U.S. DEPARTMENT OF ENERGY

Guidelines to Determine Well-to-Gate Greenhouse Gas (GHG) Emissions of Hydrogen Production Pathways using 45VH2-GREET Rev. August 2024

August 2024

Disclaimer

The current document describes the manner in which 45VH2-GREET Rev. August 2024 characterizes well-to-gate emissions of hydrogen production pathways that are included in the model and provides instructions for use of the model. Please note that background data, methodologies, and other parameters within the 45VH2-GREET Rev. August 2024 model may be revised in the future, including to add new hydrogen production pathways that are not currently in the model, to reflect new or updated background data, and to incorporate new or updated methodologies for characterizing well-to-gate emissions. If the model is revised in the future, those future releases are expected to be accompanied with additional supporting documentation describing the revisions made.

Foreword

This document describes the methodology to calculate lifecycle greenhouse gas (GHG) emissions of hydrogen production under a well-to-gate system boundary using Argonne National Laboratory's (ANL) 45VH2-GREET Rev. August 2024 model.

45VH2-GREET has been adopted by the U.S. Department of the Treasury for the purposes of calculating well-to-gate emissions of hydrogen production facilities for the clean hydrogen production tax credit established in Internal Revenue Code (I.R.F section 45V [45V tax credit]). 45VH2-GREET is one in the suite of Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) tools developed and maintained by ANL. 45VH2-GREET Rev. August 2024 is available at https://www.energy.gov/eere/GREET. 45VH2-GREET is tailored to the administration of the 45V tax credit. The model includes features that make it easy to use for taxpayers as well as hydrogen production pathways with sufficient methodological certainty to determine eligible tax credits.

This document has six key sections:

Section 1: Introduction

Section 2: Methodology

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Section 1. Introduction

45VH2-GREET Rev. August 2024, hereafter referred to as 45VH2-GREET, can be used to characterize well-to-gate GHG emissions associated with hydrogen production using the system boundary defined in the Notice of Proposed Rulemaking published by the U.S. Department of the Treasury and the Internal Revenue Service (UST/IRS NPRM) on December 22, 2023, for the 45V Credit for Production of Clean Hydrogen within the Inflation Reduction Act, hereafter referred to as the 45V NPRM.[1] The term "emissions through the point of production (well-to-gate)" is defined in the 45V NPRM to mean the aggregate lifecycle GHG emissions related to hydrogen produced at a hydrogen production facility during the taxable year through the point of production. It includes emissions associated with feedstock growth, gathering, extraction, processing, and delivery to a hydrogen production facility. It also includes the emissions associated with the hydrogen production process, inclusive of the electricity used by the hydrogen production facility and any capture and sequestration of carbon dioxide (CO_2) generated by the hydrogen production facility.

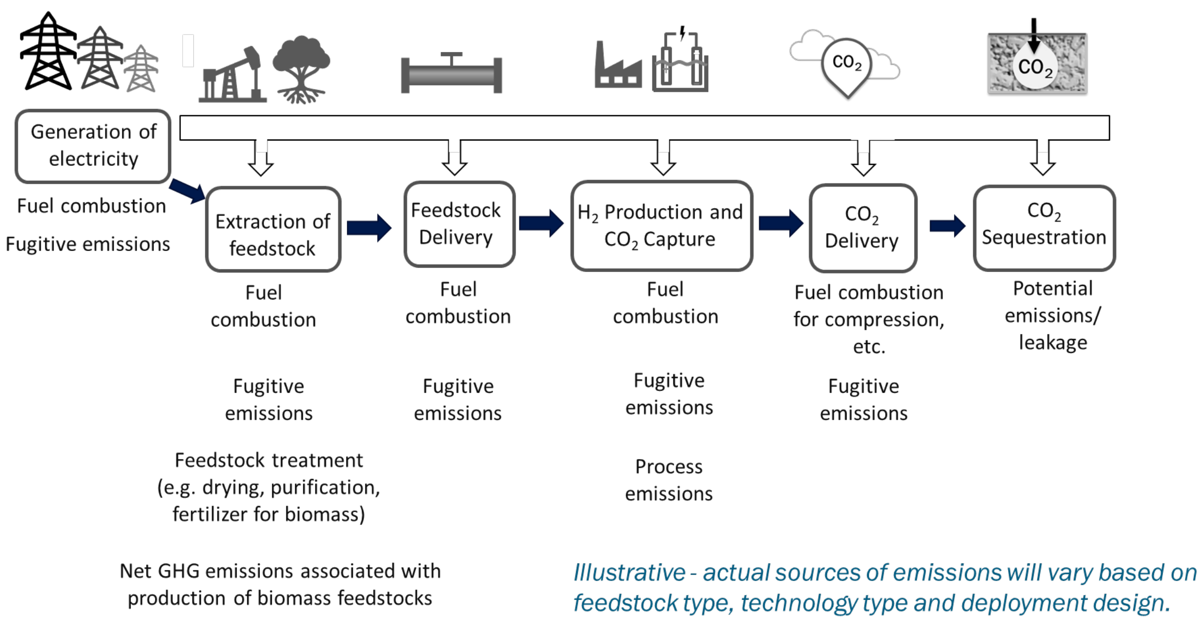

Figure 1. Examples of key activities related to GHG emissions within the well-to-gate system boundary for clean hydrogen production.

Certain parameters within 45VH2-GREET are fixed assumptions (i.e., background data) and may not be changed by the user. The 45V NPRM defines background data as parameters for which bespoke inputs from hydrogen producers are unlikely to be independently verifiable with high fidelity, given the current status of verification mechanisms. Examples of background data in 45VH2-GREET include the carbon intensity of grid electricity supplied to the hydrogen production facility in a particular region or the upstream methane leakage rates for the natural gas supply

[1] 26 U.S. Code § 45V

chain. Inputs for background data are itemized in the GREET dependency file in the 45VH2-GREET package.

All other parameters are "foreground data" and must be input by the user. Examples of these parameters include feedstock type and quantity, the type and quantity of energy used for hydrogen production, the properties of feedstock and energy used, the type and quantity of valorized co-products, the type and quantity of impurities, and the quantity of hydrogen produced for which emissions are being evaluated.[2]

Section 2. Methodology

This section presents the methodology used in 45VH2-GREET to calculate the well-to-gate GHG emissions of hydrogen production pathways via pathways currently represented in the model. 45VH2-GREET is expected to be updated approximately annually, and future versions are anticipated to include additional hydrogen production pathways not currently represented as well as refined and updated estimates of background data. Appendix A defines each of the pathways currently represented in the model. Section 2.3 explains how these pathways can be simulated.

2.1 Functional Unit

45VH2-GREET evaluates well-to-gate GHG emissions of hydrogen production using a functional unit of one kilogram (kg) of 100% hydrogen at a pressure of 300 psia (i.e., 20 bar). It is important to note that while different facilities may vary with regard to the pressure and/or purity of the gas (i.e., mol% of hydrogen in the product stream), a consistent functional unit is necessary to evaluate well-to-gate emissions associated with hydrogen production by different facilities on a consistent and transparent basis.

Accordingly, within 45VH2-GREET, users must specify both the purity and pressure of the hydrogen they produce. Pressure must be specified in the field labeled "Hydrogen Production Pressure." If a facility is producing hydrogen at a lower pressure than 300 psia, 45VH2-GREET will estimate the amount of electricity that would be required to compress 1 kg of hydrogen from the actual production pressure to the pressure of 300 psia. Similarly, if a facility is producing hydrogen at a pressure greater than 300 psia, users must input the pressure of their hydrogen and 45VH2-GREET will estimate the amount of electricity that would be required to compress 1 kg of hydrogen from 300 psia to the actual production pressure.[3] In both cases, the difference in electricity consumption will be added to or deducted from the total electricity consumption of

[2] For example, if characterizing well-to-gate GHG emissions of all hydrogen production over the course of a given year, users must input all energy and feedstock consumed in the respective year by the hydrogen production facility being evaluated and all hydrogen produced in that year by the respective facility. On this basis, 45VH2-GREET 2023 will calculate the well-to-gate GHG emissions of all hydrogen produced by the facility in that year.

[3] User inputs for pressure are capped at 725.19 psia (50 bar) in 45VH2-GREET.

the facility, and the well-to-gate GHG emissions will be calculated based on the net value of electricity consumption.[4]

In practice, hydrogen production facilities are likely to produce gas streams that are not 100% hydrogen because they contain trace impurities (i.e., gases that are not hydrogen). To account for these impurities, 45VH2-GREET requires users to input the chemical composition and quantity (mol%) of each impurity in the hydrogen product gas stream (after any purification that occurs at the hydrogen production facility), including the quantity of hydrogen (mol%). While the model is populated with several common impurities for users to select, if a user's hydrogen product gas stream contains an impurity not displayed, they must input the molar mass of that impurity next to the "All Others" category and then the respective molar concentration to ensure that it is accounted for in the well-to-gate analysis. 45VH2-GREET then levelizes the well-to-gate GHG emissions of the hydrogen production over only the kilograms of 100% pure hydrogen produced. Additionally, to complete the accounting of carbon life cycle, 45VH2-GREET assumes that any carbon-containing impurities in the gas stream will be eventually converted by the end user(s) to form CO_2 emissions and accounts for these CO_2 emissions in the well-to-gate GHG emissions of hydrogen production. (The assumption that carbon containing impurities will be converted to CO_2 is based on current practices at industrial facilities that consume hydrogen, such as petroleum refineries and ammonia plants,[5,6] as well as expected practices at potential future industrial facilities such as iron and steel making plants.[7,8]

A simplified representation of the model's approach to characterizing well-to-gate GHG emissions is shown below:

Well-to-gate GHG Emissions per kilogram of H_2 = (Emissions upstream of hydrogen production facility in kgCO_2e per kilogram of total hydrogen product gas stream + Emissions from hydrogen production facility in kgCO_2e and associated carbon capture and sequestration (CCS) per kilogram of total hydrogen product gas stream) ÷ (kilograms of H_2 per kilogram of total hydrogen product gas stream) + (Amount of impurity A [mol%] × CO_2 generated from impurity A [kgCO_2/mol impurity] + Amount of impurity B [mol%] × CO_2 generated from impurity B [kgCO_2/mol impurity] + ...) ÷ (kilograms of H_2 per mol of total hydrogen product gas stream).

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4 The carbon intensity of the associated electricity consumption will be based on the average U.S. grid mix nationwide.

5 US Environmental Protection Agency. (2015). Chapter 5.1: Petroleum Refining. In: AP 42, Compilation of Air Pollutant Emissions Factors, Volume 1, 5th Edition.

6 Lee, K. et al, "Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production," Green Chem., 2022; 24:4830-4844. https://doi.org/10.1039/D2GC00843B

7 Kumar, T.K.S., Ahmed, H., Alatalo, J. et al, "Carburization Behavior of Hydrogen-Reduced DRI Using Synthetic Bio-syngas Mixtures as Fossil-Free Carbon Sources," J. Sustain. Metall. 2022; 8:1546–1560. https://doi.org/10.1007/s40831-022-00590-0

8 Rechberger, K., Spanlang, A., Sasiain Conde, A., Wolfmeir, H. and Harris, C., "Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking," Steel Research Int., 2020; 91: 2000110. https://doi.org/10.1002/srin.202000110

For example, if a hydrogen production facility's product gas stream has a purity of 98% H_2 (mol) with impurities of 1% CO and 1% N_2, and the well-to-gate emissions associated with generating 1 kg of the product gas stream are 2 $kgCO_2e$/kg-gas, then the well-to-gate emissions associated with hydrogen production would be:

$$\frac{2\ kgCO2e}{1\ kg\ gas} X \frac{1\ kg}{1000g} X \left(\frac{0.98\ mol\ H2}{mol\ gas} X \frac{2.016g}{mol\ H2} + \frac{0.01\ mol\ CO}{mol\ gas} X \frac{28.01g}{mol\ CO} + \frac{0.01mol\ N2}{molgas} X \frac{28.02g}{mol\ N2} \right) X$$

$$\frac{1\ mol\ gas}{0.98\ mol\ H2} X \frac{1\ mol\ H2}{.002016\ kg\ H2} +$$

$$\frac{0.01\ mol\ CO}{1\ mol\ gas} X \frac{1\ mol\ CO2}{1\ mol\ CO} X \frac{0.044\ kg\ CO2}{1\ mol\ CO2} X \frac{1\ mol\ gas}{0.98\ molH2} X \frac{1mol\ H2}{0.00216\ kgH2}$$

$$= \frac{\mathbf{2.8\ kgCO2e}}{\mathbf{kg\ H2}}$$

2.2 Greenhouse Gases

45VH2-GREET accounts for methane (CH_4), nitrous oxides (N_2O) and carbon dioxide (CO_2) in its representation of greenhouse gas emissions and uses the global warming potentials (GWP) of these gases to determine kilograms of CO_2 equivalent (i.e., CO_2e) released per kilogram of hydrogen produced (i.e., kg CO_2e/kg H_2). The model uses GWP values characterized on the basis of a 100-year timeframe (i.e., GWP100) using GWP values based on the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5). Table 1 below presents GWPs of different GHGs using AR5.[9,10]

[9] GWPs of GHGs are published periodically by the Intergovernmental Panel on Climate Change (IPCC). The Fifth Assessment Report GWPs are currently utilized in reporting to the United Nations Framework Convention on Climate Change.
See: Subsidiary Body for Scientific and Technological Advice, "Common metrics used to calculate the carbon dioxide equivalence of anthropogenic greenhouse gas emissions by sources and removals by sinks," *UNFCC*; 2022, Sharm el-Sheikh. https://unfccc.int/sites/default/files/resource/sbsta2022_L25a01E.pdf

[10] The GWP of methane per IPCC AR5, and agreed for use in the Paris Agreement and the U.S Nationally Determined Contribution, is 28. 45VH2-GREET 2023 additionally accounts for radiative forcing impacts of carbon dioxide added to the atmosphere due to oxidation of fossil-based methane, which is simplistically depicted in 45VH2-GREET 2023 by increasing the GWP value by 2, consistent with alternative GWP values published in Table 8.A.1 in Chapter 8 of the IPCC AR5 report, https://www.ipcc.ch/report/ar5/syr/.

Table 1. 100-Year Global Warming Potentials of CO_2, CH_4, and N_2O in IPCC Assessment Reports

IPCC Assessment report	CO_2	CH_4[10]	N_2O
Assessment Report 5	1	28	265

2.3 Hydrogen Production Technologies and Treatment

45VH2-GREET evaluates the well-to-gate GHG emissions associated with hydrogen production from technologies that use a variety of feedstocks, including fossil energy resources, nuclear and renewable energy resources, and certain biomass resources. Technologies in 45VH2-GREET are itemized in Table 2 and described further below.

Table 2. Hydrogen Production Technologies in 45VH2-GREET

Technologies in 45VH2-GREET
• Steam methane reforming (SMR) of natural gas, with potential CCS • Autothermal reforming (ATR) of natural gas, with potential CCS • SMR of landfill gas with potential CCS • ATR of landfill gas with potential CCS • Coal gasification with potential CCS • Biomass gasification with potential CCS[11] • Low-temperature water electrolysis using electricity • High-temperature water electrolysis using electricity and/or heat from nuclear power plants and renewable electricity (as described below)

For several of these technologies, the source and quantity of electricity consumed influences the well-to-gate emissions of producing hydrogen. Section 3 describes the manner in which users must provide inputs relevant to electricity consumption. To evaluate well-to-gate emissions for the purposes of compliance with the Inflation Reduction Act's 45V Credit for Production of Clean Hydrogen, users of 45VH2-GREET will also need to ensure that any energy attribute certificates (EACs) used to reflect electricity consumed meet specifications laid out in the 45V NPRM.

The following sections describe how the hydrogen production technologies in Table 2 are represented in 45VH2-GREET.

[11] Specific biomass types included in 45VH2-GREET 2023 are corn stover and logging residue, which are assumed to have no significant market value.

Methane reforming: 45VH2-GREET can be used to model SMR and ATR, with and without CCS.[12] These systems can use fossil-based methane (conventional natural gas) or renewable natural gas (RNG) derived from landfill gas (LFG), henceforth LFG and RNG will be referred to interchangeably as the RNG entering the H_2 production facility, unless otherwise specified. Reforming facilities typically generate hydrogen and CO_2 and may also generate co-products that may be valorized (see Section 2.5). The addition of CCS equipment on methane reformers may further reduce the well-to-gate emissions of hydrogen production.

To characterize the well-to-gate emissions associated with reforming, a user must input the following foreground data:

1. Year for which hydrogen production is being simulated
2. Source of the methane (fossil natural gas or landfill gas) consumed by the hydrogen production facility
3. Amount of methane consumed by the hydrogen production facility
4. Amount of electricity consumed by the hydrogen production facility
5. Type of electricity consumed by the hydrogen production facility
6. Whether or not the hydrogen production facility includes CCS
7. If the facility includes CCS, the mass of carbon capture for subsequent sequestration consistent with amounts reported to the U.S. Environmental Protection Agency's (EPA's) Greenhouse Gas Reporting Program
8. Mass of hydrogen produced
9. If the facility does not have CCS, the amount of co-product steam produced
10. The pressure of hydrogen produced
11. Type and amounts of impurities in the hydrogen product stream (after any purification at the hydrogen production facility).

Users may also supplant 45VH2-GREET default properties for the natural gas (lower heating value [LHV], density, and carbon content) with properties specific to the feedstock they are using by selecting "Custom Feedstock Properties." For facilities with CCS, input of custom properties may be necessary to exercise the model if the facility's feedstock properties differ significantly from 45VH2-GREET defaults. 45VH2-GREET may display "Entry defies carbon balance" if the model is unable to calculate the well-to-gate carbon intensity of the pathway being modeled. This error indicates that the amount of sequestered CO_2 input by the user cannot be balanced with the other user inputs and the properties of the feedstock being simulated. The user must

[12] 45VH2-GREET 2023 only models the permanent sequestration of carbon dioxide, as in Class II or Class VI injection wells. 45VH2-GREET 2023 does not model other forms of carbon dioxide utilization (e.g. production of synthetic fuels).

review the other values input to the model to ensure that they are correct and/or input feedstock properties corresponding to the specific feedstock.

For methane reforming, 45VH2-GREET allows users to account for steam as a co-product if the steam is produced from process heat integral to the hydrogen production process. Steam may not be accounted for if it resulted from any process that was not integral to hydrogen production (e.g., combustion of fuel that was not necessary for hydrogen production). Users must input the steam they would like to account for in terms of its energy value (e.g., Btu), which is equal to the product of the amount of steam exported from the hydrogen production facility in mass units (e.g., lb) by the difference between the specific enthalpy of exported steam (in Btu/lb units) at its delivered pressure and temperature conditions and the specific enthalpy of supplied water (in Btu/lb units) at the hydrogen production facility's ambient conditions. The quantity of steam that users may input may not exceed 17.6% of the total energy content of all steam and hydrogen produced (using the LHV of hydrogen). As described in the 45V NPRM, the quantity of steam that users may input has been restricted given the expected performance of reformers that are optimized for hydrogen.[13]

45VH2-GREET does not allow users to account for steam co-products if the reformer is capturing and sequestering the CO_2 produced. The representation of reformers with CCS within this model is based on previous modeling of specific CCS systems with high rates of carbon capture,[14] which indicate that excess steam would optimally power the CCS plant rather than being valorized. The appropriateness of steam valorization in other real-world CCS systems in the future may depend on the type of technology utilized and the system's design. While pathways that incorporate both CCS and steam valorization cannot currently be evaluated using 45VH2-GREET, this assumption may be re-evaluated in future versions of the model as new CCS technologies are evaluated.

As stated above, 45VH2-GREET also allows users to model hydrogen production from RNG that is derived from LFG, which is generated from municipal solid waste (MSW) decomposition in landfills. 45VH2-GREET characterizes the emissions associated with LFG reforming by assuming a counterfactual scenario wherein 100% of the LFG that is being utilized for hydrogen production would otherwise have been captured and flared. Representation of the LFG reforming pathway also includes emissions associated with purifying and delivering the LFG to the hydrogen production facility. The CO_2 emissions from the reformer (i.e., CO_2 generated from

[13] Previous literature and independent modeling of state-of-the-art reformers has indicated that the amount of steam that reformers produce represents about 15% of the total energy content of hydrogen and steam produced by higher heating value of hydrogen, which represents about 17.6% by lower heating value of hydrogen. 45VH2-GREET utilizes lower heating value units to represent energy content. Examples of such previous literature include: National Energy Technology Laboratory. Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies. DOE/NETL-2022/3241. Pittsburgh, PA: National Energy Technology Laboratory, 2022. Technical Report, available at: Energy Analysis | netl.doe.gov

[14] National Energy Technology Laboratory. Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies. DOE/NETL-2022/3241. Pittsburgh, PA: National Energy Technology Laboratory, 2022. Technical Report, available at: Energy Analysis | netl.doe.gov

carbon embodied in the RNG) are assumed to be neutral because they reflect emissions that would otherwise have been generated by flaring.

It is important to note that the 45V NPRM provides criteria that must be met in order for a taxpayer to determine an emissions rate for a hydrogen production facility using RNG from LFG by using 45VH2-GREET. Users seeking the 45V tax credit are encouraged to review the 45V NPRM to ensure that these requirements have been met.

Gasification: This technology converts coal or biomass feedstocks into synthetic gas, using elevated temperatures and with controlled amounts of oxygen and/or steam. The resulting synthetic gas (syngas) contains hydrogen, and potentially CO, CO_2, and other trace gases and impurities. Gasification facilities can also be combined with CCS.

To characterize well-to-gate emissions of hydrogen production associated with gasification, a user must input the following foreground data:

1. Year for which hydrogen production is being simulated
2. Type of feedstock used (coal or type of biomass)
3. Amount coal or biomass feedstock consumption at the hydrogen production facility
4. Amount of electricity consumed by the hydrogen production facility
5. Amount of natural gas consumed by the hydrogen production facility, in the case of biomass gasification
6. Type of electricity consumed by the hydrogen production facility
7. Whether or not the facility includes CCS
8. Amount of carbon capture for subsequent sequestration consistent with reporting to the EPA's Greenhouse Gas Reporting Program
9. Mass of hydrogen produced
10. Pressure of hydrogen produced
11. Type and amount of impurities in the hydrogen product stream (after any purification at the hydrogen production facility).

45VH2-GREET currently allows for biomass gasification to be modeled using two feedstocks: (1) corn stover and (2) forest logging residue with no significant market value, such as bark, branches, cutter shavings, leaves, needles, and pre-commercial thinnings (i.e., not milling residues from industrial processing or whole trees). In hydrogen production pathways that use allowable feedstocks, 45VH2-GREET assumes that the emissions of biogenic CO_2 resulting from biomass gasification are equal to the CO_2 removed from the atmosphere, and therefore converted into biogenic CO_2, during growth of the feedstock.[15] Additionally, 45VH2-GREET assumes that indirect land use change (iLUC) impacts associated with these feedstocks are negligible.[16] However, GHG emissions generated during the collection, processing, and transportation of both feedstocks are accounted for in background data assumptions used to calculate the carbon intensity of these pathways. GHG emissions associated with increased use of fertilizer due to removal of corn stover for subsequent gasification are also accounted for in the well-to-gate emissions of this pathway.

Users may also supplant 45VH2-GREET default properties for coal or biomass feedstock (LHV, carbon content) with properties specific to the feedstock they are using by selecting "Custom Feedstock Properties." For facilities with CCS, input of custom properties may be necessary to exercise the model if the facility's feedstock properties differ significantly from 45VH2-GREET defaults. 45VH2-GREET may display "Entry defies carbon balance" if the model is unable to calculate well-to-gate carbon intensity of the pathway being modeled. This error indicates that the amount of sequestered CO_2 input by the user cannot be balanced with the other user inputs and the properties of the feedstock being simulated. The user must review the other values input to the model to ensure that they are correct, and/or input feedstock properties corresponding to their specific feedstock.

Electrolysis: This technology uses electricity to split water into hydrogen and oxygen. Electrolyzers can use electricity generated from a variety of primary energy sources and technologies, and certain electrolyzer technologies can also use high-temperature heat to reduce their electricity consumption. 45VH2-GREET allows users to simulate low-temperature electrolysis that consumes electricity (from a specific generator or regional grid as defined by the user) as well as high-temperature electrolysis that consumes electricity and/or heat produced from a light-water nuclear reactor or exclusively renewable electricity. 45VH2-GREET can currently only represent high-temperature electrolysis that consumes renewable electricity if the facility either:

[15] In the case of corn stover, as these materials are grown and harvested within a year, it is assumed in 45VH2-GREET 2023 that net carbon fluxes directly related to this material (the fiber itself) is zero or carbon neutral (i.e., that carbon dioxide emissions generated by gasifying corn stover are equal to those captured during growth of the feedstock). In the case of forest logging residues, as these materials otherwise would have likely decayed over time or been pile-burned, the resulting emissions associated with using the materials to produce hydrogen are expected to be negligible or about the same as if the material were not collected and used. It is also important to note that the assumption of carbon neutrality is not necessarily appropriate when hydrogen is produced from other forms of biomass. If other forms of biomass are included in future versions of 45VH2-GREET as a feedstock for hydrogen production, significant indirect effects will be accounted for as appropriate and in alignment with international best practices.

[16] iLUC impacts associated with use of these forms of biomass may impact the indirect emissions associated with hydrogen production. However, these impacts are currently assumed to be negligible in GREET given the relatively small scale at which these feedstocks are utilized today. At an individual facility scale or at the margin, use of logging residues for bioenergy currently results in an insignificant change in land use. However, these assumptions may not hold if use of logging residues for bioenergy and other applications grows to large scales. Understanding of such indirect impacts of hydrogen production is an evolving area of research. As new information is developed in this space, 45VH2-GREET estimates will continually be updated.

- Consumes renewable electricity to produce heat directly (e.g., in an electric heat pump)
- Consumes renewable electricity and heat generated through a non-combustion exothermic reaction using hydrogen produced by the electrolyzer (e.g., ammonia synthesis).

Methods of heat generation other than those described above are not currently represented in the high-temperature electrolysis pathway in 45VH2-GREET; examples of methods of heat generation not currently represented in the high-temperature electrolysis pathway include but are not limited to natural gas combustion or the reforming of hydrocarbons.

To characterize well-to-gate GHG emissions associated with electrolysis, a user must input the following foreground data:

1. Year for which hydrogen production is being simulated
2. Type of electrolysis being simulated (low-temperature or high-temperature)
3. Amount and source of electricity consumed by the hydrogen production facility
4. Amount of heat being consumed, in the case of high-temperature electrolysis (represented in the model as “Thermal Energy”)
5. Whether the hydrogen production facility generates oxygen co-products
6. Mass of oxygen co-product produced
7. Mass of hydrogen produced
8. Pressure of hydrogen produced
9. Types and amounts of impurities in the hydrogen product gas stream (after any purification at the facility).

It is important to note that the 45V NPRM provides criteria that must be met in order for a taxpayer to determine an emissions rate for a hydrogen production facility using electricity by using 45VH2-GREET. This is discussed further in Section 3.2 below. The 45V NPRM also contains criteria that RNG from LFG must meet in order for a taxpayer to use 45VH2-GREET to determine lifecycle GHG emissions of a hydrogen production facility consuming this feedstock. These criteria require that the RNG must be consumed via “direct use” and that the consumption of the RNG represents the first productive use of methane from the landfill source. Users are also encouraged to review the 45V NPRM to ensure that they are meeting all corresponding requirements associated with this pathway if they are intending to access the 45V tax credit.

2.4 Values of Background Data in 45VH2-GREET

Background data in 45VH2-GREET is itemized in the dependency file in the downloaded tool package. For convenience, examples of background data values are described in the subsequent sections.

2.4.1 Emissions of Electricity Generation

45VH2-GREET and other GREET tools include estimates of the emissions associated with generation of electricity from various power generation technologies. These estimates include the emissions associated with feedstock recovery (e.g., natural gas drilling), feedstock delivery (e.g., leakage of methane, fuel combustion at compressors or rail cars), power generation (e.g., coal combustion), and a default assumption that 4.9%[17] of generated electricity will be lost in transmission. Emissions associated with construction of power generators (e.g., solar panels, wind turbines) and associated electricity transmission infrastructure are not included in the well-to-gate system boundary in 45VH2-GREET.[18] Estimates of emissions from individual types of power generators are updated infrequently and are based on the most recent analysis completed by the ANL GREET team at the time the GREET tools are updated. Emissions factors in 45VH2-GREET for various types of power generation are itemized in Table 3 below.

Table 3. Emissions Factors of Electricity Generation from Various Primary Energy Sources in 45VH2-GREET

Primary Energy Source	Emission Factor (kgCO2e/kWhe)[19]
Residual oil	1.1
Natural gas[20]	0.54
Coal	1.1
Uranium (nuclear power[21])	0.0028
Combustion of logging residue [22]	0.052

[17] This assumption is based on 2018 estimates from the EIA regarding nationwide electricity losses relative to electricity disposition. For more information, please see: https://greet.es.anl.gov/publication-Update_td_losses_2018

[18] Emissions associated with construction (commonly referred to as "embodied emissions") are not included in the well-to-gate system boundary. These emissions would be incorporated in a lifecycle analysis that extends beyond the well-to-gate system boundary and have therefore been accounted for in other DOE analyses and version of GREET.

[19] Values have been rounded to two significant figures in this table but are available with a higher level of precision in the GREET dependency file.

[20] 45VH2-GREET 2023 contains different emissions factors for different types of natural gas turbines. The value shown depicts a weighted average of factors from various types of gas-based power generation available nationwide (e.g., combined cycle turbines, gas turbines, steam turbines). 45VH2-GREET 2023 also allows users to depict consumption of power from natural gas combined cycle turbines with a user-defined rate of carbon capture and sequestration. The emissions factor with 90% CCS is 0.134 kgCO_2e/kWh.

[21] The emissions associated with nuclear power were updated in the 2023 suite of GREET tools based on analysis completed earlier in the year. This analysis is documented in a forthcoming publication.

[22] As described in Footnote 15, the CO_2 emissions generated from the combustion of logging residue are treated as neutral in 45VH2-GREET 2023.

Primary Energy Source	Emission Factor (kgCO2e/kWhe)[19]
Hydropower	0
Geothermal energy	0.096
Wind	0
Solar	0

2.4.2 Upstream Methane

45VH2-GREET assumes that methane leakage during the natural gas recovery process and subsequent gas processing and transmission sums to ~0.9% of methane consumed by the reformer. These emissions are described further in other GREET documentation.[23] It is important to note that the landscape for methane emissions monitoring and mitigation is changing rapidly. For example, the EPA proposed enhanced data reporting requirements for petroleum and natural gas systems under its Greenhouse Gas Reporting Program and is in the process of finalizing requirements under New Source Performance Standards and Emission Guidelines that will result in mitigation of methane emissions from petroleum and natural gas systems.[24] DOE-funded research is also expected to collect important emissions data and inform mitigation approaches. With these changes, it is expected that the quality of upstream data will improve, and methane emissions rates will change over time. As GREET models continue to be updated to reflect these changes, future versions of these models may include different upstream methane leak rate estimates.

In previous years, estimates of upstream methane emissions have been updated in GREET models approximately annually. These estimates have been derived from top-down and bottom-up data from the most recent EPA Greenhouse Gas Inventory and from other recent independent publications. Each of the estimates developed and accounted for in previous versions of GREET models are described in corresponding published memos.[25]

2.4.3 Landfill Gas

45VH2-GREET allows users to simulate reforming of RNG derived from LFG. Background data associated with this pathway include (1) avoided emissions associated with the counterfactual

[23] Burnham, A. (2022). Updated Natural Gas Pathways in GREET 2022. Argonne National Lab. Argonne GREET Publication : Updated Natural Gas Pathways in GREET 2022 (anl.gov)

[24] US EPA. (2023). Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems. Proposed Rule. 2023-14338.pdf (govinfo.gov); and
US EPA. (2023). Final Rule: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review. Final Rule. ENVIRONMENTAL PROTECTION AGENCY 40 CFR Part 60 [EPA-HQ-OAR-2021-0317; FRL-8510-01-OAR] RIN 2060-AV16: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review

[25] Previously published GREET memos are available at: Argonne GREET Publications (anl.gov)

scenario, (2) emissions associated with LFG upgrading to produce pipeline-quality gas, and (3) the amount of leakage of RNG during pipeline transport.

45VH2-GREET assumes that the counterfactual scenario for LFG gas is that the gas being consumed by a reformer would otherwise have been flared. This counterfactual scenario includes estimates of (a) methane emissions associated with incomplete combustion of LFG during flaring, (b) N_2O emissions associated with LFG flaring, and (c) any other non-CO_2 emissions that result from combustion (e.g., CO). The avoided emissions associated with assumptions (a), (b), and (c) of the counterfactual are estimated at 1,065 g CO_2e/MMBtu of LFG. The CO_2 emissions generated from reforming of LFG are treated as 0, assuming they represent CO_2 emissions that would otherwise have been generated via flaring in the counterfactual. RNG is assumed to be transported to SMR or ATR plants via 680 miles of pipeline transportation.[26]

2.5 Allocation Methods to Address Co-Product Effects

Hydrogen production processes may yield co-products that are also valorized (i.e., sold by the hydrogen producer or otherwise productively used). For those co-products that have actually been valorized, 45VH2-GREET allows for users to account for certain co-products in the well-to-gate GHG emissions of the hydrogen production facility. Users may only account for a co-product if it has been valorized in a process downstream of the hydrogen production facility; co-products that were produced but not valorized may not be allocated emissions in the well-to-gate GHG emissions calculation of produced hydrogen.[27]

The specific approach used in 45VH2-GREET for co-product accounting is “system expansion” (also known as the “displacement method”). This allocation method is described further in the International Organization for Standardization (ISO) 14044:2006.[28] As described above, 45VH2-GREET does not allow users to input a quantity of steam that exceeds 17.6% of the total energy content of all steam and hydrogen produced (using the LHV of hydrogen). As described in the 45V NPRM, the quantity of steam that users may input has been restricted given the expected performance of reformers that are optimized for hydrogen production.[29] Additionally,

[26] By default, GREET assumes that the national average length of pipeline transmission between upgrading and reforming is 680 miles, regardless of whether the pipeline is for natural gas or RNG. Dunn J.B. (2013) Update to Transportation Parameters in GREET. Argonne National Laboratory. Technical Memo. https://greet.anl.gov/publication-tansportation-distribution-13.

[27] Allocation of emissions to valorized co-products is standard practice in well-to-gate life cycle analysis, including in previously published GREET models and related publications.

[28] https://www.iso.org/standard/38498.html

[29] Previous literature and independent modeling of state-of-the-art reformers has indicated that the amount of steam that reformers produce represents about 15% of the total energy content of hydrogen and steam produced by higher heating value of hydrogen, which represents about 17.6% by lower heating value of hydrogen. 45VH2-GREET utilizes lower heating value units to represent energy content. Examples of such previous literature include National Energy Technology Laboratory, *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, DOE/NETL-2022/3241 Pittsburgh, PA; and National Energy Technology Laboratory, 2022 Technical Report, available at Energy Analysis | netl.doe.gov.

as described in Section 2.3 above, users may not input co-product steam if their system employs CCS.

Table 4 itemizes the co-products that can be simulated in 45VH2-GREET and the approach used to account for them. This table may be updated in future versions of this document as additional co-products are added to future versions of 45VH2-GREET.

Table 4. Co-products in 45VH2-GREET and Accounting Mechanisms

Co-product	Accounting Mechanism
Steam	System Expansion
Oxygen	System Expansion
Nitrogen	System Expansion

Section 3. Instructions

3.1 Running the 45VH2-GREET Model

45VH2-GREET is available in Excel form at https://www.energy.gov/eere/greet.

The model is designed for use on Windows operating systems and should not be used on other operating systems. To use the Excel-based 45VH2-GREET, users must follow the steps below. Users should be aware that the process to enable macros, and the location where features like "Enable Macros" may appear will vary by operating system. Users should review the instructions to enable macros for their operating systems before attempting these steps.

1. Download the Excel package at the URL above.
2. Extract (i.e., unzip) all files into one folder. The folder into which these files are unzipped will have two files: one labeled "45VH2-GREET (Rev. August 2024)" and the other in a sub-folder titled "GREET1_dependency."
    a. Please be aware that errors may occur if the files are unzipped into a folder with connectivity issues. If a user is experiencing errors running the model (e.g., features or buttons that will not run), it is recommended to extract the files into a location with stable connectivity.
3. Enable macros on both files. This step may vary by operating system, but is commonly accomplished by:
    a. Right clicking the 45VH2-GREET (Rev. August 2024) file, selecting "Properties," and then selecting "unblock."
    b. Entering the "GREET1_dependency" folder, right clicking "GREET1_2023," selecting "Properties," and then selecting "unblock."
    c. Opening the 45VH2-GREET (Rev. August 2024) file and selecting "Enable Macros."

At this stage, the 45VH2-GREET file is ready for use. All user inputs will be in the 45VH2-GREET (Rev. August 2024) file.

To use the 45VH2-GREET file, the user must:

1. Select the calendar year for which emissions are being calculated.
2. Select the hydrogen production technology being used, and, in some cases, select the feedstock being modeled.[30]
3. Click "Enter Process Details." This button will display a menu of "Process Inputs" and "Process Outputs." Users must specify:
    a. Quantity of feedstock and energy consumed to produce hydrogen.
    b. Corresponding quantity of hydrogen produced.
    c. Pressure of hydrogen produced.
    d. Purity of hydrogen produced (in mol%) and impurity content (mol%)
    e. Source of any electricity consumed (within the "Electric Generation Source" section of "Process Inputs." More information about this step is provided in the paragraphs below.
    f. Quantity of valorized co-products
        i. To account for co-products represented in 45VH2-GREET (Rev. August 2024), users must select the corresponding Yes/No toggle and then input the quantity of valorized co-product.
    g. Where applicable (for thermal reformation and gasification pathways only), the quantity of carbon captured and sequestered. Users must account for this by selecting the respective toggle for whether CO_2 has been sequestered and then inputting the quantity of CO_2 captured and subsequently sequestered in that year.
    h. Where applicable (for thermal reformation and gasification pathways only), users may specify properties of the feedstock. 45VH2-GREET has default values for key properties, such as lower heating value and carbon content. Users may supplant these defaults with values that correspond to the feedstock that they are consuming by selecting the "Custom Feedstock Properties" option.

3.2 Accounting for Electricity in 45VH2-GREET

When specifying the source of electricity consumed (either directly or indirectly to produce heat used for hydrogen production), users may represent either (1) electricity from a specific generator or combination of generators or (2) the average annual grid mix in the North American Electric Reliability Corporation (NERC) region that the hydrogen production facility is located in. These two options are described below.

Option 1–Specific source power. This option (labeled "User Defined Mix" under "Electricity Generation Mix") allows users to use an emissions rate associated with a given type of

[30] The selection of calendar year influences 45VH2-GREET 2023's simulation of the electricity grid. The model simulates the makeup of NERC grid regions in the United States using the Energy Information Administration's Annual Energy Outlook 2022.

generator or combination of generators, provided that (a) an emissions profile is available for the subject generator(s) in 45VH2-GREET (i.e., solar, wind, geothermal, hydropower, nuclear, natural gas turbines with and without CCS, coal, residual oil combustion, and logging residue combustion) and (b) that any electricity that is claimed to be sourced from the subject generator(s) in a given calendar year is verified via the purchase and retirement of qualifying EACs, which are EACs that meet specified criteria provided in the 45V NPRM.

As described in the 45V NPRM, these criteria are important guardrails to ensuring that the hydrogen producer's electricity use can be reasonably deemed to reflect the emissions associated with the specific generators from which the EACs were purchased and retired,[31] and include:

- Deliverability: the electricity generator is located in the same region as the hydrogen producer (as discussed in Section 4 below)
- Temporal matching: the electricity generation occurs at a relevant time in relation to the time of consumption (e.g., same year, same hour)
- Incrementality: the generator meets criteria designed to ensure the electricity is incremental, as defined in the 45V NPRM.

Additional details regarding these criteria are provided in the 45V NPRM.

In ascertaining the emissions associated with consumption of electricity from specific sources of power, 45VH2-GREET assumes that 4.9% of electricity produced is lost in transmission and distribution prior to consumption, as described in Footnote 17.

After selecting "User Defined Mix," users must input the quantity of electricity consumed in the model and the share of electricity that was consumed from each generator type. To account for transmission and distribution losses, 45VH2-GREET will then automatically assume that an additional ~4.9% of electricity was produced by each generator type chosen. (For instance, if a user inputs 100 MWh of wind energy under the "User Defined Mix," 45VH2-GREET will assume that ~104.9 MWh of wind energy was produced and calculate emissions accordingly.)

Option 2–Grid power. For electricity that is consumed in the respective calendar year from source(s) other than those described in Option 1, users must assume that the electricity has an emissions profile that reflects the annual average emissions intensity of electricity in the NERC region in which the hydrogen producer is located, as determined by 45VH2-GREET. GREET tools, including 45VH2-GREET, currently characterize the emissions of electricity supplied by NERC regions based on the share of electricity supplied by each type of power generator modeled in

[31] It is important to note that 45VH2-GREET includes estimates of emissions associated with electricity generation from specific power generator types by using an attributional LCA approach in conjunction with a basic representation of consequential/induced grid considerations. Per the latter, 45VH2-GREET requires that any electricity that users input from specific power generator types meet the requirements for temporal matching, regional matching, and incrementality defined in the 45V NPRM, thereby characterizing via proxy the lifecycle GHG emissions, including potential induced gid emissions, associated with electricity consumption.

GREET in the respective regions and an assumption that 4.9% of electricity generated is lost in transmission and distribution. The share of electricity supplied by each type of power generator in each NERC region in 45VH2-GREET is based on data from the Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) 2023. See Section 4 below for expected changes to regional definitions under 45VH2-GREET in future revisions.

To exercise Option 1, the user may either (a) select a generator type from the drop-down menu after "Electric Generation Source" or (b) select "User-Defined Mix" from the drop-down menu. The "User-Defined Mix" feature allows users to input the share of eligible electricity consumed from all generator types that can be modeled with 45VH2-GREET.

Any electricity that is not substantiated via IRS's requirements for qualifying EACs must be assumed to be sourced from the facility's NERC region (Option 2) and input into 45VH2-GREET accordingly. To exercise Option 2, the user must select the NERC region that the user is in after selecting "User Defined Mix" and input the amount of electricity that was consumed in that calendar year.

Through the "User-Defined Mix" feature, users may also exercise a combination of Options 1 and 2, representing the portion of electricity consumption that meets the criteria for each option into 45VH2-GREET accordingly.

Once all relevant Process Inputs and Process Outputs have been provided by the user, the user must select the "Calculate" button.[32] The resulting well-to-gate greenhouse gas emissions per unit of hydrogen produced will appear in green below. For convenience, the results are further broken down as "Direct Facility Emissions," "Indirect Emissions," and "Co-Product Credits."

Section 4. Regions

The 45V NPRM specifies that an EAC meets the deliverability requirements if the electricity represented by the EAC is generated by a source that is in the same U.S. region as the qualified clean hydrogen production facility. The guidance further defines the term "region" to mean a region derived from the National Transmission Needs Study (hereafter referred to as the Needs Study) that was released by DOE on October 30, 2023.[33] While 45VH2-GREET currently depicts NERC regions for users intending to exercise Option 2 (described in Section 3.2), future versions of the model may also include emissions factors corresponding to the regions in the Needs Study. Accordingly, more information about these regions is provided below.

DOE has mapped U.S. Balancing Authorities to the regions defined in the Needs Study. The resulting regions can be found in Figure 2 and Table 5, inclusive of a map and related table that links balancing authorities to Needs Study regions. As per the 45V NPRM, the location of a generation source and the location of a hydrogen production facility is based on the U.S. Balancing Authority to which it is electrically interconnected (not its geographic location), with

[32] This button will not be active until key input and output values have been provided by the user.
[33] U.S. DOE. 2023. National Transmission Needs Study. [National Transmission Needs Study (energy.gov)](energy.gov)

each balancing authority linked to a single region. The Midcontinent Independent System Operator (MISO) balancing authority is an exception because it is split into two U.S. regions, as shown in Figure 2, consistent with the Needs Study and as referenced in the 45V NPRM.

Though not depicted in Figure 2 or Table 5, as per the 45V NPRM, Alaska and Hawaii are treated as two additional regions within the context of the EAC deliverability requirements, one covering the entirety of Hawaii and the other the entirety of Alaska. Similarly, as per the 45V NPRM, each U.S. territory is considered a separate region.

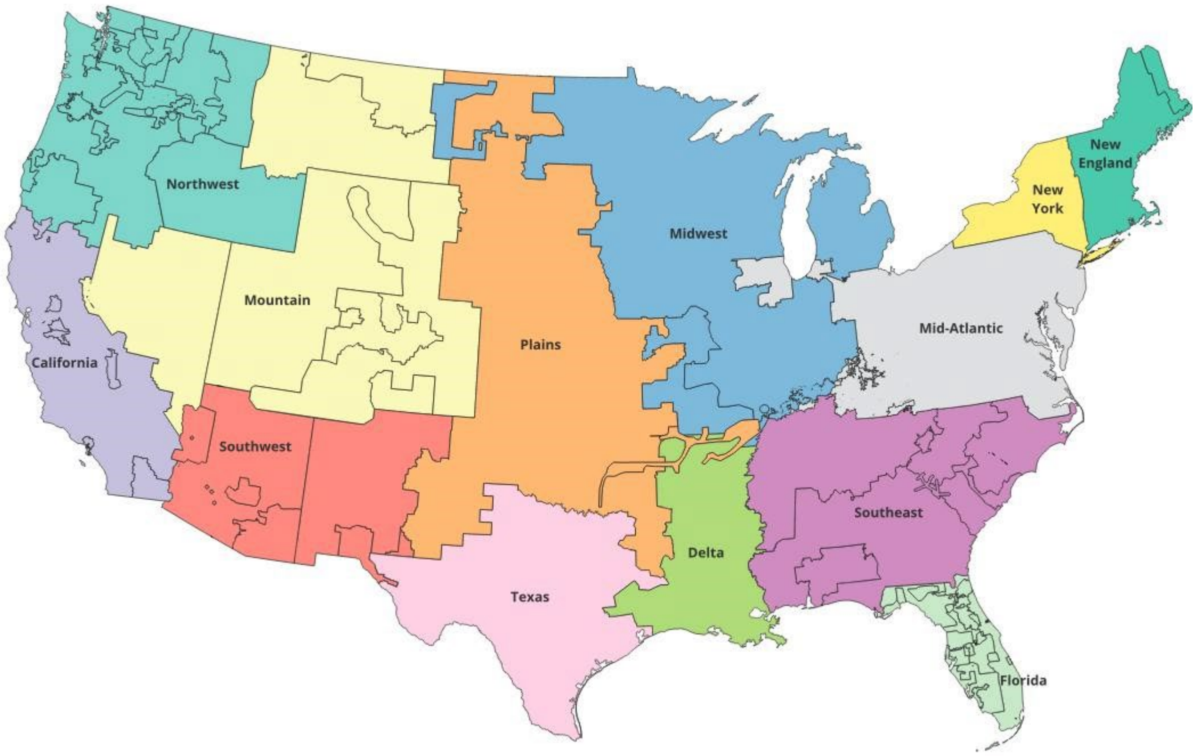

Figure 2. 45V Regions Based on Needs Study

Table 5. U.S. Balancing Authorities Linked to Regions Identified in Needs Study

Balancing Authority (from Velocity Suite)	45V region
Balancing Authority of Northern California	California
California Independent System Operator (Balancing Authority)	California
Imperial Irrigation District	California
Los Angeles Dept of Water & Power	California
Turlock Irrigation District	California
Midcontinent ISO (Balancing Authority): South, see map	Delta
Duke Energy Florida Inc	Florida
Florida Municipal Power Pool	Florida
Florida Power & Light	Florida
Gainesville Regional Utilities	Florida
Homestead (City of)	Florida
JEA	Florida
New Smyrna Beach Utilities Commission	Florida
Reedy Creek Improvement District	Florida
Seminole Electric Coop Inc	Florida
Tallahassee FL (City of)	Florida
Tampa Electric Co	Florida
East Kentucky Power Coop Inc	Mid-Atlantic
LG&E & KU Services Co	Mid-Atlantic
Ohio Valley Electric Corp	Mid-Atlantic
PJM Interconnection	Mid-Atlantic
Associated Electric Coop Inc	Midwest
Electric Energy Inc	Midwest
Gridliance Heartland	Midwest
Midcontinent ISO (Balancing Authority): North, see map	Midwest
NaturEner Power Watch LLC (GWA)	Mountain
NaturEner Wind Watch LLC	Mountain
Nevada Power Co	Mountain
Northwestern Energy	Mountain
PacifiCorp East	Mountain
Public Service Co of Colorado	Mountain
WAPA Rocky Mountain Region	Mountain
WAPA Upper Great Plains West	Mountain
New England ISO (Balancing Authority)	New England
Northern Maine	New England
New York ISO (Balancing Authority)	New York
Avangrid Renewables LCC	Northwest
Avista Corp	Northwest
Bonneville Power Administration	Northwest
Gridforce Energy Management LLC	Northwest
Idaho Power Co	Northwest
PacifiCorp West	Northwest
Portland General Electric	Northwest
PUD No 1 of Chelan County	Northwest

Balancing Authority (from Velocity Suite)	45V region
PUD No 1 of Douglas County	Northwest
PUD No 2 of Grant County	Northwest
Puget Sound Energy Inc	Northwest
Seattle City Light	Northwest
Tacoma Power	Northwest
Southwest Power Pool (Balancing Authority)	Plains
Southwestern Power Administration	Plains
Alcoa Power Generating Inc Yadkin Division	Southeast
Duke Energy Carolinas LLC	Southeast
Duke Energy Progress East	Southeast
Duke Energy Progress West	Southeast
PowerSouth Energy Coop	Southeast
South Carolina Electric & Gas Co	Southeast
South Carolina Public Service Authority	Southeast
Southeastern Power Administration (Southern)	Southeast
Southern Co Services Inc	Southeast
Tennessee Valley Authority	Southeast
Arizona Public Service Co	Southwest
Arlington Valley LLC	Southwest
El Paso Electric	Southwest
Gila River Power LLC	Southwest
Griffith Energy LLC	Southwest
New Harquahala Generating Co LLC	Southwest
Public Service Co of New Mexico	Southwest
Salt River Project	Southwest
Tucson Electric Power Co	Southwest
WAPA Desert Southwest Region	Southwest
ERCOT ISO (Balancing Authority)	Texas

Section 5. 45VH2-GREET Update Process

45VH2-GREET is a part of the suite of GREET tools developed and maintained by ANL. 45VH2-GREET includes features that make it easy to use for taxpayers, as well as hydrogen production pathways that are of sufficient methodological certainty to be appropriate for determining eligibility of tax credits. As described in Section 3.2, the model also requires that users input electricity consumption only from either (a) source specific power that is verified by qualifying energy attribute certificates as defined in the 45V NPRM or (b) the region that the hydrogen production facility is in. As described in Section 4, future versions of the model may use regions based on the Needs Study, consistent with the deliverability requirements specified in the 45V NPRM. Future versions of the model may also include additional hydrogen production pathways. Some pathways were not included in 45VH2-GREET if they required further analysis to reasonably understand direct and significant indirect emissions at the time the model was completed. Pathways that may be included in other versions of GREET but were not retained in 45VH2-GREET include:

- Reformation of RNG from animal lagoons, wastewater treatment plants, MSW that is diverted from landfills, and food waste that is diverted from landfills
- Reformation of coal mine methane
- Methane pyrolysis
- Byproduct hydrogen from chlor-alkali processes
- Gasification of other types of biomass (willow, poplar, switchgrass, and miscanthus).

The suite of GREET tools is updated annually to include new technologies and more recent estimates of background data (as described in Section 2.4). In future years, 45VH2-GREET is expected to be updated on an approximately annual basis. Updates are expected to include representation of additional hydrogen production technologies (as supporting analysis is completed by ANL) and updates to background data in a manner that is consistent with background data updates to other GREET tools.

Appendix A. Definitions of Pathways in 45VH2-GREET

This Appendix summarizes the hydrogen production pathways that are included in 45VH2-GREET. Each pathway is defined as a unique combination of a hydrogen production technology and a feedstock or combination of feedstocks. Table 6 describes the hydrogen production technologies that are represented in 45VH2-GREET. These technologies are defined by the feedstocks they are modeled to consume, the potential co-products that can be represented, and specific assumed performance or design attributes.[34] Table 7 and Table 8 describe the feedstocks that correspond to these technologies.

[34] Any hydrogen production technology that consumes feedstocks or generates co-products other than those provided in Table 6 are not considered represented in 45VH2-GREET.

Table 6. Definitions of Hydrogen Production Technologies in 45VH2-GREET

Technology	Attributes[35,36]	Feedstocks Represented[37]	Co-products Represented
Electrolysis			
Low-temperature water electrolysis	System that utilizes electricity to split water into	(1) Water, (2) Electricity	Oxygen
High-temperature water electrolysis (nuclear)	System that utilizes electricity and/or heat from a light-water nuclear reactor or from renewable electricity (as described in Section 2.3) to split water into hydrogen and oxygen	(1) Water, (2) Electricity, and/or (3) Heat from light-water nuclear reactors or renewable electricity (as defined in Section 2.3)	Oxygen

[35] All technologies represented in 45VH2-GREET are additionally assumed to (a) produce hydrogen at a pressure ≤50 bar, (b) be limited in the quantity of hydrogen they can produce, based on the energy content of feedstock consumed, and (c) be limited in the quantity of carbon dioxide they can produce for potential subsequent sequestration based on the carbon content of the feedstock. To represent parameter (b), 45VH2-GREET assumes that the amount of hydrogen a facility can produce in terms of energy content (by LHV) cannot exceed the total energy content of feedstock consumed by LHV. Hydrogen production technologies that do not meet criteria (a–c) are not represented in 45VH2-GREET.

[36] Each of the technologies depicted in Table 6 are commonly integrated with dryer and/or purification technologies. As described in Section 2.1, users of 45VH2-GREET must define the purity of the gas stream generated by the facility they are representing. Users must account for any electricity or other feedstocks consumed by associated drying or purification at the hydrogen production facility.

[37] Feedstocks are consumed by the technologies listed in different ways. Some feedstocks are converted into hydrogen, and in other cases, the feedstocks are used to supply energy to processes that generate hydrogen (e.g., electricity that is used to split water, natural gas that is burned to generate heat).

Technology	Attributes	Feedstocks Represented	Co-products Represented
Reforming			
Steam methane reforming with potential carbon capture and sequestration	System that utilizes an endothermic reaction of methane-rich gas (e.g., natural gas, landfill gas) with steam over catalyst beds to produce hydrogen, carbon dioxide, carbon monoxide, and potential other impurities. SMR systems represented in 45VH2-GREET combust fuel onsite to generate heat that drives chemical reactions to produce hydrogen. 45VH2-GREET can also simulate the integration of carbon dioxide capture with an SMR plant, for subsequent sequestration (i.e. CCS).[38] The model only represents a solvent-based CCS technology for carbon dioxide capture that optimally utilizes steam generated by the SMR.	(1) Natural gas and/or landfill gas, (2) Water, (3) Electricity	Steam[39,40]
Autothermal reforming (ATR) with potential CCS	System that produces a hydrogen gas mixture from methane-rich gas (e.g. natural gas, landfill gas), through two key processes: a) partial oxidation of the gas using oxygen, and b) reforming of the gas over catalyst beds. ATR systems represented in 45VH2-GREET are assumed to combust fuel onsite to generate heat that supplements heat from the partial oxidation to drive the production of hydrogen. 45VH2-GREET can also simulate the integration of CO_2 capture with an SMR plant, for subsequent sequestration (i.e., CCS).[38] The model only represents a solvent-based CCS technology for CO_2 capture that optimally utilizes steam generated by the SMR.	(1) Natural gas and/or landfill gas, (2) Water, (3) Electricity	Steam,[39,40] Nitrogen

[38] 45VH2-GREET only models the permanent sequestration of carbon dioxide, as in Class II or Class VI injection wells. 45VH2-GREET does not model other forms of CO_2 utilization (e.g., production of synthetic fuels).

[39] As described in the 45V NPRM and in Section 2.3 of this manual, the quantity of steam that users can input in 45VH2-GREET as a co-product of SMR without CCS has been capped based on the amount that an optimally designed reformer is expected to be capable of producing. As described in the NPRM, this cap was implemented to "avoid incentivizing generation or over-production of hydrogen co-products like steam to enable access to a higher tax credit value by artificially reducing the calculated carbon intensity of the hydrogen." 88 FR 89220, 89225. Accordingly, while real-world deployments may vary with regard to the amount of steam they generate and valorize, users may not claim steam co-product in 45VH2-GREET in excess of the cap. Any hydrogen production plant that uses SMR without CCS and meets the criteria described in Table 6 is considered to be represented in 45VH2-GREET, regardless of the quantity of steam it produces in practice.

[40] Because 45VH2-GREET only represents CCS technologies that would optimally utilize the steam produced by an SMR or ATR plant, the model does not allow users to represent steam co-products when simulating SMR or ATR with CCS. SMR or ATR plants that rely on other types of CCS that may not optimally utilize the steam are not currently represented in the model.

Technology	Attributes	Feedstocks Represented	Co-products Represented
Gasification			
Biomass gasification with potential CCS	A process that converts carbon-rich feedstock of biological origin into a mixture of gases (i.e., syngas), such as CO, CO_2, CH_4, and H_2, by reacting the feedstock at high temperatures with a controlled amount of O_2 and/or steam. The syngas is then purified or subject to a shift reaction to yield a hydrogen-rich gas stream. This process may incorporate a system that captures CO_2 that was generated in the production of the hydrogen-rich stream (e.g., CO_2 in the syngas), for subsequent sequestration.[38]	(1) Corn stover or forest residue, (2) Water, (3) Electricity, (4) Natural gas	None
Coal gasification with potential CCS	A process that converts coal into a mixture of gases (i.e., syngas), such as CO, CO_2, CH_4, and H_2, by reacting the feedstock at high temperatures with a controlled amount of O_2 and/or steam. The syngas is then purified or subject to a shift reaction to yield a hydrogen-rich gas stream. This process may incorporate a system that captures CO_2 that was generated in the production of the hydrogen-rich stream (e.g., CO_2 in the syngas), for subsequent permanent sequestration.[38]	(1) Coal, (2) Water (3) Electricity	None

Table 7 on the next page defines the feedstock for hydrogen production that 45VH2-GREET is able to represent. In representing each of these feedstocks, the model uses assumed values for parameters that users may not change (i.e., parameters that are background data). "Background data" are described further in Section 1 and are defined in the 45V NPRM as "parameters for which bespoke inputs from hydrogen producers are unlikely to be independently verifiable with high fidelity, given the current status of verification mechanisms." (88 FR 89220, 89225) While the values of background data parameters may have real-world variability, these parameters have been fixed in 45VH2-GREET to enable consistency in simulations across users, and in alignment with the 45V NPRM. Any feedstock that meets a definition in Table 7 or Table 8 is considered to be represented in 45VH2-GREET.

Table 7. Definitions of Feedstocks for Hydrogen Production Technologies in 45VH2-GREET

Feedstock	Definition
Coal[41]	All solid fuels classifiable as anthracite, bituminous, sub-bituminous, or lignite by ASTM Method D38805, Standard Classification of Coals by Rank, and coal refuse.
Corn stover	Biomass left over from the harvesting of corn, including stalks, leaves, and cobs.
Electricity	Electrical energy sourced from one or a combination of the generation types defined in Table 3, or from a regional electrical grid.[42]
Forest logging residue	The unused portions of growing-stock and non-growing-stock trees cut or killed by logging and left in the woods. These materials must have no significant market value, such as bark, branches, cutter shavings, leaves, needles, and pre-commercial thinnings removed to improve growth and quality in the remaining healthy trees in the stand (i.e., not milling residues from industrial processing or whole trees).
Landfill gas	A gas that is a natural by-product of the decomposition of organic material in landfills, which is then upgraded to yield a gas with a high concentration of methane. The term "landfill" is as defined in EPA regulations as "an area of land or an excavation in which wastes are placed for permanent disposal, and that is not a land application unit, surface impoundment, injection well, or waste pile as those terms are defined under 40 CFR § 257.2. 40 CFR 62.16730."[43]
Natural gas[41]	A naturally occurring fluid mixture of hydrocarbons (e.g., methane, ethane, or propane) produced in geological formations beneath the Earth's surface that maintains a gaseous state at standard atmospheric temperature and pressure under ordinary conditions. Natural gas does not include the following gaseous fuels: landfill gas, digester gas, refinery gas, sour gas, blast furnace gas, coal-derived gas, producer gas, coke oven gas, or any gaseous fuel produced in a process which might result in highly variable sulfur content or heating value.

[41] The definition provided for this term is consistent with its definition in regulations related to the Clean Air Act. 40 CFR 63.10042.
[42] In order to represent the consumption of electricity from a regional electrical grid, a user of 45VH2-GREET must select the NERC region where their hydrogen production facility is located, as described in Section 3.2. (As stated in Section 5, future versions of 45VH2-GREET may use grid regions aligned with those required for qualified EAC purchases, as prescribed by the 45V NPRM.) The options for grid regions in 45VH2-GREET are background data, i.e., in order to represent the consumption of electricity sourced from a regional grid, users must select one of the grid regions provided in the model. Users may not account for a grid region other than those depicted in the model.
[43] https://www.law.cornell.edu/cfr/text/40/62.16730

Table 8. Definitions of Electricity Feedstock

Name of feedstock	Definition
Residual fuel oil combustion	Electricity generated via the combustion of residual fuel oils in boilers, where residual fuel oils are defined as those that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations.[44]
Natural gas combustion	Electricity generated via the combustion of natural gas (as defined in Table 2) in combined cycle turbines, gas turbines, and/or steam turbines.
Coal combustion	Electricity generated via the combustion of coal (as defined in Table 2) to generate steam, that is then supplied to a steam turbine.
Nuclear power	Electricity produced from a nuclear fission reaction in a light-water reactor using uranium fuel.
Forest logging residue combustion	Electricity produced from combustion of logging residue (as defined in Table 2) in a boiler, followed by the use of a steam turbine.
Natural gas combined cycle turbine with CCS	Electricity generated via the combustion of natural gas (as defined in Table 2) in combined cycle turbines integrated with potential CCS. The user must define the percentage of carbon dioxide generated that is being captured and sequestered.
Hydroelectric	Electrical energy produced using the energy in a natural flow of moving water to turn a hydraulic turbine.
Geothermal	A plant in which the prime mover is a turbine that is driven by steam produced from hot reservoirs in the earth's crust.
Wind	Electrical energy produced by using kinetic energy in wind motion to turn a turbine.
Solar PV	Electrical energy produced in a photovoltaic (PV) cell when it is exposed to sunlight.

[44] These definitions have been reproduced or adapted from those used by the U.S. Energy Information Administration: Glossary - U.S. Energy Information Administration (EIA)

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