DOE Hydrogen and Fuel Cells Program Record	
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Title: GHG Emissions and Petroleum Use Reduction from Fuel Cell Deployments	
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Item

Fuel cell deployments in the United States through 2015 resulted in the reduction of 1.5 million metric tons of greenhouse gas (GHG) emissions and a savings of 19,000 barrels (0.80 million gallons) of petroleum.

Description

This analysis estimates the deployed numbers of fuel cell electric vehicles, buses, lift trucks, and stationary power in the U.S. through 2015 and the corresponding reduction in petroleum consumption and greenhouse gas emissions relative to the dominant conventional technologies, namely gasoline cars, diesel buses, battery lift trucks, and buildings' consumption of grid power and natural gas for thermal needs.

Summary

Table 1 summarizes the deployments and energy/environmental benefits for the years 2001–2015. Fuel cells have helped to reduce over 1.5 million tonnes (metric tons) of GHGs in the U.S. (cumulative).

Table 1: U.S. fuel cell deployments and cumulative environmental benefits through 2015

Fuel Cell Application	# in Operation/ Installed Capacity	Petroleum Reduction	GHGs Reduction
		(thousands of bbls)	(metric tons)
Cars	179 (primary source: California Air Resources Board)	4.9	830
Buses	19 (primary source: National Renewable Energy Laboratory)	14	1,200
Lift Trucks	~10,000 (primary sources: Fuel Cell & Hydrogen Energy Association (FCHEA), industry press releases)	Negligible	8,700
Stationary Power*	253 MWe (source: FCHEA)	Negligible	1,519,000
TOTAL	(with rounding)	**19**	**~1,530,000**

*Excludes fuel cells for backup power; petroleum and GHGs intensities from GREET 2015 model (ANL 2015).

Assumptions and data sources are discussed next.

Fuel Cell Cars

Sources for the number of fuel cell electric vehicles (FCEVs) deployed per year include California Air Resources Board 2014, 2015, and 2016; http://hondanews.com/releases/honda-and-city-of-los-angeles-celebrate-two-year-anniversary-of-hydrogen-fuel-cell-vehicles?l=en-US&mode=print, http://www.usatoday.com/story/money/columnist/healey/2013/07/27/honda-fcx-clarity-fuel-cell/2587581/, http://www.autoblog.com/2010/11/22/mercedes-benz-prices-b-class-f-cell-lease-at-849-a-month/, and http://automobiles.honda.com/fcx-clarity/fuel-cell-evolution.aspx.

Each FCEV is assumed to displace a midsize car on E10 (10% ethanol by volume in gasoline). The well-to-wheels (WTW) emissions and oil consumption per energy unit are shown in Table 2. Each vehicle is assumed to be driven 11,000 miles per year, a conservative number for benefits estimation purposes that is less than the 13,200 miles average annual mileage for a new vehicle reported in Davis et al. 2015.

Table 2: Well-to-wheels GHG emission and petroleum intensities of fuels (GREET model)

	GHG (g/kBtu)	Oil (Btu/kBtu)
E10	95	1,012
Hydrogen (California)	116	86.4

Since initial FCEV deployment occurs in California with mostly hydrogen from steam methane reforming at central plants, GREET was run for steam methane reforming with gaseous hydrogen truck delivery to retail fueling, with California grid electricity assumed for those compression, storage, and dispensing steps that require electricity. California Law SB 1505 requires hydrogen for FCEVs to be made from at least 33% renewable energy sources—mandatory for state-funded fueling stations; this would apply to 100% privately funded stations as soon as 3.5 million kg of hydrogen are sold in the state (California Air Resources Board 2015). However, to be conservative, hydrogen used in past years was assumed to have no renewable content.

Table 3: Annual benefits of FCEVs

Year	FCEVs Deployed	FCEV Stock	New Gasol ICE mpgge*	New FCEV mpgge*	GHG Savings (mtr. tons)	Oil Savings (thousands of bbls)
2003	4	4	28	50	5.4	0.03
2004	6	10	28	50	13.4	0.08
2005	5	15	28	50	20.1	0.12
2006	9	24	28	50	32.2	0.19
2007	2	26	28	50	34.8	0.21
2008	(4)**	22	28	50	29.5	0.17
2009	3	25	28	50	33.5	0.20
2010	0	25	28	50	33.5	0.20
2011	9	34	28	50	45.5	0.27
2012	19	53	28	50	71	0.42
2013	22	75	28	50	100	0.59
2014	50	121	28	50	167	1.0
2015	54	179	29	53	241	1.4
Cumul. Benefits					**830**	**4.9**

* A conservative average fuel economy estimate was used for all years until 2015.

**Negative deployment means retirement exceeded deployment, resulting in a decrease in stock. Also, for deployments occurring late in each year, they were counted in the following year to be conservative.

Although not all FCEVs on the road are as large as the FCEV version of the Hyundai Tucson (small SUV), the Tucson FCEV's fuel economy of 50 miles per gasoline gallon equivalent (mpgge) is assumed for all FCEVs through 2014, and a slightly higher 53 mpgge—with the Mirai and Tucson FCEVs deployed together—was assumed for 2015 in order to be conservative. Actual petroleum and GHG emissions reduction can be significantly higher for FCEVs because the EPA rated the Mirai at 66 mpgge. The displaced gasoline vehicle's fuel economy is assumed at 28 mpg through 2014, nearly the same as the 2015 4-cylinder Honda Accord and higher than the 23 mpg estimate for the 2015 gasoline Tucson, to be conservative in estimating FCEV benefits. For 2015, the average gasoline vehicle was assumed to achieve 29 mpg.

Fuel Cell Buses

The benefits of fuel cell (FC) buses depend on the hydrogen production method and the fuel economy of the displaced diesel buses. Table 4 shows the oil and GHG emissions intensities used, based on the GREET model, and Table 5 shows the annual deployments and calculated benefits.

Table 4: Well-to-wheels GHGs emission and petroleum intensities of diesel and hydrogen for buses (GREET model)

	GHG (g/kBtu)	Oil (Btu/kBtu)
Diesel	96	1,053
Hydrogen (U.S.)	126	92.7

Since FC bus demonstrations occur in several states with hydrogen from steam methane reforming at central plants, GREET was run for steam methane reforming with gaseous hydrogen truck delivery to retail fueling, with average U.S. grid electricity assumed for those compression, storage, and dispensing steps that require electricity.

Other assumptions:

- FC buses are assumed to be driven 23,000 miles per year based on a wide range of actual mileage statistics collected through the technology validation projects performed by the National Renewable Energy Laboratory (NREL) for the Federal Transit Authority's fuel cell bus demonstration program (http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html).
- Average fuel economy estimates for fuel cell buses and diesel buses are derived from the same NREL sources. For simplicity, a single, average annual fuel economy was assumed for each type of bus through 2015, based on the average of four projects (at three transit agencies) for FC buses in NREL's 2014 evaluation report. The weighted average fuel economy of FC buses was 5.6 mi/kg (or mpgge), with the average FC bus being ~1.5 times more efficient than the average diesel bus).[1]

Table 5: **Annual benefits of FC buses in Federal Transit Administration demonstration projects**

Year	FC Buses Deployed	FC Bus Stock	New Diesel Bus mpgge	New FC Bus mpgge	GHG Savings (metric tons)	Oil Savings (thousands of bbls)
2004	1	1	3.6	5.6	10.9	0.13
2005	2	3	3.6	5.6	33	0.40
2006	3	6	3.6	5.6	66	0.80
2007	1	7	3.6	5.6	76.5	0.93
2008	(3)	4	3.6	5.6	43.7	0.53
2009	(2)	2	3.6	5.6	21.9	0.27
2010	3	5	3.6	5.6	54.6	0.66
2011	7	12	3.6	5.6	131.1	1.59
2012	3	15	3.6	5.6	164	1.99
2013	1	16	3.6	5.6	174.8	2.13
2014	2	18	3.6	5.6	196.7	2.39
2015	1	19	3.6	5.6	208	2.52
Cumul. Benefits					**1,180**	**14.4**

*Negative deployment means retirement exceeded deployment, resulting in a decrease in stock.

<u>Lift trucks</u>

Fuel cell lift trucks (FC lift trucks) are assumed to displace battery lift trucks. The GREET model's GHG emission and petroleum use intensities are listed in Table 6. Operating assumptions for lift trucks are

[1] The fuel economy averages of the four bus platforms were 6.4, 3.8, 5.7, and 6.2 mpgge in NREL's 2014 evaluation report at http://www.nrel.gov/docs/fy15osti/62683.pdf.

listed in Table 7. The annual energy consumed in a given year is estimated by multiplying the number of FC lift trucks by the consumption in kWh per lift truck (based on 6.5 kW power assumed at the fork).

Since initial FC lift trucks deployment occurs in several states with hydrogen from steam methane reforming at central plants, GREET was run for steam methane reforming with gaseous hydrogen truck delivery to retail fueling, with average U.S. grid electricity assumed for those compression, storage, and dispensing steps that require electricity.

Table 6: Well-to-wheels GHGs emission and petroleum intensities of lift trucks (GREET model)

	GHG (g/kBtu)	Oil (kBtu/kBtu)
US Electricity	179	40.0
Hydrogen (U.S.)	126	92.7

The power of FC lift trucks was assumed at 6.5 kW at the fork (6.5 kW is the average of 3 kW and 10 kW system sizes based on Ramsden 2013, which indicates that fuel cells for Class I/II units are 8–10 kW and those for Class III units are 3 kW or less). Enersys, a company focusing on helping customers switch to battery lift trucks, estimated <5 kW for units handling less than 5,000 lbs, 5.5 kW for 5,000–<7,000 lbs, 6.5 kW for 7,000–<8,000 lbs, and 10 kW up to 12,000 lbs (Enersys 2016). Most battery lift trucks are used for 3,000–6,000 lb loads (Gaines et al. 2008). However, it appears prudent to buy somewhat oversized units that can handle occasionally larger loads, and this analysis assumed 6.5 kW for average power.

Table 7: Other assumptions used in FC lift truck benefits calculations

Value	Units
6.5	Power (kW) at the fork
1.5	Shifts per day (this assumption and those in the 3 rows that follow result in 2,360 hours/year, close to the 2,400 hours assumed in Ramsden 2013)
7	Hours per shift
225	Days worked per year
15,350	Calculated energy consumed per year (kWh) for a 6.5 kW lift truck
25%*	Charger & battery losses (efficiency is 75%)—battery lift truck
10%*	Motor losses (efficiency is 90%)—battery & FC lift trucks
10%*	Transmission & drive line losses (efficiency is 90%)—battery & FC lift trucks
54%*	Fuel cell efficiency (46% losses)—FC lift truck

*For efficiency of charger, batteries, and fuel cell, used average of values from NRC 2013 and Gaines et al. 2008 (Argonne National Laboratory report). For efficiency of motors, transmission, and drive line, the ANL report lacked details: used values from NRC spreadsheet for battery and fuel cell cars downloaded from website of NRC 2013 transition study.

From Table 7, the system efficiencies of battery and FC lift trucks are assumed to be: (a) 60.8% (combination of losses from charging, battery, motors, transmission, and drive line), and, (b) 43.7% (combination of losses from the fuel cell, motors, transmission, and drive line).

Table 8 shows the deployments and benefits of FC lift trucks. The average U.S. grid electricity's carbon intensity assumption resulted in the battery lift truck emitting somewhat more GHGs (annually 0.34 metric ton/ lift truck) than the FC lift truck even though the former has a higher initial efficiency.

<u>Stationary Fuel Cells</u>

Stationary fuel cells considered in this analysis do not include backup power (these do not run most of the time). Table 9 lists key operating assumptions of the four types of stationary fuel cells deployed in the U.S. FCHEA provided data on installed capacity of stationary fuel cells as summarized in Table 10.

Table 10 shows also their calculated benefits. As discussed in the addendum that follows the list of references, EPA's CHP analysis methodology (posted at https://www.epa.gov/chp/fuel-and-carbon-dioxide-emissions-savings-calculation-methodology-combined-heat-and-power) was used to estimate GHGs emission reduction.

Table 8: Annual benefits of FC lift trucks

Year	FC Lift Trucks Deployed	FC Lift Truck Stock	Effic.- New Battery Lift Truck	Effic. - New FC Lift Truck*	GHG Savings (metric tons)
2009	269	269	60.8%	43.7%	93
2010	318	587	60.8%	43.7%	203
2011	643	1,230	60.8%	43.7%	424
2012	1,820	3,050	60.8%	43.7%	1,052
2013	980	4,030	60.8%	43.7%	1,390
2014	2,100	6,130	60.8%	43.7%	2,115
2015	3,900	10,030	60.8%	43.7%	3,461
Cumul. Benefits					**8,740**

Table 9: Fuel cell operating assumptions*

	PEMFC	PAFC	MCFC	SOFC
LHV Electric Efficiency	39%	39%	47%	57%
LHV Combined Efficiency	85%	88%	90%	90%
Recaptured Heat, MMBtu/MWh**	1.33	1.55	1.88	0.00
Power to Heat Ratio	2.57	2.20	1.81	N.A.

*Electric efficiencies are from vendor products specifications (Bloom, FuelCell Enegy, Doosan, etc.)

**Recovered and used heat assumed to increase with higher operating temperatures, except for SOFC (Bloom SOFCs have been deployed for electricity generation without heat recovery).

Table 10: Annual benefits of stationary fuel cells (PEMFC, PAFC, MCFC, and SOFC)

Year	Fuel Cells (kW) Deployed	Fuel Cell Stock (kW)	Polymer Electrolyte Membrane (PEMFC) %	Phosphoric Acid (PAFC) %	Molten Carbonate (MCFC) %	Solid Oxide (SOFC) %	Stationary FC GHG Savings (metric tons)
2001	1,400	1,400	0.0%	100.0%	0.0%	0.0%	1,335
2002	200	1,600	0.0%	100.0%	0.0%	0.0%	1,525
2003	1,750	3,350	0.0%	77.6%	22.4%	0.0%	3,891
2004	250	3,600	0.0%	72.2%	27.8%	0.0%	4,362
2005	2,000	5,600	0.0%	82.1%	17.9%	0.0%	8,269
2006	2,250	7,850	0.0%	58.6%	41.4%	0.0%	10.506
2007	1,200	9,050	0.0%	53.0%	47.0%	0.0%	12,580
2008	3,200	12,250	0.0%	42.4%	54.3%	3.3%	18,144
2009	6,850	19,100	0.0%	53.4%	40.3%	6.3%	26,215
2010	24,100	43,200	2.3%	54.6%	19.2%	23.8%	56,077
2011	29,950	73,150	1.4%	39.1%	22.9%	36.6%	104,127
2012	72,790	145,940	1.4%	24.1%	17.2%	57.2%	221,196
2013	38,725	184,665	1.1%	21.7%	14.2%	63.0%	282,273

2014	52,000	236,665	0.9%	17.3%	17.9%	63.9%	371,625
2015	16,490	253,155	0.8%	16.3%	17.3%	65.5%	398,982
Cumul. Benefits							**1,519,000**

*Annual deployments (U.S. only) from Fuel Cell and Hydrogen Energy Association

References

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http://www.nrel.gov/hydrogen/proj_fc_market_demo.html

Addendum: Methodology for CHP Benefits Estimation (peer reviewed by FuelCell Energy and Oak Ridge National Laboratory)

This analysis used the approach recommended by the EPA Combined Heat and Power Partnership (U. S. Environmental Protection Agency 2015),[2] namely emissions savings associated with CHP should be based on the displacement of the fossil generation component of the grid (primarily coal and natural gas) and not the displacement of average grid electricity because the average grid mix includes: (1) nuclear and hydro-electric plants that do not ramp up or down and therefore their electricity is not dispatchable and (2) other renewable electricity such as wind and solar whose marginal cost of generation is zero.[3] The example discussed below is based on analyzing a MCFC, but the approach is applicable to the other fuel cells as well. Table A1 lists the major assumptions.

The comparisons are between: (a) an on-site fuel cell with heat recovery; and, (b) grid power with on-site gas-fired boilers. Consistent with EPA guidance, the displaced grid electricity is assumed to be from

[2] http://www.epa.gov/chp/fuel-and-carbon-dioxide-emissions-savings-calculation-methodology-combined-heat-and-power

[3] i.e., once the system is operating, there is virtually no increased cost in generating electricity because there is no fuel cost, meaning that utilities are not likely to ramp down their renewable generation.

a combination of coal power plants and gas-fired power plants. The MCFC is based on FuelCell Energy's current technology and the power plants' characteristics are from the Energy Information Administration 2013. Since California has more installed fuel cells than any other state, the ratio of gas-based generation to coal-based generation was assumed to be California's for the purpose of estimating fuel cell benefits. Table A1 lists the assumptions for systems with the same net electrical output, i.e., equivalent in terms of meeting the same user's needs after any losses such as transmission losses.

Table A1: Assumptions

	MCFC	**Coal-Fired Power Plant**	**Gas-Fired Power Plant**
Power Generation			
Capacity (kWe)	1,000	1,000	1,000
Availability at 90% (hrs/yr)	7,884	7,884	7,884
Plant elec. efficiency HHV (LHV) from FC vendor (for MCFC), EIA (for power plants)[4]	42.5% (47%)	33% (34.8%)	42% (46.5%)
Plant's net efficiency after T&D losses (no losses for FC)[5]	42.5% (47%)	30.9% (34.2%)	39.3% (43.5%)
Elect. output (kWh/yr)(after any T&D losses)	7,884,000	7,884,000	7.884,000
35% heat recovery (MMBtu/hr)[6]	1.08	0	0
Nat. Gas Boiler for Building's Thermal Needs		***Nat Gas Boiler***	***Nat Gas Boiler***
Efficiency (HHV)	*N/A*	*82%*	*82%*

Power plant CO_2 emissions are 53.1 and 94.5 tonnes CO_2 per billion Btu (HHV) of fuel input for natural gas and coal, respectively, for electricity at the plug.[7] Using these values and the "upstream" GHG-to-CO_2 emissions factor for each fuel from GREET 2015 (11.3% for natural gas and 1.8% for coal), life-cycle GHG emissions were calculated. Results for all three systems are shown in Table A2.

Table A2: GHG emissions benefits of fuel cell CHP relative to coal and gas-fired plants

Power Generation	**MCFC**	**Coal-Fired Power Plant**	**Gas-Fired Power Plant**
Net plant elec. efficiency, HHV (LHV) (from Table A1)	42.5% (47%)	30.9% (34.2%)	39.3% (43.5%)

[4] HHV/LHV: higher heating value/lower heating value. Fuel cell efficiency from http://www.fuelcellenergy.com/products-services/products/. Power plant's efficiency before T&D losses from http://www.eia.gov/electricity/annual/html/epa_08_01.html.

[5] Net efficiency = Generating efficiency x (1-T&D losses)
T&D loss: 6.5% loss for grid power, 0% loss for fuel cell.

[6] Assumed a moderate amount of useable heat to be conservative.

[7] www.eia.gov/survey/form/eia_1605/excel/Fuel_Emission_Factors.xls · Web view.

Effective HHV heat rate, Btu/kWh[8]	8,028	11,058	8,689
HHV Fuel consumption,[9] 10^9Btu/yr (includes T&D losses)	63.3	87.2	68.5
Life cycle GHGs emissions[10] (tonnes/yr)	3,739	8,408	4,047
Heat Generation by Boilers			
Natural gas consumption[11] HHV basis (10^9 Btu/yr)	0	14.9	14.9
GHGs emissions[12] (tonnes/yr)	0	878	878
GHGs Emissions from Power and Heat Production (tonnes CO_2/yr)	3,739	9,286	4,925
GHGs Emissions Reduction with MCFC			
- Tonnes/yr		5,547	1,185
- Percent reduction		60%	24%

Within the subset of coal and gas plants, EIA estimated the share of coal-based electricity at approximately 16% and the share of natural gas-based electricity at approximately 84% for California in 2014 (Energy Information Administration 2014). Using these percentages as weighting factors to calculate the average savings, the 1000 kWh fuel cell CHP system would reduce carbon emissions by 1,880 tonnes of GHGs per year.

References for stationary fuel cells analysis

Energy Information Administration. *Electric Power Annual 2013 Table 8.1. Average Operating Heat Rates by Energy Source.* http://www.eia.gov/electricity/annual/

Energy Information Administration. *Annual Energy Outlook 2014. Table 92. Electric Power Projections by Electricity Market Module Region. WECC/California.*

U.S. Environmental Protection Agency. Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems. February 2015. https://www.epa.gov/chp/fuel-and-carbon-dioxide-emissions-savings-calculation-methodology-combined-heat-and-power

[8] Effective heat rate = 3,412/Net efficiency.
[9] Fuel consumption = Annual power generation x Effective heat rate.
[10] Emissions = Fuel consumption x Life-cycle CO_2 content; content being 59.1 tonnes/10^9Btu for natural gas, 96.4 tonnes/10^9Btu for coal.
[11] Emissions = Heating fuel consumption x 59.1 tonnes/10^9Btu for natural gas.
[12] Natural gas consumption = Is based on boiler efficiency (82% HHV).