Well-to-Wheels Results of Advanced Vehicle Systems with New Transportation Fuels

Michael Wang
Center for Transportation Research
Argonne National Laboratory

Advanced Transportation Workshop
Global Climate and Energy Project
Stanford University, CA, October 10-11, 2005
Well-to-Wheels Analysis of Vehicle/Fuel Systems
Covers Activities for Fuel Production and Vehicle Use

Vehicle Cycle
(Under development with support from OFCVT and OPBA)

Fuel Cycle
(Ongoing development since 1995)

Well to Pump

Pump to Wheels
Petroleum Refining Is the Key Energy Conversion Step for Gasoline and Diesel

- Petroleum Recovery (97.7%)
- Petroleum Transportation and Storage (99%)
- Petroleum Refining to Gasoline (84.5-86%, Depending on Oxygenates and Reformulation) and Low-S Diesel (87%)
- NG to MeOH
- Corn
- MTBE or EtOH for Gasoline
- Transportation, Storage, and Distribution of Gasoline (99.5%)
- Gasoline and Diesel at Refueling Station

WTP Efficiency:
- Gasoline 80%
- Diesel 82%
Production and Compression Are Key Steps for Gaseous H2 Production

- **NA NG Recovery (97.5%)**
- **NA NG Processing (97.5%)**
- **G.H2 Production (71.5%)**
- **Steam or Electricity Export**
- **G.H2 Transport via Pipelines (96.3%)**
- **G.H2 Compression at Refueling Stations (89.5% & 95.0% for NG & Electric)**
- **Compressed G.H2 at Refueling Stations**
- **LNG Production (88.0%)**
- **LNG Transport via Ocean Tankers (98.5%)**
- **LNG Gasification in Ports**
- **U.S. WTP Efficiency:**
  - NA NG-based 58%
  - nNA NG-based 54%
- **nNA NG Recovery (97.5%)**
- **nNA NG Processing (97.5%)**

**Abbreviations:**
- **G.H2**: gaseous H2
- **L.H2**: liquid H2
- **LNG**: liquefied natural gas
- **NA**: North American
- **nNA**: non-North American
- **NG**: natural gas
WTW Analysis Is a Complete Energy/Emissions Comparison

As an example, greenhouse gases are illustrated here.
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- Includes emissions of greenhouse gases
  - CO$_2$, CH$_4$, and N$_2$O
  - VOC, CO, and NO$_x$ as optional GHGs

- Estimates emissions of five criteria pollutants
  - Total and urban separately
  - VOC, CO, NO$_x$, SO$_x$, and PM$_{10}$

- Separates energy use into
  - All energy sources
  - Fossil fuels (petroleum, natural gas, and coal)
  - Petroleum

- There are more than 2,000 registered GREET users worldwide; GREET and its documents are available at Argonne’s GREET website at http://greet.anl.gov
GREET Includes Transportation Fuels from Various Energy Feedstocks

- **Petroleum**
  - Gasoline
  - Diesel
  - LPG
  - Naphtha
  - Residual oil

- **Natural Gas**
  - CNG
  - LNG
  - LPG
  - Methanol
  - Dimethyl Ether
  - FT Diesel and Naphtha
  - Hydrogen

- **Nuclear Energy**
  - Hydrogen

- **Coal**
  - Hydrogen

- **Soybeans**
  - Ethanol

- **Corn**
  - Ethanol

- **Cellulosic Biomass**
  - Ethanol
  - Hydrogen
  - Methanol
  - Dimethyl Ether
  - FT Diesel and Naphtha

- **Residual Oil**
  - Coal
  - Natural Gas
  - Nuclear
  - Biomass
  - Other Renewables

- **Electricity**
GREET Includes More Than 50 Vehicle/Fuel Systems

Conventional Spark-Ignition Vehicles
- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Methanol and ethanol

Compression-Ignition Direct-Injection

Hybrid Electric Vehicles: Grid-Independent and Connected
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, and biodiesel

Spark-Ignition Hybrid Electric Vehicles: Grid-Independent and Connected
- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline, methanol, and ethanol
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas

Battery-Powered Electric Vehicles
- U.S. generation mix
- California generation mix
- Northeast U.S. generation mix

Fuel Cell Vehicles
- Gaseous hydrogen, liquid hydrogen, methanol, federal reformulated gasoline, California reformulated gasoline, low sulfur diesel, ethanol, compressed natural gas, liquefied natural gas, liquefied petroleum gas, and naphtha

Compression-Ignition Direct-Injection Vehicles
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, and biodiesel

Spark-Ignition Direct-Injection Vehicles
- Conventional gasoline, federal reformulated gasoline, and California reformulated gasoline
- Methanol and ethanol
Fuel Economy Values of a 2010 Model-Year Midsize Car (Argonne’s Simulations based on DOE FreedomCAR Goals)
Hybrid Electric Vehicles Offer Great Market Potentials

- Hybrid sales have been strong since 1999
- All major auto makers have plans to produce and sell hybrids
- Fuel economy gains among hybrid vehicle models vary significantly
- Risk exists that hybrid technologies could be used for vehicle performance

2005 data is through April 2005.
Advanced Vehicle Technologies in General
Reduce GHG Emissions

ICE and Hybrid

FCV

FC Hybrid

GHG Emissions: g/mi

RFG ICEV
Diesel ICEV
RFG HEV
Diesel HEV
FCV: NG H2
FCV: H2 from EtOH
FCV: US kWh H2
FCV: CA kWh H2
H2 FCV: Renew. kWh H2
FC HEV: NG H2
FC HEV: H2 from EtOH
FC HEV: US kWh H2
FC HEV: CA kWh H2
FC HEV: Renew. kWh H2

PTW
WTP
Since H2 Is Produced from Non-Petroleum Sources, H2 FCVs Almost Eliminate Petroleum Use
H2 FCVs With Ethanol and Average Electricity Could Increase Total NOx Emissions, But …
H2 FCVs With NG, Ethanol, and Renewable Electricity Reduce Urban NOx Emissions

ICE and Hybrid

FCV

FC Hybrid
A Path from Conventional Technologies to Hybrids and Then to Fuel Cells Can Help Achieve Zero GHG Emissions

Well-to-Wheel Greenhouse Gas Emissions (g/mi.)

- Current GV
- CI Diesel Vehicle
- Gasoline HEV
- Diesel HEV
- NG Distributed H2 FCV
- Cell. EtOH-to-H2 FCV
- Renew. Electro. H2 FCV

- Oil
- Natural Gas
- Non-Fossil Domestic

Well to Pump
Pump to Wheel
North America Has Relatively Little Conventional Oil But 30% of Unconventional Oil Reserves
WTP GHG Results Show That Oil Sands Operations Are Carbon-Intensive

WTP GHGs Emissions, Grams/bbl

Low H₂ Use for Upgrade

High H₂ Use for

Conv. Crude Gasoline
OS Gasoline: mining, NG
OS Gasoline: Mining, Coal
OS Gasoline: In-situ, NG
OS Gasoline: In-situ, Coal
OS Gasoline: In-situ, Nuclear
OS Gasoline: In-situ, NG
OS Gasoline: In-situ, Coal
OS Gasoline: In-situ, Nuclear
OS Gasoline: mining, NG
OS Gasoline: Mining, Coal
OS Gasoline: In-situ, NG
OS Gasoline: In-situ, Coal
OS Gasoline: In-situ, Nuclear
There Are Several Major Projects of Building Plants for Fischer-Tropsch Diesel From Natural Gas

- Natural Gas
- Electricity
- Natural Gas
- Water
- Electricity
- Steam
- Electricity
- Steam
- Electricity
- Steam
- Diesel, Naphtha, etc.

? here means optional
WTW GHG Emissions Results of NG-Based FTD in g/mmBtu

![Bar chart showing GHG emissions results for different fuels and processes.]
U.S. Fuel Ethanol Production Has Experienced Large Increases, and the Trend Will Continue

Source: Renewable Fuels Association
Ethanol WTP Pathways Include Activities from Fertilizer to Ethanol at Stations

- Agro-Chemical Production
- Agro-Chemical Transport
- Corn Farming
- Woody Biomass Farming
- Herbaceous Biomass Farming
- Corn Transport
- Woody Biomass Transport
- Herbaceous Biomass Transport
- Ethanol Production
- Animal Feed (Corn Ethanol)
- Transport, Storage, and Distribution of Ethanol
- Refueling Stations
- Electricity (Cellulosic Ethanol)

U.S. WTP Efficiency:
- Corn-based EtOH 60%
- Cellulosic EtOH 41%
GREET WTP Analysis Shows Positive Energy Balance Value for Corn Ethanol But Negative Energy Balance Value for Gasoline
Most of the Recent Corn EtOH Studies Show a Positive Net Energy Balance

Energy balance here is defined as Btu content a gallon of ethanol minus fossil energy used to produce a gallon of ethanol.
Corn EtOH Reduces GHGs by 18-29% While Cellulosic EtOH Yields 85-86% Reduction, on Per Gallon Basis of EtOH Used

GHG Emission Reductions Per Gallon of Ethanol to Displace An Energy-Equivalent Amount of Gasoline
Most Studies on GHG Emissions Show GHG Emission Reduction by Corn EtOH as Compared to Gasoline
Of the 11.8 Billion Bushels of Corn Produced in U.S. in 2004, About 12% Was Used for Ethanol Production

The U.S. produced 3.41 billion gallons of fuel ethanol in 2004, equivalent to 2.28 billion gallons of gasoline

In 2003, the U.S. consumed 134 billion gallons of gasoline and 39 billion gallons of on-road diesel fuels

Source: ERS/USDA, 2004, Feed Outlook (in RFA, 2005); EIA
A Recent Study by Oak Ridge National Laboratory Concludes 1.3 Billion Tons of Biomass Available in U.S. Per Year

**Bar Graphs:**
- **Total: 998 mil. Dry tons**
- **Total: 368 mil. Dry tons**

**Categories:**
- Perennial crops
- Corn stover
- Grains to biofuels
- Wheat straw
- Soybeans
- Other crop residues
- Other residues
- Manures
- CRP biomass
- Small grain residues
- Forest industry wastes
- Forest growth
- Fuel treatments (forests and other residues)
- Urban wood residues
- Fuelwood

**Total Dry Tons:**
- 998 million dry tons
- 368 million dry tons
Argonne Evaluated Bio-EtOH, Bio-FTD, and Bio-DME from Six Production Options for the RBAEF Project

1. bio-EtOH /GTCC
3. bio-EtOH /Rankine
5. bio-EtOH /bio-FTD /GTCC
7. bio-EtOH /protein /Rankine
9. bio-DME /GTCC
11. bio-FTD /GTC
### The Six Biofuel Production Options Result in CO₂ and GHG Emission Reductions

<table>
<thead>
<tr>
<th>Fuel: Fuel Production Options</th>
<th>CO₂</th>
<th>GHGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bio-DME: DME/GTCC</td>
<td>94.9</td>
<td>83.3</td>
</tr>
<tr>
<td>Bio-FTD: FTD/GTCC</td>
<td>95.6</td>
<td>84.7</td>
</tr>
<tr>
<td>Bio-FTD: EtOH/FTD/GTCC</td>
<td>96.4</td>
<td>87.4</td>
</tr>
<tr>
<td>Corn E85</td>
<td>33.3</td>
<td>20.1</td>
</tr>
<tr>
<td>Bio-E85: EtOH/ GTCC</td>
<td>70.9</td>
<td>60.9</td>
</tr>
<tr>
<td>Bio-E85: EtOH/ Rankine</td>
<td>69.7</td>
<td>60.2</td>
</tr>
<tr>
<td>Bio-E85: EtOH/FTD/GTCC</td>
<td>70.1</td>
<td>62.9</td>
</tr>
</tbody>
</table>

**For GHGs**
- More than 80% reduction with Bio-FTD and –DME
- More than 60% reduction with Bio-E85
- With 100% Bio-fuel, GHGs reductions are 82-87%.

Per gallon of gasoline equivalent
Products Per Ton of Biomass Offer Large Energy and GHG Benefits by Displacing Petroleum Fuels, Petroleum Chemicals, and Conventional Power

Less fossil use results in less GHGs

In grams per ton of biomass
Concluding Remarks

- With new transportation fuels, WTW analyses become necessary for comparing vehicle/fuel systems.
- Both vehicle efficiencies and new transportation fuels can play a major role in reducing transportation’s energy use and emissions.
- While efficiency gains for vehicles with fossil fuels offer incremental GHG benefits, vehicles with renewable fuels offer great GHG reductions.