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Realizing a Self-sustaining Renewable Hydrogen Sector in California

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***Abstract*—** This paper presents a roadmap for the build-out and deployment of renewable hydrogen (RH2) production facilities in California. The purpose is to provide a fact-base to support policy decisions and inform stakeholders. The analysis includes demand projections, forecasts of technology progress, supply chain costs and temporal and spatial facility siting scenarios. The work places specific focus on lessons from early project activity and projection through 2030 with higher level forecasts through 2050. The work concludes with research needs and policy recommendations to successfully launch and scale the California renewable hydrogen sector. The overall conclusion is that, with appropriate policy support, the renewable hydrogen sector can reach self-sustainability (price point at parity with conventional fuel on a fuel-economy adjusted basis) by the mid to late 2020s.

Keywords: hydrogen, renewable hydrogen, hydrogen production, roadmap, deployment, build-out, RH2

I. Introduction

Renewable hydrogen as a transportation fuel and in numerous other applications can serve as a foundation for deep decarbonization strategies [1]. This paper summarizes key findings and recommendations from a recently developed roadmap for the evolution of the renewable hydrogen sector in California. The roadmap is supported by several analytical foundations: analysis of the demand evolution for renewable hydrogen in California; rigorous forecasting of technology cost and performance evolution for alternative production pathways and spatially mapped least-cost facility build-out scenarios; and assessment of policy and research needs. The results show that achieving a self-sustaining renewable hydrogen sector in California (one in which the market can attract adequate private investment without subsidies other than carbon price) is feasible by the mid-to-late 2020s.

Current and announced renewable hydrogen production capacity will be inadequate to meet supply by the early 2020's. Renewable hydrogen supply shortages could slow or stall growth in the nascent fuel cell vehicle market and erode consumer confidence. The roadmap provides an information basis to guide policies and incentives to help ensure a smooth and successful ramp-up and scaling of a self-sustaining renewable hydrogen supply sector in California. The recommendations can also provide insight for other markets.

II. Renewable Hydrogen Demand Evolution

Hydrogen can serve as a zero-carbon and zero-emission transportation fuel across the full spectrum of on-road and off-road applications. Beyond its potential role in transportation, renewable hydrogen can be used to fuel non-intermittent renewable generation resources and as a primary input to fertilizer manufacture, refining, industrial processes and next-generation steel making. Fig. 1 shows the high-demand scenario from the present analysis. Assuming continued policy support and consumer adoption, renewable hydrogen could contribute nearly $2 billion (currency $ US throughout) to the California economy by 2030 and $18 billion by 2050 providing approximately 15 percent of California's energy consumption. Not only will this create tens of thousands of green energy jobs, but it will ensure continued progress on reducing air pollution in disadvantaged communities and help California go the last mile to reach 100 percent zero-carbon energy.

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III. Renewable Hydrogen Production Technology Pathways and Forecasts

Renewable hydrogen (hydrogen from 100 percent renewable inputs) can be produced in a variety of ways. The three primary pathways considered in the present analysis are: 1) electrolysis powered by renewable electricity; 2) gasification of woody biomass; 3) anaerobic digestion of high-moisture-content organic material followed by steam methane reforming (SMR).

Establishing the current cost of producing renewable hydrogen and forecasting costs out to 2050 was a key part of the RH2 production roadmap analysis. A variety of methods were used to triangulate the estimates including expert input, learning-curve analysis, and other methods. The resulting capital cost progression is shown in Fig. 2. The analysis also included forecasts of conversion efficiency and operating cost improvements.

IV. Feedstock Supply and Cost

There are two primary classes of feedstock for renewable hydrogen production: biomass and renewable electricity (direct solar conversion may be possible in the future). The DOE has sponsored an extensive study of biomass availability as a function of recovery cost across the U.S. known as the Billion Tons Report (BTR) [2].

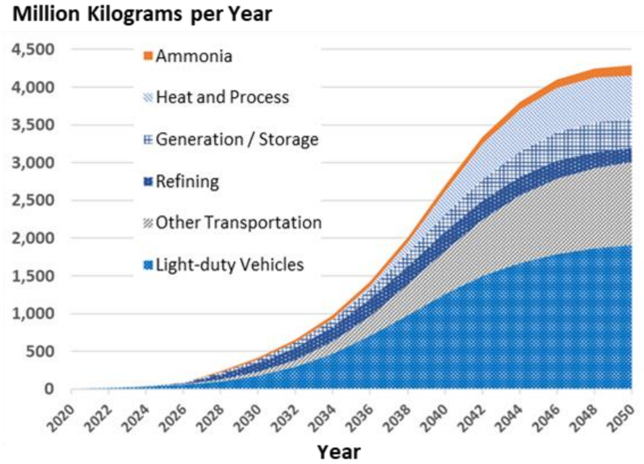

Fig. 1. Potential California Renewable Hydrogen Demand Growth

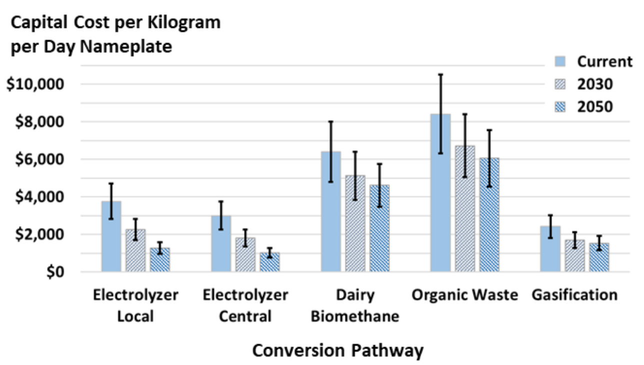

Fig. 2. Capital Cost per Unit of Renewable Hydrogen Production Capacity

TABLE I. California Biomass Feedstock Quantities

Feedstock	Quantity (Petajoules per Year)		
	$30/ US Ton	*$60/ US Ton*	*$100/ US Ton*
Woody Material [2]	227	686	1160
Energy Crops [2]	0	0	10.6
High-moisture Organic MSW [2]	0	17.7	35.7
Manure [3]	12	12	12
Landfill Gas [4]	43	43	43
Total Annual Supply	282	759	1255

Several analyses specific to California have also been undertaken. The total available supply of biomass feedstock used for this study is shown in Table 1.

Solar and wind resources in California are not unlimited but the resource potential is many times the energy needs of the state, so no hard limit was applied to these resources. Future production cost ranges for solar and wind were forecast using data from several sources such as [5] and [6]. The base case assumption was that wholesale or self-generated renewable electricity will cost $30 dollars per megawatt hour for 2030 and beyond.

V. Plant-Gate-to-Dispenser Cost Analysis

Costs incurred from the production “plant gate” through the point of use constitute a significant portion of the dispensed cost of hydrogen. The DOE HDSAM 3.1 cost model was used to estimate current and future costs for liquid and gaseous hydrogen transport and dispensing approaches. Direct hydrogen pipeline delivery is also an option but, because the required infrastructure is not currently in place and development of such infrastructure will not likely occur prior to the 2030’s or beyond, this analysis does not include that pathway. Fig. 3 presents the forecast cost progression for liquid and gaseous delivery.

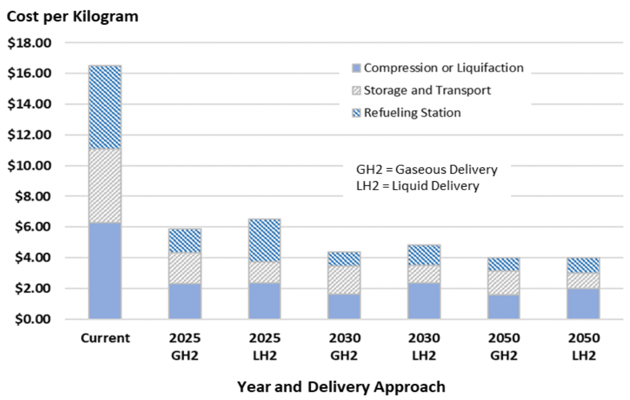

Fig. 3. Plant-Gate-to-Dispenser Cost by Year of Construction

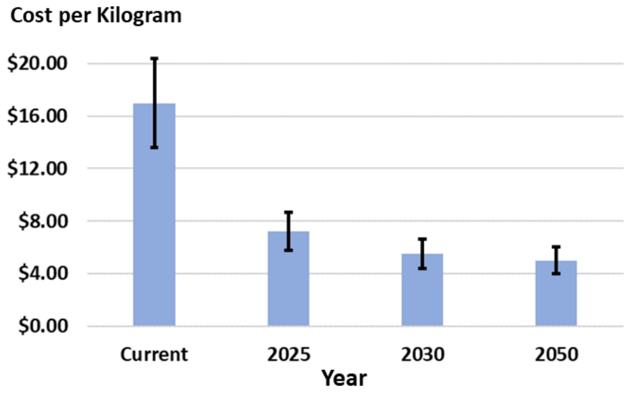

Fig. 4. Cost of Dispensed Renewable Hydrogen Net of LCFS Credits

VI. Dispensed Cost of Renewable Hydrogen

Combining the cost components developed in prior sections, Fig. 4 presents the forecast range of the dispensed cost of renewable hydrogen from a newly-built set of production and delivery facilities. The cost includes the impact of environmental credits as cost offsets. This has a net effect of reducing the dispensed cost of hydrogen by $1 to $2 per kilogram in the 2025 to 2030 time frame. The declining costs reflect both facility cost reductions (resulting from production volume growth and technology improvement) and increasing utilization of the supply and delivery chain. For example, the analysis projects utilization of the hydrogen refueling station network to increase from the current level of around 40 percent to 80 percent by 2030. The analysis did not assess the economic viability of older-vintage stations and production facilities that have higher embedded costs than new facilities but addressing that issue, for example through selective subsidies, is an important policy consideration.

VII. Siting Analysis and Build-out Scenarios

The future build-out of renewable hydrogen facilities in California will be driven largely by cost and availability of feedstock (biomass and renewable electricity). Fig. 5 shows the primary development areas for the various production technologies and feedstocks. Several build-out scenarios were developed for the RH2 Roadmap based on varying assumptions regarding demand and relative progress of technologies. Fig. 6 show the build-out under the high-demand scenario and Fig. 7 maps the 2030 production portfolio based on a siting algorithm that minimizes cost within defined siting constraints (such as exclusion of NOx emitting facilities from non-attainment areas).

VIII. Self-Sustainability – Achieving Abundant, Ubiquitous and Affordable RH2 Supply

A self-sustainable renewable hydrogen sector can be defined as one in which growing, consumer-driven demand is supplied by a steady flow of private investment across the supply and delivery chain adequate to serve that demand. On the demand side, policies to support decarbonization and pollution reductions for transportation, energy production, commercial and industrial uses and homes are the key provided that such policies provide balanced support across all avenues to reduce pollution and carbon. On the supply side, cost reduction and production and delivery capacity increases must be achieved for the potential demand to be realized.

Transportation will be the primary driver of renewable hydrogen demand through 2030 and will likely remain the largest use of renewable hydrogen as other source of demand mature beyond 2030. The cost of dispensed hydrogen vehicle fuel in California today, with an average renewable fraction of 40 percent, averages around $16 per kilogram [7] (roughly the energy equivalent of 1 gallon of gasoline and the cost equivalent of $6.40 per gallon when adjusted for fuel economy.

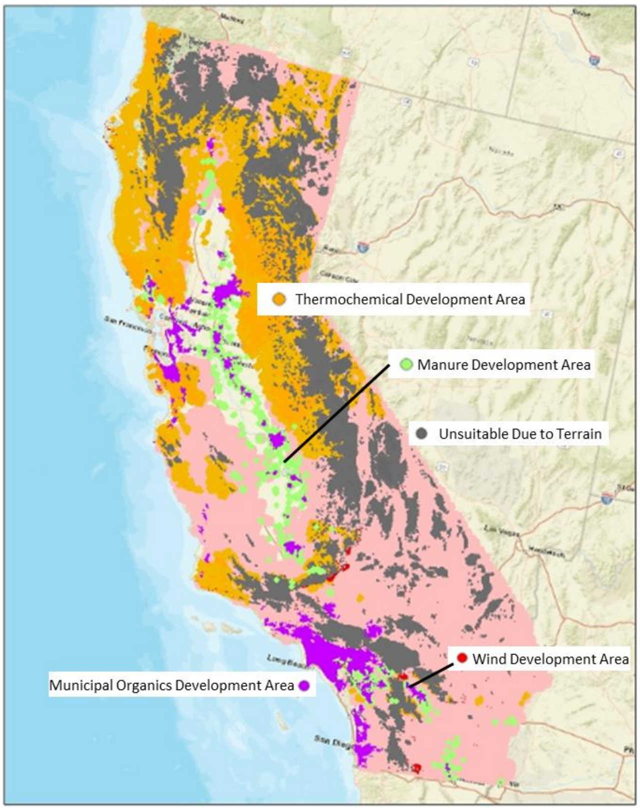

Fig. 5. Primary Resource Areas for Renewable Hydrogen Production

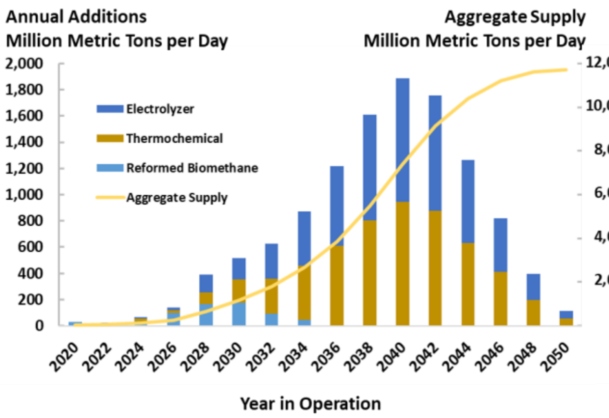

Fig. 6. High-case build-out by technology type

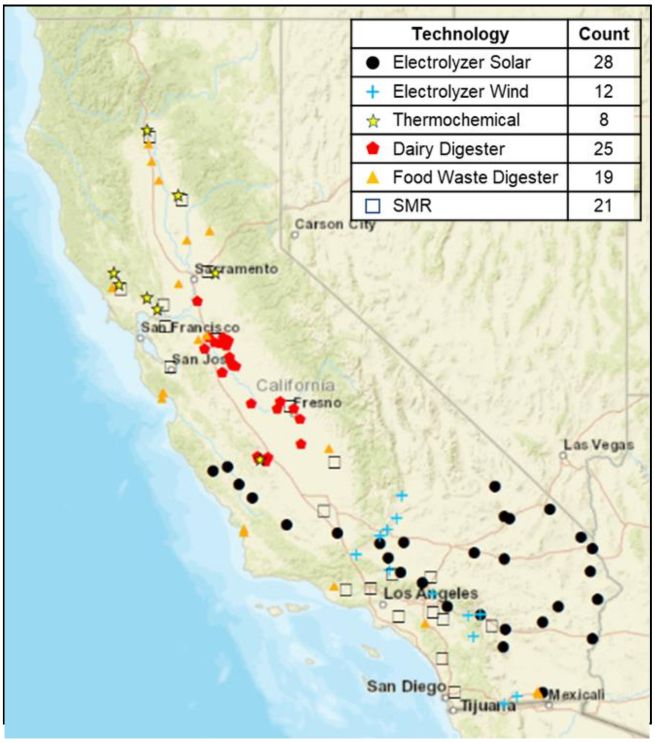

Fig. 7. 2030 High-case Spatial Detail

This price is high relative to a near-term target of $6.00 to $8.00 per kilogram for dispensed hydrogen and a long-term goal of $4.00 per gallon. However, it should be kept in mind that solar and wind technologies have seen more dramatic cost reductions and that the current network operates at a low capacity factor. The present analysis supports the projection of potential cost reduction across the renewable hydrogen production and supply chain of 40 percent to 60 percent by 2030 tracking toward the $4 per kilogram target by 2050 on the low end of the forecast range with mid-case 2050 forecast of between $5 and $6 per kilogram. Reaching the cost targets will require policy support and incentives to bridge the current nascent sector to a self-sustaining one by the mid to late 2020's. And such support will be needed across the production and supply chain.

IX. RECOMMENDATIONS AND CONCLUSINS

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 directly support market development and evolution through things such as incentives. The primary recommendations are to: provide financial support for initial electrolysis and gasification projects to provide operating history adequate to support the commercial financing of projects by the mid-2020s; continue the California low-carbon fuel standard (LCFS) program and establish mechanisms to create a credit price floor; design electric rate structures allowing electrolyzers to access wholesale power markets; consider social justice in incentive design and awards and deployment planning; address regulatory gaps creating barrios for use of the gas system for hydrogen blending and transport; enhance market transparency and support new entrants; streamline permitting.

Research, Development and Demonstration (RD&D) recommendations include: ongoing tracking to extract lessons learned from initial projects; adding zero-carbon non-renewable pathways to future analysis; conducting further quantitative research on consumer adoption for all categories of potential renewable hydrogen demand; including dedicated hydrogen infrastructure in the supply-chain analysis; and increased state RD&D on next generation technologies across the production and supply chain analysis; and increased state RD&D on next generation technologies across the production and supply chain.

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