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Hydrogen Life-Cycle Analysis in Support of Clean Hydrogen Production

Energy Systems and Infrastructure Analysis Division

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by
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CONTENTS

LIST OF ACRONYMS V

ACKNOWLEDGMENTS VI

ABSTRACT 1

1 INTRODUCTION 1

2 H_2 PRODUCTION PATHWAYS 4
- 2.1 NG Supply Chain to H_2 Production Facility 4
- 2.2 SMR of NG 5
- 2.3 SMR of NG with CCS 6
- 2.4 SMR of RNG 6
- 2.5 Water Electrolysis 7
- 2.6 Chlor-alkali 8
- 2.7 NGL Steam Cracker Plants 8
- 2.8 Coal Gasification 9
- 2.9 Biomass Gasification 9

3 H_2 PACKAGING AND DELIVERY ACTIVITIES 10
- 3.1 H_2 Liquefaction 10
- 3.2 H_2 Delivery Including T&D Assumptions 10

4 RESULTS AND DISCUSSION 11

5 SUMMARY 14

6 REFERENCES 14

FIGURES

1 The well-to-wheel analysis encompasses both the upstream activities of primary energy recovery and processing, and the downstream activities of packaging, delivering, and dispensing H_2 into vehicles. 3

2 Well-to-gate GHG emission results for various energy sources and H_2 production technology pathways 12

TABLES

1 NG upstream noncombustion methane emissions using a bottom-up/top-down hybrid approach based on Alvarez et al. and Rutherford et al. 4

2 Shares and parameters of fuel use for the NG recovery process of conventional and unconventional gas in GREET 2022. 5

3 H_2 pressure at production gates 9

4 Effect of methane leakage rate on WTG GHG emissions 12

5 Comparison of GREET 2022 WTG CI results with Lewis et al. results 13

LIST OF ACRONYMS

C-A	chlor-alkali
CCS	carbon capture and storage
CH_4	methane
CI	carbon intensity
CO	carbon monoxide
CO_2	carbon dioxide
EPA	US Environmental Protection Agency
G&B	gathering & boosting
GH_2	gaseous hydrogen
GHG	greenhouse gas
GREET®	Greenhouse Gases, Regulated Emissions and Energy Use in Technologies
HRS	H_2 refueling stations
IPCC	Intergovernmental Panel on Climate Change
LH_2	liquid hydrogen
LHV	lower heating value
LWR	light water reactor
NG	natural gas
NGL	natural gas liquid
O_2	oxygen
PEM	proton exchange membrane
PSA	pressure swing adsorption
RNG	renewable natural gas
SMR	steam methane reforming
SOEC	solid oxide electrolysis cell
tpd	metric tons per day
WTG	well-to-gate

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HYDROGEN LIFE-CYCLE ANALYSIS IN SUPPORT OF CLEAN HYDROGEN PRODUCTION

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ABSTRACT

Hydrogen is a basic molecule commonly used in the production of chemicals and as an energy carrier or fuel. Its zero-carbon content means that it does not produce carbon dioxide upon its use. However, depending on the energy source and technology for hydrogen production and delivery, there can be greenhouse gas (GHG) emissions associated with hydrogen use. Clean energy sources and carbon management measures can be deployed to provide the largest reductions in GHG emissions from hydrogen production and use.

As concerns about climate change grow, research has increasingly focused on economic production of clean hydrogen to replace less climate-neutral sources of hydrogen. There are many different methods of producing hydrogen, each resulting in different levels of life-cycle GHG emissions. A comprehensive life-cycle accounting methodology that takes all factors into account is required for holistic pursuit of clean hydrogen production.

The GREET® (Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies) model was developed in 1995 by Argonne National Laboratory with support from the US Department of Energy and is regularly updated. GREET provides in-depth life-cycle simulations for a variety of energy and chemical products and is available as an Excel spreadsheet (GREET Excel) or an application (GREET.Net). Both versions are available for public download at no charge to users.

This report accompanies the GREET 2022 release. It describes the major updates and expansions to the hydrogen technology pathways in the model, and provides data sources and sample carbon intensity results for each of the hydrogen production pathways.

1 INTRODUCTION

Hydrogen (H_2) has been used in many applications, including hydrotreating and hydrocracking of petroleum products, ammonia production, and other distributed applications.[1] Recently, due to rising concerns with climate change, there has been increasing interest in deploying clean H_2 as a zero-carbon energy carrier to decarbonize applications across energy sectors. H_2 can be produced via a variety of technologies and energy feedstock sources, such as steam methane reforming (SMR) of natural gas (NG) or biogas, electrolysis of water, or biomass

gasification. H_2 is also produced as a by-product in C-A and NG liquid cracking processes. Depending on the energy source for H_2 production, packaging, and delivery, the carbon intensity (CI) of H_2 at different points in its value chain may vary greatly.

The recent Bipartisan Infrastructure Law and Inflation Reduction Act require and incentivize clean H_2 production and deployment for various end-use applications. These include H_2 use in fuel cell vehicles, oil refining, clean ammonia and methanol production, synthetic fuel production via pairing with carbon dioxide (CO_2) waste streams, steelmaking via direct reduction of iron, power generation, and industrial heat applications. The potential for H_2 blending with NG at various levels could allow for immediate offtake of large amounts of H_2 while decarbonizing the gas supply to its existing various end uses. Such a scenario would leverage the existing pipeline infrastructure and gas-fired equipment with substantial remaining service life. H_2 allows for long-duration energy storage, facilitating integration of large shares of variable renewable power generation into the regional and national grids.[2]

The Bipartisan Infrastructure Law calls for clean H_2 at the production facility with less than 2 kg CO_{2e}/kg H_2, while the Inflation Reduction Act specified four tiers for H_2 production tax credits depending on the well-to-gate (WTG) CI of clean H_2 production. The Inflation Reduction Act named Argonne's Greenhouse Gases, Regulated Emissions and Energy Use in Technologies (GREET®) model as the tool to evaluate the WTG CI of H_2 production throughout its energy supply chain. The H_2 pathways in GREET were developed with support from the EERE's Hydrogen and Fuel Cell Technologies Office. GREET is a publicly available LCA tool that evaluates the energy and environmental performance of advanced fuels, vehicle technologies, and energy systems.[3] GREET computes fossil fuel, petroleum, and total energy use; greenhouse gas (CO_2, CH_4, and N_2O) emissions; major criteria air pollutant emissions; and water consumption associated with various technology pathways. It is available for download and use both as an Excel spreadsheet, GREET Excel, and as a standalone application, GREET.Net.

GREET is an accurate and transparent tool with extensive data accumulated over more than 25 years to assess and compare greenhouse gas (GHG) emissions from various H_2 production technology pathways. This report presents the key parameters, data sources, and carbon accounting methodology used in GREET to calculate the CI of H_2 for the various technology pathways and energy supply chains, accounting for GHG emissions from primary energy source through to the production of H_2 molecules. Later sections of the report extend the system boundary to include H_2 packaging and delivery to various end-use applications.

The system boundary for life-cycle analysis defines the scope of GHG accounting for evaluating the CI of a product or service. We initially focus on the WTG system boundary because of its relevance to the Inflation Recovery Act's production tax credit for H_2. The WTG system boundary refers to all upstream activities for fuel and feedstock procurement plus the processes used to produce H_2. The well-to-wheel system boundary extends beyond WTG to include additional downstream operations, as shown in

Figure 1, which package, deliver, and dispense H_2 to a storage tank system onboard a vehicle. This report uses a functional unit of 1 kg of H_2 for WTG GHG accounting and for the calculation of the CI of H_2 production. Traditionally, GREET has been using energy functional units for different energy products, including H_2.

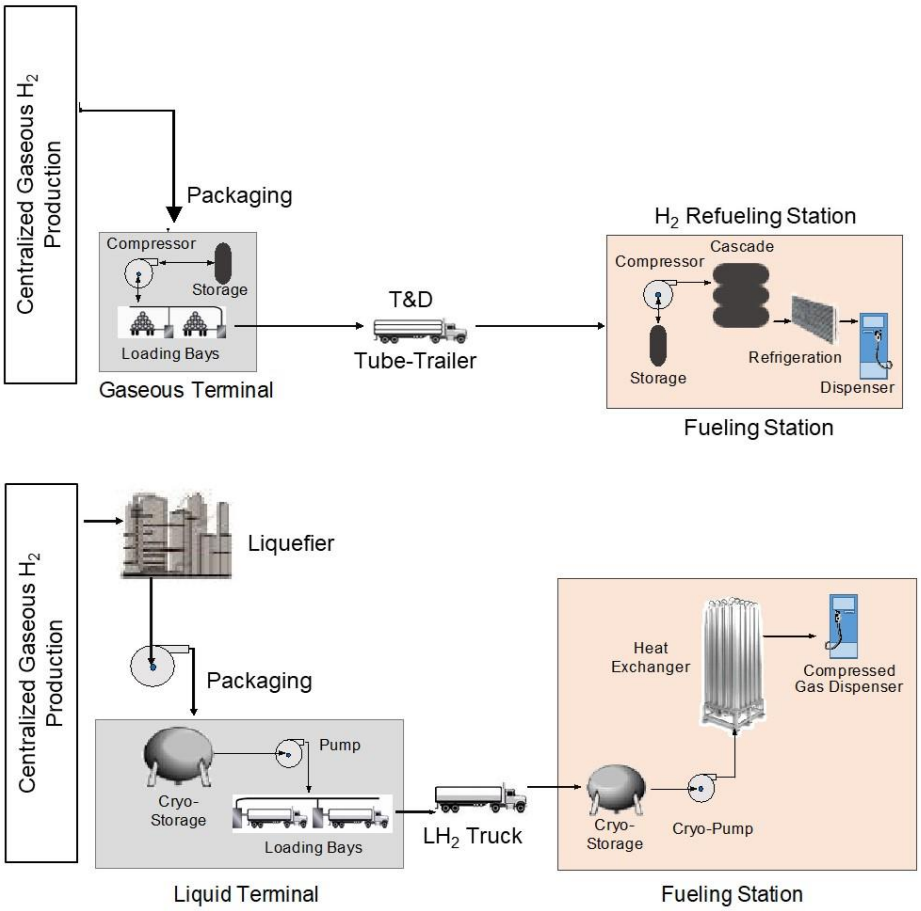

Figure 1. The well-to-wheel analysis encompasses both the upstream activities of primary energy recovery and processing, and the downstream activities of packaging, delivering, and dispensing H_2 into vehicles.

2 H_2 PRODUCTION PATHWAYS

In this section we provide details of energy supply sources and conversion technologies for various H_2 production pathways. The significant parameters impacting the WTG CI of H_2 are highlighted, along with the associated data sources.

2.1 NG Supply Chain to H_2 Production Facility

Because GHG emissions along the NG supply chain are not mitigated by CCS at the SMR facility, upstream burdens of the NG supply chain play a critical role in the WTG CI of the SMR pathway for H_2 production. Fugitive methane emissions and combustion CO_2 emissions occur with activities associated with NG recovery, processing, and transportation to the SMR plant.

Methane-related emissions can be measured using bottom-up field measurements and top-down measurements from aircraft, satellites, and weather stations.[4] The US Environmental Protection Agency (EPA) Greenhouse Gas Inventory utilizes bottom-up measurements. Some research suggests that the EPA inventory may undercount emissions.[4,5] GREET 2022 implements a hybrid bottom-up and top-down approach to estimate methane emissions throughout the NG supply chain.[6] We use the average NG transmission pipeline distance from the field to the end-use of 680 miles, which is based on national ton-miles of NG freight via pipeline as reported by the US Bureau of Transportation Statistics in 2009 (special tabulation, Table 1-50) and tons of dry NG production in the same year as reported by the Energy Information Agency.[7]

Table 1 gives the methane leakage values for various upstream process involved in the NG supply chain.[6]

Table 1. NG upstream noncombustion methane emissions using a bottom-up/top-down hybrid approach based on Alvarez et al. and Rutherford et al.[4,5]

	Default	
	Conventional	Shale
NG Stage	(g CH_4/MMBtu NG, LHV)	
Production	113.3	114.2
Completion	0.6	1.4
Workover	0.0	0.1
Liquid unloading	4.8	4.8
Well equipment	76.7	76.7
Gathering & boosting	31.2	31.2
Processing	6.0	6.0
Transmission & storage[a]	67.6	67.6
Distribution, venting & leakage	19.6	19.6
Total	206.6	207.4
Total methane leak rate as % of volume throughput	1.0%	1.0%

[a] For 680 miles

CO_2 emissions associated with NG recovery are from the production, and gathering & boosting (G&B) phases. These emissions are associated with the combustion of NG and diesel used for compression and other activities. The US national average fuel use for NG recovery was calculated using basin- and technology-level information from selected datasets of the National Energy Technology Laboratory's 2020 ONE Future report[8] using the weighted average of fuel

consumption (NG and diesel) and NG production data for all basins. The basins are divided by technologies (conventional, shale, and tight) and locations, with different fuel use estimates for each. GREET combines NG production and G&B into NG recovery. The fuel use data in Table 2 are provided for conventional and unconventional (shale and tight) technologies.

Table 2. Shares and parameters of fuel use for the NG recovery process of conventional and unconventional gas in GREET 2022.

	Conventional	Unconventional
Share of NG supply	25%	75%
NG Recovery		
Energy efficiency	96.4%	96.8%
Urban emission share	1.0%	1.0%
Shares of process fuels		
Diesel fuel	0.6%	0.2%
NG	99.4%	99.8%
Energy use: Btu/MMBtu of NG throughput		
Diesel fuel	215	66
NG: process fuel	37,209	33,285

2.2 SMR of NG

Many refineries find it advantageous to outsource H_2, steam, and power utilities in an "over the fence" relationship with an industrial partner.[9] The SMR H_2 production plant supplies refineries with H_2 and steam. Merchant H_2 may be distributed by pipeline to other customers in the region.

In SMR, methane in NG reacts with steam to produce a CO-H_2 synthetic gas (syngas). In the subsequent water-gas shift reaction, carbon monoxide (CO) in the syngas is reacted with steam to produce CO_2 and additional H_2. H_2 is then purified using a pressure swing absorption process (PSA), leaving a tail gas stream composed of residual H_2, CO, and CO_2. Direct CO_2 emissions arise during the NG reforming process and from NG and tail gas combustion (for process heat). Waste heat is used to preheat feed, combustion air, and boiler feed water, and to produce medium pressure, superheated steam for export.[9] In calculating the WTG CI of H_2 from the SMR process, a credit is calculated for exported steam, assuming emissions have been avoided from an NG boiler that would have been needed to produce the same amount and quality of SMR exported steam.

Previous versions of GREET computed SMR process CO_2 emissions as described in Sun et al.[10,11] These studies considered all US stand-alone SMR facilities as reported in EPA's National Emissions Inventory database and the Greenhouse Gas Reporting Program database. The previous GREET CO_2 results for SMR, derived from Bonaquist,[12] were found to be close to the median CO_2 from the Greenhouse Gas Reporting Program.[10]

The SMR GHG emissions in GREET 2022 have been updated using a recent National Energy Technology Laboratory report that provided mass and energy balance from SMR modeling.[13] Case 1 in Lewis et al. modeled a 480-ton-per-day SMR plant with steam export to populate SMR parameters in GREET 2022.[13] In general, NG consumption and on-site CO_2 emissions per unit of produced H_2 in an SMR facility vary with process design and configuration, operation conditions (e.g., steam to carbon ratio), feedstock property (e.g., NG composition, carbon content, and heating value), and other process design and control parameters, such as methane slip and the production of steam for export.[14]

2.3 SMR of NG with CCS

The Lewis et al. SMR study presented a case for SMR with CO_2 capture from conversion and combustion processes, and compression for CO_2 transportation and storage (case 2).[13] The modeled case assumed all by-product steam is used for the CO_2 capture process, and thus no steam is available for export. Slightly more NG was required compared with Case 1 (without CCS), and 96% of the CO_2 produced on-site was captured and delivered by pipeline for underground storage 62 km away in a deep saline formation (US Midwest). We used the Lewis 2022 SMR-CCS energy inventory to compute emissions in GREET 2022 for the SMR with CCS pathway.[13]

2.4 SMR of RNG

Renewable natural gas (RNG) can be produced from various organic waste streams by capturing methane from natural decomposition of waste biomass (e.g., landfill gas) or by converting wet waste into biogas via anaerobic digestion. Raw biogas, a mixture of CH_4 and CO_2 with water, sulfur, and other contaminants, must be upgraded by separation and purification to become pipeline-grade RNG, interchangeable with fossil NG. The default option for RNG in GREET is landfill gas (LFG), since most available RNG is from landfills.[15]

Waste feedstocks must be treated and disposed of. Thus, GHG emissions credits are taken for the avoided emissions in the "business as usual" treatment of waste (or the so-called counterfactual scenario). In the present work, we computed life-cycle emissions of LFG pathways using a carbon neutrality approach, in which CO_2 arises from biogenic carbon combustion is treated as zero emissions.[16,17] Credits were taken for the avoided methane emissions that would have occurred in the "business as usual" practice. Key considerations for the RNG supply chain include fossil energy use during RNG processing, fossil energy use for transportation operations, types of waste components, local climate conditions for methane generation, organic matter decay rates, waste collection strategy, land cover of landfill, and oxidation factors for organic matter.[18] Details of the RNG pathways are described in publications by Lee et al., Mintz et al., and Han et al.[18-23]

2.5 Water Electrolysis

H_2 can be produced from water electrolysis. The most important factor for the WTG CI of H_2 production via water electrolysis is the CI of the supplied power. The second most important factor is the electric energy used to produce a unit of H_2, which can be represented by electrolysis process energy efficiency. There are several electrolysis emerging technologies available today, with different maturity levels. The alkaline technology is the most mature, followed by the proton exchange membrane (PEM) technology, which is more energy efficient than alkaline. Solid oxide electrolysis cell (SOEC) technology is the most nascent, but the most efficient, technology.

GREET's default energy efficiency for PEM electrolyzer was taken from the DOE's Hydrogen and Fuel Cells Program Record (no. 19009).[24] The DOE Record defines efficiency as the lower heating value (LHV) of produced H_2 divided by the total electrical use, which was 60.1% (or 55.5 kWh/kg H_2) for the current state-of-the-art performance of PEM, and 65% (51.3 kWh/kg H_2) expected future performance for central H_2 production. For distributed applications, an efficiency of 59.7% (55.8 kWh/kg H_2) is considered for current state-of-the-art PEM technology, and 64.8% (51.4 kWh/kg H_2) for future PEM, assuming technology advancement. Central and distributed hydrogen production capacities were defined as 50,000 kg/day and 1,500 kg/day, respectively, in the DOE Record.

For the WTG system boundary, which excludes embodied emissions in electrolyzer manufacturing, all GHG emissions arise from power generation supplied to the electrolyzer, which is 0 for solar, wind, and hydroelectric power sources. These H_2 production scenarios via PEM electrolysis using renewable power sources are categorized as renewable PEM H_2. WTG CI of PEM electrolysis with conventional light water reactor (LWR) nuclear power includes GHG emissions related to the uranium supply chain activities, which includes mining, transportation, and enrichment.[25]

High-temperature SOECs are being developed to take advantage of higher energy efficiencies that arise at high temperatures. We used information from the DOE Hydrogen and Fuel Cells Program Record no. 20006[26], in which steam and electricity from an LWR are used to supply thermal and electric energy to the SOEC. Recent studies suggest that near-term implementations of nuclear SOEC for H_2 production would likely draw high-quality steam from the LWR steam manifold.[27] This is the same steam that would have expanded in the steam turbine to provide power. Therefore, we converted the SOEC thermal demand in the DOE Record to an equivalent electricity by assuming net steam cycle thermal efficiency of 33%. The converted thermal energy was added to the SOEC electrical power demand, resulting in a total electrolysis efficiency of 79% (LHV basis), or 42 kWh/kg H_2.

An option for credits for potential export of coproduced oxygen (O_2) is provided in GREET by considering that the coproduced O_2 will displace the O_2 produced in an air separation unit. The process data associated with O_2 production in an air separation unit are taken from Aspen modeling results.[28]

2.6 Chlor-alkali

Chlor-alkali (C-A) processes produce chlorine (Cl_2), sodium hydroxide (NaOH), and nearly pure H_2 electrochemically. Depending on technology employed and downstream process needs for other products, H_2 may be used for process heat, sold, or flared if not valorized. When H_2 is used for process heat, additional net H_2 can be obtained by substituting NG for the combusted H_2. We recently updated our C-A analysis[29] with current industrial C-A data. This work determined that almost all C-A H_2 is sold or flared, and there is no evidence of NG substitution for exported H_2. Therefore, we treat H_2, Cl_2, and NaOH as C-A co-products and allocate emissions among them on a mass basis. The mass yields of Cl_2, NaOH, and H_2 lead to allocation factors of 46%, 52%, and 1.3%, respectively. Emissions associated with H_2 compression to 20 bar is included in the WTG CI of by-product H_2 from C-A processes.

Existing C-A plants utilize a range of electrolysis technologies. The most common configuration utilizes a membrane cell, relies on grid power, and has no electricity or steam displacement credits. A less common configuration relies on combined heat and power generation to meet the thermal and electrical demands. We considered NG as a fuel for the combined heat and power plants. We developed an input energy dataset from which emissions were computed with GREET. Details of C-A processes and relevant data in GREET 2022 will be provided in a separate publication.

2.7 NGL Steam Cracker Plants

NG liquids (NGLs) are by-products of NG processing and are key feedstocks for production of light olefins in NGL steam cracker plants. H_2 is present with high concentrations in the cracking process tail gas, which is typically used as fuel by the plant furnaces. This H_2 can be recovered via PSA for export to the merchant market. In the US, current and planned NGL cracker plants can produce 3.5 million tonnes of H_2 per year by 2025, especially in the US Gulf Coast region.[30,31] Today, a portion of this by-product H_2 is purified and sold in merchant markets.

When H_2 is recovered from process tail gas for export markets, its lost heating value must be compensated for with an alternative source, such as NG. The GREET model accounts for energy use and emissions in NGL crackers that occur when the furnace fuel source changes to compensate for lost energy when H_2 is exported. For each kilogram of recovered and exported H_2, 120 MJ (LHV basis) needs to be provided by supplemental NG fuel. The GHG emissions burden of exporting 1 kg of H_2 includes the upstream emissions of procuring and transporting 120 MJ of NG to the cracker plant, plus the emissions from its on-site combustion, as well as the upstream burdens associated with electricity supply for the PSA purification process, which is assumed to be 0.5 kWh/kg H_2. More details are provided in Lee et al.[30]

2.8 Coal Gasification

H_2 may be produced via coal gasification. Cases 4 and 5 in Lewis et al.[13], which are coal gasification without CCS and coal gasification with CCS, were used to establish process energy input data for these pathways in GREET 2022. Based on Lewis et al., coal gasification w/o CCS has an overall energy efficiency (LHV basis) of 58.9%, with energy share of coal (as feedstock and process fuel) 99.1% and electricity the remaining 0.9%. Coal gasification with CCS has an overall energy efficiency (LHV basis) of 58.4%, with energy share of coal (as feedstock and process fuel) 98.2%, and electricity the remaining 1.8%, with a CO_2 capture rate of 92.5%. The electricity is considered to be sourced from the US average grid mix in GREET 2022. The process inventories in Cases 4 and 5 in Lewis et al. include H_2 product compression from 30 bar to 65 bar, while in GREET 2022 we exclude this compression electricity to be consistent with 20- bar H_2 product pressure for the WTG CI calculations. We do not include effect of 20- to 30-bar compression electricity, because it has insignificant impact on the WTG CI results. The effect of the small deviation of production gate pressure from 20 bar on the WTG CI results is insignificant, as shown in Table 3.

Table 3. H_2 pressure at production gates

Pathway[a]	Absolute Pressure (bar)	WTG effect[c] (kg CO_2e / kg H_2)
SMR, SMR-CCS	24	0.03
Coal gasification	30	0.07
Biomas gasification	26	0.04
All others	20	0

[a] SMR–steam methane reforming; CCS–carbon capture and storage.

[b] Assumed based on the pressure swing adsorption step.

[c] WTG effect refers to the slight overestimation of the carbon intensity arising when H_2 pressure exceeds 20 bar at the production gate. Computed based on electricity used during compression from 20 bar to the production gate pressure. Electricity used is assumed to be the US average grid mix.

2.9 Biomass Gasification

The H2A biomass (poplar) gasification model[32] was used as a proxy for gasification of various types of dry biomass. In that model, poplar is dried from 50 wt% to 12 wt% in a dryer fueled from the gasification by-product char. The biomass is gasified in steam and the resulting syngas is passed through a steam reformer followed by low- and high-temperature shift reactors. H_2 is recovered through PSA and the PSA tail gas fuels a steam power cycle that heats the process and generates power for on-site use. The energy efficiency of this process on an LHV basis is 44.2%, with 2.3% of total energy coming from NG, 0.6% from grid electricity, and the remaining 97.1% from biomass (as feedstock and process fuel).

The H2A biomass gasification model considers the H_2 product to be compressed from 26 bar to 70 bar. To be consistent with WTG CI of H_2 production at 20 bar from SMR and electrolysis pathways in GREET 2022, compression electricity from 26 bar to 70 bar is excluded. A further reduction of compression electricity from 20 bar to 26 bar has negligible effect on the WTG CI of H_2. The small impact of compression electricity on WTG CI results is shown in Table 3.

3 H_2 PACKAGING AND DELIVERY ACTIVITIES

All production pathways include cleanup and compression operations to deliver >99% pure H_2. SMR and electrolysis pathways produce H_2 near 20 bar at the plant boundary limits. Based on process model data in the cited references, several production methods produced H_2 above 20 bar, as shown in Table 3. Analyses with a WTG system boundary would, in principle, require corrections to a common pressure basis (e.g., 20 bar), but these corrections are insignificant, as mentioned earlier and shown in the Table 3. The underlying references do not always specify the outlet temperature, but once again the consequences in terms of WTG CO_2e intensity are negligible.

Compression computation details can be found in the Compression tab of GREET Excel. In summary, H_2 compression requires 0.71 kWh/kg H_2 for pipeline compressor, 1.90 kWh/kg H_2 for tube trailer loading, 1.87 kWh/kg H_2 for 70 MPa H_2 refueling stations (HRS), and 1.24 kWh/kg H_2 for 35 MPa HRS when the HRS is supplied by 500-bar tube trailers. These values differ when the HRS is supplied by pipeline. Pipeline transmission (e.g., for industrial use) requires approximately 0.92 kWh/tonne-km (4,590 BTU/ton-mile).

3.1 H_2 Liquefaction

Liquefaction energy intensity was defined through input from various gas industry experts to capture existing technology (liquid nitrogen precooling and Claude cycle liquefaction) as well as potential improvements from scale-up of existing technology. Although liquefiers as large as 60 metric tons per day (tpd) have been operated in the past,[33] our analysis assumes a specific energy consumption of 11 kWh/kg liquid H_2 (LH_2), which is representative of a 30-tpd liquefier built with existing technology. Since they are not proven, GREET does not consider potential future high-efficiency liquefiers that may achieve 6 kWh/kg LH_2 at the 50-tpd scale.[34]

3.2 H_2 Delivery Including T&D Assumptions

We examined scenarios in which H_2 is delivered by gaseous H_2 (GH_2) or LH_2 trucks over a total one-way distance of 161 km (100 mi). In GH_2 scenarios, a bulk loading terminal is co-located at the H_2 production site. Grid power is required for compression. In LH_2 scenarios, a liquefier is co-located at the H_2 production site.

In nuclear power scenarios, the GH_2 terminal and liquefier are assumed to use nuclear power, not the regional grid mix. For renewable power, although the GH_2 terminal and liquefier are located at the generation site, the situation is more complicated because renewable power is not always available, yet the liquefier is assumed to require uninterrupted power to maintain cryogenic temperatures and the GH_2 loading terminal is assumed to require power to load trailers from stored H_2. Therefore, we considered electric power for liquefaction and GH_2 terminal to be entirely grid-powered even when renewable solar or wind electricity is used for H_2 production via water electrolysis. Electric power for liquefaction and GH_2 terminal is assumed to be hydroelectric when the renewable electricity source for water electrolysis is from hydropower.

Additionally, in GREET 2022 there are no H_2 losses considered in the T&D or at H_2 refueling station HRS for GH_2. However, for LH_2 we assume 0.5% loss at liquefaction plant, 0.3% at LH_2 bulk terminal, 5% loss of unloaded amount at refueling station, and 4 kg loss per day per cryopump at HRS. More details are provided in Frank et al.[35] It worth noting that in GREET 2022, we did not incorporate a global warming potential for fugitive hydrogen emissions. This is planned for future releases of GREET.

4 RESULTS AND DISCUSSION

WTG GHG emissions for H_2 production using various technology pathways are shown in **Error! Reference source not found.**. Renewable electrolysis, RNG SMR, NG SMR with CCS, by-product H_2 from the C-A process, biomass gasification, and coal gasification with CCS pathways show substantial reductions in GHG emissions relative to conventional SMR. For the shown pathways, WTG GHG emissions have no dependence or weak dependence on the regional power mix, except for C-A by-product H_2.

Upstream emissions add approximately 20% to the on-site emissions for H_2 production from SMR and NGL. Most of the emissions from NG SMR with CCS are attributed to upstream emissions in the NG supply chain. In absolute terms, upstream GHG emissions dominate the total WTG emissions for SMR-CCS, all electrolysis pathways, C-A, and biomass gasification.

Sensitivities of pathways to NG (upstream) methane leakage rates were evaluated between 1.0% (nominal) and 2.0% (high). The net effect on WTG results (Table 4) was 0.8 kg CO_2e/kg H_2 for SMR, 1.1 kg CO_2e/kg H_2 for SMR-CCS, and 0.7 kg CO_2e/kg H_2 for NGL by-product H_2. Coal and biomass gasification, although thermal processes, are fueled with their respective feedstocks, not NG, and therefore were insensitive to the upstream NG methane leakage rate. C-A is powered with electricity, which is sensitive to NG upstream emissions, but the net C-A H_2 emissions were low after allocation of emissions burdens among all co-products, and are thus insensitive to the uncertainties in the NG upstream emissions. Similarly, the electrolysis pathways (SOEC and PEM) considered in this study are powered by either nuclear or renewable electricity, both of which do not depend on the upstream NG emissions.

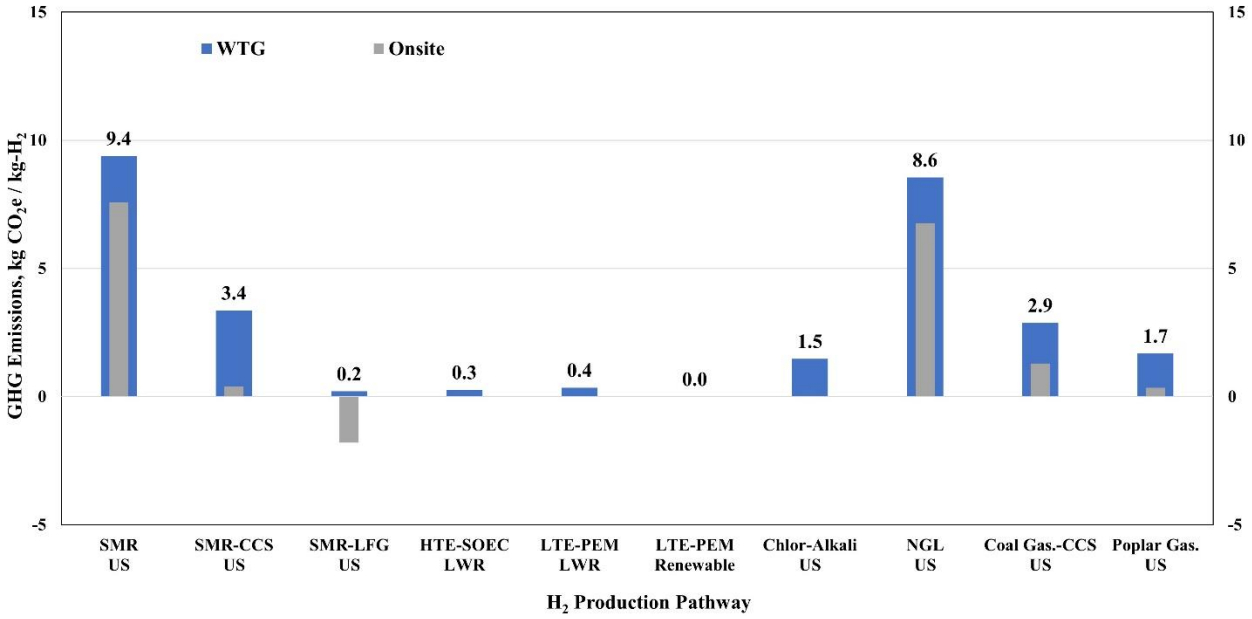

Figure 2. Well-to-gate GHG emission results for various energy sources and H_2 production technology pathways[*]

Table 4. Effect of methane leakage rate on WTG GHG emissions

	WTG Emissions (kg CO_2e / kg H_2)		
Pathway[a]	Nominal[b]	High[c]	
SMR	9.4	10.2	(0.8)
SMR-CCS	3.4	4.5	(1.1)
NGL	8.6	9.3	(0.7)
Coal gasification-CCS	2.9	2.9	(0.0)
C-A	1.5	1.5	(0.0)
Biomass gasification	1.7	1.7	(0.0)

[a] SMR–steam methane reforming; CCS–carbon capture and storage; NGL–natural gas liquid; C-A–chlor-alkali. US average electricity grid generation mix is assumed for all shown pathways.

[b] Nominal refers to 1% CH_4 fugitive emissions along NG supply chain (GREET 2022 default).

[c] High refers to 2% CH_4 fugitive emissions along NG supply chain.

[*] WTG–well-to-gate; GHG–greenhouse gas; SMR–steam methane reforming; CCS–carbon capture and storage; LFG–landfill gas; HTE-SOEC–high-temperature electrolysis-solid oxide electrolyzer cell; LTE-PEM–low-temperature electrolysis-polymer electrolyte membrane; NGL–natural gas liquid.

GREET SMR and SMR-CCS WTG GHG emissions differ from those in Lewis et al.[13], despite using the same inventory data (Table 5). The difference arises largely because of the differences in the NG upstream supply chain GHG emissions. Other differences are related to the CI of the US average electricity grid generation mix and the incorporation of H_2 compression for pipeline transport in Lewis et al.[13] Also, GREET 2022 incorporates the latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 (AR6) global warming potential for fossil and biogenic methane, while Lewis et al. uses GWPs from IPCC AR5 with atmospheric feedback, which, for methane, corresponds to 30 and 36, respectively. GREET 2022 NG upstream GHG emissions are 13 g CO_2e/MJ NG, while Lewis et al. 2022 reported 19.9 g CO_2e/MJ NG, based on Littlefield et al.[36] The NG upstream GHG emissions burden comprises contributions from methane leakage and NG combustion. GREET 2022 methane leakage rate (median US) is 1.0%, while the Lewis et al. estimate was 1.2%, as reported in Littlefield.[36] Also, the National Energy Technology Laboratory reported higher values for NG gathering and boosting and for transmission. Lewis et al.[13] used 2016 US grid mix CI for electricity use, while GREET CI results are based on the more recent 2021 US grid mix CI. As can be seen, the WTG CI of H_2 production via SMR-CCS strongly depends on NG and electricity upstream emissions, and thus SMR-CCS CI must be carefully evaluated.

Table 5. Comparison of GREET 2022 WTG CI results with Lewis et al.[13] results

	GHG Emissions (kg CO_2e / kg H_2)					
	SMR[a]	On-site	Upstream	SMR-CCS[b]	On-site	Upstream
GREET 2022	9.4	7.6	1.8	3.4	0.4	3.0
Lewis 2022[13]	10	7.1	3.1	4.6	0.4	4.2

[a] SMR includes steam displacement credits.

[b] Specific upstream emissions for SMR-CCS exceed those of regular SMR because of increased NG consumption (heat required for CO_2 capture) and increased electricity use (CO_2 compression and capture).

LFG collection and upgrading produced 11 g CO_2e/MJ LFG, to which a credit of 1.2 g CO_2e/MJ LFG was applied for avoided methane emissions that would have been emitted in the business-as-usual landfill practices. However, this credit is relatively small and not a key driver for the LFG H_2 pathway CI results. Within the system boundary of the SMR process, since the LFG burden is almost entirely biogenic carbon, emissions were only 0.4 kg CO_2e/kg H_2. A credit of 2.2 kg CO_2e/kg H_2 was applied for exported steam, leading to net negative on-site emissions of -1.8 kg CO_2e/kg H_2. In total, WTG GHG emissions for SMR of LFG are 0.2 kg CO_2e/kg H_2.

We used the average US NG T&D distance of 680 miles to compute T&D of the LFG to SMR plants. Note that, in the US, upgraded LFG is often virtually traded in lieu of NG use. Certain US regulations allow NG consumers to buy credits for RNG produced elsewhere (the book and claim approach). The RNG itself may not be literally transported to the H_2 producer.

The difference in WTG GHG emissions between 100 miles of T&D vs. 680 miles is < 0.3 kg CO_2e/kg H_2. This is large compared with the WTG emissions (0.2 kg CO_2e/kg H_2), but is small compared with a typical reference scenario, such as SMR of NG. Therefore, T&D of LFG was not explored further.

5 SUMMARY

H_2 pathways in GREET 2022 are updated and expanded to provide WTG CIs of H_2 derived from various energy sources and production technologies using most recently available data sources. Data sources, LCA system boundaries, and carbon accounting methodology are documented in this report. This report is intended to serve as a live document that may be periodically updated and expanded to reflect new development in H_2 production technologies and newly available data.

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