POLICY MEMO

The Cost of Clean Hydrogen with Robust Emissions Standards: A Comparison Across Studies

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Princeton University | May 18, 2023

Executive Summary

- **Without robust requirements for clean electricity procurement, embodied emissions from grid-connected hydrogen production subsidized by the Inflation Reduction Act could be worse than conventional 'grey' hydrogen produced from fossil methane.**
- **Recent analyses on the cost of meeting robust emissions standards have been split, with some finding that compliant clean hydrogen production would be easily competitive with grey hydrogen, and others arguing that compliance costs would prevent scale-up of clean hydrogen production in the US.**
- **A comparison of these studies shows that those finding high compliance costs for robust standards rely on unrealistically pessimistic assumptions for either electrolyzer costs or clean electricity availability.**
- **Correcting for these specific unrealistic assumptions, all available evidence demonstrates that clean hydrogen production meeting robust emissions standards will be cost-competitive in the US from day one, enabling the nascent industry to scale up and contribute to long-term emissions reductions.**

Context

Recent peer-reviewed research has demonstrated that the 'Three Pillars' standard for clean hydrogen carbon accounting – new supply, deliverability, and hourly matching – is necessary to avoid significant excess emissions from government-subsidized electrolytic hydrogen production in the United States.[1,2,3] However, some parties have argued that the cost of meeting the Three Pillars would be large enough to overwhelm the $3/kg clean hydrogen production tax credit introduced in the Inflation Reduction Act (IRA), rendering the US clean hydrogen industry "dead on arrival."[4] Others argue that while the Three Pillars standard appears necessary to avoid near-term emissions inconsistent with IRA's statutory requirements, the Treasury Department faces an unavoidable trade-off between implementing "strict" emissions accounting rules and prioritizing rapid electrolyzer deployment and improvements that could enable the realization of much larger emissions reductions over the long term.[5,6] However, this asserted trade-off only holds if the Three Pillars approach truly prevents early grid-connected hydrogen projects from being economically viable under reasonable conditions. As this memo demonstrates, such claims are not substantiated.

In this memo and its accompanying interactive levelized cost of hydrogen (LCOH) calculator tool, we compare the findings of ten recent studies assessing the cost of clean hydrogen production compliant with the Three Pillars. This comparison demonstrates that studies showing high costs for hourly-matched hydrogen production rely on unrealistically pessimistic assumptions along one or more dimensions, and that more realistic assumptions consistently lead to costs for clean hydrogen that are easily competitive with existing fossil-based production methods in many regions in the US. **In other words, when outlier assumptions that do not align with generally accepted capital cost and electricity supply data are corrected, these studies collectively support a conclusion that the economic viability of hydrogen production will not be undermined by application of the Three Pillars accounting system.** Treasury can therefore employ the Three Pillars standard to ensure hydrogen projects meet IRA's statutorily required emissions thresholds while simultaneously enabling the healthy and durable scale-up of the nascent clean hydrogen industry.

The Studies

This memo and its accompanying levelized cost of hydrogen (LCOH) calculator tool compile key data from studies conducted by a range of organizations and companies – including academics, research groups, clean energy developers and electrolyzer OEMs – listed below:

- Princeton University's ZERO Lab,
- Energy Innovation Policy & Technology LLC,
- Electric Hydrogen,
- Two additional clean energy developers,
- The MIT Energy Initiative,
- E3 and the American Council on Renewable Energy,
- The Energy Futures Initiative,
- Wood Mackenzie, and
- The Rhodium Group.

The first eight studies find that clean hydrogen projects compliant with the Three Pillars can be cost-competitive with fossil-derived 'grey' hydrogen from day one.[i] The remaining two studies conclude that the Three Pillars may lead to initial costs higher than those of grey hydrogen. To compare these studies' conclusions regarding LCOH for Three Pillars compliant hydrogen production, we break down their input assumptions into two categories:

- **Fixed facility costs**, which depend on upfront capital costs for electrolyzers and balance-of-plant, project financial lifetime and interest rate, fixed O&M, etc., and
- **Clean electricity cost and availability**, which determines how frequently the electrolyzer can be run and at what average cost.

Where the studies do not make this information available, we instead back-calculate it from their published results. The status of each cost input as known, calculated, or assumed is noted in the tool.

Fixed Cost Assumptions

The assumed fixed cost of an electrolyzer facility has a major bearing on the overall cost-competitiveness of a project. The higher the total fixed costs of a facility, the higher the electrolyzer utilization rate must be to recover these costs through production subsidies and hydrogen sales. Therefore, a combination of high fixed costs and insufficiently high electrolyzer utilization would lead to high LCOH and uncompetitive projects.

Fixed cost assumptions from each of the ten studies are shown in Figure 1. For those studies which included multiple cost cases (Princeton and Rhodium), we show assumptions from the most conservative case. Comparing assumptions across studies, we find that Wood Mackenzie is a clear outlier, with assumed fixed costs that are higher than those of all other studies by a wide margin. While Wood Mackenzie does not

[i] We define 'cost-competitive' here as starting at less than $2/kg, the estimated upper-bound cost for current grey hydrogen production from the US DOE's clean hydrogen liftoff report.[7] While some of the eight studies still advocate against the Three Pillars on the basis of cost *premium* relative to looser standards, all of these report post-subsidy costs for Three Pillars compliant hydrogen production starting well under the threshold. Aside from Clean Energy Developer 2, all of the eight studies report cost starting under $1/kg.

disclose its electrolyzer CAPEX assumption, our back calculations put it at over $2200/kW, with a final annual fixed cost for the facility of more than $400/kW-yr. By comparison, the US DOE's clean hydrogen liftoff report cites $1750/kW as the fully-installed cost for a small 2 MW PEM electrolyzer facility in 2022 - a cost which would likely be substantially lower for a commercial-scale facility.[7] Other estimates of current PEM electrolyzer costs include $700-1400/kW from IRENA,[8] $1600/kW from the IEA,[9] and $1400/kW from Bloomberg NEF.[10] Furthermore, every other study included in the tool – including by Electric Hydrogen, a leading electrolyzer OEM, and clean energy developers basing their analyses on a range of market quotes – assumes near-term electrolyzer facility installed costs between $670/kW and $1500/kW.

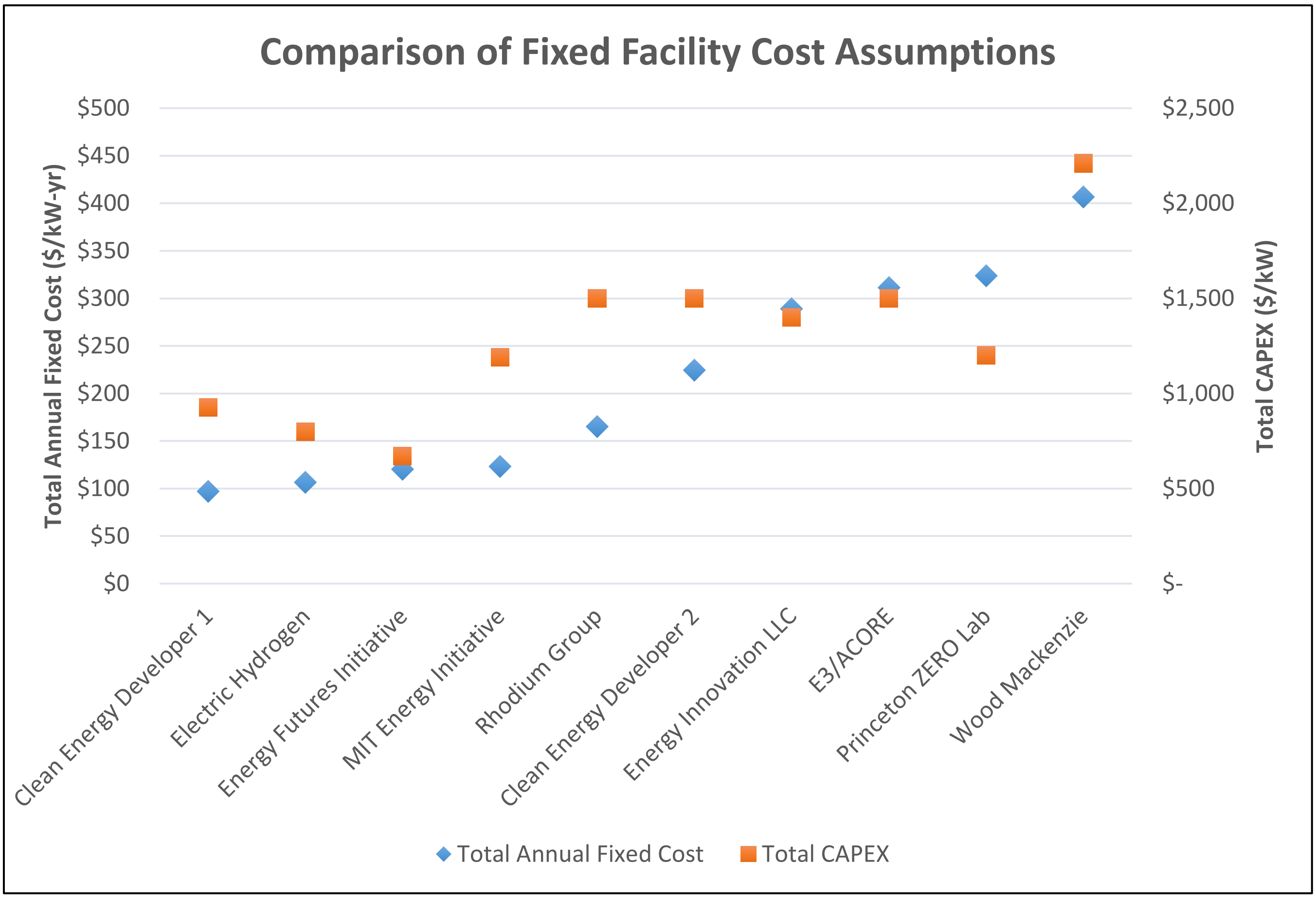

Figure 1: Fixed cost assumptions by study, including total annual fixed costs and upfront electrolyzer facility CAPEX. For context, the US DOE estimates the current fully installed capital cost of a 2MW PEM electrolysis facility at $1750/kW.[7] IRENA, IEA, and Bloomberg NEF estimate current costs in the $1400-1600/kW range.[8,9,10]

Final annual fixed costs are more variable and depend on assumed interest rates and payback periods. Studies that assume longer payback periods and mid-range electrolyzer costs (Clean Energy Developer 1, Electric Hydrogen, MITEI, and Rhodium) generally have aggregate fixed costs in the $100/kW-yr range. The studies by Princeton, Energy Innovation, and E3 assume higher electrolyzer costs and more conservative 10-year payback periods (i.e., assuming project costs are paid back in full during the 10-year 45V tax credit payment period, with zero assumed residual value), leading to annual fixed costs midway between those of Wood Mackenzie and the rest.

Clean Electricity Cost and Availability Assumptions

The second major cost driver for clean hydrogen production is procurement of clean electricity. Electricity cost has a linear impact on hydrogen production cost: for every $20/MWh increase in the cost of electricity, the LCOH increases by roughly $1/kg. The availability of clean electricity also determines how often the electrolyzer is able to run, with greater availability reducing the relative impact of facility fixed costs on the final LCOH. Given the variable nature of renewable electricity, there is typically a tradeoff between increased availability and increased cost.

Calculating the cost of sourcing hourly-matched clean electricity to enable a given electrolyzer utilization rate is a complex task. Clean electricity cost and availability are highly variable across geographies, and optimizing renewables capacity to maximize the availability of electricity to an electrolyzer facility while minimizing cost is nontrivial. However, such optimization is precisely what is needed to identify the clean energy sourcing options that enable a competitive LCOH and therefore rigorously examine the economic prospects of projects that comply with the Three Pillars.

As shown in Figure 2, the Rhodium and EFI studies are outliers in that they do not make any optimizations at all, but instead assume that an hourly-matched electrolyzer must run off of a single renewable generator with identical capacity to the electrolyzer. The electrolyzer's utilization rate is thus constrained to be equal to the capacity factor of the renewable generator. Rhodium's assumption of an identically sized solar facility, for example, leads to a very low electrolyzer utilization rate of 26%. As we discuss below, this assumption

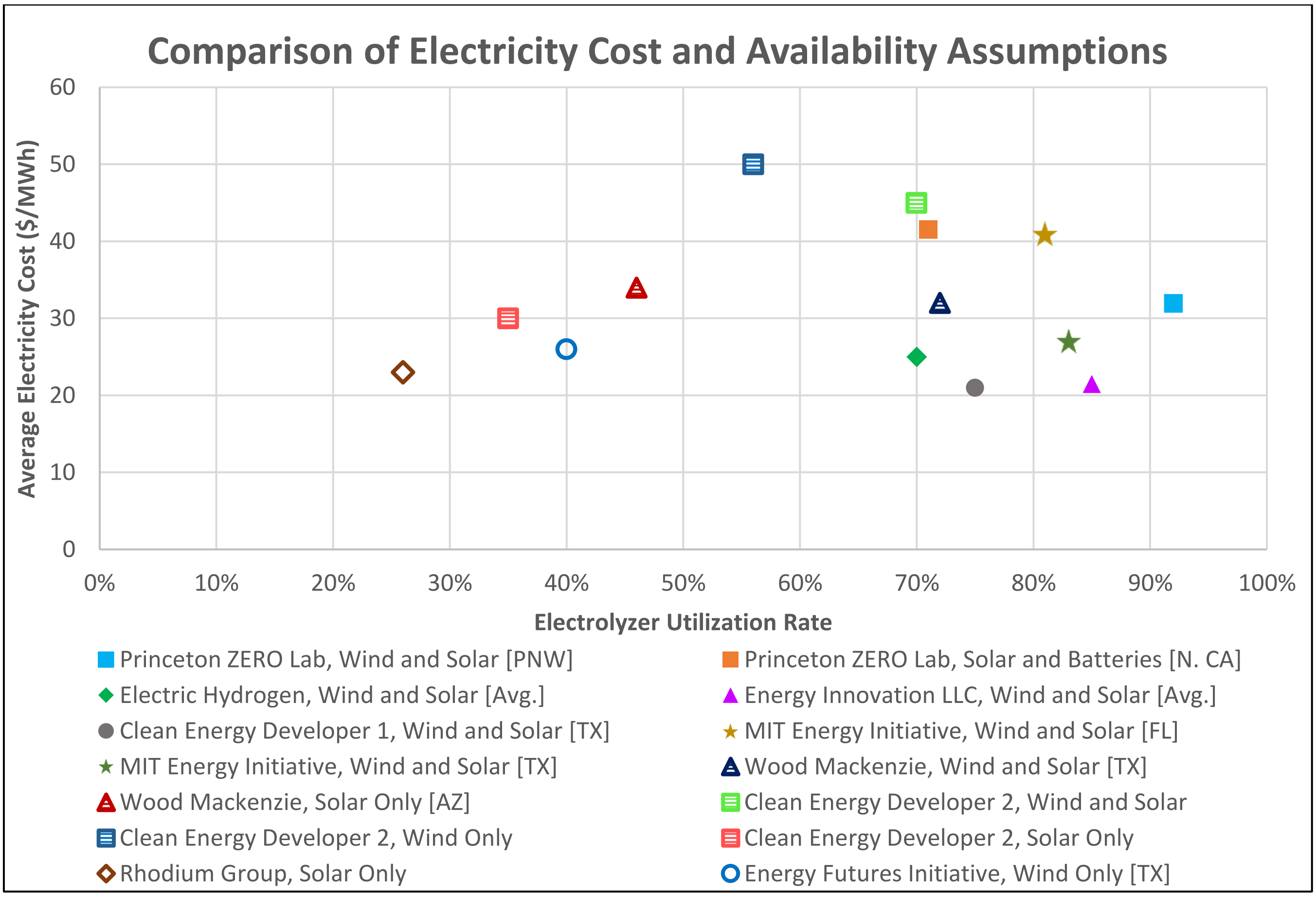

Figure 2: Average electricity cost and electrolyzer utilization rates from each study that reported these metrics, including multiple cases where available. Filled markers indicate studies that allowed both oversizing of clean generating capacity and sales of excess clean generation. Patterned markers indicate studies that allowed oversizing but not excess sales. Unfilled markers indicate studies that assumed clean generating capacity to be equal to electrolyzer capacity.

reflects one particularly expensive and pessimistic case, and Rhodium's analysis does not assess other electricity sourcing configurations – such as the oversizing of wind and solar projects relative to electrolyzer projects – which other studies confirm enable far more competitive project economics. While Rhodium does include an alternative solar-plus-batteries case in their analysis, this case is also unoptimized (i.e., the solar capacity is again fixed equal to the electrolyzer capacity) and therefore leads to both a higher electricity cost and a *lower* utilization rate than the solar-only case due to round-trip storage losses.

In contrast, all other studies allow the capacity of one or more types of renewable generators to be scaled independently of the capacity of the electrolyzer. Clean Energy Developer 2 and Wood Mackenzie do this for cases using exclusively wind, exclusively solar, or a combination of the two, allowing renewables to be overbuilt so that the electrolyzer can achieve a higher utilization rate if this is economically advantageous. These two studies assume that no value is extracted from generation of excess clean electricity beyond what is being used by the electrolyzer. Still, they find electricity costs in the $35-45/MWh range with ~70% availability, enabled by combining wind and solar power in regions where both are available. They find that cost-optimal utilization rates are lower when only wind or only solar are assumed to be available, but still greater than what was assumed in the two non-optimized studies by Rhodium and EFI. Finally, Princeton, Energy Innovation, Electric Hydrogen, Clean Energy Developer 1, and MITEI all assume that renewables can be oversized relative to electrolyzers, *and* that excess clean generation can be sold into the local electricity market to help offset the cost of generator oversizing (albeit placing limitations to account for real world grid dynamics). These studies all show utilization rates greater than 70%, and even exceeding 90%, with costs in the $21-41/MWh range for cases where both wind and solar power are available.

Comparing Outcomes and Identifying Common Findings

The LCOH tool shows how the post-subsidy LCOH changes as a function of the electrolysis facility's fixed costs, its utilization rate, and the average cost of input electricity (plots on sheet 2). Specific cost assumptions from each study can be selected via the dropdown menu in the tool. Figures 3, 4, and 5 below show results for electrolyzer costs set at $1750/kW (DOE's current benchmark for small 2MW PEM systems[7]), $1150/kW (an intermediate near-term estimate close to the average of the studies presented here, excluding the Wood Mackenzie outlier), and $550/kW (DOE's 2030 projection for 80MW PEM systems,[7] slightly higher than 2030 PEM cost projections from IEA and Bloomberg NEF[9,10]). Comparison of these results leads to the following conclusions:

1. **Oversizing wind and solar power relative to the electrolyzer consistently leads to a competitive LCOH for the full realistic range of electrolyzer capital costs.**

At $1750/kW electrolyzer CAPEX, high utilization rates are important for reducing the LCOH, and all studies that assume utilization rates below 70% come in above a target cost of $1.25/kg.[ii] **Notably, every study that assumes availability of both wind and solar power and allows sales of excess clean electricity still achieves a competitive LCOH even in this high-cost case, as does a wind and solar scenario from Wood Mackenzie that does not allow excess sales (Figure 3).**

[ii] A $1.25/kg target cost slightly undercuts the estimated average cost of $1.30/kg for current grey hydrogen production from the US DOE's clean hydrogen liftoff report.[7]

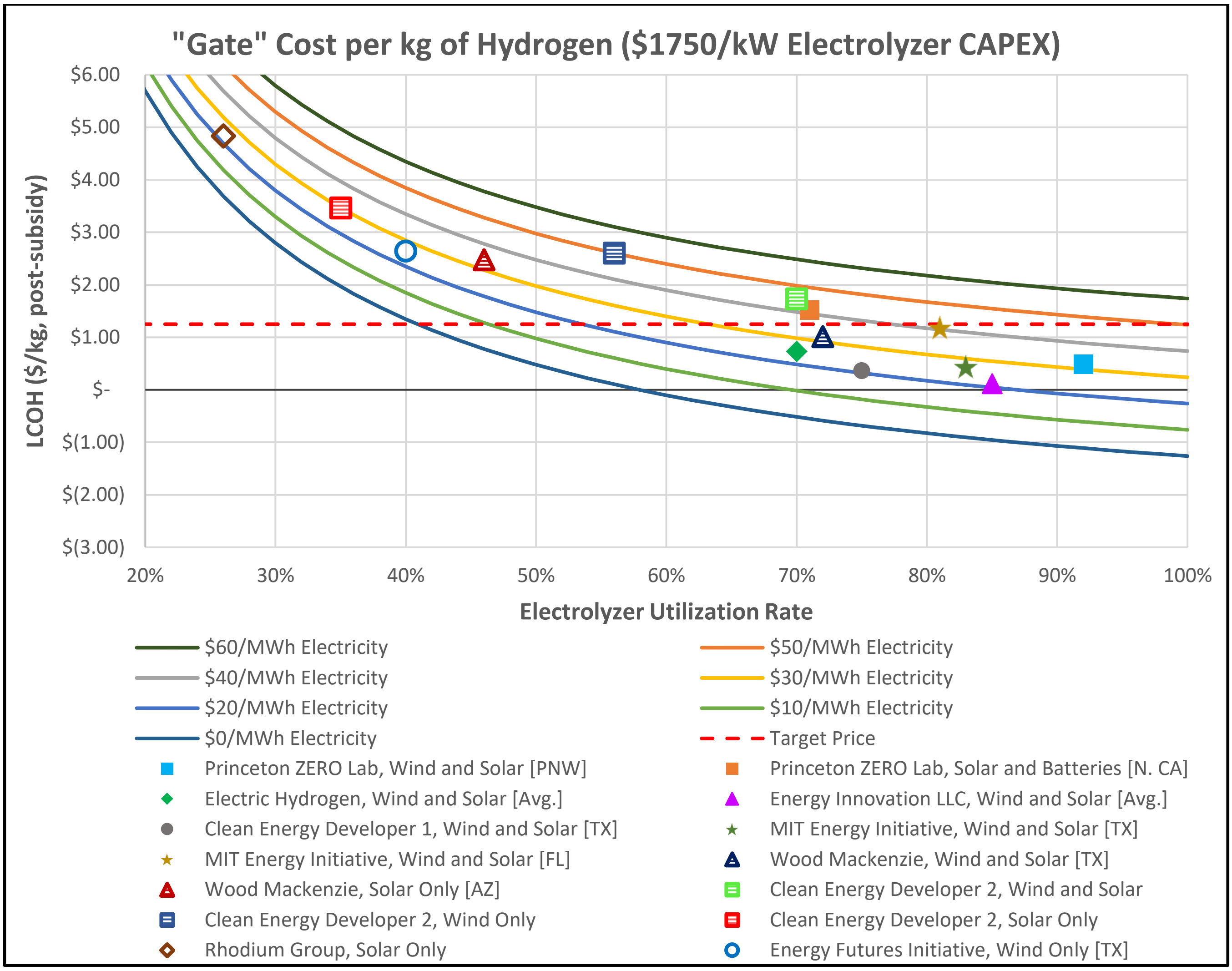

Figure 3: LCOH as a function of electricity cost and electrolyzer utilization rates, for an installed electrolyzer facility CAPEX of $1750/kW. Clean electricity cost and availability assumptions from each study are shown.

At $1150/kW electrolyzer CAPEX, even cases that neglect excess sales and assume availability of only a single renewable resource are in the money, and those that were competitive at $1750/kW are now generally being produced at *negative* cost (Figure 4). Even EFI's non-optimized wind-only scenario sits comfortably in the competitive range at these assumed costs. Rhodium's assumption of a non-oversized, solar-only system still leads to uncompetitive hydrogen production in this case, as do Clean Energy Developer 2's optimized solar-only and wind-only scenarios.

At $550/kW electrolyzer CAPEX, fixed costs become a relatively smaller component of LCOH compared to input electricity costs, and achieving a high utilization rate therefore becomes less important. In this case, every study's electricity cost and availability assumptions lead to near-zero or negative cost hydrogen production (Figure 5). These results suggest that while initial electrolyzer deployments may be focused in regions with the high-quality wind and solar resources needed to ensure high utilization rates under a Three Pillars, clean hydrogen production will rapidly become competitive nearly everywhere in the US as these initial deployments drive electrolyzers down cost and performance learning curves.

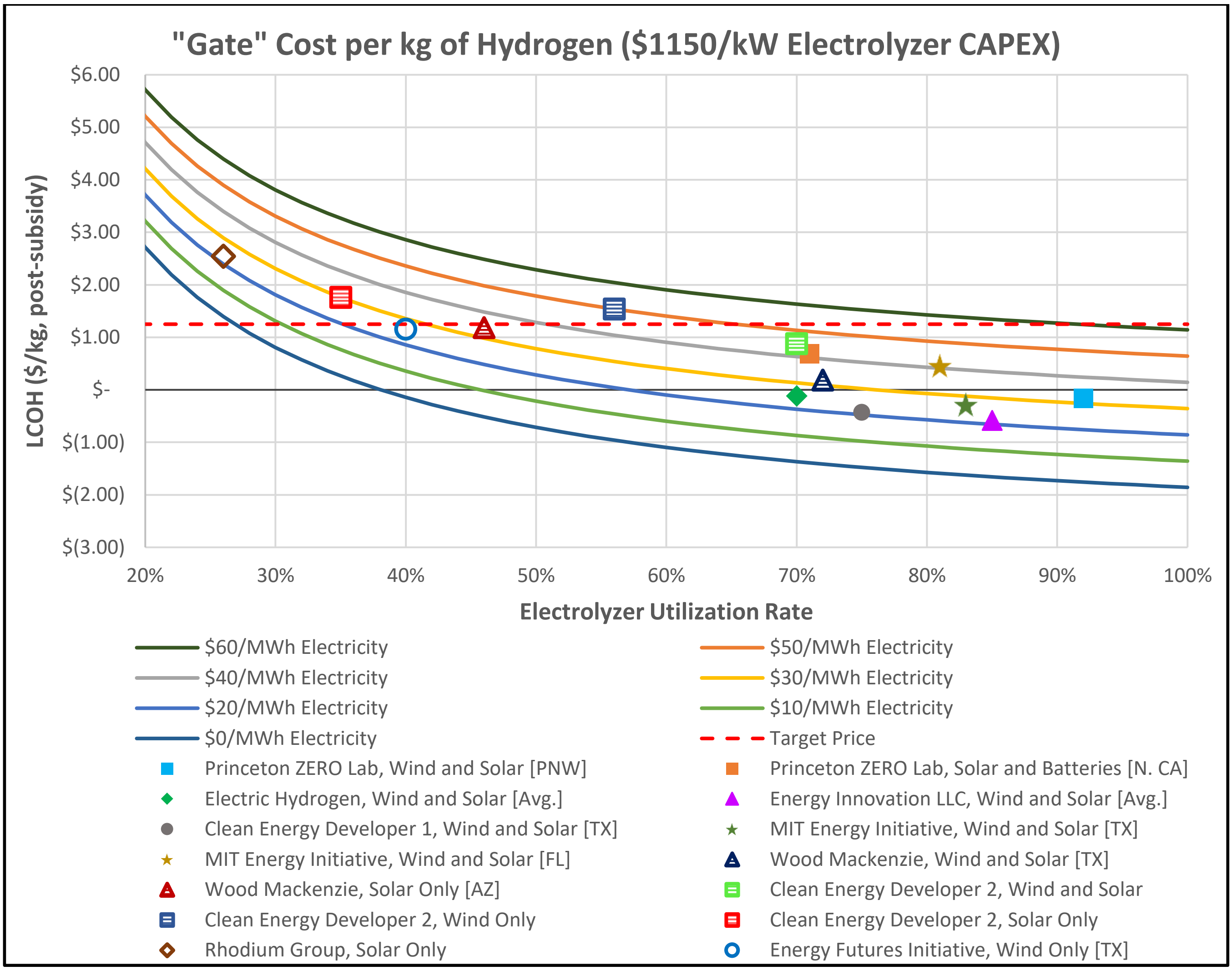

Figure 4: Same as Figure 3, for an installed electrolyzer facility CAPEX of $1150/kW.

2. **Correcting outlier assumptions in the Wood Mackenzie and Rhodium studies results in competitive LCOH for hourly matched projects.**

Studies from Wood Mackenzie and the Rhodium Group both reported post-subsidy costs for hourly-matched hydrogen production greater than $2/kg, which would be economically uncompetitive with conventional grey hydrogen production. As has been shown, these high final costs are the result of specific highly pessimistic assumptions made in each study. When those outlier assumptions are corrected, the LCOH in both studies adjusts to competitive levels.

In Wood Mackenzie's case, an assumed fixed facility cost far higher than that used in any other study (or by the US DOE) and far higher than current market prices leads to uncompetitive electrolytic hydrogen production at all but the highest utilization rates. Adjusting to more reasonable and typical fixed cost assumptions (e.g., DOE's conservative case of $1,750/kW), Wood Mackenzie's optimized renewable electricity cost and availability results lead to competitive hydrogen costs (see the marker for Wood Mackenzie's wind and solar case in Figure 3).

Conversely, Rhodium's study assumes fixed costs roughly in line with most other studies but assumes a highly simplified clean electricity matching strategy leading to extremely low electrolyzer utilization. At Rhodium's assumed facility costs, even a moderately higher utilization rate enabled by the oversizing of clean generation and/or combination of multiple renewable technologies would lead to cost-competitive hydrogen production.

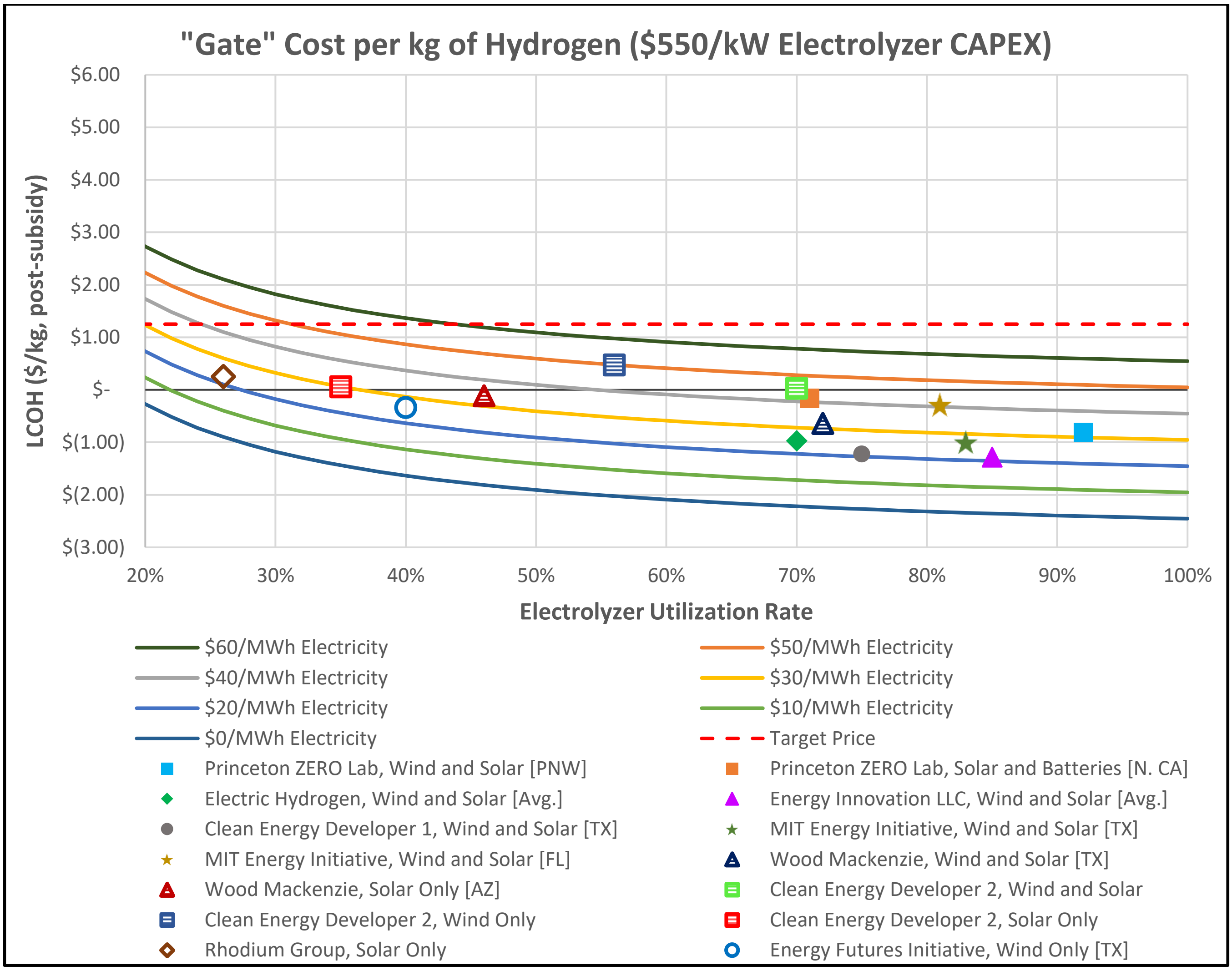

Figure 5: Same as Figure 3, for an installed electrolyzer facility CAPEX of $550/kW.

The dependence of these studies on assumptions that are unrealistically pessimistic suggests that their conclusions regarding the cost-effectiveness of hourly matching should be questioned. The models themselves are sound, but key assumptions used in each case are outliers. When these studies' unrealistically pessimistic capital cost and electricity supply assumptions, respectively, are replaced with more reasonable and generally accepted values, **both the Wood Mackenzie and Rhodium models support the conclusion that hydrogen production is economically viable when the Three Pillars accounting standard is applied.**

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Funding: This work was supported by the Princeton University Zero-Carbon Technology Consortium, which is funded by gifts from Breakthrough Energy, ClearPath, GE, and Google.

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