EXECUTIVE SUMMARY

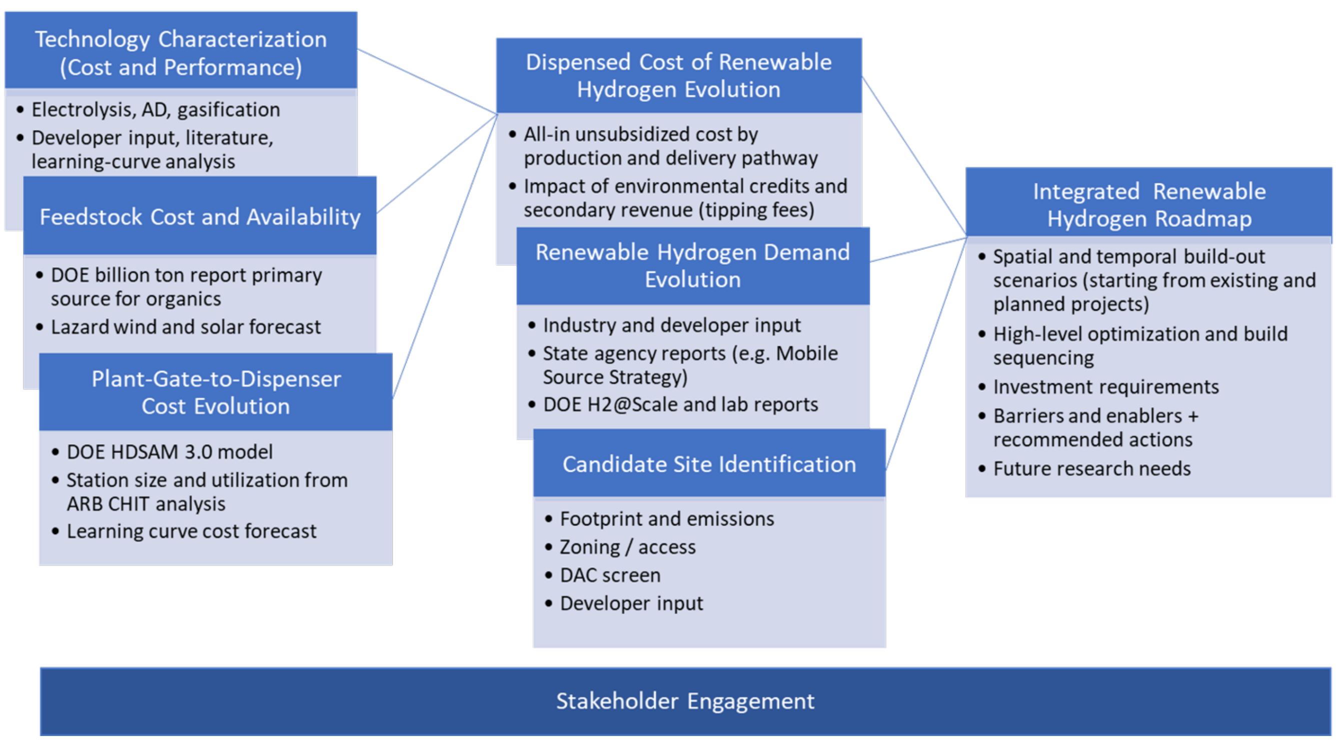
Overview

This report documents the analysis, methodology, and results of a one-year, CEC-sponsored study undertaken by the University of California, Irvine, Advanced Power and Energy Program (UCI APEP) to develop a roadmap for the evolution of the renewable hydrogen supply sector necessary to serve the growing demand for renewable hydrogen through 2050. The analysis focuses on 2020 through 2030 with a less detailed assessment of the time frame beyond 2030. The roadmap defines actions needed to support an optimal deployment of renewable hydrogen production plants needed to meet the growing demand for renewable hydrogen. The analysis builds upon insights from early market development and a series of analyses developed for the roadmap on current and future technology costs, feedstock supply and cost, siting and factory buildout, and demand growth.

This roadmap will help guide future state policy and funding decisions to support the successful buildout of a robust renewable hydrogen sector as a key part of California's zero-carbon economy. The roadmap is also a source of information for the public and interested stakeholders. An extended executive summary of the roadmap findings and recommendations can be found in Appendix C of this report.

UCI APEP developed the roadmap through several discrete tasks, as illustrated in Figure 1.

Figure 1: Renewable Hydrogen Roadmap Task Flow



Source: UCI APEP

Stakeholder Input

More than 40 interviews with industry stakeholders supported development of the RH2 Roadmap. In addition, two public webinars were conducted to provide interim results to stakeholders and provide opportunity for public comment. Appendix E summarizes key topics and themes.

Renewable Hydrogen Demand Forecast (Chapter 2)

The roadmap effort developed several scenarios for the growth in renewable hydrogen demand through 2050. Primary sources included hydrogen demand analysis (renewable and nonrenewable) developed for the U.S. Department of Energy (DOE) H2@Scale initiative and several state agency documents projecting decarbonization pathways. Although transportation, depicted in Figure 2, is expected to be the primary source of demand for renewable hydrogen, petroleum refining, power generation and storage, heat, industrial processes, and ammonia production are all additional sources of potential demand. This analysis projects a high-case demand for renewable hydrogen of more than 400 million metric tons per year in 2030 and more than 10 times that amount in 2050. Additional scenarios are detailed in Chapter 2.

Figure 2: Hydrogen in Transportation

Source: UCI APEP, Hyundai, Toyota, Honda

Technology Characterization (Chapter 3)

This task benchmarks the current cost and efficiency of the primary renewable hydrogen production pathways and forecasts the related evolution through 2050. Three classes of hydrogen production technology were assessed: electrolysis, anaerobic digestion, and thermochemical conversion. The analysis employed several methods, and the results are detailed in Chapter 3 and Appendix A. All the technology groups are projected to show significant improvement in cost and performance, with electrolysis showing the greatest reduction potential. The analysis results forecast that the U.S. Department of Energy (DOE) long-term cost target of $2 per kilogram at the plant gate is achievable by the 2030s.

Feedstock Supply and Cost (Chapter 4)

Feedstock supply and cost are important inputs to the delivered cost of hydrogen. The primary feedstocks are biomass for thermochemical conversion and anaerobic digestion and renewable electricity for electrolyzers. The primary source for the organic feedstock analysis was the DOE Billion Ton Report (BTR) and Lazard Levelized Cost of Renewable Electricity 12.0 was the primary source for wind and solar electricity. The analysis projects the potential supply of organic feedstock to be nearly 750 petajoules per year (10^{18} joules or the energy equivalent of 6 billion kilograms of hydrogen) at a cost threshold of $60 per dry ton. The resource potential for wind and solar is more than 70 times current consumption, and the cost of both wind and solar power production will be below 3 cents per kilowatt-hour by 2030. Details of the feedstock analysis can be found in Chapter 4.

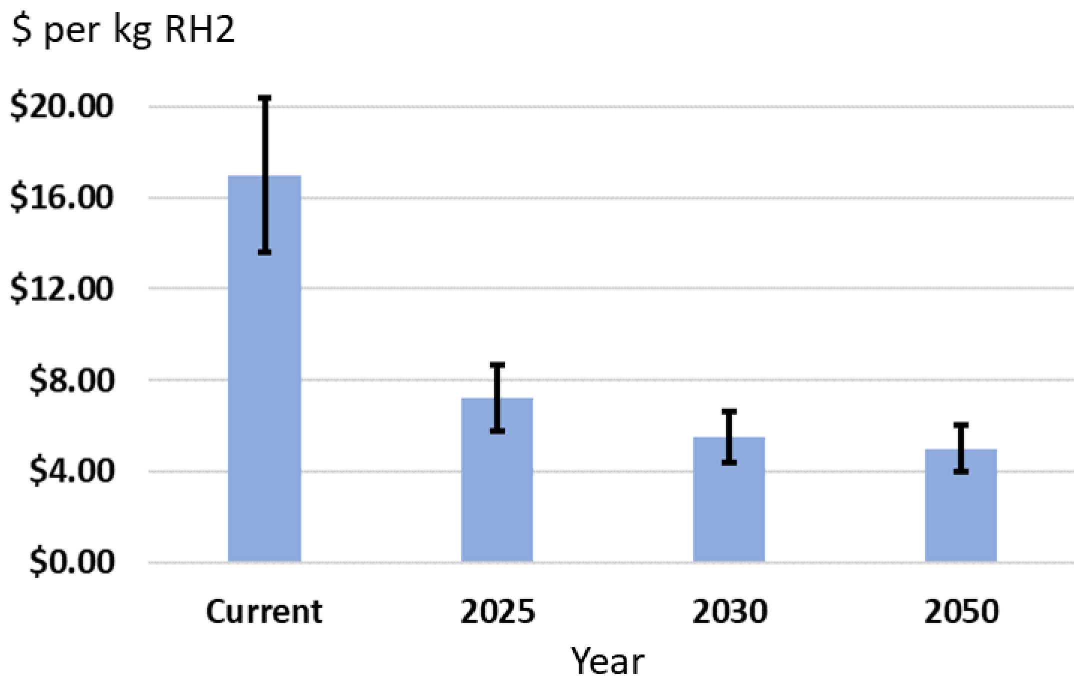
Plant-Gate-to-Dispenser Cost Evolution (Chapter 5)

The costs incurred from the production plant through the hydrogen refueling station were analyzed using the HDSAM 3.1 tool developed by Argonne National Laboratory augmented with a learning-curve forecast of cost-reduction potential. The station size and utilization follow the forecast in the 2018 AB 8 report (the annual report to the legislature on progress on hydrogen station construction). The analysis projects plant gate-to-dispenser costs to decline from around $16 per kilogram (excluding subsidies and credits) at present to a midpoint estimate of $6 by 2025, declining to below $5 by 2050 with a low-end estimate of $4 per kilogram. The biggest factor in the cost decline is increased station utilization (fuel dispenses as a fraction of full capacity) with economies of scale and technology progress also contributing. Details can be found in Chapter 5.

Dispensed Cost of Renewable Hydrogen Evolution (Chapter 6)

This task integrates technology, feedstock, and supply chain costs to derive the full dispensed cost of renewable hydrogen forecast ranges. The analysis then adds revenue from environmental credit values and tipping fees for landfill-diverted material to derive a net cost for dispensed hydrogen as a proxy for future pump price. The key findings are that the dispensed price of hydrogen is likely to meet an interim target based on fuel-economy-adjusted price parity with gasoline of $6 to $8.50 per kilogram by 2025. Furthermore, reaching the long-term DOE target of $4 per kilogram is within the forecast band for 2050, but the base forecast is around $5 per kilogram. The cost evolution is shown in Figure 3. Additional detail can be found in Chapter 6.

Figure 3: Net Cost of Dispensed Renewable Hydrogen



Source: UCI APEP

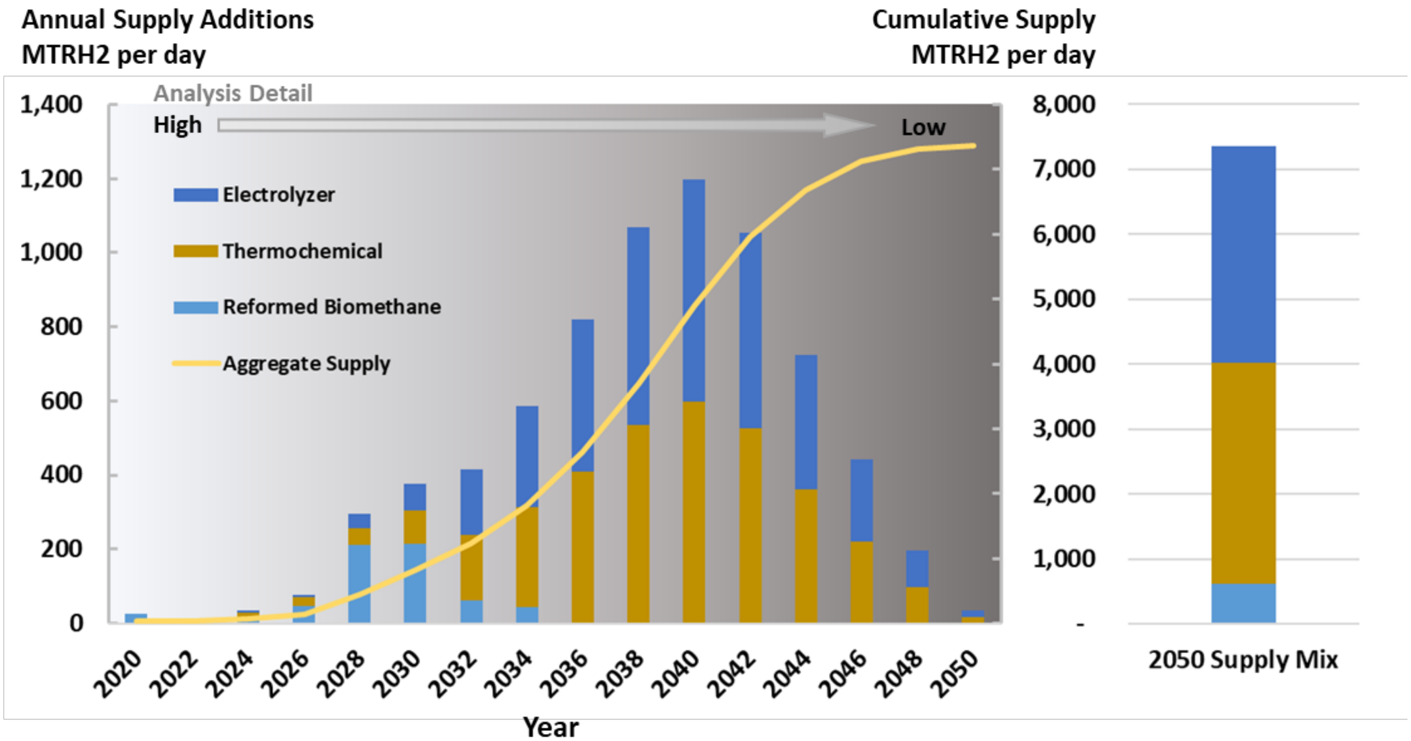
Candidate Site Identification

This analysis assessed locations across the state in a 4-km-by-4-km grid to determine suitability for siting renewable hydrogen production plants based on terrain, land use, and access to necessary infrastructure. The research team selected plant locations in the various buildout scenarios from the resulting set of candidate sites. The analysis shows that proximity to feedstock is the strongest factor in siting. Thermochemical plants are sited in forests and agricultural areas, anaerobic digestion facilities on dairies or refuse routes, and electrolyzers in solar and wind resource areas. Steam methane reformers use pipeline gas as feedstock and are sited near natural gas transmission lines. For outbound transport of produced hydrogen, all facilities are also sited near major highways. Plants that generate smog-causing emissions were excluded from disadvantaged communities in high-pollution areas.

Integrated Buildout Scenarios and Roadmap (Chapters 7 and 8)

The final step was integrating the results from prior tasks to develop time-phased buildout scenarios for renewable hydrogen production plants. Based on a defined set of assumptions and constraints including community impacts, the buildout scenarios minimize the cost of dispensed hydrogen to serve incremental demand in time steps from the present through 2050. Details of the siting analysis and buildout scenarios can be found in Chapter 7 and Appendix B. Recommendations for market support and research, development, and demonstration (RD&D) are summarized below with additional detail provided in Chapter 8 and Appendix D (RD&D needs). Figure 4 shows the base-case facility buildout. The 2050 facility count exceeds 500 across the various technology types.

Figure 4: Base-Case Facility Build 2020 to 2050



Source: UCI APEP

Recommendations

The roadmap project team developed a set of recommendations for state action based on the roadmap research and analysis, and input from stakeholders. The recommendations are presented in two categories. The first category defines actions to support market development and evolution directly through things such as incentives. The second category recommends research, development, and demonstration (RD&D) activities to refine the findings of the roadmap and support technology advances needed to achieve long-term targets.

Market Development Recommendations

1. Extend hydrogen infrastructure support to the entire supply chain (extend the current program focus on stations to renewable hydrogen production, processing and transport).
2. Focus on forms of support that attract private capital (such as loan guarantees).
3. Take steps to support a smooth expansion of capacity and avoid boom/bust cycles while promoting robust competitive markets by increasing market transparency and targeting incentives.
4. Reduce barriers to development in California: California Environmental Quality Act (CEQA), codes and standards, costs (including taxes), and local issues.

5. Develop electric rate structures specific to transmission-connected renewable fuels facilities (for example, electrolyzers and liquefaction facilities) such as whole power market access + transmission charge.
6. Promote access to the natural gas system for renewable hydrogen transport and storage—establish blending limits and interconnection requirements.
7. Take steps to ensure that a mixed gas/liquid supply chain does not create barriers to market access. For example, provide incentives for development of open access points of entry to the supply chain such as gaseous or liquid terminal facilities.
8. Ensure that renewable hydrogen development advances social justice by maximizing job creation in disadvantaged communities while minimizing negative impacts such as traffic, noise, visual impacts and air emissions.
9. Act to ensure that program eligibility, environmental accounting, and lack of definitions are not barriers to renewable hydrogen development

Future RD&D Recommendations

- Renewable hydrogen production technology and feedstock supply
- Demand, adoption, and impacts analysis
- Supply-chain forecasting and optimization (plant gate to point of use)
- Renewable hydrogen fuel production and electric grid integration