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Zero-carbon Energy Systems Research and Optimization Laboratory

RESEARCH DIGEST

Minimizing emissions from grid-based hydrogen production in the United States

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Executive Summary

- **Depending on its implementation, the Inflation Reduction Act's low-carbon hydrogen production tax credit (45V) could directly incentivize large *increases* in electricity grid CO_2 emissions.**
- **Embodied emissions from grid-connected hydrogen electrolysis could be multiple times worse than conventional 'grey' hydrogen.**
- **Requiring hydrogen producers to procure carbon-free electricity matching their annual consumption *does not reduce emissions at all*.**
- **Requiring hourly matching of electricity consumption with *additional* and *physically deliverable* clean generation can minimize emissions from hydrogen production.**
- **An hourly matching requirement has only a small impact on the cost of hydrogen production.**

Context

Clean hydrogen has been proposed as a solution to many of the challenges of economy-wide decarbonization, with potential use cases in industry, agriculture, transportation, and energy storage. With the passage of the Inflation Reduction Act, the United States introduced robust new subsidies for domestic production of clean hydrogen, including a production tax credit (PTC) of up to $3 per kilogram of hydrogen produced at an embodied emission rate less than 0.45 $kgCO_2e/kgH_2$.

However, the question of how hydrogen's embodied emissions will be calculated under this law has yet to be fully answered. Upcoming guidance from the US Treasury and IRS will determine the conditions under which hydrogen produced in the United States can qualify for the PTC subsidy, including whether producers can count input power sourced from the grid as 'clean' by purchasing certificates for clean electricity. **As our research demonstrates, this decision will be incredibly consequential in its emissions impact.** In fact, a poor implementation of this supposedly clean subsidy **would likely *increase* carbon emissions in the US by a substantial amount** by enabling direct use of fossil-fired electricity inputs and failing to drive additional clean generation to compensate this. However, with the proper requirements in place, it is possible to ensure that grid-based hydrogen producers achieve the same effective emissions rates as those using only on-site clean power.

Princeton University's Zero-carbon Energy systems Research and Optimization Laboratory conducts research to improve decision-making and accelerate rapid, affordable, and effective transitions to net-zero carbon energy systems. The ZERO Lab improves and applies optimization-based modeling tools and methods to understand complex macro-scale energy systems and uses these tools to evaluate and optimize emerging low-carbon energy technologies and generate decision-relevant insights to guide national and sub-national jurisdictions in transitioning to net-zero emissions energy systems. Prof. Jesse D. Jenkins is the Principal Investigator. For more, see http://zerolab.princeton.edu

Methods

Our study, summarized briefly in this research digest, uses the GenX electricity system optimization model to assess the mid-term impact of the clean hydrogen production tax credit on electricity system CO_2 emissions in the US. We model cost-optimal electricity system buildout from the present day through 2030 using a six-zone representation of the US Western Interconnection (Figure 1). Both capacity investment decisions and hourly operations are optimized, and are subject to the same economic and physical constraints that govern real-world electricity markets. We add hydrogen electrolyzers to individual model zones, allowing these to optimize their operations based on local electricity prices and PTC production incentives. We then measure changes in system-level emissions outcomes relative to a baseline case with no electrolyzer deployments. Using the total observed change in emissions and the total amount of hydrogen produced, we calculate the 'consequential emissions rate' of hydrogen production in the system. We calculate and report both emissions rates and hydrogen production costs under a range of possible implementations of the production tax credit, illustrating the impact of these policy choices on real-world outcomes of interest.

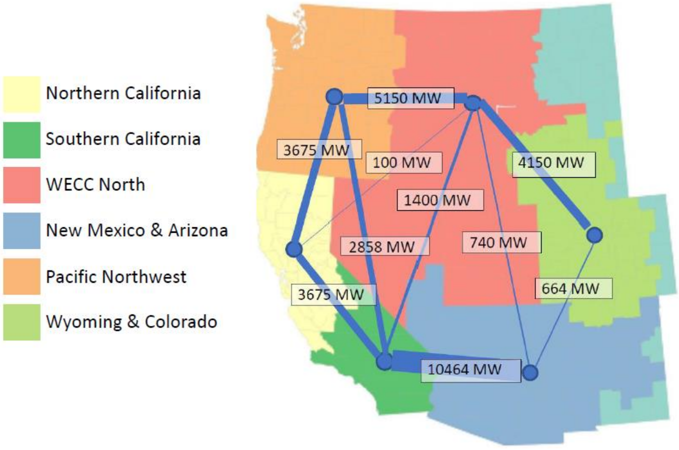

Figure 1: The six-zone representation of the US Western Interconnection grid used in our study, including existing interregional transmission capacity.

Findings

Without strong guardrails, subsidized hydrogen production could drive significant increases in emissions from the US electricity system. With a PTC subsidy of $3/kgH$_2$ and no requirements for clean electricity procurement, hydrogen production in the US grid would be expected to drive 15-40 kg of CO_2 emissions per kilogram of hydrogen produced (Figure 2). These emissions rates are far higher than the 0.45kgCO_2/kgH_2 legal threshold for PTC qualification, and even higher than the emissions rate from fossil-based 'grey' hydrogen production, which stands at roughly 10 kgCO_2/kgH_2.

A large PTC incentivizes near-constant operation of electrolyzers. At typical hydrogen sales prices, running an electrolyzer only makes economic sense when electricity prices are low. Low electricity prices are typically correlated with high generation from clean resources, leading to naturally low emissions intensities from hydrogen production. However, with a $3/kg PTC, hydrogen production becomes profitable even when high-cost fossil power plants are setting electricity prices. This strong production incentive leads to near-constant electrolyzer operation and large potential emissions impacts (Figure 4). The PTC also creates effectively unlimited demand for hydrogen at a $3/kg price floor, incentivizing continued production even when there would not naturally be enough demand to merit it.

Requiring hydrogen producers to purchase renewable energy certificates (RECs) or sign clean power purchase agreements (PPAs) matching their total annual electricity consumption does nothing to reduce real emissions rates. Traditionally, corporate emissions accounting standards in the US have allowed organizations to claim use of zero-carbon electricity by purchasing RECs or signing clean PPAs representing clean generation equal to their total annual consumption. We find that allowing hydrogen producers to claim low emissions intensities and qualify for the PTC using this approach would lead to real emissions intensities identical to the worst-case scenario described above (Figure 2).

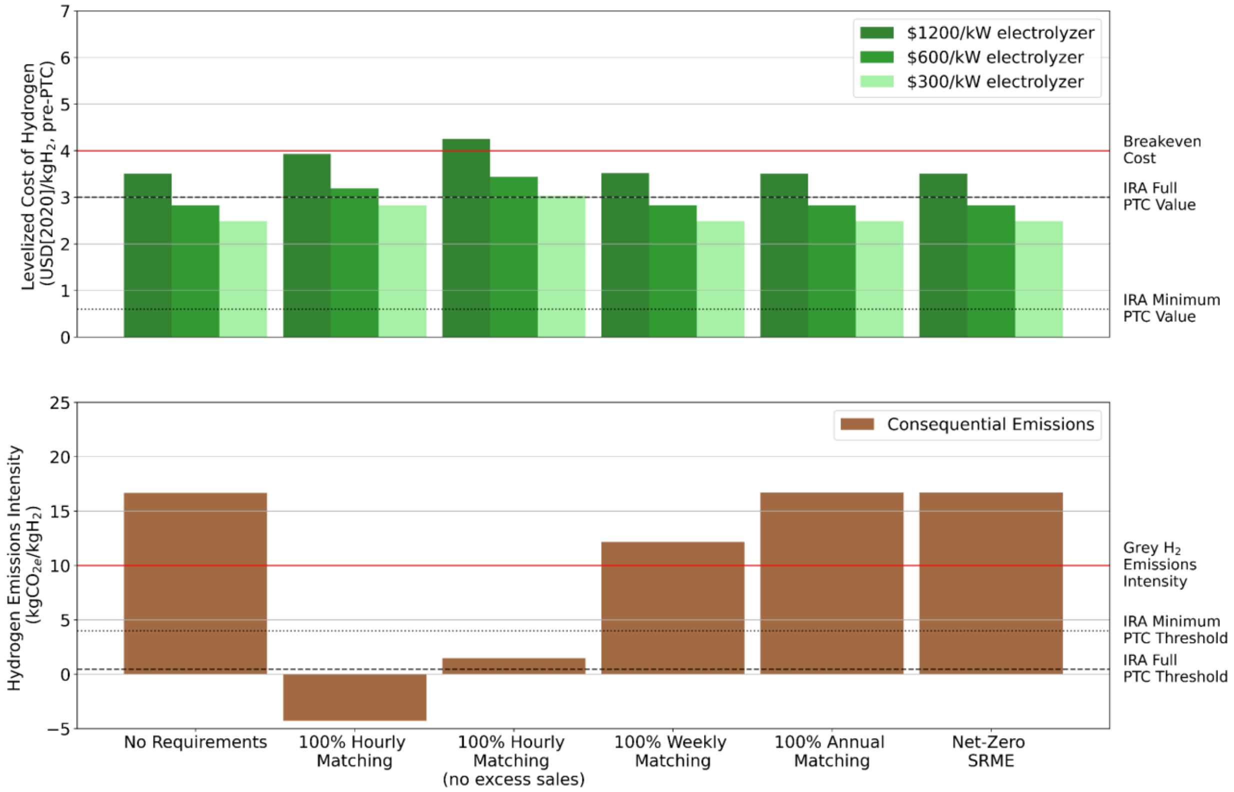

Figure 2: Cost (top) and emissions (bottom) outcomes from grid-connected hydrogen production in the US Pacific Northwest under multiple possible implementations of the clean hydrogen PTC (columns left to right). Emissions impacts are high when no clean energy procurement requirements are placed on hydrogen producers, and are eliminated by an hourly matching requirement. Other policies are ineffective at reducing real emissions. Meanwhile, hourly matching increases the overall cost of hydrogen production by 0.2-0.5 $/kg.

Annual matching is ineffective because it can be achieved without increasing the supply of clean generation in the electricity system. Subsidies for clean electricity resources in the Inflation Reduction Act lead to clean generation in 2030 far exceeding the levels mandated under state policies in the western US. The supply of RECs and clean PPAs will therefore naturally exceed the demand for these clean attributes, meaning that clean attribute demand from hydrogen producers can be met without bringing any additional clean generators online. In practice, a hydrogen producer in California could run their electrolyzer 24/7, inducing additional fossil generation during nighttime periods when local renewable generation is low, and still meet an annual matching requirement by acquiring excess RECs from solar plants that would have been built regardless (Figure 4).

Requiring *hourly* matching of electrolyzer electricity consumption with clean generation can minimize hydrogen's emissions impact. Granular time matching, on an hourly or shorter basis, ensures that an electrolyzer consumes no more electricity than is being concurrently injected into the grid by a procured clean resource. Because the net electricity demand (i.e. consumption minus procured clean generation) from electrolysis is never positive in this scenario, fossil generators are never required to generate more than they otherwise would have. Hourly matching can eliminate real emissions from hydrogen production in scenarios where other approaches cannot (see Figure 2). However, moving to less granular time matching requirements, e.g. weekly matching, quickly eliminates any emissions benefits.

***Deliverability* must be required for hourly matching to be effective.** In order to realize the emissions benefits of hourly matching, procured clean electricity must be physically deliverable in the hour in which it is claimed from the point of generation to point of consumption. Effectively, this means that the transmission pathways between these two points in the grid must not be congested. If congestion is present, the electrolyzer's electricity demand will necessarily be met by local fossil plants rather than by the non-deliverable clean resource.

***Additionality* (to the extent feasible) must be required for hourly matching to be effective.** When a hydrogen producer creates additional electricity demand, they must also contribute additional clean supply (beyond what would have existed otherwise) to truly have a low emissions impact. This condition can be enforced by requiring that clean electricity procured for hydrogen production come either from new clean resources, or from existing ones that would have otherwise been forced to retire. Allowing existing resources (not at risk of retirement) to qualify completely eliminates the emissions benefits of an hourly matching requirement (Figure 4). Unfortunately, we found that there are also certain scenarios in which true additionality can never be fully guaranteed. If a specific high-quality and limited (i.e. 'irreplaceable') renewable resource is developed for hydrogen production when it would otherwise have been used to decarbonize the grid, even hourly-matched hydrogen production using this resource can be said to have a non-zero emissions impact. This outcome is possible for any form of electrolysis, whether it is connected directly to a renewable resource or hourly-matched through the grid. Therefore, while a requirement for hourly matching with deliverability and *enforceable* additionality can minimize emissions from hydrogen production, neither it nor any other implementation of the PTC can guarantee zero emissions impact.

Additionality, deliverability, and hourly matching ensure that grid-based hydrogen production is on a level playing field with behind-the-meter production. In a behind-the-meter electrolysis facility, electrolyzers are powered directly by on-site clean generation. These facilities use 100% clean power by definition, but can only run their electrolyzers when the specific clean resources built to supply the facility are generating. Additionality, deliverability, and hourly matching requirements place these same constraints on grid-based hydrogen production facilities, and thereby ensure effectively identical emissions outcomes and a level economic playing field.

Requiring additionality, deliverability, and hourly matching does not significantly increase the cost of hydrogen. As shown in Figure 2, the cost of hydrogen produced under an hourly matching requirement is not significantly greater than the cost when enforcing no requirements at all. Across all modeled regions, we find that the increase in cost from enforcing robust requirements is typically less than \$1/kg, and often much lower. Even at current electrolyzer costs (~\$1200/kW), grid-based hydrogen production with an hourly matching requirement is likely to be profitable in most regions of the country.

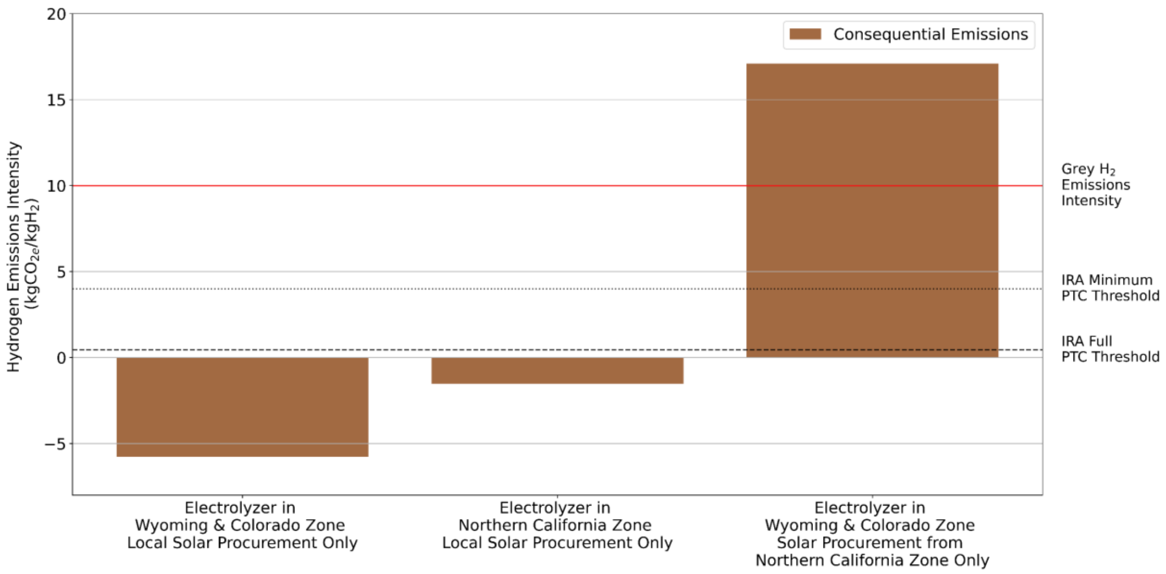

Figure 3: The impact of deliverability on hydrogen emissions outcomes. When an electrolyzer is run using hourly-matched local solar power in either the Wyoming & Colorado zone or the Northern California zone, real emissions impacts are negative. However, when an electrolyzer in Wyoming & Colorado is run using hourly-matched solar power sourced from Northern California, the emissions impact is very large. Transmission congestion between the two zones prevents delivery of this solar power in some hours, forcing the electrolyzer to rely on local fossil resources instead.

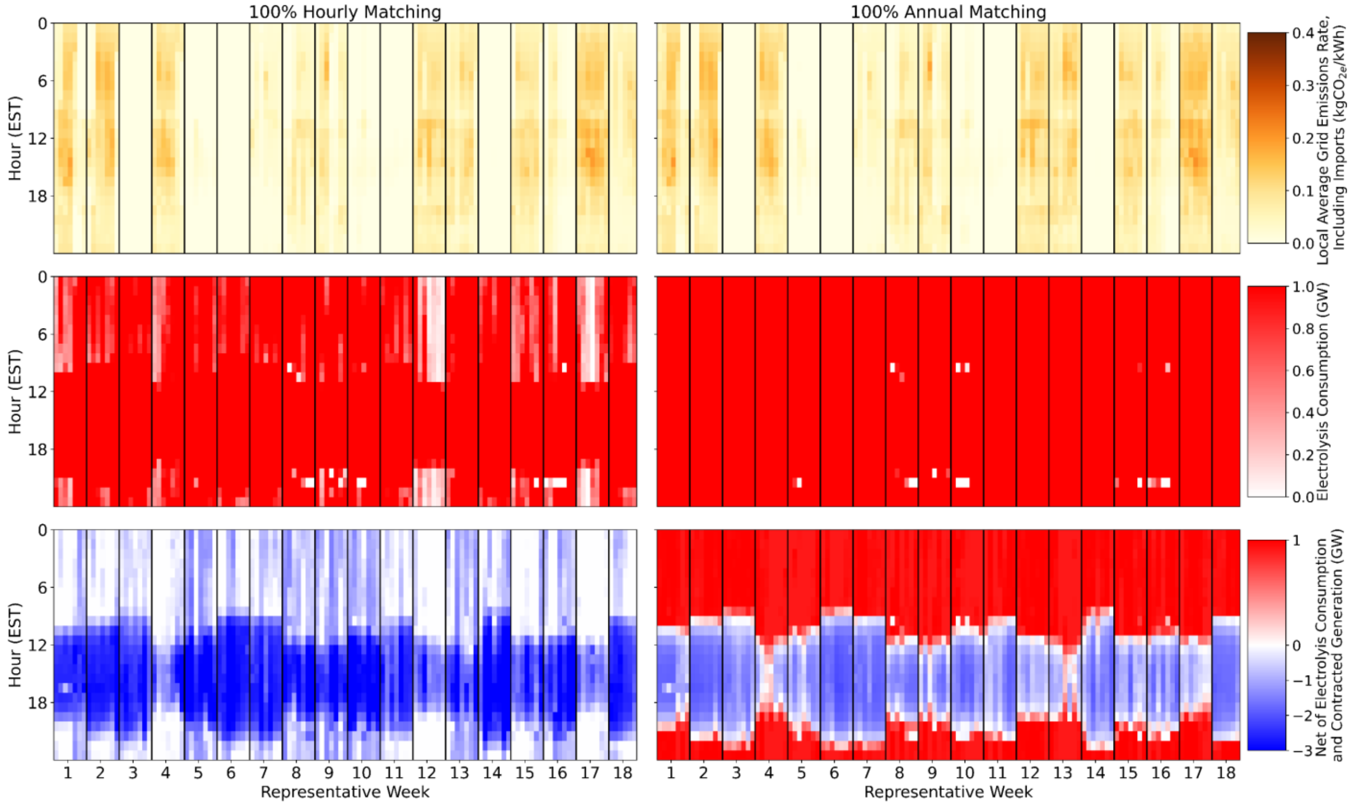

Figure 4: Time series data showing hourly grid emissions rates (top), electrolyzer utilization (middle), and electrolyzer utilization minus procured clean generation (bottom), for hourly-matched and annual matched hydrogen production in the Pacific Northwest model zone. In the annual matched case, the electrolyzer runs nearly constantly, and frequently uses more power than is being generated by its procured clean resources. It meets the annual matching requirement by procuring more solar power during the day than it is using. In the hourly-matched case, the electrolyzer must never consume more power than is being concurrently produced by its procured clean resources. It meets this requirement by procuring a more diverse mix of wind and solar power, and occasionally reducing its consumption when neither of these are available.

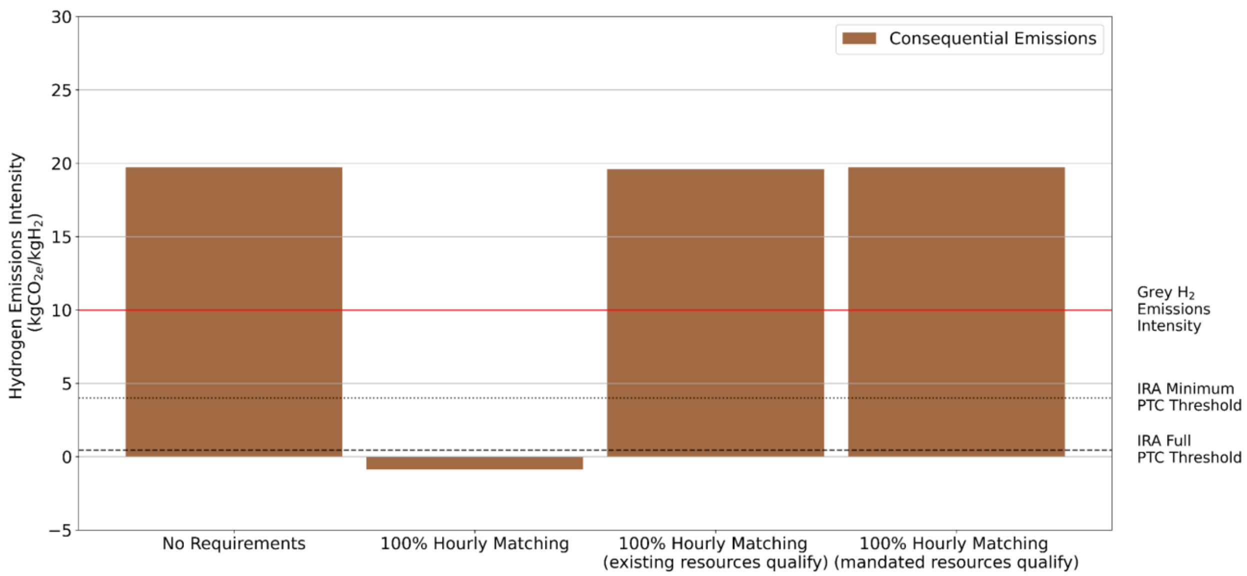

Figure 5: The impact of additionality on hydrogen emissions outcomes. When an electrolyzer is allowed to meet an hourly matching requirement using demonstrably non-additional resources, like existing generators (not at risk of retirement) or those mandated for deployment under state policies, emissions outcomes are identical to the worst-case scenario.

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