45V Hydrogen Production Tax Credits

Three-Pillars Accounting Impact Analysis

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ABOUT THIS STUDY

All conclusions of this report are independent assessments by Evolved Energy Research. This analysis was supported by the Natural Resources Defense Council. Evolved Energy Research conducted this research in the spring of 2023.

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ABOUT EVOLVED ENERGY RESEARCH

Evolved Energy Research (EER) is a research and consulting firm focused on questions posed by transformation of the energy economy. Their consulting work and insight, supported by sophisticated technical analyses of energy systems, are designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies. They have developed models to simulate and optimize economy-wide energy systems, bulk power systems operations, and utility distribution systems.

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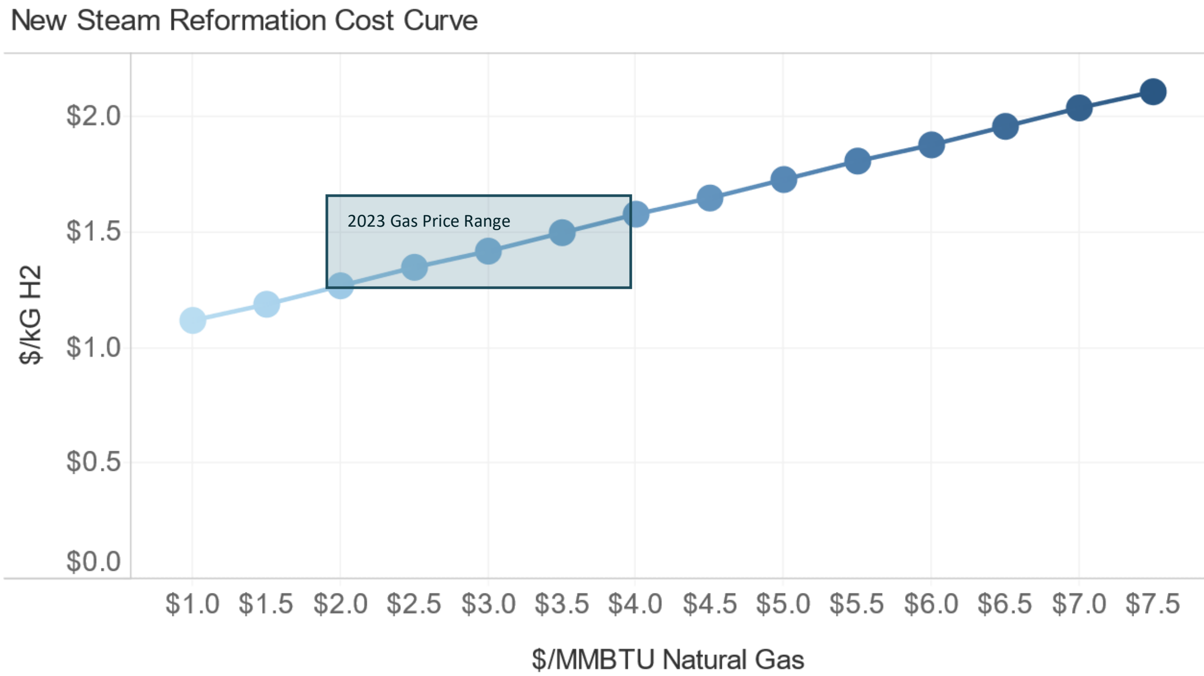
1. Introduction

The Inflation Reduction Act (IRA) of 2022[1] includes a \$3.0/kg H_2 (for a period of ten years) credit for clean hydrogen production (referred to as '45V'), but how clean hydrogen production is defined is the question facing the Treasury Department and the Internal Revenue Service as they add new sections to the tax code.

The IRA requires emissions from hydrogen production to be less than 0.45 kg CO_{2e}/kg H_2 in order to qualify for the full \$3.0/kg H_2 tax credit. This credit is extremely valuable and represents a substantial share of the economic proposition for clean hydrogen production. Figure 1 shows the cost of conventional hydrogen production from steam methane reforming: about \$1.25 - \$1.50/kg H_2 at recent natural gas prices. Receiving the credit is therefore about twice as valuable as displacing a unit of hydrogen production from conventional sources. Electrolyzed hydrogen can potentially meet this standard, depending on the direct and indirect (*i.e.*, grid-related) emissions produced by generating the input electricity, and is the focus of this analysis.

[1] https://www.congress.gov/bill/117th-congress/house-bill/5376/text

Figure 1. Cost of hydrogen production from steam methane reforming at varying gas prices



Emissions tied to electrolysis arise from the source of input electricity as well as from the emissions impacts on the grid as a result of electrolysis. Therefore, the method for determining whether that input electricity is "clean" and whether hydrogen projects drive grid emissions increases have become the focus for how the tax credit will be implemented. The Treasury Department is currently deciding the rules for how to track and account for the lifecycle emissions of hydrogen production, determining which producers will qualify for the largest tax credit. Stricter accounting rules are intended to ensure that new electrolysis loads actually use clean electricity to serve them and do not drive increased fossil fuel generation and increased grid emissions. The methods for stricter accounting are discussed in the following section. Proponents of laxer accounting rules argue that these stricter accounting could be onerous, costly, and stifle development.

Accounting mechanisms for clean hydrogen

Environmental groups, industry groups, academics, and a range of other stakeholders submitted a letter to the Treasury Department in February 2023 proposing *three-pillars* that constitute stricter lifecycle emissions accounting requirements to define clean hydrogen production.[2] Under this approach, only electrolysis complying with these requirements receives the full \$3.0/kg H_2 tax credit. The three-pillars include new clean supply, deliverability, and hourly matching. We have used this proposal as the basis for this analysis (described below). In contrast, the *limited requirements* cases don't require new clean supply (i.e., hydrogen projects can be powered by existing clean energy generators that already serve the grid); doesn't necessitate that clean generation is deliverable; and allows for annual matching in lieu of hourly matching.

New Clean Supply (or Additionality)

New clean supply permits only new electricity resources to contribute to hydrogen production, i.e., existing clean electricity resources cannot be diverted away from serving other electric loads towards hydrogen production. Without this requirement, new hydrogen electrolyzer loads can purchase clean energy credits from existing renewable or nuclear generation – or be directly powered by existing renewable or nuclear generation – that would have otherwise served existing electric loads. Electric loads must then purchase energy from somewhere else, which can include fossil generation. Without new clean supply, the poor efficiency of hydrogen production means the emissions reduction from displacing fossil fuels with hydrogen or hydrogen derived fuels may not be enough to offset the emissions increase in electricity production.[3]

[2] https://www.nrdc.org/sites/default/files/2023-03/joint-letter-45v-implementation-20230223.pdf

[3] While we modeled new clean supply as a requirement for electrolyzers, there may be in reality further qualification routes, including but not limited to the use of otherwise-curtailed clean power and/or production by facilities that would have retired but for electrolyzer demand.

Hourly Matching

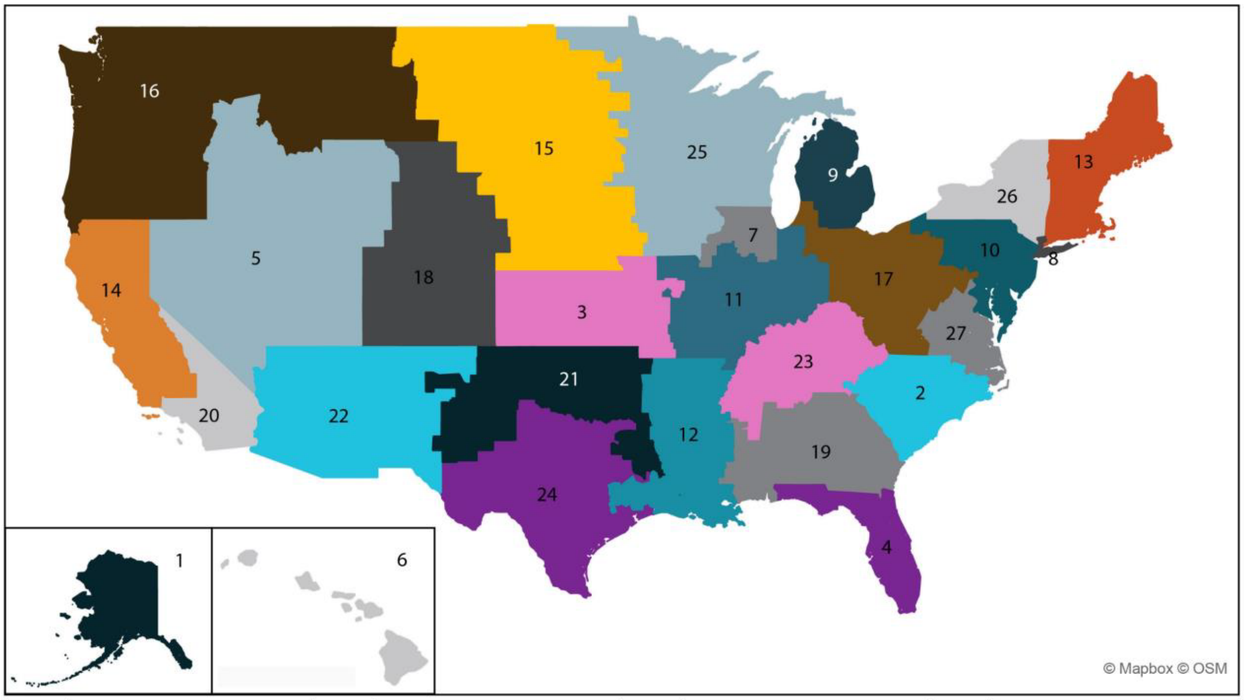
Hourly matching requires generation from new clean electricity to be matched with the production of hydrogen on an hourly basis. The strictest version of this requirement would be to produce hydrogen off-grid from dedicated renewables. However, this would drive up costs versus efficient accounting mechanisms in on-grid applications that provide the same emissions benefits but allow greater access to diverse renewable resources. Hourly matching, in the form we have tested in this paper, allows for renewable resources to be grid-connected, and a portfolio of resources can provide clean electricity with geographic (still limited to the proximate electricity zone) and technology diversity to improve aggregate capacity factors.

In our representation of hourly matching, electrolyzers cannot sell excess energy from their dedicated renewable portfolios back to the grid. We chose this conservative definition to test the most challenging circumstances in which excess renewable production coincides with periods when the local grid is already oversupplied, and electricity prices are zero. In reality, electrolysis owners will likely be able to sell excess renewable power and earn additional revenue that lowers the effective cost of electricity used for hydrogen production, so this is a deliberately conservative assumption.

Deliverability

Deliverability only allows resources that can be physically delivered to the electrolyzer to qualify as part of an electrolyzer's dedicated resource portfolio. This prevents hydrogen producers from purchasing renewable energy credits and claiming to be supplied by resources that are separated from the electrolyzer by grid constraints, while actually relying on dirtier generators closer to the electrolyzer. In practice, the definition of deliverability is likely to rely on predefined 'grid regions' or zones that separate the country based on the locations of persistent transmission constraints. In our modeling, we split the U.S. energy system into 27 zones in the model. Figure 2 shows the spatial detail at which this analysis was conducted, which reflect the electricity market module regions from the EIA's Annual Energy Outlook (with the addition of Hawaii and Alaska).

Figure 2. Zones used in the analysis



1	Alaska	8	Metropolitan New York	15	Northern Great Plains	22	Southwest
2	Carolinas	9	Michigan	16	Northwest	23	Tennessee Valley
3	Central Great Plains	10	Mid-Atlantic	17	Ohio Valley	24	Texas
4	Florida	11	Middle Mississippi Valley	18	Rockies	25	Upper Mississippi Valey
5	Great Basin	12	Mississippi Delta	19	Southeast	26	Upstate New York
6	Hawaii	13	New England	20	Southern California	27	Virginia
7	Metropolitan Chicago	14	Northern California	21	Southern Great Plains		

Within each zone, we assume that clean electricity is deliverable to electrolyzers located within the same zone. This provides opportunities for a diverse portfolio of renewable resources and sites within a grid zone to provide energy to the electrolyzer.

2. Key Findings

We conclude that the economic signals for development of clean hydrogen production and new markets from IRA are so powerful that the 45V tax credit will drive large-scale development of a hydrogen economy even if the Treasury Department should implement stricter accounting of lifecycle emissions based on the three pillars laid out above. Our results see substantial investment and scale-up of electrolysis production, regardless of accounting rules selected, indicating that Treasury can implement rules that improve emissions outcomes while performing the intended function of scaling up the clean hydrogen industry over the duration of the tax credit period.

3. Analysis Description

Background

This analysis uses a coupled modeling approach. We first project final energy demands (annually and sub-annually) through a scenario model called EnergyPATHWAYS. We then use an economy-wide supply-side optimization (RIO) to analyze energy supply decisions consistent with economics, policy prescriptions, resource availability, and reliability. Further information on the modeling framework can be found in the supporting materials of our Annual Decarbonization Perspective.[4] We ran the model for the years 2021; 2024; 2026; 2028; 2030; and 2032 in order to capture the rapidly changing economics of hydrogen deployment with declining electrolyzer costs.

This analysis leverages work conducted by EER for our Annual Decarbonization Perspective (ADP)[5] and analysis for the Princeton REPEAT[6] project. Energy supply assumptions – technology cost and performance, resource potential, and fuel costs - are consistent with the ADP. Energy demand scenarios are consistent with the IRA-Mid case produced for the REPEAT project. The changes made for this analysis are detailed below.

[4] 2022 ADP - Supporting Material

[5] 2022 ADP

[6] Princeton REPEAT

Bulk Chemicals Energy Demand

In our update cycle for the 2023 ADP, we've undertaken a decomposition of existing hydrogen uses in the economy. This includes a decomposition of AEO's projected bulk chemicals energy demand from natural gas into hydrogen and ammonia (that can potentially be satisfied with green hydrogen). All energy use that previously would have been projected as "gas" is now projected as hydrogen and ammonia and all of the technologies to produce hydrogen (currently reformation) and ammonia (Haber-Bosch) are included in the analysis as supply technologies. This projection of chemicals and ammonia production is consistent with the Energy Information Administration's (EIA) 2023 Annual Energy Outlook[7] (other energy demands are based on the REPEAT IRA-mid scenario consistent with the 2022 Annual Energy outlook).

Electrolyzer Costs

For this analysis, we've refined our projection of near-term electrolyzer costs through consultation with NRDC and their discussions with OEMs (original equipment manufacturers) and developers, shown in Figure 3. These assumptions are in line with cost curves published by a number of organizations, including the U.S. Department of Energy and International Renewable Energy Agency[8,9]. We model these as 30-year assets with a replacement life of 15 years. This is to align electrolyzer infrastructure lifetime with the supporting infrastructure like renewables,

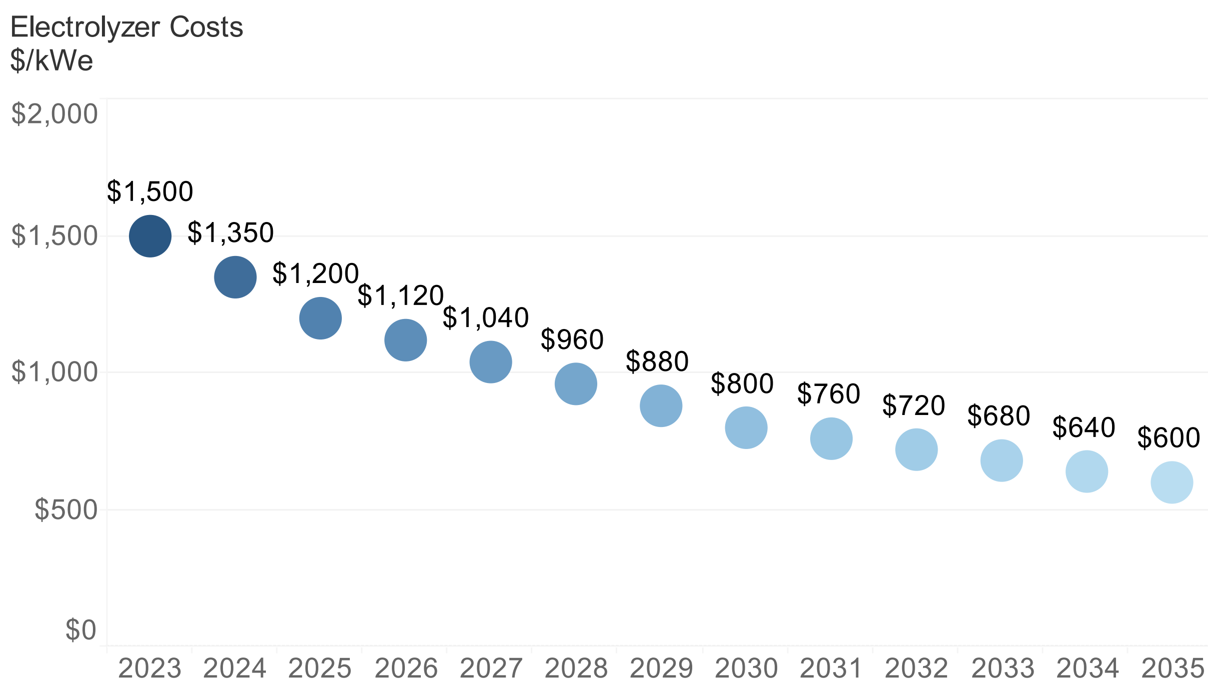
[7] https://www.eia.gov/outlooks/aeo/

[8] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

[9] https://www.nrel.gov/docs/fy19osti/72740.pdf

storage, pipelines, etc. and to model a scenario where they are anticipated to run for the entire 30-year period (not turn off at the cessation of their eligibility for the 45V tax credit).

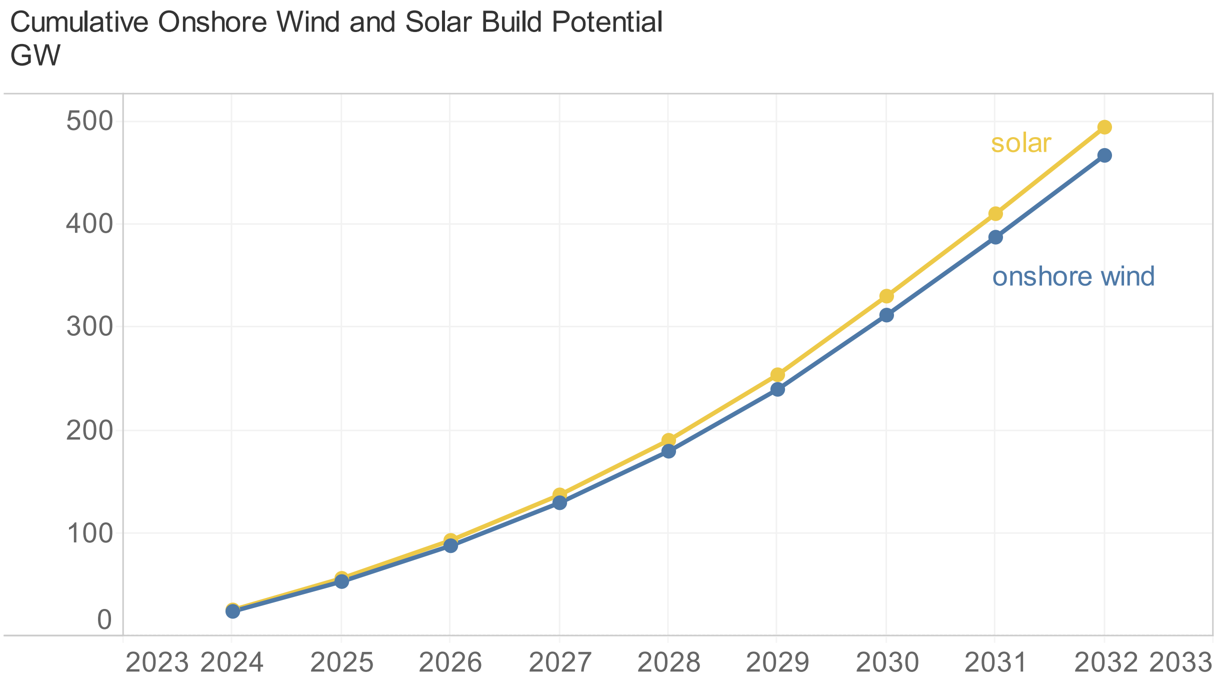
Figure 3. Electrolyzer cost projections



Renewable Build Constraints

The passage of the IRA has placed an emphasis on understanding the constraints on the rate of renewable buildout possible now that economics are not the principal restricting factor. We model growth constraints on solar; onshore wind; and offshore wind to reflect an inability to scale to the levels of economic deployment we would otherwise see. There is a limit to how fast these resources can be sited and permitted, how fast supply chains can be scaled, how fast transmission can be sited and permitted, and the availability of labor for construction. This is specifically constraining for solar and wind through the end of the IRA's clean electricity production tax credit period. We model a year-over-year maximum growth in annual build of 20% through 2030 (from the maximum historical deployment) and then a year over-year growth rate of 5% through 2032. The result of that constraint in terms of the maximum new build of wind and solar through 2030 is shown in Figure 4.

Figure 4. Maximum onshore wind and solar build through 2032



Hydrogen Pipelines

In other modeling exercises, we allow for the development of inter-zonal pipeline infrastructure to allow for the delivery of electrolyzed hydrogen from regions with a surplus of renewable generation to regions that have more limited resources. However, in this study, and based on stakeholder feedback and concerns about the difficulty of building pipelines in the modeled time-period (today-2032), we do not allow inter-zonal pipelines to be constructed.

Hydrogen Modeling in Focus

Hydrogen Supply

The RIO model is designed to co-optimize the deployment of energy supply technologies both in the electric sector and other sectors (in this case fuels). It necessitates the balancing of supply and demand on economically relevant timescales. In this case, we balance the demand and supply of hydrogen on a daily basis. This supply can come from existing steam reformation; new steam reformation; electrolyzed hydrogen; and bio-energy with carbon capture and sequestration (BECCS) hydrogen. The relative competition between all of these is highly dependent on the IRA tax credits. The balancing of hydrogen on a daily basis can also utilize two types of hydrogen storage technologies – salt cavern storage (where regionally available) and a hydrogen storage technology represented as 'underground pipes.' The principal competition in this analysis, with the inclusion of the 45V tax credits, is between electrolyzed hydrogen and existing and new steam reformation as well as the use of electrolyzed hydrogen for end-uses where hydrogen isn't currently utilized. As stated in the section above, we don't allow the construction of pipelines to deliver hydrogen between zones, though the existing hydrogen pipeline between Texas and Louisiana is represented in the model.

Hydrogen Demand

The model includes a variety of hydrogen uses that we allow or disallow based on our two demand cases. These include:

- *Restricted* demand, representing current end-uses of hydrogen and new demands determined exogenously. Existing demands include petroleum refining, bulk chemicals, etc., and reflect the bulk of hydrogen demand in this case. Demands determined exogenously (i.e., determined by the user) include a defined deployment of fuel-cell vehicles and additional demand for hydrogen in bulk chemicals.

- *Economic* demand, including the same forecasted demand as the Restricted demand case, but further allows for the optimized deployment of hydrogen in new applications, including the power sector; fuels sector (ammonia for shipping or Fischer-Tropsch fuels to replace diesel and jet fuel); and industrial heat sector (displacing natural gas usage in boilers).

Detail on each potential hydrogen demand is shown below in Table 1. In the model, the ultimate deployment of electrolyzed hydrogen towards these applications is determined by either their economic competitiveness against natural gas for most industrial and power uses and their competitiveness against petroleum products for synthetic fuel production.

Table 1. Hydrogen demand by scenario

	Description	Baseline 2030 Demand (Mt)	Restricted Demand	Economic Demand
Ammonia Production and other bulk chemicals	AEO 2023 end-use demand adjusted to decompose hydrogen and ammonia (Haber-Bosch) demand	5.1	☑	☑
Transport	Based on modeled adoption of HFCV across all on-road transportation from Princeton REPEAT analysis	1.7	☑	☑
Petroleum Refining	Refinery hydrogen demand represented explicitly within RIO. Declines with reduced demand for refined fossil products.	Optimized	☑	☑

Synthetic Fuels – Fischer-Tropsch/methanation	Model can construct and operate Fischer-Tropsch and methanation facilities to produce synthetic hydrocarbon fuels with H_2 as a feedstock. Also requires captured carbon feedstocks which can be sourced with IRA-incented carbon capture on cement, biofuels, direct air capture.	Optimized		☑
Synthetic Fuels – Ammonia as shipping fuel	Model can construct and operate new Haber-Bosch facilities using H2 as a feedstock. Ammonia can displace a share of residual fuel oil associated with shipping.	Optimized		☑
Power	Model can blend hydrogen in new and existing gas plants up to 7% by energy.	Optimized		☑
Industrial Steam	Model can construct and build hydrogen boilers (in competition with new and existing fuel boilers, CHP, heat pumps, thermal storage, etc.) to produce steam for industry	Optimized		☑

Scenarios

This section summarizes the scenarios run in this analysis, shown in Table 2. The differing credit requirements is the focus of the analysis; varying the demand scenarios and annual build constraints on renewables are meant to illustrate potential bounds on economic deployment and emissions impacts for two principal uncertainties identified: how “new” markets for hydrogen might develop with the proliferation of very low-cost hydrogen and how the ability of the U.S. to construct renewables affects both electrolyzer deployment and emissions outcomes.

Table 2. Scenario definitions

Scenario	45V Credit Requirement	Demand Scenario	Annual Build Constraint on Renewables
1	Three-pillars	Restricted	Yes
2	Limited Requirements	Restricted	Yes
3	No Credit	Restricted	Yes
4	Three-pillars	Restricted	No
5	Limited Requirements	Restricted	No
6	No Credit	Restricted	No
7	Three-pillars	Economic	Yes
8	Limited Requirements	Economic	Yes
9	No Credit	Economic	Yes

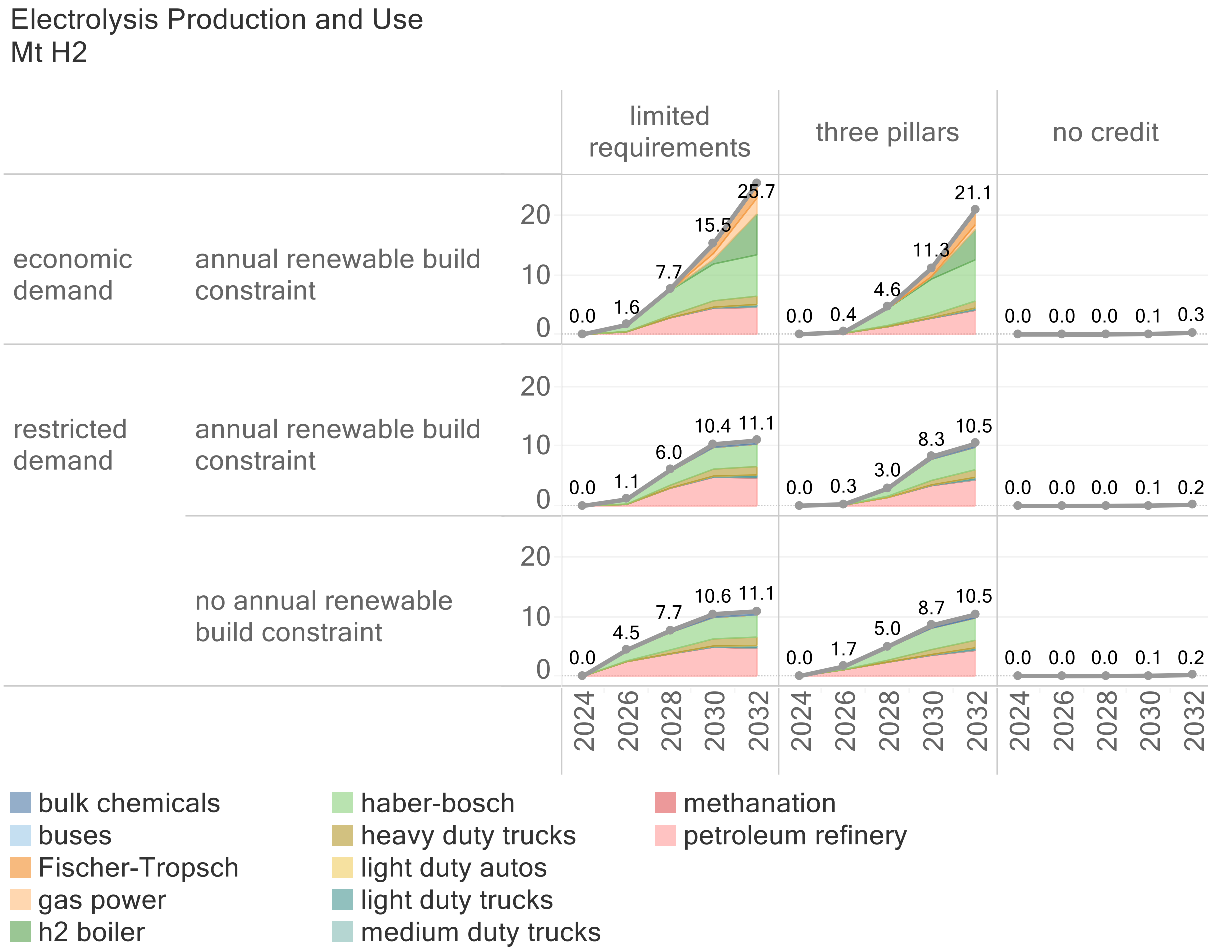
4. Results

Electrolyzed Hydrogen Production and Use

Figure 5 shows the overall annual production of hydrogen in the nine scenarios. Firstly, this shows how critical federal incentives are to economic deployment of electrolyzed hydrogen over the next decade. There is very limited deployment in any of our *no credit* cases while the economic deployment in any case with 45V is substantial. Three-pillars accounting for tax credit qualification has only a limited effect on the scale of electrolyzer deployment and hydrogen production through 2032 with deployment of electrolyzed hydrogen ranging from 10.5 – 21.1 Mt. In our *limited requirements* cases, this range is 11.1 – 25.7 Mt.

In all modeled scenarios, a substantial share of produced hydrogen goes towards displacement of existing hydrogen uses (refineries, bulk chemicals, ammonia production). In the *economic* demand cases, additional hydrogen uses are shown to be economic and rapidly deployed, including Haber-Bosch production to produce green ammonia for shipping (to displace diesel and residual fuel oil); Fischer-Tropsch processes to produce refined fuel alternatives (jet-fuel, diesel, and gasoline); and direct use in industry.

Figure 5. Electrolysis production and uses



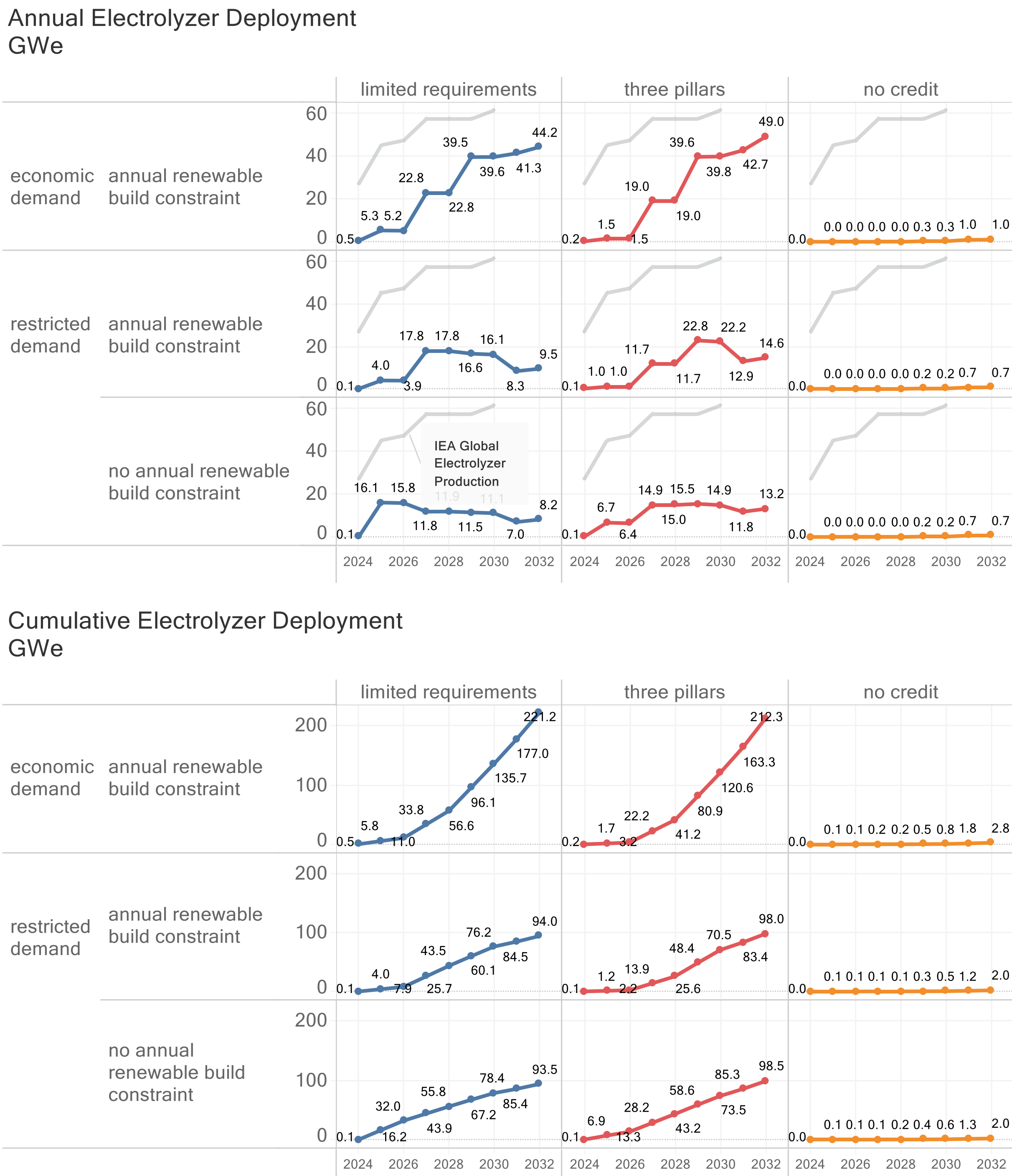
Three-pillars accounting has relatively little economic impact on deployment of electrolyzers by 2030 and 2032. Limited accounting requirements may increase the economic potential of electrolyzer deployment in the very near-term, but this transient advantage may not materialize nor increase deployment relative to three-pillars accounting due to near-term supply chain constraints.

The impact of renewable build constraints is more impactful, especially in early years. The ability to site renewable generation, meeting the clean energy targets of existing load and providing low-cost energy to electrolyzers, is more binding than the relative economic impact of three-pillars accounting.

The annual deployment of electrolyzer capacity (GW_e) both annually and cumulatively over the study period is shown below in Figure 6**.** Cumulative electrolyzer deployment under the *limited requirements* and *three-pillars* cases are nearly identical through both 2030 and 2032. The annual deployment is compared to the IEA's projection of global electrolyzer production capacity through 2030.[10] In economic demand scenarios, electrolyzer deployment represents the majority share of projected global production capacity by the late 2020s.

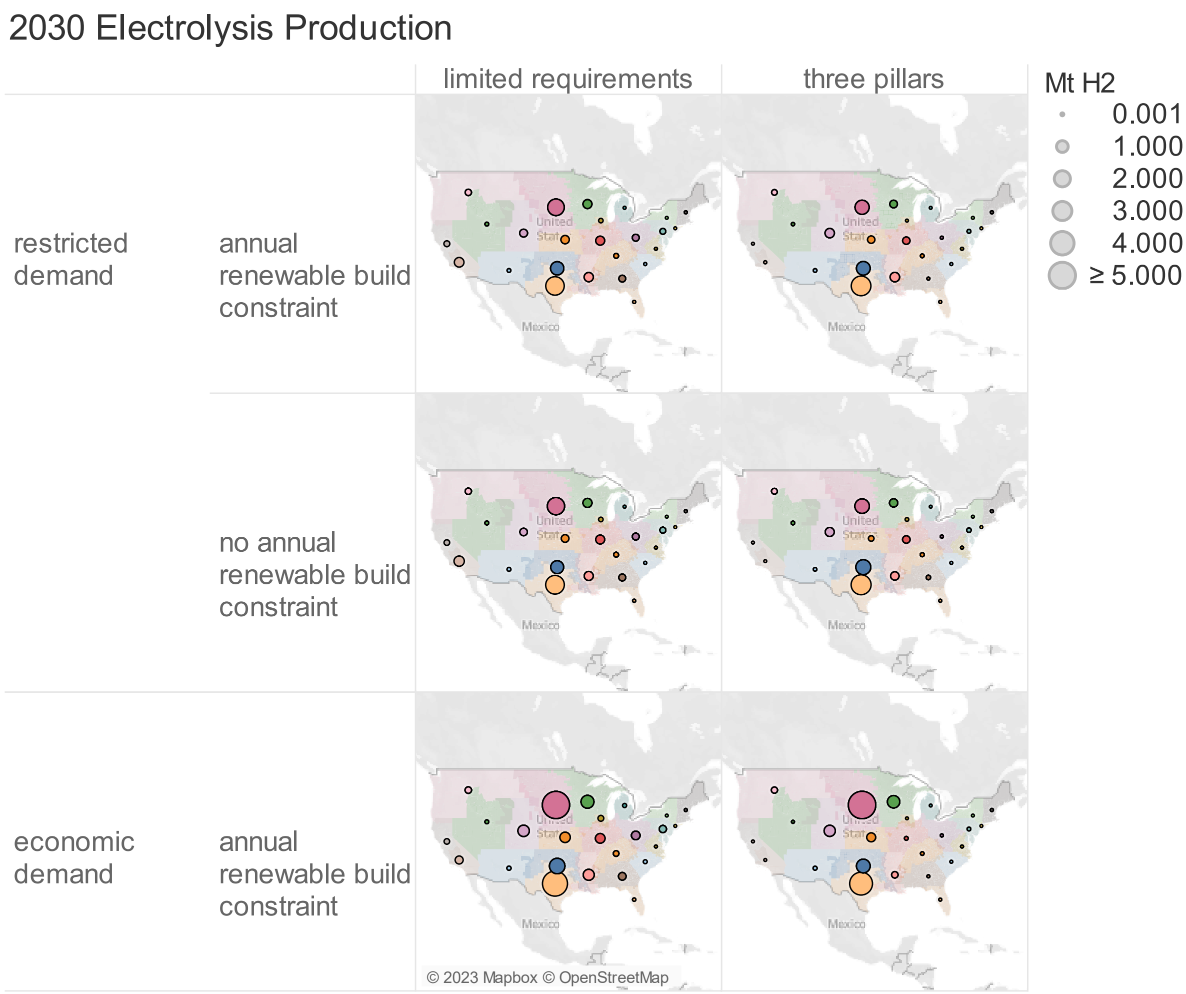
[10] https://www.iea.org/reports/electrolysers

Figure 6. Electrolyzer deployment by scenario



The impact of three pillars accounting on where electrolyzers are located regionally is also limited (Figure 7). Much of the hydrogen demand in the economy is likely to be located in regions with significant renewable resources, with an obvious overlap of hydrogen demand with the wind belt. This tracks with other studies that we conducted examining pathways to a net-zero GHG U.S. economy by 2050, whereby we find that electrolytic hydrogen production is fairly concentrated in regions with plentiful renewable energy sources. It is therefore important that the implementation of the 45V credits be congruous with the medium and long-term economic viability of clean hydrogen production.

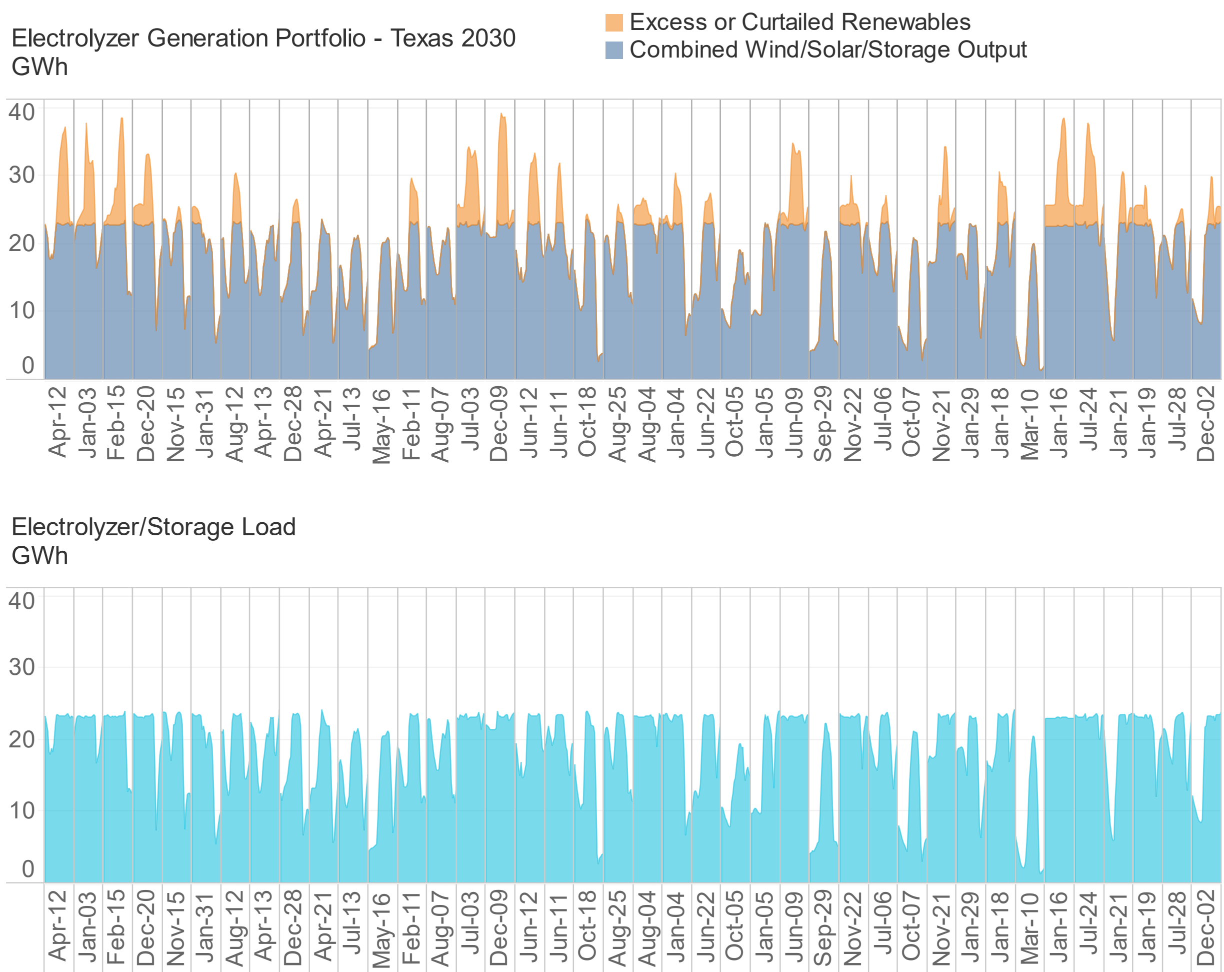
Figure 7. Electrolysis production by region



Electrolyzer Operations

The RIO model develops optimized portfolios of storage and renewable generation (including curtailment) to satisfy electrolyzer operations. This is a unique contribution because it allows for the development of portfolios of resources that simpler approaches do not (i.e., equal splits of wind and solar or single-resource portfolios or portfolios where nameplate generation capacity exactly equals electrolyzer load). The hourly operations (across sample days) of the generation portfolio and the electrolyzer load in Texas in 2030 under three-pillars crediting are shown in Figure 8.

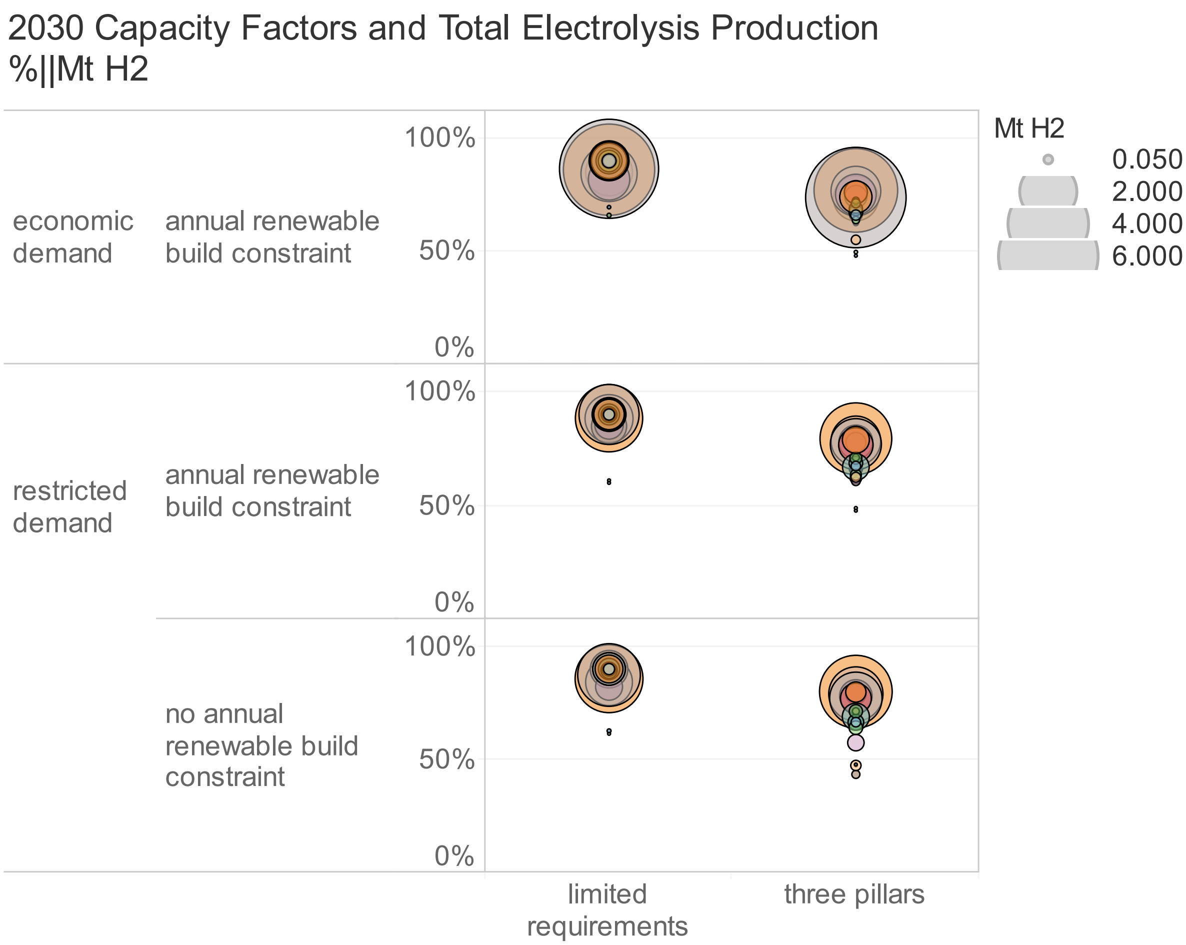
Figure 8. Electrolyzer hourly operations by sample day in Texas in 2030[11]



Regions where blended portfolios of wind and solar can be developed see most electrolyzer deployment. These regions can support electrolyzer capacity factors greater than 70% under hourly matching requirements. Figure 9 shows the capacity factors and total electrolysis production across zones by scenario. In regions with only solar available we see more limited deployment, though some may be cost-effective to offset the operations of steam reformation.

[11] We show the sampled days, but the 365-day representation maps these sample days back in an order based on a similarity score. Please see: [2022 ADP - Supporting Material]() for additional information on the day-binning approach used by RIO.

Figure 9. Capacity factors and total electrolysis production [12]



Hydrogen Price Impact

Our analysis finds that three-pillars accounting has a modest impact on the delivered cost of hydrogen and as shown in previous sections of the report, this impact does not significantly hinder the cost-competitiveness against alternatives.

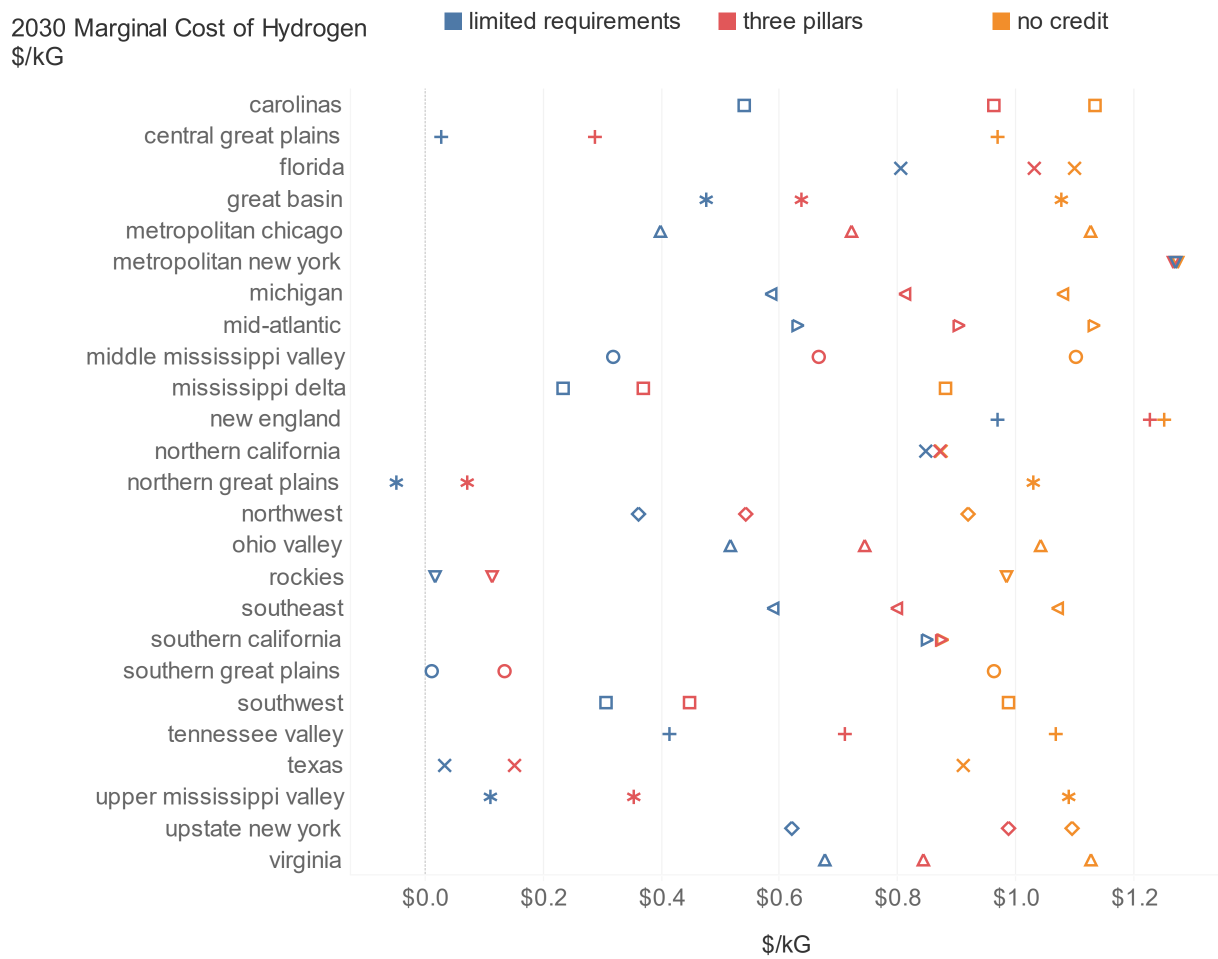
[12] The size of the bubbles represents the total electrolyzer production and their position represents their average annual capacity factors.

The RIO model is an inter-temporal optimization, but for an assessment of the marginal cost of hydrogen, we ran the model as a single-year optimization[13]. The marginal prices of hydrogen shown in Figure 10 are the cost to deliver hydrogen in 2030 from existing steam reformation facilities; new steam reformation facilities; and/or new electrolysis facilities. The marginal prices in the *no credit* case largely reflect the cost of hydrogen delivery from existing and new steam reformation facilities. In regions where there is no impact to the marginal price from 45V tax credits, this indicates electrolysis production is not an economic option: Electrolytic hydrogen costs are not low enough to beat steam reformation, so none is built, and the marginal cost is set by steam reformation all cases. In regions where the marginal price declines with the 45V tax credits, this indicates that electrolysis is deployed to displace steam reformation facilities: Electrolytic hydrogen can be produced more cheaply than from steam reformation, and the lower marginal cost is set by electrolytic hydrogen.

Of particular interest is the marginal cost of hydrogen in both the *limited requirements* case as well as the *three-pillars* case because this illustrates the point that while three-pillars accounting has an impact on the marginal price of hydrogen in most regions (especially regions with limited clean energy goals and regions with limited renewable resources), three-pillar compliant projects remain economic against alternative fossil-based hydrogen production technologies in the vast majority of regions. Additionally, the overall generosity of the tax credit is illustrated, with the marginal prices of hydrogen production approaching zero (inclusive of capital and O&M costs, as well as the cost of the renewable portfolios to supply the energy with their accompanying tax credits) in regions with high-quality renewables, including Texas, the Great Plains and the Rockies. In regions where electrolysis is competitive -- which is the vast majority of regions -- the three-pillars requirement adds $0.10-$0.40/kg to the marginal cost of hydrogen.

[13] This model run aligns with the restricted demand scenarios with no annual renewable build constraints.

Figure 10. Marginal cost of hydrogen under different scenarios by region

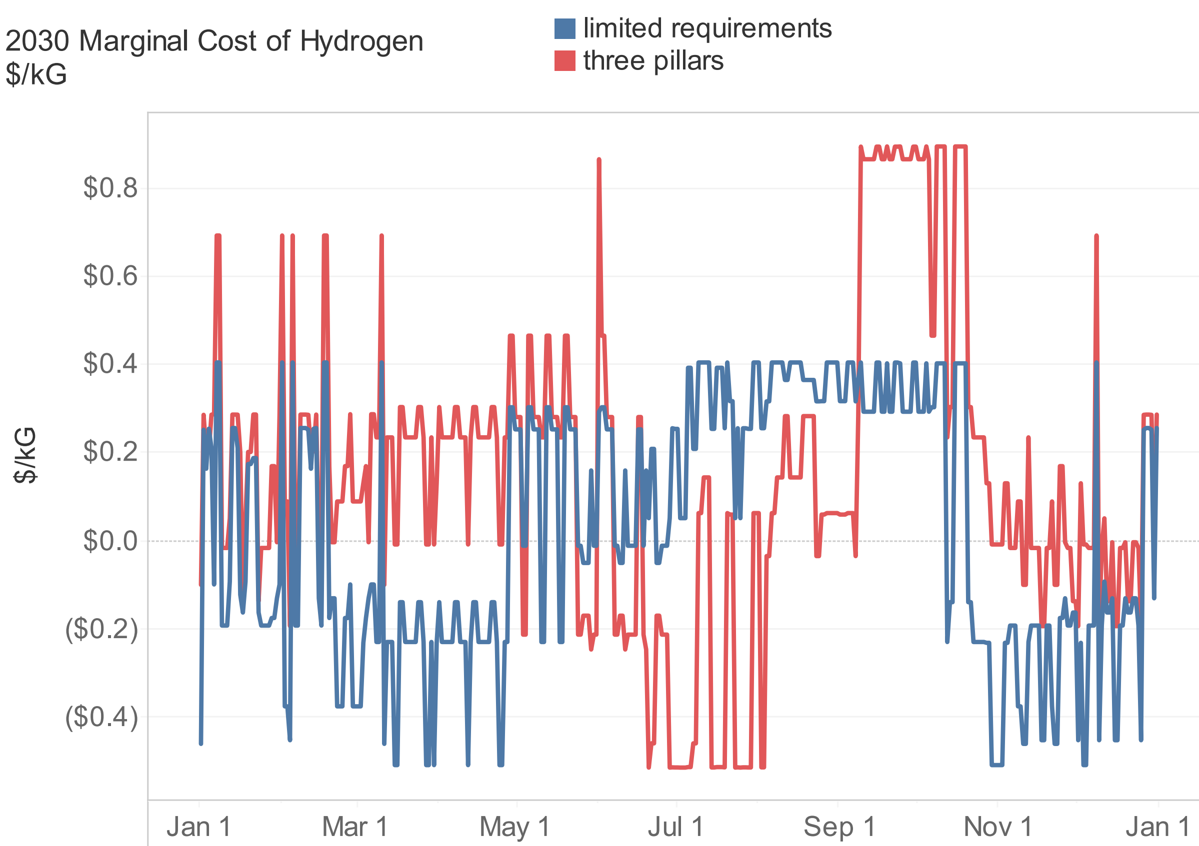


These cost impacts align with our deployment analysis, with levels of hydrogen production being impacted only in Northern and Southern California in 2030, though electrolytic hydrogen becomes economic there by as early as 2032 owing to declining electrolyzer prices. New England and Metropolitan New York are the only two regions in our model where electrolyzer production may be uneconomic against fossil alternatives in the near to medium term, but those regions do not include significant hydrogen demand anyway. While we do not allow for any buildout of inter-regional pipelines in this study, those would serve to deliver hydrogen to those limited regions that may not otherwise have adequate resources to produce electrolytic hydrogen.

In most regions, necessitating additional investments in renewable generation, hydrogen storage, or electrolyzer capacity to comply with the three-pillars modestly increases the cost of hydrogen from a baseline of negative or close to zero-cost under limited requirements, remaining significantly below the cost of steam reformation and therefore extremely cost-competitive. These economics support deployment of electrolytic hydrogen production regardless of whether three-pillars or limited accounting is adopted.

These marginal costs are the result of meeting supply and demand every day with a portfolio of hydrogen technologies and storage assets. We can therefore look at the marginal cost of delivering hydrogen in each region over the course of the year. For illustration, we can examine the marginal price in Texas (the region with the highest level of hydrogen production), shown in Figure 11. Three-pillars accounting does result in higher delivered price volatility (due to the necessity for hourly matching and the relative cost of following the variable generation profile to produce hydrogen in every hour) whereas the cost of annual matching is effectively capped at the price of a renewable energy credit + marginal electricity price of a gas generator.

Figure 11. Marginal cost of hydrogen by hour in Texas 2030



This illustrates the dynamic from an emissions perspective that we'll discuss further in the next section, which is that the credit is generous enough to drive perverse outcomes in many hours. Instead of simply burning gas in an existing steam reformer (with roughly 75% efficiency), the tax credit incentivizes A) using limited renewables that would have otherwise served grid-based loads in an electrolyzer (efficiency of 69%) while simultaneously B) increasing gas usage in a thermal powerplant (50% efficiency) to serve the grid-based loads, resulting in an efficiency less than half the alternative and increased gas usage.

While annual matching limits the cost of producing hydrogen in the highest-priced hours, it does so through by encouraging the hydrogen system to be balanced with fossil fuel electricity generators while procuring renewable energy credits to receive the tax credit. This incentivized behavior and resulting investments are not aligned with the valuable benefits that hydrogen can provide to a decarbonizing U.S. economy in the long-term through sector coupling. Annual matching forgoes the opportunity for favorable interactions between the hydrogen sector and the rest of the economy where hydrogen production shifts with variable renewable grid generation and relies on hydrogen storage, supporting reliability and low electricity costs and decarbonizing end-uses more cost-effectively. Annual matching disincentivizes those operational behaviors as well as the supporting infrastructure (e.g., hydrogen storage) that we will need to develop to take full advantage of the opportunities offered by sector coupling. In contrast, hourly matching incentivizes those operational behaviors and investments that bolster the value of the hydrogen sector to grid and economywide decarbonization, including ramping operations based on the availability of clean electricity, investing in hydrogen storage, and/or relying on existing steam methane reformation as back-up.

Emissions Impact

We find that emissions impacts are significantly improved with three-pillars accounting in all cases (*economic* vs. *restricted* demand; *annual renewable build constraint* vs. *no annual renewable build constraint*). The figures below reflect the net impact of hydrogen production emissions and avoided emissions linked to hydrogen's replacement of fossil fuels in the range of applications specific to each demand scenario. For example, if electrolyzed hydrogen production emissions are 100 MMT CO_2, and avoided emissions for replacing existing “grey” hydrogen are 50 MMT CO_2, the total net emissions are 50 MMT CO_2. Emissions increases relative to the *no credit* baseline mean that reduced emissions linked to hydrogen displacement of fossil fuels in various applications are not sufficient to compensate for the emissions increases on the electricity grid driven by hydrogen production.

Depending on the scenario, the emissions impacts of 45V can be either positive or negative against the baseline. However, when comparing *three-pillars* cases relative to *limited requirements* cases, *three-pillars* cases avoid 47-109 MMT CO_2 in 2030 and 22-115 MMT CO_2 in

2032. Cumulatively, they avoid 192-416 MMT CO_2 through 2030 and 247-643 MMT CO_2 through 2032.

Figure 12 Annual emissions impact off of *no credit* baseline

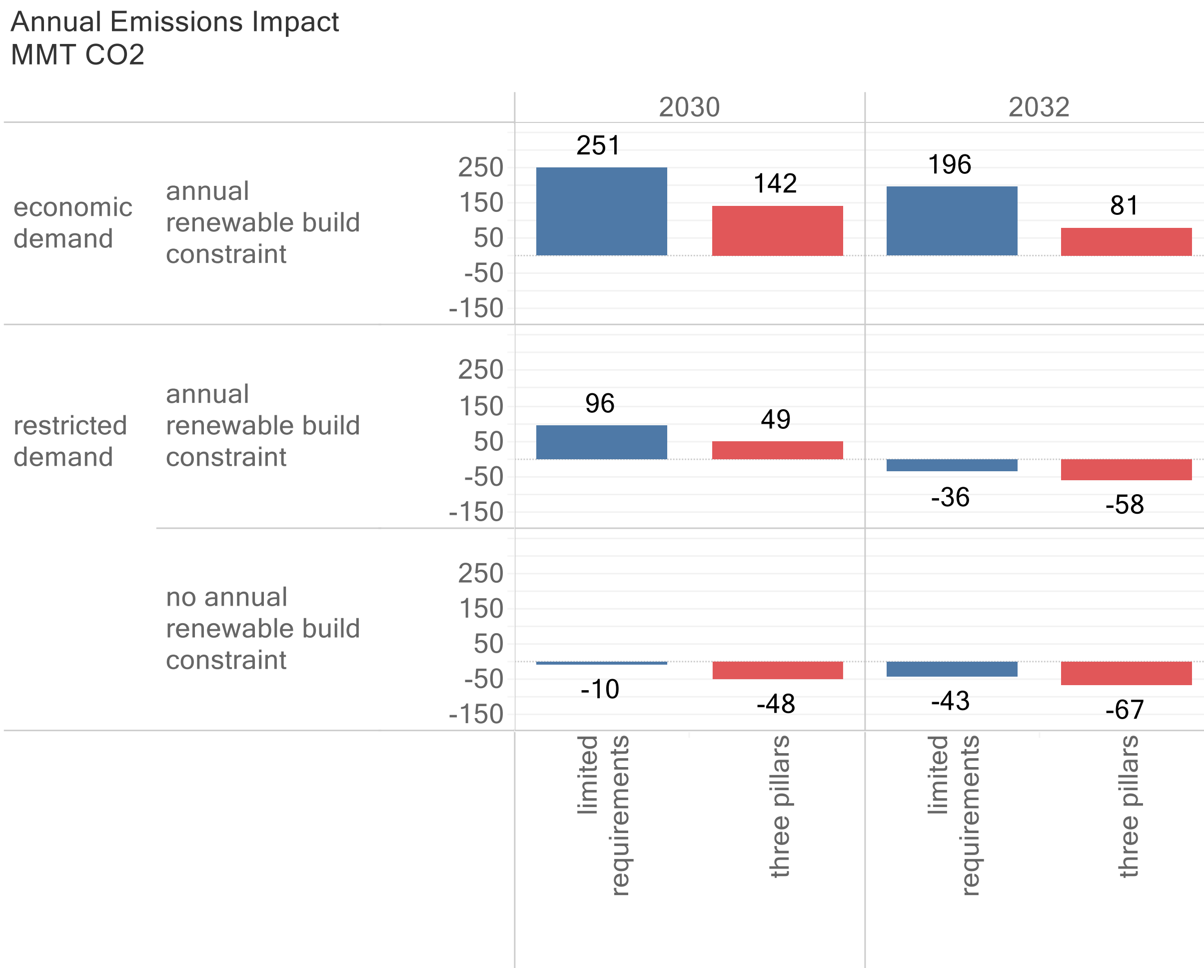
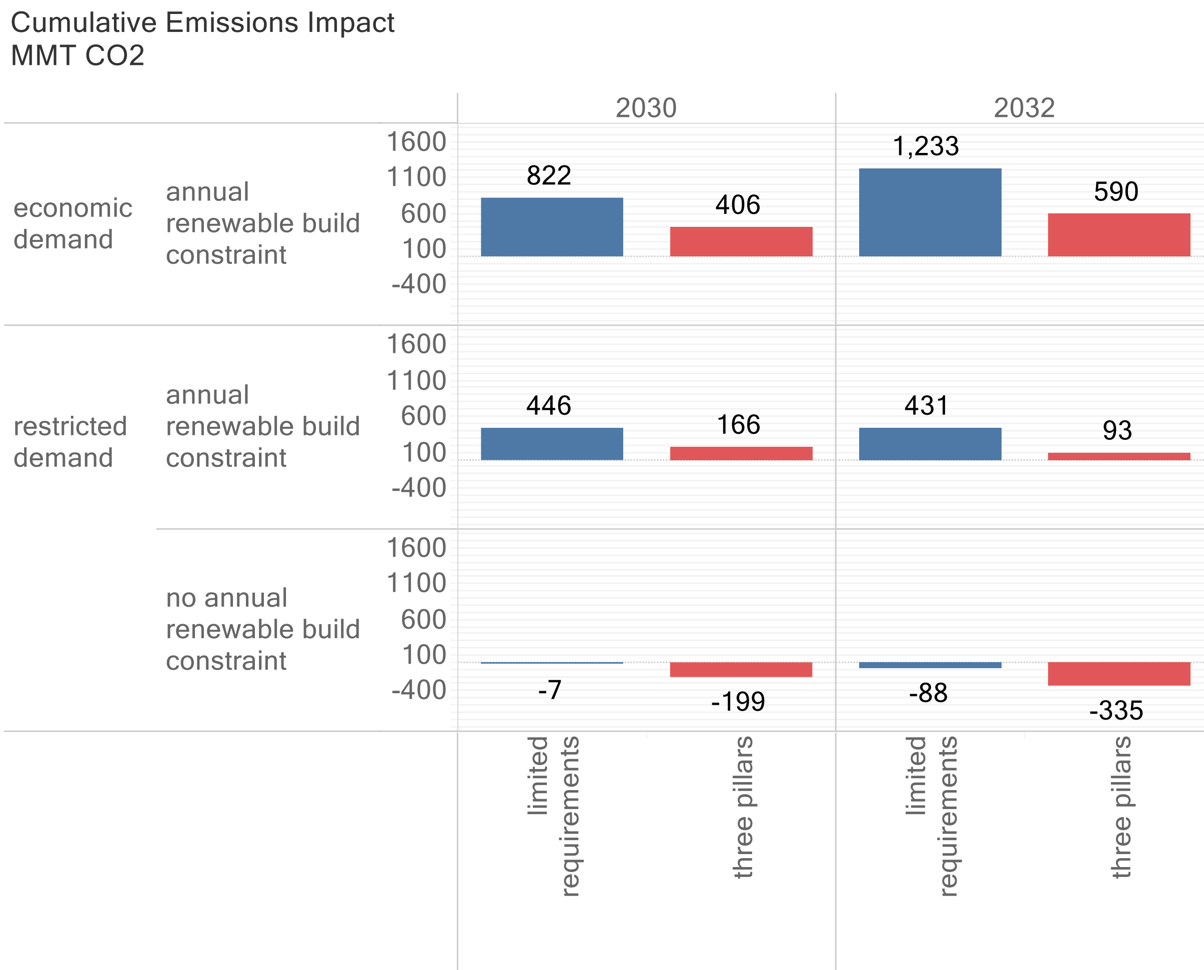


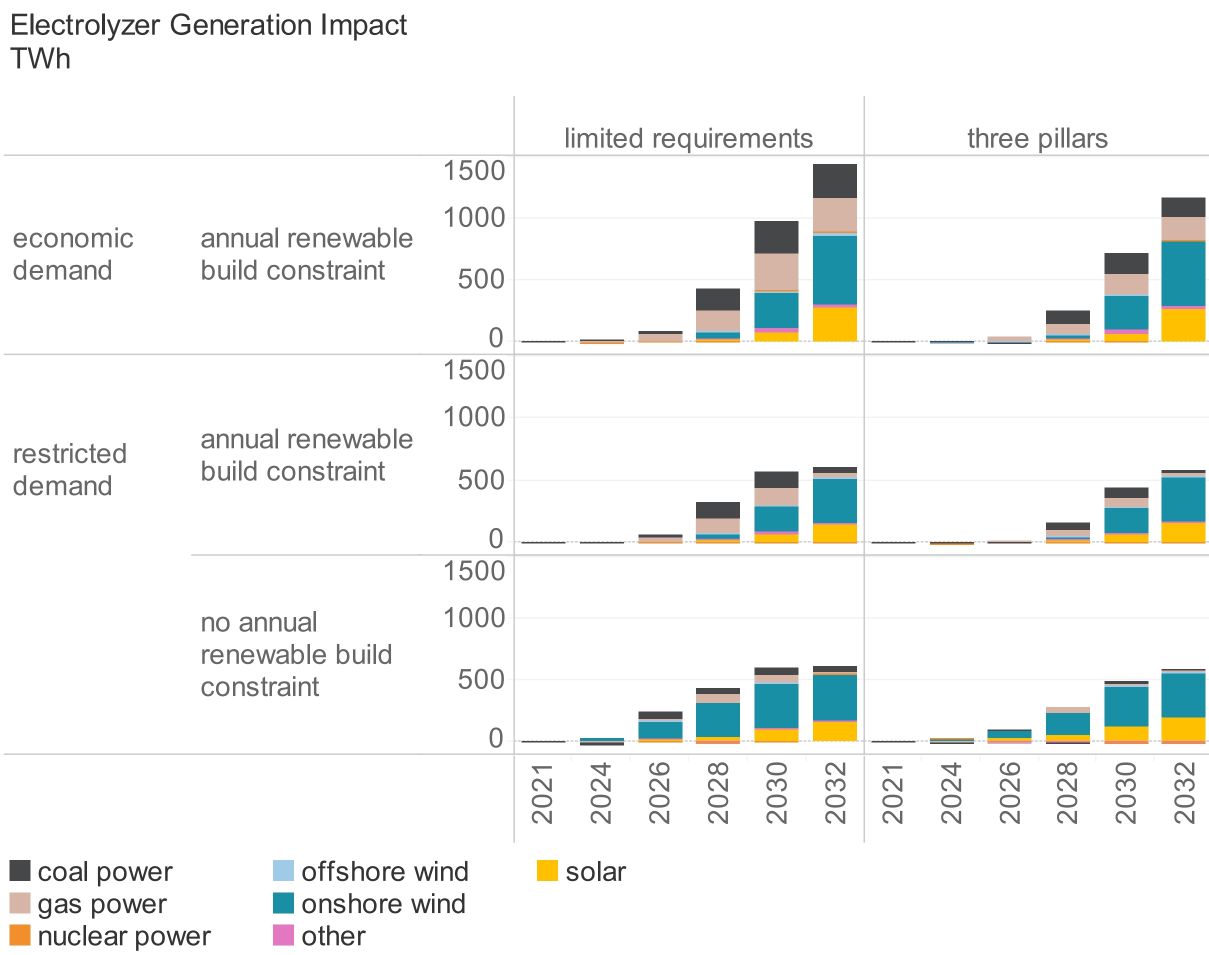
Figure 13 Cumulative emissions impact off of *no credit* baseline



This is the result of the marginal impact to electricity generation as a function of electrolyzer deployment and crediting requirements. In all cases, electrolyzer deployment spurs a degree of increase in fossil fuel generation, shown in Figure 14, though significantly less in the *three-pillars* cases relative to *limited requirements*. Under annual matching, electrolyzers can balance their operations by drawing power from the grid without meaningful limitations, leading to a significantly more pronounced increase in fossil fuel generation. When renewable build constraints are relaxed under restricted demand, the *three-pillars* cases almost entirely prevent increases in fossil fuel generation to serve increased power demand.

The share of incremental fossil fuel added to the system because of electrolyzer additions is reduced in the long-term with the decline in renewable costs and/or the relaxation of annual build constraints (these become less binding in the long-term). This illustrates the challenge of ensuring that new clean supply requirements deliver "additional" renewables onto the grid. Narrowly, an electrolyzer can be required to purchase clean electricity, and thereby avoid electrolysis-induced marginal generation from fossil fuels. But systemically, how this decision affects the marginal purchaser of clean energy in each zone is a material question, subject to several factors (such as build constraints) beyond the electrolyzer's control given that electrolyzers, due to how lucrative the tax credit is, do not represent the marginal purchaser.

Figure 14. Electrolyzer impact of generation by source relative to the No Credit baseline



5. Discussion

Our analysis finds that the three pillars will have limited impact on the economic deployment of electrolyzers and will support substantial deployment through 2030 and beyond. While the three pillars may have an impact of hydrogen production costs, our analysis finds that they do so from a subsidized price approaching zero, and so have very little impact on economic deployment through the period of 45V tax credit eligibility. The robustness of this finding is further bolstered by our conservative representation of hourly matching (disallowing excess sales of renewable electricity). Electrolyzer deployment seems more likely to be constrained in the near-term by supply chains rather than economics.

The modest increase in the price of delivered hydrogen under three-pillars accounting improves emissions outcomes by incentivizing a higher share of electrolyzer load being met by clean energy resources and by reducing the risk that new electrolyzer load increases the utilization of coal and gas generation capacity. Three-pillars accounting can't guarantee that the 45V tax credit reduces emissions over the baseline in our study period, but it significantly improves the odds of that outcome.

Furthermore, hourly matching incentivizes the type of operations that will ultimately be valuable in the long-term. If electrolyzed hydrogen is only viable when balanced by the electricity system, it will not have nearly as large a role in a decarbonized energy system as we have projected in previous net-zero analyses. The opportunity for flexibility is critical to the economics. Encouraging this type of learning is as important to the development of hydrogen markets as is simply buying down the cost of electrolyzers.