DOE Hydrogen and Fuel Cells Program Record	
Record #: 16001	**Date:** January 8, 2016
Title: Well-to-Wheels Greenhouse Gas Emissions for Methanol to Hydrogen Pathways	
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The methanol → hydrogen → fuel cell vehicle and direct methanol fuel cell vehicle pathways are estimated to have 30 to 35% less greenhouse gas (GHG) emissions as compared to today's gasoline internal combustion engine vehicle. In comparison, the natural gas → hydrogen → fuel cell vehicle pathways have 45 to 50% less GHG emissions as compared to today's gasoline internal combustion engine vehicle.

The Department of Energy's (DOE) Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy and Argonne National Laboratory evaluated the well-to-wheels (WTW) GHG emissions for several natural gas pathways to produce alternatives to petroleum fuels for use in light-duty vehicles. This record documents the assumptions and results for GHG emissions associated with the production of hydrogen (H_2) from natural gas for use in mid-size light-duty vehicles. Three pathways were considered for hydrogen and methanol production from natural gas for use in fuel cell vehicles:

(1) Steam methane reforming (SMR) of natural gas at central locations (with pipeline delivery) or at distributed facilities (i.e., at refueling sites) to produce hydrogen for dispensing into a fuel cell electric vehicle (FCEV).

(2) Conversion of natural gas to methanol (MeOH) at central facilities followed by the distribution of methanol to refueling sites where methanol is reformed to produce hydrogen that is dispensed into a FCEV.

(3) Synthesis of natural gas to MeOH at central facilities followed by the distribution of methanol to refueling sites where methanol is dispensed into a direct methanol fuel cell (DMFC) vehicle. The advantage of the second and third options is the relative ease of transporting and distributing methanol due to its higher volumetric energy density compared to hydrogen gas.

Rationale:

The analysis was carried out by expanding and modifying the 2014 version of the GREET^{TM} (**G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation) model [1]. Figure 1 compares the GHG emissions associated with the production and use of hydrogen in FCEVs and of MeOH in DMFC vehicles to the GHG emissions associated with the production and use of petroleum gasoline and compressed natural gas (CNG) in internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs). Figure 1 also shows a renewable pathway for hydrogen production via electrolysis using electricity generated from wind power. The GHG emissions associated with that pathway are due to compression energy for pipeline delivery and dispensing at refueling stations using U.S. average generation mix. Note that gasoline is a mix of 10% corn-based ethanol and 90% gasoline blendstock by volume (also known as E10). Figure 1 shows two main stages for the WTW GHG emissions: well-to-pump (WTP) and pump-to-wheels (PTW). The WTW GHG emissions combine CO_2, CH_4, and N_2O emissions with their global warming potential [2] into grams of equivalent CO_2 per mile of vehicle travel (gCO_{2e}/mile).

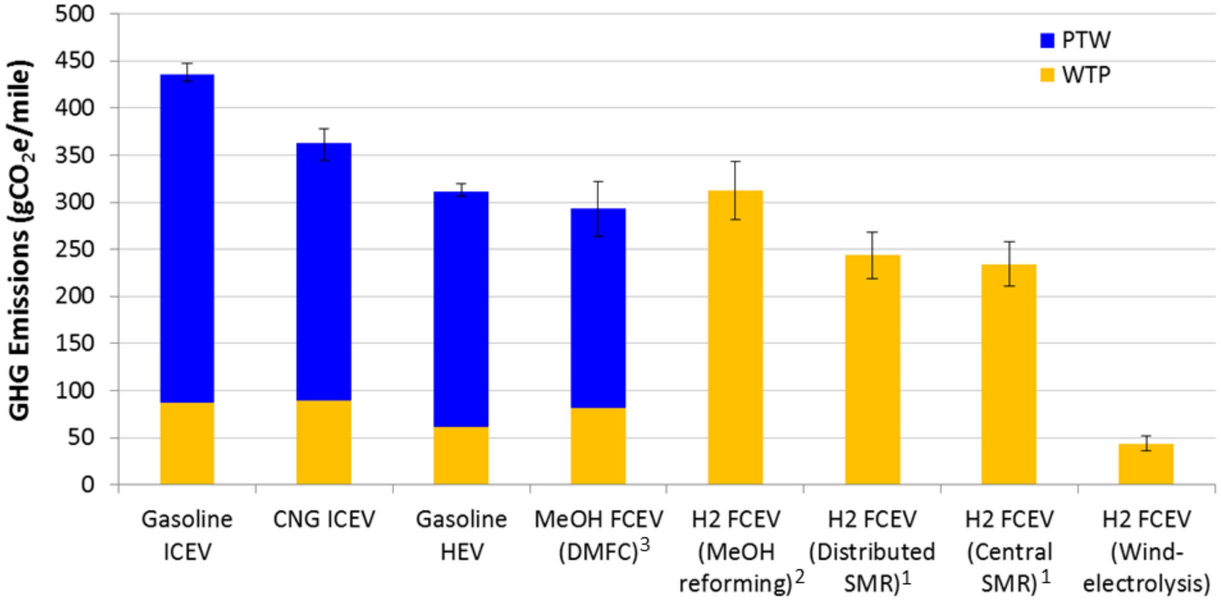

Figure 1. WTW GHG emissions of H2 FCEV pathways compared to gasoline and CNG ICEV pathways (superscripts in labels refer to pathway numbers noted above)

Key Assumptions for Alternative Fuel Pathways and Vehicle Technologies:

The key parametric assumptions and their technical variability for the individual fuel production pathways are summarized in Table 1, while the key assumptions for various vehicle technologies are summarized in Table 2. Fuel economy assumptions on EPA's urban and highway drive cycles for advanced vehicle technologies are the result of a discussion with vehicle manufacturers and input from DOE's Vehicle Technologies Office. Since EPA's urban and highway drive cycles do not account for more aggressive and higher speed driving in the real world, or the use of accessories (e.g., air conditioning), the fuel economy from the drive cycles was adjusted to estimate "on-road" real world fuel economy using EPA formulas and methodology [3, 4] as explained in Elgowainy et al. [5]. The 25 miles per gallon (mpg) fuel economy of baseline gasoline ICEV represents model year 2010 of midsize class cars [14]. Fuel economy estimates for gasoline HEV and CNG ICEV are based on fuel economy ratios relative to the baseline gasoline ICEV as provided by Joseck and Ward (see Table 2) [15]. Fuel economy for MeOH FCEV (DMFC) is assumed to be 2/3 of that for H_2 FCEV (based on the ratio of their peak fuel cell efficiencies, i.e., 0.4/0.6).

This record was reviewed by Todd Ramsden from the National Renewable Energy Laboratory, Dr. George D. Parks from FuelScience LLC, and Sanjiv Malhotra from SRA International.

Table 1. Key assumptions for processes in fuel production pathways[1]

Pathway	**Key Parameters**	**Assumption (and distribution type and definition when applicable)**	**Data Sources and Comments**
Petroleum gasoline (blend of 90% gasoline blendstock and 10% corn ethanol by volume)	Conventional crude - recovery efficiency	98%, Triangular (Mean: 98%, p10: 97%, p90: 99%)	Brinkman et al. [6]
	Refining efficiency for gasoline and diesel	88.6%, Normal (mean: 88.6%, p10: 86.9%, p90: 90.3%)	Elgowainy et al. [7]
	Lower heating values of crude oil (Btu/gal)	129,670, Triangular (Min: 129,000, Likeliest: 129,670, Max: 130,000)	Brinkman et al. [6]
	Lower heating values of conventional gasoline (Btu/gal)	116,090, Triangular (Min: 108,000, Likeliest: 116,090, Max: 123,500)	Brinkman et al. [6]
	Lower heating values of low sulfur diesel (Btu/gal)	129,490, Triangular (Min: 121,030, Likeliest: 129,490, Max: 141,740)	Brinkman et al. [6]
North American natural gas	Share of shale gas in total natural gas supply in the U.S.	37%	EIA AEO 2013 [8]
	North American conventional natural gas recovery efficiency	95.7%, Normal (Mean: 95.7%, SD: 1.8%)	Burnham et al. [9]
	North American shale gas recovery efficiency	96.5%, Normal (Mean: 96.5%, SD: 1.8%)	Burnham et al. [9]
	North American conventional and shale gas processing efficiency	97.2%, Normal (Mean: 97.2%, SD: 1.8%)	Burnham et al. [9]
	NG compression efficiency at refueling station: electric compressor	97.9%, Triangular (Min: 96.9%, Likeliest: 97.9%, Max: 98.9%)	GREET [1]
Methanol	Conversion efficiency of natural gas to methanol	67% Triangular (Min: 64.9%, Likeliest: 67%, Max: 69.1%)[2]	Brinkman et al. [6]
Hydrogen production from SMR of natural gas	Central plant H_2 production efficiency	72%	H2A Central Natural Gas Production Model [10]
	Gaseous H_2 compression efficiency	91.5%, Triangular (Min: 90.8%, Likeliest: 91.5%, Max: 93.3%)	Hydrogen Delivery Scenario Analysis Model (HDSAM), version 2.3 [11]
	Distributed H_2 production efficiency	71.4%	H2A Distributed Natural Gas Production Model [12]

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[1] Efficiency values are based on lower heating value (LHV) of inputs and outputs

[2] Similar to efficiency values in Bromberg and Cheng [13] when adjusted on a LHV basis (low: 62%, med: 67%, high: 70%)

Table 2. Key fuel economy assumptions for mid-size light-duty vehicle technologies

Vehicle Technology	**Fuel Economy** (Adjusted from urban and highway test cycles to on-road performance)
Baseline gasoline ICEV [miles per gallon or MPG]	25 MPG [14], Weibull distribution* (p10: 23.5, p90: 26.8)
Gasoline HEV [miles per gallon or MPG]	35 MPG**
Fuel economy for CNG and H2 fuel cell vehicles in miles per gasoline-gallon equivalent (MPGGE)	
CNG ICEV	25 MPGGE[¥]
H_2 FCEV	57 MPGGE[§], Triangular distribution (min: 52, max: 68)
MeOH FCEV	38 MPGGE[Ŧ], Triangular distribution (min: 35, max: 45)

*Distribution function for baseline gasoline ICEV fuel economy is scaled from previous DOE Record [15]

**Fuel economy ratio of 141% for gasoline HEV relative to gasoline ICEV is from previous DOE Record [15]

[¥] Fuel economy ratio of 100% for CNG ICEV relative to gasoline ICEV is from previous DOE Record [15]

[§] Low end of fuel economy for H_2 FCEV is from early market demonstrations, and high-end is from Wipke et al. [16]

[Ŧ] Fuel economy ratio for MeOH FCEV relative to H2 FCEV is assumed to equal the ratio of their peak fuel cell efficiencies of 40% and 60%, respectively.

References:

[1] Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, GREET, 2014, Argonne National Laboratory, http://greet.es.anl.gov/

[2] IPCC, Climate Change 2013: The Fifth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.climatechange2013.org/report/full-report/

[3] EPA, 2008, “Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2008,” EPA420-R-08-015, U.S. EPA Office of Transportation and Air Quality, Washington, D.C.

[4] EPA, 2006, “Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates,” EPA420-R-06-017, U.S. EPA Office of Transportation and Air Quality, Washington, D.C.

[5] Elgowainy, et al., 2010, Well-To-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles, Center for Transportation Research, Argonne National Laboratory, https://greet.es.anl.gov/publication-xkdaqgyk

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[7] Elgowainy, A, Han, J, Cai, H, Wang, M, Forman, G and DiVita, V, 2014. Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries, Environmental Science & Technology, 48 (13), 7612-7624.

[8] Energy Information Administration, 2013, Annual Energy Outlook 2013, April 2013, DOE/EIA-0383(2013), U.S. Department of Energy, Washington, D.C.

[9] Burnham, A, Han, J, Clark, C, Wang, M, Dunn, J, Palou-Rivera, I, 2011. Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal and Petroleum. Environmental Science & Technology, 46(2):619-27.

[10] Hydrogen Analysis (H2A) Central Natural Gas Production Model, Case Studies, EERE/DOE, http://www.hydrogen.energy.gov/h2a_prod_studies.html

[11] Hydrogen Delivery Scenario Analysis Model, HDSAM, EERE/DOE, http://www.hydrogen.energy.gov/h2a_delivery.html

[12] Hydrogen Analysis (H2A) Distributed Natural Gas Production Model, Case Studies, EERE/DOE, http://www.hydrogen.energy.gov/h2a_prod_studies.html

[13] Bromberg, L and Cheng, WK, 2010. "Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation," MIT Report PSFC/JA-10-49, http://www.methanol.org/Energy/Resources/Alternative-Fuel/MIT-Methanol-Report-Final-Nov-2010.aspx

[14] EPA, 2014. "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014," EPA-420-R -14-023, U.S. EPA Office of Transportation and Air Quality, Washington, D.C.

[15] U.S. DOE (Department of Energy) Hydrogen and Fuel Cells Program Record, 2014. "Cradle to Grave Lifecycle Analysis of Vehicle and Fuel Pathways," Record# 14006, http://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

[16] Wipke K, Anton D, Sprik S, 2009. "Evaluation of Range Estimates for Toyota FCHV-adv under Open Road Driving Conditions," Technical Report SRNS-STI-2009-00446. Aiken, SC: Savannah River Nuclear Solutions.