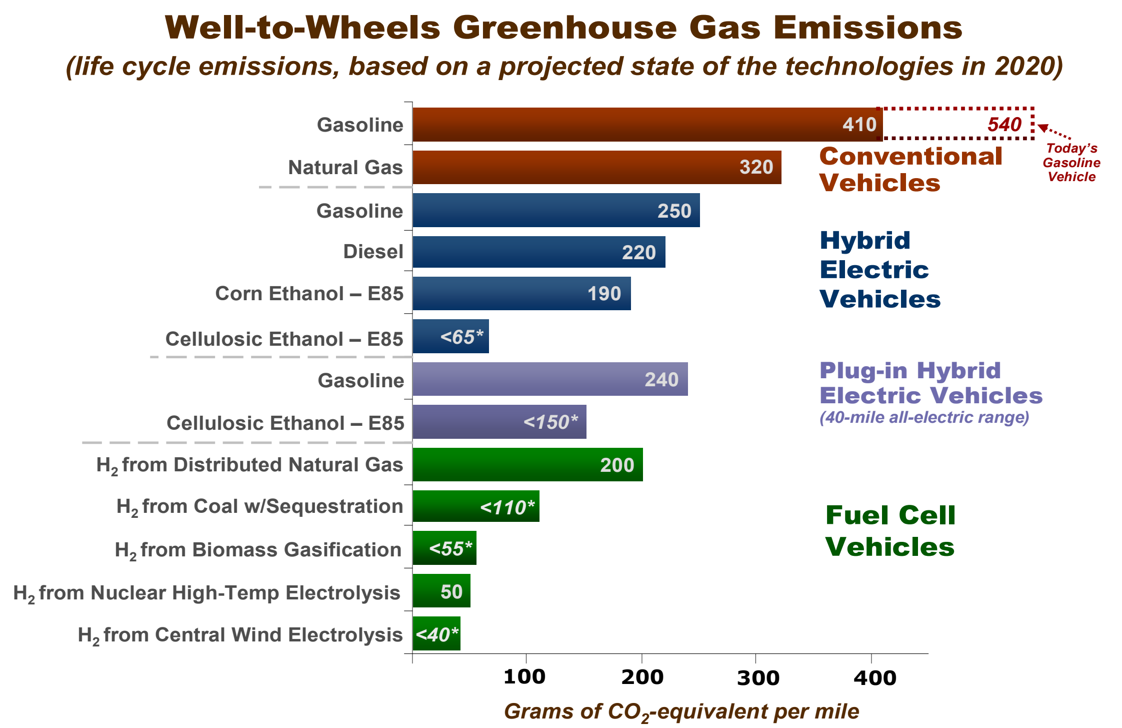
DOE Hydrogen Program Record	
Record #: 9002	**Date:** March 25, 2009
Title: Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use	
Originator: Fred Joseck	
Approved by: Sunita Satyapal	**Date:** March 25, 2009

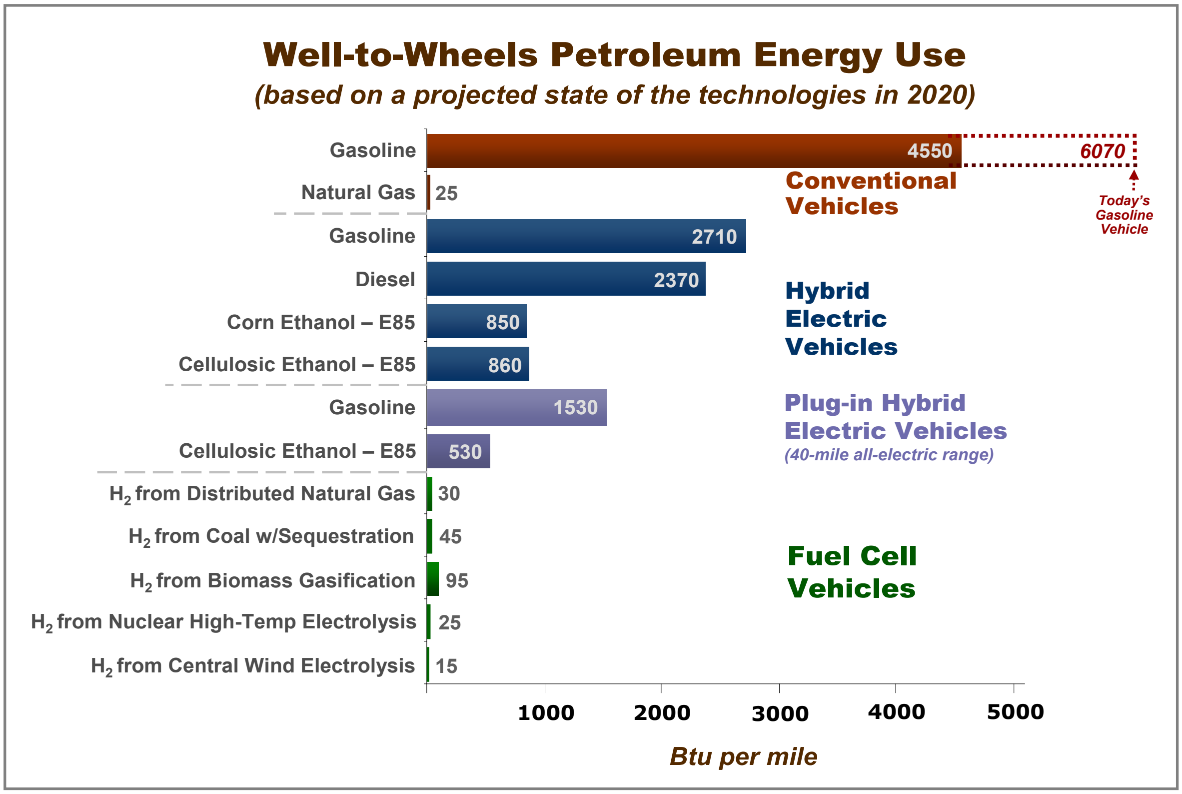
Items:

DOE is pursuing a portfolio of technologies with the potential to significantly reduce greenhouse gas (GHG) emissions and petroleum consumption. This record documents the assumptions and results of analyses conducted to estimate the emissions and petroleum energy use resulting from several fuel/vehicle pathways.



***Net emissions from these pathways will be lower if these figures are adjusted to include:**

- The displacement of emissions from grid power–generation that *will* occur when surplus electricity is co-produced with cellulosic ethanol
- The displacement of emissions from grid power–generation that *may* occur if electricity is co-produced with hydrogen in the biomass and coal pathways, and if surplus wind power is generated in the wind-to-hydrogen pathway
- Carbon dioxide sequestration in the biomass-to-hydrogen process



<u>Data, Assumptions, References:</u>

- Results for all pathways are based a projected state of the technologies in 2020, and they incorporate fuel economy improvements based on new corporate average fuel economy (CAFE) standards adopted in the Energy Independence and Security Act of 2007 (EISA 2007).
- Results for all pathways represent a weighted average of petroleum use and emissions by light trucks and cars, based on a projection by the Energy Information Administration (EIA) of new-vehicle sales in 2020, which shows a proportion of 51% light trucks and 49% cars. For the specific projected values, see the following spreadsheet from the EIA's *Annual Energy Outlook 2008*: www.eia.doe.gov/oiaf/archive/aeo08/supplement/sup_tran.xls (lines 1014 and 1040).
- Estimated fuel economies for all fuel/vehicle pathways are based on a combination of urban and highway fuel economies, with 55% urban driving and 45% highway driving.
- Argonne National Laboratory's (ANL's) Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model (version 1.8b, September 2008) was used to determine all the well-to-wheels (WTW) greenhouse gas (GHG) and petroleum energy use estimates shown in the table below. For more information on the GREET model, see: www.transportation.anl.gov/modeling_simulation/GREET/index.html.
- Key input parameters for hydrogen production simulations were developed by the National Renewable Energy Laboratory using the H2A hydrogen production and delivery models (version 2.01). For more information on the H2A models, see: www.hydrogen.energy.gov/h2a_analysis.html.
- The Hydrogen Macro-System Model (MSM) version 1.0 – build 1061 (developed by the National Renewable Energy Laboratory and Sandia National Laboratories) was used to

guarantee consistency of assumptions between the H2A models and GREET. For more information on the MSM, see: www.hydrogen.energy.gov/pdfs/review08/an_4_ruth.pdf

- Fuel economies for all fuel/vehicle pathways were determined using ANL's Powertrain Systems Analysis Toolkit (PSAT Model) V6.2 SP1, summer 2008. For more information on the PSAT Model, see: www.transportation.anl.gov/modeling_simulation/PSAT/index.html.
- Fuel economy estimates for fuel cell vehicles are based on the gallon gasoline equivalent (gge) of hydrogen, which is 1.02 kg of hydrogen (with an energy content of 116,000 Btu on a lower heating value [LHV] basis).
- Hydrogen used in fuel cell vehicles is assumed to be dispensed from filling stations at 6,250 psi for 5,000-psi vehicle tank pressure.
- Upstream energy and emissions associated with electricity use are based on the EIA's reference-case projections for the national average generation mix in 2020: 51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual fuel oil, 1.0% biomass, and 8.4% other renewables (including hydropower). These figures are derived from the *Annual Energy Outlook 2007*, which is available on the Web at: www.eia.doe.gov/oiaf/archive/aeo07/index.html.
- These results will be periodically updated to reflect changes in the assumptions and refinements to the models used.
- Assumptions used to generate this latest set of results are based on discussions among DOE staff and the following technology analysts: Amgad Elgowainy, Argonne National Laboratory (ANL); Mark Ruth, National Renewable Energy Laboratory; Margaret Singh, ANL; and Michael Wang, ANL.

Vehicle/Fuel Pathway	Well-to-Wheels Greenhouse Gas Emissions *(grams of CO_2-equivalent/mile)*	Well-to-Wheels Petroleum Energy Use *(BTUs/mile)*	Pathway-Specific Assumptions
Future Conventional Vehicle: Gasoline -------------------- ***Today's*** *Conventional Vehicle: Gasoline*	410 -------------- *540*	4550 ------------- *6070*	• Fuel economy of 28 mpg was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.82. -- • *Fuel economy of 21 mpg was used. This is the on-road fuel economy, which was determined by multiplying the EPA lab-rated fuel economy by 0.82.*
Conventional Vehicle: Natural Gas	320	25	• Fuel economy of 29 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.82.
Hybrid-Electric Vehicle: Gasoline	250	2710	• Fuel economy of 47 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85.
Hybrid-Electric Vehicle: Diesel	220	2370	• Fuel economy of 53 miles per gge (which is roughly equal to 59 miles per gallon of diesel) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85.

Hybrid-Electric Vehicle: Corn Ethanol (E85)	190	850	• Fuel economy of 47 miles per gge (which is roughly equal to 35 miles per gallon of E85) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85.
Hybrid-Electric Vehicle: Cellulosic Ethanol (E85)	65	860	• Feedstock is a hybrid poplar grown as a bio-energy crop. • Fuel economy of 47 miles per gge (which is roughly equal to 35 miles per gallon of E85) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Does not include reductions in *net* GHG emissions and petroleum use that will occur through co-production of cellulosic ethanol and electricity. Surplus electricity produced in this manner (and not used for internal production processes) will replace some grid electricity and effectively displace associated emissions and petroleum use.
Plug-in Hybrid Electric Vehicle (w/ 40-mile all-electric range): Gasoline	240	1530	• The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[1] Based on PSAT simulations, a mid-sized PHEV with 40-mile all-electric range was assumed to have a fuel consumption of 700 Btu/mile and an electricity consumption of 716 Btu/mi in the blended mode of operation (primarily charge-depletion), and a fuel economy of 47 mpg in the charge-sustaining mode of operation. The share of distance travelled in the blended mode was assumed to be 63%. The 0.85 on-road adjustment factor was used for liquid-fuel operation. The electricity-fueled operation was not adjusted for on-road performance.
Plug-in Hybrid Electric Vehicle (w/ 40-mile all-electric range): Cellulosic Ethanol (E85)	150	530	• Feedstock for ethanol production is a hybrid poplar grown as a bio-energy crop. • The conventional definition of fuel economy does not apply to plug-in hybrid vehicles (PHEVs).[1] Based on PSAT simulations, a mid-sized PHEV with 40-mile all-electric range was assumed to have a fuel consumption of 700 Btu/mile and an electricity consumption of 716 Btu/mi in the blended mode of operation (primarily charge-depletion), and a fuel economy of 47 miles per gge in the charge-sustaining mode of operation. The share of distance travelled in the blended mode was assumed to be 63%. The 0.85 on-road adjustment factor was used for liquid-fuel operation. The electricity-fueled operation was not adjusted for on-road performance. • Does not include reductions in *net* GHG emissions and petroleum use that will occur through co-production of cellulosic ethanol and electricity. Surplus electricity produced in this manner (and not used for internal production processes) will replace some grid electricity and effectively displace associated emissions and petroleum use.
Fuel Cell Vehicle: Hydrogen from Distributed Natural Gas	200	30	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • 94% energy efficiency for forecourt compression.

[1] Energy use is represented here in Btu/mile, due to the complexities involved in assessing fuel economies in the charge-depleting mode in terms of miles/gallon or miles/gge. For more information on this subject, see: A. Elgowainy, et al., *Well-To-Wheels Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles,* Center for Transportation Research, Argonne National Laboratory, 2009, www.transportation.anl.gov/pdfs/TA/559.pdf.

.

Fuel Cell Vehicle: Hydrogen from Coal Gasification with Carbon Sequestration	110	45	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • 94% energy efficiency for forecourt compression. • Does not include potential reductions in *net* GHG emissions and petroleum use that are possible through co-production of hydrogen and electric power, which could replace some grid electricity and effectively displace associated emissions and petroleum use.
Fuel Cell Vehicle: Hydrogen from Biomass Gasification	55	95	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Feedstock is a hybrid poplar grown as a bio-energy crop. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • 94% energy efficiency for forecourt compression. • Does not include potential reductions in *net* GHG emissions and petroleum use that are possible through co-production of hydrogen and electric power, which could replace some grid electricity and effectively displace associated emissions and petroleum use. • Does not include additional potential reductions in GHG emissions that are possible if CO_2 is sequestered.
Fuel Cell Vehicle: Hydrogen from Nuclear High-temperature Electrolysis	50	25	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Hydrogen is produced using only nuclear-generated electricity and thermal energy—nearly all petroleum use and GHG emissions in this pathway are associated with delivery, storage, and dispensing of hydrogen. • 94% energy efficiency for forecourt compression. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • Electrolyzer efficiency is 74.6% (LHV); it uses 44.7 kWh per kg of hydrogen produced.
Fuel Cell Vehicle: Hydrogen from Central Wind Electrolysis	40	15	• Fuel economy of 65 miles per gallon gasoline equivalent (gge) was used. This is the projected on-road fuel economy, which was determined by multiplying the projected EPA lab-rated fuel economy by 0.85. • Hydrogen production process uses only wind-generated electricity—nearly all petroleum use and GHG emissions in this pathway are associated with delivery, storage, and dispensing of hydrogen. • Electrolyzer efficiency is 74.6% (LHV); it uses 44.7 kWh per kg of hydrogen produced. • Hydrogen is delivered by pipeline to the forecourt in gaseous form at 300 psi. • 94% energy efficiency for forecourt compression. • Does not include potential reductions in *net* GHG emissions and petroleum use possible by using excess wind electricity to displace some grid electricity. It is likely that most wind-to-hydrogen plants would be designed with an excess capacity of installed wind-power to minimize cost by ensuring the most efficient use of the system's electrolyzers. As a result, at times of peak wind-power generation, there would be more power generated than the electolyzers could utilize—this would replace some grid power, and effectively displace associated emissions and petroleum use.