HTAC Subcommittee Report: U.S. Hydrogen Roadmap

Charter and Activities

A U.S. Hydrogen Roadmap Subcommittee was proposed in the November 2019 HTAC Meeting, and approved by the U.S. Department of Energy (DOE) in January.

Lead: Joe Powell (HTAC Chairman)

Members: Henry Aszklar, Charlie Freese, Bob Hebner, Hal Koyama, Andy Marsh, Bob Mount, Frank Novachek, Sunita Satyapal (DOE), Kathy Ayers (NEL Hydrogen), and Jean Baronas (California Energy Commission).

Charter:

Subcommittee to review the industry-led U.S. Hydrogen Roadmap and the draft DOE Hydrogen and Fuel Cell Technologies Office (HFTO) Multi-Year Plan (MYP); identify gaps and barriers to reaching the vision/goals; provide recommendations to HTAC at the Spring HTAC meeting based on their findings (e.g., Where can HTAC contribute analysis, etc.? How can multi-sector use of hydrogen be accelerated?); and provide feedback to DOE on gaps, challenges, and recommended DOE actions.

Timing and scope:

- Full rollout of U.S. Hydrogen Roadmap delayed due to coronavirus (beyond April 2).
- DOE seeks input by May (preferred), or by June 15 in time for October 1 fiscal year planning.
- Full roadmap released in early March for review.
- DOE to provide briefing in March on draft HFTO Multi-Year Plan (MYP).
- Incorporate dashboard metrics (EPACT) from Frank Novachek / Nick Irvin.

Meetings: 26 March Teleconference with Subcommittee and DOE. DOE provided a briefing on the outline of the HFTO MYP.

HTAC Analysis of U.S. Roadmap and HFTO Multi-Year Plan (MYP)

The industry-led *Roadmap to a U.S. Hydrogen Economy*[1] underscores the need for "sector coupling" or integrating across multiple end-uses for hydrogen to obtain the economies of scale needed to unlock opportunity. This represents an important shift away from a focus on light-duty mobility, to examine broader opportunities where hydrogen can provide an advantage in difficult-to-decarbonize sectors. The roadmap considers stepwise progression to 2030 and beyond, with metrics for an "Ambitious" scenario vs. a "Business-as-Usual (BAU)" scenario. Research and technology needs are articulated for applications in heavy duty transport, residential heating and power, industrial heat, and decarbonization of heavy industries such as steel and cement.

The U.S. Hydrogen Roadmap is an impressive industry-developed document detailing a more than ten-fold opportunity for hydrogen expansion across multiple sectors as an energy vector in the U.S. economy, to address future energy transmission, storage, and end-use needs, leveraging the nation's natural gas and renewable resources and building on its early lead in hydrogen technology.

The roadmap focuses on an "Ambitious" scenario where there is an aligned U.S. and global interest in addressing decarbonization, vs. a "Business-as-Usual (BAU)" case. The reality is that a "patchwork" of varying interests across the U.S. and globally (in the developed and developing world) is likely to continue. A scenario considering how this patchwork environment would evolve and impact the opportunities and needed technologies for hydrogen deployment should be considered in designing programs and policy. Individual states (e.g., California), clusters of states (e.g., Northeastern U.S.), and countries (e.g., Germany and Japan) may exhibit ambitious goals, along with individual companies operating within the U.S. where stakeholders are requiring reductions in carbon footprints.

The U.S. has historically been a technology leader in hydrogen. Currently, South Korea has articulated a goal of becoming the world leader for reasons of economic opportunity, analogous to its entry into electronics to obtain dominance with corporate leaders like Samsung and LG. Similar aspirations appear in Germany. It is not clear from the Roadmap whether hydrogen is perceived as a global export opportunity for U.S. business, relative to the myriad deployment opportunities within the U.S.

Of the hydrogen opportunities identified in the Roadmap, medium- and heavy-duty trucking and transport is perhaps the most intriguing, because of the ability to become cost-competitive (or better) relative to gasoline or diesel by 2030, without the need for subsidy. This sector is one of the larger scale applications, and commands among the highest price for hydrogen utilization given policies active in California, Germany, China, and emerging elsewhere.[2] With continued technology improvements and economies of scale, hydrogen fuel cell sport utility vehicles (SUVs) are projected by 2030 to have total costs of ownership (TCO) that are competitive with both internal combustion engine (ICE) vehicles and battery electric SUVs.[3]

The roadmap does not provide enough information to fully assess the integrated merits of hydrogen in a future economy powered by low cost renewable energy, including full life-cycle impact assessments. A study of comparative U.S. infrastructure costs—similar to a recent study in Germany[4]—is warranted. Such a study would help in selecting the best future investments, including the possible electrification of roadways for long-haul heavy-duty transport as an alternative to hydrogen.[5] Similarly, holistic energy system modelling is needed to identify cost synergies between hydrogen for grid storage and use in other sectors (vs. competing options).

Public confidence in hydrogen safety is a key "must have" for rollout of an expanded hydrogen economy. The scale and scope of hydrogen use will increase dramatically with broadening cross-sector hydrogen utilization in the U.S. and globally. The creation of the Center for Hydrogen Safety (HTAC recommendation 2018) is an important step toward achieving a level of safety that provides the needed assurance. CHS should be supported by both industry and government in its mission and expanding needs for its services.

Costs must be driven down across the supply chain to enable additional hydrogen applications. H2@Scale is a great initial program to drive down supply costs via economies of scale and stacking or clustering end use sectors.

Current policy has favored investment in R&D, with cost reduction via economy of scale being left to industry to lead. R&D, including demonstration projects to help eliminate problems in the scale-up of the research results, is an effective path to economic growth. Governments invest in research that provides knowledge that companies, from major corporations to start-ups, use to manufacture and distribute products. Occasionally, the funding of R&D is necessary, but not sufficient. This can occur when the market is not growing rapidly enough so that the manufacturers can further reduce cost through better economies of scale.

Under these circumstances, a prudent and targeted subsidy can tip the balance to bring manufacturing cost to an affordable level, after which the subsidy would no longer be needed. This is typically achieved by setting an end to the subsidies based on a predetermined production volume. Other mechanisms to aid deployment include the DOE's loan programs or tax code incentives.

While there is no recommendation at this time to use these approaches, they should be considered as available tools for HFTO to use prudently. Not only will this help to increase the impact of the HFTO program, but also help those making private investments leverage DOE investment. The HFTO strategy of having industry-lead teams leverage DOE funding for scale-up is a good one!

Systems modeling and assessments to consider full integration of hydrogen and electrical power is critical to make correct investment decisions in technology and infrastructure, either for investment in the U.S. or for understanding global technology export market opportunities. Hydrogen can complement electrification as a means for incorporating low-cost renewable energy, via storage and higher-density end use applications. Modeling and analysis that includes likely future technology evolution is needed to minimize investment in redundant, competing infrastructure and technologies, vs. finding synergy. Hydrogen applications across the spectrum of use should be addressed holistically, to identify cost saving opportunities from H2@Scale.

The recent pivot away from focus on light-duty vehicles toward inclusion of heavy-duty transport, as suggested by HTAC, is indeed supported because this is where the value proposition for hydrogen vs. battery electric is most differentiated. R&D programs to improve fuel cell efficiency and durability, and reduce costs while assuring safety in heavy-duty applications, are critical to realizing this potential. Sector potentials should not just consider site utilization per day, but also total aggregate utilization as this can be large for distributed production across a number of "niche" industries.

Scale-up of electrolyzers used for hydrogen production is key. Electrolyzers are less developed than fuel cells, and substantial cost reductions can be anticipated via new fundamental technologies and application of advanced manufacturing. Much of the HFTO scope has (correctly) been focused on fuel cells and electrolyzers. However, H2@Scale also includes many sectors where hydrogen combustion is a viable means for deployment. Close coordination with DOE offices focused on fossil fuels is needed to develop and roll out technologies for hydrogen use in these sectors.

Countries such as Germany are considering linking economic stimulus packages in response to Covid-19 to hydrogen infrastructure.[6, 7] As stated above, infrastructure is important to driving down costs for either hydrogen or electrification pathways in the future energy system. This underscores the importance of full energy system modeling and assessment to help define synergies between hydrogen and power infrastructure across the U.S. economy, so that effective stimulus packages and future funding can be best targeted toward the public good in incorporating advantaged U.S. resources in solar, wind, and natural gas.

Multi-Year Plan (MYP)—Specific Feedback

Highlights of the draft HFTO MYP were presented to the HTAC Roadmap Subcommittee on 26 March.[8] The following observations are offered as feedback by the subcommittee, for consideration as the MYP is further developed.

"Niche" industries mentioned in the MYP tend to be smaller per facility, certainly very much smaller than refineries or ammonia plants, but as a collective they can represent a significant amount of distributed hydrogen consumption. These uses include metal/glass facilities which can require a megawatt or more or power. The food industry also uses hydrogenation for many processes, underscored by its contacting of HTAC member companies to ensure continuation of supply during the recent COVID-19 crisis.

- For electrolysis, HTAC members agree with the MYP and strongly support the view that manufacturing of larger-scale high volume systems is a critical area for development in the near term. The supply chain for electrolyzers is well behind fuel cells. Consequently, there are opportunities for cost reduction. The significant investment outside the U.S. makes it critical that the U.S. also has sufficient domestic investment to exploit the global advances to strengthen the domestic economy.
- The plan would benefit from more clarity on the criteria used to determine when a particular area of R&D is ready for a demonstration project. The choice of demonstration projects should emphasize how the government cost-shared demonstration amplifies the impact of the larger private investment. Not only will this help justify the project, but it will also help those making private investments leverage DOE investment. Key to success for the program and the taxpayer in general, is DOE helping industry to leverage the U.S. government's investment in R&D and *vice versa*.
- A major potential use of hydrogen is in transportation electrification—cars, trucks, forklifts, buses, trains, ships, and aircraft. Studies have indicated that hydrogen becomes cost effective first in heavier duty wheeled vehicles and can make a difference across the entire spectrum. The multiyear plan should make the point that DOE does not intend to address all of these individually. Rather, the approach should be to give priority to investments in infrastructure for trucks today, and choose projects for their potential to enhance a wide range of transportation applications. The same issue arises with storage. The plan should predict how the field would evolve without DOE investment and then show the investment criteria used to select areas of appropriate government investment that can make a difference.
- HFTO has had industry leads on economy-of-scale projects. That is appropriate and should be highlighted. Industry, DOE labs, and universities are jointly engaged in R&D collaborations. This has been highly successful and instrumental in progress to date. Forward plans should take advantage of this success and explicitly include it in strategy. Industry should lead scale-up activities, and (at this stage of hydrogen technology development) should also be integrally involved in setting and advising on research targets, to ensure relevance and best use of available funding.

- The MYP timeline includes approaches to address safety needs and regulatory barriers. HTAC highly supports efforts to "stimulate the development of regulations for the safe growth of a hydrogen economy."
- The HFTO program is one piece of significant government spending in different agencies related to the same set of issues and targets. An excellent strategy is to acknowledge those efforts and show why hydrogen is important to overall success.
- Industry looks at volume multiplied by product value to set priorities based on total market potential. Heavy duty mobility can drive the scale needed to get the cost of hydrogen ($/kilogram) down to market acceptable ranges; it also represents the highest value $/kg hydrogen end use. HTAC thus supports emphasizing heavy duty mobility as a driver for accelerating commercial adoption.
- Hydrogen transport costs are high, so integrating sector use helps drive scale to reduce costs. For this reason, hydrogen combustion technologies to enable industrial and residential heating and power are useful in getting to scale. Not all of the technology is fully in place to swap natural gas for hydrogen: burner design and retrofits, flash back, safety, appliances, and allowed blending into existing natural gas pipelines and infrastructure are all considerations. It would be helpful to partner with other offices in DOE to push these to TRL 9+ to enable deployment. Some of these may be "low-hanging fruit" for hydrogen adoption.
- Infrastructure costs are high, making up close to 60% of the total cost of ownership for heavy-duty trucks (U.S. Hydrogen Roadmap, *op. cit.)*, and may be a key roadblock to the deployment of hydrogen opportunities. Carrier options—including liquid hydrogen (LH2), liquid organic hydrogen carriers (LOHC), or ammonia—may offer lower capex rollouts of significant scale relative to pipeline transmission. Consider adding "hydrogen carriers" as part of "enabling scale" in the MYP.
- Hydrogen carrier options are also relevant to hydrogen export market opportunities: carbon pricing policy may be higher in other locations (e.g., the European Union and Japan), allowing the opportunity for the U.S. to have a hydrogen export business similar to liquefied natural gas (LNG) by using carriers in the nearer term. One is then exporting hydrogen to supply heavy duty truck applications in other parts of world. These opportunities may come relatively soon, as drivers for rapid technology adoption to address carbon footprints are strong outside the U.S. Liquid carriers are an option for supplying larger quantities of hydrogen, beyond just pipelines and on-site production. There is significant technology development needed among the various hydrogen carrier options to enable transport of larger quantities of hydrogen without pipelines, including the distribution to end use for heavy-duty applications.
- It is useful to think in terms of project deployments to address specific applications. For example, when looking at supplying hydrogen to California markets for specific plays in heavy duty mobility or industrial heating and power, one can brainstorm where all the gaps are for "not being able to deploy today," which then drives the technology R&D platform needed. Application-specific workshops can help identify specific gaps.
- Historically, cost-shared early deployments via public-private partnerships have led to major successes, such as the U.S. fuel cell forklift example that is touted worldwide as a success story for hydrogen. Other examples are evident from Japan's Ene-Farm program[9] and Europe's Ene-Field concept[10] for stationary power, as well as other global examples of partnerships for fuel

cell buses or rail. These partnerships can provide seed money to help incentivize risk-taking to overcome "valley of death" bottlenecks in new technology deployment.

- Grid storage is a potentially important sector-use for hydrogen to obtain economies of scale. It provides the opportunity for hydrogen to augment and synergize with electrification as well as direct hydrogen end-use.
- Safety is highly important to enabling scale and public acceptance. Excellent progress has been made in safety codes and standards and incident sharing via H2Tools and the Hydrogen Safety Panel. The Center for Hydrogen Safety provides a mechanism to ensure the sustainability of these resources and further enhances national and international communications on safety and best practices.

Subcommittee Observations and Recommendations to DOE

1. Build upon and leverage HFTO's strong track record of success in driving industry, academia, and national laboratory partnerships to address the emerging cross-sector opportunity of H2@Scale. This entails continuing R&D needed to underpin the multisector use of hydrogen to achieve cost reductions via H2@scale. Support for hydrogen safety knowledge and dissemination, codes, and standards is also a must-have for successful deployment of hydrogen opportunities.
2. Continue to support hydrogen safety initiatives as key for public acceptance to reach economic potential.
3. While the roadmap considers the extremes of Ambitious and Business-as-Usual (BAU) scenarios, a hybrid or patchwork scenario is more likely, where some regions or sectors may have policy incentives and others may not. This patchwork policy scenario substantially increases the likelihood that some regions or sectors will exist where commercial-scale hydrogen deployments will be incentivized or advantaged. Recent observations of air quality improvements with COVID-19 lockdowns may further incentivize zero-emission vehicles.
4. The DOE should consider export of hydrogen to global markets as an economic opportunity for the U.S. The U.S. is strong in renewable and natural gas resources and has been a leader to date in hydrogen and fuel cell technologies. Export of clean or green hydrogen to regions where carbon footprint reduction is incentivized, but where production costs for hydrogen are higher, provides an opportunity for job creation and economic growth in the U.S. This growth can then drive further technology development for advantage in U.S. military and space applications.
5. Prioritize fuel cell durability and cost as key enablers for achieving advantaged deployment of hydrogen fuels cells on the basis of total cost of ownership in the absence of global policy incentives. The reduction in number of on-board components for electrified drive trains (including hydrogen fuel cell) together with the energy density needs for heavy duty trucking and transport provide a compelling value proposition for hydrogen deployment in this sector, if R&D can further reduce costs.
6. Electrolyzer technology as a whole is less mature than fuel cells. Continued support for both early-phase R&D and scale-up to integrated systems is therefore recommended. Electrolyzers will play a key role in manufacture of "green" hydrogen and integration with grid services where policy incentives for reduced emissions and carbon footprints are being formulated.
7. Initiate cross-DOE collaboration on blending of hydrogen into existing natural gas pipelines, to overcome any final barriers to deployment. A number of industrial customers (e.g., data

centers) have stakeholders highly committed to decarbonization, which will incentivize paying a premium for green hydrogen. While hydrogen has less value when used directly in heating or power applications than for use as a liquid transport fuel (IEA Future of Hydrogen 2019),[2] blending into natural gas for use in heat and power markets can be achieved at low cost, and hence help enable economies of scale.

8. Infrastructure is more of a challenge for hydrogen than for electrification at low levels of adoption. To this end, HTAC recommends:
    a. A set of combined electrification (grid) and hydrogen infrastructure cost studies for high levels of adoption of renewable energy and electrified vehicle fleets (both light and heavy duty) in the U.S.
    b. Further emphasis of systems analysis to show the cost advantage of integrating hydrogen end-use applications with its uses in grid storage to obtain economies of scale.
    c. Creation of public-private partnerships centered around industrial ports and commercial fleets. This approach can jump-start roadmaps into action plans, especially for regions where air quality nonattainment is an issue with commercial implications. Required infrastructure investment is less per amount of hydrogen deployed, and hence required hydrogen cost reductions are likely to be achieved. Global response to COVID-19 economic stimulus includes consideration of hydrogen infrastructure investment. The U.S. should also look closely at prudent hydrogen infrastructure investment opportunities based upon projections for economic growth.

It is an exciting time for hydrogen. Over the last two years there has been a large upswing in global interest in hydrogen as a vector for decarbonization and improved air quality, and growing recognition of the economic opportunity hydrogen can provide in transport and storage of renewable energy. The technology portfolio championed and driven by DOE for multiple decades is now positioned to break through in commercial adoption, driven by a patchwork of global and state policies; consumer interests; and the cost simplification of electric drive trains combined with the energy density of hydrogen, which drives adoption in certain market sectors. A key role for the DOE and HFTO is disseminating knowledge to communicate the opportunity and bring together stakeholders to realize the benefits of shared infrastructure and scale, thus facilitating translation of the hydrogen roadmap into specific actions and projects.

Bibliography of Recent Hydrogen Roadmaps

- United States: Road Map to a U.S. Hydrogen Economy (n.d.), http://www.fchea.org/us-hydrogen-study.
- Hydrogen Council: Studies (accessed 2020), https://hydrogencouncil.com/en/category/studies/.
- Japan: *Formulation of a New Strategic Roadmap for Hydrogen and Fuel Cells*, Ministry of Economy, Trade and Industry (METI) (March 12, 2019), https://www.meti.go.jp/english/press/2019/0312_002.html.
- Europe: *Hydrogen Roadmap Europe*, Hydrogen Europe (February 11, 2019), https://www.hydrogeneurope.eu/news/hydrogen-roadmap-europe-has-been-published.
- IEA: *The Future of Hydrogen* (2019), https://www.iea.org/reports/the-future-of-hydrogen.

- IEA: *Technology Roadmap: Hydrogen and Fuel Cells* (2015), http://ieahydrogen.org/pdfs/TechnologyRoadmapHydrogenandFuelCells-(1).aspx.
- International Renewable Energy Association (IRENA): *Hydrogen: A renewable energy perspective* (September 2019), https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective.
- California: *Joint Agency Staff Report on Assembly Bill 8: 2019 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California*, California Energy Commission and California Air Resources Board (2019), https://ww2.energy.ca.gov/2019publications/CEC-600-2019-039/CEC-600-2019-039.pdf.
- E4Tech: Hydrogen and Fuel Cells: Opportunities for Growth – A Roadmap for the UK (August 2016), https://www.e4tech.com/resources/126-hydrogen-and-fuel-cells-opportunities-for-growth-a-roadmap-for-the-uk.php.
- Wood Mackenzie: *The future for green hydrogen* (October 25, 2019), https://www.woodmac.com/news/editorial/the-future-for-green-hydrogen/.
- United Kingdom: "External Hydrogen and Fuel Cell Resources," UK Hydrogen and Fuel Cell Association (UKFCHA) (accessed 2020) http://www.ukhfca.co.uk/resources-2/.
- Norway: The Norwegian Hydrogen Guide 2017 (n.d.), https://www.hydrogen.no/assets/files/files/hydrogenguide/nhf-hydrogenguiden-2017.pdf.
- Norway: *HyLAW: National Policy Paper – Norway* (2019), https://www.hylaw.eu/sites/default/files/2019-03/National%20Policy%20Paper%20-%20Norway%20%2810.03.2019%29.pdf.
- Italy: *The Hydrogen Challenge: The potential of hydrogen in Italy* (October 10–11, 2019), https://www.snam.it/it/hydrogen_challenge/repository_hy/file/The-H2-challenge-Position-Paper.pdf.
- Germany: *A Hydrogen Roadmap for Germany*, Fraunhofer (October 2019), https://www.fraunhofer.de/content/dam/zv/de/ueber-fraunhofer/wissenschaftspolitik/Positionen/2019-10-a-hydrogen-roadmap-for-germany.pdf.
- Netherlands: *Government Strategy on Hydrogen* (2020), https://www.government.nl/binaries/government/documents/publications/2020/04/06/government-strategy-on-hydrogen/Hydrogen-Strategy-TheNetherlands.pdf.

EndNotes

[1] *Road Map to a US Hydrogen Economy: Reducing emissions and driving growth across the nation*, Fuel Cell & Hydrogen Energy Association et al. (2020): http://www.fchea.org/us-hydrogen-study.

[2] *The Future of Hydrogen*, International Energy Agency (IEA) (June 2019), https://www.iea.org/reports/the-future-of-hydrogen.

[3] "Update on electric vehicle costs in the United States through 2030," International Council on Clean Transportation, working paper (June 2019), https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf.

[4] Robinius, Linßen, Grube, et al., *Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles*, Energy & Environment Volume 408 (Verlag Jülich: Forschungszentrum Jülich GmbH Zentralbibliothek, 2018) ISBN 978-3-95806-295-5, https://juser.fz-juelich.de/record/842477/files/Energie_Umwelt_408_NEU.pdf

[5] "Electric truck ready for dynamic wireless charging on public roads in Sweden; Smartroad Gotland," *Green Car Congress* (February 26, 2020), https://www.greencarcongress.com/2020/02/20200226-electreon.html.

[6] Birol, "Put clean energy at the heart of stimulus plans to counter the coronavirus crisis," International Energy Agency (March 14, 2020), https://www.iea.org/commentaries/put-clean-energy-at-the-heart-of-stimulus-plans-to-counter-the-coronavirus-crisis.

[7] Amelang and Wehrmann, "IEA urges Germany to focus on hydrogen, import LNG," *Clean Energy Wire* (February 29, 2020), https://www.cleanenergywire.org/news/iea-urges-germany-focus-hydrogen-import-lng.

[8] Satyapal, "FCTO Multi-Year Plan Update – Draft materials for HTAC review, Presentation to Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)," US Hydrogen Roadmap Subcommittee (March 26, 2020).

[9] "Panasonic, Tokyo Gas update Ene-Farm product," Fuel Cells Bulletin Volume 2013, Issue 1 (January 2013): 1, https://doi.org/10.1016/S1464-2859(13)70001-4.

[10] "European ene.field project highlights fuel cell micro-cogeneration," Fuel Cells Bulletin Volume 2017, Issue 11 (November 2017): 6–7, https://doi.org/10.1016/S1464-2859(17)30382-6.