APPENDIX A: EPA AVERT ANALYSIS OF UPSTREAM ELECTROLYSIS EMISSIONS

DAN ESPOSITO, ERIC GIMON, AND MIKE O'BOYLE

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This appendix details the methodology and findings of our analysis of short-run marginal greenhouse gas emissions from electrolysis when forgoing each of the three design principles of additionality, deliverability, and hourly time-matching. Our assessment uses the United States Environmental Protection Agency's (EPA) Avoided Emissions and Generation Tool (AVERT)—a free tool that evaluates changes in emissions from power plants resulting from energy policies.[2] At the time of our analysis, 2021 was the latest year of available data.

Our analysis shows that forgoing any of these principles would create conditions in which an electrolyzer could earn the top value of the Inflation Reduction Act's (IRA) Section 45V Clean Hydrogen Production Tax Credit (45V) without satisfying the requisite threshold for upstream and production GHG emissions. Achieving more accurate GHG emissions impacts over the life of the policy requires assessing long-run marginal GHG emissions, which includes "both operational and structural" impacts to the power system rather than assuming a static system.[3,4]

METHODOLOGY

AVERT calculates short-run marginal emissions rates by assuming a 0.5 percent displacement of existing demand by one of six resource categories for each of 14 regions (together spanning the contiguous 48 U.S. states). The resource categories include onshore wind, offshore wind, utility-scale photovoltaic (PV), distributed PV, portfolio energy efficiency (EE), and uniform EE. Since AVERT uses actual historical power plant operations data, EPA recommends it not be used to examine emissions changes more than five years out from the test year.

We used AVERT data to isolate the short-run marginal GHG emissions impacts of forgoing one of the three design principles of additionality, deliverability, and hourly time-matching. As part of this analysis, we split the deliverability principle into two components—line loss accounting (i.e., accounting for the extra clean energy generation needed to overcome electrical transmission line losses en route to the electrolyzer) and regionality (i.e., siting clean energy and electrolyzers in the same or different AVERT regions).

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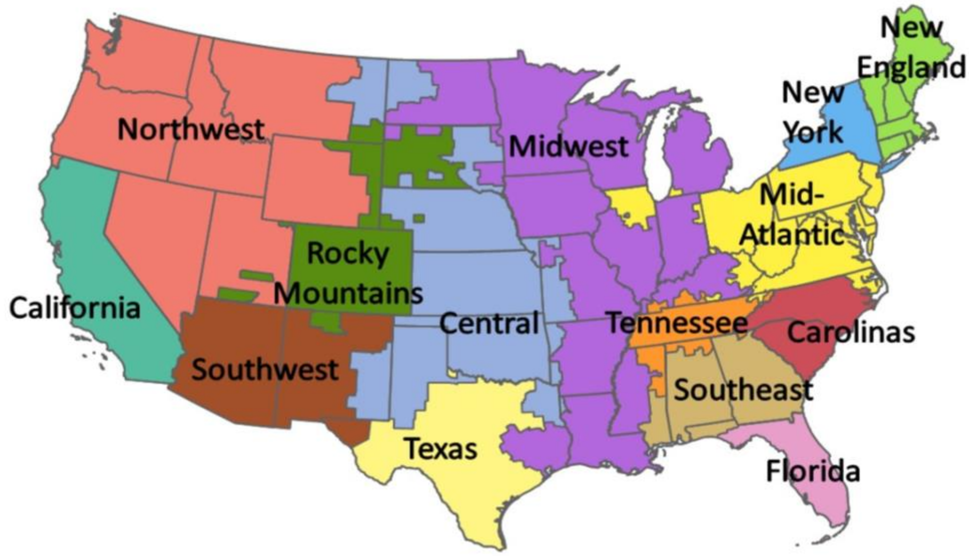
[1] This appendix complements an April 2023 Energy Innovation paper titled "Smart Design of 45V Hydrogen Production Tax Credit Will Reduce Emissions and Grow the Industry," found here: https://energyinnovation.org/publication/smart-design-of-45v-hydrogen-production-tax-credit-will-reduce-emissions-and-grow-the-industry/.

[2] https://www.epa.gov/avert.

[3] See: https://www.cell.com/iscience/fulltext/S2589-0042(22)00185-7?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2589004222001857%3Fshowall%3Dtrue.

[4] Our analysis does not assess *downstream* GHG emissions impacts from using hydrogen to replace other fuels, as this lies outside the scope of the IRA's definition of lifecycle GHG emissions of hydrogen production. However, these downstream emissions reductions often do little to offset upstream production emissions; for example, if hydrogen replaces natural gas in combustion applications (e.g., burning in furnaces or turbines), it will only cut emissions by 6 $kgCO_2/kgH_2$, while production emissions can be as high as 40 $kgCO_2/kgH_2$.

Figure A1. AVERT regions



Per the EPA, "the AVERT regions are generally aggregations of balancing authorities, and are similar, but not identical, to the mapping used in [the U.S. Energy Information Administration's (EIA)] Hourly Electric Grid Monitoring dataset (EIA 930). This map is for representational purposes only, as the interconnectedness of regions means that the boundaries drawn here are only approximate."[5]

Step 1: Determining the marginal emissions of new electrolyzer load

We used AVERT's uniform EE metric as a basis for estimating the short-run marginal GHG emissions caused by additional, local,[6] around-the-clock (24/7)[7] electrolysis demand. The uniform EE emissions metric includes transmission line losses, as its definition is "energy savings [at the point of use that are] consistent throughout the year." That is, the uniform EE metric estimates the marginal GHG emissions reduction of cutting electricity demand by 0.5 percent on an around-the-clock basis; the converse of this metric thus estimates the marginal GHG emissions increase of raising electricity demand by 0.5 percent from a new grid-connected electrolyzer, which causes upstream power generators to increase their generation enough to serve the new demand *and* account for line losses.

The "Regional Emissions Rates" table in AVERT provides data for the "Avoided CO_2 Rate" in pounds of CO_2 per megawatt-hour (MWh) by region for the six resource categories. We converted these rates to kilograms (kg) of CO_2 emitted (or avoided) per kg of hydrogen (H_2) produced by applying an electrolyzer efficiency of 50 kilowatt-hours (kWh) per kg H_2.[8]

We assumed line losses of 8.39 percent for the Western Interconnection, 7.50 percent for the Eastern Interconnection, and 4.95 percent for the Texas Interconnection, using EIA data.[9] Applying these losses to the uniform EE metric removes the GHG emissions impact of forgoing line loss accounting in a 45V accounting framework.

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[5] https://www.epa.gov/avert.

[6] "Local" here means located within the same AVERT region as the facilities from which the electrolyzer is drawing power.

[7] Throughout the analysis, "24/7" is an overly restrictive proxy for hourly matched electricity supply and demand. That is, 24/7 operations for both new clean energy and electrolysis are not *necessary* to meet an hourly matching requirement, but they are *sufficient*.

[8] The electrolyzer efficiency rounds up from 49.9 kWh/kgH_2 in this Plug Power spec sheet: https://resources.plugpower.com/electrolyzers/ex-4250d-f041122.

[9] These assumptions are average losses over transmission *and* distribution lines. The farther electrolyzers are located from clean energy, the greater the loss component will be. Electrolyzers connected to the transmission system will experience relatively fewer losses than those connected to the distribution system, all else equal. See AVERT's Library tab, Table 2: https://www.epa.gov/avert.

We also assume new onshore wind or utility PV comes online to offset some of, all of, or more than these new GHG emissions from electrolysis, except for the "no additionality" analysis.[10] Table A1 summarizes the relevant AVERT data resulting from converting the emissions impacts of adding supply (emissions avoided) and adding demand (emissions increased) to $kgCO_2/kgH_2$ and isolating the emissions impacts of line losses.

Table A1. Avoided or induced CO_2 emissions rate ($kgCO_2/kgH_2$)

Region	Onshore Wind	Utility PV	Electrolysis With Line Losses	Electrolysis Without Line Losses	Line Losses
California	(22.35)	(22.57)	24.51	22.45	2.06
Carolinas	(32.49)	(32.57)	35.31	32.66	2.65
Central	(39.70)	(38.34)	42.32	39.15	3.17
Florida	(22.78)	(23.78)	24.89	23.03	1.87
Mid-Atlantic	(33.35)	(34.20)	36.38	33.65	2.73
Midwest	(38.65)	(38.37)	41.66	38.53	3.12
New England	(22.34)	(22.90)	24.30	22.48	1.82
New York	(22.60)	(23.73)	24.78	22.92	1.86
Northwest	(32.66)	(32.72)	35.73	32.73	3.00
Rocky Mountains	(40.44)	(39.39)	43.66	40.00	3.66
Southeast	(30.56)	(32.52)	34.40	31.82	2.58
Southwest	(28.44)	(28.06)	30.99	28.66	2.32
Tennessee	(29.35)	(29.77)	32.06	29.65	2.40
Texas	(27.66)	(27.14)	28.89	27.46	1.43

Step 2: Varying the principles

We used the data in Table A1 to estimate the short-run marginal GHG emissions impacts of forgoing additionality, regionality, line losses, and hourly time-matching in designing 45V guidance.

- To estimate the impact of forgoing **additionality,** we used AVERT's uniform EE metric but removed line losses (see "electrolysis without line losses" column). This represents the emissions impact from adding new 24/7 electricity demand without building anything new to offset the emissions; that is, buying existing clean energy—or taking existing clean energy off the grid for behind-the-meter electrolysis operations—does nothing to reduce the emissions incurred from adding new demand.
- To estimate the impact of forgoing **regionality,** we subtracted "electrolysis without line losses" in one region from "electrolysis without line losses" in another region. The subtracted component represents new 24/7 (time-matched) clean electricity built in a separate region from the electrolyzer. AVERT data cannot be used to estimate GHG emissions that might result from locating new clean energy and electrolyzers within the same region, which might be significant depending on the level of transmission congestion that exists between the projects.

[10] There is some uncertainty as to whether contracts with existing clean energy resources and their associated Renewable Energy Certificates (RECs) will lead to higher renewable energy project revenues and therefore prompt more renewables to come online. This analysis assumes there will be ample RECs or zero-emissions credits from existing nuclear and hydro facilities—as well as wind and solar facilities in states that have exceeded their clean energy standards or that lack those standards—such that it is appropriate to assume contracts with existing clean energy resources do not lead to new demand for clean energy projects that would offset the emissions from new electrolyzers.

- To estimate the impact of forgoing **line loss accounting,** we applied the previously mentioned EIA assumptions of average line losses by U.S. interconnection to the “electrolysis with line losses” column, corresponding to the relevant AVERT region in each instance.
- To estimate the impact of forgoing **hourly time-matching,** we subtracted “onshore wind” or “utility PV” from “electrolysis without line losses” for a given region. The former components represent new, local clean energy that offsets 0.5 percent of demand on an annual average basis; the latter component represents new, local electrolysis demand that incurs 0.5 percent of demand on an annual average basis. The difference represents the emissions increase—or decrease—resulting from the time mismatch of variable clean energy generation and uniform electrolysis demand.

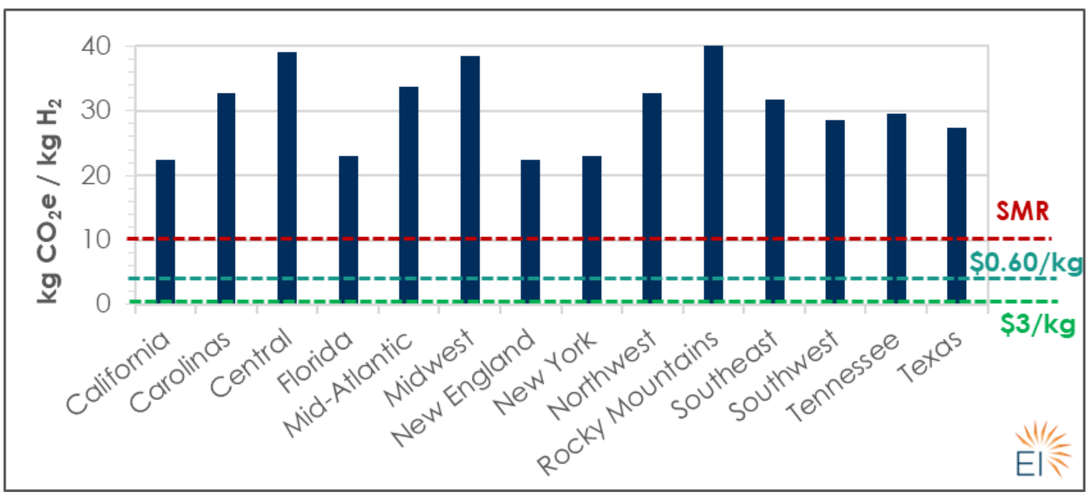
RESULTS

This section discusses and illustrates the results of our analysis of the short-run marginal GHG emissions impacts of forgoing additionality, regionality, line losses, and hourly time-matching in designing 45V guidance.

Additionality

Forgoing additionality in 45V guidance design results in substantial, immediate, and widespread GHG emissions impacts. We find electrolysis that takes credit for non-additionality clean energy would incur 22 to 40 $kgCO_2/kgH_2$ across all 14 modeled regions making up the 48 contiguous U.S. states. Even the lower bound of this emissions rate range is more than twice that of steam methane reformation (SMR) and approximately 50x that of the emissions threshold for earning the $3/kg tax credit.

Figure A2. Short-run marginal GHG emissions impacts of forgoing additionality (2021)



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 AVERT with 2021 data. It is not representative of emissions impacts in later years and does not assess long-run marginal GHG emissions impacts.

Regionality

Forgoing regionality in 45V guidance design (as part of the deliverability principle) results in GHG emissions impacts that can be large—though the specifics depend on location. For example, our analysis shows that an electrolyzer built in the Rocky Mountains region would produce hydrogen with a GHG emissions intensity greater than 17 $kgCO_2/kgH_2$ if the corresponding new, hourly-matched clean energy resources were built in California. This rate is more than 1.5x that of SMR and nearly 40x that of the emissions threshold for earning the $3/kg tax credit.

When considering only *short-run* marginal GHG emissions, the opposite emissions rate would hold true if the electrolyzer and clean energy swapped locations. However, with no regionality requirement, new clean energy would likely be concentrated in some regions (e.g., where it's easiest to build clean energy, such as Texas) while electrolyzers might be concentrated in others (e.g., where hydrogen offtake is most accessible). Over time, these clean energy deployments could crowd out projects that would have been built anyway; further, this discrepancy in where clean energy and electrolyzers are built would change the marginal emissions impacts of additional deployments.

While our AVERT analysis shows forgoing regionality could demonstrably put individual projects well outside of the $3/kg threshold, the analysis is limited to estimating short-run marginal impacts. Studies that assess *long-run* marginal GHG emissions are necessary to tease out collective emissions impacts from this policy design over 10 to 20 years of 45V-driven capital investments.

Figure A3. Short-run marginal GHG emissions impacts of forgoing regionality (2021)

Build new 24/7 clean electricity in…	Build new electrolyzers in…													
Region	Cal.	Car.	Cen.	FL	Atl.	Mid.	NE	NY	NW	RM	SE	SW	TN	TX
California (Cal.)	0.00	10.21	16.70	0.57	11.19	16.08	0.02	0.47	10.28	17.54	9.37	6.21	7.20	5.01
Carolinas (Car.)	-10.21	0.00	6.49	-9.63	0.99	5.87	-10.18	-9.74	0.07	7.34	-0.84	-3.99	-3.01	-5.20
Central (Cen.)	-16.70	-6.49	0.00	-16.12	-5.50	-0.61	-16.67	-16.23	-6.42	0.85	-7.33	-10.48	-9.50	-11.69
Florida (FL)	-0.57	9.63	16.12	0.00	10.62	15.51	-0.55	-0.10	9.70	16.97	8.79	5.64	6.63	4.43
Mid-Atlantic (Atl.)	-11.19	-0.99	5.50	-10.62	0.00	4.89	-11.17	-10.72	-0.92	6.35	-1.83	-4.98	-3.99	-6.19
Midwest (Mid.)	-16.08	-5.87	0.61	-15.51	-4.89	0.00	-16.06	-15.61	-5.80	1.46	-6.71	-9.87	-8.88	-11.07
New England (NE)	-0.02	10.18	16.67	0.55	11.17	16.06	0.00	0.45	10.25	17.52	9.34	6.19	7.18	4.98
New York (NY)	-0.47	9.74	16.23	0.10	10.72	15.61	-0.45	0.00	9.81	17.07	8.90	5.74	6.73	4.54
Northwest (NW)	-10.28	-0.07	6.42	-9.70	0.92	5.80	-10.25	-9.81	0.00	7.26	-0.91	-4.07	-3.08	-5.27
Rocky Mountains (RM)	-17.54	-7.34	-0.85	-16.97	-6.35	-1.46	-17.52	-17.07	-7.26	0.00	-8.17	-11.33	-10.34	-12.53
Southeast (SE)	-9.37	0.84	7.33	-8.79	1.83	6.71	-9.34	-8.90	0.91	8.17	0.00	-3.16	-2.17	-4.36
Southwest (SW)	-6.21	3.99	10.48	-5.64	4.98	9.87	-6.19	-5.74	4.07	11.33	3.16	0.00	0.99	-1.20
Tennessee (TN)	-7.20	3.01	9.50	-6.63	3.99	8.88	-7.18	-6.73	3.08	10.34	2.17	-0.99	0.00	-2.19
Texas (TX)	-5.01	5.20	11.69	-4.43	6.19	11.07	-4.98	-4.54	5.27	12.53	4.36	1.20	2.19	0.00

The first row represents regions where new electrolyzers are deployed, while the first column represents regions where new 24/7 clean energy resources are deployed. Shades of red represent increases in GHG emissions, while shades of green represent decreases in GHG emissions. The diagonal line of zeros (where electrolyzers and clean energy are deployed in the same region) is an oversimplification due to data limitations in AVERT—namely, it ignores the potential presence of intraregional congestion. Notably, without regionality, electrolyzers could cause GHG emissions that are more than 1.5x as high as those from SMR. Analysis uses AVERT with 2021 data. It is not representative of emissions impacts in later years and does not assess long-run marginal GHG emissions impacts, which may be much higher.

Line losses and hourly time-matching

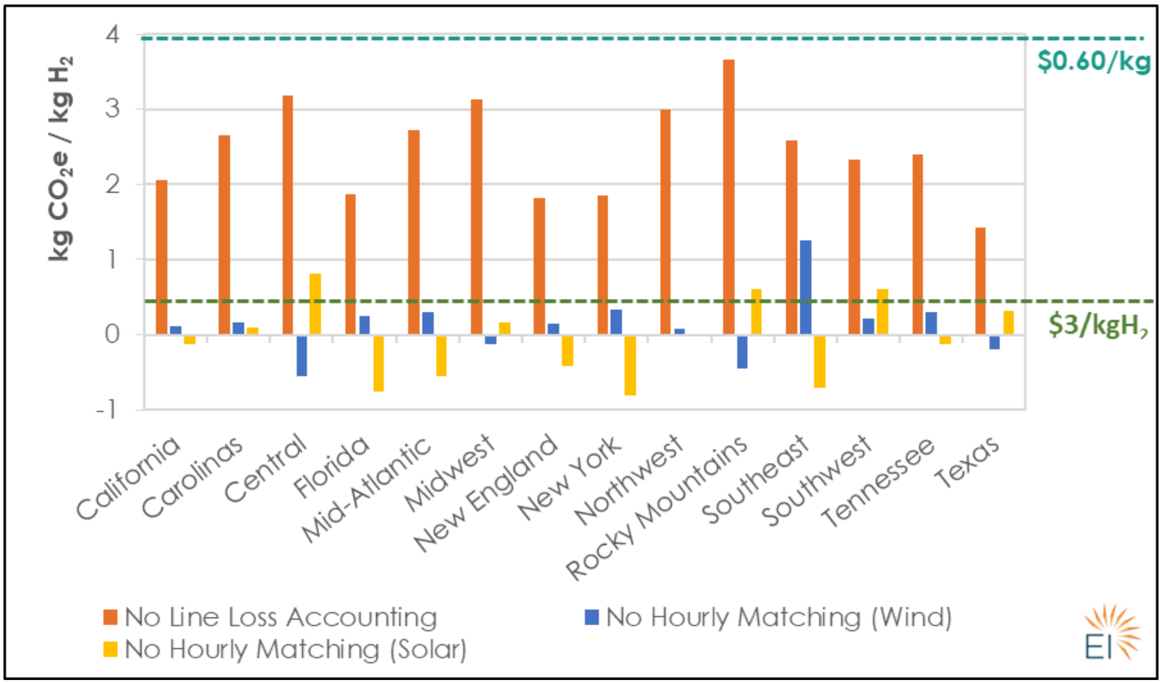
Forgoing line loss accounting in 45V guidance design (as part of the deliverability principle) results in GHG emissions impacts that push projects in every U.S. region beyond the threshold for earning the $3/kg tax credit. The projects could still qualify for one of the other 45V tax credit tiers—assuming all other design principles are fully satisfied—but they would emit GHGs at rates that should bar them from qualifying for the top value.

Forgoing hourly time-matching in 45V guidance design can result in GHG emissions impacts that push electrolysis beyond the threshold for earning the $3/kg tax credit—though outcomes vary by region and resource choice. For example, our analysis shows an electrolyzer built in the Southeast would produce hydrogen with a GHG emissions intensity of more than 1 $kgCO_2/kgH_2$ if the corresponding new, local clean energy resource were onshore wind. This rate is more than double the allowable limit of the top tax credit tier.

Our analysis also shows that hourly time-matching has a relatively small *short-run* marginal GHG emissions impact in 2021 across all regions and resource choices, including instances where emissions decrease. However, with no hourly time-matching requirement, new clean energy would likely be built in a manner that does not account for electrolyzers' operating profiles (e.g., overbuilding utility PV such that projects generate enough energy on an annual basis to serve electrolysis demand but see production limited to the same subset of afternoon hours). Over time, these clean energy deployments might crowd out projects that would have been built anyway; further, this discrepancy in when clean energy resources generate power and when electrolyzers use power would change the marginal emissions impacts of additional deployments.

Our AVERT analysis shows that forgoing hourly time-matching could demonstrably put individual projects above the $3/kg threshold, in line with the findings of another study by E3.[11] However, both studies are limited to estimating short-run marginal impacts. Studies that assess *long-run* marginal GHG emissions are necessary to tease out collective emissions impacts from this policy design over 10 to 20 years of 45V-driven capital investments—such as a study by Princeton University that shows annual and weekly time-matching frameworks are "universally ineffective at reducing consequential emissions from grid-based hydrogen production."[12]

Figure A4. Short-run marginal GHG emissions impacts of forgoing line losses and time-matching (2021)



Without line loss accounting, electrolyzers everywhere in the U.S. risk causing GHG emissions that are higher than the threshold for earning the $3/kg 45V tax credit. Without hourly time-matching, electrolyzers can similarly cause GHG emissions that rise above this threshold. Analysis uses AVERT with 2021 data. It is not representative of emissions impacts in later years and does not assess long-run marginal GHG emissions impacts, which may be much higher.

CONCLUSION

There are a few key takeaways from our AVERT analysis of short-run marginal GHG emissions from forgoing one of the three principles of 45V guidance design:

- Electrolyzers could drive very high GHG emissions immediately if 45V guidance ignores additionality or regionality requirements;

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[11] Figure 1 shows six scenarios where annual matching results in a GHG emissions intensity above the threshold required to earn the $3/kg tax credit: https://acore.org/wp-content/uploads/2023/04/ACORE-E3-Analysis-of-Hourly-and-Annual-GHG-Emissions-Accounting-for-Hydrogen-Production.pdf.

[12] See also Figure 2, which shows an annual matching requirement would still drive consequential emissions of approximately 15 to 40 $kgCO_2/kgH_2$: https://iopscience.iop.org/article/10.1088/1748-9326/acacb5.

- Transmission line losses must be accounted for to earn the $3/kg credit value, although they are often left out of the conversation; and
- Hourly time-matching is necessary to verify compliance with the emissions threshold for 45V's top tax credit tier, even if some cases in the near-term may satisfy the requirement through annual matching. Further study is needed to understand the long-term implications as the power system evolves.

We also want to reiterate the critical difference between short- and long-run marginal emissions analyses. Our short-run analysis demonstrates the necessity of the three principles to verify compliance with 45V's emissions thresholds, but it likely underestimates true emissions impacts from adopting loose guidance in two ways. First, it doesn't capture how marginal emissions rates will change over time as the power system develops under a loose framework, such as if electrolyzers were deployed across the U.S. but most corresponding new clean energy were built in Texas. Second, it doesn't capture *structural* impacts over the long term, such as how these clean energy deployments built to serve electrolysis might displace similar investments that might have been made regardless.