DOE Hydrogen and Fuel Cells Program Record	
Record #: 5012a	**Date:** December 21, 2005
Title: Well-to-Wheels Analyses for Solar & Wind Hydrogen Production	
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Approved by: JoAnn Milliken	**Date:** January 6, 2006

Item:

This record explains the basis for the differences between the analyses of well-to-wheels energy use and greenhouse gas emissions conducted via Argonne National Laboratory's GREET Model, cited in the U.S. Department of Energy's *Solar and Wind Technologies for Hydrogen Production Report to Congress,*[1] and those conducted by the National Research Council, cited in the report *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.*[2]

Well-to-Wheels Energy Use and Greenhouse Gas Emissions - Argonne National Laboratory's GREET Model

Producing hydrogen via electrolysis using wind and solar energy requires very little energy from petroleum-derived fuels. Using grid energy to increase the capacity factor of the electrolysis components does not substantially increase the quantity of petroleum consumed. Figure 1 depicts well-to-wheels energy use for several scenarios. Total energy use for distributed wind electrolysis technology with 50% grid assistance to the electrolyzer is 4,600 Btu/mile; 34% of the total pathway energy, including compression and dispensing, is renewable. This distributed future case is for the 2015 timeframe and assumes electrolyzer research is successful.

Figure 1 also depicts results for future central wind and solar electrolysis options, both with 50% of the electrolysis energy coming from the electrical grid. Total energy consumption of the central wind case is slightly higher than the distributed case because of the energy used in hydrogen delivery. Lower electrical conversion efficiency increases the total energy use of the solar/grid electrolysis case, although 47% of the energy is renewable. These future cases are for the 2030 timeframe and assume a pipeline distribution infrastructure. If current delivery technology such as tube trailer or liquid hydrogen were assumed, the results would change significantly. Fuel cell vehicles running on hydrogen produced from water by wind and solar energy resources will use significantly less petroleum energy than gasoline-fueled vehicles. Critical assumptions

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1 http://www.eere.energy.gov/hydrogenandfuelcells/congress_reports.html

2 *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, pp 61-62, 189.

are listed under Figure 2. Once the technologies are mature and systems can be fully analyzed, it is expected that photoelectrochemical, photobiological, and thermochemical hydrogen production technologies would have similar low petroleum use and be competitive with improved conventional technologies on an overall energy use basis.

[1] **Figure 1: Well-to-Wheels Energy Use**

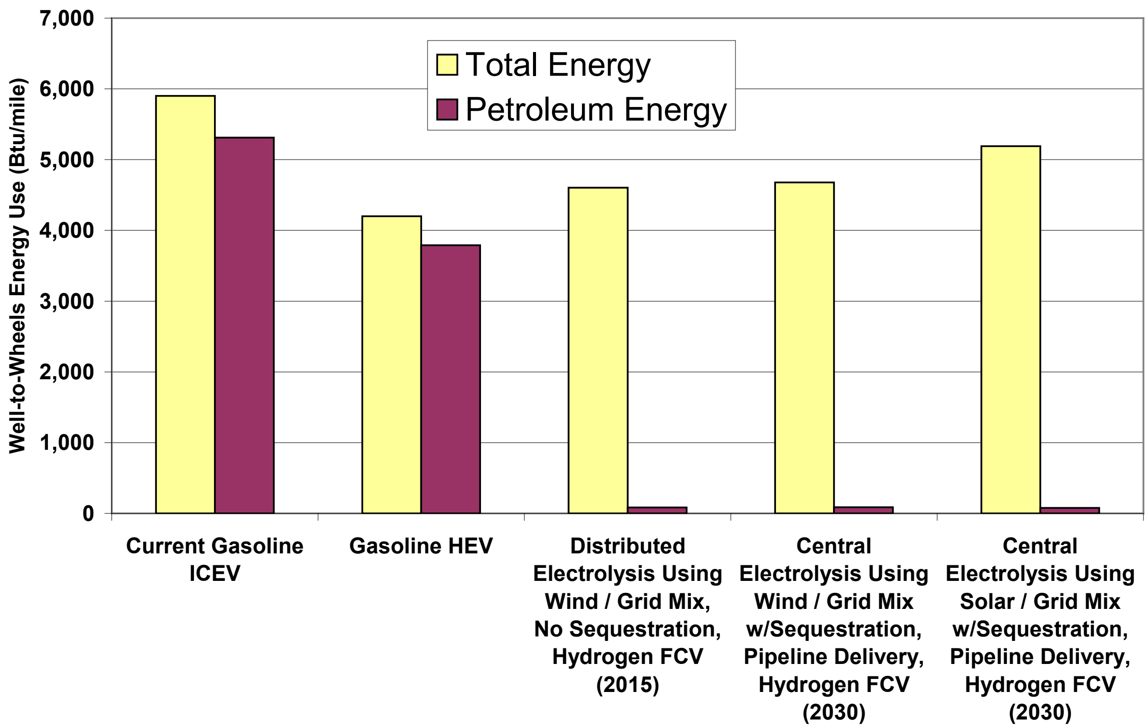
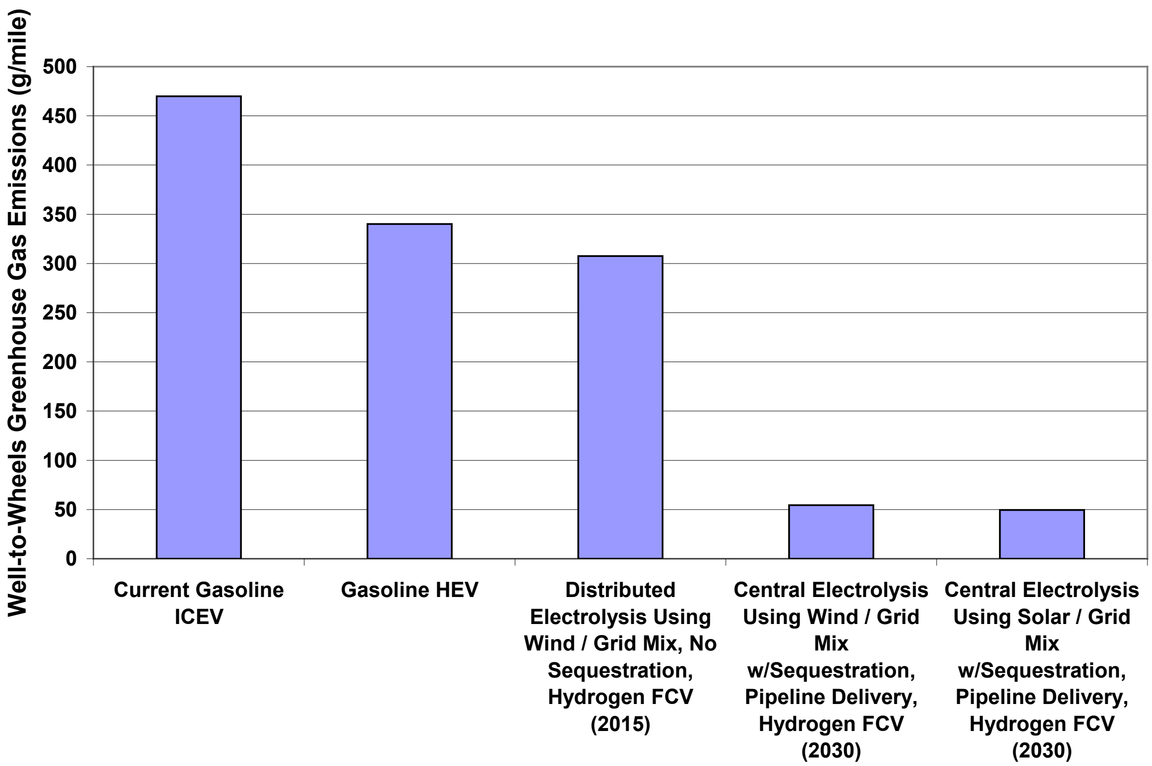


Figure 2 illustrates that fuel cell vehicles running on hydrogen produced from wind and solar energy resources will generate fewer greenhouse gas emissions than gasoline-fueled vehicles. When grid electricity is used to increase the capacity factor of the electrolysis components, as illustrated in the distributed wind/electrolysis case below, the majority of the greenhouse gas emissions are due to the fossil-based component of the electrical grid.

Assuming a future scenario where fossil-fueled power plants on the grid are able to sequester 85% of their greenhouse gas emissions, as shown in the central cases below, greenhouse gas emissions are significantly reduced. Again, the central case timeframe is 2030. Without such sequestration, the greenhouse gas emissions would still be below those from a gasoline-powered hybrid electric vehicle due to the higher efficiency of the vehicle. Greenhouse gas emissions from the central cases are also due to grid-powered pipeline delivery compression and compression at the fueling station. Once the technologies are mature and systems can be fully analyzed, it is expected that photoelectrochemical, photobiological, and thermochemical hydrogen production technologies would have similarly low greenhouse gas emissions.

Figure 2: Well-to-Wheels Greenhouse Gas Emissions



Note: Well-to-wheels petroleum use, renewable energy use, and greenhouse gas emissions are calculated with the GREET model from Argonne National Laboratory. All hydrogen cases assume a 50%/50% mix of electricity from renewable/grid sources, with the grid assistance being used to increase the capacity factor on the electrolyzer components. Central Electrolysis Using Wind/Grid Mix and Central Electrolysis Using Solar/Grid Mix assume that 85% of the carbon produced by the grid is to be sequestered. For central cases, hydrogen delivery is by pipeline over 100 km, with pipeline energy supplied by the electrical grid with 85% carbon sequestration. For all cases, electrolyzer efficiency equals 44.5 kWh/kg hydrogen. For dispensing at fueling stations, hydrogen is compressed to 6,000 psi using grid energy, as defined by GREET. Fuel cell vehicle is as defined by GREET model. All cases assume that technology targets are achieved. All cases represent system configurations that have economic potential to compete with conventional gasoline and gasoline hybrid electric vehicle technology.

Figures 1 and 2 are based on results from Version 1.7 of the GREET model, run November 9, 2005. The following major assumptions provide additional information about the model:

Case 1: Distributed electrolysis using 50% wind, 50% grid

Compression to 6,000 psi; compression efficiency 92.5%; grid electricity used for compression

Electrolyzer energy use = 44.5 kWh/kg

No CO_2 sequestration

Case 2: Central electrolysis using 50% wind, 50% grid
Electrolyzer energy use = 44.5 kWh/kg
Grid sequesters 85% of its CO_2
Pipeline delivery; pipeline uses grid electricity with sequestration
Compression of hydrogen at fueling station to 6,000 psi, using grid electricity with sequestration

Case 3: Central electrolysis using 50% PV solar, 50% grid
Electrolyzer energy use = 44.5 kWh/kg
Grid sequesters 85% of its CO_2
Pipeline delivery; pipeline uses grid electricity with sequestration
Compression of hydrogen at fueling station to 6,000 psi, using grid electricity with sequestration

The full GREET model inputs for the solar and wind hydrogen cases are available at http://www.hydrogen.energy.gov/program_records.html:

Case 1: Distributed Electrolysis Wind-Grid 2015.xls (U.S. Department of Energy Hydrogen Program, Record # 5012b).
Case 2: Central Electrolysis Solar-Grid 2030.xls (U.S. Department of Energy Hydrogen Program, Record # 5012c).
Case 3: Central Electrolysis Wind-Grid 2030.xls (U.S. Department of Energy Hydrogen Program, Record # 5012d).

Well-to-Wheels Energy Use and Greenhouse Gas Emissions - National Research Council Results

The National Academies' National Research Council report gives the total energy use results for solar- and wind-based electrolysis systems. According to the bar chart on page 61, energy use for current distributed wind electrolysis with 70% grid assistance and current distributed solar (photovoltaic) electrolysis with 80% grid assistance are approximately 4,000 and 4,500 Btu/mile, respectively. The bar chart on page 62 shows energy use for future distributed solar (photovoltaic) electrolysis with 80% grid assistance to be just under 4,000 Btu/mile.

The energy use of future wind electrolysis with 60% grid assistance is not shown on the bar charts; however, using data from page 189, it can be calculated at 2,982 Btu/mile. The calculation is as follows:

$$\frac{A * B * C * D}{E * F}$$

Where: A = 60% grid energy
B = 946 kWh electricity used
C = 24 hours/day
D = 3414.69 Btu/kWh
E = 480 kg/day hydrogen
F = 65 miles/kg hydrogen

Total = 2,982 Btu/mile

The methodology employed in the National Academies' study (abbreviated as NRC) assumes that the electricity produced from the solar photovoltaic cells and wind turbines is not counted in the total energy reported. This is stated in footnote #20 on page 60 of the NRC report. However, well-to-wheels calculations, such as those performed by the ANL GREET model, generally do include the electricity produced from renewables. If the wind-generated electricity is included, to be consistent with the concept of well-to-wheels (WTW) analysis, the WTW energy consumption increases to 4,970 Btu/mile (=2,982/0.6). This value is not appreciably different from the GREET result presented above. The total difference amounts to 370 Btu/mile. Areas of difference between the NRC report and GREET model include 1) the efficiency of the electrolyzer, 2) the ratio of grid to wind energy going to the electrolyzer, 3) grid losses, 4) grid mix assumptions, and 5) system boundary definition. These differences are examined below.

1) Electrolyzer Efficiency: The LHV efficiencies used in the NRC and GREET calculations were 72% and 76%, respectively. The impact of these different assumptions is 69 Btu/mile. The NRC result would be lower if the assumptions were consistent.

2) Wind/Grid Ratio: The NRC report assumes that 60% of the energy to the electrolyzer comes from the grid; the GREET calculations assume a 50% split between wind and grid energy. This difference accounts for 249 Btu/mile of the difference in the energy value. The NRC result would be lower if the assumptions were consistent.

3) Grid Losses: The NRC report did not include grid losses, while the GREET cases did. Grid losses account for 185 Btu/mile of the difference in the energy value. The NRC result would be higher if the assumptions were consistent.

4) Grid Mix: Another area of difference is grid mix assumptions. The NRC report assumes that all grid energy is supplied by future natural gas combined cycle power plants at 50% efficiency (see text on page 60 and footnote #17 on page 58). GREET assumes a grid mix that includes coal, natural gas, oil, and 30% nuclear and renewable energy, with a total efficiency of 56.1%. Thus, while the NRC assumption that all grid electricity would come from marginal installations of new technology is probably a simplification of the likely scenario, the higher efficiency of the GREET mix serves to lower the GREET estimate.

By using this 50% efficiency, we can reproduce the bars shown in Figures 5-12 and 5-13 of the NRC report. The grid mix assumption difference accounts for 152 Btu/mile of the difference in the energy value. The NRC result would be lower if the assumptions were consistent.

Summary for energy use comparison:

4,970 – 69 – 249 + 185 – 152 = 4,685 Btu/mile
Difference not accounted for = 4,685 – 4,600 = 85 Btu/mile = 1.8%

5) System Boundary Definition: Other major differences could not be found as documentation of upstream energy consumption is sparse in the NRC report. Another possible explanation for the difference in total energy consumption between the NRC report and the calculations in the GREET model is footnote #19 on page 60 of the NRC report:

"For the hydrogen technologies, these measurements are not strictly well-to-wheels. The energy used is from the point of feedstock delivery to the conversion facility and ignores energy used to produce the feedstock or to transport the feedstock from the point of extraction ("well") to the conversion facility."

Thus, the process operations included in the NRC report are different than those included in the GREET model. We concur with the statement made in the continuation of footnote #19: "Because this use of energy is small compared with the total energy delivered to the point of use, the committee's calculations only underestimate the energy use of the hydrogen technologies by a small percentage…"

Parametric differences between the NRC report and the Report-to-Congress are shown in the following table:

	NRC Report (page 189)	**ANL GREET Model**
Case	Distributed electrolysis using 40% wind, 60% grid	Distributed electrolysis using 50% wind, 50% grid
Electrolyzer efficiency	72% LHV	76% LHV
H_2 pressure	5,878 psi	6,000 psi
Energy for compression	4,268 Btu/kg = 1.25 kWh/kg	7,200 Btu/kg = 2.7 kWh/kg (from GREET model)
Compressor efficiency	Not specified; calculated as 96.3%	94% (from GREET model)
Grid losses	Not accounted for	7.3% (this is a distributed case; need to generate more wind energy than electrolyzer needs to account for grid losses)
Vehicle equivalent mileage	65 miles per gallon	64.4 miles per gallon (from GREET model)
Plant-gate energy consumption	2,484 Btu/mile	2,689 Btu/mile
WTW energy consumption	2,982 Btu/mile – this value is not given in the report; calculated using assumption of 50% electrical efficiency. 4,970 if wind-generated electricity is included.	4,600 Btu/mile

Upstream electricity power plants	Natural gas combined cycle power units at 50% efficiency (page 60); assumes only new capacity will supply electricity for hydrogen plants (margin, page 58).	Grid mix (GREET) at 56.1% efficiency
Carbon emissions	2.48 kg C/kg H_2 (CO_2 only, based on note on page 58)	5.5 kg C/kg H_2 (includes CO_2, methane, and N_2O)
	The difference is due to the following factors: 1) the grid mix being assumed, 2) the ratio of wind-to-grid being used by the electrolyzer, 3) the fact that the NRC report is only stating CO_2 emissions instead of all greenhouse gas emissions, and 4) system boundary definition.	