Webtool Technical Documentation

This Technical Documentation pertains to HyPEC versions 1.01 through 1.02

Webtool Overview

The GTI Hydrogen Production Emissions Calculator (HyPEC, the webtool) applies user input for hydrogen production pathway assumptions to calculations based on the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model (GREET) spreadsheet tool, developed by Argonne National Laboratory. The results of this webtool are based on the most recent GREET version at the time of development, GREET 2021[1]. As a result, many of the selectable inputs in the webtool return exact GREET results[2]. However, some values are user-accessible GREET inputs, but their effects are calculated within this tool instead of in pre-run GREET cases. These inputs are user-defined values that return results that are based on a foundation of values from GREET calculations and match exact GREET values within +/- 0.25%. Lastly, there are webtool inputs that are not user-accessible GREET inputs (i.e. not on the "Inputs" worksheet), such that this tool provides additional flexibility. Altogether, this webtool delivers user-friendly, easy-to-access life-cycle assessment (LCA) results that are underpinned by the rigorous methodology of GREET, without requiring expert knowledge on using GREET.
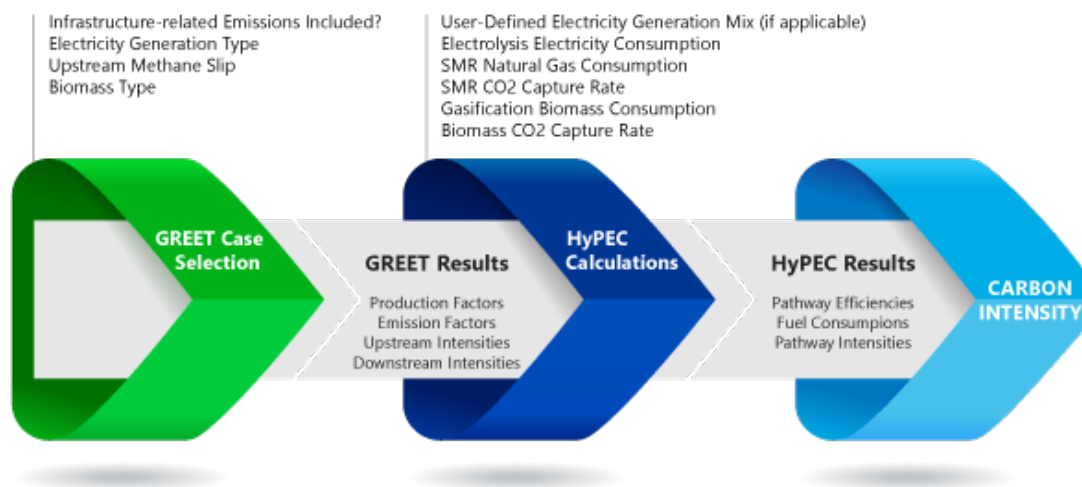

Figure 1. Flow diagram for combined lookup & calculation approach.

To achieve this blend between authentic GREET results and custom calculations while simultaneously decreasing runtimes, a novel approach is used in this webtool. GREET calculations were performed for 14,832 cases that covered a wide range of input values to produce a database of GREET results that includes production factors, emission factors, and stream intensities (e.g. carbon intensity of electricity).

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[1] Latest GREET version at time of webtool development: GREET1_2021.xlsm

[2] Guidance is provided later in this document for how to retrieve analogous results from the GREET spreadsheet tool.

For additional questions about the webtool approach, contact the GTI Energy LCA team: HyPEC@gti.energy

For a set of user input values, the webtool retrieves relevant information from the database of GREET results and performs calculations to generate carbon intensity values, which are reported in the summary bar chart. The flow of this process is described in Figure 1. A comparison of the 14,832 cases in the database against showed that the webtool results matched GREET identically for many cases and agreed to within 0.21% (within 0.01 kg CO2e/kg H2) across all cases (see Appendix A: Webtool Accuracy Vs. GREET).

The high level of sophistication in GREET is required to fully characterize the nature by which upstream energy source and carrier pathways are integrated. For example, the production of natural gas uses various fuels in its value chain stages, including petroleum derived fuels, natural gas, and electricity.
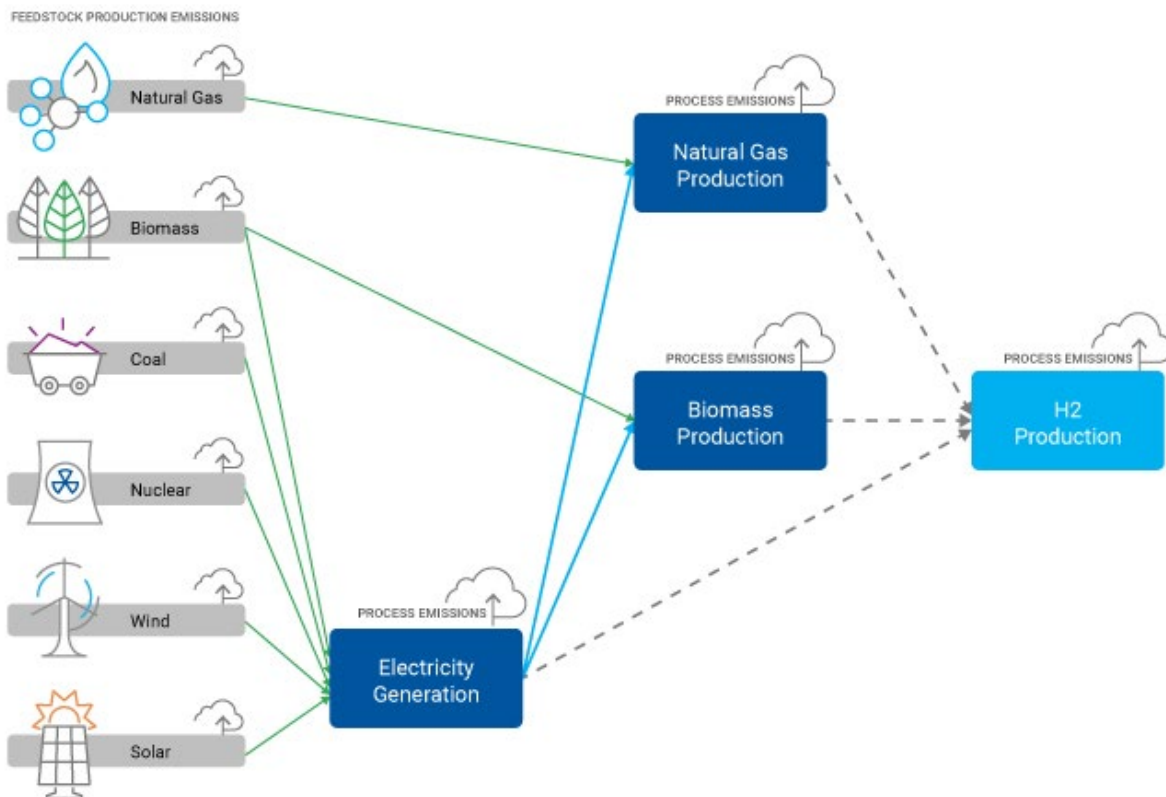

Figure 2. Simplified description of feed/fuels for H2 production by pathways in webtool, including fuels required for feedstock/fuel production.

As an example, consider the production of hydrogen by Steam Methane Reforming (SMR), which requires natural gas feedstock, natural gas fuel, and electricity "fuel". There are on-site emissions from conversion of the natural gas feedstock (mainly CO_2 byproduct, other minor byproducts) and combustion of the natural gas fuel (CO_2, CH_4, N_2O, and other pollutants). Sourcing the natural gas used by the SMR has emissions associated with the natural gas value chain (production, processing, transmission, etc.), as well as its own upstream emissions related to sourcing the fuels used throughout its value chain. Use of electricity has no on-site emissions at the SMR facility, but sourcing the electricity used by the SMR has emissions with the upstream electricity production, as well as its own upstream emissions related to sourcing the fuels used for electricity generation (coal, natural gas, nuclear, etc.).

It becomes clear that there is no definitive start to the pathway, rather GREET iteratively determines the emission intensity of all fuels and feedstocks, which are often intertwined. Every fuel included in GREET has a complicated emission history when described in a fully inclusive scope.

GREET Assumptions and Inputs

The values presented by this tool were prepared with the latest Excel version of the GREET fuels model, GREET1_2021.xlsm. Unless otherwise specified, the default values from GREET were used. Emission intensities of three atmospheric pollutants are calculated throughout this model: CO_2, CH_4, and N_2O. The calculated CO_2 emissions tabulate the total generated CO_2, both from direct emissions and the decomposition of emitted VOCs and CO.

Only two model inputs that are not included as webtool inputs were assigned different from their default value. The *Basis of H2 Production Assumptions* input (Table 6.1, cell: Inputs!E205), which was set to use the H2A Model by NREL (value = 1), whereas the default was Industry data/user-defined (value = 2). This update was chosen because the industry data option does not inherently permit CO_2 capture/sequestration for SMR plants. Note, the H2A model option does not include coproduction of steam coproduction. Next, the *Scenarios for H2A Model Cases* input (Table 6.1a, cell: Inputs!E207), which was set to current (value = 1), whereas the default was future (value = 2). The current/future setting updates hydrogen production efficiencies, so providing results with current selected gears this tool toward the current landscape rather than future projections.

GREET and Webtool Default Values and Additional Options

	Default GREET assumptions	GREET location of input or reported value	Other GREET options	Range within the Webtool
GWP methane	GWP100= 30	Fuel_Specs!B128	GWP20=86	Same
Methane Leakage	0.99%	Inputs!E121	0.70%, User defined	0-10%
SMR CO2 capture rate	0%	Inputs!F244	90%	0-100%
Biomass gasification CO2 capture rate	0%	Inputs!F246	-	0-100%
Electricity Grid Mix	US Mix (EIA AEO 2020)	Inputs! F715 & F716	Multiple options based on: • Regions • Individual Fuels • User-defined input	EIA AEO 2020 Mix EIA AEO 2030 Mix EIA AEO 2050 Mix NREL 2030 Mix, 1 NREL 2050 Mix, 1 NREL 2030 Mix, 2 NREL 2050 Mix, 2 Natural Gas Only

				Coal Only Wind Only Solar PV Only Nuclear Only
Electrolyzer system efficiency	72.6%	Hydrogen!BO192	Not changeable	
SMR system efficiency	72.0%	Hydrogen!B192	Not changeable	Up to 100%
Biomass gasification efficiency	44.0%	Hydrogen!AC192	Not changeable	
Hydrogen distribution distance			Not changeable	
Transmission distance	50 miles	T&D_Flowcharts!M1021	Any distance	50 miles

Lookup Table

A table of cases using the GREET model is used to provide exact GREET calculations for as many webtool options as possible. Inputs whose values were adjusted between all possibilities include:

- Emissions associated with construction of infrastructure & equipment (see Life Cycle Assessment Scope section)
- Electricity source (preset generation mix, see Electricity GHG Intensity section)
- Upstream methane slip (preset options and *all* possible user-defined options, see Upstream Methane Slip section)
- Biomass type fed to biomass gasification unit

For any case defined by the above inputs, reported values or calculations from GREET were recorded after model runs off-line from the webtool. The types of values recorded from GREET for each of the hydrogen production pathways include:

- Pathway constants (feedstock shares, fuel shares, chemical constants)
- GREET values for model assumptions/default (H2 production efficiency, fuel rates)
- Emission intensities for feedstocks/fuels used in hydrogen production

For combinations not allowed natively in GREET we have created a separate method (GTI calculation). Although results with/without CO2 capture for SMR and biomass gasification are distinguished using the calculation methods described in the sections below, GREET cases were run with/without CO2 sequestration to verify accuracy against the calculations for user-defined 0% and 90% capture rates.

GTI Calculations

Using the results from the lookup table, a process-scale approach for life cycle analysis is used for the hydrogen production, transmission, and compression/precooling steps in the GREET model. In this approach, hydrogen production is treated as a black box where the net emission intensity of the produced hydrogen is the sum of influences from the feedstock, fuel, and any on-site process emissions.

All of the methods and calculations are identical to the GREET Excel approach that is traceable in cell formulas, but this separate procedure allows for 1) a more reasonable number of pre-run cases run in GREET, and 2) flexibility with additional user-defined values that are not designated inputs in GREET.

Using the black box approach, the emission intensity for each pollutant is calculated for both the upstream and on-site contributions using a weighted-average of the emissions intensity ($e_{j,i}$) and flow rate of a feed stream. Feedstock and fuel emission factors for each pollutant have been retrieved from GREET for distinct cases, and they are combined as needed, according to fuel shares defined in GREET, overriding feed/fuel consumptions provided by the user, and CO2 capture rates provided by the user. The general formula for calculating an emission intensity for each GHG, *i*, using this black box approach is applied to feeds and fuels, *j*, for the pathway:

$$Emission_{step,i} = \sum_{j=0}^{n \ of \ streams} e_{j,i} \cdot stream\_flow_{j,i}$$

The black box approach above calculates the emission intensities of the feedstock sourcing step (*Emission_{feed}*) and the fuel combustion step (*Emission_{fuel}*). The transmission and compression steps for this tool use identical assumptions of GREET defaults across hydrogen pathways, including transmission distance, compression pressure, etc. The emission intensities for these two final steps are combined with feedstock and fuel emissions to calculate the total emission intensity of each pollutant for the pathway.

$$Emission_{total,i} = Emission_{feed,i} + Emission_{fuel,i} + Emission_{trans,i} + Emission_{comp,i}$$

Global warming potentials are applied to the emission intensities according to the time horizon chosen. This converts raw emissions of various GHGs to a single basis of CO2 equivalents (CO2e). The fifth IPCC Assessment Report defines global warming potentials (GWPs) both with and without climate-carbon feedback[3]. GREET provides the user with a single set of GWPs for each time horizon that bracket the with/without climate-carbon values suggested by the IPCC. Energy content of fuels is communicated in GREET on a Lower Heating Value (LHV) basis (e.g. g CO2e/MMBtu H2).

Global Warming Potentials (g CO2e/g)

	20-year Horizon	100-year Horizon
Carbon Dioxide	1	1
Methane	85	30
Nitrous Oxide	264	264

Global Inputs

Most inputs in the Global Inputs section were iterated in GREET through all possible combinations to generate a lookup table of pre-run GREET cases. Any inputs that had too much detail to feasibly be included in the collection of lookup cases is incorporated as a GTI calculation. The sections below

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[3] https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

describe, for each webtool input, the locations in GREET of any allowable or custom inputs, as well as the GTI calculations for non-GREET inputs.

Life Cycle Assessment Scope

The first input, *Include Emissions Associated with Construction of Infrastructure & Equipment*, opts to include emissions related to construction, infrastructure, and equipment for all available sectors: petroleum well drilling and infrastructure (Inputs tab, cell E109), natural gas well construction/infrastructure/maintenance (Inputs tab, cell E147), coal well construction and infrastructure (Inputs tab, cell E201), farming equipment production (Inputs tab, cell E466), and power plant construction and infrastructure (Inputs tab, cell E786). Although some fuels affected by the inputs above have no direct use in the hydrogen production pathways being analyzed (e.g. petroleum-based fuels), they can have trickle-down effects on the feeds/fuels being used.

The emissions associated from this infrastructure construction activity are based on emission factors for constructions materials estimated in the GREET model. Although some fuels affected by the inputs above have no direct use in the hydrogen production pathways being analyzed (e.g., petroleum-based fuels), they can have indirect effects on the feeds/fuels being used. GREET version 2021, which this webtool leverages, does not include emissions associated with construction of infrastructure for hydrogen production plants – accordingly, this webtool does not include such associated emissions.

Land use changes associated with biomass feedstock production can lead to additional impacts on greenhouse gas emissions. GREET version 2021, which this webtool leverages, does not include land use change impacts for the wood feedstocks (poplar and willow) used in this webtool. While GREET version 2021 does include land use change impacts with changing land use from food crop production to switchgrass production, these changes only impact the ethanol production pathway in GREET, and as such, they do not have any discernible impact on the hydrogen production pathways in GREET. Hence, for the biomass feedstocks considered here, land use change impacts for hydrogen production are not directly included in GREET version 2021 and are therefore not included in this webtool. See the Technical Documentation for further information.

The emissions associated with handling of hydrogen downstream of the production plant are also included by default in GREET. Firstly, this includes the transportation of hydrogen from the production plant to refueling stations over an assumed 750 miles of pipeline (700 miles from the hydrogen plant to bulk terminal, 50 miles from bulk terminal to refueling station). Next, hydrogen is prepared for refueling at the station through compression to 14,000 psia and precooling. HyPEC provides the flexibility to independently one or both of these segments using the *Include H2 Transportation Emissions* and the Include *H2 Refueling Compression Emissions* inputs.

Global Warming Potentials

The *Global Warming Potential Time Horizon* input determines the global warming potentials for methane and N2O relative to CO2 according to GREET Fuel Specs Table 2 (Fuel_Specs tab, rows 127-131). GREET GWP values are based on the IPCC Fifth Assessment Report (AR5) GWP values.

Electricity GHG Intensity

The Electricity Source input specifies a preset blend of fuels used to generate the grid electricity used by all three hydrogen production pathways. There are three types of blends provided:

1) [EIA Annual Energy Outlook](#) (AEO) mixes for 2020, 2030, and 2050. These are used in GREET when estimating grid electricity emission intensities for these three years (2020 is default).
2) NREL Cambium fuel blend estimates from the [Electrification Futures Study](#) (EFS)[4]. Projected fuel blends at 2030 and 2050 are available for two scenarios[5]:
   a) "Low-RE-Cost_High Electrification" – Low cost of renewable energy, high electrification of total energy consumption
   b) "Emissions-Constraints_High Electrification" – Annual and national limits on direct CO2 emissions from electricity generation, high electrification of total energy consumption
3) Single fuel electricity generation

Electricity Generation Fuel Mixes for Webtool Electricity Source Presets

Electricity Source	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
2020 US Mix	0.38%	39.57%	19.95%	20.42%	0.32%	7.37%	0.41%	8.90%	2.22%	0.48%
2030 US Mix	0.20%	34.12%	16.47%	15.07%	0.28%	7.03%	0.60%	15.24%	9.41%	1.58%
2050 US Mix	0.11%	35.20%	11.79%	11.92%	0.24%	5.82%	1.00%	13.97%	16.78%	3.16%
2030 US Mix-Low-Cost Renewables	0.00%	22.44%	12.04%	15.13%	0.92%	6.26%	0.54%	26.85%	15.83%	0.00%
2050 US Mix-Low-Cost Renewables	0.00%	20.98%	0.71%	5.31%	0.24%	4.08%	0.33%	38.61%	29.73%	0.00%
2030 US Mix-Emissions Constraints	0.00%	28.39%	19.63%	15.15%	0.94%	6.32%	0.88%	12.89%	15.81%	0.00%
2030 US Mix-Emissions Constraints	0.00%	14.96%	0.00%	5.34%	0.26%	4.15%	0.75%	40.23%	34.31%	0.00%
Natural Gas Only	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Coal Only	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Wind Only	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Solar PV Only	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
Nuclear Only	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

The fuel mixes above have previously been run in GREET to determine the emission intensities of stationary and transportation electricity. The individual fuel share values from the table are used for the User-Defined Mix of both Stationary Use (Fuel_Prod_TS tab, cells CN915:CS915 and CN942:CR942) and Transportation Use (Fuel_Prod_TS tab, cells CF915:CK915 and CF942:CJ942) electricity. The emission

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[4] Murphy, C, et al., Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72330. https://www.nrel.gov/docs/fy21osti/72330.pdf.
[5] https://scenarioviewer.nrel.gov/?project=fc00a185-f280-47d5-a610-2f892c296e51&mode=view&layout=Default

intensities for the three pollutants are subsequently used in the process-scale LCA calculations for the hydrogen pathways in the webtool.

If a user-defined fuel blend is input to the tool, only six of the above fuels are available: natural gas, coal, nuclear, biomass, wind, and solar PV. Calculating the exact emission intensity of any fuel blend on-demand would require an active connection to the GREET model. Instead, only the emission intensities of each individual fuel were calculated using GREET. The intensities are calculated using a binomial expression to account for the linear empirical effect of user-defined methane slip on each factor. The calculation of the emission intensity for each pollutant i and each fuel j is a linear expression of two factors, a and b:

$$Emission_{i,j} \ (g \ of \ i \ /MMBtu \ Electricity) \ = a_{i,j} \cdot slip + b_{i,j}$$

The values of these intensities, with and without infrastructure included, have been determined empirically using GREET, and the values used by the webtool are summarized below.

CO2 Emission Intensities for Electricity Generation by Individual Fuels (g/MMBtu electricity delivered)

	No Infrastructure		With Infrastructure	
	Slope, a	Intercept, b	Slope, a	Intercept, b
Natural Gas	1,457	143,975	1,836	146,696
Coal	3.81	310,312	5.06	310,725
Nuclear	5.68	549.8	7.19	687.7
Biomass	7.66	9,193	9.77	22,039
Wind	0.00	0.00	0.02	1,683
Solar PV	0.00	0.00	0.33	12,731

CH4 Emission Intensities for Electricity Generation by Individual Fuels (g/MMBtu electricity delivered)

	No Infrastructure		With Infrastructure	
	Slope, a	Intercept, b	Slope, a	Intercept, b
Natural Gas	38,790	30.65	38,806	34.63
Coal	71.22	498.9	75.49	500.0
Nuclear	100.7	1.28	100.8	1.50
Biomass	156.9	44.44	157.5	73.90
Wind	0.00	0.00	0.362	3.80
Solar PV	0.00	0.00	4.565	24.20

N2O Emission Intensities for Electricity Generation by Individual Fuels (g/MMBtu electricity delivered)

	No Infrastructure		With Infrastructure	
	Slope, a	Intercept, b	Slope, a	Intercept, b
Natural Gas	0.010	2.23	0.014	2.25
Coal	3.03E-05	7.19	4.13E-05	7.20
Nuclear	3.78E-05	0.01	5.11E-05	0.012
Biomass	9.00E-05	18.66	1.10E-04	18.84
Wind	0.000	0.000	1.59E-07	0.018
Solar PV	0.000	0.000	2.33E-06	0.196

The user can enter any mixture of the six available fuels that sums to 100%, and the tool will calculate emission intensities, $e_{i,total}$, for each pollutant, i, using weighted averages of the fuel shares, $share_j$:

$$Emission_{elec,i} \ (g \ of \ i/MMBtu \ Electricity) \ = \ \sum_{j=0}^{n=6 \ fuels} share_{i,j} \cdot e_{i,j}$$

The emission intensities for the three pollutants are subsequently used to calculate upstream emissions associated with the electricity consumption in the process-scale LCA calculations for the hydrogen pathways. This approach is not used by GREET, as it rigorously iterates calculated electricity emission intensity through the production of all other fuels, but this method provides the flexibility for the user to specify any combination of fuel shares. It sacrifices some accuracy, as described in the table of estimated averages and maximum errors below. See more details on these errors in Appendix A.

Estimated Magnitude of Error in GTI Calculated Electricity Emission Intensities

	Without Infrastructure			With Infrastructure		
	CO2	CH4	N2O	CO2	CH4	N2O
Average	0.2%	0.2%	0.2%	0.5%	0.5%	0.7%
Maximum	0.7%	0.8%	0.8%	2.4%	2.4%	3.2%

Upstream Methane Slip

This input refers to the leakage rate of methane for the entire value chain for natural gas production. GREET provides Table 4.3 (Inputs tab) for detailed input of this leakage, including Recovery (four sub-stages), Gathering and Boosting, Processing, Transmission and Storage, and Distribution. The input is also subdivided into conventional natural gas and shale gas production. Two predefined leakage profiles are provided in GREET: Bottom Up/Top Down (BU/TD) Hybrid (default), EPA.

Methane Leakage Options in GREET2021 (vol% CH4 / natural gas throughput)

	BU/TD Hybrid		EPA	
	Conventional	Shale gas	Conventional	Shale gas
Recovery - CH4 Leakage and Venting	0.60%	0.61%	0.39%	0.41%
Recovery - Completion CH4 Venting	0.00%	0.01%	0.00%	0.01%
Recovery - Workover CH4 Venting	0.00%	0.00%	0.00%	0.00%
Recovery - Liquid Unloading CH4 Venting	0.04%	0.04%	0.02%	0.02%
Well Equipment - CH4 Venting and Leakage	0.40%	0.40%	0.22%	0.22%
Gathering and Boosting - CH4 Venting and Leakage	0.17%	0.17%	0.15%	0.15%
Processing - CH4 Venting and Leakage	0.03%	0.03%	0.02%	0.02%
Transmission and Storage - CH4 Venting and Leakage	0.26%	0.26%	0.18%	0.18%
Distribution - CH4 Venting and Leakage	0.09%	0.09%	0.09%	0.09%
Total	0.98%	0.99%	0.69%	0.70%

To simplify input for this tool, the user provides a single leakage rate for the entire supply chain, and this is applied to both conventional natural gas and shale gas production according to the allocation defined by the BU/TD Hybrid default in GREET. This allocation is summarized in the table below, which assumes the GREET default supply blend of 46% conventional gas and 54% shale gas.

Methane Leakage by Stage Assumed in Webtool (BU/TD Basis)

Stage	Leakage Allocation
Recovery – Completion	0.8%
Recovery – Workover	0.0%
Recovery – Liquid Unloading	3.6%
Well Equipment	40.2%
Gathering and Boosting	17.1%
Processing	3.1%
Transmission and Storage	26.0%
Distribution	9.5%

Note that because natural gas is used at centralized plants for fuel production and hydrogen production, the distribution stage of the natural gas value chain is not considered in any leakage calculations within GREET. The pre-run cases considered leakage rates between 0.0% – 10.0% with 0.1% granularity, and the user-defined methane leakage inputs in GREET were populated (Inputs tab, cells V125:W132).

Technology-Specific Inputs

Most inputs in the Technology-Specific section fed into the calculations based on the pre-run GREET cases (generally described in the *Calculations* section). Where possible, these calculations follow the exact method in GREET, but new calculations were formulated where the GREET model is too inflexible to generate the desired scenarios. Details of these deviations from the model are described in the sections below along with descriptions of available GREET outputs.

Electrolysis

The electrolysis pathway used from GREET is for Refueling Stations, converting grid electricity to gaseous hydrogen. This was chosen for the flexibility of applying any electricity generation fuel mix for the grid in lieu of other centralized options that use a single dedicated electricity source (e.g. solar, nuclear). The NREL H2A model being used in GREET provides predictions for Polymer Electrolyte Membrane (PEM) electrolyzers in this distributed case[6]. Electrolyzer technologies are evolving, and correspondingly, so is the energy consumption required for electrolysis plants. Reports from IEA and IRENA provide an overview of electrolysis technologies and their estimated performance.

The only input for the electrolysis pathway in this tool is the electricity consumption required to produce hydrogen, which is linked to efficiency. GREET uses a default electrolysis efficiency of 66.8% for the H2A model basis, which corresponds to electricity demand of 1.497 J/J H2. Additional electricity is used for hydrogen transmission and compression. If the user of this tool chooses to provide a non-default electricity consumption as a user-defined value, this input is a non-standard GREET modification, which changes the electricity consumption for hydrogen production by electrolysis (represented in the Hydrogen tab, cell BO217).

The upstream emissions are calculated using the emission intensities of the generated electricity. This would generally use the weighted average black box approach, but it simplifies to an expression for a single fuel (electricity):

$$Emission_{fuel,i} = emission\_factor_{elec\ feed,i} \cdot fuel\_flow_{elec\ feed,i}$$

These emission rates for CO2, CH4, and N2O are documented in GREET on the Hydrogen tab in cells BD236, BD234, and BD235, respectively. Since electricity is the only fuel consumed for hydrogen production, there are no on-site emissions considered. Since the electrolysis pathway chosen in GREET is for refueling stations (on-site hydrogen production), the GREET calculations disregard transmission of product hydrogen, so transmission emissions from the SMR and biomass gasification pathways were used. Transmission assumptions are identical for both pathways, so emission calculations are the same.

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[6] NREL H2A model: https://www.nrel.gov/hydrogen/h2a-production-models.html

The Refueling Station electrolysis pathway includes compression of the product hydrogen, with calculated emissions identical to the SMR and biomass gasification pathways. The total emissions for the pathway are the sum of the feedstock, fuel (0 in this case), transmission, and compression:

$$Emission_{total,i} = Emission_{fuek,i} + Emission_{trans,i} + Emission_{comp,i}$$

The *Calculations* section details how the total emission intensities of the individual greenhouse gases are converted to a CO2e basis for individual reporting and for calculating the total GHG emission intensity. As described in the general documentation, there are several types of efficiency that could be reported: electrolyzer efficiency (stack efficiency), system efficiency, and overall efficiency.
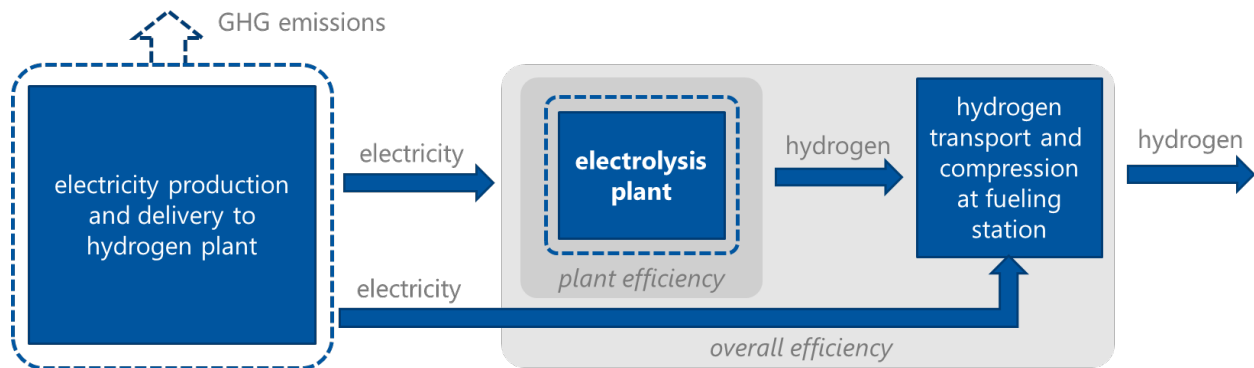
Figure 3. Boundaries for calculating three types of energy efficiency of Electrolysis.

Electrolyzer/stack efficiency cannot be determined with the level of granularity of inputs for this tool without assumptions of the portion of energy consumed by areas of the plant outside of the electrolyzer. System efficiency is typically defined in GREET based on user inputs (Hydrogen tab, cell BO192), and feed/fuel consumption is calculated from it. For this tool, process efficiency is determined using the single fuel rate. This is not a displayed output for the webtool.

$$System\ Efficiency\ (\%) = {1}/{flow_{fuel,elec}\ (J\ elec/J\ H_2)}$$

The webtool does not display the process efficiency as an output. Instead, it reports the overall efficiency for the pathway, which is calculated using the energy consumption for all stages. The overall hydrogen production efficiency is calculated considering the sum of energy inputs throughout hydrogen production, transmission, and compression. Transmission is assumed to transport hydrogen 750 miles by pipeline, and compression brings the delivered hydrogen to 14,000 psia. The transmission and compression electricity demands are 0.33 and 0.10 J electricity/J H2, respectively.

$$Overall\ Efficiency\ (\%) = {1}/{(flow_{fuel,elec} + flow_{trans,elec} + flow_{comp,elec})}$$

Steam Methane Reforming (SMR)

North American Natural Gas to Gaseous Hydrogen, or an SMR, is a Central Plant pathway for hydrogen production in GREET. The pathway is designed to flexibly include coproduction of steam or electricity, but neither are included for the calculations in this tool. While SMR technology is mature, plants that

integrate carbon capture are still in the early stages of development and deployment, such that the technology is evolving. Correspondingly, the natural gas and electricity consumption required for these plants is evolving. Reports from IEA and others provide an overview of SMR technology with and without carbon capture, and its estimated performance.

GREET calculations are subdivided into emissions related to hydrogen production, non-combustion emissions (conversion of NG feedstock into H2 + CO2), transmission, and compression. In the GREET spreadsheet model, these are displayed in Table 3 of the Hydrogen tab, in columns B, C, G, and H, respectively. Inputs for this pathway in this tool include natural gas consumption and CO2 capture rate.

For the H2A model and current technology status, GREET defines the default overall efficiency of hydrogen production as 72.0%, which corresponds to 1.388 J input/J H2. GREET specifies that 59.5% of this input energy is feedstock (natural gas feed), or 0.826 J NG feed/J H2. The remaining 0.562 J input/J H2 is fuel, and GREET defines the fuel shares as 97% natural gas (0.545 J/J H2) and 3% electricity (0.017 J/J H2).

GREET Default Constants for SMR Process

	Location	Unit	No Capture	With Capture (90%)
H2 Production Efficiency	Hydrogen tab, B192	%	72.0	72.2
NG Feed Share	Hydrogen tab, B195	%	59.5	59.7
NG Feed Consumption	-	Btu/MMBtu H2	826,585	826,585
NG Fuel Share[7]	Hydrogen tab, B201	%	97.0	96.8
NG Fuel Consumption	Hydrogen tab, B211	Btu/MMBtu H2	544,695	540,745
Electricity Fuel Share	Hydrogen tab, B205	%	3.0	3.2
Electricity Fuel Consumption	Hydrogen tab, B217	Btu/MMBtu H2	17,040	17,968
Electricity for Capture[8]	Hydrogen tab, B217	Btu/MMBtu H2	0	26,775

If the user provides a user-defined natural gas consumption different than the default, the electricity demand is held constant, and the individual feedstock and fuel natural gas flow rates are calculated by scaling the GREET default flow rates.

$$NG\ feed\ = \frac{User\ NG}{GREET\ feed\ NG\ + GREET\ fuel\ NG} \cdot GREET\ feed\ NG$$

$$NG\ fuel\ = \frac{User\ NG}{GREET\ feed\ NG\ + GREET\ fuel\ NG} \cdot GREET\ fuel\ NG$$

If CO2 capture is specified by the user, the calculated values of **Captured CO2** and **Cap Elec** are determined, whose steps are detailed in the CO2 Capture section below. The total subsequent electric consumption rate to be used in the emission intensity calculation is:

$$flow_{elec} = flow_{elec,H2\ Process} +\ Cap\ Elec$$

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[7] In the SMR process, this is the total fuel share * individual fuel share, or (1-feed share) * fuel share
[8] This calculation is combined with the determination of electricity consumption for H2 production.

The feedstock emissions are calculated using the upstream emission intensities of the natural gas feedstock. Using a single feedstock, this weighted calculation simplifies to a simple expression for the natural gas feed. The emission factors for this portion account for both upstream emissions of natural gas sourcing.

$$Emission_{feed,i} = emission\_factor_{NG\ feed,i} \cdot NG\ feed$$

GREET tabulates a more detailed recording of these feedstock emissions. The upstream emissions due to natural gas sourcing are in column B (Feedstock) of Table 4.1 (Hydrogen tab), and the emissions due to reforming of the natural gas are in column C (Non-Combustion Emissions) of Table 3 (Hydrogen tab). A simplification by this model is the use of constant emission factors for this feedstock contribution. Given the inputs in this model, the emission factors mainly affect inputs in the Global section, and user selections in the SMR section only have minor effects as the hydrogen production emissions iterate through the model. If a user-defined natural gas consumption rate of the SMR is provided, the Feedstock emission intensities are scaled accordingly.

$$Emission_{feed,i} = \frac{User\ NG}{GREET\ feed\ NG + GREET\ fuel\ NG} \cdot Emission_{feed,i,GREET}$$

Natural gas and electricity are fuels consumed for this hydrogen production pathway. Emissions related to this fuel consumption (and their sourcing) are recorded in column B (H2 Production) of Table 3 (Hydrogen tab) of GREET. The weighted calculation in this black box method combines the individual contributions for each fuel, *j*, using their flow rate (BTU fuel/MMBtu H2) and their emission factors for each GHG, *i* (g GHG/BTU fuel).

$$Emission_{fuel,i} = \sum_{j=0}^{\#\ of\ fuels} emission\_factor_{j,i} \cdot flow_{fuel,j}$$

In the case of calculating fuel emissions for CO2 (*i* = CO2), any applicable captured CO2 is removed from the calculated emission intensity.

$$Emission_{fuel,CO2} = \sum_{j=0}^{\#\ of\ fuels} emission\_factor_{j,CO2} \cdot flow_{fuel,j} - Captured\ CO2$$

Considering the calculated feedstock and fuel contributions in addition to the transmission and compression contributions described in the separate section below, the total emissions for the pathway are the sum of the feedstock, fuel, transmission, and compression:

$$Emission_{total,i} = Emission_{feed,i} + Emission_{fuel,i} + Emission_{trans,i} + Emission_{comp,i}$$

The *Calculations* section details how the total emission intensities of the individual greenhouse gases are converted to a CO2e basis for reporting and for calculating the total GHG emission intensity. As described in the general documentation, there are several types of efficiency that could be reported: SMR efficiency (reformer efficiency), system efficiency, and overall efficiency.
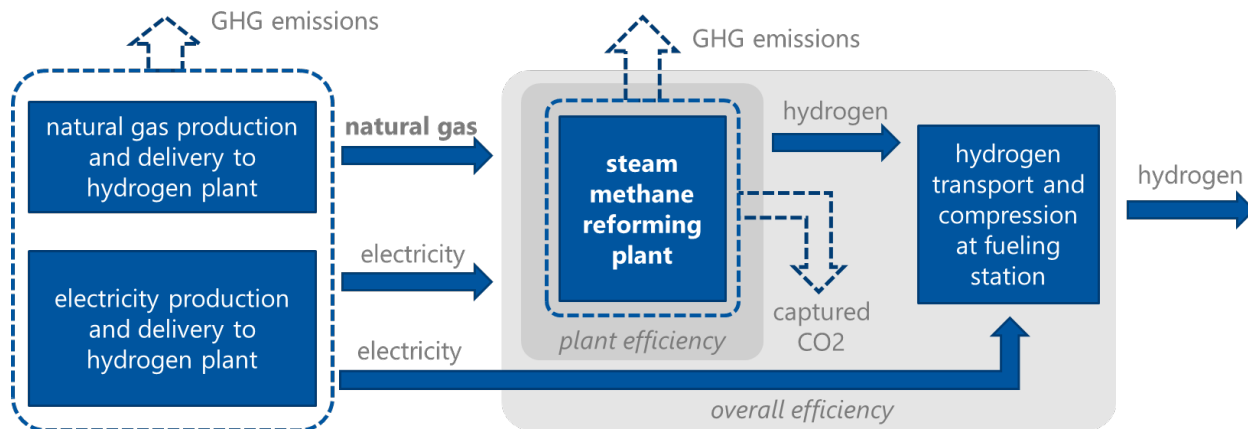
Figure 4. Boundaries for calculating three types of energy efficiency of SMR.

Efficiency of the SMR unit itself cannot be determined with the level of granularity of inputs for this tool without assumptions of the portion of energy consumed by areas of the plant outside of the reformer. System efficiency is typically defined in GREET based on user inputs (Hydrogen tab, cell B192), and feed/fuel consumptions is calculated from it. For this tool, process efficiency is determined using the feed and fuel rates. It should be noted that the electricity consumption also includes 357 kWh/ton atomic carbon removed by the carbon capture unit (if applicable). Transmission is assumed to transport hydrogen 750 miles by pipeline, and compression brings the delivered hydrogen to 14,000 psia. The transmission and compression electricity demands are 0.33 and 0.10 J electricity/J H2, respectively.

$$System\ Efficiency\ (\%)\ = {}^{1}\!/_{(flow_{feed,NG} + flow_{fuel,NG} + flow_{fuel,elec})}$$

The webtool displays the process efficiency as an output along with the overall efficiency for the pathway, which is calculated using the energy consumption for all stages. The overall efficiency for the pathway is calculated using the energy consumption for all stages. The overall hydrogen production efficiency is calculated considering the sum of energy inputs throughout hydrogen production, transmission, and compression.

$$Overall\ Efficiency\ (\%)$$
$$= {}^{1}\!/_{(flow_{feed,NG} + flow_{fuel,NG} + flow_{fuel,elec} + flow_{trans,elec} + flow_{comp,elec})}$$

Biomass Gasification

Biomass to Gaseous Hydrogen, or biomass gasification for hydrogen production, is a Central Plant pathway in GREET. The pathway is designed to flexibly include coproduction of steam or electricity, but neither are included for the calculations in this tool. GREET calculations are subdivided into emissions related to hydrogen production, transmission, and compression. In the GREET spreadsheet model, these are displayed in Table 3 of the Hydrogen tab, in columns AC, AJ, and AK, respectively. Inputs in the webtool for this pathway include biomass type, biomass consumption, and CO2 capture rate. By default, the biomass is collected and transported at 40 wt% moisture. This parameter can be edited in GREET, but it is not an input in HyPEC.

Unlike the previous two technologies, the Industry Data option is selected in place of the H2A model in order to permit CO2 capture as an option. GREET specifies the default overall efficiency of hydrogen production as 44.0%, which corresponds to 2.23 J input/J H2. GREET specifies that the first 1.000 J biomass/J H2 is converted to hydrogen. The remaining 1.13 J input/J H2 is fuel, which is allocated as shown in the table below. Note that GREET does not indicate a shift in process efficiency or fuel shares when shifting to the CO2 capture scenario, unlike SMR.

GREET Default Constants for Biomass Gasification

	Location	Unit	No Capture	With Capture (90%)
H2 Production Efficiency[9]	Hydrogen tab, AC192	%	44.0	44.0
Feedstock Share	Hydrogen tab, AC195	Btu/MMBtu H2	1.000	1.000
Biomass Feed Consumption	-	Btu/MMBtu H2	1.000	1.000
Biomass Fuel Share[10]	Hydrogen tab, AC202	%	96.43	96.43
Biomass Fuel Consumption	Hydrogen tab, AC212	Btu/MMBtu H2	1.227	1.227
NG Fuel Share	Hydrogen tab, AC201	%	2.28	2.28
NG Fuel Consumption	Hydrogen tab, AC211	Btu/MMBtu H2	28,966	28,966
Electricity Fuel Share	Hydrogen tab, AC205	%	1.29	1.29
Electricity Consumption	Hydrogen tab, AC217	Btu/MMBtu H2	16,418	16,418
Electricity for Capture[11]	Hydrogen tab, AC217	Btu/MMBtu H2	0	76,802[12]

If the webtool user provides a user-defined biomass consumption different than the default, the natural gas and electricity demands are held constant, and the fuel biomass flow rate is calculated by removing the 1.0 MMBtu.

$$Biomass\ fuel\ =\ User\ Biomass\ -\ 1.0\ MMBtu\ Biomass\ feed\ /MMBtu\ H2$$

If CO2 capture is specified by the user, the calculated values of **Captured CO2** and **Cap Elec** are determined, whose steps are detailed in the CO2 Capture section below. The total subsequent electric consumption rate to be used in the emission intensity calculation is:

$$flow_{elec} = flow_{elec,H2\ Process} + Cap\ Elec$$

The feedstock emissions are calculated using the upstream emission intensities of the biomass feedstock. Using a single feedstock, this weighted calculation simplifies to a simple expression for the biomass feed. The emission factors for this portion account for both upstream emissions of natural gas sourcing.

$$Emission_{feed,i} = emission\_factor_{biomass\ feed,i} \cdot flow_{feed,NG}$$

In GREET, the upstream emissions due to biomass sourcing are in column L (Feedstock) of Table 4.1 (Hydrogen tab). There are no emissions included for the CO2 generated during gasification because the

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[9] Does not include the energy required for CO2 capture
[10] In Biomass Gasification, this is the fuel share shown in the GREET cell listed
[11] This calculation is combined with the determination of electricity consumption for H2 production.
[12] This value is for the GREET default biomass type of Poplar Wood. Willow Wood = 77,241 BTU electricity /MMBtu Switchgrass = 78,765 BTU electricity was the temperature a Google of the temperature to p.m.: about 4 PM a Google was whether Sunday what about Monday 11 today was the temperature at 1 PM /MMBtu H2

biomass is a biogenic source. This model uses constant emission factors for this feedstock contribution. Given the inputs in this model, the emission factors mainly affect inputs in the Global section, and user selections in the Biomass Gasification section only have minor effects as the hydrogen production emissions iterate through the model. If a user-defined biomass consumption rate is provided, the Feedstock emission intensities are scaled accordingly.

$$Emission_{feed,i} = \frac{User\ Biomass}{GREET\ feed\ Biomass + GREET\ fuel\ Biomass} \cdot Emission_{feed,i,GREET}$$

Natural gas and electricity are fuels consumed for this hydrogen production pathway. Emissions related to these fuels (and their sourcing) are lumped into column AC (H2 Production) of Table 3 (Hydrogen tab) of GREET along with the combustion emissions associated with the biomass allocated as fuel. The weighted calculation in this black box method combines the individual contributions for each fuel, j, using their flow rate (BTU fuel/MMBtu H2) and their emission factors for each GHG, i (g GHG/BTU fuel). The emission factors have been retrieved from GREET for each case to align with the calculation method.

$$Emission_{fuel,i} = \sum_{j=0}^{\#\ of\ fuels} emission\_factor_{j,i} \cdot flow_{fuel,j,i}$$

In the case of calculating fuel emissions for CO2 (i = CO2), any applicable captured CO2 is removed from the calculated emission intensity.

$$Emission_{fuel,CO2} = \sum_{j=0}^{\#\ of\ fuels} emission\_factor_{j,CO2} \cdot flow_{fuel,j} - Captured\ CO2$$

Considering the calculated feedstock and fuel contributions in addition to the transmission and compression contributions described in the separate section below, the total emissions for the pathway are the sum of the feedstock, fuel, transmission, and compression:

$$Emission_{total,i} = Emission_{feed,i} + Emission_{fuel,i} + Emission_{trans,i} + Emission_{comp,i}$$

GREET also includes two columns in its biomass gasification pathway that are blacked out in the 2021 version, indicating that they are not fully vetted for inclusion. These are direct and non-combustion emissions for synthesis in this hydrogen production process (Hydrogen tab, Table 3, columns AE & AF). All emissions are 0 for the no capture/sequestration scenario, but there is a significant negative CO2 emission for the 90% capture/sequestration scenario. The GREET formula shows that this negative emission is accounting for the sequestration of the feedstock portion of biomass feed, which has already been counted in the biomass gasification step (column AC). This negative emission is included twice in the pathway total CO2 emissions calculation (Hydrogen tab, cell M300), but the GTI LCA team has chosen to neglect this undocumented emission for this tool.

The *Calculations* section details how the total emission intensities of the individual greenhouse gases are converted to a CO2e basis for reporting and for calculating the total GHG emission intensity. As

described in the general documentation, there are several types of efficiency that could be reported: SMR efficiency (reformer efficiency), system efficiency, and overall efficiency.
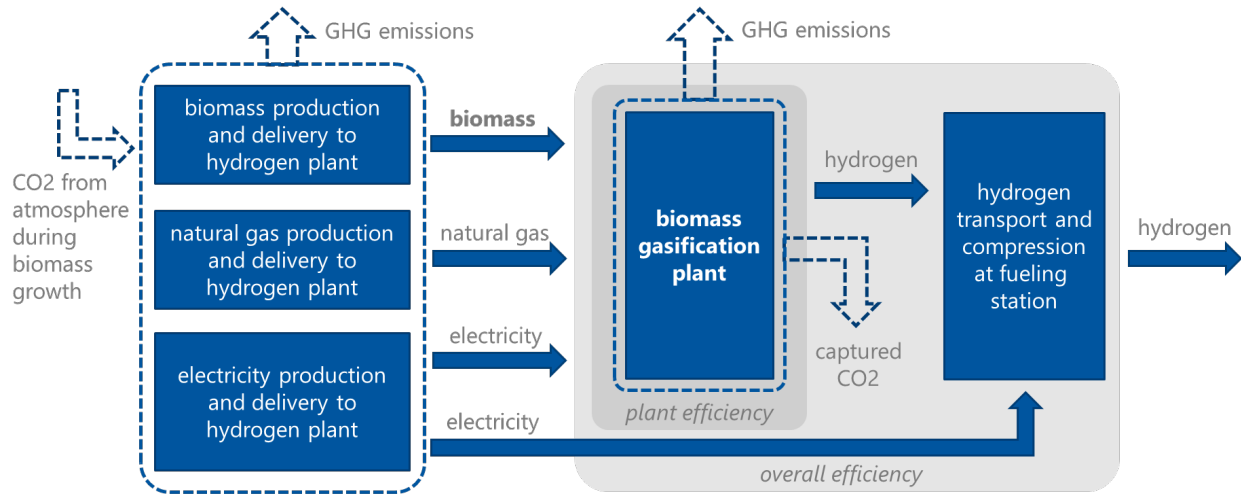

Figure 5. Boundaries for calculating three types of energy efficiency of Biomass Gasification.

Efficiency of the gasification unit itself cannot be determined with the level of granularity of inputs for this tool without assumptions of the portion of energy consumed by areas of the plant outside of the reformer. System efficiency is typically defined in GREET based on user inputs (Hydrogen tab, cell AC192), and feed/fuel consumptions is calculated from it. For this tool, process efficiency is determined using the feed and fuel rates. It should be noted that the electricity consumption also includes 357 kWh/ton atomic carbon removed by the carbon capture unit (if applicable). Transmission is assumed to transport hydrogen 750 miles by pipeline, and compression brings the delivered hydrogen to 14,000 psia. The transmission and compression electricity demands are 0.33 and 0.10 J electricity/J H2, respectively

$$System\ Efficiency\ (\%)\ = {}^1\!/(flow_{feed,biomass} + flow_{fuel,biomass} + flow_{fuel,NG} + flow_{fuel,elec}$$

The webtool displays the process efficiency as an output along with the overall efficiency for the pathway, which is calculated using the energy consumption for all stages. The overall efficiency for the pathway is calculated using the energy consumption for all stages. The overall hydrogen production efficiency is calculated considering the sum of energy inputs throughout hydrogen production, transmission, and compression.

$$Overall\ Efficiency\ (\%)$$
$$= {}^1\!/(flow_{feed,biomass} + flow_{fuel,biomass} + flow_{fuel,NG} + flow_{fuel,elec} + flow_{trans,elec} + flow_{comp,elec}$$

CO2 Capture (SMR and Biomass Gasification Pathways)

In the SMR and Biomass Gasification pathways, the user can provide a user-defined CO2 capture rate, in which case several new calculations are fed into the framework. The GREET values for system efficiency, feedstock share, and fuel shares are used to calculate initial values of feedstock and fuel flows. If a user-

defined consumption is also provided (natural gas for SMR, biomass for Biomass Gasification), the scaled feed and/or fuel flowrates are used for this CO2 capture calculation. The scaling methods applied for SMR and Biomass Gasification differ from each other, and they are described in their respective sections above.

This CO2 capture calculation considers CO2 generated by reforming/gasifying feedstock and by combusting carbon-containing fuel. In SMR this is CO2 generated from reforming natural gas and combusting natural gas. In Biomass Gasification, this is CO2 generated from gasifying biomass and producing heat from excess biomass. Stoichiometric factors calculate the amount of carbon generated, assuming that all carbon is combusted.

For SMR:

$$Generated\ C\ \left(\frac{g}{MMBtu\ H2}\right) = NG\left(\frac{BTU\ NG}{MMBtu\ H2}\right) \cdot \frac{22\frac{g\ NG}{ft^3 NG} \cdot 0.724\frac{g\ C}{g\ NG}}{983\frac{BTU\ NG}{ft^3 NG}}$$

For Biomass Gasification:

$$Generated\ C\ \left(\frac{g}{MMBtu\ H2}\right) = Biom.Cons.\left(\frac{BTU\ NG}{MMBtu\ H2}\right) \cdot \frac{C\ ratio\frac{g\ C}{g\ Biom.}}{LHV\frac{BTU\ Biom.}{ton\ Biom.}}$$

The values for density, lower heating value (LHV), and carbon ratio in the Biomass Gasification pathway are specific to the biomass type, which can be specified by the user. The values for these three constants are provided in GREET and are summarized below.

	LHV	C ratio
	MMBtu/ton	*%*
Willow	15.396	48.7
Poplar	15.929	50.1
Switchgrass	14.447	46.6

For both hydrogen production pathways, the carbon fully oxidizes into CO2.

$$Generated\ CO2\ \left(\frac{g}{MMBtu\ H2}\right) = Generated\ C\ \Big/ 0.2727\frac{g\ C}{g\ CO2}$$

Considering the amount of CO2 generated from natural gas conversion and combustion, the CO2 capture rate provided by the user (% Captured) is used to specify the **Captured CO2** and **Emitted CO2** variables.

$$Captured\ CO2\ \left(\frac{g}{MMBtu\ H2}\right) = Generated\ CO2 \cdot \%\ Captured$$

$$Emitted\ CO2\ \left(\frac{g}{MMBtu\ H2}\right) = Generated\ CO2 - Captured\ CO2$$

Finally, the electricity required for operating the carbon capture equipment is calculated. GREET uses 357 kWh/ton atomic carbon in its carbon capture calculations throughout the model, so this value is used here as well. The formula to calculate total electricity for capture converts this factor to BTU elec/ton atomic carbon to work with GREET units:

$$Cap\ Elec\ =\ Captured\ CO2\ \cdot\ 1218135\frac{BTU\ elec}{ton\ C}$$

The calculated values for **Captured CO2** and **Cap Elec** are fed into the pathway calculations for SMR and Biomass Gasification.

Hydrogen Transmission and Hydrogen Compression Steps

Given that hydrogen produced by any of the three pathways is identical, the transmission and delivered hydrogen compression steps are treated identically across the model. There are no model inputs for that directly affect the transmission and compression steps. Both steps use 100% electricity as fuel by default. Therefore, the emission intensities of these steps are affected by the electricity generation fuel blend chosen by the user. To account for this effect, the actual emission intensity for each step is calculated using the electricity demands and the electricity emission factors used in the fuel emissions calculation above. The default GREET electricity flow for the compression step is clearly displayed in the *Compression and Precooling* steps. Using the SMR process as an example, this is displayed in the Hydrogen tab, cell H217. The electricity flow for transmission is more deeply ingrained in the T&D and T&D_Flowcharts tabs.

	Electricity Demand (BTU/MMBtu H2)
Transmission	33,370
Compression	102,186

$$Emission_{trans,i} = emission\_factor_{elec,i} \cdot flow_{trans,elec,i}$$

$$Emission_{comp,i} = emission\_factor_{elec,i} \cdot flow_{comp,elec,i}$$

These calculated emissions are used in each of the hydrogen production pathway calculations for total emission rates (**Emission$_{total,i}$**).

Acronyms and Chemical Compounds

CH4   Methane

GREET   Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model

GWP   Global warming potential

N2O   Nitrous oxide

CO   Carbon monoxide

CO2   Carbon dioxide

SMR   Steam Methane Reforming

VOCs   Volatile organic carbon molecules

Appendix A: Webtool Accuracy Vs. GREET

As described in the body of this technical documentation, the emission intensity values presented rely on a combination of GREET pre-run case data and calculation results. The calculations were developed to align with the default methodology in GREET while allowing flexibility to incorporate pathway inputs that are not available in the 2021 version of GREET. After implementation of this approach, the results have been analyzed to assess their accuracy against GREET.

Accuracy of Webtool with GREET Inputs

Given that this unique approach to providing GREET results does not keep an active connection to the GREET model, it is important to validate its results against the original model. Disregarding webtool inputs that provide opportunities to steer from typical GREET inputs, the following fields have values that can be modified to stay within the bounds of the GREET tool:

- Include Emissions Associated with Construction of Infrastructure & Equipment (No/Yes)
- Electricity Source (12 preset options only)
- Upstream Methane Slip (including user-defined values 0.0%-10.0%, 0.1% increments)
- SMR CO2 Capture (0% or 90% only)
- Biomass Type (3 types)
- Biomass CO2 Capture (0% or 90% only)

A run matrix of all variations of the above variables was constructed, providing 14,832 cases for comparison. This corresponds to the same cases in the databases for providing webtool results. The calculations by this webtool generally matched GREET very well, with total GHG emission errors of 0.0 ± 0.0 (0.00% ± 0.00%), 33.3 ± 40.7 (0.06% ± 0.06%), and 6.6 ± 3.2 (0.01% ± 0.02%) for Electrolysis, SMR, and Biomass Gasification respectively. The calculated net GHG emissions for all three pathways matched GREET within a maximum error of 0.18%. The N2O estimates for SMR exhibited the maximum single error of 0.21%.
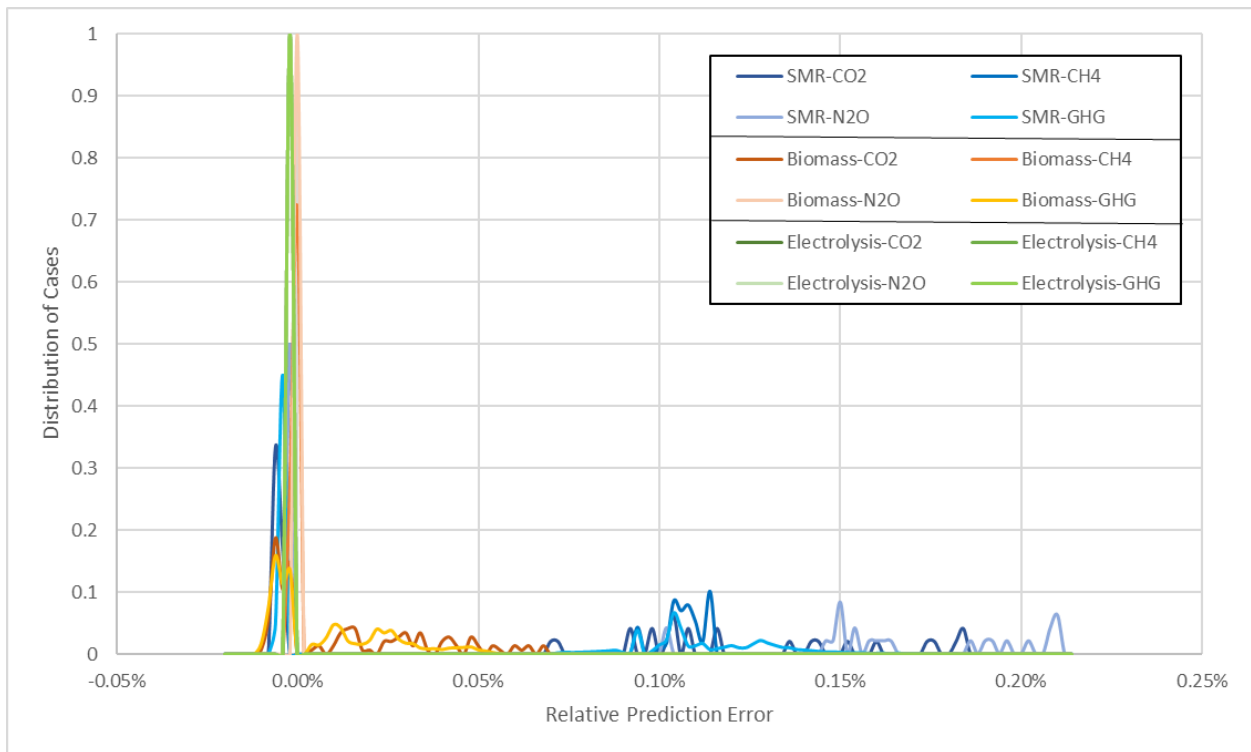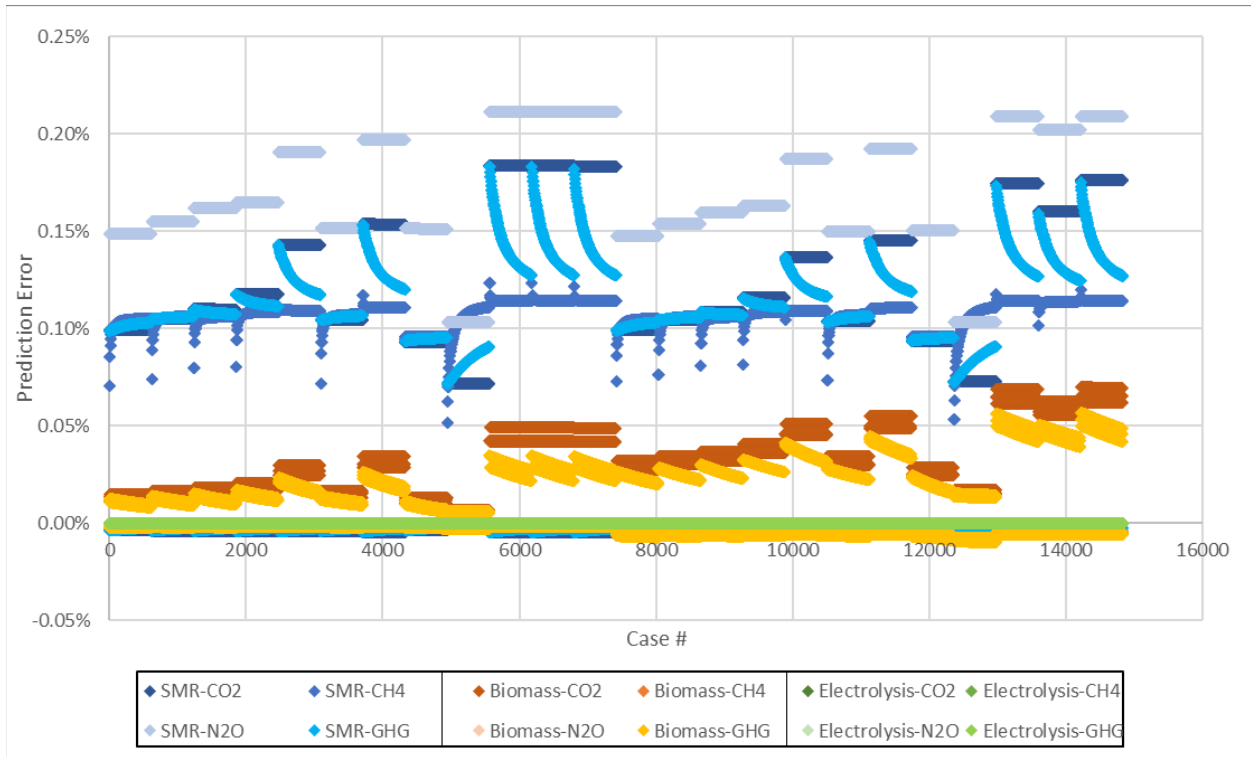
User-Defined Fuel Blends for Electricity Generation

The webtool has made simplifications when specifying user-defined fuel blends for electricity generation (Global Inputs > Electricity GHG Intensity > Electricity Source). Electricity is used in many locations within the hydrogen production pathways considered for this tool. Not only is electricity consumed in the hydrogen production facility and during hydrogen transmission/compression, but it is also consumed upstream during production of the feeds and fuels used for these pathways (e.g. natural gas, biomass, etc.).

In GREET, specifying a custom fuel blend for the Stationary and Transportation electricity uses applies the resulting electricity emission intensity to all uses of this energy type throughout the model. These electricity consumption locations include all the types listed above, including feed and fuel production, hydrogen production, hydrogen transmission, and hydrogen compression.

The method for applying custom electricity generation fuel blends in this tool makes assumptions to cooperate with the pre-run cases approach. The emission intensities for generated electricity were retrieved for individual fuels, so using a weighted average to calculate the emission intensities of fuel blends disregards any possible additive or reductive effects of blending fuels only electricity emission intensity. Also, the calculated emission intensities are *only* applied to the electricity consumed on-site for hydrogen production. Upstream facilities that produce the feeds and fuels used in the hydrogen production pathways consume electricity, but this methodology must assume the default Electricity Source configuration (EIA AEO 2020) for calculating these upstream emissions to detach from the detailed, iterative, Excel-based GREET model.

Calculation results in GREET and the webtool were executed for all combinations of custom fuel blends in increments of 16.6% (giving the option for equal shares of all six fuel options).

Accuracy of Electricity Emission Factors

Emission factors were retrieved (g GHG/MMBtu electricity) from GREET for user-defined fuel blends for comparison to the estimation method described in the Electricity GHG Intensity section. This retrieval exercise could be completed with either Stationary or Transportation electricity with the following steps:

1. Specify User Defined Mix (13) for Electricity Generation Mix on the Inputs tab. Transportation = cell F715, Stationary = cell F716.
2. Specify desired fuel blends on the Fuel_Prod_TS tab using both User Defined Mix tables for Electric Generation Mixes (non-renewable fuels) and Technologies for Other Power Plants (renewable fuels). For Transportation, this corresponds to cell ranges CF915:CK915 and CF967:CK967. For Stationary, this corresponds to cell ranges CN915:CR915 and CN967:CR967.
3. Retrieve the calculated emission factors from the Electric tab as the sum of the Feedstock (upstream) and Fuel (combustion) contributions.
   a. CO_2 (total): Transportation = F221 + G221, Stationary = B221 + C221
   b. CH_4: Transportation = F218 + G218, Stationary = B218 + C218
   c. N_2O: Transportation = F219 + G219, Stationary = B219 + C219

All combinations of user-defined fuel blends as defined above were run in GREET with these steps, and analogous emission factors were calculated using the estimation method described in the Electricity GHG Intensity section using binomial factors. Relative errors of the estimates were calculated as follows:

$$Error = \frac{GTI\ Estimate - GREET\ Result}{GREET\ result} \cdot 100\%$$

The table below summarizes the distribution of the errors calculated with the equation above, and it shows clearly that the electricity emission factors are estimated more accurately when no infrastructure is considered. The average absolute error in predicting the emission factors **with no** infrastructure considerations for CO2, CH4, and N2O is 0.18%, 0.17%, and 0.16%, respectively. In contrast, the average absolute error in predicting the emission factors **with** infrastructure considerations is 0.50%, 0.52%, and 0.68%. The inclusion of infrastructure adds additional intricacies and interlacing effects for the different fuel inputs, so there are additive effects that are not properly accounted with the binomial estimate method.

Error Distribution of Generated Electricity Emission Intensity Estimates in Webtool

Error thru:	No Infrastructure			With Infrastructure		
	CO2	CH4	N2O	CO2	CH4	N2O
-1.00%	0%	0%	0%	14%	16%	23%
-0.75%	0%	0%	0%	5%	6%	8%
-0.50%	1%	1%	1%	13%	16%	16%
-0.25%	6%	6%	9%	16%	15%	11%
0.00%	27%	28%	41%	21%	22%	30%
0.25%	44%	49%	37%	23%	21%	7%
0.50%	19%	15%	10%	3%	0%	0%
0.75%	2%	1%	1%	1%	0%	0%
1.00%	0%	1%	1%	0%	0%	0%
1.00%+	0%	0%	0%	4%	4%	4%

The scope of this analysis was then expanded to the accuracy of full hydrogen production pathway emission intensity calculations for the same set of all combinations of user-defined fuel blends. With the electricity emission intensity errors trickling through, all GREET hydrogen pathway intensities demonstrated generally larger relative error than was observed for the electricity emission intensities, with more error when infrastructure is considered. The Electrolysis hydrogen pathway had the largest maximum error due to its much more significant use of electricity compared to SMR and biomass. However, the average absolute error of the electrolysis pathway was not significantly different than the biomass pathway; average pathway emission intensities with no infrastructure were 0.12%, 0.90%, and 0.18% for SMR, Biomass, and Electrolysis. Average pathway emission intensities with infrastructure were 0.12%, 0.56%, and 0.52% for SMR, Biomass, and Electrolysis.

Error Distribution of Total H2 Production Pathway Emission Intensities Using User-Defined Electricity Generation Fuel Mixes in Webtool

Error thru	No Infrastructure			With Infrastructure		
	SMR	Biomass	Electrolysis	SMR	Biomass	Electrolysis
-2.0%	0%	0%	0%	0%	0%	1%
-1.5%	0%	0%	0%	0%	0%	4%
-1.0%	0%	0%	0%	0%	1%	9%
-0.5%	0%	2%	1%	0%	7%	20%
0.0%	18%	18%	32%	38%	27%	36%
0.5%	82%	25%	65%	62%	29%	25%
1.0%	0%	23%	2%	0%	18%	0%
1.5%	0%	11%	0%	0%	13%	1%
2.0%	0%	4%	0%	0%	5%	3%
2.0%+	0%	17%	0%	0%	0%	0%