U.S. DEPARTMENT of ENERGY | Office of Critical Minerals and Energy Innovation

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

Rev. December 2025

SECTION 1

Introduction

Disclaimer

The current document describes the manner in which 45VH2-GREET Rev. December 2025 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. December 2025 model may be revised in the future, including adding new hydrogen production pathways that are not currently in the model. 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 emissions of hydrogen production under a well-to-gate system boundary using the 45VH2-GREET Rev. December 2025 model, hereafter referred to as 45VH2-GREET.

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.C. 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 Argonne National Laboratory. 45VH2-GREET Rev. December 2025 is available at https://www.energy.gov/cmei/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. In addition, it is designed specifically to evaluate the emissions of hydrogen production processes and to meet the requirements and objectives of I.R.C. section 45V.

This document has six key sections:

Section 1: Introduction

Section 2: Methodology

Section 3: Instructions

Section 4: Regions

Section 5: Update Process

Appendix A: Definitions of Pathways

List of Acronyms

ANL	Argonne National Laboratory
AR5	Fifth Assessment Report of IPCC
ATR	autothermal reforming
Btu	British thermal unit(s)
CCS	carbon capture and sequestration
CH_4	methane
CMM	coal mine methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DOE	U.S. Department of Energy
EAC	energy attribute certificate
e.g.	exempli gratia, Latin meaning “for example”
eGRID	Emissions & Generation Resource Integrated Database
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
g	gram(s)
G&B	gathering & boosting
gCH_4	grams methane
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GHGT-15	15th Annual Conference on Greenhouse Gas Control Technologies
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GWP	global warming potential
GWP100	GWP values characterized on the basis of a 100-year timeframe
H_2	hydrogen
H_2O	water

HHV	higher heating value
i.e.	id est, Latin meaning “that is”
IPCC	Intergovernmental Panel on Climate Change
I.R.C.	Internal Revenue Code
ISO	International Organization for Standardization
kg	kilogram(s)
kWh	kilowatt-hour(s)
kWhe	kilowatt-hour(s) equivalent
lb	pound(s)
LHV	lower heating value
LFG	landfill gas
MMBtu	million metric British thermal units
mol%	mole percentage
N	nitrogen
N_2O	nitrous oxide
NETL	National Energy Technology Laboratory
NG	natural gas
O_2	diatomic oxygen
POX	partial oxidation
PSA	pressure swing adsorption
psia	pounds per square inch absolute
RNG	renewable natural gas
SMR	steam methane reforming
SOTA	state-of-the-art
WWTP	wastewater treatment plant

Table of Contents

List of Figures

List of Tables

1 Introduction

45VH2-GREET Rev. December 2025, hereafter referred to as 45VH2-GREET, can be used to characterize well-to-gate greenhouse gas (GHG) emissions associated with hydrogen (H_2) production using the system boundary defined in the final regulations published in January 2025 for the 45V tax credit (IRS 2022), enacted by the Inflation Reduction Act, hereafter referred to as the 45V Final Regulations. The term "emissions through the point of production (well-to-gate)" is defined in the 45V Final Regulations to include emissions associated with feedstock growth, gathering, extraction, processing, and delivery for a given hydrogen production process, as well as electricity consumption by the process. It also includes emissions from hydrogen production itself, including emissions from purification of the hydrogen stream prior to its sale or use, and capture of carbon dioxide (CO_2) generated by the process for subsequent sequestration (see Figure 1).

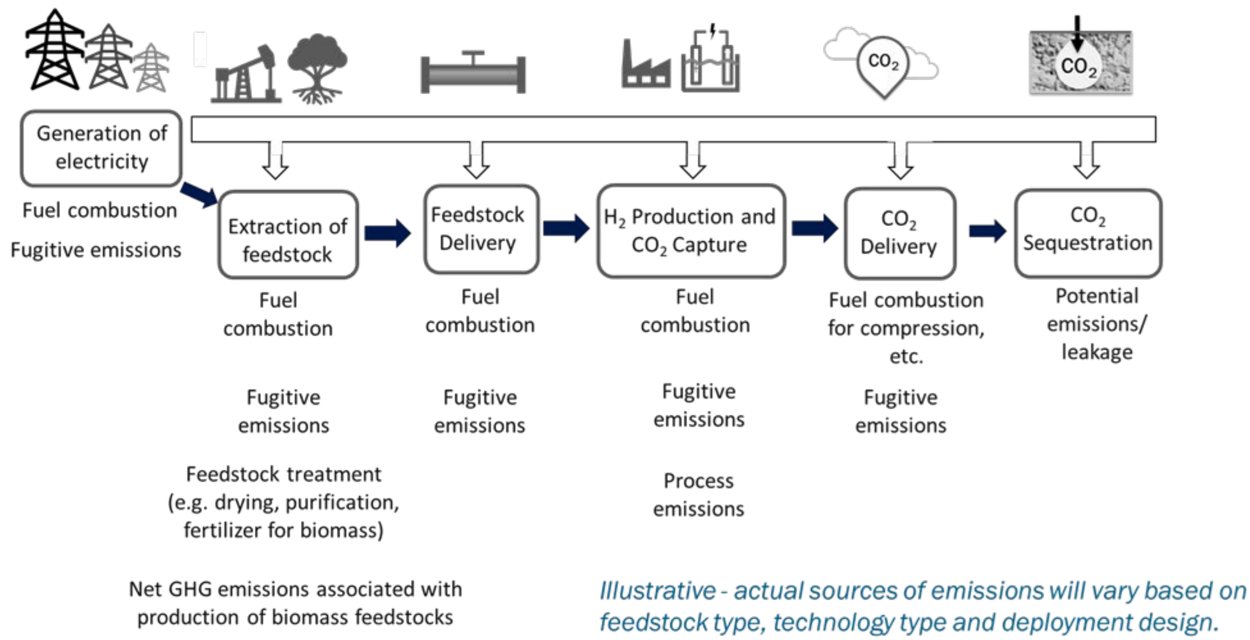

Figure 1. Examples of key activities related to GHG emissions within the well-to-gate system boundary for clean hydrogen production

Certain parameters within 45VH2-GREET are fixed assumptions (i.e., background data) and may not be changed by the user. The 45V Final Regulations deem parameters in 45VH2-GREET as background data if bespoke inputs from hydrogen producers are unlikely to be independently verifiable in the context of tax administration. (IRS 2025) Examples of background data in 45VH2-GREET include the carbon intensity of grid electricity supplied to the hydrogen production process in a particular region or, in some cases, the upstream methane emissions rates for the natural gas (NG) supply chain.[1] Inputs for background data are itemized in the GREET dependency file in the 45VH2-GREET package.

User inputs to 45VH2-GREET are “foreground data.” 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 mixed gases in the hydrogen gas stream, and the quantity of hydrogen produced for which emissions are being evaluated.

[1] The current release of 45VH2-GREET gives users the ability to supply bespoke values of upstream methane losses if those values are derived from their natural gas suppliers’ reporting to the EPA’s Greenhouse Gas Reporting Program, as defined under 40 CFR Part 98 Subpart W (89 FR 42062, May 14, 2024), and if those values have been verified by EPA. More information about this update is provided in Section 2.5.2.

SECTION 2

Methodology

2 Methodology

This section presents the methodology used in 45VH2-GREET to calculate the well-to-gate GHG emissions of hydrogen production pathways currently represented in the model. 45VH2-GREET is expected to be updated at least 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. Within this functional unit, the pressure of hydrogen production is fixed at 300 psia (20 bar) if (a) the hydrogen is produced at or above 300 psia, (b) the hydrogen is produced below 300 psia but will be compressed prior to use, or (c) if the hydrogen is produced below 300 psia and it is unknown whether the hydrogen will be compressed or not prior to use. If the hydrogen is produced below 300 psia and the user knows that the hydrogen will not be compressed prior to use, then the functional unit is 100% hydrogen at the pressure that the hydrogen is produced. 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 processes on a consistent and transparent basis. The pressure is fixed at 300 psia for most cases to allow for consistent comparisons across different hydrogen production facilities and technologies. Commercial hydrogen production facilities typically generate hydrogen at about 300 psia today. Accordingly, 300 psia is assumed to reasonably reflect the condition hydrogen must be in to be productively used. This value is relaxed for the niche circumstances wherein a user knows with certainty that the hydrogen is produced at a lower pressure but is not compressed prior to use.

Within 45VH2-GREET, users must specify the pressure of the hydrogen that they produce if they meet the criteria for a functional unit of 1 kg of 100% hydrogen at 300 psia. Pressure must be specified in the field labeled “Hydrogen Production Pressure.” When a user specifies a pressure value, a popup appears wherein the user must identify the grid region in which their hydrogen production facility is located. If a process 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 and add this value to the total calculated electricity consumption of the process. Similarly, if a process 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 and deduct this value from the total calculated electricity consumption of the process.[2] In both cases, the well-to-gate GHG emissions will be calculated based on the net value of electricity consumption.[3]

If a user is producing hydrogen below 300 psia and knows that the hydrogen will not be compressed before use, the user must leave the "Hydrogen Production Pressure" field as is. (The field is populated with a default value of "300" and the user must leave that field as is.) In this case, the electricity consumption associated with compression from the actual production pressure up to 300 psia will not be accounted for in determination of the user's well-to-gate GHG emissions.

In practice, hydrogen production facilities are likely to produce gas streams that are not 100% hydrogen. Some processes produce gas streams that contain trace impurities (i.e., gases that are not hydrogen). Other processes produce syngas, wherein hydrogen is mixed with other gases (e.g., carbon monoxide, nitrogen). To account for these mixed gases (impurities or constituents of syngas), 45VH2-GREET requires users to input the quantity (mol%) of each mixed gas constituent in the hydrogen gas stream. In order to be treated as a "mixed gas," a chemical must form within the hydrogen gas stream as a result of the hydrogen production process. Gases may not be treated as "mixed gases" if they are vented by the hydrogen production facility.

The 45V Final Regulations state that, if the taxpayer knows or has reason to know the purification of a hydrogen gas stream (that is, removal of a mixed gas or impurity) is necessary for a hydrogen gas stream to be productively used, or to be sold for productive use, any lifecycle GHG emissions relating to such purification (for example, emissions from electricity used in purification, or carbon dioxide that is separated from a hydrogen gas stream and then vented as part of purification) are treated as emissions through the point of production (well-to-gate). (IRS 2025; IRS 2025a) Accordingly, the quantities of mixed gases and hydrogen that a taxpayer accounts for in 45VH2-GREET must represent the state of the hydrogen gas stream after any purification that occurs prior to productive use of the hydrogen or sale of the hydrogen for productive use. Furthermore, users must account for any process inputs that correspond to such purification of the hydrogen gas stream (regardless of whether the purification is performed by the hydrogen producer or by a party downstream prior to productive use of the hydrogen). For instance, if a reformer is integrated with carbon capture technologies, pressure swing adsorption (PSA) technologies, or any other technology that removes mixed gases before the hydrogen is sold or used, the concentration of mixed gases and hydrogen must reflect the gas stream after such purification takes place. Additionally, the user must account for any electricity that is consumed by technologies that remove the mixed gases (e.g., carbon capture, PSA technologies) within 45VH2-GREET. Similarly, if a reformer generates syngas that is purified (e.g.,

[2] User inputs for pressure are capped at 725.19 psia (50 bar) in 45VH2-GREET.
[3] The carbon intensity of the associated electricity consumption will be based on the grid region in which the facility is located.

through removal of CO_2) before it is converted into a chemical (e.g., ammonia or methanol), the concentrations of mixed gases and hydrogen must represent those in place after any such purification takes place, and the process inputs must account for such purification.

The 45V Final Regulations further state that, if the taxpayer knows or has reason to know that a hydrogen gas stream contains less than 99% hydrogen and will be combusted without purification, any lifecycle GHG emissions relating to the purification needed to purify the hydrogen gas stream to contain 99% hydrogen are treated as emissions through the point of production (well-to-gate). 45VH2-GREET does not currently represent specific purification technologies that may be utilized in such a scenario. Accordingly, users interested in evaluating the emissions associated with hydrogen production in such a pathway (wherein the hydrogen gas stream is not purified to 99% in practice, but the emissions that would have resulted from such purification must be estimated and accounted for) may apply to DOE's Emissions Value Request Process.

While the model is populated with several common mixed gases for users to select, if a user's hydrogen gas stream contains a mixed gas that is not displayed, they must select "Define additional mixed gases/impurities" and select the number of mixed gases or impurities that will be added. A table to input mixed gases and impurities will appear, which the user must populate. Under "Formula", the user can input the chemical formula of the impurity or mixed gas; this column is optional and will not affect the result. Under "mol[%]" the user must input the concentration of the impurity or mixed gas within the hydrogen gas stream in mol% (i.e., moles of impurity or mixed gas divided by total moles of gas). Under "Molar Mass" the user must input the molar mass of the impurity or mixed gas. Under "Carbon Number" the user must input the number of moles of carbon in each mole of the impurity or mixed gas. The Carbon Number is used by 45VH2-GREET to calculate the number of moles of carbon dioxide that will be emitted by the reformer, after accounting for the moles of carbon that will be sequestered or transformed into impurities or mixed gases; carbon within impurities or mixed gases is not treated as an emission. Once the user supplies all relevant information about impurities, 45VH2-GREET levelizes the well-to-gate GHG emissions of the hydrogen production over only the kilograms of 100% pure hydrogen (H_2) produced.

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 kg carbon dioxide equivalent (CO_2e) per kilogram of total hydrogen gas stream + Emissions from hydrogen production process in kg CO_2e per kilogram of total hydrogen gas stream) ÷ (kilograms of H_2 per kilogram of total hydrogen gas stream)

For example, if the gas stream of a hydrogen production process has a purity of 98% H_2 (by mole) with impurities of 1% carbon monoxide (CO) and 1% nitrogen (N_2), and the well-to-gate emissions associated with generating 1 kg of the hydrogen gas stream are

2 kg CO_2e/kg-gas, then the well-to-gate emissions associated with hydrogen production would be as follows:

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

$$\frac{1\ mol\ gas}{0.98\ mol\ H2} X \frac{1\ mol\ H2}{.002016\ kg\ H2} = \frac{\mathbf{2.6\ kgCO2e}}{\mathbf{kg\ H2}}$$

2.2 Greenhouse Gases

45VH2-GREET accounts for methane (CH_4), nitrous oxides (N_2O), and CO_2 in its representation of greenhouse gas emissions and uses the global warming potentials (GWPs) of these gases to determine kilograms of CO_2 equivalent (CO_2e) released per kilogram of hydrogen produced (kg CO_2e/kg H_2). The model uses GWP values characterized on the basis of a 100-year timeframe (GWP100); these GWP values are based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). Table 1 presents GWPs of different GHGs using AR5.[4],[5] (el-Sheikh 2022; IPCC 2014)

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

IPCC Assessment Report	CO_2	CH_4	N_2O
Assessment Report 5	1	28	265

2.3 Process-by-Process Accounting and Accounting Period

2.3.1 Primary Feedstocks

Users of 45VH2-GREET must calculate the average emissions for each hydrogen production process over the course of a taxable year by accounting for all inputs consumed by the process during that year. As described in the 45V Final Regulations, processes are distinguished by the "primary feedstock" they consume. (IRS 2025a) In alignment with the 45V Final Regulations, 45VH2-GREET only allows users to select a single primary feedstock at a time when representing the emissions associated with hydrogen production. Some hydrogen production facilities may have multiple processes,

[4] GWPs of GHGs are published periodically by the IPCC. The AR5 GWPs are currently utilized in reporting to the United Nations Framework Convention on Climate Change.

[5] The GWP of methane per IPCC AR5 is 28. 45VH2-GREET 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 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.

if they consume multiple primary feedstocks. For instance, steam methane reforming (SMR) could have two primary feedstocks if it consumes water and renewable natural gas (RNG) from landfill gas (LFG), as well as water and fossil natural gas. In cases where a facility has multiple primary feedstocks, the user must simulate each process distinctly. For certain pathways, the “primary feedstock” is either water (e.g., electrolysis) or a combination of a hydrocarbon and water (e.g., use of fossil natural gas and water in SMR). In such pathways, the model does not ask users to input the amount of water consumed because its emissions impact is expected to be negligible. For instance, when accounting for process inputs to SMR, users are required to select their primary feedstock (e.g., “Fossil natural gas and water”) and to input the amount of fossil natural gas consumed, but not the amount of water consumed.

In the future, 45VH2-GREET may be expanded to enable users to represent consumption of multiple primary feedstocks at the same hydrogen production facility and then output distinct carbon intensities that correspond to hydrogen production from each primary feedstock. Until the model is revised, users can simulate facilities that consume multiple primary feedstocks as described in the following paragraphs.

After opening 45VH2-GREET, users must: (1) select the simulation year, (2) select the hydrogen production technology, and (3) select one of the primary feedstocks consumed by the facility (e.g., “Fossil Natural Gas + Water”). The user must then sum the total quantity of primary feedstocks being consumed at the facility during the analysis period. For instance, if the facility consumes 1 MMBtu of natural gas and 2 MMBtu of LFG in a year, the sum would be 3 MMBtu. Within 45VH2-GREET, the user must then represent all of the inputs and outputs from the hydrogen production facility, across processes.[6] For instance, if the facility produces 19 kg of hydrogen from fossil natural gas and LFG combined, and consumes 2.5 kWh of electricity across both processes combined, the user must input these values when simulating either process in the model. When representing the quantity of primary feedstock consumed (e.g., amount of fossil natural gas consumed), the user must provide the sum previously calculated rather than the actual amount of primary feedstock consumed. (In the previous example this would be 3 MMBtu for the quantity of fossil natural gas or LFG, rather than 1 MMBtu or 2 MMBtu.) The user must then click “Calculate.” The user must then repeat these steps for the other primary feedstocks. The only difference between runs for one primary feedstock versus another is the selection the user makes under “Primary Feedstock” in 45VH2-GREET. For instance, in the above example, the user would repeat the simulation but select “Renewable Natural Gas from Landfill + Water” rather than “Fossil Natural Gas + Water.”

For each process, the user must calculate the ratio of each primary feedstock consumed to the sum total of primary feedstock consumed; for instance, the ratio would be 1/3 for the process using fossil natural gas in the previous example and would be 2/3 for the process using LFG. The user must then multiply the total amount of hydrogen

[6] Detailed instructions on how to account for inputs and outputs are provided in Section 3.

produced by the facility by each of these ratios. The carbon intensity of the amount of hydrogen corresponding to each ratio is that value produced by 45VH2-GREET for that primary feedstock in the simulations above. For instance, in the example above, 6.3 kg of hydrogen produced by the facility would have a carbon intensity corresponding to the 45VH2-GREET simulation wherein “Fossil Natural Gas + Water” was selected as the “Primary Feedstock,” and 12.7 kg of hydrogen would have a carbon intensity corresponding to the 45VH2-GREET simulation wherein “Renewable Natural Gas from Landfill + Water” was selected as the “Primary Feedstock.”

2.3.2 Accounting Period

As described in the 45V Final Regulations, beginning in 2030, taxpayers may elect to utilize “sub-annual” (i.e., “hour-by-hour”) accounting methods to characterize the emissions associated with the use of electricity in a hydrogen production facility, in lieu of “annual accounting.” With sub-annual accounting, the user can determine the emissions of a hydrogen production process over contiguous segments of time that are shorter than a year but that are each at least one hour long. Emissions may vary across segments of time in a given tax year if the user chooses to account for differences in electricity consumption during the year, including varying types of electricity consumed, amounts of electricity consumed, and amounts of hydrogen produced. Other process inputs and outputs must be accounted for using an approach that reflects the annual average performance of the hydrogen production process. Both options are described in Sections 2.3.2.1 and 2.3.2.2. In future versions of 45VH2-GREET, the user interface is expected to be modified to more easily enable sub-annual accounting.

2.3.2.1 Annual Accounting

In order to characterize the emissions associated with all hydrogen produced by a given hydrogen production process at a facility in a given year, the user must account for the sum total of primary feedstock and other inputs (e.g., electricity) consumed, hydrogen produced, co-product produced (as applicable), and carbon dioxide sequestered (as applicable) in the year.

Under “Hydrogen Production Pressure,” the user must account for the average pressure of hydrogen production by the process over the course of the year, as described in Section 2.1.

Under “Product Hydrogen Composition,” the user must account for the average share of impurities or mixed gases across the entire hydrogen gas stream produced by the process in that year.

If the user intends to account for custom feedstock properties, the user must account for the average lower heating value, density, and/or carbon ratio of the feedstock consumed by the process in that year (as applicable).

2.3.2.2 Sub-Annual Accounting

In order to characterize the emissions associated with hydrogen produced by a given process in a sub-annual timeframe, the user must first ascertain the emissions of all hydrogen produced in the year through the approach described in Section 2.3.1. As described in the 45V Final Regulations, sub-annual accounting may only be exercised if the value obtained through annual accounting is not greater than 4 kg CO_2e/kg H_2. Across all segments of time in a given taxable year, the user can vary the type of electricity consumed, the amount of electricity consumed, and the amount of hydrogen produced. However, all other process inputs and outputs must reflect an annual average performance of the process (as described in the following steps).

To characterize the emissions on a sub-annual timeframe, the user must first:

1. Calculate the average value of each quantitative process input per kilogram of hydrogen produced in the year (e.g., average amount of natural gas consumed per kilogram of hydrogen produced in the year), with the exception of electricity.
2. Calculate the average amount of co-product generated in the year per kilogram of hydrogen produced and the average amount of carbon dioxide sequestered in the year per kilogram of hydrogen produced.
3. Calculate the average pressure of hydrogen produced and the average impurity content of the hydrogen gas stream in the given year.
4. If the user intends to account for custom feedstock properties, calculate the average lower heating value, density, and/or carbon ratio of the feedstock consumed in that year (as applicable).

For each sub-annual time segment, the user must then:

5. Multiply each value in Step 1 by the number of kilograms of hydrogen produced within the given time segment, and account for the resulting values in the Process Inputs section.
6. Multiply each value in Step 2 by the number of kilograms of hydrogen produced within the given time segment, and account for the resulting values in the Process Outputs section.
7. Account for the value in Step 3 and Step 4 in the respective sections. For Step 3, the user must follow the direction in Section 2.1 of this document.
8. Account for the quantity of electricity consumed within the given time segment and the associated electricity source.
9. Account for the kilograms of hydrogen produced in the given time segment.
10. Select “Calculate.”

2.4 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 inputs, including fossil energy resources, nuclear and renewable energy resources, and certain biomass resources. Technologies in 45VH2-GREET are itemized in Table 2 and described in detail in this section (2.4).

Table 2. Hydrogen Production Pathways in 45VH2-GREET

Processes in 45VH2-GREET
SMR with potential carbon capture and sequestration (CCS). Users must select a single primary feedstock to the SMR. Primary feedstocks currently represented are fossil natural gas and water, RNG from landfill gas and water, RNG from animal manure and water, RNG from wastewater treatment plants (WWTP) and water, and pipeline-quality coal mine methane (CMM) and water.
Autothermal reforming (ATR) with potential CCS. Users must select a single primary feedstock to the ATR. Primary feedstocks currently represented are the same as those available for SMR with potential CCS.
Partial oxidation (POX) with potential CCS. Users must select a single primary feedstock to the POX. Primary feedstocks currently represented are the same as those available for SMR and ATR with potential CCS.
Coal gasification with potential CCS.
Gasification of corn stover with potential CCS.
Low-temperature water electrolysis using electricity.
High-temperature water electrolysis using electricity and/or heat.
Co-electrolysis of water and CO_2.
Hydrogen produced as a by-product of chlorine manufacturing.

For several of the technologies represented in 45VH2-GREET, the source and quantity of electricity consumed influences the well-to-gate emissions of producing hydrogen. Section 3.2 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 45V tax credit, 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 Final Regulations.

The following sections describe how the hydrogen production technologies in Table 2 are represented in 45VH2-GREET. When representing user inputs, users must also align with the directions for process-by-process annual and sub-annual accounting provided in Section 2.3. (As described in the 45V Final Regulations, users may only utilize sub-annual accounting beginning in 2030 to account for lifecycle GHG emissions associated with electricity used in hydrogen production).

Methane reforming and POX: 45VH2-GREET can be used to model SMR, ATR, and POX with and without carbon capture and sequestration (CCS).[7] The following "primary feedstocks" are represented in 45VH2-GREET for these technologies: fossil natural gas with water,[8] RNG derived from LFG and water, RNG derived from WWTP sludge and water, RNG derived from animal manure and water, and pipeline-quality gas derived from CMM along with water. In alignment with the 45V Final Regulations, 45VH2-GREET treats hydrogen production from each of these primary feedstocks as a distinct process, i.e., users cannot simulate the use of blends of primary feedstocks.

SMR, ATR, and POX facilities typically generate hydrogen and CO_2 and may also generate co-products that may be valorized (see Section 2.6). The incorporation of CCS equipment may further reduce the well-to-gate emissions of hydrogen production.

To characterize the well-to-gate emissions associated with SMR, ATR, and POX, a user must input the following foreground data:

1. Year for which hydrogen production is being simulated.
2. Primary feedstock consumed by the hydrogen production process.
3. Amount of fossil natural gas, RNG from LFG, RNG from WWTP sludge, RNG from animal manure, or pipeline-quality gas from CMM consumed by the hydrogen production process, in terms of lower heating value, volume, or mass.
4. Amount of electricity consumed by the hydrogen production process.
5. Type of electricity consumed by the hydrogen production process.
6. Whether or not the hydrogen production process includes CCS and the method of carbon capture.
7. If the process includes CCS, the mass of carbon capture for subsequent sequestration may be accounted for if the carbon is disposed of in secure geological storage, pursuant to section 45Q(f)(2) and any regulations established thereunder.
8. If the process (a) does not have CCS, (b) utilizes cryogenic capture for CCS, or (c) utilizes pressure swing adsorption (PSA) for CCS, the user may account for the amount of co-product steam produced (if any). If the user accounts for the amount of co-product steam produced for export at a facility with CCS, the user

[7] 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 carbon dioxide utilization (e.g., production of synthetic fuels).

[8] The 45V Final Regulations state that the emissions associated with fugitive methane other than coal mine methane must be represented as equivalent to the carbon intensity of natural gas. (26 CFR 1.45V-1(a)(11)) Accordingly, to represent consumption of fugitive methane other than coal mine methane within a reformer, a user must select "fossil natural gas and water" as the primary feedstock.

must also account for the amount of steam used to drive CCS within the process (if any).

9. The pressure of hydrogen produced, as described in Section 2.1 of this document.
10. Type and amounts of impurities and mixed gases in the hydrogen stream (after any purification).
11. Certain aspects of the natural gas supply chain as described in Section 2.5.2 (if applicable).

Users may supplant 45VH2-GREET default chemical properties for methane inputs (lower heating value [LHV], density, and carbon content) with properties specific to the feedstock they are using by selecting “Custom Feedstock Properties.” For processes with CCS, input of custom properties may be necessary to exercise the model if 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 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 processes that (a) do not have CCS, (b) use cryogenic capture for CCS, or (c) use PSA for CCS, 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). This must be calculated by multiplying the amount of steam co-produced by the hydrogen production process 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 process’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). The quantity of steam that users may input has been restricted given the expected performance of reformers that are optimized for hydrogen.[9]

---

[9] Previous literature and independent modeling of state-of-the-art (SOTA) reformers has indicated that the amount of steam that reformers produce represents about 15% of the total energy content of hydrogen and steam produced on a higher heating value (HHV) of hydrogen basis, which represents about 17.6% by LHV of hydrogen. 45VH2-GREET utilizes LHV units to represent energy content. Examples of such previous literature include NETL’s *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*.

Several specific configurations of reformers and similar processes (e.g., POX) and CCS are currently represented in 45VH2-GREET. In the model, reformers are either (a) integrated with solvent-based CCS systems and do not co-produce steam, (b) integrated with CCS systems that use cryogenic CO_2 capture or PSA and may co-produce steam, or (c) not integrated with CCS and may co-produce steam.[10] (NETL 2013, NETL 2022, GHGT-15 2021) DOE is aware that some CCS systems that are not cryogenic or PSA-based may not utilize all steam produced by the reformer, and the reformer therefore may co-produce steam. At this time, 45VH2-GREET does not include reformers that are integrated with such systems and also co-produce steam.

As stated earlier, 45VH2-GREET allows users to model hydrogen production from several forms of RNG and from pipeline-quality gas derived from CMM. Key assumptions associated with these feedstocks are described in Sections 2.5.3–2.5.6.

It is important to note that the 45V Final Regulations provide criteria that must be met in order for a taxpayer to determine an emissions rate for a hydrogen production process using natural gas alternatives. Until the Secretary of the Treasury determines that an existing certificate system meets the requirements laid out in the 45V Final Regulations, taxpayers may not use natural gas alternative certificates (i.e., book and claim) to claim the energy attributes of natural gas alternatives. Therefore, users seeking to represent consumption of natural gas alternatives in 45VH2-GREET must be capable of substantiating use of such gas by maintaining a direct pipeline connection to the supplier or by other documented physical methods of exclusive delivery of such gas. Users seeking the 45V tax credit are encouraged to review the 45V Final Regulations.

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 of coal or biomass feedstock consumption at the hydrogen production process, in terms of lower heating value.

---

[10] The representation of solvent-based CCS systems in 45VH2-GREET is based on previous modeling of specific CCS systems with high rates of carbon capture, wherein excess steam from the reformer would optimally power the CCS plant rather than being valorized. The representation of cryogenic and PSA-based CCS systems is based on literature indicating that such systems do not typically utilize steam. Examples of such literature include NETL's *Appendix B: Carbon Dioxide Capture Technology Sheets* and GHGT-15's *Cryogenic Carbon Capture™ (CCC) Status Report*.

4. Amount of electricity consumed by the hydrogen production process.
5. Amount of natural gas consumed by the hydrogen production process, in the case of biomass gasification, in terms of lower heating value.
6. Type of electricity consumed by the hydrogen production process.
7. Whether or not the process includes CCS.
8. Amount of carbon dioxide that is captured and disposed of in secure geological storage, pursuant to section 45Q(f)(2) and any regulations established thereunder.
9. Mass of hydrogen produced.
10. Pressure of hydrogen produced, as described in Section 2.1 herein.
11. Type and amount of impurities in the hydrogen product stream (after any purification).

45VH2-GREET currently allows for biomass gasification to be modeled using corn stover feedstock. The model assumes that the emissions of biogenic CO_2 resulting from gasification are equal to the CO_2 removed from the atmosphere during growth of the feedstock.[11] However, GHG emissions generated during the collection, processing, and transportation of corn stover 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 (e.g., LHV, carbon content) with properties specific to the feedstock they are using by selecting “Custom Feedstock Properties.” For processes that incorporate CCS, input of custom properties may be necessary to exercise the model if 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

[11] Since corn stover is grown and harvested within a year, it is assumed in 45VH2-GREET 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). Previous versions of 45VH2-GREET also represented logging residue feedstock. This feedstock has been removed given ongoing national laboratory analysis regarding indirect emissions associated with its consumption. If logging residue or 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.

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

Electrolysis: This technology uses electricity to split water into hydrogen and oxygen. Electrolyzers can use electricity generated from a variety of energy sources and technologies, and certain electrolyzer technologies can also use high-temperature heat to reduce their electricity consumption. Certain types of electrolyzers can utilize both carbon dioxide and water in a “co-electrolysis” process that yields both hydrogen and carbon monoxide (i.e., syngas). 45VH2-GREET allows users to simulate low-temperature electrolysis that consumes electricity (from a specific generator or regional grid as defined by the user), high-temperature electrolysis that consumes electricity and/or heat, as well as co-electrolysis of water and carbon dioxide.

45VH2-GREET can simulate high-temperature electrolysis that consumes heat generated by power generators only if the process:

1. Consumes electricity and/or heat produced by a light water nuclear reactor; or
2. Consumes electricity and/or heat generated using exclusively electricity inputs (e.g., in an electric heat pump); or
3. Consumes electricity and/or heat generated via a non-combustion exothermic reaction that exclusively uses electricity and hydrogen produced by the electrolyzer (e.g., ammonia synthesis).

In the first case, the user must account for the amount of electricity and/or heat supplied by the light water nuclear reactor. In the second and third cases, the user must account for the total amount of electricity consumed for heat generation, as well as the total amount of electricity consumed by the electrolyzer.

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 water electrolysis being simulated (low-temperature, high-temperature, or co-electrolysis of water and carbon dioxide).
3. Amount and source of electricity consumed by the hydrogen production process.
4. Amount of heat being consumed, in the case of high-temperature electrolysis (represented in the model as “Thermal Energy”).

5. In the case of co-electrolysis, mass of carbon dioxide consumed.
6. Whether the hydrogen production process generates oxygen co-products.
7. Mass of oxygen co-product produced.
8. Mass of hydrogen produced.
9. Pressure of hydrogen produced, as described in Section 2.1 herein.
10. Types and amounts of impurities or mixed gases in the hydrogen gas stream (after any purification). (If a user exercises co-electrolysis, the user must account for the share of carbon monoxide and other gases that are produced and mixed in with the hydrogen.) These gases must be accounted for in the "Product Hydrogen Composition" table.

It is important to note that the 45V Final Regulations provide criteria that must be met in order for a taxpayer to determine an emissions rate using 45VH2-GREET for a hydrogen production process using electricity. This is discussed further in Section 3.2. Users are encouraged to review the 45V Final Regulations to ensure that they are meeting all corresponding requirements associated with this pathway if they are intending to claim the 45V tax credit.

If a user exercises "co-electrolysis," the model will estimate the share of electricity that is used by the electrolyzer to produce hydrogen based on the ratio of moles of hydrogen produced versus moles of carbon monoxide produced, along with the ratio of the theoretical efficiency of hydrogen production from water relative to the theoretical efficiency of carbon monoxide production from carbon dioxide.

By-product hydrogen from chlorine plants: This technology is a form of electrolysis, wherein electricity is used to split saltwater into hydrogen, sodium hydroxide, and chlorine. 45VH2-GREET allocates emissions of this process to each of these co-products based on their relative market value. The market value of hydrogen is assumed to be $1/kg, the market value of chlorine is assumed to be $0.69/kg, and the market value of caustic soda is assumed to be $0.36/kg. Market value allocation was chosen because (a) system expansion was infeasible due to the fact that the process modeled (brine electrolysis) is the incumbent method of producing chlorine and caustic soda and (b) hydrogen and the co-products do not share any physical traits that can be varied independently.

To characterize well-to-gate GHG emissions associated with by-product hydrogen from chlorine plants, a user must input the following foreground data:

1. Year for which hydrogen production is being simulated.
2. Amount and source of electricity consumed by the hydrogen production process.

3. Amount of natural gas consumed to produce steam for heat or power.[12]
4. Quantity of chlorine or sodium hydroxide co-products (that are valorized).
5. Mass of hydrogen produced.
6. Pressure of hydrogen produced, as described in Section 2.1 herein.
7. Types and amounts of impurities or mixed gases in the hydrogen gas stream (after any purification).

2.5 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.

2.5.1 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 fuel recovery (e.g., natural gas drilling), fuel delivery (e.g., leakage of methane, fuel combustion at compressors or rail cars), power generation (e.g., coal combustion), and default assumptions of transmission and distribution losses, as described in Section 3.2. 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.[13] Estimates of emissions from individual types of power generators are updated infrequently and are based on the most recent analysis completed by the Argonne National Laboratory (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.

[12] Natural gas is assumed to be consumed within an industrial boiler.
[13] 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 versions of GREET.

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

Source of Electricity	Emission Factor ($kg\ CO_2e/kWhe$)[14]
Residual oil fuel combustion	1.05
Natural gas combustion[15]	0.488
Natural gas combined cycle turbine with CCS[16]	*Depends on amount of CCS represented*
Coal combustion	1.06
Nuclear power (Wang et al. 2023)	0.00253
Hydroelectric	0
Geothermal	0.091
Wind	0
Solar PV	0

In order to depict power generation from natural gas combined cycle turbines with CCS, the user must account for the amount of carbon dioxide captured and sequestered in a given year divided by the amount of carbon dioxide produced by the turbine in that year. The numerator must reflect the total amount of carbon dioxide captured and sequestered by the turbine and must be determined pursuant to section 45Q(f)(2) and any regulations established thereunder. The denominator must be developed by assuming complete combustion of the carbon content of the natural gas consumed by the turbine and is equal to the following:

> Average carbon content of gas consumed in that tax year (kg carbon per unit volume of gas) * 44 kg CO_2/12 kg carbon * volume of gas consumed in that tax year.

2.5.2 Aspects of Upstream Natural Gas Supply Chain

45VH2-GREET gives users three options to represent emissions associated with the upstream natural gas supply chain.

1. This option is exercised in the model by default when a pathway using natural gas feedstock is selected, unless the user elects to use Options 2 or 3 below. In this option, the model uses exclusively default assumptions (i.e., background data) for energy consumption and emissions associated with natural gas recovery, gathering

[14] 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. Units represent kilograms of carbon dioxide-equivalent per kilowatt-hour of electricity generated.
[15] 45VH2-GREET 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).
[16] For reference, the emissions factor determined by 45VH2-GREET for 90% CCS is 0.113 kg CO_2e/kWh.

& boosting (G&B), processing, transmission, and storage. By default, 45VH2-GREET assumes that the average upstream methane emissions rate equals ~0.7% of the methane consumed by the reformer. These emissions are described further in other GREET documentation. (Burnham 2024)

2. A user can exercise this option to input bespoke values (i.e., foreground data) for specific steps of the natural gas supply chain upstream of the hydrogen production facility. These steps include (i) the recovery process, (ii) G&B, (iii) processing, (iv) transmission, and (v) storage. **Users may only exercise this option if (a) they are calculating their bespoke values using facility-specific data for facilities that are reporting to the EPA under the newly updated GHGRP rules under 40 CFR Part 98 Subpart W (89 FR 42062, May 14, 2024)** (EPA 2024)**, (b) the bespoke values are consistent with data the facilities have reported to the EPA under the aforementioned GHGRP rules, and (c) the aforementioned data reported to GHGRP have been verified by EPA.**[17]
3. A user can exercise a combination of Options 1 and 2 by representing a specific share of natural gas supply as having bespoke values and/or by using bespoke values only for certain user-specified segments, as described in the paragraph below.

To exercise Options 2 or 3, a user must first select "Custom NG Upstream Properties" under the "H2_User_Inputs" tab. The user will then be directed to a tab labeled "NG_Supply_Chain." Within this tab, the user must first specify the share of natural gas consumed by the hydrogen producer for which they would like to supply bespoke values, in Cell C2.[18] Then, the user can supply bespoke inputs for any of the five categories described in Sections 2.5.2.1–2.5.2.5, after selecting "Yes" for the corresponding category.[19] For any of these categories, the user can also select "No," in which case the model will use 45VH2-GREET defaults to represent the category.

When the user selects "Yes" for a given category, two tables with yellow and green cells will appear. The green cells depict 45VH2-GREET defaults for informational purposes and may not be changed by the user. **The yellow cells are prepopulated with 45VH2-GREET defaults that the user may supplant with bespoke values. If the user does not know the value for a particular parameter, the user must leave this cell as is (with the default) rather than supplanting with a bespoke value.** If a given cell is not

---

[17] 2025 is the first reporting year under the aforementioned GHGRP rules.
[18] In Cell C2, "100%" reflects Option 2, and any other value between 0% and 100% reflects Option 3. When calculating carbon intensity, 45VH2-GREET will only use the bespoke values provided on this tab for the share of natural gas defined in cell C2. The model will use its defaults to represent the balance of natural gas consumption by the hydrogen production facility.
[19] Across the natural gas supply chain, some equipment is utilized for raw gas that will eventually be processed into natural gas. In the following Sections 2.5.2.1–2.5.2.5, the term "natural gas" refers to such raw gas as well as conventional natural gas (i.e., processed raw gas).

relevant to a user, the user must make that cell 0. For instance, if a user is sourcing all of their natural gas from conventional drilling, they must make the values for all unconventional and offshore related cells “0”.

Once the EPA begins verifying data submitted under the new GHGRP rules, hydrogen producers will be required to represent facility-specific data where it is available and will be able to use default factors for segments where it is not available.[20]

2.5.2.1 Custom (user defined) NG Source Shares

This category refers to the share of a user’s natural gas that is sourced from conventional, unconventional, and offshore practices, by LHV.[21]

2.5.2.2 Custom (user defined) NG Energy Inputs

This category refers to the share of energy consumed in each process within the natural gas supply chain, in Btu/MMBtu gas. In practice, each process may involve equipment that is used for multiple products, as well as equipment that is used for a single product. For instance, energy consumption for “conventional recovery” may encompass drilling equipment that recovers petroleum and natural gas (two products) and may also involve acid gas removal units that only process gas (one product). In cases where equipment is used for multiple products, the share of feedstock consumed by that equipment must be determined based on energy allocation.[22]

To conduct energy allocation, the user must first determine the ratio of natural gas that the equipment yields relative to the total quantity of all products the equipment yields, in terms of LHV. In cases where the equipment solely handles natural gas (e.g., acid gas removal equipment), this ratio is 1. For each piece of equipment, the user must then multiply this ratio by the total quantity of energy consumed by the equipment. The user must sum the resulting values corresponding to each piece of equipment in a given process and then divide this sum by the total amount of natural gas at the end of the process in terms of LHV. The resulting value is the energy intensity of the process that must be incorporated into 45VH2-GREET.

[20] The 45VH2-GREET user interface for the natural gas supply chain may be updated in the future to represent categories and steps within the natural gas supply chain in a more granular manner, such that information from specific reporting entities (e.g., compressor stations, and shares of conventional vs. unconventional vs. offshore natural gas) can be accounted for.
[21] “Conventional” refers to processes involving recovery of natural gas from porous rock formations, typically using vertical drilling techniques. “Unconventional” refers to processes involving recovery of natural gas from shale and tight formations and coalbed methane. “Offshore” refers to recovery of natural gas from the ocean or lake floor.
[22] Across the natural gas supply chain, some equipment is utilized for raw gas that will eventually be processed into natural gas. Across Sections 2.5.2.1–2.5.2.5, the term “natural gas” refers to such raw gas as well as conventional natural gas (i.e., processed raw gas).

For instance:

- For “conventional recovery,” the denominator “MMBtu” is the total amount of raw gas recovered from conventional drilling.
- For “conventional G&B,” the denominator is the amount of gas that is available for processing following gathering and boosting.
- For “processing,” the denominator is the amount of natural gas available for transmission following processing.
- For “Transmission Segment I,” the denominator is the amount of natural gas available for storage or use following transmission.
- For “storage,” the denominator is the amount of gas available for transmission or use following storage.

For example, to determine the user input for electricity consumed in “conventional recovery,” a user would have to:

a. Identify all equipment involved in the recovery process.
b. Determine the amount of electricity consumed by each piece of equipment.
c. Allocate electricity consumed by each piece of equipment to natural gas, as described above.
d. Sum the values of electricity allocated to natural gas, calculated in (c).
e. Divide the sum in (d) by the total amount of raw gas recovered from conventional recovery in terms of LHV.

With regard to natural gas transmission, if the user only knows the amount of energy consumed for a portion of the transmission, the user must account for that portion in “Transmission (including compression) Segment I (User Defined).” In “Transmission (including compression) Segment II Distance (User Defined),” the user must then input the number of miles for which the quantity of energy consumption is unknown in all cells of that row. If the user does not know the number of miles for which energy consumption is unknown, they must leave this value as 680 miles.

2.5.2.3 Custom (user defined) NG Supply Chain Electricity

This category refers to the type of electricity consumed in natural gas recovery through processing, as well as transmission and storage. The user must first select the grid region in which their facilities are located. If the user is sourcing electricity from specific types of generators rather than the regional grid, the user must input the share of electricity coming from those generator types and the share coming from the regional grid under “User Defined Technology Shares.” The sum of user inputs in this category must equal 100% in order to run 45VH2-GREET.

45VH2-GREET does not prescribe how electricity from specific power generators must be verified when being consumed by equipment in the natural gas supply chain. Users that choose to input a bespoke value for electricity consumption within the natural gas supply chain can verify its accuracy using EACs. A previous DOE report provides additional information regarding the merits of EACs for verification. (DOE 2023)

Once the user completes the entries in this table, 45VH2-GREET will display a green-colored table for informational purposes immediately below the tables with user entries, showing the share of electricity that the model is assuming to be sourced from each generator type. Users may not change any of the values in the green table.

2.5.2.4 Custom (user defined) NG Flaring and CO_2 Emission Rate

This category refers to the ratio of gas flared and carbon dioxide emitted in each process, relative to gas output at the end of that process. The carbon dioxide emissions refer to carbon dioxide impurities within gas that may be emitted in a given step of the process. 45VH2-GREET combines user inputs regarding quantity of gas flared with default assumptions regarding the composition of this gas to calculate the carbon intensity of this step.[23]

To determine the ratio of flaring (Btu/MMBtu) in a given process, the user must first identify all equipment used for flaring within that process. For each piece of equipment, the user must determine the share of gas that is flared by energy allocation. To conduct energy allocation, the user must determine the fraction of natural gas that the equipment yields relative to the total products it yields, in terms of LHV. The user must then multiply this fraction by the total amount of gas from that step that is flared, in terms of LHV. The resulting value is the amount of flared gas that is allocated to the natural gas yielded by this equipment. The user must sum the values of flared gas allocated to natural gas across all equipment within the given process, then divide the sum by the total amount of natural gas yielded by the process. The resulting fraction is the ratio of flaring for that process.

For instance, if a piece of conventional drilling equipment generates 1 MMBtu (LHV) of raw gas that will be processed into natural gas along with 2 MMBtu of petroleum, then the fraction of natural gas is 1/3. If this drilling generates 3,000 Btu of gas that is then flared, then the amount of flaring that is allocated to the natural gas would be 1,000 Btu. The amount of flaring allocated to natural gas must similarly be calculated across all other equipment in the conventional drilling process, and these values must then be summed. The sum must then be divided by the total amount of gas that is recovered

---

[23] 45VH2-GREET assumes that gas flared during the “Recovery” and “G&B” steps contains 74%, 79%, and 75% methane by weight for conventional, unconventional, and offshore, respectively. 45VH2-GREET assumes that gas flared during the processing, transmission, and storage steps contains 91%, 94%, and 93% methane by weight for conventional, unconventional, and offshore, respectively. 45VH2-GREET assumes a flaring efficiency of 98% to determine corresponding CO_2 emissions.

from conventional drilling to determine the total flaring ratio to input in the "Conventional" column for "Recovery–Flaring."

2.5.2.5 Custom (user defined) Methane Leakage and Venting Rate Inputs

This category refers to the amount of methane emitted in each step of the natural gas supply chain (e.g., through venting and leaks). The user defined input in this table is provided in units of g CH_4 emitted per MMBtu of gas output by the process.

If the user knows the amount of methane leakage or venting during transmission of some or all of their natural gas supply, the user must input the corresponding value in the "Segment I" row. If the user does not know the amount of methane leakage or venting during transmission of some or all of their natural gas supply, the user must input the number of pipeline miles for which this data is not known in all cells of the "Segment II Distance" row. If the user does not know the mileage corresponding to the unknown share, they must leave this value as "680". 45VH2-GREET will use this mileage along with model defaults to estimate the share of methane leakage or venting. The "Segment II (Greet Default, Fixed)" row is for informational purposes and must not be changed.

To determine the share of methane leaked or vented in a given process, the user must sum the amount of methane emitted from each step within that process after energy allocation. To conduct energy allocation, the user must determine the fraction of natural gas the step yields relative to the total products it yields, in terms of LHV. The user must then multiply this fraction by the total amount of methane that is leaked or vented by the given step. The resulting product is allocated to the natural gas. The user must sum these values across all steps within the given process, then divide the sum by the total amount of gas yielded by the process.

For instance, if pneumatic devices used in conventional drilling for both oil and gas vent 90 g of methane while yielding 1 MMBtu of gas and 2 MMBtu of petroleum, the share of methane venting allocated to the natural gas would be 30 g. This value (30 g) must be summed with corresponding values for other equipment used in conventional drilling, and the total must be divided by the quantity of gas yielded by conventional drilling.

2.5.3 Landfill Gas

45VH2-GREET allows users to simulate reforming of RNG derived from LFG, if such RNG is delivered via a direct pipeline connection to the RNG supplier. Background data associated with this pathway include (1) avoided emissions associated with the counterfactual scenario, (2) emissions associated with LFG upgrading to produce pipeline-quality gas, and (3) the amount of leakage of RNG during pipeline transport.

In accordance with the 45V Final Regulations, 45VH2-GREET assumes that the counterfactual scenario for LFG 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 and (b) N_2O emissions associated with LFG flaring. The avoided emissions associated with assumptions (a) and (b) 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 “anyways emissions” (i.e., those that would otherwise have been generated by flaring) and therefore treated as zero in this 45VH2-GREET pathway. Given that under the 45V Final Regulations the use of book-and-claim accounting for RNG and CMM is not currently permitted, RNG is assumed to be transported to SMR or ATR plants via one mile of directly connected pipeline.

2.5.4 RNG from Anaerobic Digestion of Wastewater Sludge

45VH2-GREET allows users to simulate reforming of RNG derived from the anaerobic digestion of WWTPs, if such RNG is delivered via a direct pipeline connection to the RNG supplier. Background data associated with this pathway include (1) avoided emissions associated with the counterfactual scenario, (2) emissions associated with WWTP digestion to produce biogas, (3) emissions associated with upgrading the biogas to RNG, and (4) the amount of leakage of RNG during pipeline transport.

In accordance with the 45V Final Regulations, 45VH2-GREET assumes that the counterfactual scenario for WWTP gas is that the gas is sourced from a digester that uses ~55% of its gas in a boiler to produce steam and partially heat the digester, flares ~44% of it, and loses ~1% to leaks. (Lee et al. 2016) This assumption reflects current waste handling practices at large WWTPs that could otherwise upgrade their biogas to RNG. This counterfactual scenario includes estimates of (a) methane emissions associated with incomplete combustion of WWTP gas during flaring, (b) N_2O emissions associated with WWTP gas flaring, (c) any other non-CO_2 emissions that result from combustion (e.g., CO), and (d) any emissions associated with disposal of the residue. The avoided emissions associated with assumptions (a) and (b) of the counterfactual are estimated at -31.2 g CO_2e/MMBtu of WWTP gas. Given that under the 45V Final Regulations the use of book-and-claim accounting for RNG and CMM is not currently permitted, RNG is assumed to be transported to SMR or ATR plants via one mile of directly connected pipeline.

2.5.5 RNG from Animal Manure

In accordance with the 45V Final Regulations, 45VH2-GREET allows users to simulate RNG derived from the anaerobic digestion of any source of animal manure if such RNG is delivered via a direct pipeline connection to the RNG supplier. Background data associated with this pathway include (1) avoided emissions associated with the counterfactual scenario, (2) emissions associated with delivery of manure to the digester, (3) emissions associated with the digestion of manure to produce biogas, (4) emissions associated with upgrading biogas to pipeline-quality RNG, and (5) the amount of leakage of RNG during pipeline transport. More information about the counterfactual scenario is described in the technical paper A Generic Counterfactual Greenhouse Gas Emission Factor for Life-Cycle Assessment of Manure-Derived Biogas and Renewable Natural Gas. (DOE 2025) The biogas is assumed to be upgraded to RNG, using assumptions of upgrader performance described in the above white paper. The resulting carbon intensity of the RNG (including avoided emissions and emissions associated with upgrading) is -33.011 g CO_2e/MMBtu. Given that under the 45V Final

Regulations the use of book-and-claim accounting for RNG and CMM is not currently permitted, RNG is assumed to be transported to SMR or ATR plants via one mile of directly connected pipeline.

2.5.6 Pipeline-Quality Gas Derived from Coal Mine Methane

45VH2-GREET allows users to simulate the use of pipeline-quality gas derived from CMM if such RNG is delivered via a direct pipeline connection to the RNG supplier. Background data associated with this pathway include (1) avoided emissions associated with the counterfactual scenario, (2) emissions associated with CMM upgrading to produce pipeline-quality gas, and (3) leakage of CMM-derived gas during pipeline transport.

In accordance with the 45V Final Regulations, 45VH2-GREET assumes that the counterfactual scenario for pipeline-quality gas derived from CMM 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 CMM during flaring, (b) N_2O emissions associated with CMM flaring, and (c) any other non-CO_2 emissions that result from combustion (e.g., CO). The destruction efficiency of methane during the flaring process is assumed to be 98%. (EPA 2018) The CO_2 emissions generated from reforming of CMM-derived gas are treated as zero, assuming they represent CO_2 emissions that would otherwise have been generated via flaring in the counterfactual. Given that under the 45V Final Regulations the use of book-and-claim accounting for RNG and CMM is not currently permitted, CMM-derived gas is assumed to be transported to SMR or ATR plants via one mile of directly connected pipeline.

2.6 Allocation Methods to Address Co-Product Effects

Hydrogen production processes may yield co-products. In 45VH2-GREET, the term co-product represents an output from the hydrogen production process that is distinct from the hydrogen gas stream (i.e., is not mixed in with the hydrogen gas stream, is not separated from the hydrogen gas stream with the intent of mixing back in, and is productively used or sold for a productive use.)

45VH2-GREET utilizes "system expansion" (also known as the "displacement method") to address co-products where feasible. This method is described further in the International Organization for Standardization (ISO) 14044:2006. (ISO 2006). Where system expansion is not feasible, the model may use alternative methods to allocate emissions. Currently, the model allocates emissions to chlorine and caustic soda based on market value, when representing by-product hydrogen from chlorine manufacturing.

As described in Section 2.4, 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 Final Regulations, the quantity of steam that users may input has been restricted given the expected performance of reformers that are optimized for hydrogen production.[24] (NETL 2022) Additionally, as described in Section 2.4, if a user's reformer or POX facility is integrated with CCS, they may only represent co-product steam if the CCS facility is cryogenic or PSA-based.

Table 4 itemizes the co-products that can be simulated in 45VH2-GREET and the approaches 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
Chlorine	Market value allocation
Caustic soda	Market value allocation

[24] Literature and independent modeling of SOTA reformers indicated the amount of steam reformers produce represents about 15% of total energy content of H_2 and steam produced by HHV of H_2, which represents about 17.6% by LHV of H_2. 45VH2-GREET utilizes LHV units to represent energy content. Example: NETL's *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*.

SECTION 3

Instructions

3 Instructions

3.1 Running the 45VH2-GREET Model

45VH2-GREET is available in Excel form at https://www.energy.gov/cmei/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. Users should also close any other instances of Microsoft Excel before attempting to run 45VH2-GREET and should save the file in a static location rather than one that automatically refreshes or syncs.

1. Download the Excel package at the URL https://www.energy.gov/cmei/greet.
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. December 2025)” 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.
    b. 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. December 2025) file, selecting “Properties,” then selecting “unblock.”
    b. Opening the “GREET1_dependency” folder, right clicking “GREET1_202,” selecting “Properties,” and then selecting “unblock.”
    c. Opening the 45VH2-GREET (Rev. December 2025) 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. December 2025) 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.
3. Select the “primary feedstock’ being consumed.

4. Click “Enter Process Details.” This button will display a menu of “Process Inputs” and “Process Outputs.” Users must specify:
    a. Quantity of each input consumed to produce hydrogen.
    b. Corresponding quantity of hydrogen produced.
    c. Pressure of hydrogen produced, as described in Section 2.1 herein.
    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 Section 3.2.
    f. Quantity of valorized co-products.
        i. To account for co-products represented in 45VH2-GREET (Rev. December 2025), 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 Electricity Source Selection 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 region in which the hydrogen production facility is located. Regions within 45VH2-GREET are depicted as defined in the 45V Final Regulations.

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 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, and residual oil combustion) and (b) 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 criteria specified in the 45V Final Regulations. This requirement applies to electricity sourced both from a grid-connected generator and from a behind-the-meter generator.

As described in the 45V Final Regulations, these criteria are important guardrails to ensure that the hydrogen producer's electricity use can be reasonably deemed to address the potential emissions associated with the specific generators from which the EACs were purchased and retired,[25] and include:

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

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

Taxpayers must acquire and retire qualifying EACs for each unit of electricity that the taxpayer claims from a specific source. For example, one megawatt-hour of electricity used to produce hydrogen would need to be matched with one megawatt-hour of qualifying EACs.

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. Users must then input in the model the quantity of electricity consumed and the share of electricity that was consumed from each generator type.

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 region in which the hydrogen producer is located, as determined by 45VH2-GREET. The emissions factors for electricity consumption from each region (kg

[25] 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 life-cycle assessment 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 Final Regulations (26 CFR 1.45V-4(d)), thereby characterizing via proxy the lifecycle GHG emissions, including potential induced gid emissions, associated with electricity consumption.

CO_2e/kWh) are based on (1) 2023 Energy Information Administration (EIA) reporting identifying the amount of electricity generated by specific types of generation in each region, (EIA 2025a) (2) emissions factors from the EPA's Emissions & Generation Resource Integrated Database (eGRID) 2022 (EPA 2022) to estimate direct emissions from each type of generator, (3) emissions factors from R&D GREET 2024 to estimate upstream emissions associated with each type of fuel consumed, and (4) estimates of transmission and distribution losses within each region, based on state level reporting to the EIA. ANL has published a white paper, Development of Life Cycle Greenhouse Gas Emission Intensities of Electricity by National Transmission Needs Study Region, further describing the analysis that yielded emissions factors for reach region. (Lu et al. 2024)

Any electricity that is not substantiated via Internal Revenue Service's (IRS's) requirements for qualifying EACs must be assumed to be sourced from grid power, using regions defined in the 45V Final Regulations. To exercise Option 2, the user must select the grid region in which the hydrogen producer is located 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 in 45VH2-GREET accordingly.

Once all relevant Process Inputs and Process Outputs have been provided by the user, the user must select the "Calculate" button.[26] The resulting well-to-gate greenhouse gas emissions per unit of hydrogen produced will appear in green below the "Calculate" button. For convenience, the results are further broken down as "Direct Facility Emissions," "Indirect Emissions," and "Co-Product Credits."

[26] This button will not be active until key input and output values have been provided by the user.

SECTION 4

Regions

4 Regions

The 45V Final Regulations specify 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 45V Final Regulations also describe circumstances in which an EAC may meet the deliverability requirements in certain instances of actual cross-region delivery where the deliverability of such generation can be tracked and verified. The guidance includes a table mapping specific balancing authorities to specific regions.

These regions can be found in Table 5, consistent with the 45V Final Regulations.

Though not depicted in Table 5, as per the 45V Final Regulations, Alaska, Hawaii, and U.S. territories are treated as additional regions. 45VH2-GREET does not currently represent U.S. territories, but they may be added in future versions of the model and may be evaluated through the Emissions Value Request Process. (DOE 2024)

As discussed in Section 3.2, for electricity use that is not attributed to a specific source, users must assume that the electricity has an emissions profile that reflects the annual average emissions intensity of electricity in the region in which the hydrogen producer is located. Rounded values of these regional annual average emission intensities are listed in Table 6. (Lu et al. 2024)

Table 5. U.S. Balancing Authorities Linked to Regions as Defined in 45V Final Regulations

Balancing Authority (from Velocity Suite)	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	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

Balancing Authority (from Velocity Suite)	Region
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	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
PUD No 1 of Douglas County	Northwest
PUD No 2 of Grant County	Northwest

Balancing Authority (from Velocity Suite)	Region
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

Emissions factors associated with each of these regions are itemized in Table 6.

Table 6. Emissions Factors Corresponding to Regions as Defined in 45V Final Regulations

Region	Emissions Factor (kg CO_2e/kWh)
California	0.23
Delta	0.44
Florida	0.43
Mid-Atlantic	0.41
Midwest	0.58
Mountain	0.62
New England	0.31
New York	0.28
Northwest	0.160
Plains	0.464
Southeast	0.37
Southwest	0.39
Texas	0.40
Alaska	0.57
Hawaii	0.76

SECTION 5

45VH2-GREET Update Processes

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. Future versions of the model may include additional hydrogen production pathways. Some pathways were not included in 45VH2-GREET because their programming was not yet complete when the model was published. Others were not included 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:

- Methane pyrolysis
- Gasification of other types of biomass
- Geologic hydrogen.

The suite of GREET tools is updated annually to include new technologies and more recent estimates of background data (as described in Section 2.5). In future years, 45VH2-GREET is expected to be updated on at least an annual basis. Updates are expected to include representation of additional hydrogen production pathways (as supporting analysis is completed by ANL).

References

Burnham, A. 2024. *Updated Natural Gas Pathways in GREET 2024*. Lemont, IL. Argonne National Laboratory. https://greet.anl.gov/publication-update_ng_2024.

DOE. 2023. *Assessing Lifecycle Greenhouse Gas Emissions Associated with Electricity Use for the Section 45V Clean Hydrogen Production Tax Credit*. https://www.energy.gov/sites/default/files/2023-12/Assessing_Lifecycle_Greenhouse_Gas_Emissions_Associated_with_Electricity_Use_for_the_Section_45V_Clean_Hydrogen_Production_Tax_Credit.pdf.

DOE. 2024.*45V Emissions Value Request*. U.S. Department of Energy. https://www.energy.gov/cmei/45v-emissions-value-request.

DOE. 2025. *A Generic Counterfactual Greenhouse Gas Emission Factor for Life-Cycle Assessment of Manure-Derived Biogas and Renewable Natural Gas*. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2025-01/generic-counterfactual-greenhouse-gas-emission-factor-for-life-cycle-assessment-of-manure-derived-biogas-and-renewable-natural-gas_010225.pdf.

EIA. 2025a. "Form EIA-923 detailed data with previous form data (EIA-906/920)." U.S. Energy Information Administration. https://www.eia.gov/electricity/data/eia923/.

el-Sheikh, Sharm. 2022. "Common Metrics used to Calculate the Carbon Dioxide Equivalence of Anthropogenic Greenhouse Gas Emissions by Sources and Removals by Sinks." Subsidiary Body for Scientific and Technological Advice. UNFCC. Climate Change Conference November 2022. https://unfccc.int/sites/default/files/resource/sbsta2022_L25a01E.pdf.

EPA. 2018. "AP-42 13.5 Industrial Flares." U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2020-10/documents/13.5_industrial_flares.pdf

EPA. 2022. "eGRID Technical Guide." U.S. Environmental Protection Agency. https://www.epa.gov/egrid/egrid-technical-guide.

EPA. 2024. "Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems." 40 CFR Part 98 Federal Register Notice 89 FR 42062. May 14, 2024. U.S. Environmental Protection Agency. https://www.federalregister.gov/documents/2024/09/04/2024-18933/greenhouse-gas-reporting-rule-revisions-and-confidentiality-determinations-for-petroleum-and-natural.

GHGT-15. 2021. *Cryogenic Carbon Capture™ (CCC) Status Report.* 15th International Conference on Greenhouse Gas Control Technologies. Abu Dhabi, United Arab Emirates. https://www.osti.gov/servlets/purl/1781602.

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate*

Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC. Geneva, Switzerland. pp.151. https://www.ipcc.ch/report/ar5/syr/.

IRS. 2022. "26 USC 45V: Credit for Production of Clean Hydrogen." https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title26-section45V&num=0&edition=prelim#:~:text=26%20USC%2045V%3A%20Credit%20for%20production%20of%20clean%20hydrogen. See "Credit for Production of Clean Hydrogen and Energy Credit." 90 FR 2224, January 10, 2025). https://www.federalregister.gov/documents/2025/01/10/2024-31513/credit-for-production-of-clean-hydrogen-and-energy-credit.

ISO. 2006. "Environmental Management—Life Cycle Assessment—Requirements and Guidelines." International Organization for Standardization. ISO 14044:2006. https://www.iso.org/standard/38498.html.

Lee, U., J. Han, M. Demirtas, M. Wang, L. Tao. 2016. *Lifecycle Analysis of Renewable Natural Gas and Hydrocarbon Fuels from Wastewater Treatment Plant's Sludge*. Argonne National Laboratory. ANL/ESD-16/19. https://greet.anl.gov/publication-sludge-2016.

Lu, Z., A. Elgowainy, P. Vyawahare, C. Ng. 2024. *Development of Life Cycle Greenhouse Gas Emission Intensities of Electricity by National Transmission Needs Study Region*. Lemont, IL. Argonne National Laboratory. ANL/ESIA-24/26. https://greet.anl.gov/publication-ele_ci_needs.

NETL. 2013. *Appendix B: Carbon Dioxide Capture Technology Sheets. Pittsburgh, PA. National Energy Technology Laboratory*. DOE/NETL-2013. https://netl.doe.gov/sites/default/files/2017-12/CO2-Capture-Tech-Update-2013-Post-Combustion-Membranes.pdf.

NETL. 2022. *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*. Pittsburgh, PA. National Energy Technology Laboratory. DOE/NETL-2022/3241. https://www.netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9.

IRS. 2025. "26 CFR Part 1: Credit for Production of Clean Hydrogen and Energy Credit." Department of the Treasury. Federal Register Vol. 90, No. 6, 2224. January 10. https://www.govinfo.gov/content/pkg/FR-2025-01-10/pdf/2024-31513.pdf.

IRS. 2025a. "26 CFR 1.45V-1(a)(9) Lifecycle GHG Emissions." Department of Treasury. Federal Register. https://www.ecfr.gov/current/title-26/chapter-I/subchapter-A/part-1/subject-group-ECFRe427f958a26c8f4/section-1.45V-1.

Wang, M., A. Elgowainy, U. Lee, et al. 2023. *Summary of Expansions and Updates in R&D GREET® 2023*. Lemont, IL. Argonne National Laboratory. ANL/ESIA-23/10. https://greet.anl.gov/publication-greet-2023-summary.

SECTION 6

Appendix A

Definitions of Pathways in 45VH2-GREET

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 process input or combination of inputs. Table A.1 describes the hydrogen production technologies that are represented in 45VH2-GREET. These technologies are defined by the inputs they are modeled to consume, the potential co-products that can be represented, and specific assumed performance or design attributes.[27] Table A.2 and Table A.3 describe the inputs that correspond to these technologies.

Table A.1. Definitions of Hydrogen Production Technologies in 45VH2-GREET

Technology	Attributes[28,29]	Inputs Represented[30]	Co-products Represented
ELECTROLYSIS			
Low-temperature water electrolysis	System that utilizes electricity to split water into hydrogen and oxygen	(1) Water, (2) Electricity	Oxygen
High-temperature water electrolysis	System that utilizes electricity and/or heat (as described in Section 2.4) to split water into hydrogen and oxygen	(1) Water, (2) Electricity, and/or (3) Heat (as defined in Section 2.4)	Oxygen

[27] Any hydrogen production technology that consumes inputs or generates co-products other than those provided in Table A.1 is not considered represented in 45VH2-GREET.

[28] 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 inputs 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 process can produce in terms of energy content (by LHV) cannot exceed the total energy content of all inputs consumed (by LHV). If a hydrogen production technology does not meet criteria (a–c), it is not represented in 45VH2-GREET.

[29] Each of the technologies depicted in Table A.1 is 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 hydrogen production process they are representing. Additionally, users must account for any electricity or other fuels consumed by drying or purification of feedstock conducted prior to the hydrogen production.

[30] Inputs are consumed by the technologies listed in different ways. Some inputs are converted into hydrogen, and in other cases, the process inputs 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[28,29]	Inputs Represented[30]	Co-products Represented
Co-electrolysis	System that utilizes electricity to split water and carbon dioxide into hydrogen and carbon monoxide	(1) Water (2) Carbon dioxide (3) Electricity	Oxygen
By-product hydrogen from chlorine plants	System that utilizes electricity and/or heat to split brine into hydrogen, chlorine, and caustic soda	(1) Brine (2) Electricity (3) Natural Gas	Chlorine, caustic soda
REFORMING			
Steam methane reforming with potential carbon capture and sequestration (CCS)	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. Steam methane reforming (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).[31] The model currently only represents specific configurations of reformers and CCS. Namely, the model currently only represents reformers that are either (a) integrated with	(1) Natural gas, renewable natural gas (RNG) derived from landfill gas, RNG derived from animal manure, RNG derived from wastewater treatment plant (WWTP) sludge, or pipeline-quality gas derived from coal mine methane (CMM)	Steam[32,33]

[31] 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).

[32] As described in Section 2.4 of this manual, the quantity of steam that users can input in 45VH2-GREET as a co-product of reformers has been capped based on the amount that an optimally designed reformer is expected to be capable of producing. 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 a reformer and meets the criteria described in Table A.1 is considered to be represented in 45VH2-GREET, regardless of the quantity of steam it produces in practice.

[33] 45VH2-GREET only represents reformers that either (a) are integrated with solvent-based CCS systems, and do not co-produce steam, (b) are integrated with CCS systems that use cryogenic CO_2 capture or PSA and may co-produce steam, or (c) are not integrated with CCS and may co-produce steam. DOE is aware that some CCS systems that are solvent-based may not utilize all steam produced by the reformer, and the reformer therefore may co-produce steam. At this time, 45VH2-GREET does not represent reformers that are integrated with such CCS systems and also co-produce steam. Additionally, the amount of steam co-product claimed in cases (b) and (c) must be within the limits described in Section 2.4.

Technology	Attributes[28,29]	Inputs Represented[30]	Co-products Represented
	solvent-based CCS systems, and do not co-produce steam, (b) integrated with CCS systems based on cryogenic CO_2 capture or pressure swing adsorption (PSA) and may co-produce steam, or (c) not integrated with CCS and may co-produce steam. Additionally, the model only represents reformers that receive their methane-rich process inputs (e.g., natural gas, RNG) via pipelines. Other methods of gas delivery (e.g., via tube trailer) are not represented.	(2) Water, (3) Electricity	
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. The model currently only represents specific configurations of reformers and CCS. Namely, the model currently only represents reformers that either (a) are integrated with solvent-based CCS systems, and do not co-produce steam, (b) are integrated with CCS systems based on cryogenic CO_2 capture or PSA and may co-produce steam, or (c) are not integrated with CCS and may co-produce steam. 31 Additionally, the model only represents reformers that receive their methane-rich process inputs (e.g., natural gas, RNG) via pipelines. Other methods of gas delivery (e.g., via tube trailer) are not represented.	(1) Natural gas, RNG from landfill gas, RNG derived from animal manure, RNG derived from WWTP sludge, or pipeline-quality gas derived from CMM; (2) Water; (3) Electricity	Steam[32,33] Nitrogen
Partial oxidation (POX) with potential CCS	System that produces a hydrogen gas mixture from methane-rich gas (e.g., natural gas, landfill gas) through chemical reactions between the gas and oxygen. 45VH2-GREET currently only represents specific configurations of POX and CCS. Namely, the model currently only represents POX systems that either (a) are integrated	(1) Natural gas, RNG from landfill gas, RNG derived from animal manure, RNG derived from WWTP sludge, or pipeline-quality	Steam[32,33] Nitrogen

Technology	Attributes[28,29]	Inputs Represented[30]	Co-products Represented
	with solvent-based CCS systems, and do not co-produce steam, (b) are integrated with CCS systems based on cryogenic CO_2 capture or PSA and may co-produce steam, or (c) are not integrated with CCS and may co-produce steam. [31] Additionally, the model only represents POX that receives methane-rich process inputs (e.g., natural gas, RNG) via pipelines. Other methods of gas delivery (e.g., via tube trailer) are not represented.	gas derived from CMM; (2) Water; (3) Electricity	
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.30	(1) Corn stover, (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.30	(1) Coal, (2) Water (3) Electricity	Nitrogen

Table A.2 defines the inputs for hydrogen production and Table A.3 defines the types of electricity inputs that 45VH2-GREET is able to represent. Any input that meets a definition in Table A.2 or Table A.3 is considered to be represented in 45VH2-GREET.

Table A.2. Definitions of Inputs for Hydrogen Production Technologies in 45VH2-GREET

Input	Definition
Coal[a]	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 A.3, or from a regional electrical grid.
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 U.S. Environmental Protection agency (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.” [b]
Natural gas[b]	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.
Water	A liquid comprising H_2O at a purity sufficient for the hydrogen production facility being modeled.
Carbon dioxide	Carbon dioxide at a purity sufficient for use in the co-electrolysis process.
Brine	Saltwater mixture sourced from salt wells in the United States and delivered to a chlorine manufacturing plant via pipeline.

a The definition provided for this term is consistent with its definition in regulations related to the Clean Air Act. (EPA 2012).b Adapted from definitions in the Clean Air Act (EPA 2021)

Table A.3. Definitions of Electricity Inputs

Name of Electricity Input	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. (EIA 2025b)
Natural gas combustion	Electricity generated via the combustion of natural gas in combined cycle turbines, gas turbines, and/or steam turbines.
Coal combustion	Electricity generated via the combustion of coal (as defined in Table A.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.
Natural gas combined cycle turbine with CCS	Electricity generated via the combustion of natural gas (as defined in Table A.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.

References for Appendix A

EIA. 2025b. "Glossary." U.S. Energy Information Administration. https://www.eia.gov/tools/glossary/index.php?id=C.

EPA. 2012. "§63.10042 What definitions apply to this subpart?" Clean Air Act. U.S. Environmental Protection Agency. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-63/subpart-UUUUU/subject-group-ECFRa89b8b3960eee2f/section-63.10042.

EPA. 2021. "§63.16730 Definitions." Clean Air Act. U.S. Environmental Protection Agency. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-62/subpart-OOO/section-62.16730.

For more information, visit: energy.gov/

December 2025

U.S. DEPARTMENT *of* ENERGY

Office of Critical Minerals and Energy Innovation