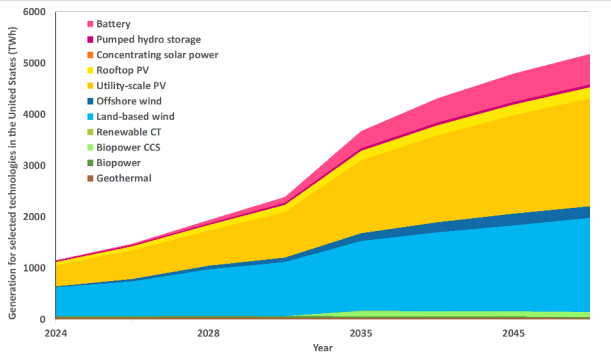


Opportunities and Implications for low-cost Hydrogen Production from Water Electrolysis in a Decarbonizing Power Sector

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Power sector decarbonization and renewable deployments could drive trends in wholesale power markets

Decarbonization of the United States electric power sector by 2035 would substantially increase renewable deployments (Fig. 1)

Variable renewable energy (VRE) generation shifts temporal trends in power markets and can put downward pressure on wholesale electricity prices when VRE generation is high and grid energy demand is low.

Fig. 1 (left): growth in generation for selected technologies under NREL Standard Scenario: Mid-case with 100% decarbonization by 2035. [1]

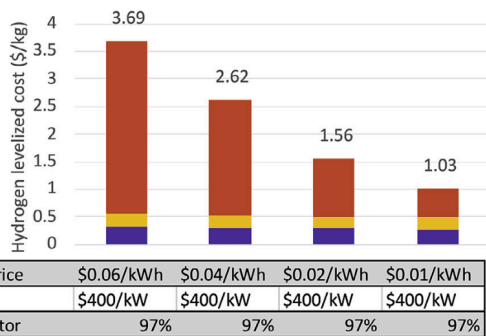


Fig. 2 (above): cost contributions to levelized cost of hydrogen production for various electricity prices. [2]

Integration opportunities for electrolytic hydrogen

The cost of hydrogen production via electrolysis is driven by electricity prices. (Fig. 2)

Dynamic operation of electrolyzers via direct connection to VRE or integration into wholesale power markets could drive the cost of hydrogen production down. (Fig. 3)

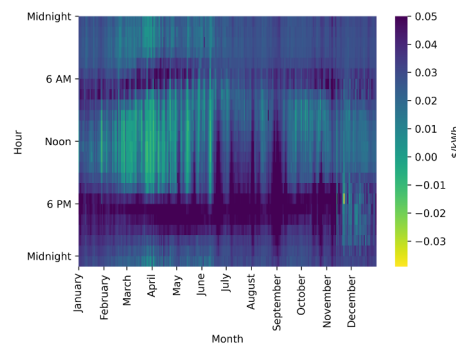


Fig. 3 (above): 2017 electricity price heatmap for Palo Verde wholesale market node, Arizona, U.S. [2]

Technology implications and R&D challenges

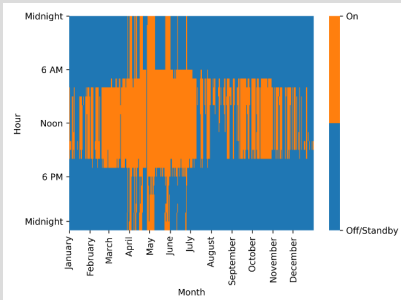


Fig. 4 (above): simulated 2030 hourly grid costs for Palo Verde, Arizona, U.S. [3]

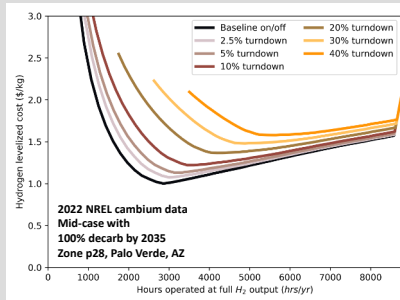


Fig. 5 (above): estimated hydrogen levelized costs under various electrolyzer operating profiles and turndown ratios in Palo Verde, Arizona, U.S. [3]

Meeting existing and future hydrogen demands with electrolysis could require global deployments on the order of multiple TW by 2050. (Fig. 7)

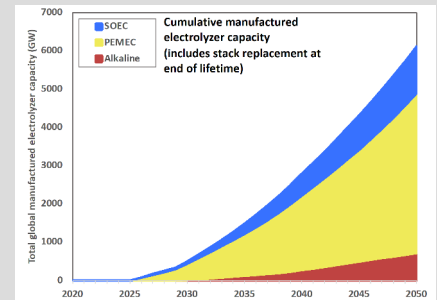


Fig. 7 (above): cumulative manufactured electrolyzer capacity under global decarbonization trajectories. [5]

Dynamic operation reduces levelized production costs but requires frequent electrolyzer on/off cycling and ramping. Innovative operating strategies with batteries and turning down without shutting off could minimize the effect of performance degradation from aggressive operating profiles. (Figs. 4,5)

Low-cost hydrogen production via dynamic operation requires lower electrolyzer capital costs.

Capital cost reduction strategies include (but are not limited to) manufacturing economies of scale, reduced catalyst loadings, and performance advances. (Fig. 6)

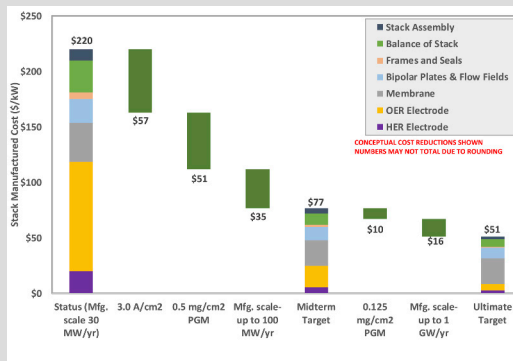


Fig. 6 (above): conceptual cost reduction strategies for PEM electrolyzer stacks. [4]

Key conclusions and future work

- Lower electrolyzer stack and balance of plant capital costs are key enablers for dynamic operating strategies and therefore support low-cost electrolytic hydrogen production.
- Achieving low capital costs without sacrificing the durability and performance of the electrolyzer stack ensures that dynamic operation does not result in excessive performance degradation.
- Analysis on the deployment of electrolyzers on the order of hundreds of GWs can inform strategies for end-of-life management and impacts to electricity markets and renewable deployments.