Well-to-Wheels Analysis
Presented to HTAC on July 31, 2007

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Outline

• Well-to-Wheels Analysis Methodology
• Greenhouse gases, Regulated Emissions, and Energy Transportation (GREET) Model
• H2A Production and Delivery Models
• Well-to-Wheel (WTW) Results
• Pathway Hydrogen Cost Results
• Comparison of H2A to NAS Study
  ❖ Biomass comparison
  ❖ Coal Gasification comparison
  ❖ Others
• Summary
DOE Well-to-Wheels Analysis Methodology
A “Systems” Approach

Well-to-Wheels Overview

Vehicle Cycle

Fuel Cycle

Well to Pump

Pump to Wheels

Source: ANL

Vehicle Analysis (PSAT Model)
(Output: Vehicle Fuel Economy)

H₂ Production & Delivery (H₂A Model)
(Output: Fuel Pathway Efficiency)

Well-to-Wheels Analysis (GREET Model)

Analysis Output
- Comparison of Hydrogen FCVs, Gasoline and alternative fueled ICE & HEVs, Electric and other vehicle platforms on a WTW basis.
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- Argonne GREET development effort has been funded by DOE since 1995
- Includes emissions of greenhouse gases
  - CO$_2$, CH$_4$, and N$_2$O
  - VOC, CO, and NO$_x$ as optional GHGs
- Estimates emissions of six criteria pollutants
  - Total and urban separately
  - VOC, CO, NO$_x$, SO$_x$, PM$_{10}$, and PM$_{2.5}$
- Separates energy use into
  - All energy sources
  - Fossil fuels (petroleum, natural gas, and coal)
  - Natural gas
  - Coal
  - Petroleum

- New versions of GREET 1 and 2 series were released in June 2007
- There are more than 3,500 registered GREET users worldwide
GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstocks

**Petroleum:**
- Conventional Oil Sands
  - Gasoline
  - Diesel
  - LPG
  - Naphtha
  - Residual oil

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

**Nuclear Energy**
- Hydrogen
  - FT Diesel
  - Methanol
  - Dimethyl Ether

**Coal**
- Hydrogen
  - Coke Oven Gas
  - FT Diesel
  - Natural Gas
  - Nuclear
  - Biomass
  - Other Renewables
  - Hydrogen

**Sugar Cane Cellulosic Biomass:**
- Ethanol
- Hydrogen
- Methanol
- Dimethyl Ether
- FT Diesel
  - Fast growing trees
  - Crop residues
  - Forest residues

**Other Renewables:**
- Electricity
  - Hydrogen
GREET Includes Many Hydrogen Production Pathways and Options

- **NA NG**
  - Gaseous H2
  - Liquid H2

- **NNA NG**
  - Gaseous H2
  - Liquid H2

- **NNA Flared Gas**
  - Gaseous H2
  - Liquid H2

- **Nuclear Energy**
  - Gaseous H2
  - Liquid H2
  - Central Plant Production
    - No C Sequestration
    - C Sequestration
  - Distributed Production
    - Central Plant Production
      - HTGR H2O Splitting
      - HTGR Electrolysis
    - Distributed Production
      - LWR Electrolysis
      - HTGR Electrolysis

- **Biomass**
  - Gaseous H2
  - Liquid H2
  - Central Plant Production
    - No C Sequestration
    - C Sequestration
  - Distributed Production
  - Central Production via PV

- **Coal**
  - Gaseous H2
  - Liquid H2
  - Central Plant Production
    - No C Sequestration
    - C Sequestration
  - Distributed Production via Electrolysis

- **Methanol**
  - Gaseous H2
  - Liquid H2
  - Central Plant Production
    - No C Sequestration
    - C Sequestration
  - Distributed Production via Electrolysis

- **Ethanol**
  - Gaseous H2
  - Liquid H2
  - Central Plant Production
    - No C Sequestration
    - C Sequestration
  - Distributed Production via Electrolysis

- **Solar Energy**
  - Gaseous H2
  - Liquid H2
  - Central Production via PV

- **Electricity**
  - Gaseous H2
  - Liquid H2
  - Distributed Production via Electrolysis

- **Central Plant Production Standalone**
  - Steam Co-Generation
  - Electric Co-Generation

- **Coal**
  - Coke/COG
  - H2
  - Central Plant Production Standalone
    - Steam Co-Generation
    - Electric Co-Generation

- **HTGR** – high-temp. gas-cooled reactors
Calculation Logic for a Given WTP Production Activity in GREET

1. Emission factors (gms/mmBtu of fuel burned)
2. Combustion tech. share (%)
3. Process energy efficiency (%)
4. Process fuel type share (%)
5. Facility urban location share (%)

- **Energy use by fuel type and by combustion tech. (Btu/mmBtu of fuel output)**
  - Total emissions (gms/mmBtu of fuel output)
  - Energy use by total, fossil, and petroleum energy (Btu/mmBtu of fuel output)
  - Urban emissions (gms/mmBtu of fuel output)
Calculation Logic for a Given WTP Transportation Activity in GREET

Energy intensity by mode (Btu/ton-mile)

Transportation distance (miles)

Process fuel type share (%)

Transportation mode share (%)

Emission factors (gms/mmBtu of fuel burned)

Segment of urban transport (%)

Energy use by mode (Btu/ton of fuel transported)

Energy use by mode and by fuel type (Btu/mmBtu of fuel transported)

Energy use by total, fossil, and petroleum energy (Btu/mmBtu of fuel output)

Total emissions (gms/mmBtu of fuel output)

Urban emissions (gms/mmBtu of fuel output)
GREET Includes More Than 75 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
- Gaseous and liquid hydrogen
- Methanol and ethanol

**Compression-Ignition Direct-Injection Hybrid Electric Vehicles: Grid-Independent and Connected**
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, E-diesel, and biodiesel

**Spark-Ignition Hybrid Electric Vehicles: Grid-Independent and Connected**
- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

**Battery-Powered Electric Vehicles**
- U.S. generation mix
- California generation mix
- Northeast U.S. generation mix
- User-selected 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, E-diesel, and biodiesel

**Spark-Ignition Direct-Injection Vehicles**
- Conventional gasoline, federal reformulated gasoline, and California reformulated gasoline
- Methanol and ethanol
WTW Key Assumptions and Data Sources

- **WTP key assumptions**
  - Energy efficiencies of fuel production activities
  - GHG emissions of fuel production activities
  - Emission factors of fuel combustion technologies

- **WTP data sources**
  - Open literature
  - H2A models for H2 pathways
  - Engineering analyses such as ASPEN simulations
  - Stakeholder inputs

- **PTW key assumptions**
  - Fuel economy of vehicle technologies
  - Tailpipe emissions of vehicle technologies

- **PTW data sources**
  - Open literature
  - Vehicle fuel economy simulations with models such as Argonne’s PSAT model
  - Tailpipe emissions with EPA Mobile, CA EMFAC, and vehicle testing results

- **Large uncertainties exist in key assumptions**
  - GREET is designed to conduct stochastic simulations
  - Distribution functions are developed for key assumptions in GREET
H2A Model

Background

Purpose

- Improve transparency and consistency of analyses
- Improve understanding of the differences among analyses
- Seek better industry validation
- Analysis portfolio development
- Provide research direction

History

- Began in February 2003, financial support from U.S. DOE
- Developed by team of analysts from labs, industry, consulting firms, universities, and Key Industrial Collaborators (KIC)
H2A Model Description

• Excel spreadsheet
• Discounted cash flow rate-of-return analysis
• Constant Plant Utilization (ie. always at near full capacity operation)

• User enters:
  ❖ Installed Plant Capital Cost
  ❖ Replacement costs and other O&M
  ❖ Feedstock Consumption Rates/Efficiencies
  ❖ Feedstock Cost (can be constant or varying with year)

• Model returns:
  ❖ Levelized selling price of hydrogen required to attain a specified internal rate of return
H2A Cash Flow Modeling Tool

Standard Price and Property Data

Feedstock and Utility Prices
Physical Property Data

Information

Description

Title

Spreadsheet Examples

Cost Analysis

Financial Inputs
Cost Inputs
Replacement Costs

Performance Assumptions
Process Flowsheet
Stream Summary

Results

Cost of H2
Cost Contribution
Sensitivity Analyses

Technical Analysis

Spreadsheets

Press this button to determine the minimum hydrogen selling price

Table A. Feedstock and Utility Prices, 2000 $

<table>
<thead>
<tr>
<th>Description</th>
<th>Base Case</th>
<th>H2A Guidelines</th>
<th>Val Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference $ Year (in half-decade increments)</td>
<td>2000</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Assumed Start-up</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After-Tax Real IRR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depreciation Type (MACRS, Straight Line)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depreciation Schedule Length (No. of Years)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analysis Period (ye)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant Life (ye)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assumed Inflation Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>State Income Taxes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Key Financial Parameters
Forecourt and Central

- Reference year: (2005 $)
- Debt versus equity financing: (100% equity)
- After-tax internal rate of return: (10% real)
- Inflation rate: (1.9%)
- Effective total tax rate: (38.9%)
- Design capacity: (varies)
- Capacity factor: (90% for central (exc. wind); 70% for forecourt)
- Length of construction period: (0.5 – 3 years for central; 0 for forecourt)
- Production ramp up schedule: (varies according to case)
- Depreciation period and schedule: (MACRS -- 20 yrs for central; 7 yrs for forecourt)
- Plant life and economic analysis period: (40 yrs for central; 20 yrs for forecourt)
- Cost of land: ($5,000/acre for central; land is rented in forecourt)
- Burdened labor cost: ($50/hour central; $15/hour forecourt)
- G&A rate as % of labor: (20%)
Hydrogen Production Strategy

Produce hydrogen from **renewable**, **nuclear**, and **coal** with technologies that will all yield virtually zero criteria and greenhouse gas emissions

**Distributed Natural Gas**
- Transition strategy
- “Well-to-wheels” greenhouse gas emissions substantially less than gasoline hybrid-electric vehicle
- Not a long-term source for hydrogen (imports and demand in other sectors)

**Nuclear/Renewable**
- Electrolysis (one option)
- Electricity not necessarily produced as an intermediary, options being pursued include:
  - Gasification of biomass
  - Reforming of renewable liquids
  - Photoelectrochemical
  - Photobiological
  - Thermochemical (solar and nuclear)

**Coal**
- Only with carbon capture & sequestration
- Gasification process produces hydrogen directly
- Electricity not produced as an intermediary
WTW Analysis Results
Vehicle Fuel Economy used in the analysis:

<table>
<thead>
<tr>
<th>Year</th>
<th>Gaso. ICE</th>
<th>Gaso. HEV</th>
<th>E85 ICE</th>
<th>H2 ICE</th>
<th>FCV HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>24</td>
<td>34</td>
<td>24</td>
<td>29</td>
<td>57</td>
</tr>
<tr>
<td>2015</td>
<td>28</td>
<td>39</td>
<td>28</td>
<td>34</td>
<td>66</td>
</tr>
</tbody>
</table>

Sources: H2A and GREET models
Vehicle Fuel Economy used in the analysis:

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<td>28</td>
<td>34</td>
<td>66</td>
</tr>
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Sources: H2A and GREET models
Well-to-Wheels Greenhouse Gas Emissions

Vehicle Fuel Economy used in the analysis:

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<th>Fuel Economy, mpgge</th>
<th>Gaso. ICE</th>
<th>Gaso.HEV</th>
<th>E85 ICE</th>
<th>H2 ICE</th>
<th>FCV HEV</th>
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<td>28</td>
<td>39</td>
<td>28</td>
<td>34</td>
<td>66</td>
</tr>
</tbody>
</table>

Sources: H2A and GREET models
GHGs vs. Petroleum Energy Use for Technologies

- Low Petroleum Use and High Greenhouse Gas Emissions
- Increased Petroleum Energy Use
- High Petroleum Use and High Greenhouse Gas Emissions
- Low Petroleum Use and Low Greenhouse Gas Emissions

Technology Examples:
- Gasoline ICE
- Gasoline HEV
- E85 HEV (corn)
- H2 - Dist. Nat Gas 2005
- H2 - Dist. Nat Gas 2015
- H2 - Dist. Wind 2005
- H2 - Dist. Wind 2015
- H2 - Coal Gasif. 2005
- H2 - Coal Gasif. 2030
- H2 - Cent. Biomass 2005
- H2 - Cent. Biomass 2030
- H2 - Cent. Nuclear 2030
- H2 - Cent. Wind 2005
- H2 - Cent. Wind 2030
- H2 - Cent. Wind 2015
- H2 - Dist. Wind 2015
Comparison of DOE and NAS
Greenhouse Gas Emissions (GHG) for the Current Case

Differences and Assumptions

- NAS only includes the hydrogen production in their emissions estimates.
- DOE/ANL WTW GHGs are based on the total fuel cycle which includes the feedstock production, hydrogen production and delivery.
- Fuel Economy: The NAS used 65 mpgge and the DOE used 57 mpgge.
- Biomass case: The NAS assumed 70% production efficiency and DOE assumed 45% efficiency. DOE/ANL includes liquid truck delivery from a liquefaction plant.
- Central Coal: The NAS does not include delivery. DOE/ANL includes liquid truck delivery from a liquefaction plant.

• Source of DOE WTW information is from the ANL GREET model.
• Source of NAS information is from the NAS report “Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs”
Comparison of DOE and NAS WTW
Total Energy Use for the Current Case

Differences and Assumptions
• NAS uses a hydrogen fuel economy of 65 mpgge. DOE/ANL used a hydrogen fuel economy of 57 mpgge.
• NAS used pipeline delivery for the central coal case. The DOE/ANL used liquid delivery from a liquefaction plant.
• Biomass case: The NAS assumed 70% production efficiency and DOE assumed 45% efficiency.

• Source of DOE WTW information is from the ANL GREET model.
• Source of NAS information is from the NAS report “Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs”
Pathway Hydrogen Cost Analysis
Cost Comparison of DOE H2A and NAS Hydrogen Production Pathways for the Current Case

Differences and Assumptions

- **Central Coal:**
  - NAS assumes pipeline delivery and DOE assumes the current delivery is liquid truck for the Central Coal Gasification case.
  - Capacity difference
- **Biomass case:** The NAS assumed 70% production efficiency and DOE assumed 45% efficiency.
  - Capacity difference
- **Dist. Wind:**
  - The NAS assumed the cost of the electrolyzer was $1228/kW and DOE assumed the cost was $780/kW.
  - The NAS assumed the size to be 480 kg/d for the production facility. DOE assumed the size to be 1,500 kg/d.
  - The NAS assumed an electricity price of $0.07/kWhr and DOE assumed price of $0.05/kWhr.
- **Dist. Natural Gas:**
  - The NAS assumed the size to be 480 kg/d for the production facility. DOE assumed the size to be 1,500 kg/d.

- Source of DOE WTW information is from the H2A model.
- Source of NAS information is from the NAS report “Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs”
Comparison of NAS and DOE H2A Hydrogen Production from Distributed Natural Gas Reforming

Cost Elements

<table>
<thead>
<tr>
<th>Production</th>
<th>NAS H2 cost, $/kg</th>
<th>DOE H2A Model H2 cost, $/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>1.64</td>
<td>1.33</td>
</tr>
<tr>
<td>Feedstock</td>
<td>1.37</td>
<td>0.88</td>
</tr>
<tr>
<td>Other variable</td>
<td>0.27</td>
<td>0.30</td>
</tr>
<tr>
<td>Fixed</td>
<td>0.23</td>
<td>0.58</td>
</tr>
<tr>
<td>Total</td>
<td>3.51</td>
<td>3.09</td>
</tr>
</tbody>
</table>

The lower efficiency will increase the cost of hydrogen production.

Impact on the hydrogen cost

<table>
<thead>
<tr>
<th>Key Factor</th>
<th>H2A Dist. Natural Gas Assumption</th>
<th>NAS Dist. Natural Gas Assumption</th>
<th>Impact on the hydrogen cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen production rate</td>
<td>1,500 kg/day</td>
<td>480 kg/day</td>
<td>The lower rate increases the plant production cost due to economies of scale.</td>
</tr>
<tr>
<td>Hydrogen production efficiency</td>
<td>69%</td>
<td>60%</td>
<td>The lower efficiency will increase the cost of hydrogen production.</td>
</tr>
</tbody>
</table>

The lower rate increases the plant production cost due to economies of scale.

The lower efficiency will increase the cost of hydrogen production.
Comparison of NAS and DOE H2A Hydrogen Production from Distributed Wind Electrolysis

<table>
<thead>
<tr>
<th>Cost Elements</th>
<th>NAS H2 cost, $/kg</th>
<th>DOE H2A Model H2 cost, $/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital</td>
<td>2.44</td>
<td>1.80</td>
</tr>
<tr>
<td>Feedstock</td>
<td>0.17</td>
<td>0.02</td>
</tr>
<tr>
<td>Other variable</td>
<td>3.68</td>
<td>3.10</td>
</tr>
<tr>
<td>Fixed</td>
<td>0.35</td>
<td>0.80</td>
</tr>
<tr>
<td>Total</td>
<td>6.64</td>
<td>5.72</td>
</tr>
</tbody>
</table>

The higher electrolyzer cost will increase the cost of the hydrogen product.

<table>
<thead>
<tr>
<th>Key Factor</th>
<th>H2A Dist. Wind Electrolysis Assumption</th>
<th>NAS Distributed Wind Electrolysis Assumption</th>
<th>Impact on the hydrogen cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen production rate</td>
<td>1,500 kg/day</td>
<td>480 kg/day</td>
<td>The lower rate increases the plant production cost due to economies of scale.</td>
</tr>
<tr>
<td>Electricity price</td>
<td>$0.052/kWhr</td>
<td>$0.07/kWhr</td>
<td>The higher electricity price will increase the cost of the hydrogen product.</td>
</tr>
<tr>
<td>Electrolyzer cost</td>
<td>$780/kW</td>
<td>$1228/kW</td>
<td>The higher electrolyzer cost will increase the cost of the hydrogen product.</td>
</tr>
</tbody>
</table>
## Comparison of NAS and DOE H2A Hydrogen Production from Biomass Gasification

<table>
<thead>
<tr>
<th>Cost Elements</th>
<th>NAS H2cost, $/kg</th>
<th>DOE H2A Model H2 cost, $/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital</td>
<td>2.44</td>
<td>0.52</td>
</tr>
<tr>
<td>Feedstock</td>
<td>0.98</td>
<td>0.58</td>
</tr>
<tr>
<td>Other variable</td>
<td>0.44</td>
<td>0.31</td>
</tr>
<tr>
<td>Fixed</td>
<td>0.77</td>
<td>0.21</td>
</tr>
<tr>
<td>Total</td>
<td><strong>4.63</strong></td>
<td><strong>1.62</strong></td>
</tr>
<tr>
<td>Delivery</td>
<td>2.42</td>
<td>3.50</td>
</tr>
<tr>
<td>Total delivered H2</td>
<td><strong>7.05</strong></td>
<td><strong>5.12</strong></td>
</tr>
</tbody>
</table>

![3D bar chart showing the cost breakdown for NAS and H2A. The chart compares Capital, Feedstock, Other Variable Cost, Fixed, and Delivery costs for each.](chart.png)
**Comparison of NAS and DOE H2A Hydrogen Production from Biomass Gasification**

<table>
<thead>
<tr>
<th>Key Factor</th>
<th>NAS Study Assumption</th>
<th>H2A Assumption</th>
<th>Impact on the hydrogen cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasifier Type</td>
<td>Shell High Pressure Oxygen Blown Gasifier</td>
<td>Batelle Indirectly Heated, Low Pressure (without oxygen)</td>
<td>The Shell gasifier type has a significantly higher capital cost than the Batelle</td>
</tr>
<tr>
<td>Gasifier Operating Pressure, psia</td>
<td>1515</td>
<td>40</td>
<td>Higher pressure increases the equipment cost of the Shell gasifier.</td>
</tr>
<tr>
<td>Source of process oxygen</td>
<td>Cryogenic Air Separation Unit (ASU)</td>
<td>None</td>
<td>The need for the ASU for the Shell gasifier adds significant capital cost.</td>
</tr>
<tr>
<td>Hydrogen production rate</td>
<td>24,000 kg/day</td>
<td>155,000 kg/day</td>
<td>The lower rate will increase the plant production cost due to economies of scale.</td>
</tr>
<tr>
<td>Spare gasifier vessels</td>
<td>1</td>
<td>0</td>
<td>The spare, high pressure gasifier vessel will increase the capital cost and the cost of hydrogen.</td>
</tr>
<tr>
<td>Feedstock cost</td>
<td>$53/dry ton</td>
<td>$38/dry ton</td>
<td>The higher feedstock cost will increase the cost of hydrogen</td>
</tr>
<tr>
<td>Feedstock usage factor</td>
<td>15.1 kg of biomass/kg of hydrogen</td>
<td>13.6 kg of biomass/kg of hydrogen</td>
<td>The NAS configuration requires more biomass because 15% is used to dry the feedstock. The H2A model uses the process waste heat to dry the biomass. The higher feedstock usage factor will increase the hydrogen cost.</td>
</tr>
</tbody>
</table>
Comparison of NAS and DOE H2A Hydrogen Production from Coal Gasification

<table>
<thead>
<tr>
<th>Cost Elements</th>
<th>NAS H2 Cost, $/kg</th>
<th>DOE H2A Model H2 Cost, $/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital</td>
<td>0.46</td>
<td>1.00</td>
</tr>
<tr>
<td>Feedstock</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>Other variable</td>
<td>0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>Fixed</td>
<td>0.15</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.96</strong></td>
<td><strong>1.62</strong></td>
</tr>
<tr>
<td><strong>Delivery</strong></td>
<td>0.96</td>
<td>3.50</td>
</tr>
<tr>
<td><strong>Total delivered H2</strong></td>
<td>1.92</td>
<td>5.12</td>
</tr>
</tbody>
</table>

**Graph:**
- Red: Capital
- Blue: Feedstock
- Green: Other Variable Cost
- Yellow: Fixed
- Light grey: Delivery

**Legend:**
- NAS
- H2A
## Comparison of NAS and DOE H2A Hydrogen Production from Coal Gasification

<table>
<thead>
<tr>
<th>Key Factor</th>
<th>H2A Coal Gasification Assumptions</th>
<th>NAS Coal Gasification Assumptions</th>
<th>Impact on the hydrogen cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasifier Type</td>
<td>Texaco High Pressure Oxygen Blown Gasifier</td>
<td>Texaco High Pressure Oxygen Blown Gasifier</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Gasifier Operating Pressure, psia</td>
<td>1515</td>
<td>1515</td>
<td>No difference</td>
</tr>
<tr>
<td>Source of process oxygen</td>
<td>Cryogenic Air Separation Unit (ASU)</td>
<td>Cryogenic Air Separation Unit (ASU)</td>
<td>No difference</td>
</tr>
<tr>
<td>Hydrogen production rate</td>
<td>308,000 kg/day</td>
<td>1,200,000 kg/day</td>
<td>The lower rate of the H2A coal gasifier increases the plant production cost due to economies of scale.</td>
</tr>
<tr>
<td>Spare gasifier vessels</td>
<td>1</td>
<td>1</td>
<td>No difference</td>
</tr>
<tr>
<td>Feedstock cost</td>
<td>$30/tonne</td>
<td>$32/tonne</td>
<td>The higher feedstock cost increases the cost of hydrogen of the H2A coal gasifier.</td>
</tr>
<tr>
<td>Feedstock usage factor</td>
<td>7.8 kg of coal/kg of hydrogen</td>
<td>6.5 kg of coal/kg of hydrogen</td>
<td>The higher feedstock usage factor increases the hydrogen cost for the H2A gasification.</td>
</tr>
</tbody>
</table>
Assumption:
- The energy cost data was based on the EIA 2005 AEO High “A” case including the gasoline price (untaxed).
- The hydrogen costs were obtained from the H2A model.
- The greenhouse gas emissions were obtained from the GREET model.
Petroleum Energy Use vs. Fuel Cost for Technologies

Assumption:
- The energy cost data was based on the EIA 2005 AEO High “A” case including the gasoline price (untaxed).
- The hydrogen costs were obtained from the H2A model.
- The petroleum use was obtained from the GREET model.

- The energy cost data was based on the EIA 2005 AEO High “A” case including the gasoline price (untaxed).
- The hydrogen costs were obtained from the H2A model.
- The petroleum use was obtained from the GREET model.
Summary

- Hydrogen provides the benefits of reducing petroleum use compared to other vehicle systems.
- Hydrogen produced from a portfolio of pathways will reduce greenhouse gas emissions from light duty transportation vehicles.
- Hydrogen fuel cell vehicles are competitive with gasoline vehicles on fuel cost, petroleum use and greenhouse gas emissions.
- Comparison of results of various studies can be difficult and not conclusive due to difference and transparency of assumptions.
Thank You

For More Information

Systems Analysis

Fred Joseck
(202) 586-7932
fred.joseck@ee.doe.gov
Backup
## Well-to-Wheels Energy and Greenhouse Gas Emissions Data

<table>
<thead>
<tr>
<th></th>
<th>Gasoline ICE Vehicle</th>
<th>Gasoline Hybrid Electric Vehicle</th>
<th>Distributed Ethanol Reformer - FCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-to-Wheels Total Energy Use (Btu/mile)</td>
<td>5,900</td>
<td>4,200</td>
<td>5740</td>
</tr>
<tr>
<td>Well-to-Wheels Petroleum Energy Use (Btu/mile)</td>
<td>5,300</td>
<td>3,800</td>
<td>190</td>
</tr>
<tr>
<td>Well-to-Wheels Greenhouse Gas Emissions (gm/mile)</td>
<td>470</td>
<td>340</td>
<td>90</td>
</tr>
<tr>
<td>Cost of Hydrogen ($/gge, delivered)</td>
<td></td>
<td></td>
<td>4.44</td>
</tr>
</tbody>
</table>

### Distributed Ethanol Reforming Key Assumptions

1. Well-to-Wheels energy, petroleum and greenhouse gas emissions from Argonne Nat. Lab. GREET model.
2. Cost, resource requirements, energy requirements, fuel and feedstock energy content and efficiency values from H2A 1,500 kg/day Forecourt Ethanol Reformer.
3. Costs include hydrogen production, compression, storage and dispensing to the vehicle.
4. Ethanol feedstock price is based on the DOE Biomass Program's target of $1.05/gal.
5. Electricity prices for current and future cases based on 2015 commercial rate($0.08/kWh) electricity by EIA Energy Outlook Hi A case. Price is in 2005$.
6. Operating capacity factor is 70%.
7. Capital costs are $1.47/kg.
8. Assumes the feedstock is cellulosic ethanol.

Source: NREL and ANL
Well-to-Wheels Analysis: Hydrogen Pathways

Distributed Natural Gas: Transition Strategy

**Energy Use for Delivery at the Forecourt**

- **Hydrogen Gas**
  - 116,000 Btu
  - 1 gge H₂

- **Compression, Storage, & Dispensing**
  - 5,000 psi
gas fill

- **Energy Losses**
  - 7,200 Btu

**Well-to-Wheels Energy and Greenhouse Gas Emissions Data**

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Well-to-Wheels Total Energy Use (Btu/mile)</td>
<td>5,900</td>
<td>4,200</td>
<td>3,700</td>
<td>2,800</td>
</tr>
<tr>
<td>Well-to-Wheels Petroleum Energy Use (Btu/mile)</td>
<td>5,300</td>
<td>3,800</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Well-to-Wheels Greenhouse Gas Emissions (g/mile)</td>
<td>470</td>
<td>340</td>
<td>260</td>
<td>200</td>
</tr>
<tr>
<td>Cost of Hydrogen ($/gge, Delivered)</td>
<td>3.10</td>
<td></td>
<td>2.00</td>
<td></td>
</tr>
</tbody>
</table>

Source: NREL and ANL

1. Well-to-Wheels energy, petroleum and greenhouse gas emissions from Argonne Nat. Lab. GREET model.
2. Cost, resource requirements, energy requirements, fuel and feedstock energy content and efficiency values from H2A 1,500 kg/day Forecourt SMR.
3. Costs include hydrogen production, compression, storage and dispensing to the vehicle.
5. Electricity prices for current and future cases based on 2015 commercial rate($0.08/kWh) electricity by EIA Energy Outlook Hi A case. Price is in 2005$.
6. Operating capacity factor is 70%.
7. Capital costs are $1.40/kg (Current) and $0.60/kg (Future).
Well-to-Wheels Analysis: Hydrogen Pathways
Distributed Hydrogen Production from Wind

Figure represents the future 2015 case.

<table>
<thead>
<tr>
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<tr>
<td>Well-to-Wheels Total Energy Use (Btu/mile)</td>
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<td>4,200</td>
<td>6,200</td>
<td>4,500</td>
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<td>Well-to-Wheels Petroleum Energy Use (Btu/mile)</td>
<td>5,300</td>
<td>3,800</td>
<td>130</td>
<td>100</td>
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<td>Well-to-Wheels Greenhouse Gas Emissions (g/mile)</td>
<td>470</td>
<td>340</td>
<td>490</td>
<td>310</td>
</tr>
<tr>
<td>Cost of Hydrogen ($/gge, Delivered)</td>
<td>5.70</td>
<td>3.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: NREL and ANL

Distributed Wind Key Assumptions

1. Electricity prices for current case based on 2015 industrial rate ($0.052/kWh) electricity by EIA Energy Outlook Hi A case. The future electrical price is $0.038/kWh based on Excel estimate. Price are in 2005$.
2. Basis is 1 kg of hydrogen, dispensed from filling station for 5000 psi fills for a forecourt capacity of 1,500 kg/day.
3. Current electrolyzer uses 53 kWh/kg of hydrogen. Future electrolyzer uses 45 kWh/kg of hydrogen. LHV efficiencies: 64% for current and 76% for future.
4. Installed electrolyzer capital cost is $730/kW for current and $250/kW for future.
5. Operating capacity factor is 70%.
6. The electrolyzer is supplied with electricity from 30% wind, 70% grid for the current case and from 50% wind, 50% grid for the future case.
7. Wind generated electricity is assumed to be transported via the electrical grid to distributed electrolyzers.
Centralized Hydrogen Production from Wind

Energy Use For Delivery
Energy Use for Delivery Transport
2,000 Btu

Energy Use For Delivery Operations at the Forecourt
7,200 Btu

Hydrogen Gas
116,000 Btu
1 gge H₂

Compression, Storage, & Dispensing
5,000 psi gas fill

Energy Losses
9,200 Btu

Figure represents the future 2030 case.

Well-to-Wheels Energy and Greenhouse Gas Emissions Data

<table>
<thead>
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<td>20</td>
<td>100</td>
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<td>Well-to-Wheels Greenhouse Gas Emissions (g/mile)</td>
<td>470</td>
<td>340</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Cost of Hydrogen ($/gge, Delivered)</td>
<td>9.50</td>
<td>2.70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Central Wind Key Assumptions
1. Basis is 1 kg of hydrogen, dispensed from filling station for 5000 psi fills for a plant capacity of 125,000 kg/day.
2. Current electrolyzer uses 53 kWh/kg of hydrogen. Future electrolyzer uses 45 kWh/kg of hydrogen. LHV efficiencies: 64% for current and 76% for future.
3. Installed electrolyzer capital cost is $800/kW for current and $180/kW for future.
4. The electrolyzer is supplied with electricity from 100% wind and with a 41% capacity factor for the current case and from 50% wind, 50% grid with a 97% a capacity factor for the future case.
5. Hydrogen delivery from a central site in current case is by liquid truck at $3.50/kg and in the future is by pipeline at $1.00/kg.
6. For the future case, electricity is assumed to be generated from fossil-based power plants capable of sequestering 85% of the carbon emissions.

Source: NREL and ANL
Well-to-Wheels Analysis: Hydrogen Pathways
Centralized Hydrogen Production from Coal

Central Coal Key Assumptions
2. Electricity prices for the current and future cases are based on the 2015 EIA High A case industrial rate of $0.052/kWh. Price is in 2005$.
3. Basis is 1 kg of hydrogen, dispensed from filling station for 5000 psi fills for a plant capacity of 308,000 kg/day.
4. Hydrogen delivery from the central site in current case is by liquid truck at $3.50/kg and in the future is by pipeline at $1.00/kg.
5. The operating capacity factor is 90%.
6. The levelized capital cost is $1.00/kg of hydrogen for the current case and $0.67/kg of hydrogen for the future case.
7. In the current and future cases, 85% of CO2 is captured and sequestered at $15/metric ton of CO2.

<table>
<thead>
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<tr>
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<td>5,100</td>
<td>3,200</td>
</tr>
<tr>
<td>Well-to-Wheels Petroleum Energy Use (Btu/mile)</td>
<td>5,300</td>
<td>3,800</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>Well-to-Wheels Greenhouse Gas Emissions (g/mile)</td>
<td>470</td>
<td>340</td>
<td>210</td>
<td>60</td>
</tr>
<tr>
<td>Cost of Hydrogen ($/gge, Delivered)</td>
<td>5.10</td>
<td>2.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Centralized Hydrogen Production from Biomass

Central Biomass Key Assumptions

1. Biomass is assumed to be woody biomass at a price of $38/bone dry ton. Price is in 2005$.
2. Electricity prices for the future cases based on the 2015 EIA High A case industrial rate of $0.052/kWh. Price is in 2005$.
3. Basis is 1 kg of hydrogen, dispensed from filling station for 5000 psi fills for a plant capacity of 155,000 kg/day.
4. The levelized capital cost for the current case is $0.34/kg of hydrogen and $0.47/kg of hydrogen.
5. Hydrogen delivery from the central site in current case is by liquid truck at $3.50/kg and in the future is by pipeline at $1.00/kg.
6. For the future case, electricity is assumed to be generated from fossil-based power plants capable of sequestering 85% of the carbon emissions.
7. The operating capacity factor is 90%.

Well-to-Wheels Energy and Greenhouse Gas Emissions Data

<table>
<thead>
<tr>
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<th></th>
<th></th>
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<tbody>
<tr>
<td>Well-to-Wheels Total Energy Use (Btu/mile)</td>
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<td>340</td>
<td>190</td>
<td>30</td>
</tr>
<tr>
<td>Cost of Hydrogen ($/gge, Delivered)</td>
<td></td>
<td></td>
<td>5.10</td>
<td>2.40</td>
</tr>
</tbody>
</table>
Centralized Hydrogen Production from Nuclear Sulfur-Iodine Process

Energy Use for Delivery Transport 2,000 Btu

Energy Use For Delivery Operations at the Forecourt 7,200 Btu

Figure represents the future 2030 case.

<table>
<thead>
<tr>
<th>Central Nuclear Key Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Nuclear Fuel Cycle cost of $9.3/MWh – based on U308@$38/lb, enriched@$55/SWU (separable work unit).</td>
</tr>
<tr>
<td>2. Electricity prices for the future cases based on the 2015 EIA High A case industrial rate of $0.052/kWh. Price is in 2005$.</td>
</tr>
<tr>
<td>3. Basis is 1 kg of hydrogen, dispensed from filling station for 5000 psi fills for a plant capacity of 768,000 kg/day.</td>
</tr>
<tr>
<td>4. Hydrogen delivery from the central site in the future case is by pipeline at $1.00/kg.</td>
</tr>
<tr>
<td>5. The levelized capital cost is $1.30/kg of hydrogen.</td>
</tr>
<tr>
<td>6. The operating capacity factor is 90%.</td>
</tr>
</tbody>
</table>

### Well-to-Wheels Energy and Greenhouse Gas Emissions Data

<table>
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<tr>
<td>Cost of Hydrogen ($/gge, Delivered)</td>
<td></td>
<td></td>
<td>3.20</td>
</tr>
</tbody>
</table>

Source: NREL and ANL
DOE WTW Analysis Effort: Pump-to-Wheels (PTW) Fuel Economy Assumptions

Legend:
GV – Gasoline ICE
GHEV – Gasoline Hybrid Electric Vehicle
DHEV – Diesel Hybrid Electric Vehicle
FCH – Fuel Cell Hybrid Electric Vehicle
The cost of producing hydrogen from coal and biomass is not sensitive to the price changes in coal and biomass feedstocks.

Hydrogen Production from Central Coal & Central Biomass

Notes:
- The numbers in the text box indicate the current prices for coal and biomass.
- Analysis based on H2A model for the current case.
- Hydrogen delivery includes liquefaction and liquid delivery costs.
Commercialization of Biomass Gasification

300 ton/day gasifier
Burlington Electric, VT

Varnamo Sweden, 100 mt/day, 6 MWe + 9 MWth demo run for 5 years, now being retrofitted for BTL


Foster Wheeler CFB Gasifier, Lahti Finland, 1,445 mt/d; 30,000 hours of operation at >95% availability

Source: NREL