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Determining Life Cycle Emissions of Hydrogen Production Using the 45VH2-GREET Model for the 45V Hydrogen Production Tax Credit

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Executive Summary

This study provides an analysis of life cycle greenhouse gas (GHG) emissions associated with hydrogen production pathways in the context of the 45V clean hydrogen production tax credit (45V PTC) under the 2022 Inflation Reduction Act (IRA). The 45V PTC mandates a well-to-gate system boundary for assessing life cycle GHG emissions, focusing on emissions up to the point of hydrogen production, including feedstock-related emissions. Central to this study is the use of the 45VH2-GREET model to determine the well-to-gate life cycle GHG emissions. The study focuses on three hydrogen production pathways:

- Low-temperature electrolysis (Case 1)
- Natural gas steam methane reforming (SMR) (Case 2)
- Natural gas autothermal reforming (ATR) (Case 3)

For hydrogen production via low-temperature electrolysis, the study reveals that facilities must source the vast majority of the electricity from zero-carbon sources to qualify for the full $\$3.00/\text{kgH}_2$ 45V PTC value. For hydrogen production via SMR using 100% fossil natural gas (FNG) feedstock, high carbon capture and storage (CCS) rates, at least 82 – 96% depending on electricity source, are key to qualify for any level of the 45V PTC. Although 100% landfill natural gas (LFG) feedstock significantly increases the eligibility range for 45V PTC, some level of CCS technology is still required with CCS rates of at least 34 – 42%, depending on electricity source, to qualify for any level of the 45V PTC. Similarly, for hydrogen production via ATR using 100% FNG feedstock, high CCS rates, at least 80 – 94%, depending on electricity source, are necessary to qualify for any level of the 45V PTC. However, certain regions with high grid carbon intensity (CI) may not be eligible to qualify even with 100% CCS rates. Using 100% LFG feedstock increases the potential to qualify for 45V PTC, but still necessitates some level of CCS technology with at least 6 – 28% CCS, depending on electricity source. Additionally, the analysis considered the use of valorized co-products, specifically oxygen, steam, and nitrogen, to reduce the CI of produced hydrogen, thereby aiding in meeting eligibility requirements for the 45V PTC.

This study underscores the importance of integrating zero-carbon electricity (ZCE), implementing CCS technology and co-product valorization, and careful selection of feedstocks to maximize eligibility for the 45V PTC. Additionally, it provides insights into the various limitations of the latest 45V-GREET model, identifying opportunities for future research to further evaluate the model's fixed assumptions and constraints. The findings are valuable for stakeholders in the hydrogen production industry aiming to leverage the 45V PTC to promote low-carbon hydrogen production.

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Glossary

45V NPRM Section 45V Notice of Proposed Rulemaking.

45V PTC Section 45V Clean Hydrogen Production Tax Credit.

ATR Autothermal reforming. A hydrogen production process which combines steam methane reforming and partial oxidation into a single process unit.

CCS Carbon capture and storage. The 45VH2-GREET only models the permanent sequestration of carbon dioxide, as in Class II or Class VI injection wells and does not model other forms of carbon utilization (e.g., production of synthetic fuels) [18].

CI Carbon intensity. A measure of the amount of carbon dioxide (CO_2) or carbon dioxide equivalents (CO_2e) produced per unit of mass or unit of energy. In 45VH2-GREET, carbon intensity is expressed in $kgCO_2e$ per kgH_2.

COD Commercial operations date. The date on which a facility that generates electricity begins commercial operations [25].

DOE U.S. Department of Energy.

EAC Energy Attribute Certificate. A legal instrument that represents an exclusive claim to the attributes of a unit of energy [17].

FNG Fossil natural gas. Conventional pipeline natural gas.

GHG Greenhouse gas.

IIJA Infrastructure Investment and Jobs Act. It is also known as the Bipartisan Infrastructure Law.

IRA 2022 Inflation Reduction Act.

IRS U.S. Internal Revenue Service.

LCA Life cycle assessment. An evaluation of the impacts throughout a product's life cycle to provide a more accurate picture of the true environmental trade-offs [3].

LCOH Levelized cost of hydrogen. The cost of hydrogen over its lifetime.

LFG Landfill natural gas. A renewable natural gas generated from municipal solid waste decomposition in landfills [18].

NERC North American Electric Reliability Corporation. A non-profit international regulatory authority whose mission is to assure effective and efficient reduction of risks to the reliability and security of the grid [12].

NG Natural gas.

NPC U.S. National Petroleum Council. A federally chartered advisory committee that provides advice to the Secretary of Energy on matters related to oil and natural gas industries [10].

NTNS National Transmissions Needs Study. A study conducted by the DOE to identify transmission needs that are currently harming consumers or expected to do so in the future and that could be alleviated by transmission solutions [21].

PEM Polymer electrolyte membrane. A type of ion-conducting membrane made from a polymer material that is used in electrolysis to produce hydrogen and oxygen from water [19].

PER Provisional emissions rate. A life cycle GHG emissions rate that can be requested when a rate cannot be determined by the most recent 45VH2-GREET model, because either the feedstock or hydrogen production technology is not included [25].

PWA Prevailing Wage and Apprenticeship Requirements. Requirements that ensure workers are paid wages and benefits that are comparable to the local standards for similar work and employ apprentices from registered apprenticeship programs [24].

REC Renewable Energy Certificate. A market-based instrument that represents the property rights to the environmental, social, and other non-power attributes of renewable electricity generation [23].

SMR Steam methane reforming. A hydrogen production process in which high-temperature steam is used to produce hydrogen from a methane source, such as natural gas.

ZCE Zero-carbon electricity. Electricity with 0 $kgCO_{2e}$ /kWh emission factors, such as wind and solar PV, procured and verified through qualifying EACs [18].

1 Introduction

1.1 Overview of the 45V Clean Hydrogen Production Tax Credit

The 45V Clean Hydrogen Production Tax Credit (45V PTC), introduced under the 2022 Inflation Reduction Act (IRA), incentivizes low-carbon hydrogen production. To refine and adapt the implementation of the 45V PTC effectively, the Notice of Proposed Rulemaking (45V NPRM) was published on December 26, 2023. This release initiated a 60-day public commenting period, ending on February 26, 2024, followed by a 3-day public hearing from March 25 to March 27, 2024, during which 98 speakers provided oral testimony [27]. Over 30,000 comments were submitted for this docket, highlighting the wide-ranging input from various sectors and reflecting a significant stakeholder engagement. As major recipients of funding through the Infrastructure Investment and Jobs Act (IIJA), the seven regional hydrogen hubs are key stakeholders in the deployment of hydrogen infrastructure. Each hub submitted comments on the proposed legislation, including feedback in a joint letter that noted concerns in its alignment with the regional and technical realities of hydrogen production and use.

The 45V PTC credit is structured in progressive tiers based on the life cycle greenhouse gas (GHG) emissions of the hydrogen production. Providing the prevailing wage and apprenticeship (PWA) requirements are met, the highest value credit of \$3.00/kgH_2 is awarded for hydrogen produced at the lowest carbon intensity (CI), less than 0.45 kilograms of carbon dioxide-equivalent per kilogram of hydrogen (kgCO_{2e} /kgH_2) with higher CI production methods receiving progressively lower credits, scaling down to \$0.60/kgH_2 for CI greater than 2.5 kgCO_{2e} /kgH_2 and up to 4 kgCO_{2e} /kgH_2 as summarized in Table 1 [8]:

Table 1: The value of the 45V PTC varies based on different CI thresholds, where values assume PWA requirements are satisfied by the qualified clean hydrogen production facility.

Life Cycle GHG Emissions [kgCO_{2e} /kgH_2]	**45V PTC Value** [\$/kgH_2]
< 0.45	$3.00
0.45 – 1.5	$1.00
1.5 – 2.5	$0.75
2.5 – 4.0	$0.60

1.2 Life Cycle GHG emissions for Electricity using Energy Attribute Certificates

As currently proposed in the 45V NPRM, the 45V PTC requires the assessment of life cycle GHG emissions within a well-to-gate system boundary. This requirement means that GHG emissions up to the point of hydrogen production, including emissions associated with any feedstocks required for the production process are considered [18]. For various hydrogen production pathways, electricity is a primary feedstock, and its source and quantity significantly impact the well-to-gate GHG emissions. As described in the U.S. Department of Energy's recent paper, assessing the life cycle GHG emissions associated with electricity in the context of 45V PTC involves [17]:

1. Evaluating the GHG emissions from the specific electricity generation sources with which the hydrogen producer has a contractual relationship, and
2. Considering the broader grid-level changes in generation and capacity.

The report further explains how GHG emissions associated with specific sources can be substantiated with Energy Attribute Certificates (EACs). EACs are legal instruments that represent the attributes of a unit of energy. They include renewable energy certificates (RECs), which are commonly used by electricity generators and suppliers in the U.S., and they can also more broadly encompass various types of energy such as gas, thermal, and electrical energy [22].

In the context of electricity sourced for the 45V PTC eligibility, EACs play a crucial role. When an EAC meets three specific criteria, known as the "three pillars", the induced grid emissions can be reasonably treated as zero. Consequently, hydrogen producers can consider the GHG emissions to be the life cycle GHG emissions associated with the specific generators from which the qualifying EACs were associated [17]. The three EAC criteria that must be satisfied, regardless of whether a hydrogen producer is purchasing off-site electricity from a generator located at some distance or electricity from an on-site behind-the-meter generator, are:

1. **Incrementality:** The generation must be incremental, meaning it represents an increase in low- or zero-carbon electricity generating capacity rather than merely reallocating existing low-carbon generating capacity from its current use. If existing generating capacity is shifted away from its current use, the original user of that electricity would likely turn to a more carbon-intensive alternative, leading to an overall increase in induced grid emissions. Ensuring that the generation is truly incremental ensures that the hydrogen produced does not induce an increase in grid GHG emissions. The 45V NPRM provides that electricity sourced from an electricity generating facility with a commercial operations date (COD) within 36 months of the hydrogen production facility service start date meets the EAC incrementality requirement [25].

2. **Temporal Matching:** The generation must occur within a time period that aligns with the hydrogen producer's electricity consumption. This requirement ensures the hydrogen production is directly tied to when low-GHG emitting sources are available. The 45V NPRM allows for annual matching until January 1, 2028. After this transition period, electricity generation must occur in the same hour that the hydrogen producer uses the electricity to meet the EAC temporal matching requirement [25].

3. **Deliverability:** The generation must occur within the same geographic location as the hydrogen production facility. The geographic location is defined as the regions outlined in the U.S. Department of Energy's (DOE) National Transmission Needs Study (NTNS) released in October 2023, with 15 total U.S. regions as shown in Figure 1 [21]. The 45V NPRM states that electricity sourced within the same region as the relevant hydrogen production facility meets the EAC deliverability requirement [17].

Figure 1: The NTNS regions are used to determine EAC eligibility per the deliverability requirement [25].

An EAC that meets the incrementality, temporal matching, and deliverability requirements, referred to as a "qualifying EAC", can be used to verify the use of low- or zero-carbon sources of electricity for hydrogen production. A qualifying EAC allows the taxpayer to claim that the hydrogen facility's electricity comes from a specific generator, rather than the regional grid-mix. For each unit of electricity claimed from such a source, a qualifying EAC must be acquired and retired, and this process must be recorded in a qualified registry or accounting system to prevent double counting [25]. Currently, there are nine registries across the U.S. [25]. Under the 45V PTC, the three pillars for qualifying EACs are intended to ensure that the tax credit leads to genuine low-carbon hydrogen production and contributes to broader decarbonization goals.

In March 2023, the European Union (EU) Parliament adopted similar legislation, setting requirements for incrementality, temporal matching, and deliverability for both domestically produced and imported hydrogen to qualify as "renewable" [4]. In the EU, these requirements are referred to as "additionality" (incrementality), "temporal correlation" (temporal matching), and "geographic correlation" (deliverability). This alignment between U.S. and EU regulations highlights a global commitment to reducing GHG emissions through hydrogen production and supporting the transition to a low-carbon economy.

2 45VH2-GREET Model

2.1 Overview

Argonne National Laboratory released the 45VH2-GREET model to specifically support the implementation of 45V PTC. This model assesses the life cycle GHG emissions of hydrogen production pathways within a well-to-gate system boundary, meaning it calculates GHG emissions considering all stages from feedstock extraction to hydrogen production to quantify a CI value. The CI value is then used to determine tax credit eligibility as defined by the 45V NPRM. The key features of the 45VH2-GREET model include [18]:

Life Cycle Analysis: The model conducts an analysis of both direct and indirect GHG emissions to establish a CI value for hydrogen production methods. This calculation is done using a combination of user-supplied data and fixed background data.

Hydrogen Production Pathways: As of its latest revision released in March 2024, the model supports six hydrogen production pathways consisting of [2]:

- Steam methane reforming (SMR) of natural gas (NG), including fossil and landfill gas, with potential carbon capture and storage (CCS)
- Autothermal reforming (ATR) of NG, including fossil and landfill gas, with potential CCS
- Coal gasification with potential CCS
- Biomass gasification with potential CCS
- Low-temperature water electrolysis using electricity
- High-temperature water electrolysis using electricity

Co-Product Credits: The model allows for accounting of co-products in the GHG emissions calculations for determining CI. This method includes valuing co-products such as steam, nitrogen, and oxygen that are generated during hydrogen production, using a method known as “system expansion” or the “displacement method,” which allocates emissions based on the co-product’s displaced production and its associated emissions elsewhere [18].

Electricity Carbon Intensity Accounting: This model uses two main approaches for quantifying the CI of the electricity source. For grid-mix sources, the model uses the average CI of electricity from the North American Electric Reliability Corporation (NERC) regional markets, based on the Energy Information Administration’s Annual Energy Outlook 2023, to determine the GHG impact of the electricity used in hydrogen production [18]. This determination is critical for reflecting the regional variations in electricity generation and the corresponding emissions profiles. The NERC regions and descriptions are shown in Figure 1 and

Table 2, respectively.

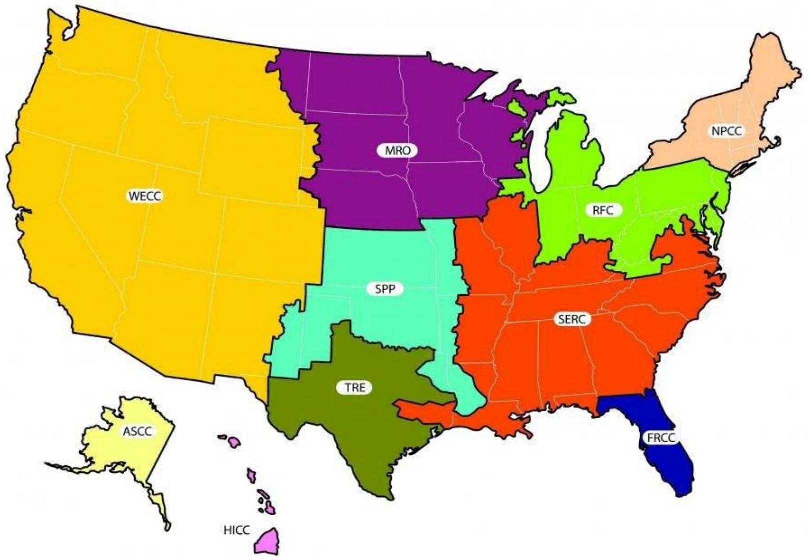


Figure 2: The NERC regions are used for grid-mix electricity in the most recent 45VH2-GREET model, released in March 2024, while regions for EAC eligibility, as specified by 45V NPRM, are defined per NTNS.

Table 2: There are ten NERC regional entities represented in 45VH2-GREET for using grid-mix electricity, where regional boundaries intersect with state geographic boundaries, and states are not entirely served by a single NERC entity.

NERC Region Acronym	NERC Region Name
ASCC	Alaska Systems Coordinating Council
FRCC	Florida Reliability Coordinating Council
HICC	Hawaiian Islands Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RFC	Reliability First Corporation
SERC	SERC Reliability Corporation
SPP	Southwest Power Pool
TRE	Texas Regional Entity
WECC	Western Electricity Coordinating Council

For user-defined sources, users can specify the electricity generation sources, provided an emissions profile is available for the selected generators (e.g., solar, wind, NG, etc.) and that the electricity use is verified through qualifying EACs that meet the three key pillars as outlined in the 45V NPRM.

Fixed Assumptions or Background Data: The model includes immutable background data for parameters that cannot be independently verified with high fidelity, such as upstream methane leakage rates and emissions factors for primary energy sources.

Designed for ease of use in determining 45V PTC eligibility, the 45VH2-GREET model will be updated annually to reflect the most current scientific and technological data, including additional hydrogen production pathways and updates to background data as methodological certainty develops [18]. These annual updates might introduce uncertainties for long-term project planning, as each taxable year requires the model's most current version. As highlighted in a public letter from the seven regional hydrogen hubs commenting on the 45V NPRM, the model's fixed assumptions, despite its comprehensive approach, can occasionally overlook specific project details. This oversight might disadvantage cleaner technologies and introduce investment uncertainties, potentially destabilizing financial forecasts for projects that initially met the tax credit guidelines [1]. Additionally, fixed model parameters, specifically for inputs like upstream methane leakage, discourage producers from decarbonizing supply chains and reducing methane emissions to qualify for a higher tier in the tax credit. Notably, some other relevant and emerging hydrogen production pathways are not yet included in 45VH2-GREET. These pathways include pyrolysis, natural (or geologic) hydrogen, photolysis, thermolysis, and others. As noted in the 45V NPRM, stakeholders can petition for a Provisional Emissions Rate (PER) for hydrogen production technologies or feedstocks not yet included in the model [26]. On April 11, 2024, the U.S. Internal Revenue Service (IRS) released proposed guidance describing the PER process, including how to request an emissions value from the DOE. However, further instructions detailing the application requirements for such a request are still pending release from the DOE [26]. This delay in published instruction might unfairly hinder these other hydrogen production pathways from qualifying for the tax credit.

In this study, the assessment focused on three hydrogen production pathways: natural gas steam methane reforming (SMR), natural gas autothermal reforming (ATR), and low-temperature electrolysis. The first pathway considered is SMR, the most common commercial method for producing hydrogen, accounting for roughly 95% of the current U.S. annual hydrogen supply [20]. The CO_2 that is emitted during SMR production can be captured and stored to produce low-carbon hydrogen. The second pathway assessed is ATR, which combines SMR and partial oxidation reactions into a single process unit [8], offering a higher thermal efficiency than SMR [16]. According to a recent report released by the U.S. National Petroleum Council (NPC), around two-thirds of announced NG reforming and CCS projects plan to implement ATR technology, including four of the regional hydrogen hubs, due to its CO_2 capture advantages compared to SMR [11]. Lastly, low-temperature electrolysis for hydrogen production was considered. This generally refers to processes that use an electrical current to decompose water into its constituent molecules, hydrogen and oxygen, operating at a temperature slightly elevated from ambient, and examples include aqueous alkaline or polymer electrolyte membrane (PEM) electrolysis [8]. When powered by zero-carbon electricity (ZCE) (i.e., electricity with 0 $kgCO_{2e}$/kWh emission factors procured and verified through qualifying EACs) electrolysis has the potential to produce hydrogen with zero CI, a critical characteristic for its continued market development and deployment. All seven of the regional hydrogen hubs plan to implement some form of hydrogen production via renewable-sourced electricity [13]. Both ATR and renewable-sourced low-temperature electrolysis are expected to lead deployment efforts for hydrogen production in the U.S. [11].

2.2 Case 1: Low-Temperature Electrolysis

In this case study, the 45VH2-GREET model was used to evaluate the impact of regional-grid mix electricity on the CI of hydrogen production via low-temperature electrolysis. The input parameters used for modeling are summarized in Table A1, and the results are shown in Figure 3.

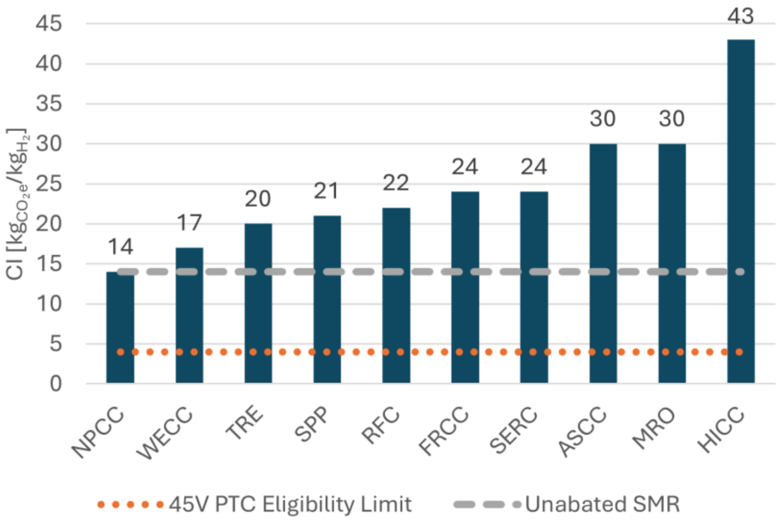


Figure 3: The CI of hydrogen production using low-temperature electrolysis with 100% grid-mix electricity varies

by region.

2.2.1 Regional Variations in Carbon Intensity

There are significant variations in regional grid generation mixes and the corresponding emissions profiles. The highest CI was recorded in HICC (Hawaii) at 43 $kgCO_{2e}/kgH_2$, primarily due to the prevalent use of residual oil in the region’s fuel mix. ASCC (Alaska) and the MRO (Midwest) also showed higher CIs, at 30 $kgCO_{2e}/kgH_2$ each, attributed to substantial coal usage in each region’s fuel mix. In contrast, the lowest CI was noted in the NPCC (Northeast) at 14 $kgCO_{2e}/kgH_2$. WECC (West) and TRE (Texas) followed closely at 17 and 20 $kgCO_{2e}$ /kgH_2, respectively, due to a higher integration of renewable energy sources [2].

Using 100% grid-mix electricity yields CI values that surpass the maximum CI limit for 45V PTC eligibility, which is set at 4 $kgCO_{2e}/kgH_2$. Additionally, these CI values exceed the GHG emissions of SMR without CCS, referred to as unabated SMR, which ranges between 12 to 14 $kgCO_{2e}/kgH_2$ [2]. Consequently, stakeholders cannot qualify for the 45V PTC in any U.S. region when using 100% grid-mix electricity.

2.2.2 Evaluating Grid-mix Electricity Limits

The regional variations in grid-mix electricity limits that would allow eligibility for the 45V PTC were also evaluated. This assessment assumed the remaining electricity would be obtained from zero-carbon sources with qualifying EACs, as explained in Section 1.2.

The results of the regional grid-mix electricity limits for maximum (\$3.00/kgH_2) and minimum (\$0.60/kgH_2) 45V PTC eligibility are summarized in Figure 4. The NPCC region resulted in the highest allowances for grid-mix electricity. Specifically, it allows for a 28.5% grid-mix to achieve the minimum 45V PTC eligibility, assuming the remaining 71.5% is sourced from ZCE. To qualify for the full \$3.00/kgH_2 tax credit, even the grid with the lowest CI, NPCC, can only have 3.1% of its input electricity not sourced from ZCE.

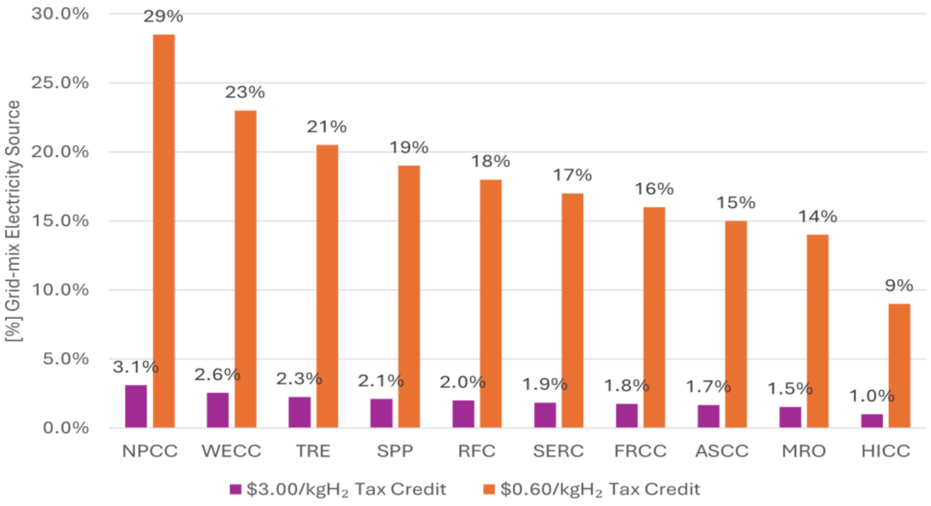


Figure 4: The limits on grid-mix electricity allowances for 45V PTC eligibility vary by region. The purple bars show

the amount of grid-mix supplied electricity allowable to receive the full \$3.00/ kgH_2 tax credit, and the orange bars show the amount of grid-mix supplied electricity allowable to receive any value of the tax credit.

2.2.3 Carbon Intensity Impact of Valorized Oxygen Co-Products

The final assessment in Case 1 examined the CI impact of valorized co-products, specifically oxygen, for hydrogen produced via low-temperature electrolysis. On average, the maximum oxygen co-product credit reduced the CI by 0.2 kgCO_{2e}/kgH_2, as shown in Figure 5.

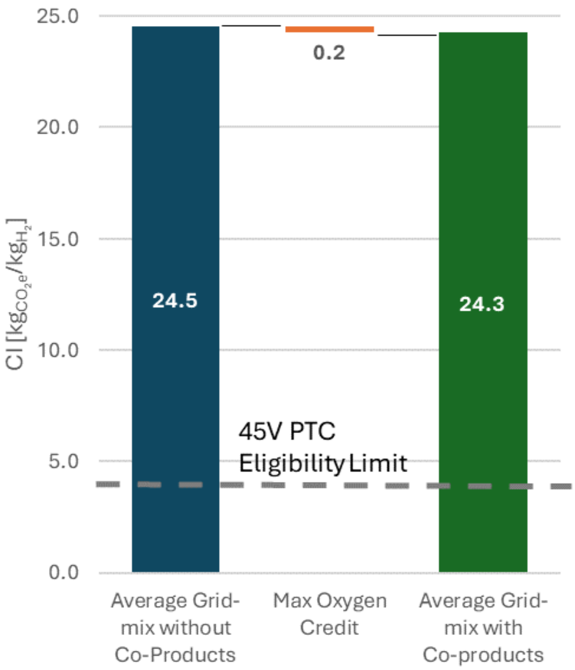


Figure 5: The average CI impact of co-product credits, maximized at 7.93 kg (99.9%) of oxygen, for low-temperature electrolysis using 100% average grid-mix electricity is 0.2 kgCO_{2e} /kgH_2.

Using 100% grid-mix electricity, the CI impact is insufficient for stakeholders to qualify for 45V PTC. However, it may allow facilities using a blend of ZCE and grid-mix electricity to increase the allowances of grid-mix electricity and still qualify for the 45V PTC, but only by 1 – 2%. Ultimately, oxygen co-product credits have a limited benefit to the CI of produced hydrogen, and the economic viability of implementing an oxygen capture and purification system would have to be carefully considered by the hydrogen production facility.

2.3 Case 2: Natural Gas Steam Methane Reforming (SMR)

The SMR process involves reacting NG with steam to produce hydrogen, carbon monoxide, and carbon dioxide. This pathway utilizes two primary feedstocks: NG and electricity. Given its current widespread use and established infrastructure for hydrogen production, SMR presents significant opportunity for reducing GHG emissions through the integration of CCS technologies. In this case study, the CI values of hydrogen production via SMR using conventional pipeline NG, referred to as “fossil natural gas” (FNG), and landfill natural gas (LFG) feedstock, were evaluated. The team assessed the CI impact of CCS rates along with regional grid-mix electricity and ZCE to provide insights into the potential for SMR to meet the eligibility criteria for 45V PTC. To illustrate the effect of regional grid-mix electricity, three regions were selected for analysis in addition to the ZCE scenario. The NPCC was selected, representing the U.S. region with the lowest average grid CI, and the HICC region was selected as it represents the highest average grid CI; together, they reveal the range of regional grid-mix electricity and its effect on the calculated CI value for hydrogen production. The TRE region, representing Texas, was also of particular interest due to its existing hydrogen infrastructure, experienced workforce, and natural resources [8]. Additionally, the CI impact of steam co-product credits was evaluated to determine the potential benefit. This analysis aims to provide insights into the feasibility and optimization of SMR technology for achieving low-carbon hydrogen production in alignment with the 45V PTC requirements. The input parameters used in the 45VH2-GREET model are listed in Table A2.

2.3.1 Fossil Natural Gas (FNG): SMR carbon capture rates by electricity source for 45V PTC eligibility

Using the 45VH2-GREET model, the CCS rates required for 45V PTC eligibility using FNG for different electricity sources were evaluated. The results of the assessment are summarized in Figure 6.

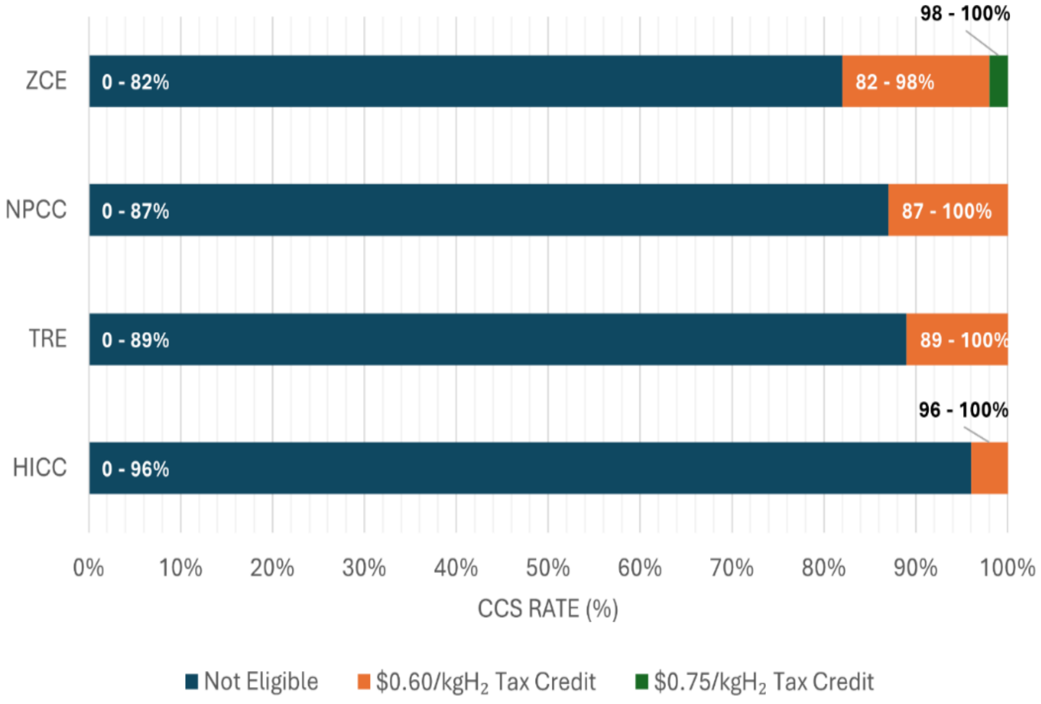


Figure 6: The carbon capture rates needed for 45V PTC eligibility through SMR using 100% FNG feedstock vary based on the grid region or use of ZCE.

The results reveal that even when using ZCE, a reformer with CCS technology, delivering high CCS rates of at least 82%, is required to achieve minimum 45V PTC eligibility at \$0.60/kgH$_2$. To be eligible for \$0.75/kgH$_2$ using ZCE, an impractical CCS rate of at least 98% would be necessary. Current state-of-the-art CCS technology can deliver a 90% capture rate, and future projects have been proposed with up to 95% capture rates [5]. Nonetheless, even with CCS technology and ZCE feedstock, it is still not feasible to achieve the full 45V PTC at \$3.00/kgH$_2$ due to the indirect emissions associated with the FNG supply chain (e.g., GHG emissions associated with NG recovery and delivery) [18].

2.3.2 Landfill Natural Gas (LFG): SMR carbon capture rates by electricity source for 45V PTC eligibility

The CCS rates required for 45V PTC eligibility using LFG for different electricity sources were further evaluated. The results of the assessment are summarized in Figure 7. LFG is defined as renewable NG generated from municipal solid waste decomposition in landfills [18]. A key limitation in the 45VH2-GREET model is that it does not support a mix of FNG and LFG for a single hydrogen production facility, meaning the feedstocks cannot be combined in the model to calculate a CI value. As currently specified in the 45V NPRM, stakeholders must adhere to two key requirements for LFG to qualify:

1. **Direct Use Requirement:** Stakeholders can only use the 45VH2-GREET model for LFG provided via “direct use”. This requirement means there is a direct and dedicated pipeline connection between the source of the gas that is being procured (e.g., LFG processing facility) and the hydrogen production facility until the final regulations for the 45V PTC are issued [25].
2. **First Productive Use Requirement:** The LFG must result from “first productive use” of the methane from the landfill source. This requirement ensures that the LFG has not been previously used for any other purpose before being employed in the hydrogen production process, thereby maximizing its emissions benefit. It is important to note that other sources of renewable NG feedstocks are not included in the latest release of the 45VH2-GREET. However, stakeholders can petition the use of other renewable NG sources via PER process noted in Section 2.1, but they must also meet the direct use and first productive use requirements until the final regulations are issued [25]. As noted in the 45V NPRM, additional conditions for using renewable NG will be established in the final regulations. These conditions are anticipated to address requirements for renewable NG certificates and are expected to be logically consistent though not identical to the requirements for electricity-derived EACs concerning incrementality, temporal matching, and deliverability. These requirements will take into account the differences between electricity and renewable NG, including different sources of emissions, markets, available tracking and verification methods, and the potential for perverse incentives. The 45V NPRM also solicited comments on various questions related to these conditions to inform future updates to 45VH2-GREET and the final regulations [25].

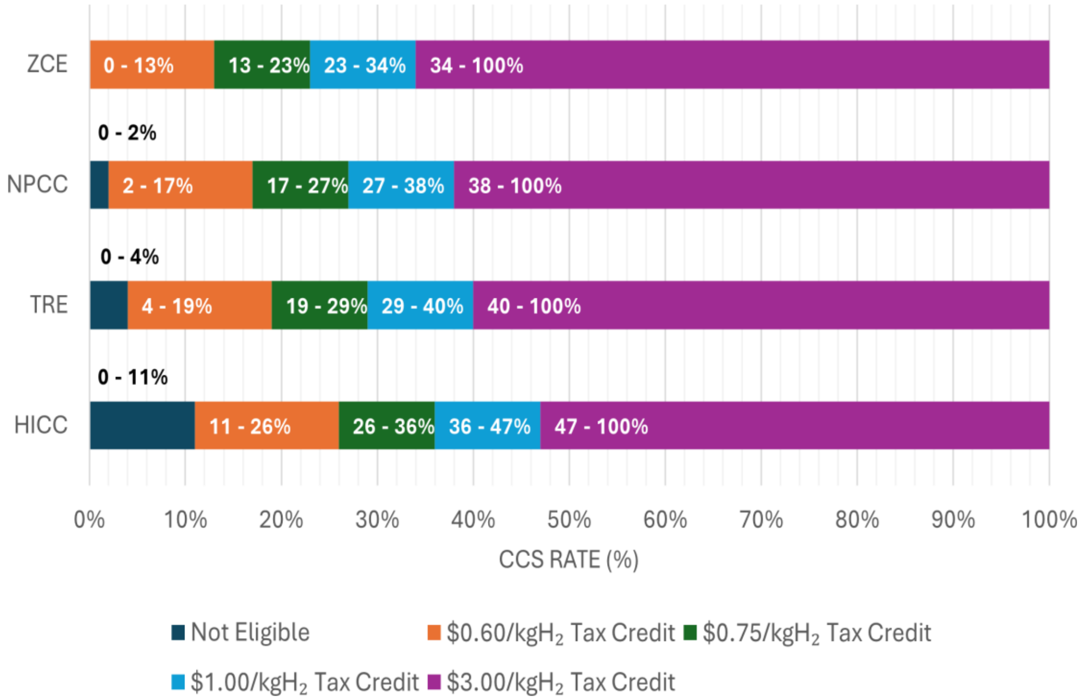
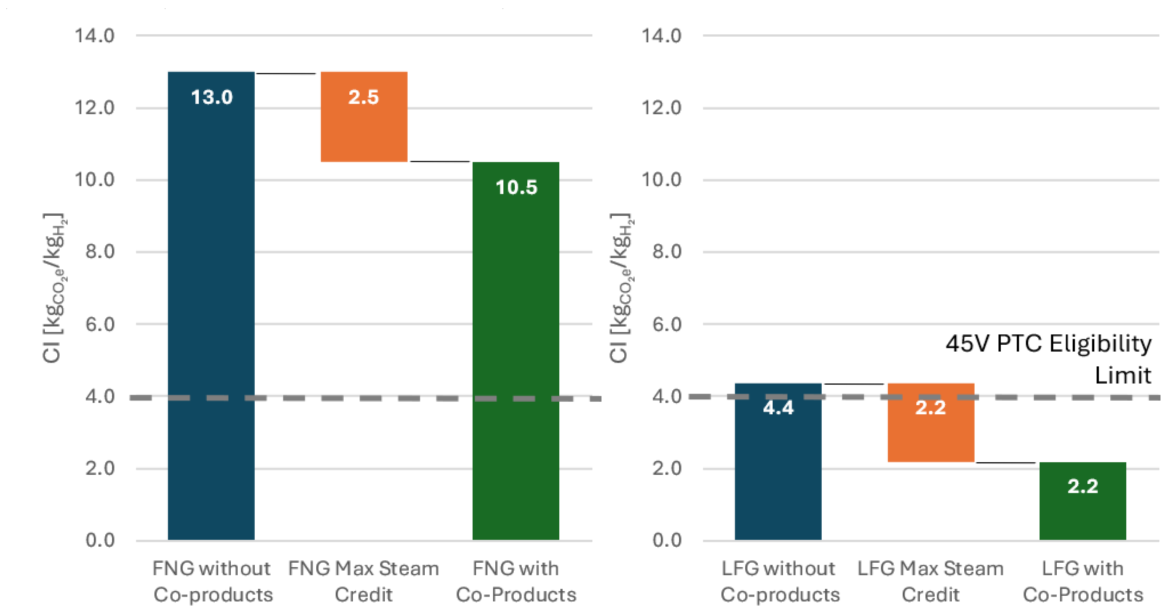


Figure 7. The carbon capture rates needed for 45V PTC eligibility through SMR using 100% LFG feedstock vary based on the grid region or use of ZCE.

The results reveal that even when using entirely LFG as the methane feedstock a reformer with CCS technology is still required to achieve 45V PTC tax eligibility in all regions using grid-mix electricity. This finding aligns with a recent study, which concludes that the 45Q tax credit, intended to encourage CCS for reducing GHG emissions, is more beneficial than the 45V PTC for NG projects at reducing the levelized cost of hydrogen [9]. Even when using ZCE, at least a 34% capture rate is necessary to achieve the full 45V PTC at $3.00/kgH$_2$. Although unabated SMR using LFG may seem like a low-carbon production pathway for hydrogen, implementing CCS technology is still necessary to reduce its life cycle GHG emissions to achieve 45V PTC eligibility. This requirement is because even though LFG is associated with lower direct facility emissions compared to FNG, the emissions associated with upgrading LFG to pipeline-quality NG and the methane leakage during pipeline transportation contribute significantly to the indirect GHG emissions of LFG feedstock [2].

2.3.3 Carbon Intensity Impact of Valorized Steam Co-Products

The last assessment in Case 2 examined the CI impact of valorized co-products, specifically steam, for hydrogen produced via SMR. According to the 45V NPRM, the amount of steam co-product reformers can claim is limited to the quantity an optimally designed reformer can produce [25]. This restriction, included in the 45VH2-GREET model, prevents the over-production of steam to artificially qualify for higher tax credit values. Assuming the maximum claim of 24,290 BTU of steam (based on the energy inputs listed in Table A2), the associated emissions credits result in an average CI reduction of 2.2-2.5 kgCO$_{2e}$/kgH$_2$ as shown in Figure 8.



(a) The average CI impact of co-product credits, maximized at 24,490 BTU of steam, for SMR using 100% FNG is 2.5 $kgCO_{2e}/kgH_2$.

(b) The average CI impact of co-product credits, maximized at 24,490 BTU of steam, for SMR using 100% LFG is 2.2 $kgCO_{2e}/kgH_2$.

Figure 8: These charts compare the average CI impact of co-product emissions credits for SMR using 100% FNG (panel (a), left) and 100% LFG (panel (b), right). Note that emissions credit for valorized steam is only applicable to reformers without CCS.

Since steam co-product credits are only applicable to reformers without CCS, the CI reduction is insufficient for stakeholders using FNG feedstock with unabated SMR to qualify for 45V PTC. However, using LFG feedstock, the average steam co-product credits allow stakeholders to qualify for at least the minimum 45V PTC at \$0.60/kgH_2 across all electricity regions. In the best-case scenario using ZCE, stakeholders can qualify for the \$0.75/kgH_2 tax credit. Ultimately, steam co-product credits are only beneficial to 45V PTC eligibility under specific conditions and will not enable stakeholders to qualify for the full 45V PTC at \$3.00/kgH_2 for unabated SMR, regardless of whether FNG or LFG is used.

2.4 Case 3: Natural Gas Autothermal Reforming (ATR)

ATR is a hydrogen production technology that combines the principles of SMR and partial oxidation within a single reactor using two primary feedstocks: NG and electricity. This process offers higher thermal efficiency and improved CCS capabilities compared to traditional SMR, making it a promising pathway for low-carbon hydrogen production. In this case study, the team evaluated the CI of hydrogen produced via ATR using both FNG and LFG as feedstocks. The CI impact of various CCS rates and different electricity sources was evaluated to determine eligibility for 45V PTC. Additionally, the potential benefits of valorized co-products, nitrogen and steam, in CI reduction of hydrogen produced via ATR was assessed. This analysis aims to offer insights into the feasibility and optimization of ATR technology for achieving low-carbon hydrogen production in alignment with the 45V PTC requirements. The input parameters used in the 45VH2-GREET model are listed in Table A3.

2.4.1 Fossil Natural Gas (FNG): ATR carbon capture rates by electricity source for 45V PTC eligibility

Using the 45VH2-GREET model, the CCS rates required by ATR facilities for 45V PTC eligibility using FNG for different electricity sources were assessed. The results of this assessment are shown in Figure 9.

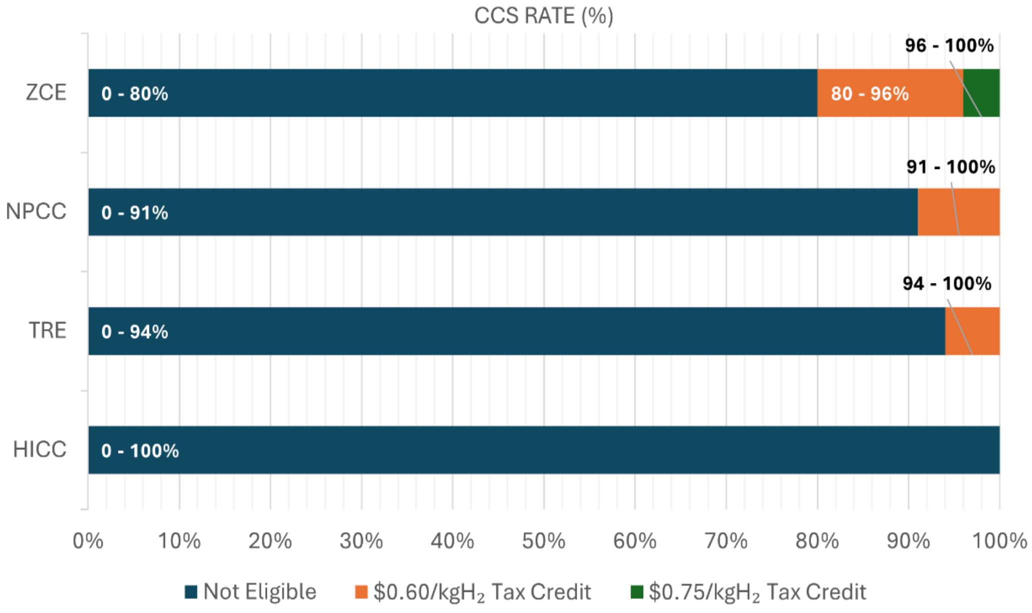


Figure 9: The carbon capture rates needed for 45V PTC eligibility through ATR using 100% FNG feedstock vary based on the grid region or use of ZCE.

The findings indicate that even when using ZCE, a CCS rate of at least 80% is required to qualify for the minimum 45V PTC credit of \$0.60/kgH$_2$. With a CCS rate of at least 96%, ATR facilities using ZCE can qualify for a higher credit of \$0.75/kgH$_2$. When using grid-mix electricity, a minimum CCS rate of 91% is required to meet the minimum 45V PTC value. Notably, the most carbon-intensive grid (HICC) is ineligible for any 45V PTC, even with 100% CCS rate. In comparison, SMR facilities need a CCS rate of at least 82% when using ZCE and 87% when using grid-mix electricity. This represents only a slight difference compared to the requirements for ATR facilities. One benefit of ATR is that it generates a single CO_2 stream that must be captured, leading to expectations that it will be able to achieve higher capture rates at less cost compared to SMR [5].

Including the valorized nitrogen co-product enhances the eligibility range for ATR facilities. Using ZCE, only 69% CCS is needed to achieve the minimum 45V PTC value, and some regions using grid-mix electricity can meet the minimum 45V PTC threshold with 80% CCS. When using ZCE at very high CCS rates exceeding 96%, ATR facilities can qualify for up to \$1.00/kgH$_2$. When using grid-mix electricity, ATR facilities in the HICC region remain ineligible for 45V PTC at any level of CCS. These results are shown in Figure 10.

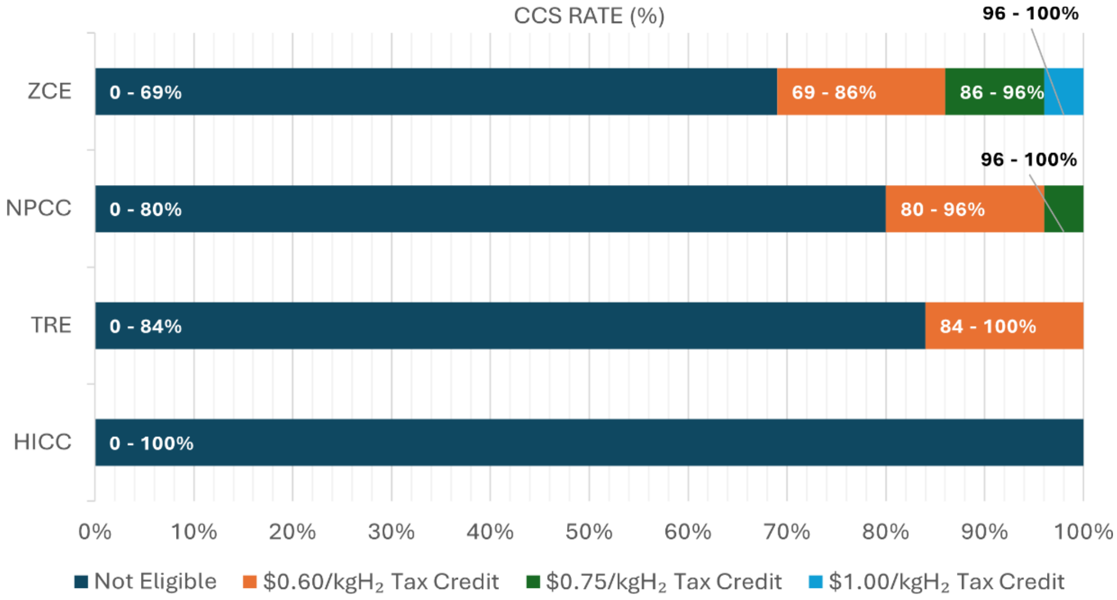


Figure 10: The carbon capture rates necessary for 45V PTC eligibility through ATR using 100% FNG feedstock with maximum valorized nitrogen co-product (14.68 kg) vary based on grid region or use of ZCE.

2.4.2 Landfill Natural Gas (LFG): ATR carbon capture rates by electricity source for 45V PTC eligibility

Using LFG significantly increases the eligibility range of ATR for the 45V PTC, as shown in Figure 11. Facilities can even qualify for the full \$3.00/kgH_2 tax credit at certain CCS rates. Even without any CCS, facilities using ZCE can qualify for the minimum 45V PTC amount. At CCS rates above 33%, ZCE facilities qualify for the full \$3.00/kgH_2 tax credit. At CCS rates above 66%, ATR facilities in the HICC region using grid-mix electricity can qualify for the full \$3.00/kgH2 tax credit.

Including the maximum valorized nitrogen co-product at these facilities further enhances the eligibility range across the various tiers of the 45V PTC, as shown in Figure 12. Even without any CCS, facilities in certain regions using grid-mix electricity can qualify for the minimum 45V PTC amount at \$0.60/kgH_2. Additionally, at CCS rates above 55%, ATR facilities using grid-mix electricity and LFG in any U.S. region can qualify for the full \$3.00/kgH2 tax credit.

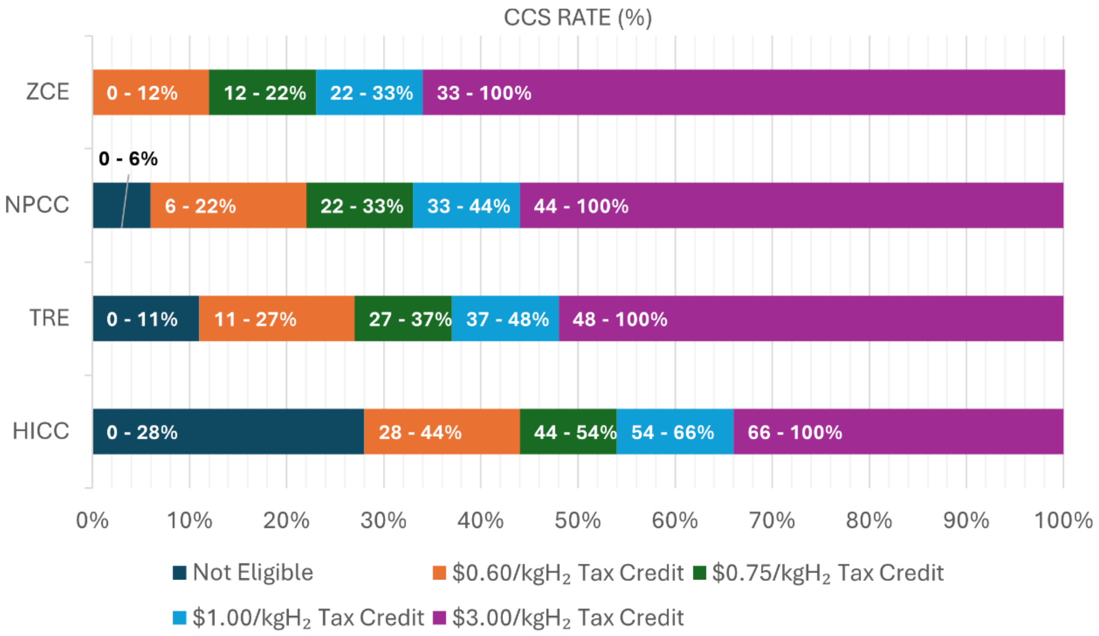


Figure 11: The carbon capture rates necessary for 45V PTC eligibility through ATR using 100% LFG feedstock vary based on grid region or use of ZCE.

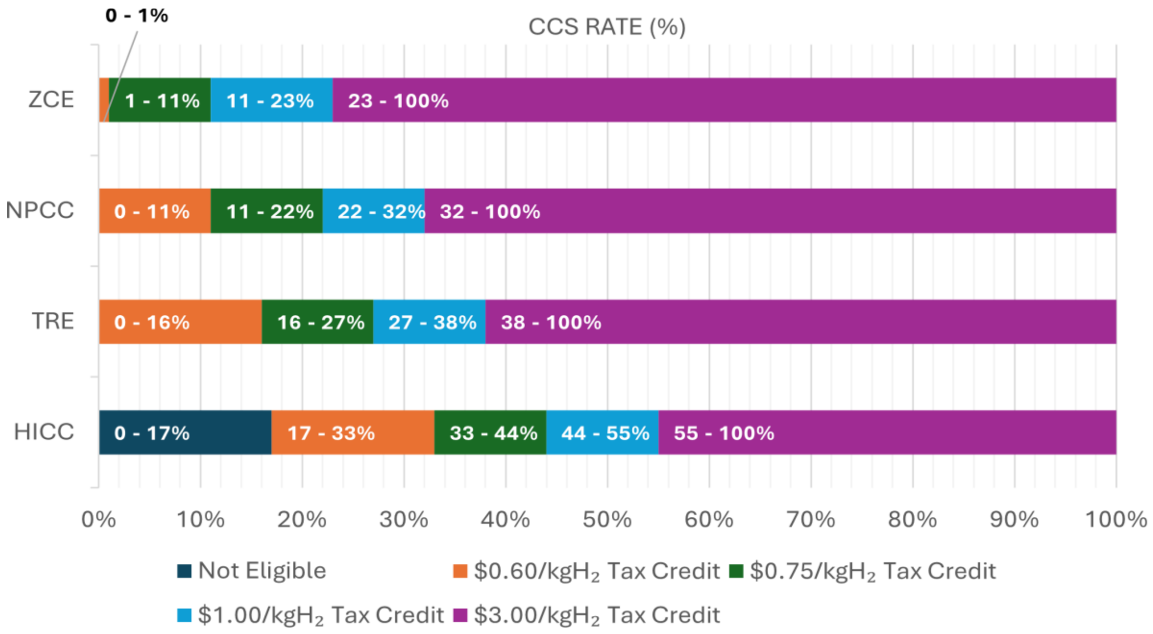
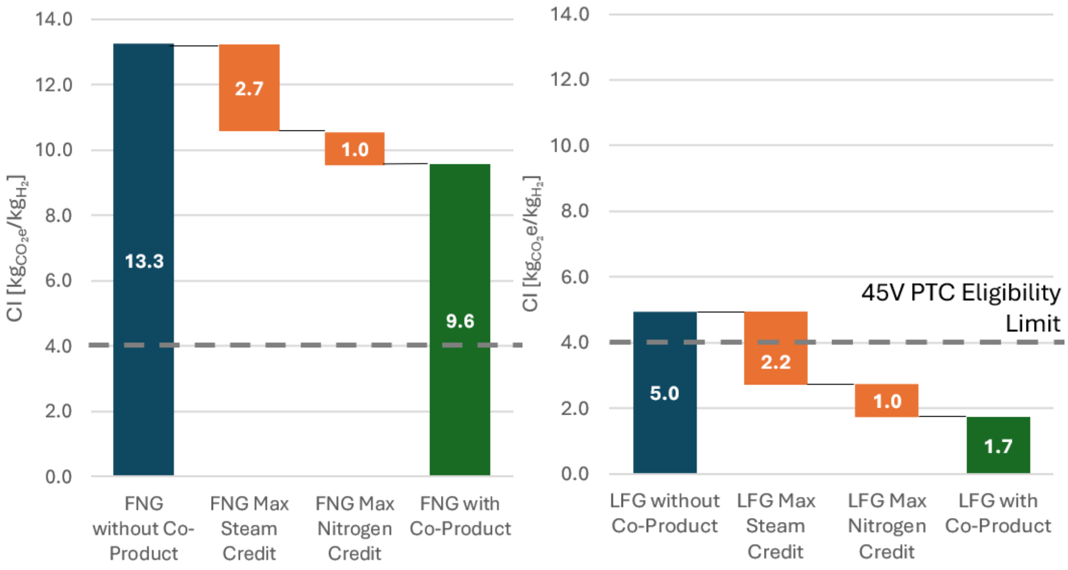


Figure 12: The carbon capture rates necessary for 45V PTC eligibility through ATR using 100% LFG feedstock with maximum valorized nitrogen co-product (14.68 kg) vary based on grid region or use of ZCE.

2.4.3 Carbon Intensity Impact of Valorized Steam and Nitrogen Co-Products

The final assessment in Case 3 examined the CI impact of valorized co-products, both steam and nitrogen for hydrogen produced via ATR. The steam co-product credit reduced the CI by between 2.2 to 2.7 $kgCO_{2e}/kgH_2$, and the maximum nitrogen co-product reduced the CI by 1.0 $kgCO_{2e}/kgH_2$, as shown in Figure 13.



(a) The average CI impact of co-product credits, maximized at 24,490 BTU of steam and 14.68 kg nitrogen, for ATR using 100% FNG is 2.7 and 1.0 $kgCO_{2e}/kgH_2$ respectively.

(b) The average CI impact of co-product credits, maximized at 24,490 BTU of steam and 14.68 kg nitrogen, for ATR using 100% LFG is 2.2 and 1.0 $kgCO_{2e}/kgH_2$ respectively.

Figure 13: These charts compare the average CI impact of co-product credits for ATR using 100% FNG and 100% LFG. Note that emissions credit for valorized steam is only applicable to reformers without CCS, referred to as unabated ATR.

With FNG feedstock, even this reduction in CI is insufficient to bring the facilities into the range of tax credit eligibility without additional CCS. However, using LFG feedstock, the co-product credits may allow facilities to qualify for the 45V PTC without any CCS required.

3 Conclusions and Future Work

The 45VH2-GREET model serves as a critical tool for assessing the life cycle GHG emissions of various hydrogen production pathways to determine eligibility for the 45V PTC. The study provides an analysis of tax credit eligibility conditions for three hydrogen production pathways: low-temperature electrolysis (Case 1), SMR (Case 2), and ATR (Case 3), using FNG and LFG feedstocks.

Case 1 focused on hydrogen production via low-temperature electrolysis. The team found that the CI varies significantly due to the different regional grid-mix electricity profiles across the U.S. The NPCC has the lowest grid CI, while the HICC has the highest grid CI. Using 100% grid-mix electricity yields CI values that exceed the maximum limit for 45V PTC eligibility and yields a higher CI than unabated SMR. Therefore, stakeholders must rely on a significant percentage of ZCE verified through qualifying EACs, at least 71 – 91% depending on electricity source, to be eligible for any level of the tax credit for hydrogen production via low-temperature electrolysis.

Case 2 focused on hydrogen production via SMR. SMR using FNG feedstock requires high CCS rates, at least 82 – 96% depending on electricity source, to qualify for minimum 45V PTC eligibility at \$0.60/kgH_2. Although SMR using LFG feedstock shows better potential for meeting the 45V PTC requirements, CCS technology must still be employed. A CCS rate of at least 34 – 42% depending on the electricity source is required to achieve the minimum 45V PTC eligibility, in addition to meeting the direct use and first productive use requirements for LFG.

Case 3 focused on ATR for hydrogen production. ATR offers higher thermal efficiency and improved CCS capabilities compared to SMR. ATR using FNG also requires high CCS rates, at least 80 – 94% depending on electricity source, to achieve minimum 45V PTC eligibility, and stakeholders may not be eligible to qualify for any 45V PTC tax credit even with 100% CCS rates in regions with highly carbon-intensive grid-mix electricity, such as HICC. ATR using LFG feedstock significantly increases the eligibility range for meeting 45V PTC requirements. Nonetheless, CCS technology must still be employed. A CCS rate of at least 6 – 28% depending on the electricity region is required to qualify for minimum 45V PTC eligibility. Only when ZCE is employed can stakeholders qualify for the minimum 45V PTC without CCS technology.

The inclusion of valorized co-product credits (oxygen, steam, and nitrogen) was found to reduce the overall CI of hydrogen production, but these credits are only applicable under specific conditions. For hydrogen production via low-temperature electrolysis using 100% grid-mix electricity, the inclusion of oxygen co-product credits does not enable stakeholders to qualify for any level of 45V PTC. However, facilities using a blend of ZCE and grid-mix electricity would be allowed to increase the percentage of grid-mix electricity by 1 – 2% while still maintaining eligibility for 45V PTC. Moreover, the inclusion of steam and nitrogen co-product credits for hydrogen production via SMR and ATR using FNG feedstock does not enable stakeholders to qualify for any level of 45V PTC. In contrast, when using LFG feedstock, co-product credits significantly increase the eligibility range, but on average, stakeholders can qualify for partial 45V PTC at \$0.75/kgH_2 in either unabated SMR or ATR scenario.

Future work focusing on more specific use cases and project parameters is worth considering, particularly examining the overall cost and tradeoffs of different pathways. The team recommends the following additional analyses:

- A techno-economic analysis evaluating the levelized cost of hydrogen (LCOH) for each case study is recommended to better assess the viability of each hydrogen production method. This analysis should also include an optimization study on the LCOH for hydrogen production via low-temperature electrolysis, considering the purchase price of EACs for ZCE.
- A comparative study of the 45VH2-GREET model’s background assumptions against other life cycle assessment (LCA) tools, such as the Open Hydrogen Initiative LCA toolkit, is suggested [6]. This comparison should allow for custom modeling parameters, including considerations of hydrogen fugitive emissions and water consumption, to evaluate life cycle GHG emissions.
- Since the current 45VH2-GREET model does not support mixing of FNG and LFG feedstocks, an

evaluation of mixing rates at assumed CCS rates to determine eligibility for the various 45V PTC tiers should be considered.

In summary, the 45VH2-GREET model is key for stakeholders aiming to leverage the 45V PTC for clean hydrogen production. By understanding the nuances of different hydrogen production pathways as it relates to 45V PTC, stakeholders can make informed decisions to optimize the hydrogen production processes to maximize eligibility for tax credits.

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Appendix: 45VH2-GREET Model Input Parameters

Table A1: The model inputs are used for the low-temperature electrolysis analysis (Case 1).

Variable Definition	**Value**	**Notes**
Simulation Year	2024	
Hydrogen Production Technology	Low Temperature Electrolysis	
Electricity Input	50 kWh	[7]
Electric Generation [Source]/[Mix]		Regional grid-mix electricity: [Grid mix]/[(Region) Mix]; OR Zero-carbon electricity: [User-defined mix]/[100% So- lar PV]
Valorized Co-Product (Oxygen)		0 kg for Figures 3 and 4; OR 7.93 kg (99.9%) for Figure 5
Hydrogen Production	1 kg	[7]
Hydrogen Production Pressure	300 psia	Model functional unit; after any purification at the hydrogen production facility [18]
Hydrogen Production Purity	100%	Model functional unit [18]

Table A2: The model inputs are used for the SMR production pathway analysis (Case 2).

Variable Definition	Value	Notes
Simulation Year	2024	
Hydrogen Production Technology	Steam Methane Reforming (SMR)	
SMR Feedstock		Landfill Gas; OR Fossil Natural Gas
NG Input	0.168 mmBTU	[15]
Electricity Input	1.503 kWh	[15]
Electric Generation [Source]/[Mix]		Regional grid-mix electricity: [Grid mix]/[(Region) Mix]; OR ZCE: [User-defined mix]/[100% Solar PV]
CO_2 Capture and Storage	Yes	
Sequestered CO_2/ Percentage of CO_2 Captured		Inputs vary per Tables 6 and 7; values must be consistent with amounts reported to the U.S. Environmental Protection Agency's GHG Gas Reporting Program [18]
Hydrogen Production	1 kg	[15]
Valorized Co-Product (Steam)		0 BTU for Figures 6 and 7. The model does not account for steam co-products in reformers with CCS technology, as previous modeling indicates excess steam is best used to power the CCS plant rather than being valorized [18]; 24,290 BTU for Figure 8 which represents the maximum claim for steam co-product [18]
Hydrogen Production Pressure	300 psia	Model functional unit [18]
Hydrogen Production Purity	100%	Model functional unit; after any purification at the hydrogen production facility [18]
NG Lower Heating Value (LHV) @32F and 1atm	983 Btu/ft3	Model default NG properties [2]
NG Density @32F and 1atm	22 g/ft3	Model default NG properties [2]
NG Carbon Ratio @32F and 1atm	72.4 % by weight	Model default NG properties [2]

Table A3: The model inputs are used for the ATR production pathway analysis (Case 3).

Variable Definition	Value	Notes
Simulation Year	2024	
Hydrogen Production Technology	Autothermal Reforming (ATR)	
ATR Feedstock		Landfill Gas; OR Fossil Natural Gas
NG Input	0.158 mmBTU	[14]
Electricity Input	3.495 kWh	[14]
Electric Generation [Source]/[Mix]		Regional grid-mix electricity: [Grid mix]/[(Region) Mix]; OR Zero-carbon electricity: [User-defined mix]/[100% So- lar PV]
CO2 Capture and Storage	Yes	
Sequestered CO2/ Percentage of CO2 Captured		Inputs vary per Tables 9 and 11; values must be consistent with amounts reported to the U.S. Environmental Protection Agency’s GHG Reporting Program [18]
Hydrogen Production	1 kg	[14]
Valorized Co-Product (Nitrogen)		“No” for values in Figures 9 and 11; “Yes” for values in Figures 10 and 12
Amount of Nitrogen Co-Product	14.68 kg	Maximum allowable mass for values in Figures 10 and 12
Valorized Co-Product (Steam)		0 BTU for Figures 9, 10, 11 and 12 The model does not account for steam co-products in reformers with CCS technology, as previous modeling indicates excess steam is best used to power the CCS plant rather than being valorized [18]; 24,290 BTU for Figure 13 which represents the maximum claim for steam co-product [18]
Hydrogen Production Pressure	300 psia	Model functional unit [18]
Hydrogen Production Purity	100%	Model functional unit; after any purification at the hydrogen production facility [18]
NG Lower Heating Value (LHV) @32F and 1atm	983 Btu/ft3	Model default NG properties [2]
NG Density @32F and 1atm	22 g/ft3	Model default NG properties [2]
NG Carbon Ratio @32F and 1atm	72.4 % by weight	Model default NG properties [2]