SMART DESIGN OF 45V HYDROGEN PRODUCTION TAX CREDIT WILL REDUCE EMISSIONS AND GROW THE INDUSTRY

DAN ESPOSITO, ERIC GIMON, AND MIKE O'BOYLE

APRIL 2023[i]

EXECUTIVE SUMMARY

The United States cannot achieve net-zero greenhouse gas (GHG) emissions without carbon-free hydrogen. Today, this molecule serves the chemicals and refining industries, and fossil fuel-derived hydrogen production contributes about 1.5 percent of total U.S. climate pollution. Shifting to cleaner hydrogen production can replace these dirty sources while cutting GHG emissions in industries that are hard or impossible to electrify.

Congress included a production tax credit (PTC) for clean hydrogen in Section 45V of the Inflation Reduction Act (IRA) to help scale the nascent industry. The tax credit's value is tied to the lifecycle GHG emissions of hydrogen production—including upstream emissions—with the highest tranche set at $3 per kilogram (kg) of hydrogen that is nearly emissions free.

Congress tasked the U.S. Treasury Department with deciding how hydrogen producers must account for their emissions to qualify for these incentives. Treasury accepted public comments in December 2022 and is working on final rules at the time of this paper's publication.

This research shows loose 45V guidance could create tens to hundreds of millions of tons of GHG emissions annually at a cost of $30 billion annually in federal funding while setting the

ENERGY
INNOVATION
POLICY & TECHNOLOGY LLC®

www.energyinnovation.org

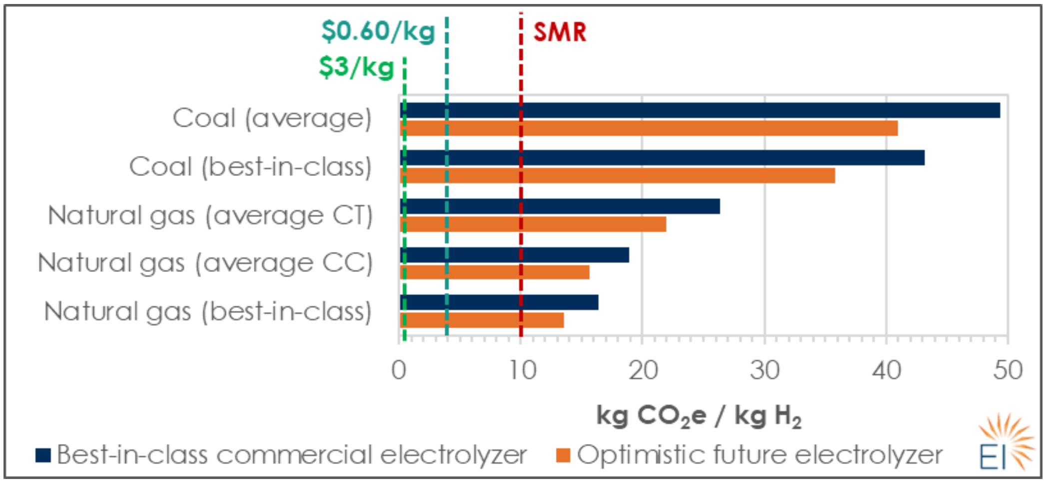
98 Battery Street, Suite 202
San Francisco, CA 94111
policy@energyinnovation.org

---

clean hydrogen industry up for failure. However, Treasury can implement rules that accurately account for electrolyzer emissions by following the design principles of additionality, deliverability, and time-matching, and this framework would build a clean hydrogen industry that is profitable from the start and can thrive after 45V expires.

The leading technology pathway for producing hydrogen at such low lifecycle GHG emissions rates is electrolysis—a process that uses electricity to split water atoms into hydrogen and oxygen. The emissions intensity of electrolytic hydrogen is therefore entirely dependent on upstream emissions from the electricity used. Because electrolysis is highly energy intensive, even small shares of fossil fuel power quickly result in more GHG emissions from hydrogen production than the IRA allows under 45V. In fact, meeting the 0.45 kilograms of carbon dioxide per kilograms of hydrogen ($kgCO_2/kgH_2$) threshold via electrolysis requires using at least 97 percent carbon-free electricity.

Figure ES-1. Emissions intensities from fossil fuel-powered electrolysis[ii]



The most efficient commercially available and potential future electrolyzers produce hydrogen at rates up to 5x that of steam methane reformation and orders of magnitude above the IRA's 0.45 $kgCO_2e/kgH_2$ threshold for earning $3/kg tax credits if causing fossil fuel power plants to increase their output, as would happen under loose 45V guidance.

Treasury has the difficult task of balancing administrability with precision. In theory, rules that are too lax would allow higher near-term GHG emissions from hydrogen production as a tradeoff to help grow a clean hydrogen industry that would reduce emissions by a much greater degree in the

---

[ii] "Best-in-class commercial electrolyzer" and "optimistic future electrolyzer" assume efficiencies of 49.9 kWh/kgH_2 and 41.4 kWh/kgH_2, respectively. These efficiencies do not include loads from auxiliary power consumption, such as for cooling electrolyzers or operating compressor pumps, meaning actual emissions intensities are likely higher. See https://resources.plugpower.com/electrolyzers/ex-4250d-f041122 and https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/.

decades to come. However, rules that are too stringent would keep GHG emissions in check but risk throttling electrolyzer deployment by making compliance too expensive.

That is a false dichotomy. This paper shows Treasury can strike the right balance in accurately accounting for lifecycle GHG emissions from hydrogen production while growing the clean hydrogen industry at the scale needed to meet long-term decarbonization goals. This approach is possible and in the best near- and long-term interests of the clean hydrogen industry, power grid, and U.S. climate goals. For these tax credits to succeed, they must be designed with current and future technology costs and operational needs in mind.

This report shows how Treasury can balance the objectives of hydrogen growth and accurate lifecycle GHG emissions accounting, demonstrating three major conclusions:

- Accurate 45V emissions accounting is **essential** for reducing near-term *and* long-term GHG emissions, ensuring the clean hydrogen industry maintains sustainable growth over time
- Three **design principles** underpin accurate emissions accounting under 45V, each of which is administrable and is being adopted by important international trading partners
- Electrolysis projects are **economically viable** under accurate 45V guidance

Importance of accurate 45V guidance

The first section of this paper explains our analysis of the GHG emissions and long-term industry growth implications of poor tax credit design. We explain how loose regulatory compliance regimes as proposed in some stakeholders' comments to Treasury—such as allowing electrolyzers to use power from existing clean energy resources—would cause massive near-term GHG emissions increases as the hydrogen industry scales. Specifically, such guidance would worsen GHG emissions from hydrogen production by 1.5 to 5 times that of conventional fossil-derived production, generating tens to hundreds of millions of tons of new GHG emissions annually through electrolysis at an annual cost of $30 billion in federal funding.[iii]

We also highlight long-term risks to the clean hydrogen industry from loose guidance. A highly-polluting start to the industry would undermine public trust in and support for hydrogen as well as damage credibility among trading partners. We emphasize the temporary role of the tax credit and the need to develop sustainable business models that avoid a "credit cliff," where hydrogen production becomes eternally reliant on government subsidies to pencil out in a low-carbon economy. For the clean hydrogen industry to scale, greater deployment is not enough—electrolyzers must find ways to make money by harnessing clean, cheap power, which will be overwhelmingly wind and solar in the coming decades.

[iii] This finding assumes electrolyzers scale to meet the U.S. Department of Energy's goal of producing 10 million metric tons of "clean" hydrogen annually by 2030, with no other technology contributing to this goal. See: https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf.

Design principles for accurate 45V guidance

The second section of this paper defines the three principles necessary to ensure accurate lifecycle GHG emissions accounting under 45V. It covers our analysis assessing the emissions impact of failing to adhere to each principle and cites separate research that confirms these risks. It then offers practical administrable measures Treasury and other stakeholders should consider and compares these recommendations to similar regulations in the European Union. The three principles are:

- **Additionality** requires electrolyzers to draw electricity from new sources of clean electricity that were induced as a direct result of the electrolyzer coming online. This can be administered by requiring hydrogen producers to sign power purchase agreements (PPAs) with clean energy producers that came online within two to three years of the electrolyzer's operational start.
- **Deliverability** requires electrolyzers to use local sources of clean electricity that are physically deliverable to the electrolyzer, accounting for congestion and transmission line losses. Deliverability administration is possible by requiring hydrogen electrolyzers and contracted sources of new clean energy to be located in the same defined region (such as power market zones)—with criteria for sourcing electricity from adjacent regions—while purchasing enough clean power to cover transmission line losses.
- **Time-matching** requires electrolyzers to run at the same time as clean electricity generation, plus meet an annual average emissions test to determine their appropriate annual credit value. We argue a phase-in for hourly time-matching by 2026 is feasible and administrable, given the industry's substantial recent progress developing tools to assess and validate demand and clean energy time-matching. We also highlight gaming concerns in addition to adverse emissions impacts of lax time-matching requirements and propose an annual average emissions test to validate emissions accuracy.

The section concludes by discussing how Treasury can account for some amount of GHG emissions from electrolytic hydrogen production, given that 45V does not require hydrogen to be zero-carbon to qualify. Specifically, Treasury can establish marginal GHG emissions rates by region to account for emissions from any fraction of electricity use that is not fully compliant with the three principles.

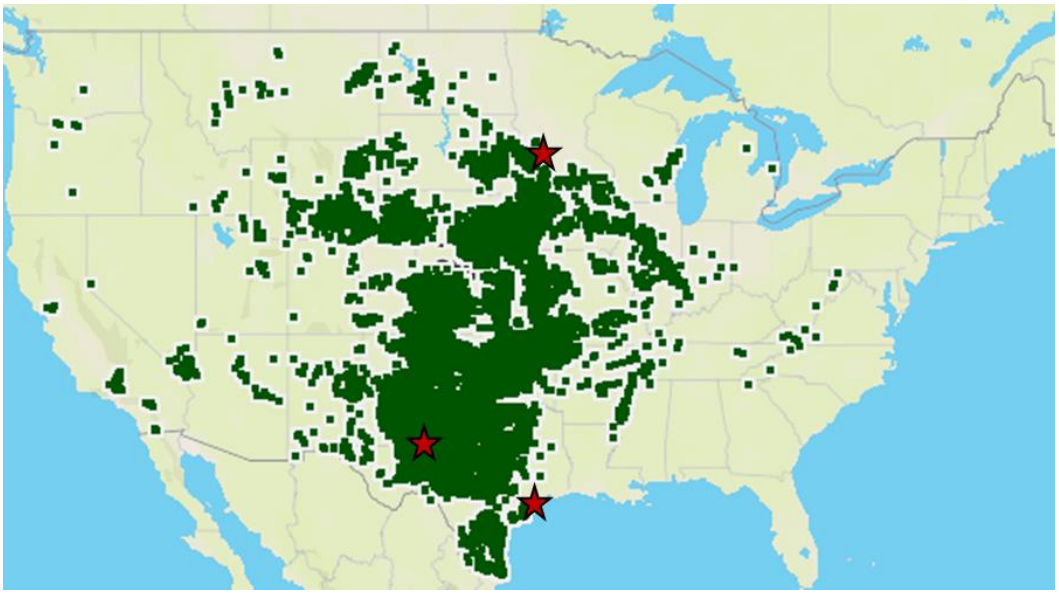
Table ES-1. Framework for implementing accurate 45V guidance

Design Principle	Component	Description
Additionality	New projects	Electrolyzers must source electricity via PPAs from new clean energy projects that began operations less than 36 months before the start of hydrogen production. Repowered projects must also meet a capital expenditure requirement, such as exceeding 30% of the costs of a greenfield project.
	Uprates	Electrolyzers must source electricity via PPAs from uprated clean energy facilities, limited to only the new margin of power output.
	Curtailed power	Electrolyzers can draw electricity from the grid if operators can prove that renewable energy facilities in the area would have otherwise been curtailed (e.g., zero or negative real-time power price).
Deliverability	Regionality	Electrolyzers must source electricity from clean energy projects located at least within the same NERC Reliability Assessment Area or power market zone—whichever is more granular.
	Congestion	As an exemption, electrolyzers can source electricity from clean energy projects located in neighboring interconnected zones if owners can show that zonal prices for the clean energy project are higher than or equal to those for the electrolyzer.
	Line losses	Electrolyzers must account for transmission line losses from their clean energy projects, which can be offset by procuring extra clean energy; owners can either use a loss rate preset by Treasury for a given interconnection or prove that their losses are lower.
Time-Matching	Hourly tracking	Electrolyzers can annually match their operations with clean energy procurement; beginning in 2026, operations must shift to hourly matching, including projects that began operations before 2026.
	Annual average emissions test	Electrolyzers will earn the 45V credit value equal to the annual sum of GHGs emitted divided by the sum of hydrogen produced.
Grid Power		Power consumed by electrolyzers that does not meet the above three principles should be assigned a regional marginal emissions rate, such as from the EPA AVERT tool.

Financial viability of accurate 45V guidance

The third section of this paper demonstrates the economic viability of hydrogen projects satisfying the three principles at a more restrictive configuration than our proposal—using electrolyzers that source power from co-located wind and solar energy facilities. We analyze the economics of these projects in Houston, Southwest Minnesota, and West Texas. Using conservative electrolyzer cost assumptions, we find that under 45V, projects co-located with wind and solar hybrids can achieve high electrolyzer utilization rates and robust profitability today. These results imply that abundant high quality wind and solar resources throughout the middle of the country would make profitable hydrogen projects possible across a wide swath of the Interior West, Great Plains, and Texas from the outset. This shows accurate 45V emissions accounting is compatible with the rapid growth of electrolyzers, which will have to chase cheap, clean power to scale after IRA incentives wind down beginning in 2032.

Figure ES-2. U.S. locations with wind and solar resources averaging less than $25/MWh



Dots represent locations where solar and wind resources have combined average levelized costs of electricity less than $25/MWh (including IRA clean energy tax credits), suggesting projects compliant with the three pillars may be financially viable. Stars indicate sites tested in our financial analysis. Sites are identified using exclusion criteria from NREL's ReEDS model. Green squares are not to scale—each site is 11.5x11.5 km. More than 6,900 sites representing more than 1,000 gigawatts of electrolyzer capacity met these criteria. Credit: Umed Paliwal, University of California, Berkeley.

Treasury's 45V guidance design will largely determine the climate impact of electrolytic hydrogen production, as well as long-term growth and viability of the burgeoning clean hydrogen industry. Loose guidance would be highly detrimental on both fronts, worsening GHGs from hydrogen production by up to five times and setting the industry up for failure once the tax credit expires.

Fortunately, accurate guidance is possible by setting standards that closely approximate compliance with three principles—additionality, deliverability, and time-matching—and by accounting for GHG emissions from any use of grid power. Because these principles would be financially viable from the start, Treasury should have confidence that adopting accurate 45V guidance will spur robust growth of clean electrolytic hydrogen, reducing GHG emissions today and long after the policy expires.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Energy Innovation® colleagues Anand Gopal and Sarah Spengeman for their review and communications contributions to this report. The authors would also like to acknowledge peer reviewers for their input, guidance, and contributions to this paper. The contents and conclusions, including any errors and omissions, are the responsibility of the authors, and peer reviewer input does not imply their support or endorsement of the work. Peer reviewers include Rachel Fakhry and Sam Krasnow with Natural Resources Defense Council; Danny Cullenward with the Institute for Carbon Removal Law and Policy at American University; Chelsea Baldino with International Council on Clean Transportation; Alejandro Hernandez with Regulatory Assistance Project; Wilson Ricks with Princeton University; John Coequyt, Nathan Iyer, Taylor Krause, and Alex Piper with RMI; and Mike Sloan with Synergetic.

Contents

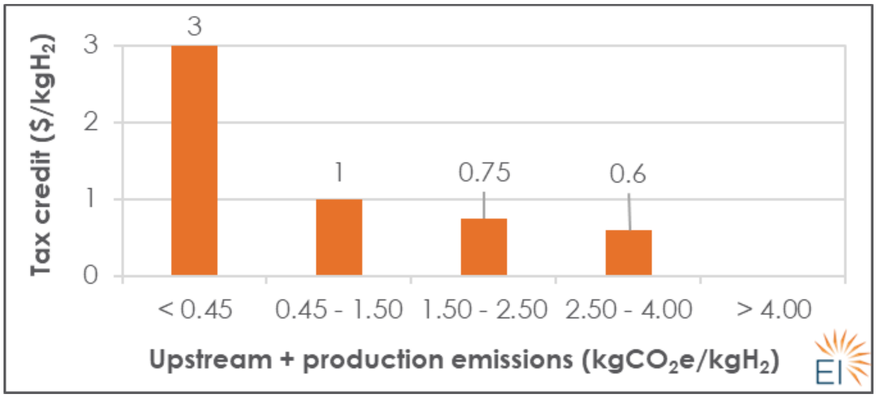
INTRODUCTION

Hydrogen is a gaseous fuel and basic chemical feedstock that can be used as a chemical reagent or energy carrier. Most hydrogen today is made via steam methane reformation (SMR)—an emissions-intensive process that strips hydrogen from methane gas—and used to make fertilizer or refine oil. However, hydrogen can be produced without emitting GHGs using electrolysis powered by clean energy.

Growing a domestic clean hydrogen industry is essential to help decarbonize chemical feedstocks and sectors that likely cannot be economically electrified over the long term, such as aviation, marine shipping, and some industrial applications. Accomplishing this goal requires reducing the capital costs of hydrogen-producing technologies, ensuring hydrogen is truly clean, and building the right infrastructure to support the fuel's transport, storage, and uptake by appropriate end uses.

Recognizing this need, Congress included a Clean Hydrogen Production Tax Credit (45V) in the IRA. As shown in Figure 1, the tax credit's value is tied to the embodied lifecycle GHG emissions of hydrogen production—including upstream emissions—with the highest tranche set at $3/kg for hydrogen that is nearly emissions free.[iv] While this design allows many low-carbon hydrogen production processes to receive support, the leading technology pathway to produce hydrogen capable of achieving the top tax credit is electrolysis—specifically, using clean electricity to split hydrogen from water via an electrolyzer, with oxygen as the only byproduct.

Figure 1. IRA 45V Clean Hydrogen Production Tax Credit values



Congress tasked the U.S. Treasury with writing rules to assess lifecycle GHG emissions of clean hydrogen for awarding 45V tax credits. This accounting is complex, but it is very important to get right. All emissions from electrolysis are caused by the use of electricity, which has upstream effects

---

[iv] To qualify for the $3/kgH_2$ subsidy, the IRA requires the emissions intensity of hydrogen production (including upstream impacts) to fall below $0.45 kgCO_2e/kgH_2$—approximately 95 percent lower than hydrogen produced via SMR.

on the power grid. As electrolyzers are highly energy intensive, even a modest increase in fossil fuel power generation resulting from their operations could drive hydrogen production emissions higher than SMR and far higher than IRA emissions thresholds.

Some stakeholders have argued in favor of Treasury adopting looser accounting approaches, which give electrolyzers more flexibility in compliance but guarantee at least a near-term increase in GHG emissions. They claim more rigorous guidance that accurately accounts for electrolyzers' upstream emissions could stifle the growth of clean electrolytic hydrogen just as it is primed for liftoff.

But this is a false dichotomy. Accurate accounting methods would not threaten the nascent industry and instead would set clean hydrogen up for long-term success vital to economy-wide decarbonization. Treasury need not compromise on accuracy in 45V implementation, nor contravene the IRA's lifecycle GHG requirements, to ensure the timely growth of clean electrolytic hydrogen. In fact, shortcuts risk being counterproductive over the long term.

The three major conclusions of this paper are:

- Accurate 45V emissions accounting is **essential** for reducing near-term *and* long-term GHG emissions, ensuring the clean hydrogen industry maintains sustainable growth over time
- Three **design principles** underpin accurate emissions accounting under 45V, each of which is administrable and is being adopted by important international trading partners
- Electrolysis projects are **economically viable** under accurate 45V guidance

IMPORTANCE OF ACCURATE 45V GUIDANCE

Accounting guidance for upstream GHG emissions from electrolysis could take many forms:

- The **loosest guidance** would allow electrolyzers to use electricity from the grid and buy renewable energy certificates (RECs) from existing clean energy projects. As we will demonstrate, this hydrogen production would be clean in name only, ignoring upstream GHG emissions impacts caused by electrolysis and the IRA's lifecycle GHG requirements.
- The **most stringent guidance** would require electrolyzers to be powered exclusively by new off-grid clean energy projects. This would be unquestionably clean and comply with the IRA, but it would also be quite restrictive.
- This paper argues in favor of a middle ground that adheres to statutory GHG limits while granting more flexibility. Such **accurate guidance** would allow electrolyzers to connect to the grid but require them to source power from new, deliverable, time-matched clean energy.

This section argues that accurate guidance is essential for two key reasons. First, 45V has a direct impact on GHG emissions—loose guidance would use federal subsidies to drive much higher climate-warming emissions, while accurate guidance would ensure electrolyzed hydrogen is truly clean from the start. Second, 45V will play a major role in shaping the clean hydrogen industry over the long term—loose guidance would set the industry up for failure by propping up business models and infrastructure that can't survive without such lucrative subsidies, while accurate guidance would provide a strong foundation for the industry to grow and thrive over time.

DIRECT EMISSIONS IMPACT

Under loose guidance, electrolyzers could take credit for clean electricity while producing hydrogen that is much dirtier than today's processes, violating the IRA's lifecycle GHG requirements and worsening climate change. Two realities underpin this conclusion: electrolyzer operations generally cause fossil fuel power plants to increase their output, and electrolyzers are highly energy intensive relative to other clean energy end uses.

How electrolysis impacts the grid

Power systems operate by optimizing for marginal cost—the most expensive resources are called upon only when needed. All else equal, new sources of electricity demand draw on the next available least-expensive, or "marginal," resource.[1] Zero-carbon resources on the market today are generally not marginal, instead running at their maximum output when available. This is because they have zero or low marginal costs—sunlight, wind, and water are free, and nuclear fuel is cheap.[v] Today, fossil fuel power plants are on the margin in the vast majority of hours everywhere in the U.S.,[2] including 85 percent of the time in the country's largest competitive power market.[3]

Electrolyzers are big new sources of demand that will draw on the marginal resource. Under loose 45V guidance, electrolyzers could claim to offset this added demand by purchasing RECs or signing bilateral contracts with existing carbon-free resources, essentially increasing demand without increasing new clean power supply. Under these conditions, the power system will respond by increasing output from the marginal generator (in nearly all cases today, natural gas or coal). This dynamic underpins our focus on additionality as a bedrock principle of accurate emissions accounting.

As we discuss later, the concept of marginal emissions is foundational to accurate upstream emissions accounting associated with electricity consumption. Even contracting with power from new clean energy resources can drive higher emissions if that power isn't directly deliverable to the electrolyzer or time-matched with its operations. This also holds true with a mostly-clean power grid. When an electrolyzer causes an increase in fossil fuel power generation, its hydrogen production's upstream emissions necessarily include these resultant GHG emissions.

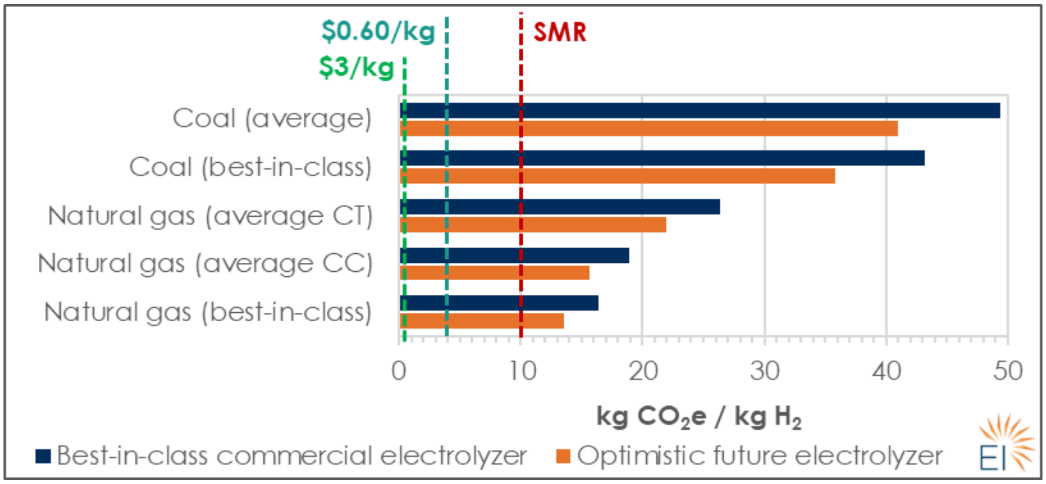
---

[v] The average U.S. nuclear power plant operated in 93 percent of all hours in 2021, with the remaining hours generally needed for periodic maintenance. See: https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php.

Electrolyzers' energy intensity

Electrolysis consumes so much electricity that the use of fossil power to make hydrogen will increase GHG emissions 1.5 to 5 times relative to SMR per kilogram of hydrogen (see Figure 2). These emissions rates imply 45V could create tens to hundreds of millions of tons of new GHG emissions annually through electrolysis at a cost of $30 billion annually in taxpayer-supported funding.[vi]

Figure 2. Emissions intensities from fossil fuel-powered electrolysis[vii]



The most efficient commercially available and potential future electrolyzers produce hydrogen at rates up to 5x that of SMR and orders of magnitude above the IRA's 0.45 $kgCO_2e/kgH_2$ threshold for earning $3/kg tax credits if causing fossil fuel power plants to increase their output, as would happen under loose 45V guidance.

Electrolyzers' high energy intensity helps explain why 45V differs from other federal clean technology policies and why it is essential that guidance accurately accounts for resulting emissions.

First, other clean technologies like electric vehicles (EVs) and electric heat pumps have significant efficiency advantages over their fossil fuel counterparts. For example, EVs reduce emissions relative to today's average U.S. internal combustion engine (ICE) light-duty vehicle (LDV) even when

---

[vi] The exact number depends on the amount of hydrogen produced via electrolysis, which marginal generators ramp up to serve the new demand, and what hydrogen ultimately displaces downstream.

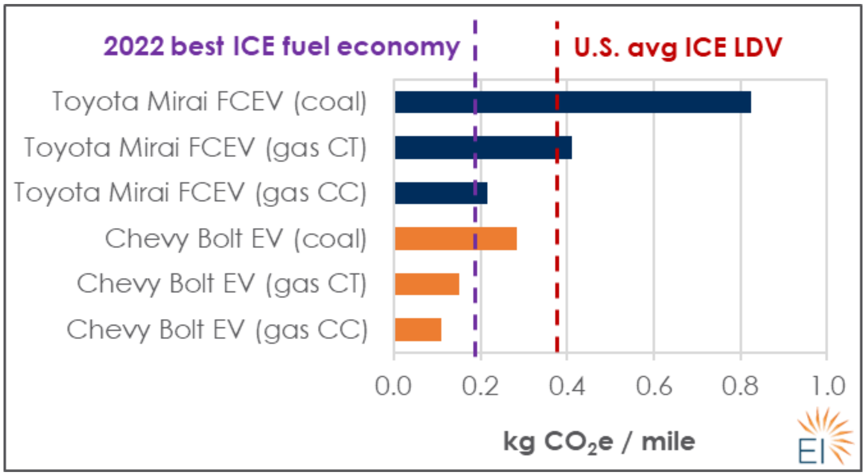
[vii] "Best-in-class commercial electrolyzer" and "optimistic future electrolyzer" assume efficiencies of 49.9 kWh/kgH_2 and 41.4 kWh/kgH_2, respectively. These efficiencies do not include loads from auxiliary power consumption, such as for cooling electrolyzers or operating compressor pumps, meaning actual emissions intensities are likely higher. See https://resources.plugpower.com/electrolyzers/ex-4250d-f041122 and https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/.

charged exclusively by coal power. The hydrogen-powered fuel cell electric vehicle (FCEV) equivalent would be approximately twice as emissions-intensive per mile (see Figure 3).[viii]

Second, IRA policy support for EVs, heat pumps, and batteries subsidize capital costs rather than miles driven, heat moved, or electricity discharged. 45V differs by paying out for production, meaning under loose guidance, electrolyzers would be incentivized to increase GHG emissions.

Third, the IRA wisely calls for including upstream lifecycle GHG emissions in assessing the tax credit value awarded to clean hydrogen production to account for electrolyzers' high energy intensity and the production-based incentive structure, whereas federal support for other clean energy technologies is not tied to lifecycle GHG emissions.

Figure 3. Vehicle emissions intensities across technologies



Electric vehicles reduce GHG emissions relative to today's average U.S. ICE LDV regardless of their electricity source, while FCEVs can be more than 2x worse depending on the emissions intensity of their hydrogen. Parentheses denote which power plant is assumed to provide electricity to the vehicle (or the electrolyzer making hydrogen for the vehicle). Vehicle models are 2021 unless otherwise specified.

LONG-TERM CLEAN HYDROGEN INDUSTRY IMPACT

Loose guidance may seem like a means to deploy electrolyzers more rapidly, thereby ensuring lower capital costs and more prevalent hydrogen infrastructure by the time the U.S. power grid is fully decarbonized. However, such rules risk derailing rather than supporting the clean hydrogen industry, ultimately impeding longer-term efforts to decarbonize hard-to-electrify sectors. Two conditions are necessary to avoid this risk: public trust in and support for clean electrolytic

---

[viii] That said, the times in which EVs charge do matter for long-term emissions reductions; state utility regulators should do all they can to incentivize customers to charge when renewable energy is widely available.

hydrogen, and a durable industry foundation that facilitates its sustainable growth after 45V expires.

Building public trust in and support for clean electrolytic hydrogen

High GHG emissions from electrolysis under loose 45V guidance could lead to legal challenges, given the IRA's requirement to account for upstream lifecycle GHG emissions. They could also undermine credibility among international trading partners who have more stringent requirements, create conflicting state and federal standards, and generally confuse what counts as "clean" for the purposes of corporate emissions inventories and state policy goals.

Hydrogen could also quickly lose public support should the industry cause widespread harm. For example, loose guidance could drive existing sources of clean energy to divert their power to electrolysis; the resultant surge in fossil fuel generation would increase GHG emissions, harmful air pollution, electricity prices, and reliability risks.[ix] Such connections between hydrogen and these adverse outcomes may drive distrust and opposition from consumer advocates, non-governmental organizations, environmental justice communities, and the general public.

Any backlash could delay or thwart 45V's implementation as well as hydrogen project development around the country. By contrast, accurate 45V guidance would ensure climate, community, and international trade benefits from day one, setting the industry up for success.

Building a strong foundation for the clean hydrogen industry's sustainable growth

The U.S. Department of Energy anticipates a need to eventually produce clean hydrogen at prices as low as $0.40/kg to serve all suitable end-uses.[x,4] Even with a free, perfectly-efficient electrolyzer, achieving these prices requires average power costs of $10 per megawatt-hour (MWh). In a post-45V world, this benchmark is only possible by using electrolyzers capable of flexibly ramping up and down to capture electricity during the cheapest hours, with access to low-cost transport and storage infrastructure to stabilize supply for offtakers.

Several conditions must be met to achieve this successful clean hydrogen industry:

- Electrolyzers must be concentrated in regions with high renewable resource quality, especially wind[xi]
- Hydrogen must primarily serve high-value applications like industrial feedstocks that will remain competitive over the long term

---

[ix] All else equal, electricity prices would rise due to power markets calling on the next available least-expensive marginal generators to backfill for lost clean energy (which is generally the cheapest source of electricity). Reliability risks would rise due to spare power generation capacity being committed—though these would be mitigated if electrolyzers were to ramp down during periods of high electricity demand.

[x] This lower bound refers to the hydrogen price needed to serve seasonal clean electricity storage services.

[xi] Wind production profiles are more conducive to running electrolyzers at higher capacity factors without needing an intermediate electricity storage medium.

- Projects must be able to survive and grow after 45V expires
- Flexible electrolyzer technologies must be grid-connected to help balance—and benefit from—a high variable renewable energy (VRE) system
- Hydrogen storage and transportation solutions must deployed at scale

Loose 45V guidance risks building a clean hydrogen industry that fails all five conditions.

It would fail the first three conditions by making electrolyzers viable in parts of the country with relatively poor renewable resource quality while facilitating the sale of unsustainably cheap hydrogen to specious end-uses like pipeline blending and refueling light-duty FCEVs.[xii] Under loose guidance, such arrangements may look attractive in the near term due to the tax credit's temporary market distortion but would be uncompetitive after the credit cliff. Post-45V, new renewables will allow cheaper clean hydrogen production elsewhere, and alternative technologies like heat pumps and EVs will ultimately displace hydrogen's fleeting entry into these markets.

The fallout from this development would be a wave of lost jobs and stranded investments—especially longer-lived assets like refueling stations—or an attempt to extend 45V indefinitely at a high cost to U.S. taxpayers that would also prolong the higher GHG emissions described earlier.

In contrast, accurate 45V guidance would catalyze early electrolyzer deployments in parts of the country where it's easiest to build renewables, wind resource quality is highest, and much of the country's industry is concentrated—Texas, the Interior West, and the Great Plains. Under accurate guidance, once 45V expires, electrolysis would remain viable, as would projects built to replace SMR hydrogen and to decarbonize hard-to-electrify sectors.[xiii]

As electrolyzer costs fall and dedicated hydrogen pipelines are built, project development would accelerate across the country, supporting more natural, robust growth for the clean hydrogen industry and securing larger GHG reductions.

Loose guidance would fail the last two conditions by incentivizing deployment of less-flexible electrolyzer technologies that have lower capital costs and could maximize 45V revenue by producing credit-eligible hydrogen around-the-clock. However, such operations aren't desirable long term, as inflexible electrolyzers would have trouble price-hunting for the cheap input power they will need without the tax credit[xiv] and fail to integrate higher shares of VRE onto the grid.

[xii] For detail on why blending hydrogen in pipelines is a poor use of the fuel, see https://energyinnovation.org/publication/assessing-the-viability-of-hydrogen-proposals-considerations-for-state-utility-regulators-and-policymakers/ and https://www.sciencedirect.com/user/error/ATP-2?pii=S2542435122004160.

[xiii] Notably, the U.S. has no demand-side hydrogen policy that would ensure the fuel mostly replaces carbon-intensive fuels that can't be economically electrified (e.g., jet fuel for aviation, bunker oil for marine shipping, metallurgical coal for steel production). So, a fortunate outcome of accurate 45V guidance design would be electrolyzers being most economic near places best suited to serve applications like ammonia production and steelmaking.

[xiv] That is, absent an effective $60+/MWh subsidy in 45V, electrolyzers will need to selectively run during hours when electricity prices are sufficiently low.

Around-the-clock operations would also do little to support the buildout of hydrogen storage and transportation solutions needed to bridge gaps in intermittent production.

Accurate guidance would ensure 45V deploys more flexible electrolyzer technologies, as they will be needed to follow wind and solar output. This capability will be invaluable in a high VRE future, allowing electrolyzers to soak up excess renewable generation and ramp down during periods of high demand. Accurate guidance would also mean electrolyzers rarely produce hydrogen around-the-clock given they must follow clean energy generation profiles. Projects could supply offtakers that need steady streams of hydrogen by overbuilding electrolyzer capacities and including on-site hydrogen storage or by joining forces with other producers and hydrogen distribution platforms—thus enabling a consistent output. In fact, the tax credits are rich enough to enable a range of solutions to firm hydrogen supply to specific offtakers.

Treasury can meet the IRA's statutory requirements, ensure 45V reduces near- and long-term GHG emissions, *and* provide a strong foundation from which to grow a sustainable, truly clean hydrogen industry by setting accurate guidance for GHG emissions accounting from electrolysis. The next section lays out such a workable framework.

DESIGN PRINCIPLES FOR ACCURATE 45V GUIDANCE

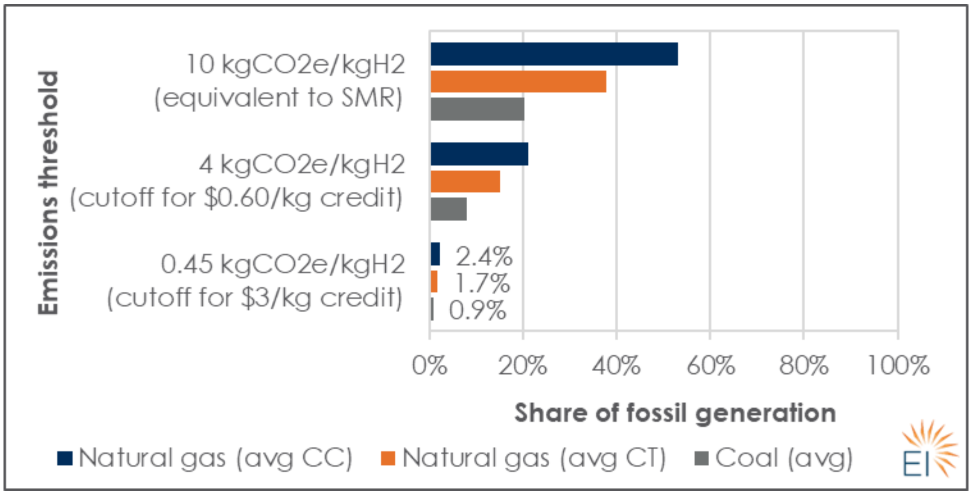
Accurate 45V guidance for accounting for electrolyzers' upstream GHG emissions from electricity use requires a framework that adheres as closely as possible to three principles:[xv]

- **Additionality:** using new sources of clean electricity that were induced as a direct result of the electrolyzer coming online
- **Deliverability:** using local sources of clean electricity that are physically deliverable to the electrolyzer, including accounting for congestion and transmission line losses
- **Time-matching:** ensuring electrolyzers run at the same time as clean electricity generation, plus meeting an annual average emissions test

Any disparity between these principles and the final 45V implementation framework is likely to cause an increase in fossil fuel power generation. As the below figure shows, even small shares of fossil power attributed to electrolysis can push hydrogen production outside the \$3/kgH_2 threshold. In fact, an electrolyzer supplied by 80 percent carbon-free electricity and 20 percent coal-based electricity would emit the same GHG emissions as SMR.

[xv] More detail on the need for these three principles can be found in Energy Innovation's comments to the Treasury on 45V guidance design: https://www.regulations.gov/comment/IRS-2022-0029-0145.

Figure 4. Share of fossil power used for electrolysis before crossing key thresholds



Today's best-in-class commercial electrolyzers (efficiency of 49.9 kWh/kg)[5] can consume no more than 2.4 percent of fossil electricity (with the rest zero-carbon) before exceeding the GHG emissions threshold for the top 45V tax credit value.

Fortunately, a workable set of regulations is possible that would ensure electrolyzers can meet 45V's $3/kgH$_2$ threshold. The European Commission is paving the way through a Delegated Act it adopted in February 2023, which proposes rules designed to "ensure that [clean electrolyzed hydrogen] can only be produced from 'additional' renewable electricity generated at the same time and in the same area as their own production."[6]

The EU rules have on-ramps or phase-ins for some requirements, such as deferring additionality until 2028 and hourly time-matching until 2030. However, the U.S. and EU have important differences that necessitate Treasury adopting a greater degree of stringency for 45V compliance. For example, unlike the U.S., the EU has a GHG emissions cap covering the electricity sector, ensuring leakage from looser requirements is offset elsewhere. At the time of this writing, the EU is planning to unveil a comparatively less generous clean hydrogen production subsidy.[xvi,7]

This section will explore the three principles we recommend for achieving accurate 45V emissions accounting: additionality, deliverability, and time-matching. For each principle, we provide a definition, discuss the GHG emissions impact of excluding them from a 45V compliance framework, cover any special considerations that might apply, summarize how the EU approaches them, and

---

[xvi] The U.S. has a very large ($3/kg) tax credit with uncapped funding made available to all projects that qualify for Treasury's rules, whereas the EU's proposed system includes limited funding disbursed to projects that clear competitive a central auction. Capped subsidies and competition will encourage EU electrolyzers to price-hunt for low-cost (generally clean) power, while 45V's fixed, substantial, and uncapped tax credits will incentivize U.S. electrolyzers to run even when the dirtiest, least-efficient plants are on the margin.

make recommendations to Treasury on how to implement each principle in its final guidance. We then discuss how Treasury can allow some GHG emissions in its framework.

ADDITIONALITY

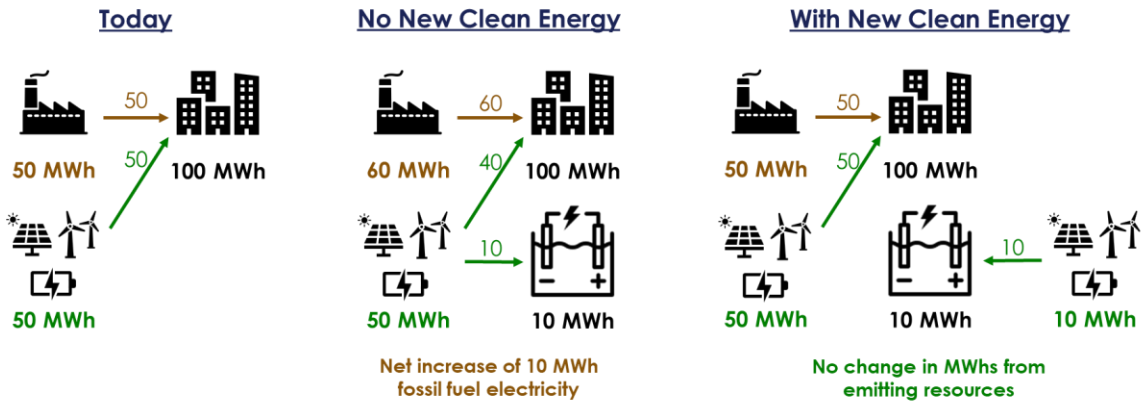
Additionality requires electrolyzers to draw electricity from new sources of clean electricity that were induced as a direct result of the electrolyzer coming online.

Emissions impact of forgoing additionality

Absent additionality, electrolyzers would unquestionably raise GHG emissions. Additionality is also the bedrock upon which the other two principles lie—without additionality, time-matching and deliverability don't avoid emissions as intended.

To illustrate the risk, consider what would happen if projects could consume carbon-free electricity from existing, "non-additional" clean generation. For example, electrolyzers seeking the 45V tax credit could sign agreements with existing nuclear and renewable energy projects to purchase their "clean" attributes or draw clean power directly from these facilities before it hits the grid. While that approach would allow the hydrogen producer to claim clean attributes, it will generally increase fossil fuel generation. That is, when new electrolyzer demand claims existing clean power, the rest of the power grid will respond by calling on the marginal generator to make up the difference—almost always a fossil fuel power plant. The net effect is more fossil generation even if contractually the electrolyzer only consumes clean power. Only *new* clean energy can prevent this harmful outcome (see Figure 5).

Figure 5. Illustrative depiction of importance of additionality

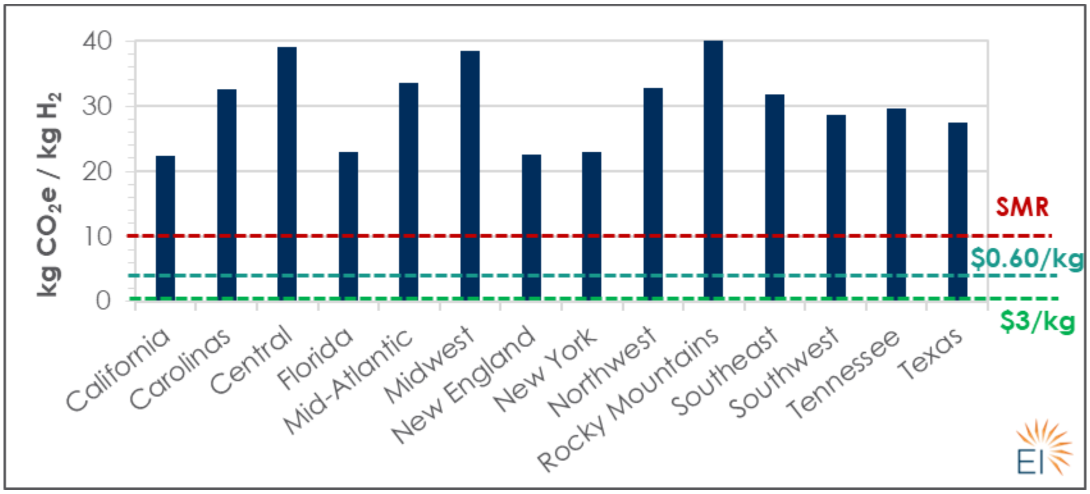


In the "No New Clean Energy" case, a new electrolyzer appears to draw power exclusively from clean energy resources but causes a fossil fuel power plant to ramp up, creating new GHG emissions. In the "With New Clean Energy" case, the electrolyzer draws power exclusively from new clean energy resources; so long as the deliverability and time-matching principles are also met (presumed to be true in this illustration), this arrangement will not affect other plants' output.

As shown in Figure 2, forgoing additionality can increase GHG emissions from hydrogen electrolysis as much as 5 times compared to SMR and upwards of 100 times above the 45V threshold for the top tax credit value.

Using the U.S. Environmental Protection Agency's (EPA) Avoided Emissions and Generation Tool (AVERT), we find electrolysis that takes credit for non-additional clean energy would incur 22 to 40 $kgCO_2/kgH_2$ across all 14 modeled regions comprising the 48 contiguous U.S. states (see Figure 6).[xvii] Similarly, a Princeton study finds that hydrogen electrolysis with no additionality requirement would cause GHG emissions rates greater than 20 $kgCO_2/kgH_2$ in an 82 percent carbon-free California power grid in 2030.[8] Another study from Rhodium Group assessed additionality's impact on GHG emissions as hydrogen production grows under 45V, finding 73 million metric tons (MMT) higher annual CO_2 emissions in a 60-81 percent clean grid in 2030.[9]

Figure 6. Electrolysis emissions impact of forgoing additionality



Without additionality, electrolyzers everywhere in the U.S. would cause GHG emissions that are at least twice as high as those from SMR. Analysis uses the EPA AVERT tool and 2021 data. See Appendix A for more details.

[xvii] The analysis used 2021 data. See Appendix A for more details and graphics: https://energyinnovation.org/publication/smart-design-of-45v-hydrogen-production-tax-credit-will-reduce-emissions-and-grow-the-industry

Special considerations

Additionality can be broken into three types of projects: building a new clean energy project, increasing an existing clean energy project's capacity via an uprate;[xviii] and using clean electricity that would have otherwise been curtailed.[xix]

Most electrolyzers will meet the additionality principle through the first option of inducing the deployment of a **new** clean energy project that would not otherwise have been built. While clear in theory, this is an impossible condition to prove without a counterfactual. However, Treasury can design guidance that gives high confidence additionality was achieved, such as requiring electrolyzers to sign PPAs with clean energy facilities that come online within two to three years of the electrolyzer's operational start.[xx] In addition, the hydrogen facility must retire RECs associated with these PPAs, thereby preventing their sale to other entities, except for the share of clean power generated that exceeds the electrolyzer's consumption.[xxi]

This category also includes repowering, which involve substantially modifying or rebuilding a clean energy facility to increase its lifetime or capacity, such as tearing down wind turbines nearing retirement and building new, larger turbines in their place. Repowering projects ought to meet the same requirements as new builds, plus criteria to guard against existing facilities trying to classify small tweaks as full repowerings. This may take the form of a capital expenditure requirement, such as investments that exceed 30 percent of the costs of a greenfield project.

Electrolyzers should also be considered to meet additionality if they cause an existing clean energy project to increase its capacity or output via **uprates.** Specifically, nuclear power plants can apply for an increase in their maximum power level through the U.S. Nuclear Regulatory Commission.[xxii,10] When a PPA with an electrolyzer makes it economically viable for a nuclear facility to increase its capacity, only this new (uprated) margin of contracted power output should qualify as "additional" for 45V compliance.

Lastly, a valuable feature of flexible electrolyzers is their ability to capture clean electricity that would have otherwise been **curtailed.** As shown in Figure 7, curtailment alone will rarely be enough to finance electrolyzer deployments at today's capital costs. Even in high-renewable markets like

---

[xviii] In theory, actions that prevent a clean energy facility from retiring would also count as additional. However, this would only reasonably apply to nuclear power plants (having higher going-forward costs than other clean energy resources), which are highly unlikely to retire during the life of 45V. This is because the U.S. nuclear fleet benefits from several policies designed to make them whole, such as the IIJA's Civil Nuclear Credit Program, the IRA's production tax credit for existing nuclear facilities, and several state zero-emission credit programs that support nuclear assets.

[xix] Renewable energy facilities curtail their electricity generation when they have the ability to produce more electricity than the grid can accept.

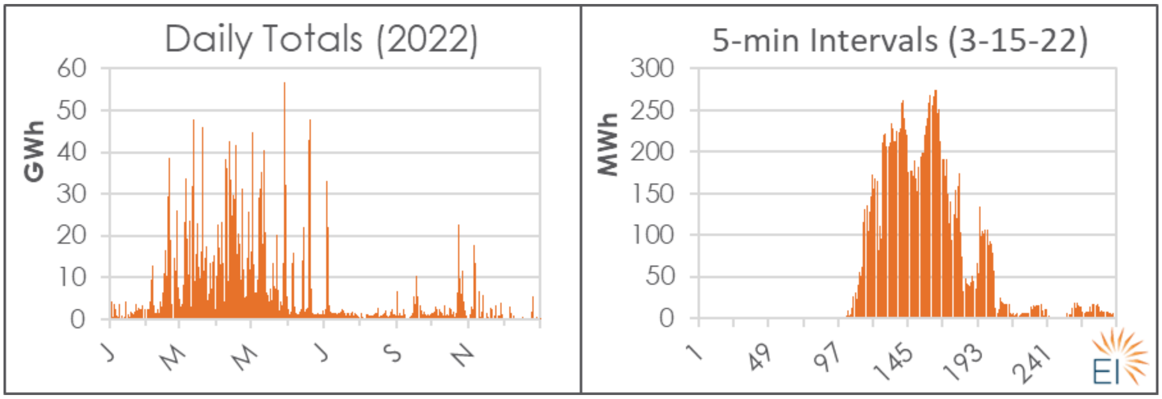
[xx] A PPA provides evidence that the electrolyzer was foundational to the clean energy project being financeable.

[xxi] States will need to ensure these rules serve, and don't undermine, state renewable or clean energy standard accounting.

[xxii] For example, this may involve using more highly enriched uranium fuel to power the reactor.

California, curtailment is minimal in much of the year. So, while an additionality framework should ideally have a mechanism to give credit to capturing otherwise-curtailed clean electricity, it should be viewed as a supplement to building new clean energy projects rather than an option that can support 45V-compliant projects by itself.

Figure 7. Wind and solar curtailment profiles for the California ISO[xxiii]



Electrolyzers designed to strictly capture otherwise-curtailed electricity would not be viable at scale in today's power system. In this example for the California ISO, a 1 MW, 10 MW, and 100 MW electrolyzer would only have access to enough otherwise-curtailed electricity to run at full load in 42%, 24%, and 8% of all 5-minute intervals, respectively.

Implementation

The EU's rules for additionality provide a useful starting point for designing 45V guidance:

- EU rules deem clean energy projects to be "new" if they came into operation less than 36 months before an electrolyzer begins its hydrogen production. If the clean energy project is grid-connected, it must also have a PPA with the electrolyzer. The three-year window gives developers flexibility to build multiple projects (e.g., solar, wind, electrolyzer), while the PPA provides evidence that the electrolyzer was necessary for clean energy project financing. These rules also apply for repowers, which further require capital investments to exceed "30% of the investment that would be needed to build a new installation."[11]
- EU rules make no mention of allowing uprates to qualify.[xxiv]

[xxiii] Electrolyzers will be much more likely to operate in a manner that prioritizes the capture of otherwise-curtailed renewable energy after 45V expires; but, in the meantime, electrolyzers receiving the highest-value tax credit will be much less discerning, able to afford much more expensive power while still turning a profit.

[xxiv] EU rules also do not allow retirement postponements to qualify as "additional."

- The EU framework permits electrolyzers to capture clean electricity from the broader power grid that otherwise would have been curtailed if project owners submit evidence from the grid operator.[xxv] In the U.S., this may show up through zero or negative electricity prices.

EU policy also differs in several important respects that distinguish the EU market from the U.S. and limit the application of EU's logic to Treasury's 45V guidance.

First, though EU rules defer additionality until 2028 to help jump-start electrolyzer deployment, the EU GHG emissions cap covers the electricity sector, forcing upstream electrolyzer emissions to be offset by actions taken elsewhere—even for projects that come online before the additionality requirement kicks in. In contrast, the U.S. has no comparable emissions cap, and it also has a high, uncapped, fixed rate production subsidy that will trigger a larger market response under today's electrolyzer costs.

Second, EU rules require that new clean energy projects do not receive other subsidies to be considered "additional." This isn't applicable in the U.S., as the IRA explicitly clarifies that new renewables providing electricity to electrolyzers should be allowed to earn investment or production tax credits.

Third, the EU does not explicitly consider uprates. Treasury can permit this option by requiring electrolyzers to have a PPA with the uprated facility, limiting the "additional" power to the new margin of power output.

DELIVERABILITY

Deliverability requires electrolyzers to use local sources of clean electricity that are physically deliverable to the electrolyzer, including accounting for congestion and transmission line losses.

Emissions impact of forgoing deliverability

Absent deliverability, pairing electrolyzers and new hourly-matched clean energy projects still risks significantly raising GHG emissions.[xxvi] Demand and supply have different marginal effects in different regions—unless the clean power and electrolyzer are connected by adequate transmission and operating in the same market, the electrolyzer's new demand will pull one type

---

[xxv] "Electricity taken from the grid that is used to produce [hydrogen] may also be counted as fully renewable if [it] is consumed during an imbalance settlement period during which the fuel producer can demonstrate, based on evidence from the national system operator, that [renewable energy resources] were redispatched downwards [and] the electricity consumed for the production of [hydrogen] reduced the need for redispatching by a corresponding amount." See: https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf.

[xxvi] The concept of deliverability only really comes into play when the additionality principle has been met. Otherwise, where the electrolyzer is built still matters (e.g., affecting whether coal or natural gas resources are marginal and whether it can capture otherwise-curtailed renewable energy), but the electrolyzer will raise GHG emissions regardless.

of marginal resource online while the clean energy's new supply will push another type of marginal resource offline.

For example, consider an electrolyzer built in Colorado and corresponding new, hourly-matched clean energy resources built in Texas—a state that includes a separate power grid with high wind and solar resource quality and an easier development environment. Our AVERT analysis shows this type of project would produce hydrogen with a GHG emissions intensity of over 12 $kgCO_2/kgH_2$—still worse than SMR.[xxvii] More generally, Rhodium Group finds hydrogen production in high-emitting parts of the country could increase emissions 63-100 MMT in 2030.[12]

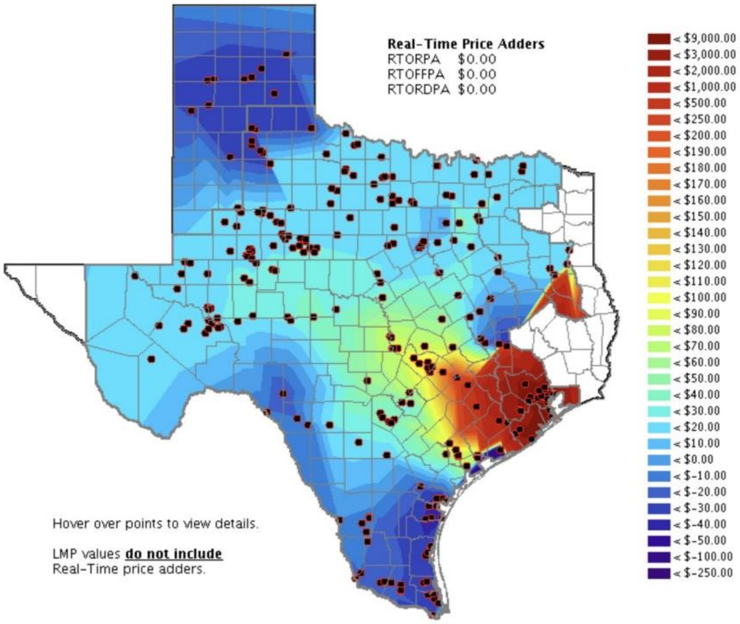
Transmission connectivity is as important as location—it is necessary but not sufficient to require that project pairings be built in the same interconnection, region, or power market. Figure 8 shows transmission congestion can cause similar unfavorable results even at the power market level.

Consider a new wind farm built in wind-rich West Texas and an electrolyzer built in Houston. During times of high congestion, West Texas wind is likely being curtailed, while in import-constrained Houston, the electrolyzer might cause a local fossil fuel resource to ramp up. This dynamic can show up anywhere in the country where transmission congestion limits the delivery of electricity from clean energy resources to electrolyzers.[xxviii]

[xxvii] The analysis, which used 2021 data, found projects could reach a GHG emissions intensity beyond 17 $kgCO_2/kgH_2$ if building clean energy in California and an electrolyzer in the Rocky Mountains region. See Appendix A for more details and graphics: https://energyinnovation.org/publication/smart-design-of-45v-hydrogen-production-tax-credit-will-reduce-emissions-and-grow-the-industry

[xxviii] For example, consider new clean energy in upstate New York and southeast California (which have more favorable development environments) with electrolyzers in New York City and Los Angeles (which have more offtake potential).

Figure 8. Example of transmission congestion in the Texas power market



Dark red reflects high power prices while dark blue reflects low-to-negative power prices. The differential represents transmission congestion between these locations on the power grid.

Special considerations

The deliverability principle ensures electricity from clean energy resources is physically deliverable to the electrolyzer with no material congestion that would cause fossil fuel power plants to ramp up. However, accurate adherence to the principle also requires accounting for transmission line losses—the reality that some amount of electricity is lost to resistance any time it is transmitted from one point to another. Even small line losses can quickly push hydrogen production beyond 45V's \$3/kgH_2 threshold. If the power filling in comes from coal, line losses of less than 1 percent would push production past this threshold, as would line losses less than 2.5 percent if topped off by a natural gas combined cycle power plant. Line losses averaged 5 percent from 2017 through 2021 in the U.S., meaning these outcomes are certainly possible.[xxix,13]

Implementation

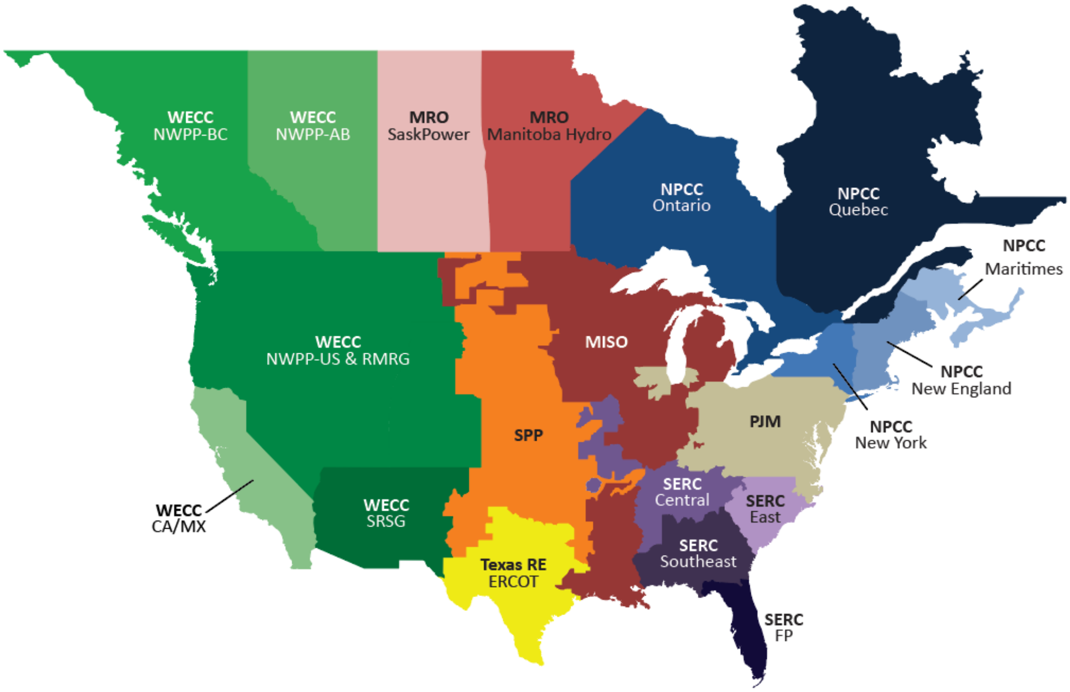
The EU's rules for deliverability (or "geographical correlation") again provide a helpful frame of reference for 45V guidance design. The framework generally requires the electrolyzer and

---

[xxix] These losses include transmission *and* distribution, which might not be applicable for many projects. However, accurate guidance entails accounting for any losses occurred (even if lower than this average) when considering GHG emissions caused by electrolyzers.

contracted clean energy resources to be located within the same "bidding zone," which consist of countries or subdivisions within countries. The appropriate U.S. parallel would be North American Electric Reliability Corporation (NERC) Reliability Assessment Areas or, where applicable, power market zones. NERC Reliability Assessment Areas are used to plan for reliability but are still broad enough to contain significant pockets of congestion.[14] However, U.S. power markets—which are roughly nested as individual NERC Reliability Assessment Areas—should be further subdivided into load zones, which are largely defined by transmission capability.[xxx]

Figure 9. NERC Reliability Assessment Areas



The EU manages interzonal congestion by allowing projects to be located in separate interconnected zones during times when the clean energy projects' zone has higher or equal power prices to the electrolyzer's zone. This price signal suggests that even with congestion, the clean energy project should be able to send electricity to the electrolyzer's zone.

[xxx] Transmission congestion can still exist even within load zones; however, a tighter restriction—such as requiring projects to connect to the same node—is likely unworkable without effectively requiring co-located projects.

The U.S. can adopt this exception as long as the adjacent zones lie within the same interconnection (i.e., Eastern, Western, or Texas)[xxxi] and enough liquidity and price transparency exists in the market for this to be a reliable metric of congestion.[xxxii]

The EU does not consider line losses; however, the large geographic scope of some NERC Reliability Assessment Areas and 45V's very low GHG emissions threshold for earning the highest-value tax credit suggests U.S. rules should account for these impacts. Treasury can preset transmission line loss rate assumptions for each interconnection or region, giving project owners the option of proving that their losses are lower. Losses would be easy to offset, as electrolyzers need only procure slightly more electricity from their paired clean energy resources.

TIME-MATCHING

Time-matching requires electrolyzers to run at the same time as clean electricity generation, plus meet an annual average emissions test to determine their appropriate annual credit value.

Emissions impact of forgoing time-matching

Absent time-matching, pairing new, deliverable clean energy and electrolyzers similarly risks raising GHG emissions.[xxxiii] Consider an electrolyzer producing hydrogen around-the-clock that purchases enough electricity from a new, deliverable solar farm sized to match the electrolyzer's annual consumption. The solar farm would generate more than the electrolyzer needs in the middle of the day, causing one type of marginal resource to ramp down. The electrolyzer's operations would then continue in the evening and overnight when the solar farm isn't available, causing a different type of marginal resource to ramp up. The differential in these marginal emissions rates would then be attributable to the electrolyzer.

These emissions impacts depend on the specific project locations and configurations—and under loose regulations, emissions from annually-matched hydrogen production would actually grow as the power system gets cleaner. Princeton modeling finds that annual and even weekly time-matching could result in GHG emissions on par with electrolysis powered directly by the grid with

---

[xxxi] Another proposal is to allow clean energy projects and electrolyzers to be located in different zones if they purchase firm transmission rights. However, this approach starts to collide with additionality—unless the project owner builds or partly funds a new transmission line, it's effectively taking existing transmission capacity off the system that might have been subscribed by renewables in a world without competition from 45V.

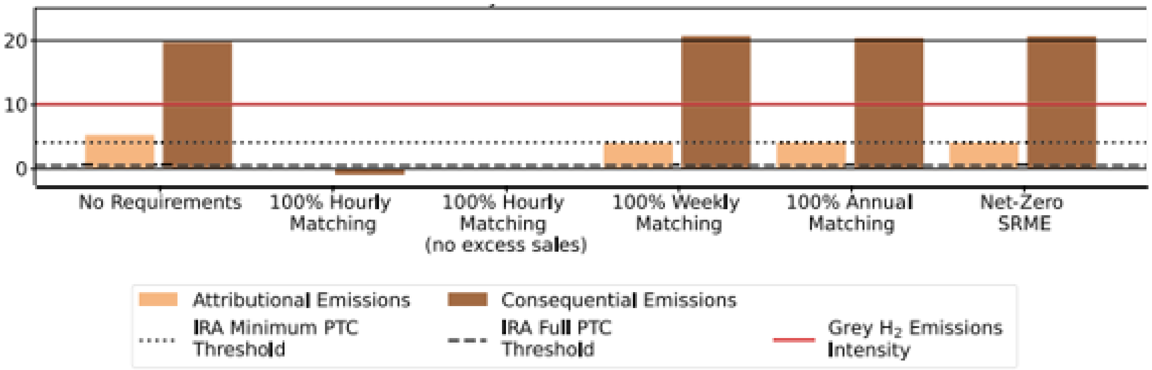
[xxxii] For example, in the non-California West or Southeast, where relatively little power is traded in real-time, trading hub prices may not be a good indicator of congestion (or lack thereof) in one direction or another.

[xxxiii] The concept of time-matching only really comes into play when the additionality principle has been met. Otherwise, there are still positives from requiring time-matching (e.g., doing so encourages the deployment of more flexible electrolyzer technologies), but the electrolyzer will raise GHG emissions regardless.

no clean energy contract (see Figure 10).[15] Similarly, Rhodium Group finds hydrogen production under annual average time-matching could increase emissions 34-58 MMT in 2030.[16]

Hourly time-matching is necessary to ensure that an electrolyzer's operations don't compel fossil fuel generation to ramp up, with University of California, Davis research finding its importance will only increase as more variable renewable energy comes online.[17]

Figure 10. Modeled emissions rates from 1 GW electrolyzer in Northern California (2030)



Source: Princeton (truncated from Figure 2).[18] Y-axis represents hydrogen emissions intensity in kgCO$_2$e/kgH$_2$.

This concept is now well-established, as demonstrated by several clean energy leaders. For example, Google recognized the importance of matching its clean energy supply to its data center operations in 2018 and has been working to close the gap.[19] Peninsula Clean Energy recently announced its commitment to time-match 99 percent of its load to clean energy generation by 2025, finding it would drive a mere 2 percent cost increase to its customers relative to status quo.[20] However, unlike corporate customers and energy providers, electrolyzers do not need to operate 24/7 to be financially viable, which will make time-matching simpler and cheaper.

Figure 11. Hourly carbon-free energy performance at an example Google data center

Source: Google.[21]

Research agrees hourly accounting is the minimum granularity acceptable for accurately assessing and controlling GHG emissions.[22] Hourly accounting is also necessary—if not sufficient—for closing loopholes that expose 45V to gaming risks based on how emissions are reported.

Special considerations

The time-matching principle carries two nested gaming risks that, if left unaddressed, could subvert the statute and award undue revenue to electrolyzers.

The first gaming risk is emissions bucketing**,** wherein electrolyzers could allocate most emissions caused by the electrolyzer to a small subset of hours while claiming all other hours emitted just enough GHGs to stay within the \$3/kgH$_2$ credit threshold.

Suppose an electrolyzer produced 100 kgH$_2$ in a year and procured enough additional, deliverable clean energy such that its annual GHG emissions totaled 300 kgCO$_2$. With annual time-matching, the electrolyzer could claim that 85 kgH$_2$ were zero-carbon and the remaining 15 kgH$_2$ had an emissions rate of 20 kgCO$_2$/kgH$_2$ (approximately that of electrolysis from a natural gas combustion turbine). This scenario would yield a payout of \$255.[xxxiv] However, if emissions were spread to all hydrogen production, the average rate would be 3 kgCO$_2$/kgH$_2$ for a total payout of \$60.[xxxv] This outcome arises from 45V's non-linear credit structure and implies emissions bucketing should not be allowed. Hourly tracking of electricity production and electrolyzer operations is necessary to prevent this gaming outcome.

The second gaming risk is subsidizing emissions-intensive hydrogen production, wherein electrolyzers could earn 45V revenue for part of their annual operations (used to pay off capital costs) and make unsubsidized, highly-emitting hydrogen for the other part of the year. This risk can remain even after emissions bucketing has been addressed via an hourly matching requirement.

Suppose an electrolyzer produced 100 kgH$_2$ in a year, procuring half of its power from additional, deliverable, time-matched clean energy and the other half from grid power. Without safeguards in place, the facility could earn \$150 in 45V revenue despite making hydrogen with an annual average emissions intensity of SMR or greater.[xxxvi]

At first glance, this risk might seem unlikely. If the electrolyzer needs to sell its hydrogen at \$1-2/kg, it would need to buy power at or below \$20-40/MWh for its hours of production that fall outside 45V compliance—a range that is still generally inexpensive and where clean energy is often the marginal resource. However, coal power plants also frequently fall within this range.

[xxxiv] Calculation is 85 kgH$_2$ x \$3/kgH$_2$ = \$255.

[xxxv] Calculation is 100 kgH$_2$ x \$0.60/kgH$_2$ = \$60.

[xxxvi] Calculations are 50 kgH$_2$ x \$3/kgH$_2$ = \$150; (50 kgH$_2$ x 0 kgCO2/kgH$_2$) + (50 kgH$_2$ x 20 kgCO$_2$/kgH$_2$) / (100 kgH$_2$) = 10 kgCO$_2$/kgH$_2$, assuming grid power has an emissions rate similar to a natural gas combined cycle.

Allowing electrolyzers to earn tax credits during hours of low-carbon hydrogen production without accounting for hours of high-carbon hydrogen production would also incentivize the deployment of inflexible electrolyzer technologies, which have lower capital costs.[23] These facilities could run around-the-clock, capturing clean energy only incidentally and buying grid power in other hours. Even if grid power is occasionally expensive, developers might find the tradeoff worthwhile to avoid having to invest in hydrogen storage. This type of policy design could raise GHG emissions dramatically while promoting investments that steer away from the flexible technologies and storage solutions that a clean hydrogen industry will need in a post-45V world.

Figure 12. Illustrative gaming risks

HOURLY ELECTROLYZER OPERATIONS (hours 1–6)

ACCURATE ACCOUNTING (AVG)

Hour	Production	Emissions	Emissions Rate	Credit Value	Credit Revenue
1	1 kgH_2	20 $kgCO_2$	20 $kgCO_2/kgH_2$	$0/kg	$0
2	1 kgH_2	3 $kgCO_2$	3 $kgCO_2/kgH_2$	$0.60/kg	$0.60
3	1 kgH_2	1 $kgCO_2$	1 $kgCO_2/kgH_2$	$1/kg	$1
4	1 kgH_2	0 $kgCO_2$	0 $kgCO_2/kgH_2$	$3/kg	$3
5	1 kgH_2	0 $kgCO_2$	0 $kgCO_2/kgH_2$	$3/kg	$3
6	1 kgH_2	0 $kgCO_2$	0 $kgCO_2/kgH_2$	$3/kg	$3
SUM					**$10.60**
AVG	6 kgH_2	24 $kgCO_2$	4 $kgCO_2/kgH_2$	$0.60/kg	**$3.60**
1	1 kgH_2	20 $kgCO_2$	20 $kgCO_2/kgH_2$	$0/kg	$0
2	1 kgH_2	4 $kgCO_2$	4 $kgCO_2/kgH_2$	$0.60/kg	$0.60
3-6	4 kgH_2	0 $kgCO_2$	0 $kgCO_2/kgH_2$	$3/kg	$12
SUM					**$12.60**

SUBSIDIZING EMISSIONS-INTENSIVE HYDROGEN (hours 1–6 and SUM, first block)

EMISSIONS BUCKETING (second block)

Black text shows an electrolyzer that produces 1 kgH2 in each of six hours but with different GHG emissions rates. Red text illustrates the "emissions bucketing" risk, in which emissions are grouped into the fewest possible hours (assuming an example upper limit of 20 $kgCO_2/kgH_2$) to maximize the number of hours qualifying for $3/kg. Orange text illustrates the "subsidizing emissions-intensive hydrogen" risk, in which each hour is paid at the value of its emissions rate but ignores the cumulative emissions impact of all hours. Green text illustrates "accurate accounting," which sums all hourly hydrogen production and GHG emissions in a year and assesses one credit value; hourly tracking is still essential to guard against "negative" emissions rates (i.e., buying more clean energy in one hour than the electrolyzer used).

These potential gaming outcomes would be inconsistent with Congress's intentions for the 45V tax credit. The companion IRA investment tax credit includes language that allows Treasury to recoup the full value of the tax credit if the supported clean hydrogen facility's annual average GHG emissions rate exceeds the limit facilities initially promise.[xxxvii]

[xxxvii] Under Section 48(a)(15)€, the statute makes clear that the Secretary shall issue "regulations or other guidance which recaptures so much of any credit allowed under this section as exceeds the amount of the credit which would have been allowed if the expected production were consistent with the actual verified production (or all of the credit so allowed in the absence of such verification)."

Treasury’s 45V guidance should achieve the same outcome and prevent subsidizing highly-emitting hydrogen production.

Implementation

The EU’s proposed time-matching rules include a phased approach, requiring monthly time-matching from the outset and transitioning to hourly matching beginning in 2030. Notably, the phase-in does not allow for grandfathering, meaning projects built before 2030 will still need to comply with hourly matching once that year begins.

Treasury’s rules for 45V should be similar but more stringent, starting with annual or monthly matching with a transition to hourly matching for *all* projects (including those built earlier) ideally by January 1, 2026. This phase-in allows plenty of time for hourly tracking systems to scale and mature but ensures developers design all electrolysis and clean energy projects with hourly matching in mind at the outset. Earlier compliance is both more feasible and more important for 45V. Unlike the U.S., the EU has a regulatory barrier whereby its 27 member-states need to update national energy tracking legislation and, as mentioned earlier, the EU has an emissions cap that covers the electricity sector which will catch emissions leakage from a later phase-in date. An early phase-in is also desirable as Treasury cannot readily mitigate the above-described gaming risks without hourly matching in place.

Mechanisms to facilitate hourly matching have already been developed and implemented in the U.S. and can quickly scale to ensure compliance across the country. The nonprofit registry M-RETS has offered hourly tracking services since 2019, and its coverage extends everywhere in the country except New England and New York.[24] PJM—the largest U.S. power market—also began offering hourly certificates in March 2023 through its Environmental Information Services subsidiary.[25] Third-party entities like EnergyTag can track hourly data if the registries in New England and New York cannot or choose not to provide such services.[26]

These entities are confident they can scale up within 18 months, suggesting a phase-in by 2026 offers ample time.[27] They will also likely be scaling up to support the Biden administration’s plans to reach 50 percent hourly matching of electricity demand with carbon-free electricity by 2030.[28]

Lastly, Treasury should implement an **annual average emissions test** to prevent the gaming risk of subsidizing emissions-intensive hydrogen production. This test could work as follows:

- For a given hour of electrolysis, the operator buys enough power from additional, deliverable clean energy resources (confirmed via hourly credits) to match consumption, accounting for line losses. Some grid power is allowable (see next section), and the operator also cannot procure more clean energy in a given hour than the electrolyzer is consuming (i.e., no negative emissions rates). That hour is assigned an emissions value in $kgCO_2$.
- At the end of the tax year, the operator divides the electrolyzer’s total GHGs emissions (by adding up all hourly emissions values) by its total annual hydrogen production to get an annual average emissions value in $kgCO_2/kgH_2$.

- The total 45V payout then becomes the operator's total annual hydrogen production multiplied by the 45V credit tier that the annual average emissions rate falls into.

To mitigate risk, operators can continuously monitor their electrolyzers' average emissions rates. For example, if an operator sees its electrolyzer's emissions rate fall outside of the \$3/kgH_2 range, it can run more conservatively (relative to its clean energy production) to bring the average back within the desired credit tier. Such volatility would likely be rare, however, as economically viable projects will likely overbuild clean energy supply relative to electrolyzers' demand to boost the latter's utilization rate and total hydrogen production (see next section). Electrolyzers are unlikely to have to follow minor instantaneous disruptions like fluctuations in wind speed, instead only needing to ramp down for more dramatic lulls in clean energy output.

ACCOUNTING FOR GRID POWER EMISSIONS

45V does not require electrolyzers to produce entirely zero-carbon hydrogen to earn tax credits—several tiers of credit values exist, and even the top tier allows a small share of GHG emissions. So, any accounting framework must allow for and quantify the use of some grid power, including for the purposes of assessing emissions from transmission line losses or hours that under-procure clean energy.

Treasury has several options available (of varying fidelity) for estimating emissions from any power consumed by electrolyzers that do not fully meet the three principles:

- Treasury could use the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model to estimate GHG emissions from grid power for a given region; however, GREET uses **average** grid emissions rates rather than marginal rates, making it an inaccurate tool for assessing electrolyzers' impact on the grid (i.e., forcing the marginal generator to ramp up when not using additional, deliverable, time-matched clean energy).
- Treasury could make a consistent **assumption** for the GHG emissions rate of grid power, such as tying it to the average U.S. natural gas combined cycle; while predictable, this methodology would undercount emissions when coal or oil are marginal and overcount emissions when lower-carbon resources are marginal.
- Treasury could use the EPA AVERT tool to estimate GHG emissions from grid power for a given region; AVERT uses **marginal** grid emissions rates, making it perhaps the best available option for accurately assessing electrolyzers' impact on the grid. Where available, power markets' own marginal emissions methodologies can also be relied upon.

IMPLEMENTATION SUMMARY

The three design principles, along with a method for estimating emissions from grid power, work together to ensure that electrolyzers can verifiably meet the 45V emissions thresholds.

The table below summarizes how Treasury can implement this framework, keeping hydrogen production emissions low and fostering the sustainable growth of a truly clean hydrogen industry long after 45V expires.

Table 1. Framework for implementing accurate 45V guidance

Design Principle	Component	Description
Additionality	New projects	Electrolyzers must source electricity via PPAs from new clean energy projects that began operations less than 36 months before the start of hydrogen production. Repowered projects must also meet a capital expenditure requirement, such as exceeding 30% of the costs of a greenfield project.
	Uprates	Electrolyzers must source electricity via PPAs from uprated clean energy facilities, limited to only the new margin of power output.
	Curtailed power	Electrolyzers can draw electricity from the grid if operators can prove that renewable energy facilities in the area would have otherwise been curtailed (e.g., zero or negative real-time power price).
Deliverability	Regionality	Electrolyzers must source electricity from clean energy projects located at least within the same NERC Reliability Assessment Area or power market zone—whichever is more granular.
	Congestion	As an exemption, electrolyzers can source electricity from clean energy projects located in neighboring interconnected zones if owners can show that zonal prices for the clean energy project are higher than or equal to those for the electrolyzer.
	Line losses	Electrolyzers must account for transmission line losses from their clean energy projects, which can be offset by procuring extra clean energy; owners can either use a loss rate preset by Treasury for a given interconnection or prove that their losses are lower.
Time-Matching	Hourly tracking	Electrolyzers can annually match their operations with clean energy procurement; beginning in 2026, operations must shift to hourly matching, including projects that began operations before 2026.
	Annual average emissions test	Electrolyzers will earn the 45V credit value equal to the annual sum of GHGs emitted divided by the sum of hydrogen produced.
Grid Power		Power consumed by electrolyzers that does not meet the above three principles should be assigned a regional marginal emissions rate, such as from the EPA AVERT tool.

ECONOMIC VIABILITY OF ACCURATE 45V GUIDANCE

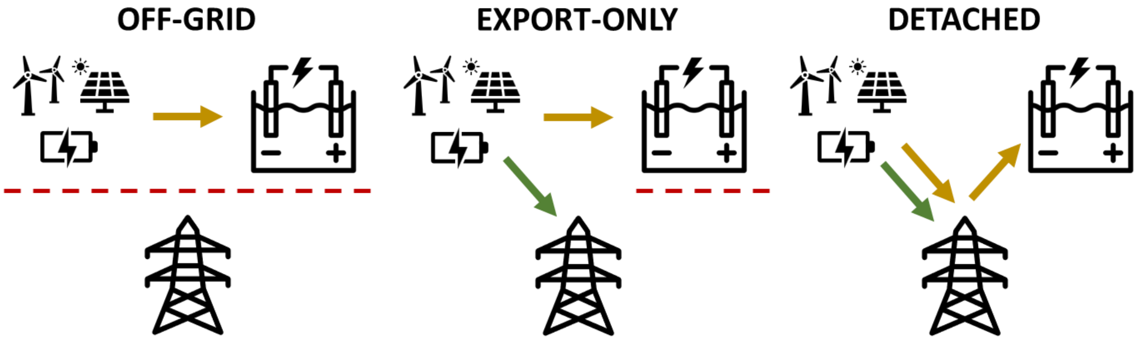
Loose 45V guidance would make electrolysis cheap across the country but at the cost of increasing GHG emissions and propping up projects that can't survive without 45V revenue. Accurate guidance would keep GHG emissions low and support an industry that can thrive long after the credit cliff, but it does so by imposing some necessary developmental and operational guardrails. This section shows 45V is still lucrative enough to make 45V-compliant projects economically viable at scale.

Specifically, this section illustrates different project configurations and demonstrates that co-located electrolyzer and clean energy projects—which are easier to understand and clearly compliant with 45V emissions rates—are profitable business models in parts of the U.S. with favorable renewable resource quality. The three principles offer flexibility to allow these components to be separated geographically, which can further improve project economics by using the best land for clean energy development and building electrolyzers near hydrogen off-takers.

PROJECT DESIGNS

Developers seeking to build clean electrolysis projects will take one of three approaches, illustrated in the below diagram. "Off-grid" projects involve building co-located clean energy portfolios and electrolyzers that are not connected to the power grid. "Export-only" projects take the same configuration but allow the clean energy portfolio to connect and send electricity to the grid. "Detached" projects site clean energy and electrolyzers on different points on the grid, requiring proof of compliance with the three principles to ensure accurate GHG emissions accounting. As Figure 13 moves from left to right, the clean energy has a wider market, and the hydrogen electrolyzer has more locational flexibility.

Figure 13. Illustrative clean electrolytic hydrogen project configurations



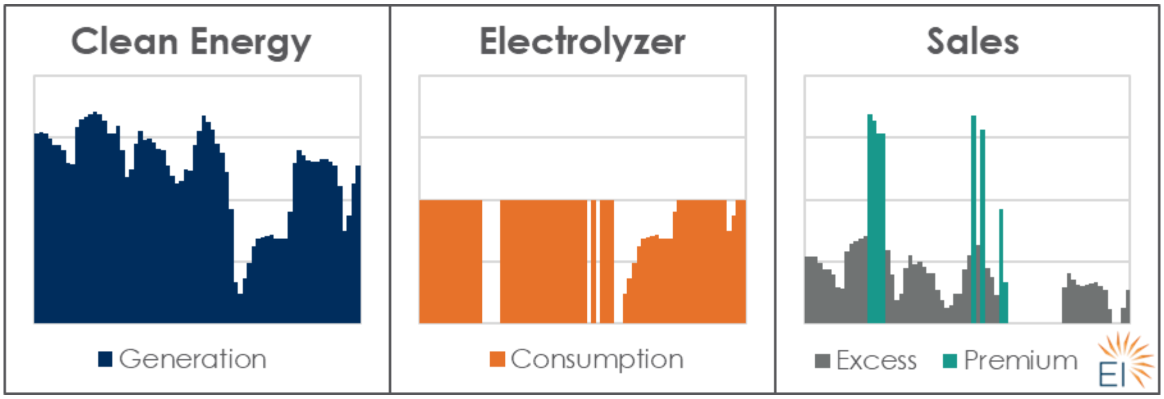
Yellow arrows represent clean power sent to the electrolyzer, whether directly (physical) or via the grid (virtual). Green arrows represent clean power sent to the grid that is not used by the electrolyzer (due to extra supply or high prices).

Developers are already showing off-grid projects are economic under 45V. For example, AES and Air Products announced a joint investment of $4 billion to build, own, and operate 1.4 gigawatts of new wind and solar resources and enough electrolyzers to produce more than 200 metric tons of hydrogen per day, targeting commercial operations by 2027.[29] The project may later include battery storage to boost electrolyzers' operations, but it is financially viable absent storage or a grid connection.[xxxviii,30]

Export-only projects make new revenue streams available that are impossible to monetize in an off-grid setup.[xxxix] Under this configuration, developers can oversize their clean energy portfolios to boost electrolyzer operations (see Figure 14), increasing revenue from 45V credits as well as clean hydrogen sales.

However, they can also sell excess power to the grid and turn off their electrolyzer during hours of high market power prices to monetize the full clean energy portfolio's output at a premium.[xl] This configuration also makes it easier to finance the project, as the viability of the clean energy projects (which can sell to the grid) is less dependent on the viability of the electrolyzer (which otherwise would have been the only offtaker).

Figure 14. Illustrative operations and revenue streams for export-only projects



Electrolyzers with paired oversized clean energy projects can achieve relatively stable clean hydrogen production by selling excess electricity to the grid; they can also leverage flexibility during significant clean energy shortages or periods of high market power price value by ramping the electrolyzer down and selling the full clean energy output to the grid.

[xxxviii] Based on publicly-available information about the project at the time of this paper's publication.

[xxxix] Any grid-connected project will face one new risk: needing to interconnect to the power grid—a process which can incur high costs, delays, and overall uncertainty.

[xl] The project would choose to turn off the electrolyzer and send all electricity to the grid when power prices rise above the combined value of the 45V credit and the hydrogen offtake price, or roughly $80/MWh if assuming an offtake price of $1/kg. The exception would be if it were more valuable to maintain an uninterrupted stream of hydrogen (e.g., as part of an offtake agreement) than to briefly halt operations.

Detached projects have the same operational framework as export-only projects but with electrolyzers and clean energy resources geographically separated, offering greater locational flexibility. Thus, if export-only projects are financially viable, detached ones likely are by extension, with potentially higher grid interconnection costs[xli] and the minor, mostly administrative, added expenses of proving their compliance with the three principles (e.g., through a PPA, accounting of transmission line losses, and use of hourly credits).

PROJECT ECONOMICS

We analyzed the economics of co-located, hourly-matched, new wind, solar, and electrolyzer projects (i.e., export-only configurations), finding they are financially viable from the outset.

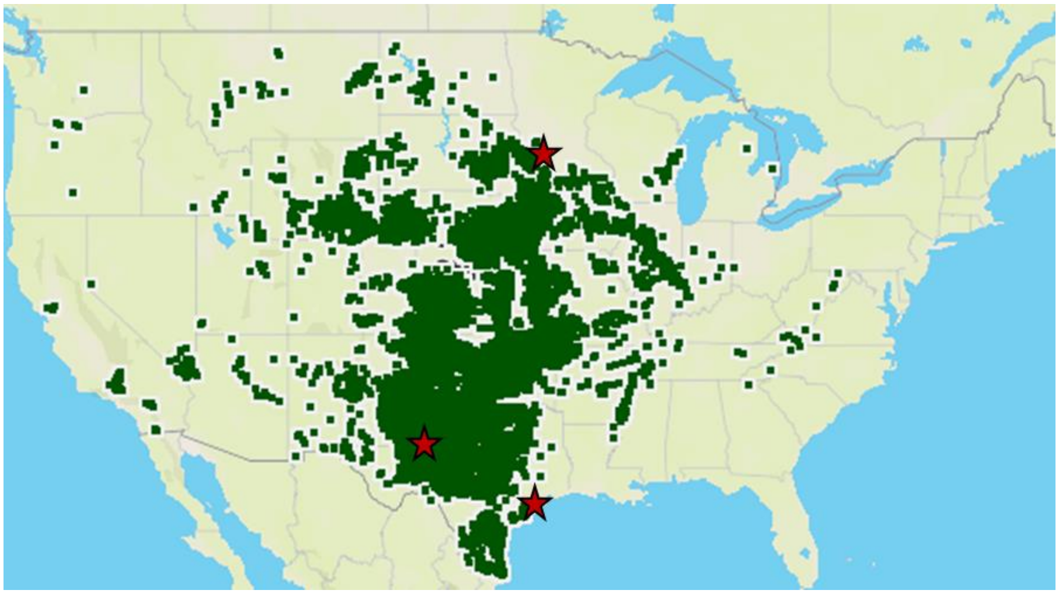
Our analysis oversized wind and solar projects relative to the electrolyzer's capacity, allowing them to earn extra revenue by selling power to the grid. However, as renewables are competitive on their own, we constrained the revenue projects could earn from power sales and picked years of low power prices. This kept the focus on the value of electrolysis while ensuring our findings are conservative with significant potential to be more profitable.[xlii] We also set the offtake price of electrolytic hydrogen to $1/kg to ensure it can compete with SMR-derived hydrogen.

The key determinant of project economics was choosing locations with a strong wind resource and decent solar resource. As wind is both a better match for electrolyzer operations and varies more across the country, desirable sites more closely match areas of high wind quality. Wide swaths of the U.S. meet this description, concentrated in the Great Plains, Interior West, and Texas.

[xli] Interconnection costs might not change between export-only and detached projects if the former plan to leverage opportunities to sell all of the clean energy facility's power to the grid when prices are high. However, if an export-only configuration plans to only sell excess electricity, an alternative detached arrangement would incur higher costs.

[xlii] Average historical power prices are higher than the cost of new wind and solar (<$40/MWh), meaning without constraints, models would build even more renewables; however, this power is most often useful to electrolysis, such as when market power prices are under $80/MWh (the rough value of a $3/kgH$_2$ tax credit and $1/kgH$_2$ sale price).

Figure 15. U.S. locations with wind and solar resources averaging less than $25/MWh



Dots represent locations where solar and wind resources have combined average levelized costs of electricity less than $25/MWh (including IRA clean energy tax credits), suggesting projects compliant with the three pillars may be financially viable. Stars indicate sites tested in our financial analysis. Sites are identified using exclusion criteria from NREL's ReEDS model. Green squares are not to scale—each site is 11.5x11.5 km. More than 6,900 sites representing more than 1,000 gigawatts of electrolyzer capacity met these criteria. Credit: Umed Paliwal, University of California, Berkeley.

We modeled three test sites in our analysis: Houston (decent wind, good solar, and near industry and a major metro area), Southwest Minnesota (good wind, decent solar, and opportunity for new green ammonia production), and West Texas (great wind and solar and abundant land).

As summarized below, export-only projects are profitable even after paying costs for electrolyzer equipment, supporting and auxiliary equipment, operations and maintenance, financing, and a tax shield.[xliii] They deliver competitive hydrogen at today's project costs, supporting electrolyzer utilization rates upwards of 80 percent.

[xliii] Key assumptions include PEM electrolyzer costs of $1,400/kW ($196/kW-yr assuming 7% WACC over 10 years), operations and maintenance costs of $90/kW-yr, and finance and tax shield costs of $90/kW-yr. Wind and solar costs come from the National Renewable Energy Laboratory's Annual Technology Baseline report (post-IRA), renewable production assumptions come from Renewables.Ninja, and power prices use historical zonal ISO hourly day-ahead prices. Full assumptions and results will be released as Appendix B: see https://energyinnovation.org/publication/smart-design-of-45v-hydrogen-production-tax-credit-will-reduce-emissions-and-grow-the-industry

Table 2. Summary results of export-only project financial analysis (1 MW electrolyzer)

Metric	West Texas	Near Houston	Southwest Minnesota
Electrolyzer capacity (MW)	1	1	1
Electrolyzer capacity factor (%)	88.1	81.8	87.0
Solar capacity (MW)	3.0	3.5	2.0
Solar capacity factor (%)	25.9	20.8	21.2
Solar levelized cost ($/MWh)	16.20	19.32	27.47
Wind capacity (MW)	2.0	2.8	4.0
Wind capacity factor (%)	43.6	34.5	45.2
Wind levelized cost ($/MWh)	19.20	23.93	16.39
Share of power sold to grid (%)	47	52	61
Revenue from hydrogen sales and 45V (%)	79	72	76
Revenue from excess power sales to grid (%)	16	22	24
Revenue from premium power sales to grid (%)	5	6	0
Profits ($/kW-yr)	**143**	**85**	**61**

Two additional insights are important to supplement this analysis.

First, electrolyzers do not need to run around the clock to be profitable. In fact, utilization does little to reduce the cost of hydrogen beyond a 50 to 70 percent utilization rate, after which electricity prices are the major determinant of hydrogen production costs.[31] This share will fall as electrolyzer capital costs continue to decline, meaning more projects will be economic in more places with time (i.e., not just what's shown in the above map). When capital costs are lower and electrolyzers only need to run 20 to 30 percent of the time to be profitable, solar-only projects will become viable. This is a desirable long-term outcome—flexible electrolyzers that run only in very low-priced hours (especially when 45V expires) can help integrate higher shares of renewable energy onto the grid and eventually create business models that use otherwise curtailed power.

Second some industrial hydrogen consumers may require an uninterruptible supply of hydrogen. However, this does not mean electrolyzers must run around the clock. Instead, developers can oversize their electrolyzers relative to their offtakers' needs and build hydrogen storage to smooth fluctuations in production.[xliv] Hydrogen storage costs vary greatly, but those near geologic storage

---

[xliv] Other options may be available to accommodate fluctuations in clean hydrogen production as well. For example, industrial customers may be able to access SMR-based hydrogen to fill in for gaps in clean hydrogen access, and

such as salt caverns will be on the low end (especially where several projects can share a single site) while those using above-ground pressurized containers will be higher. In interconnected hydrogen hubs, pipelines may also be an option to give offtakers consistent supplies while electrolyzers' production varies. In any case, our analysis shows these projects have profit margins that can support storage or pipeline investments.

In sum, our analysis shows export-only projects are financially viable under 45V today in large parts of the U.S., suggesting more flexible detached project configurations are economic as well. Several major renewable energy and electrolyzer developers confirm this finding, signing onto a letter stating "hydrogen projects that satisfy the three [principles] can be extremely competitive from the outset."[32] Thus, Treasury need not compromise on accurate 45V guidance to ensure the near- and long-term success of clean electrolytic hydrogen.

CONCLUSION

Treasury's design of 45V guidance will be critically influential to both the level of GHG emissions caused by electrolytic hydrogen production and the long-term growth and viability of the burgeoning clean hydrogen industry.

Loose guidance would be highly detrimental on both fronts, increasing GHGs from hydrogen production by two to five times and setting up the industry for failure once the tax credit expires.

Fortunately, setting standards that closely approximate compliance with three principles—additionality, deliverability, and time-matching—and that account for GHG emissions from any use of grid power can avoid considerable harm and achieve major benefits.

With analyses showing projects that meet these principles would be financially viable from the start, Treasury should adopt accurate 45V guidance with confidence that it will spur robust growth of clean electrolytic hydrogen, supporting GHG emissions reductions today and long after the policy expires.

---

developers are testing more flexible ammonia production processes (allowing for more intermittent hydrogen supply)—see: https://www.sciencedirect.com/science/article/abs/pii/S1540748922000347.

REFERENCES

---

[1] "Marginal Emissions Rate - A Primer" (PJM), accessed March 28, 2023, https://www.pjm.com/-/media/etools/data-miner-2/marginal-emissions-primer.ashx.

[2] LShaver, "What Is Marginal Energy?," *Stack Exchange*, February 20, 2019, https://sustainability.stackexchange.com/questions/7112/what-is-marginal-energy.

[3] "2022 Quarterly State of the Market Report for PJM: January through September" (Monitoring Analytics, LLC, 2022), https://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2022/2022q3-som-pjm-sec3.pdf. Figure 3-48.

[4] "Pathways to Commercial Liftoff: Clean Hydrogen" (U.S. Department of Energy, March 2023), https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf. Figure 10.

[5] "Plug EX-4250D Electrolyzer (English)," Plug Power, April 20, 2022, https://resources.plugpower.com/electrolyzers/ex-4250d-f041122.

[6] "Questions and Answers on the EU Delegated Acts on Renewable Hydrogen," European Commission, February 13, 2023, https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_595.

[7] Kate Abnett, "EU Plans Subsidies for Hydrogen Made Using Renewable Energy -Draft Document," Reuters, March 16, 2023, https://www.reuters.com/business/energy/eu-plans-subsidies-hydrogen-made-using-renewable-energy-draft-document-2023-03-16/.

[8] Wilson Ricks, Qingyu Xu, and Jesse D. Jenkins, "Minimizing Emissions from Grid-Based Hydrogen Production in the United States," *Environmental Research Letters* 18, no. 1 (January 2023): 014025, https://doi.org/10.1088/1748-9326/acacb5. Supplementary Figure 19.

[9] Ben King et al., "Scaling Green Hydrogen in a Post-IRA World," *Rhodium Group* (blog), March 16, 2023, https://rhg.com/research/scaling-clean-hydrogen-ira/.

[10] "Power Uprates," U.S. Nuclear Regulatory Commission, March 27, 2023, https://www.nrc.gov/reactors/operating/licensing/power-uprates.html.

[11] "Supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by Establishing a Union Methodology Setting out Detailed Rules for the Production of Renewable Liquid and Gaseous Transport Fuels of Non-Biological Origin" (European Commission, February 10, 2023), https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf.

[12] King et al., "Scaling Green Hydrogen in a Post-IRA World."

[13] "How Much Electricity Is Lost in Electricity Transmission and Distribution in the United States?," U.S. Energy Information Administration, November 14, 2022, https://www.eia.gov/tools/faqs/faq.php.

[14] "ERO Enterprise | Regional Entities," North American Electric Reliability Corporation, accessed April 10, 2023, https://www.nerc.com/AboutNERC/keyplayers/Pages/default.aspx.

[15] Ricks, Xu, and Jenkins, "Minimizing Emissions from Grid-Based Hydrogen Production in the United States."

[16] King et al., "Scaling Green Hydrogen in a Post-IRA World."

[17] Gregory J. Miller, Kevin Novan, and Alan Jenn, "Hourly Accounting of Carbon Emissions from Electricity Consumption," *Environmental Research Letters* 17, no. 4 (April 2022): 044073, https://doi.org/10.1088/1748-9326/ac6147.

[18] Ricks, Xu, and Jenkins, "Minimizing Emissions from Grid-Based Hydrogen Production in the United States."

[19] "24/7 by 2030: Realizing a Carbon-Free Future" (Google, September 2020), 7, https://www.gstatic.com/gumdrop/sustainability/247-carbon-free-energy.pdf.

[20] Jan Pepper et al., "Achieving 24/7 Renewable Energy by 2025," *Peninsula Clean Energy*, January 2023, 7, https://www.peninsulacleanenergy.com/wp-content/uploads/2023/01/24-7-white-paper-2023.pdf.

[21] "24/7 by 2030: Realizing a Carbon-Free Future," 7.

[22] Miller, Novan, and Jenn, "Hourly Accounting of Carbon Emissions from Electricity Consumption."

---

[23] Mike O'Boyle et al., "Coal Cost Crossover 3.0 Interactive Visual Feature," Energy Innovation: Policy and Technology LLC, January 29, 2023, https://energyinnovation.org/2023/01/29/coal-cost-crossover-3-0-interactive-visual-feature/.

[24] "M-RETS Hourly Tracking," *M-RETS* (blog), accessed April 10, 2023, https://www.mrets.org/hourlydata/.

[25] "PJM EIS To Produce Energy Certificates Hourly" (PJM EIS, February 13, 2023), https://www.pjm-eis.com/-/media/about-pjm/newsroom/2023-releases/20230213-pjm-eis-to-produce-energy-certificates-hourly.ashx.

[26] "Granular Certificate Scheme Standard" (EnergyTag, March 31, 2022), https://energytag.org/wp-content/uploads/2022/03/20220331-EnergyTag-GC-Scheme-Standard-v1-FINAL.pdf.

[27] "Re: Implementation of the IRA 45V Clean Hydrogen Tax Credits as It Relates to Guidelines for Emissions Accounting of Grid-Connected Electrolyzers" (NRDC, February 23, 2023), https://www.nrdc.org/sites/default/files/2023-03/joint-letter-45v-implementation-20230223.pdf.

[28] "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability," The White House, December 8, 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/.

[29] AES, "Air Products and AES Announce Plans to Invest Approximately $4 Billion to Build First Mega-Scale Green Hydrogen Production Facility in Texas," PR Newswire, December 8, 2022, https://www.prnewswire.com/news-releases/air-products-and-aes-announce-plans-to-invest-approximately-4-billion-to-build-first-mega-scale-green-hydrogen-production-facility-in-texas-301697873.html.

[30] "Air Products/AES Green Hydrogen Project," Air Products, December 8, 2022, https://investors.airproducts.com/events/event-details/air-products-conference-call-3.

[31] IEA, "The Future of Hydrogen – Analysis," IEA, June 2019, https://www.iea.org/reports/the-future-of-hydrogen. Figure 13.

[32] "Re: Implementation of the IRA 45V Clean Hydrogen Tax Credits as It Relates to Guidelines for Emissions Accounting of Grid-Connected Electrolyzers."