to net zero with solutions that work for people and nature. We invited experts, industry, and economic development partners to explore the future role of and demand for LNCF in Arizona and the region. The Nature Conservancy partnered with Evolved Energy Research (EER), a leading research and consulting firm focused on the transition to a low-carbon energy economy, to present analytical findings related to the role of LNCF in decarbonizing the US economy.

We convened three facilitated meetings between February and April of 2023 to understand the challenges associated with LNCF, explore the various barriers to and opportunities for LNCF in a net-zero transition, as well as align community and business stakeholders around priority actions to support LNCF demand and production efforts that could be beneficial in Arizona.

Interviews

In preparation of the convening, it was important to understand the perspectives, knowledge, and background of meeting participants. EER conducted a series of interviews in which select participants shared their interests and aspirations related to LNCF in Arizona. These interviewees included representatives from Arizona State University, Western Resource Advocates, the Arizona Commerce Authority, First Solar, and the Arizona Tech Council.

The interviews demonstrated significant alignment among meeting participants on the potential for developing an LNCF industry in the state and important sensitivities to how that industry develops. Interviewees identified the desire to broadly share technological knowledge and expertise related to the state of hydrogen, ammonia, e-fuel[1], and biofuel markets. Interviewees expressed special interest in aligning on likely hydrogen end-uses, as well as hydrogen storage and transport infrastructure needs. Interviewees also highlighted the importance of ensuring diverse perspectives and bringing together people who otherwise may not have the opportunity to engage in these conversations.

The interviews concluded with interviewees sharing their goals for LNCF convenings. Identifying a common goal for meeting participants, with concrete steps that could be taken in furtherance of that goal, was the highest priority discussed. More specifically, interviewees hoped to see future partnership opportunities for participants, whether research-based or otherwise, and follow-up meetings for participants to stay involved to continue the advancement of agreed-upon goals. The remainder of this report summarizes the broad takeaways and key topics from the LNCF meetings as well as the research resources and assumptions that supported these discussions.

Evolved Energy Research Modeling

The Nature Conservancy contracted with Evolved Energy Research (EER) to provide technical guidance and national and regional data on LNCF supply and demand economics in the Southwest and Western US through 2050. EER is a leading research and consulting firm focused on the transition to a decarbonized economy. EER's engineers, economists and software developers have created proprietary, industry-leading analytical tools specifically adapted to modeling net-zero scenarios. Their models are particularly relevant for researching the role of clean fuels in a net-zero economy because they extend beyond the electric sector, co-optimizing investment and operations across the electricity, pipeline gas, hydrogen, liquid fuel, heat production and carbon management sectors. EER is the energy modeling team behind the Princeton Net Zero America Project, Third Way's Carbon-Free Europe analysis, and several state and regional net-zero energy strategy reports[2].

All of EER's projections and conclusions shared in the LNCF convenings were drawn from their 2022 Annual Decarbonization Perspective (ADP) report, an evaluation of different US-wide net-zero 2050 pathways. The findings shared in this report are drawn from the ADP Central case, which assumes economy-wide electrification is a leading decarbonization strategy in the US. Total fuel demand declines dramatically through 2050 as a result, with most residual fuel demand concentrated in difficult-to-electrify sectors, especially industry and transportation. Where results are cited for the Southwest, they represent combined results for Arizona and New Mexico. The modeling results presented at the convenings were updated relative to EER's 2022 published ADP results to include key incentives from the Inflation Reduction Act (IRA), including a $3/kg production tax credit for qualified clean hydrogen, production tax credits for wind and solar, and carbon sequestration tax credits.

It is important to note that in their ADP analysis, EER imposed an economy-wide emissions constraint such that the US achieves net-zero greenhouse gas emissions by 2050. The model then prioritizes the most cost-efficient infrastructure investments required to serve energy demand while meeting emissions constraints. EER's modeling tools represent a broad range of decarbonization technologies on both the supply and demand sides, including negative emission technologies. The model allows

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[1] E-fuels, also referred to as electrofuels or synthetic fuels, are liquid or gaseous hydrocarbon fuels produced from hydrogen and carbon dioxide or carbon monoxide.

[2] Links to these reports, as well as additional detail on EER's other engagements and publications, are available at https://www.evolved.energy/about.

continued fossil fuel use where economic, without requiring carbon capture at their point of use, allowing their emissions to be offset with negative emission technologies elsewhere in the economy.

US Fuel Demand and Supply in a Decarbonized Economy

Fuel Demand

In EER's analysis, fuel demand declines significantly through 2050 due to widespread electrification of transportation and buildings[3]. Figure 1 illustrates the changes in fuel demand by sector. By 2050, residual fuel demand is primarily concentrated in difficult-to-decarbonize end uses. Demand for direct hydrogen and ammonia is primarily seen in freight trucks, light-duty trucks, shipping, and bulk chemicals. Compared to hydrogen and ammonia, methane and liquid hydrocarbons (whether fossil fuels, e-fuels or biofuels) are used more widely in the economy through 2050, taking advantage of vast existing hydrocarbon fuel storage and delivery networks in the US. In contrast, hydrogen and ammonia require costly new fuel delivery and storage infrastructure.

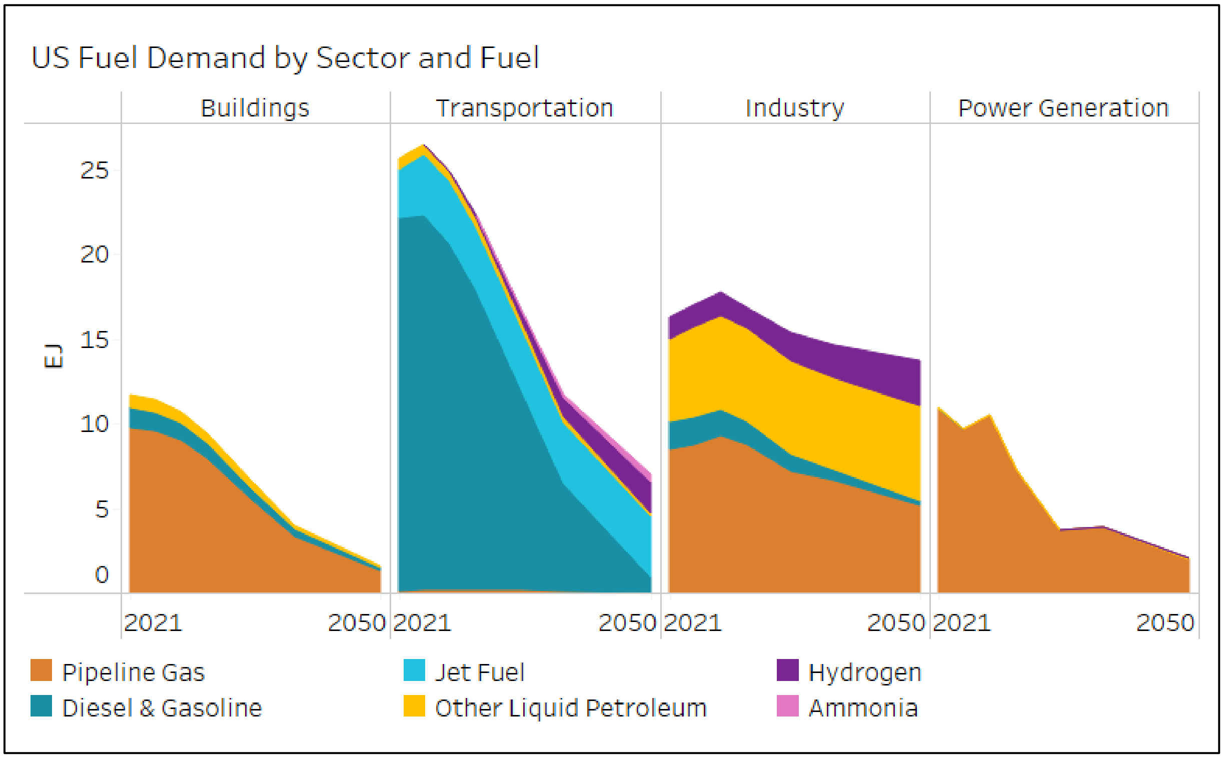

Figure 1: Modeled US fuel demand by sector and fuel type, 2021 to 2050.

Exactly which end-uses are most appropriately converted to hydrogen, ammonia, or other e-fuels is an area of ongoing research and uncertainty. The "Clean Hydrogen Ladder," also known as the "Liebreich's Ladder," ranks potential end-uses for hydrogen from most to least competitive. Figure 2 summarizes the Clean Hydrogen Ladder with the "unavoidable" uses of hydrogen in fertilizer and chemical feedstocks, as well as difficult-to-electrify end-uses like shipping and steel production. The "uncompetitive" end-uses

[3] Demand for fuels in a decarbonized economy is sensitive to key policy, technology, and consumer behavior outcomes. The fuel demand projections shown here are not a forecast; they represent ERR's central scenario that anticipate how the use of fuels in the US could change over time.

are those where hydrogen has some key disadvantage: for example, H2FC cars are likely uneconomic compared to battery electric vehicles; domestic heating faces limitations in delivering hydrogen fuel to homes without costly new infrastructure; power system balancing is more economically met with battery storage and continued use of natural gas in small quantities. EER's ADP analysis largely aligns with Liebreich's Ladder[4], with hydrogen applications in the top three rungs of the ladder accounting for over 70% of hydrogen used in ADP's central scenario.

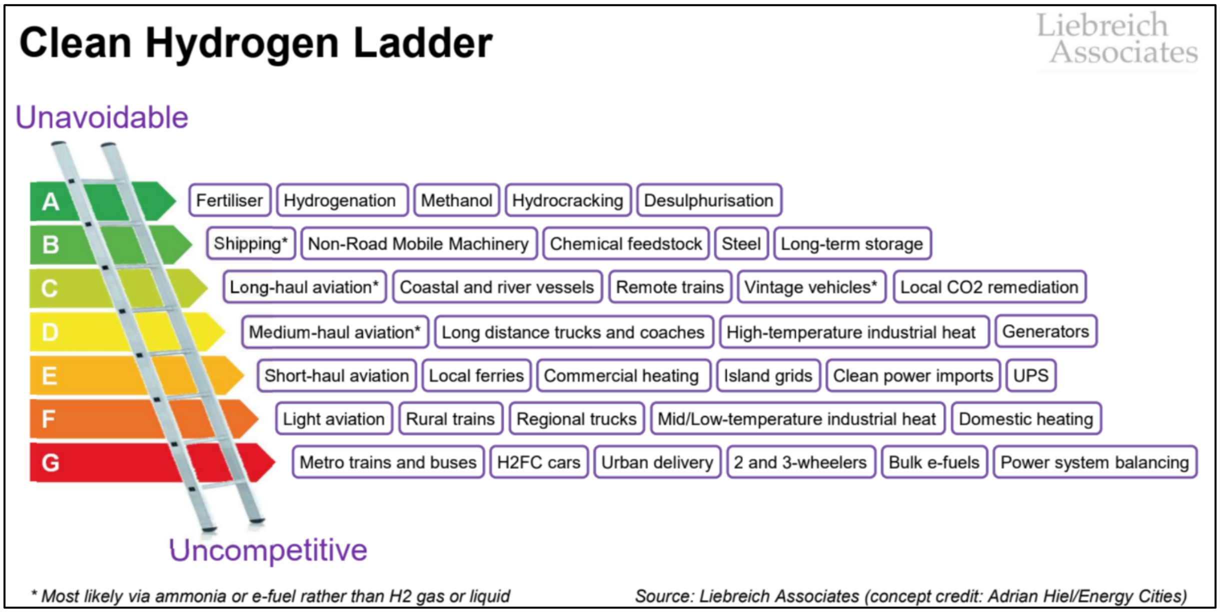

Figure 2: The Clean Hydrogen Ladder[5], produced by Liebreich Associates, organizes potential hydrogen end uses from most to least competitive.

Fuel Supply

In EER's analysis, different fuel sources compete economically to meet total fuel demand. Hydrogen demand can be met with electrolysis, methane reforming (with or without carbon capture), or biomass gasification. Ammonia is assumed to be produced from hydrogen via the Haber-Bosch process. Fossil fuels, biofuels, and e-fuels (produced with captured carbon via the Fischer-Tropsch process) compete to supply liquid and gaseous hydrocarbon fuel demand.

4 See EER's whitepaper "The Clean Hydrogen Ladder", available at https://www.evolved.energy/post/adp2022-hydrogen.
5 Liebreich, Michael. "The Clean Hydrogen Ladder [Now Updated to v4.1]." LinkedIn, Aug. 2021, https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/

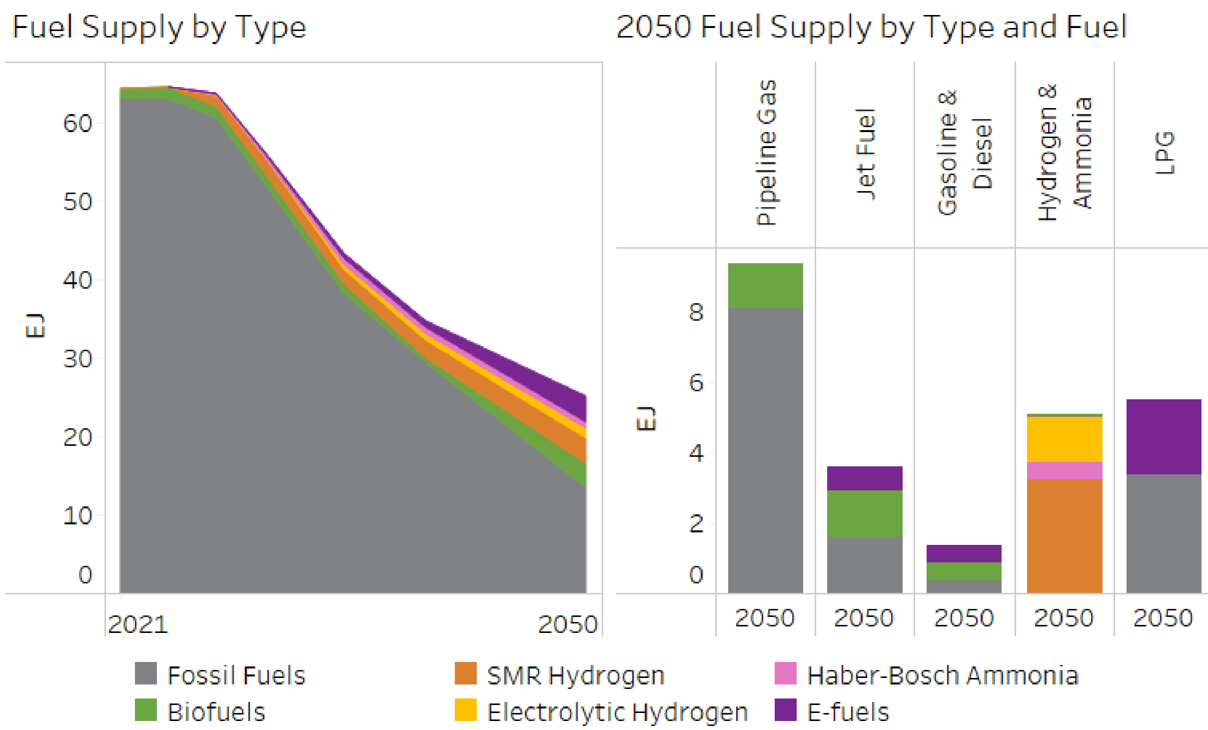

Figure 3: Modeled US fuel supply by fuel type, 2021 to 2050, and 2050 fuel supply disaggregated by end-use fuel. Nearly all LPG demand in 2050 is for bulk chemical production.

In EER's modeling (Figure 3), fossil fuels continue to dominate the US fuel supply in 2050, though LNCFs make up a growing share of the total. In a net-zero scenario, the continued use of fossil fuels in hard-to-electrify sectors requires offsets from negative emission technologies (carbon capture and sequestration, with carbon sourced from direct air capture or biomass). Despite the high cost of negative emission technologies, fossil fuels continue to be an economic option in difficult-to-electrify sectors through 2050. This is especially true for natural gas, which is a low-cost fossil fuel with relatively high-cost alternatives.

Each different fuel type has its own natural resource requirements and economic drivers, which influence the geographic siting of fuel production industries. Understanding Arizona's role in a changing US fuel landscape requires an evaluation of the state's resource endowments and the resource requirements of particular fuels.

Fuel Production Opportunity in Arizona

Though fossil fuel extraction and refining continue to be important pieces of the US fuel supply landscape through 2050 in EER's analysis, Arizona is not a center for those industries today and is not anticipated to participate at scale in the future. Similarly, though biofuels are an important source of decarbonized fuels in the US in EER's modeling, limited biomass resources in the Southwest result in limited biofuel production and consumption in the region. The primary source of biofuels in the Southwest is a limited number of landfill gas capture sites.

The economics of electrolytic hydrogen production, as well as ammonia and e-fuels that use hydrogen as an input, are closely linked to clean electricity cost and availability. Arizona's strong solar resource makes it a possible hub for producing fuels from electricity. Evaluating the specific requirements of hydrogen, ammonia, and e-fuels suggests that the primary opportunity in Arizona is electrolytic hydrogen production for direct use.

Producing Hydrogen

The availability and affordability of clean electricity drives electrolysis economics. According to EER's modeling, roughly 65% of electrolytic hydrogen production is likely to be located in the middle of the country, primarily in Texas and the Midwest, due to access to high-capacity-factor wind. Though Arizona has a strong solar resource, electrolyzers operating entirely on solar power are limited by solar capacity factor, making them less economically competitive than electrolyzers with access to high-capacity-factor wind or a blend of wind and solar.

> Arizona's abundant solar, proximity to California, and geologic hydrogen storage resource make the state an attractive location for electrolytic hydrogen production.

A stronger case for siting electrolysis in Arizona is the proximity to California, which is likely to become a center of direct hydrogen demand. Because moving energy via hydrogen pipeline is ten times less expensive[6] than electricity transmission over significant distances, it's more cost-effective for California to import hydrogen from the Southwest via pipeline than to import Southwest photovoltaic electricity and produce hydrogen locally. In EER's analysis, California's direct hydrogen demand is 2 Mt/year[7] in 2050, about three times the Southwest demand. The rest of the Western US is projected to require an additional approximately 2 Mt/year.

In general, the extent of hydrogen pipeline expansion will influence the opportunity for Southwest hydrogen production. If a US-wide hydrogen pipeline network can be constructed in the coming decades, California's hydrogen demand could be supplied by low-cost production in Texas and the Midwest. If pipeline expansion is constrained by siting and permitting issues, such that the West is disconnected from hydrogen supply in other regions, Arizona is likely to play a more prominent role in supplying hydrogen to California and other western states.

Hydrogen storage is another key resource that is likely to influence hydrogen electrolysis siting, since storage is necessary for matching seasonally-varying fuel supply and fuel demand. Salt cavern storage formations are the most technologically mature geologic storage option (compared to natural aquifers and depleted natural gas or oil fields), and are much less costly than man-made storage tanks[8]. Per the National Energy Technology Laboratory, Arizona is home to a meaningful quantity of salt cavern storage potential.

[6] Argonne National Laboratory, "System Level Analysis of Hydrogen Storage Options" (Project Id: ST00 U.S. Department of Energy Hydrogen and Fuel Cells Program; https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf
[7] Mt (megatonne) = 1 million tonnes or 1 billion kilograms.
[8] Argonne National Laboratory, "System Level Analysis of Hydrogen Storage Options" (Project Id: ST00 U.S. Department of Energy Hydrogen and Fuel Cells Program; https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf

Water is another hydrogen electrolysis resource requirement that should not be ignored in the Southwest. The "Water Considerations" section of this report examines water requirements for producing electrolytic hydrogen in the Southwest.

Producing Ammonia

Transporting ammonia via a pipeline or truck is much less expensive than transporting hydrogen. This dynamic means that ammonia production is likely to be co-sited with the lowest-cost green hydrogen resources in the country, which EER's models anticipate will be in the Midwest and Texas. However, as in the case of direct hydrogen demand, Arizona's proximity to California creates a potential opportunity to supply ammonia to California, to the extent that it is expensive or infeasible to transport ammonia from other regions.

There are two main potential markets for ammonia demand: existing ammonia demand for fertilizer production, and shipping fuel. The shipping fuel opportunity is highly uncertain, as ammonia is one of several potential decarbonized fuels that could be used to serve shipping demand. Nonetheless, the largest ammonia opportunity for Arizona is the west coast shipping fuel market. A high estimate for California's ammonia shipping fuel market is approximately half the size of the direct hydrogen market. Ammonia is likely a longer-term opportunity that will begin in the 2030s and not substantially grow until the 2040s. Arizona should monitor West Coast shipping decarbonization efforts to understand how this opportunity will unfold.

Producing E-Fuels

E-fuels are drop-in fuels that directly replace fossil fuels. They are costly to produce but have the benefit of integrating easily into existing fuel transport and storage networks. Because the two chemical inputs to e-fuels are hydrogen and carbon, and because drop-in fuels are easier to transport than either of those precursors, e-fuel production is likely to be co-sited with both hydrogen production and a supply of CO2. For e-fuels to have a net neutral emissions footprint, they must use carbon supplied by either direct air capture (DAC) or biofuel production (in which excess carbon is captured from biomass).

In EER's modeling, neither DAC nor biofuel production are sited at scale in Arizona. Biofuel production is limited by the lack of available biomass in the region. DAC potential is limited by economics: because DAC technology has very high capital costs, the most economic DAC facilities will operate at high-capacity factors, meaning they need to be located in regions with high-capacity factor wind or a blend of wind and solar. (Nuclear power is conceptually a source of zero-carbon baseload electricity that could power DAC plants, but it is too high-cost to compete with wind and solar). EER's analysis suggests Arizona is unlikely to become a center for DAC or e-fuel production.

Water Considerations

As Arizona contemplates its role in a clean fuel production economy, it is critical to consider water cost and availability issues in the Southwest. Arizona's strong solar resource, salt cavern geologic hydrogen storage potential, and proximity to California make it an attractive potential location for siting electrolytic hydrogen production. Water is a key input to hydrogen electrolysis; the quantity of water required to produce electrolytic hydrogen is somewhat uncertain in the long term but it's possible to estimate a range.

The theoretical minimum requirement for water to produce hydrogen is 9 kg of water for each kg of hydrogen produced. In practice, the requirement is closer to 15 kg of water per kg of hydrogen because of the water treatment processes required to achieve the water purity necessary for electrolysis. That value represents the minimum quantity of water directly transformed into hydrogen, and therefore consumed—i.e., not able to be reclaimed. When other water needs, such as electrolyzer cooling and solar panel washing are accounted for, the total water requirement increases to 43 kg per kg of hydrogen[9]. Much of that additional water use can theoretically be reclaimed or returned to the environment.

Using those two water intensity estimates (15-43 kg water per kg hydrogen) to create a range, if Arizona were to produce 1 megaton of hydrogen per year, the water requirement would be between 12,000 to 35,000 acre-feet (see Figure 4). For context, in 2017, Arizona's total water usage was 7 million acre-feet, with 5% (365,000 acre-feet) dedicated to industrial demand[10], and the rest consumed by agriculture, irrigation and municipal demand. The water required to produce 1 megaton of hydrogen annually is equivalent to 0.2-0.5% of Arizona's 2017 total water demand, and 3-10% of the state's 2017 industrial water demand. These estimates represent the amount of water that would be required to support an electrolysis industry in Arizona at scale.

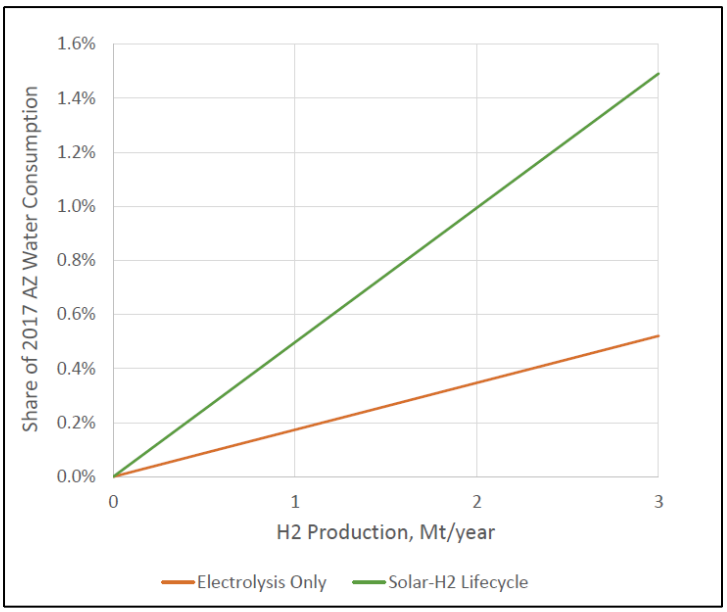

Figure 4: Projected Hydrogen production as related to the percentage of Arizona water consumption required based on production method.

These water demand estimates are significant in the context of Arizona's broader water concerns. A hydrogen electrolysis facility is a 30-year investment, meaning that developers will need to secure long-term water rights for their projects. The cost and long-term security of those rights are important areas for future evaluation if Arizona seeks to attract hydrogen production investment.

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[9] Water consumption estimates from: Philip Woods, Heriberto Bustamante, Kondo-Francois Aguey-Zinsou, "The hydrogen economy - Where is the water?", Energy Nexus, Volume 7, 2022, 100123, ISSN 2772-4271. https://doi.org/10.1016/j.nexus.2022.100123

[10] 2017 water consumption data from AZ Central: https://www.azcentral.com/story/news/local/arizona-environment/2019/02/12/arizona-water-usage-state-uses-less-now-than-1957/2806899002/

Early-Stage Hydrogen Projects

Arizona State University- SHINe

The Infrastructure Investment and Jobs Act (IIJA) includes $9.5 billion for clean hydrogen production. Eight billion dollars of that will be granted to at least four (but potentially as many as 10) hydrogen hubs in the United States. 79 groups submitted hydrogen hub proposals, including a collaboration through Arizona State University, called the Southwest Clean Hydrogen Innovation Network (SHINe). SHINe's proposal focuses on leveraging Arizona's high-quality solar, vicinity to regional markets (such as California), and creating an economic opportunity for Arizonans.

Regional Hydrogen Projects

Most of the currently proposed hydrogen projects in the US are actively seeking hydrogen hub funding. These proposals represent a wide range of public and private entities, hydrogen production methods, transportation and storage methods and target sectors. Which of these hubs are awarded will play a major role in determining which infrastructure projects move forward.

A few regional projects proposed in the Southwest are designed to serve Southern California. Those proposed projects include:

1. The Los Angeles Department of Water and Power (LADWP) Scattergood Generating Station is an $800M conversion of a 350 MW combustion turbine from natural gas to hydrogen, aligned with LADWP's goal to supply 100% clean electricity by 2035.
2. The Intermountain Power Project Renewed plans to convert an existing 840 MW Utah coal plant to a gas and hydrogen combustion turbine; LADWP is one of several power offtakers.

The Scattergood Generating Station project and the Intermountain Power project will burn 30% hydrogen and 70% natural gas when they are first brought into service, gradually converting to 100% hydrogen over time.

In addition, two hydrogen pipeline projects have also been proposed in Southern California, (1) the HyBuild Initiative, proposed by the Green Hydrogen Coalition, would construct a 400+ mile hydrogen pipeline from central Utah to the LA Basin and (2) Southern California Gas has proposed the Angeles Link, a hydrogen pipeline that would connect the LA Basin to southeast California. Both pipeline projects are early-stage.

Discussion Results and Action Items

Participants identified a set of actions that could inform future LNCF opportunities in Arizona and increase engagement on issues associated with the industry's decarbonization challenges. These actions are only the first of many but were identified by members as high-priority items that would be of significant value to Arizona residents if completed.

The Story

The participants identified the importance of developing and sharing a relevant stakeholder-centric communication piece—the story—that summarizes and emphasizes the value and opportunity that this industry can provide to Arizona to further Arizona's low and no-carbon fuels goals. This piece would cover topics such as why Arizona is positioned well, and the need to take action and share with key audiences such as economic development groups, state and federal policymakers, the Arizona State Office of Resiliency, and other industry-based groups.

Economic Business Case

Participants in the convening would like to see an exploration of the economic and business impacts of a low and no-carbon future for Arizona. Participants would like to develop a core set of fact-based and easy-to-understand points covering a range of important subjects such as the cost-benefit, trade-offs, on/off-grid pros/cons, environmental impacts, etc.), the Arizona jobs impact, the supply chain requirements, federal funding opportunities and more.

Policy Evaluations

Participants also expressed a desire to create a framework that evaluates existing and hypothetical policy options that would support hydrogen investment and development if implemented in Arizona. Members would like to track LNCF policy developments in California and other U.S. states to evaluate them for potential opportunities in Arizona. Additionally, members highlighted the importance of evaluating federal policy incentives and opportunities for Arizona, especially those that may arise from the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA).

Other Actions

Other high-priority action items that participants would like to see explored include, but are not limited to, collaboration with regional hydrogen hubs—including assisting with the siting of any potential hydrogen facilities in Arizona, a case study analyzing the Arizona hydrogen water consumption projection, and an analysis of existing low and no carbon fuel regional stakeholders.

Appendix

Participants

We would like to acknowledge all the participants in the LNCF convenings. Their time and energy spent attending and contributing to those conversations were invaluable, and without them this report would not be possible.

Alana Langdon- Nikola Motors
Alex Routhier- Western Resource Advocates
Chico Hunter- Salt River Project
Chris Camacho- Greater Phoenix Economic Council
Christian Stumpf- The Nature Conservancy
Dave Richins- Rio Tinto
Diane Brown- Arizona Public Interest Research Group
Ellen Stetchel- Arizona State University
Gary Dirks- Arizona State University
Greg Bernosky- Arizona Public Service
Heather Carter- Greater Phoenix Leadership
Joe Varela- Southwest Gas
Kathleen Lee- Greater Phoenix Economic Council
Laura French- TSMC
Linda Qian- Intel
Marisa Walker- Arizona Commerce Authority
Parikhit Sinha- First Solar
Robert Sandoval- TSMC
Scott Root- Kitchell
Stephanie Herndon- Greater Phoenix Leadership
Steven Zylstra- Arizona Tech Council

Contributors

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