EARTHJUSTICE

February 23, 2024

U.S. Department of the Treasury, Internal Revenue Service
Office of Tax Policy
Ben Franklin Station
P.O. Box 7604, Room 5203
Washington, DC 20044
Submitted via www.regulations.gov, IRS-2023-0066

Re: Docket IRS-2023-0066, Section 45V Credit for Production of Clean Hydrogen

Over the past year, analysis by a broad range of experts and stakeholders has shown the importance of rigorous guidelines for implementing Internal Revenue Code Section 45V's clean hydrogen production tax credits. On a high level, appropriate Treasury Department guidance will require sound carbon accounting practices, so that taxpayers can only claim credits for producing hydrogen whose climate impacts actually meet statutory thresholds. Without appropriate guidance, taxpayers could claim hundreds of billions of dollars for producing hydrogen in a manner that exacerbates the climate crisis, increases health-harming pollution, and harms consumers by driving up electric rates.

To inform the Treasury Department's decisions on implementing Section 45V, I have attached the following documents:

- EPRI and GTI Energy, Impacts of IRA's 45V Clean Hydrogen Production Tax Credit (Nov. 2023) – Attachment A;
- Evolved Energy Research, 45V Hydrogen Production Tax Credits: Three-Pillars Accounting Impact Analysis (June 2023) – Attachment B;
- Wilson Ricks, Qingyu Xu, and Jesse Jenkins, Minimizing emissions from grid-based hydrogen production in the United States, Environmental Research (Jan. 2023) – Attachment C;
- Wilson Ricks and Jesse Jenkins, The Cost of Clean Hydrogen with Robust Emissions Standards: A Comparison Across Studies (Apr. 19, 2023) – Attachment D;
- Tim Schittekatte, et al, Producing hydrogen from electricity: how modeling additionality drives the emissions impact of time matching requirements (May 10, 2023) – Attachment E;
- Dan Esposito, Eric Gimon and Mike O'Boyle, Energy Innovation, Smart Design of 45V Hydrogen Production Tax Credit Will Reduce Emissions and Grow the Industry (Apr. 2023) – Attachment F;

- Julie McNamara, Biomethane Threatens to Upend the Clean Hydrogen Tax Credit (May 25, 2023) – Attachment G;
- Jeff St. John, The biomethane boondoggle that could derail clean hydrogen, Canary Media (Sept. 11, 2023) – Attachment H;
- Letter to Secretary Yellen Re: Implementation criteria for the Section 45V hydrogen tax credit related to methane leakage, treatment of Biomethane, and hydrogen emissions (June 13, 2023) – Attachment I;
- Letter from coalition of consumer advocates to Mr. Podesta, Deputy Secretary Adeyemo, Assistant Secretary Batchelder, and Mr. Hanlon (Oct. 26, 2023) – Attachment J;
- Letter from coalition of environmental and hydrogen industry groups Re: Implementation of the IRA 45V clean hydrogen tax credits as it relates to guidelines for emissions accounting of grid-connected electrolyzers (Feb. 23, 2023) – Attachment K;
- Letter of EDF Renewables, EDP Renewables, Intersect Power, and Leeward Renewable Energy to Secretary Yellen (July 18, 2023) – Attachment L;
- Letter of companies in the hydrogen industry to Secretary Batchelder, Mr. Hanlon, Mr. Paul, Mr. Podesta, Mr. Zaidi, and Secretary Granholm (June 15, 2023) – Attachment M;
- Clean Air Task Force and Natural Resources Defense Counsel letter Re: Notice 2022-49 (Apr. 10, 2023) – Attachment N;
- Environmental coalition letter to Mr. Podesta and Mr. Zaidi (June 16, 2023) – Attachment O;
- Leah Stokes, Before We Invest Billions in This Clean Fuel, Let's Make Sure It's Actually Clean, New York Times (Apr. 14, 2023) – Attachment P;
- Letter of eight U.S. senators to Secretary Yellen and Climate Counselor Zindler (Oct. 16, 2023) – Attachment Q;
- Letter of five U.S. senators to Commissioner Werfel (May 25, 2023) – Attachment R;
- Letter of members of the Green Hydrogen Catapult to Assistant Secretary Batchelder, Mr. Hanlon, Mr. Paul, Mr. Podesta, Mr. Zaidi, and Secretary Granholm (Nov. 6, 2023) – Attachment S;
- Letter to Secretary Granholm from environmental and environmental justice organizations (June 5, 2023) – Attachment T.

Respectfully submitted,
Sara Gersen
Senior Attorney, Clean Energy
Earthjustice

Attachment A

LCRI LOW-CARBON RESOURCES INITIATIVE

EPRI

GTI ENERGY

WHITE PAPER

Impacts of IRA's 45V Clean Hydrogen Production Tax Credit

THE LOW-CARBON RESOURCES INITIATIVE

This report was published under the Low-Carbon Resources Initiative (LCRI), a joint effort of EPRI and GTI Energy addressing the need to accelerate development and deployment of low- and zero-carbon energy technologies. The LCRI is targeting advances in the production, distribution, and application of low-carbon energy carriers and the cross-cutting technologies that enable their integration at scale. These energy carriers, which include hydrogen, ammonia, synthetic fuels, and biofuels, are needed to enable affordable pathways to economy-wide decarbonization by mid-century.

For more information, visit www.LowCarbonLCRI.com.

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EXECUTIVE SUMMARY

Hydrogen and low-carbon fuels could play important roles in reaching economy-wide net-zero emissions, especially for applications in industry, transport, and energy storage. The Inflation Reduction Act (IRA) contains novel production tax credits for clean hydrogen (45V), which depend on the life-cycle emissions intensity of hydrogen production. This complexity raises questions about impacts of 45V tax credits on hydrogen production and emissions, which also depend on the assumed cost and performance of hydrogen production technologies, power sector responses, and hydrogen demand.

Our analysis uses EPRI's US-REGEN model to understand potential impacts of the 45V subsidy on hydrogen supply and demand, emissions, electricity generation, and fiscal costs under scenarios that vary qualification criteria and the scope of the demand response for hydrogen. Scenarios varying the criteria for qualified generation used for electrolytic hydrogen production are based on three "pillars," which refer to requirements for hourly temporal matching, additionality or use of new resources, and local deliverability. We expand the literature on 45V impacts by using a full energy systems model—encompassing fuel production, transport, storage, and use—to capture hydrogen demand feedbacks outside of the power sector as well as the dispatch dynamics of grid-connected electrolysis.

Impacts on Hydrogen Production: The analysis indicates that 45V credits could lead to significant deployment of electrolytic hydrogen, even with more stringent qualification criteria including hourly matching of zero-carbon electricity generation and electrolysis production.

- 45V tax credits could cover around 90% of electrolytic hydrogen production costs in the most favorable cases (e.g., high-quality wind resource regions with lower electrolysis capital costs), and around 40% of production costs in the most expensive configurations.
- 45V subsidies could lead to significant deployment of new hydrogen production from electrolysis, ranging from 13–24 MtH_2 annually by 2035 (compared with about 10 MtH_2 of production today, which is largely from conventional steam methane reforming). Scenarios with less stringent certification criteria generally have greater hydrogen deployment and tax credit uptake.
- Based on scenarios that include only current state and federal policies and incentives, electrolytic hydrogen production peaks in 2035 and declines thereafter, given the expiration of the tax credits and return to unsubsidized price levels. Production in the post-subsidy period depends on the future policy environment and company goals, as net-zero targets could create additional incentives for low-carbon hydrogen.
- 45V-induced hydrogen demand is largely for electric generation and blending into existing natural gas pipelines, which are flexible demands that can be reversed if incentives change after tax credits expire. Converting electricity to hydrogen and back to electricity incurs roundtrip losses of around 65%, which has impacts on clean electricity demand and emissions.

Emissions Implications of Qualification Rules: Net effects of 45V on economy-wide emissions depend on qualification criteria.

- Depending on the qualification criteria for input generation, 45V can lead to a net decrease or a net increase in economy-wide CO_2 emissions during the subsidy period, relative to a scenario without 45V credits (Figure ES-1).
- All three qualification pillars—hourly temporal matching, use of new generation resources, and local deliverability—are required to ensure net economy-wide CO_2 reductions from 45V across all scenarios during the subsidy period. Scenarios with only annual matching can lead to similar or slightly lower emissions than without 45V, depending on assumptions about hydrogen demand. When the qualification criteria allow existing zero-carbon resources, emissions increase relative to the No 45V case, and increase further when deliverability is not required. With less stringent criteria, emissions from additional electricity generation to power electrolysis are larger than emissions reductions from displaced conventional hydrogen production and end-use fossil fuel consumption.

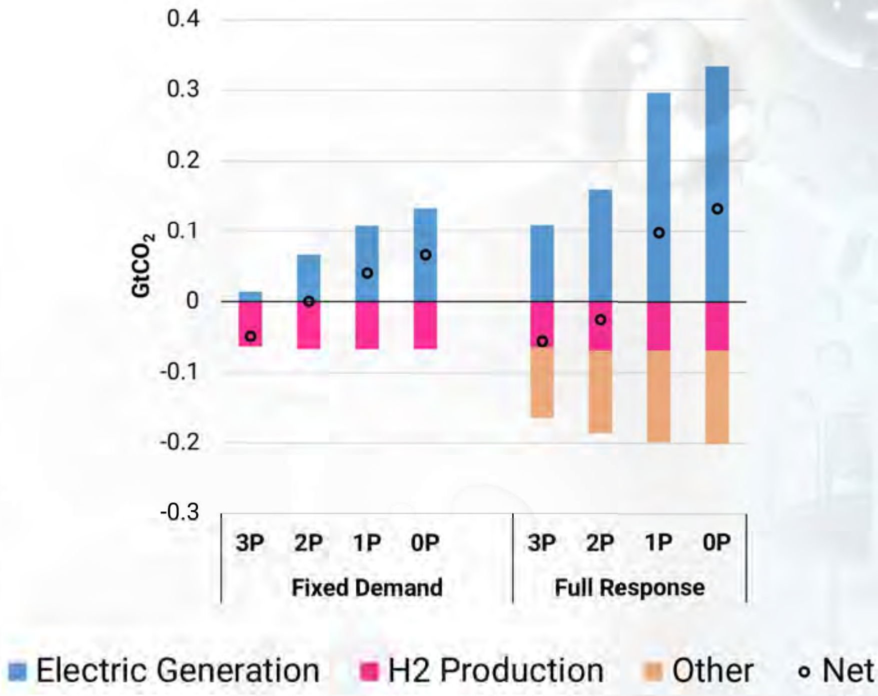


Figure ES-1. *Change in 2035 CO_2 emissions in hydrogen demand scenarios vs. No 45V Case, assuming different qualification criteria. 3P includes requirements for hourly matching, new clean generation, and deliverability; 2P removes hourly matching; 1P removes hourly matching and new generation requirements; and 0P removes all three pillars. Fixed Demand assumes no incremental non-electric hydrogen demand, while Full Response includes non-electric demand feedbacks.*

- Scenario differences in the net emissions impact are due to the gap between the actual change in generation (or "consequential") and attributed generation nominally designated for qualification, which becomes larger as qualification criteria are relaxed. Less stringent criteria lead to more natural gas-fired generation despite all nominally attributed generation coming from zero-carbon resources. Even with the most stringent "three pillar" criteria (including requirements for hourly matching, new clean generation, and deliverability), the emissions intensity of incremental electricity generation is greater than zero, though these increases in electric sector CO_2 are more than offset by reductions in CO_2 from hydrogen production.
- After the subsidy period, CO_2 emissions are slightly lower than in the baseline without 45V in all cases, because some remaining electrolysis continues to displace non-electric production, and because the induced build-out of wind and solar during the 45V subsidy period leads to slightly greater installed capacity levels afterwards.

Fiscal Expenditures and Abatement Costs: 45V credits could entail cumulative fiscal costs of $385-756 billion and $750/t-$CO_2$ reduced.

- 45V credits may have cumulative fiscal costs of $386 to $756 billion (in real 2022 dollar terms), although only 13–25% of this cost occurs during the 10-year budget period ending in 2032.
- The net increase in uptake of other IRA incentives as a result of 45V could add cumulative fiscal costs of $90 to 176 billion.
- These high fiscal costs and modest emissions reductions under the three pillars scenarios indicate very high fiscal outlays per tonne of CO_2 reduced for IRA's 45V hydrogen tax credits, which can exceed $750/t-$CO_2$. These costs are approximately an order-of-magnitude higher than the implied abatement costs of other IRA credits.
- Tax credits are aimed not only at reducing emissions but also at encouraging technological change and providing operational experience for hydrogen production, transport, storage, and use. Such experience can contribute to buying down learning curves so that low-emitting hydrogen is ready to deploy when needed as the economy approaches net-zero levels, as illustrated in EPRI's Net-Zero 2050 report (Blanford, et al., 2022).

Several factors beyond 45V tax credits could influence future hydrogen and use:

- **Hydrogen hubs:** $7 billion for the Regional Clean Hydrogen Hubs program as part of the Bipartisan Infrastructure Law (the seven selected projects across the country were announced in October 2023).
- **Company targets:** Company net-zero targets may mean that purchasers have a greater willingness-to-pay for hydrogen that meets stringent certification criteria, perhaps going further than qualification criteria for 45V. This research indicates that the cost premium of hourly matched hydrogen production is relatively small ($0.1-0.2/kgH_2$) for good wind and solar resource locations.

LIST OF ABBREVIATIONS

0P	Scenario that relaxes qualification criteria for the $3/kgH_2$ 45V credit, allowing annual-matched, existing/new zero-carbon resources anywhere in the U.S.
1P	Scenario that allows both annual matching and existing zero-carbon resources, enforcing only the deliverability pillar
2P	Scenario where additionality and deliverability pillars are enforced, but only annual matching is required
3P	Scenario where all three pillars for 45V credits are enforced (temporal matching, additionality, and deliverability)
45Q	Inflation Reduction Act tax credit for captured CO_2
45V	Inflation Reduction Act clean hydrogen production tax credit
45Y	Inflation Reduction Act clean electricity production tax credit
48E	Inflation Reduction Act clean electricity investment tax credit
111	Section 111 of the Clean Air Act new and existing source performance standards
CCS	carbon capture and storage
CO_2	carbon dioxide
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
GHG	greenhouse gas
GW	gigawatt
H2	hydrogen
IRA	Inflation Reduction Act of 2022
ITC	investment tax credit
kg	kilogram
kW-e	kilowatt-electric
LHV	lower heating value
MISO	Midcontinent Independent System Operator
MMBtu	one million British thermal units
Mt	million metric tonnes
NPV	net present value
PJM	PJM Interconnection
PTC	production tax credit
SMR	steam methane reforming
SPP	Southwest Power Pool
US-REGEN	U.S. Regional Economy, GHG, and Energy
ZERC	zero-emissions resource credits

INTRODUCTION

Hydrogen and low-carbon fuels could play important roles in reaching economy-wide net-zero emissions, especially for applications in industry, transport, and energy storage where other low-emitting options are more limited or costly. For instance, modeling of economy-wide net-zero CO_2 pathways in the U.S. by 2050 concluded that, "Hydrogen's use as a low-carbon fuel is projected to increase, whether through fuel cell vehicles, blending with the natural gas supply to support needs in buildings, or through direct use for process heating in industries" (Blanford, et al., 2022). Deployment of hydrogen and hydrogen-derived fuels are larger when carbon removal and carbon capture are limited, which increases electrolytic hydrogen production, fuels synthesis from hydrogen and biogenic carbon, and direct use for medium- and heavy-duty vehicles and high-temperature process heat.

The Inflation Reduction Act (IRA) signed into law in August 2022 includes many subsidies for deployment of a wide range of clean energy technologies, as well as incentives for development of domestic supply chains and investment in under-served communities. It is projected to have significant impacts on both emissions and fiscal expenditures (Bistline, et al., 2023; Bistline, Mehrotra, Wolfram, 2023). Among the key measures are expanded and increased tax credits for wind and solar power generation, nuclear energy, battery storage, carbon capture, electric vehicle adoption, domestic clean energy manufacturing, and building efficiency and electrification.

One of the most complex elements of the IRA is the 45V production tax credit for clean hydrogen. This incentive is substantively different than most other IRA incentives in several important ways:

- It is entirely new. While many other IRA incentives build upon existing subsidies and programs, there has been no previous federal policy support in the U.S. for hydrogen production.
- The magnitude of the 45V credit depends on a life-cycle greenhouse gas (GHG) emissions assessment. Most other IRA incentives are directly tied to a specified activity, such as investment in a qualified technology, which is more straightforward to define and verify. For 45V, the level of subsidy depends on the GHG intensity of its supply chain, which introduces definitional ambiguity and enforcement challenges.
- The magnitude of the 45V subsidy relative to production costs is potentially much larger than for any other IRA incentive. In particular, the highest tier of \$3 per kgH_2, which is likely available only for electrolytic hydrogen (i.e., produced using electricity and water as inputs), could cover up to 90% of levelized production costs in some cases, while credits for solar and wind, for example, could offset 30% of levelized costs. Moreover, the electrolytic production pathway is also the most complex to assess from a life-cycle GHG perspective and raises broader questions about emissions attribution from interventions that alter grid operations and investments.
- The significant electricity consumption of electrolytic hydrogen production could—depending upon how the program is implemented—potentially lead to emissions increases relative to a counterfactual without hydrogen tax credits.

As with other IRA tax credits, there is no budgetary limit on 45V uptake, implying that fiscal costs are uncapped under the law. For all of these reasons, the introduction of 45V has generated a flurry of commercial interest, analysis, and public scrutiny of the details.[1] Implementation guidance from the Treasury Department has been delayed until at least October 2023, extending the debate and the window of opportunity for further clarification of the issues. These questions extend beyond 45V tax credits, given how guidelines related to these credits could influence state emissions standards, EPA rules (e.g., the proposed power plant regulations under Section 111 of the Clean Air Act), trade policy, and other areas where low-emitting hydrogen plays a role. Beyond hydrogen, guidelines for these tax credits raise broader questions about emissions attribution from interventions that alter grid operations and investments, including end-use electrification, energy efficiency, direct air capture, and electricity-derived fuels.

In this paper, we present a quantitative analysis of the potential impacts of the 45V subsidy under alternative implementation scenarios. We first review the literature of other studies examining 45V impacts. We then provide an overview of the structure of the 45V incentive as specified in the IRA and illustrate the implications for non-electric hydrogen production technologies (e.g., conventional production from natural gas and the potential for carbon capture).

1 Summaries of existing analysis are found in the literature review section.

Next, we discuss the electrolytic hydrogen production pathway and highlight the key uncertainties and difficulties associated with estimating its cost and life-cycle emissions. Model results are first presented for a simple bounding case with dedicated zero-carbon electric generation for electrolytic hydrogen production. These results are expanded to integrated modeling scenarios with grid-connected electrolysis under various specifications of the qualification criteria. Finally, we discuss implications of 45V production incentives for hydrogen demand across the economy. We conclude with overall implications for hydrogen production volumes, emissions, and costs from 45V-induced investments.

LITERATURE REVIEW

Several recent modeling studies that investigate potential effects of hydrogen tax credits on emissions, cost, hydrogen production, and the power sector mix are summarized in Table 1. These studies vary in their geographic focus, sectoral scope, and scenario design. Our study is unique in several respects:

- **Regional variation:** Instead of focusing on a few regions, our analysis examines implications of 45V credits under 16 different regional circumstances. This breadth illustrates potential heterogeneity in regional resources, wind and solar resource potential, existing infrastructure, state policies, and other factors that may be important in understanding the economics of hydrogen supply and demand.
- **Economy-wide energy system modeling:** Most existing studies focus on the power sector and do not explicitly represent hydrogen demand endogenously. Such feedback between hydrogen demand and the power sector may be important for emissions effects of 45V credits.
- **Endogenous electrolyzer investment:** Unlike most other studies that assume fixed levels of electrolysis deployment, our analysis allows electrolyzer deployment to vary on a region- and scenario-specific basis and has endogenous sizing and dispatch of electrolyzers.

Discussions about requirements for hydrogen production to minimize emissions impacts often focus on three "pillars:"

- **Temporal matching:** Electrolytic H_2 production and qualifying electricity generation can be matched across different timeframes, including hourly and annually.
- **Additionality:** Electrolysis must have clean electricity supplied by new resources.[2]
- **Deliverability:** Electrolytic H_2 production occurs nearby qualifying electricity generation. Such geographical correlation or localization requirements also could help minimize grid congestion from these new loads.

Several research groups, companies, and environmental organizations wrote a letter to the Department of the Treasury in February 2023 and stated that, "Additionality, deliverability, and hourly matching are necessary to guard against negative consequences" (link). Recent studies in Table 1 investigate potential impacts of these requirements on emissions, costs, and other outcomes.

These studies provide conflicting guidance on the emissions implications of hourly matching requirements. Studies like Ricks, et al. (2023) indicate that, "requiring grid-based hydrogen producers to match 100% of their electricity consumption on an hourly basis with physically deliverable, 'additional' clean generation" can provide emissions rates "equivalent to electrolysis exclusively supplied by behind-the-meter carbon-free generation." In contrast, Olson, et al. (2023) find that CO_2 emissions can be lower with annual matching than with hourly matching for many regions and scenarios. Cybulsky, et al. (2023) illustrate how this discrepancy could be caused by modeling differences in additionality requirements. Their analysis distinguishes between "compete" frameworks—where H_2 and non-H_2 demand compete for new clean electricity generation—and "non-compete" ones—a more stringent definition of additionality that only considers low-emitting supply additional if it would not be deployed in a counterfactual without electrolysis. Cybulsky, et al. (2023) find in their Texas and Florida case studies that the consequential emissions effects under annual matching are significantly lower in the "non-compete" framework, which they argue is closer to "today's context" for many markets. Zeyen, et al. (2022) conclude that emissions differences decrease between annual and hourly matching requirements when the background electricity system has more low-emitting resources.

2 There are additional questions about whether all new clean supply would qualify as "additional" or just new resources that would not have been added without electrolytic hydrogen demand, about the eligibility of otherwise-curtailed generation from existing clean resources, and about whether generation from clean facilities that would have otherwise retired would be eligible. For this analysis, we define additional as new clean capacity.

One important limitation of the studies above is that many do not model hydrogen demand explicitly or capture emissions effects associated with reductions in fuels that hydrogen displaces. These effects could be important for comparing emissions under hourly matching vis-à-vis annual matching, especially if annual matching lowers production costs and consequently increases hydrogen demand relative to its applications with unsubsidized pricing.

Table 1. *Summary of recent modeling studies of hydrogen subsidies*

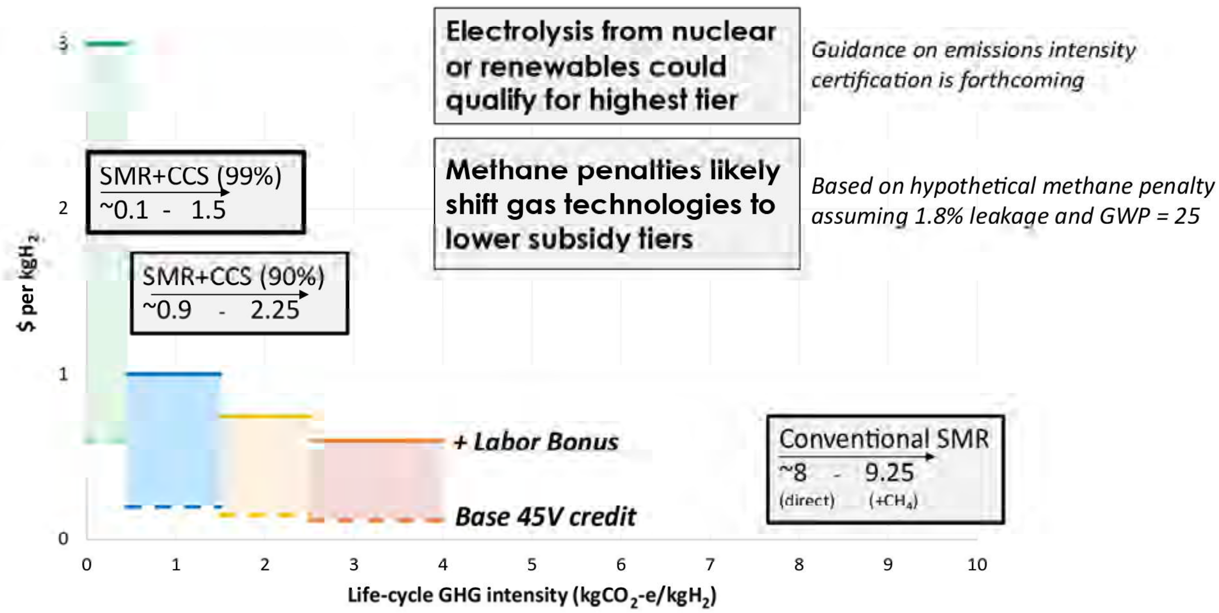
	THIS ANALYSIS	CYBULSKY, ET AL. (2023)	HH (2023)	OLSON, ET AL. (2023)	RICKS, ET AL. (2023)	ZEYEN, ET AL. (2022)
Region	16 U.S. regions	ERCOT, FRCC	27 U.S. regions	ERCOT, MISO, SPP, PJM	Western U.S.	Germany and neighbor countries
Time Horizon	2025 through 2050	2021	2024 through 2032	2025/2030	2030	2025/2030
Model Scope	Full energy supply and demand	Power sector and H_2 supply	Full energy supply and demand	Power sector and H_2 supply	Power sector and H_2 supply	Power sector and H_2 supply
Electrolyzer Investment	Endogenous	Exogenous	Endogenous	Exogenous	Exogenous	Exogenous
H_2 Demand	Endogenous, hourly demand	Constant hourly demand	Endogenous; exogenous sensitivity	Constant hourly demand[3]	No demand enforced	Constant hourly demand
H_2 Storage	Yes	Yes	Yes	No	No	Yes
Electric Sector Investments	Endogenous	Endogenous	Endogenous	Exogenous	Endogenous	Endogenous
Temporal Matching	HM with excess sales; AM	HM with excess sales; AM	HM without excess sales; AM	HM and AM with energy and emissions match	HM with and without excess sales; WM; AM	HM without excess sales and with 20%; MM; AM
Additionality Definition	Compete	Compete; non-compete	Compete	Non-compete	Compete	Non-compete
Deliverability	With/without requirements	With requirements	With requirements	With requirements	With requirements	With requirements

HM = hourly matching; WM = weekly matching; MM = monthly matching; AM = annual matching; HH = Haley and Hargreaves (2023)

3 Electrolysis load is assumed constant "except the top 10% highest priced hours" (Olson, et al., 2023).

45V STRUCTURE

The 45V incentive (§13204 in the IRA) is a production tax credit valued at $0.60/kgH₂ for life-cycle intensity of 2.5–4 $kgCO_2$-e/kgH_2, increasing on a sliding scale up to $3/$kgH_2$ for intensity below 0.45 $kgCO_2$-e/kgH_2 (Figure 1). Similar to other IRA incentives, these levels are conditional on prevailing wage and apprenticeship requirements; the credit values are 80% lower if these labor bonus criteria are not met. The credit values are also indexed to inflation, with the specified nominal values expressed in year 2022 dollars. The life-cycle GHG intensity of production is to be determined by ANL's GREET model, although guidance on the details of the assessment has not been released. Credits apply for projects that have commenced construction by the end of 2032 and continue for 10 years from project start. 45V clean hydrogen production credits can be combined with 45Y clean electricity production and 48E clean electricity investment credits, but cannot be combined with 45Q credits for carbon capture.



NB: Tax credits awarded for a period of 10 years for qualified projects

Figure 1. *Summary of IRA 45V Hydrogen Production Tax Credit.*

NON-ELECTRIC HYDROGEN PRODUCTION

The U.S. currently produces around 10 million metric tonnes (Mt) per year of hydrogen for non-energy uses in various industries, particularly as a feedstock for ammonia and fertilizer production and as a reactant to reduce sulfur in petroleum refining. Essentially all current domestic production uses a conventional steam methane reforming (SMR) process, where natural gas provides heat and feedstock hydrogen (along with water). The direct carbon emissions intensity from SMR hydrogen production is around 8 $kgCO_2/kgH_2$,[4] or roughly twice the threshold to qualify for the minimum 45V incentive. However, any life-cycle GHG intensity would likely include an accounting for methane emissions from upstream natural gas production, processing, and distribution. There is significant uncertainty and variation in estimates of gas-related methane emissions, as well as ambiguity of attribution in specific applications and translation to CO_2 equivalence. Using current median estimates of relevant parameters, upstream methane from SMR hydrogen production could account for an additional 1.25 $kgCO_2\text{-}e/kgH_2$.[5]

One option for low-carbon hydrogen is SMR production with carbon capture and storage (CCS). Based on input assumptions for EPRI's US-REGEN model, SMR+CCS production would have a direct CO_2 intensity of around 0.9 $kgCO_2/kgH_2$ with 90% capture and as low as 0.1 $kgCO_2/kgH_2$ with higher capture rates. Similarly, pyrolysis technologies convert methane to hydrogen using very high heat and produce a solid carbon waste stream with very low or zero direct CO_2 emissions. Still, any hydrogen production technology using natural gas would presumably be subject to upstream methane accounting, and the resulting adder (even if lower than current estimates due to future reductions in methane leakage rates) would likely preclude qualification for the lowest GHG intensity tier (below 0.45 $kgCO_2\text{-}e/kgH_2$). Thus SMR+CCS or pyrolysis technologies would likely only be eligible for the \$0.75 or \$1/kgH_2 subsidy tiers. This subsidy would be available for the first 10 years of project operation. Assuming a 40-year project lifetime, the actual reduction to the levelized hydrogen production cost, using 45V credits, would be lower at around \$0.41 to \$0.55/kgH_2.[6]

4 Based on US-REGEN input assumptions, the natural gas input to SMR is ~0.15 MMBtu per kgH_2, which based on 54 $kgCO_2$/MMBtu for the direct carbon content of natural gas translates to ~8 $kgCO_2/kgH_2$.

5 Assuming 1.8% for system-wide leakage rate of delivered gas and a 100-year global warming potential of 25.

6 Based on an assumed project life of 40 years and a discount rate of 7%, the discounted net present value (NPV) of the first 10 years of production represents roughly 55% of total project NPV.

Note that hydrogen production with SMR+CCS could alternatively claim the 45Q subsidy for captured carbon of $85/tCO$_2$, which translates to around $0.69 to $0.76/kgH$_2$.[7] The 45Q credit can be claimed for 12 years instead of 10 for 45V, resulting in a levelized reduction of $0.42 to $0.46/kgH$_2$ using this subsidy pathway. Thus, the 45Q and 45V incentives are roughly equivalent in magnitude for natural gas-based hydrogen production. Moreover, the value of either IRA incentive for SMR+CCS or pyrolysis is similar in magnitude to the cost premium for these technologies over conventional SMR production. Based on assumed costs for new capacity in US-REGEN, the estimated levelized hydrogen production cost for conventional SMR is around $1.07/kgH$_2$ and around $1.55/kgH$_2$ for SMR+CCS (both assuming a gas price of $3/MMBtu), suggesting a levelized cost premium of around $0.48/kgH$_2$.

The upshot of these observations is that the value of IRA incentives for SMR+CCS (and potentially pyrolysis) is similar in magnitude to the cost premium for these technologies over conventional SMR production. Hence, they could potentially motivate investments in carbon capture retrofits of existing plants or new capacity using CCS or pyrolysis, reducing the carbon footprint of the hydrogen production industry. However, this subsidy pathway would be unlikely to result in materially lower hydrogen production costs and thus unlikely to motivate additional investment in new applications using hydrogen to replace existing energy carriers (e.g., hydrogen fuel cell vehicles or hydrogen replacing natural gas for process heat or electric generation). At current fuel prices, and absent a carbon price or other policy-based adder on fossil fuel use, hydrogen as an energy carrier is generally not competitive.

45V can create an incentive for expanded deployment of hydrogen technologies, especially when it reduces the production cost of hydrogen lower than the cost from conventional SMR. One possible scenario for this to occur is through electrolytic hydrogen via zero-carbon electric generation, which would qualify for the highest 45V subsidy tier of $3/kgH$_2$.[8] This pathway is discussed in the subsequent section. In addition, company net-zero targets may mean that purchasers have a greater willingness-to-pay for low-carbon hydrogen, especially for companies with more limited or costly decarbonization options. 45V tax credits can help to reduce the magnitude of this cost premium, potentially encouraging greater investments.

ELECTROLYTIC HYDROGEN PRODUCTION

The production of hydrogen with electrolysis uses electric energy to separate hydrogen from water. In current market conditions, the electrolytic hydrogen pathway is for most applications much more expensive than conventional SMR. Although some electrolytic hydrogen production exists today, it operates at very small scales in the U.S., and the technologies are at an early stage of commercialization. There is significant promise for improvements in electrolysis capital cost with scale and learning, which translates to a broad range of uncertainty around cost projections for the near- and medium-term (Bedilion, et al., 2023). Complicating the picture further is the relationship between the source of the electric input and its cost. A simplistic representation might assume that an electrolytic hydrogen producer operated its capacity at a full constant load and paid a flat industrial price for electricity. While this setting might describe small-scale electrolysis activities today, it likely would not hold for a future market in which electrolysis is used for bulk hydrogen production. Even in today's market conditions, a producer could likely achieve lower costs by optimally dispatching the electrolyzer against a real-time wholesale price of electricity, absorbing a lower capacity factor but concentrating production in hours with lower electricity prices. This flexible operational model will only become more compelling as shares of variable renewable generation increase and will be especially salient in the context of aligning with qualified zero-carbon generation. On the other hand, opportunistic dispatch requires both operational flexibility, which may be limited with some electrolysis technologies (Motealleh et al., 2023), and hydrogen storage (Chiaramonte, 2023), whose costs and availability vary significantly by region.

7 A 90% capture rate implies roughly 8.1 kgCO$_2$ captured per kgH$_2$ produced. Up to 8.9 kgCO$_2$/kgH$_2$ could be captured with a 99% capture rate. These calculations are based on assumed LHV efficiency of 68% for SMR+CCS.

8 It may also be possible for hydrogen production from a biomass feedstock with carbon capture to qualify for the highest subsidy tier, depending on how biogenic carbon is treated in the life-cycle assessment. For this analysis we assume that the bio-hydrogen pathway does not qualify for the 45V incentive (Chiaramonte, 2023).

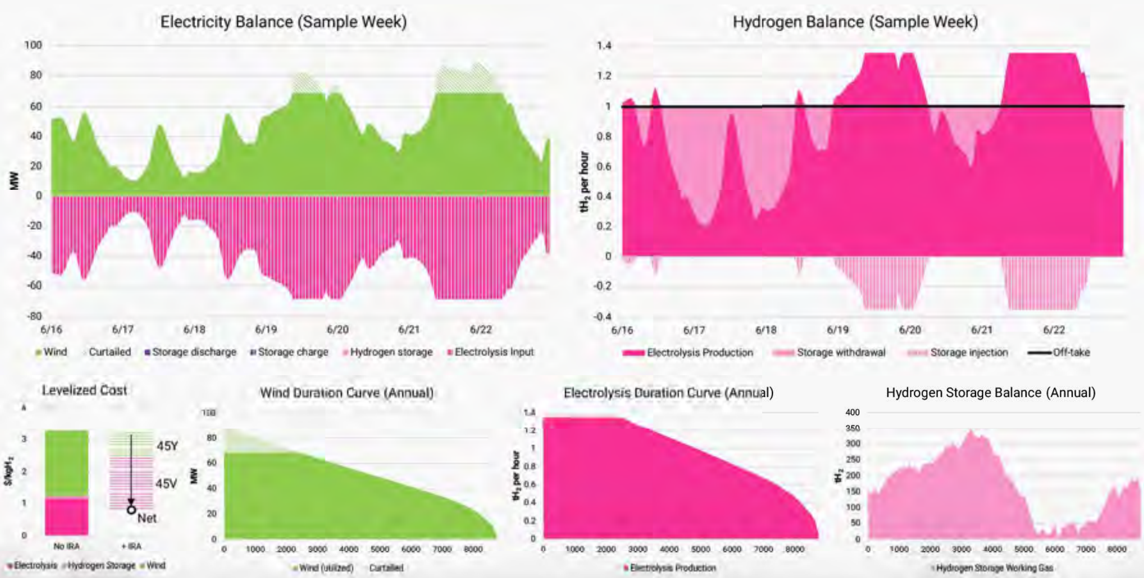
ELECTROLYSIS WITH DEDICATED GENERATION

To understand the costs of supplying electrolytic hydrogen production powered exclusively by zero-carbon generation, one approach is to model production with dedicated electric generation, i.e., not grid-connected. This configuration both ensures the life-cycle emissions qualification criteria for the 45V subsidy are met without ambiguity and is relatively straightforward to calculate based on assumptions for capital costs and resource profiles for a given location. In the context of variable generation from wind or solar, the calculation does require an optimization of the relative sizing of electrolysis, renewable generation capacity, batteries, and hydrogen storage. Analysis of this trade-off (see sidebar) shows that it is not optimal simply to set nominal electrolysis capacity equal to nominal renewable capacity and align hydrogen production exactly with renewable output. Instead, a lower average cost can be achieved by over-sizing renewable capacity relative to electrolysis capacity, causing some generation to be curtailed during periods of high output but increasing the capacity factor of the electrolyzer over the course of the year. In the case of solar generation, it is economic to include battery storage in the configuration as well. In all cases using variable renewable resources, some level of seasonal hydrogen storage is required to enable a constant delivery profile.

MODELING ELECTROLYTIC HYDROGEN PRODUCTION WITH DEDICATED ZERO-CARBON GENERATION

Optimal configuration of generation, storage, and electrolysis was calculated for each zero-carbon resource type (wind, solar, nuclear) in each of 16 U.S. regions with the objective of delivering a constant off-take profile for produced hydrogen. Assumptions for hourly regional resource shapes and technology cost and performance are based on US-REGEN inputs. Scenarios included a range of assumptions for electrolysis capital costs, with the high end at $2,800/kW-e corresponding to the results of a recent EPRI study (Kern and Mancuso, 2022) on current engineering-based estimates for total capital requirement for a central-scale PEM electrolysis plant. The default and lower costs of $1,400/kW-e and $700 kW-e correspond to projected cost declines from scale and learning over the 45V subsidy period.

This figure illustrates results for electrolysis production from dedicated wind generation in the Southwest Power Pool (SPP) region assuming default electrolysis capital costs and a nominal constant off-take of 1 tH_2 per hour. In the optimal configuration, nominal wind capacity is estimated to be 42% larger than the nominal electrolysis capacity, resulting in a 66% capacity factor for the electrolyzer and curtailment of 5% of wind. The levelized cost of hydrogen is $3.29/$kgH_2$ before accounting for IRA incentives, falling to around $0.80/$kgH_2$ including 45Y and 45V. 45Y offsets around 30% of the wind generation cost, while 45V more than offsets the electrolysis capital and non-electric operating costs. These costs for SPP wind represent the most favorable economics over all region/technology combinations in the U.S.



Modeling of hydrogen production with dedicated generation from wind, solar, and nuclear across regions of the U.S. indicates that without IRA incentives, the cost of electrolytic hydrogen production ranges from under \$3 to around \$7 per kgH_2. This range includes variation in the capital cost for electrolysis as well as regional renewable resources. The lowest production costs for zero-carbon resources obtain in Midwest regions using wind generation. Note that when the same modeling experiment is conducted with natural gas included as a generation option (again, without IRA production and investment incentives), a gas-fired combined cycle power plant is the lowest cost pathway overall for electrolytic hydrogen, at a cost of around \$2.50 per kgH_2 (assuming a gas price of \$3/MMBtu). However, this pathway is more costly and much less efficient than conventional SMR for producing hydrogen from natural gas. Accordingly, the direct carbon intensity of electrolysis from gas-fired combined cycle is approximately 16.9 $kgCO_2/kgH_2$, or roughly twice that of conventional SMR.[9]

Using these results as a benchmark, the same approach can be used to illustrate the impact of IRA incentives on the costs of electrolytic hydrogen production. **One key feature of the 45V hydrogen production subsidy is that it can be combined or "stacked" with the 45Y clean electricity production credit for zero-carbon generation, and with the 48E investment tax credit for storage and other zero-carbon technologies.** Examining first the impacts of 45Y and 48E alone (shown as "No 45V" in Figure 2), the dedicated generation model shows production costs for zero-carbon electrolytic hydrogen in the range of \$1.84 to \$5.63 per kgH_2. Moreover, the low end of the range, again corresponding to high-quality wind resource regions in the Midwest with low electrolysis costs, is below the cost of production using gas-fired combined cycle as the generation source (again assuming a \$3/MMBtu gas price), or roughly equivalent with reference electrolysis costs. The implication is that an adoption subsidy for electrolytic hydrogen (such as 45V) could potentially translate to increased renewable deployment based on 45Y and 48E incentives even without any explicit stipulations on the generation source. However, as the analysis in the subsequent section shows, the more likely outcome is some combination of wind and gas or other fossil, which might not result in a significant improvement below conventional SMR in terms of emissions intensity.

Finally, applying the dedicated generation model with 45V included alongside the other IRA incentives illustrates the potentially large relative magnitude of the subsidy. The range across regions, resources, and electrolysis capital cost uncertainty for the subsidized production cost of zero-carbon electrolytic hydrogen is \$0.20 to around \$4 per kgH_2. In other words, value of the subsidy (which translates to around \$1.64 per kgH_2 in levelized terms, accounting for a project investment life that exceeds the subsidy period of 10 years) **covers around 90% of production costs in the most favorable cases (high-quality wind resource regions with lower electrolysis capital costs), and around 40% of production costs even in the most expensive configurations.**

The dedicated generation scenario represents in a sense the most restrictive interpretation of the qualification criteria for the highest tier of the 45V subsidy. Even in such a setting, the results show that the subsidized costs of production could be significantly lower than conventional SMR, suggesting a potentially large impact on hydrogen deployment. Nonetheless, it is unlikely that physically separate production will be required to qualify electrolytic hydrogen as low- or zero-carbon. When the analysis is extended to consider the more plausible case of grid-connected electrolysis, the questions of how the qualification criteria are defined and implications for costs, emissions, and adoption become more complex. Additionally, an integrated economy-wide analysis is needed to assess the potential scale of incremental hydrogen demand resulting from 45V-subsidized production. The next section describes an analysis with the US-REGEN model of alternative 45V implementation scenarios.

9 Based on a heat rate of 6.26 MMBtu per MWh and 50 kWh per kgH_2.