Well-to-Wheels Analysis

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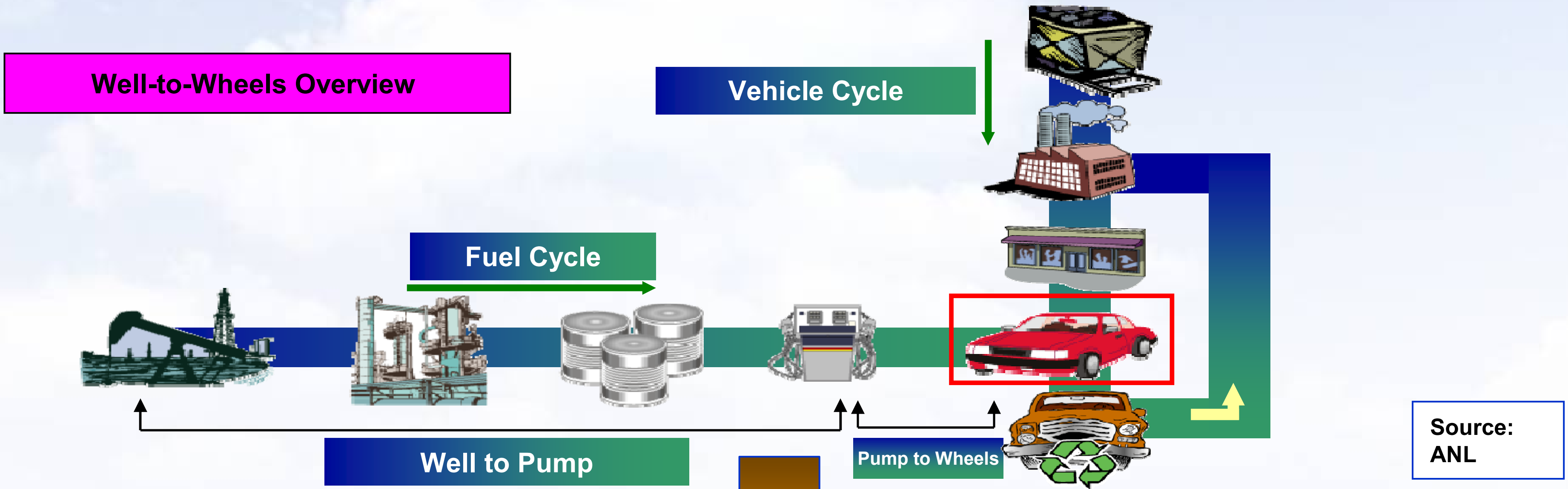
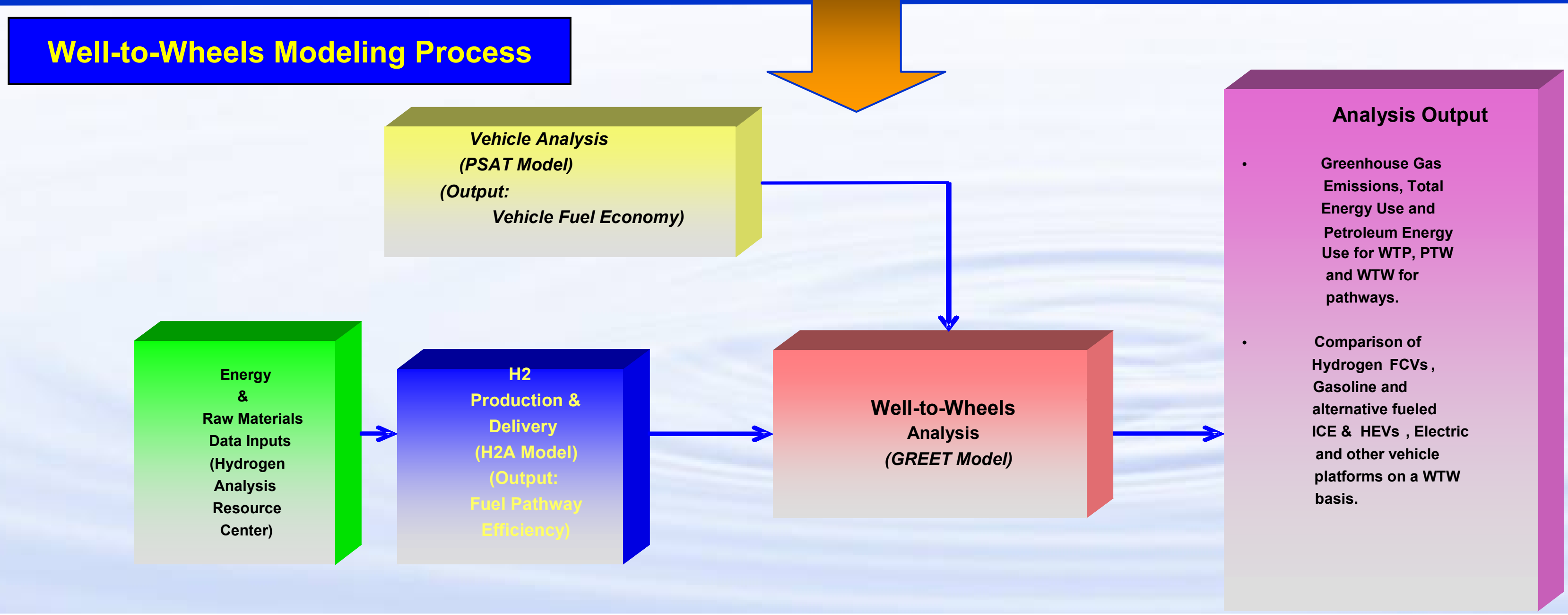
DOE Hydrogen Program

Outline

- Well-to-Wheels Analysis Methodology
- **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy **T**ransportation (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

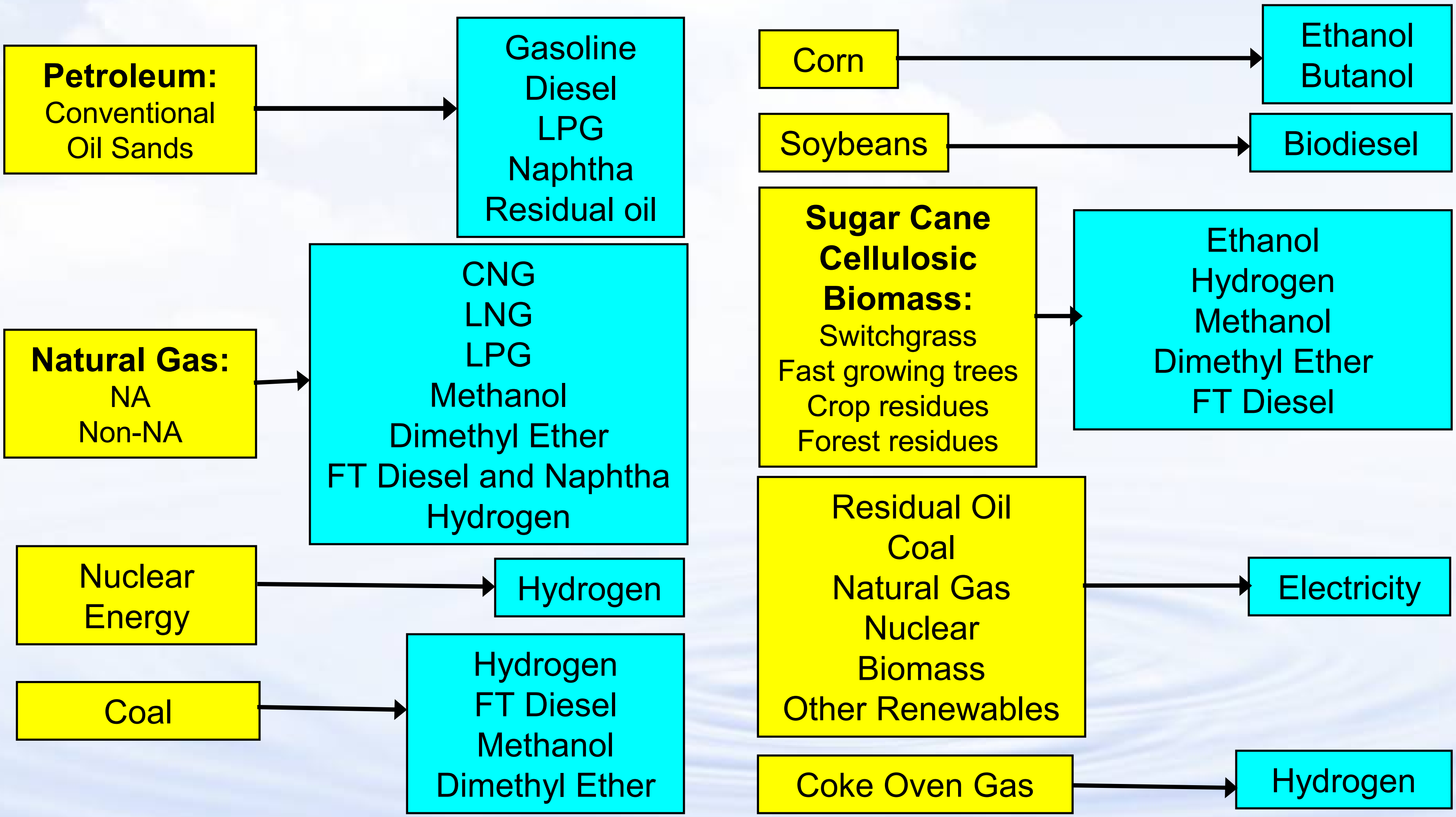




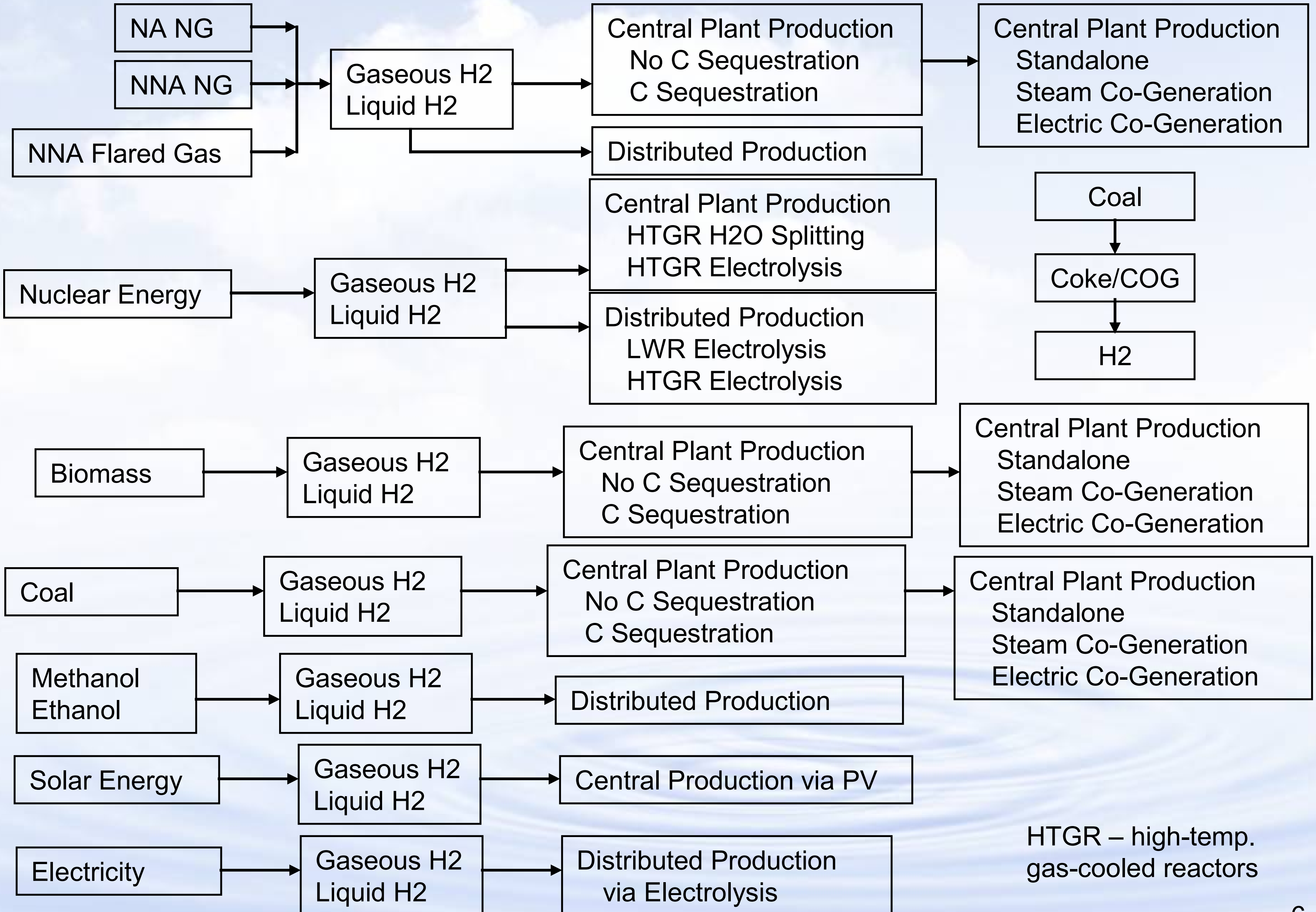
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- **Argonne GREET development effort has been funded by DOE since 1995**
- **Includes emissions of greenhouse gases**
  - CO_2, CH_4, and N_2O
  - 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
- **GREET and its documents are available at Argonne's website at *http://www.transportation.anl.gov/software/GREET/index.html***
  - 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

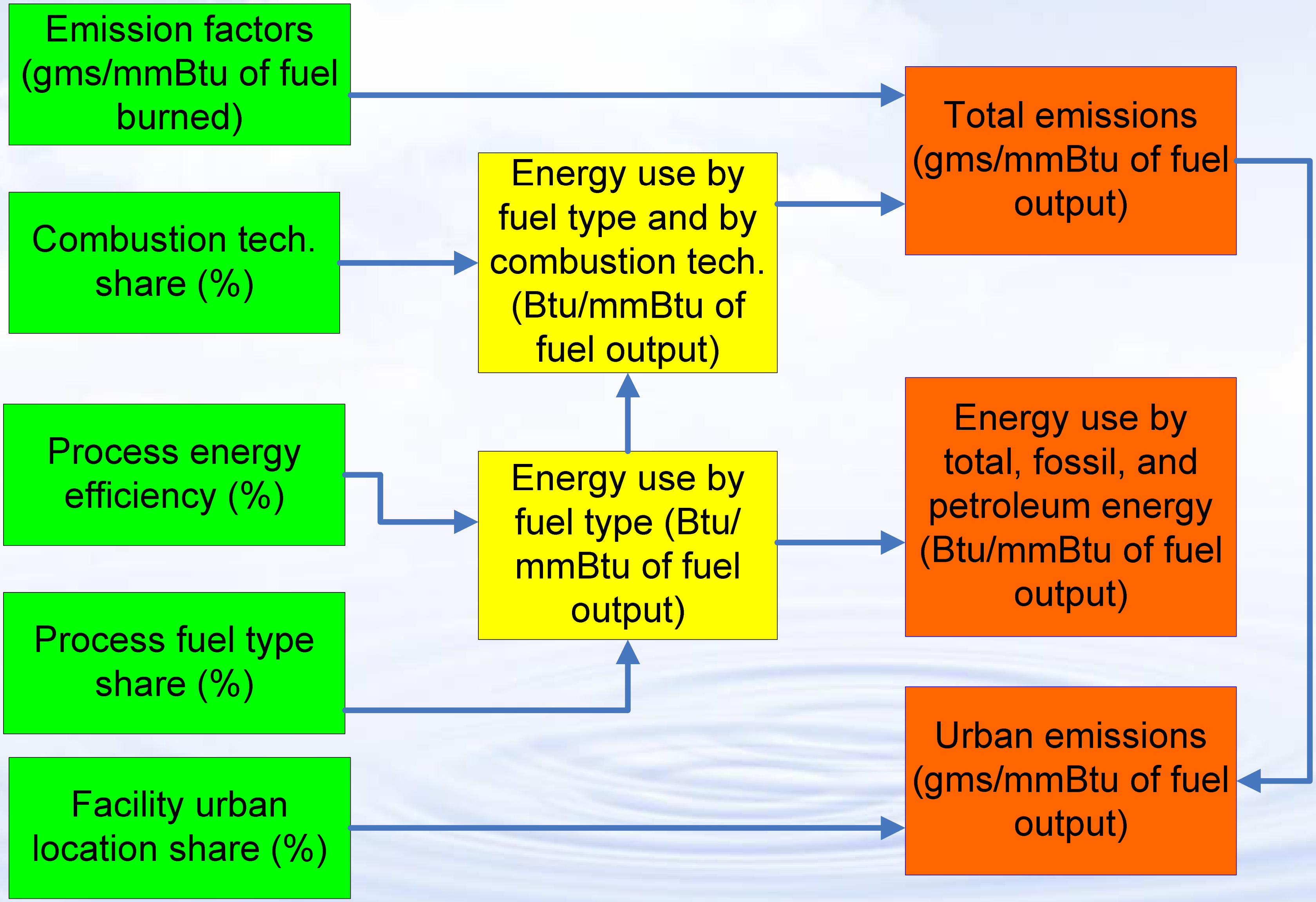


GREET Includes Many Hydrogen Production Pathways and Options

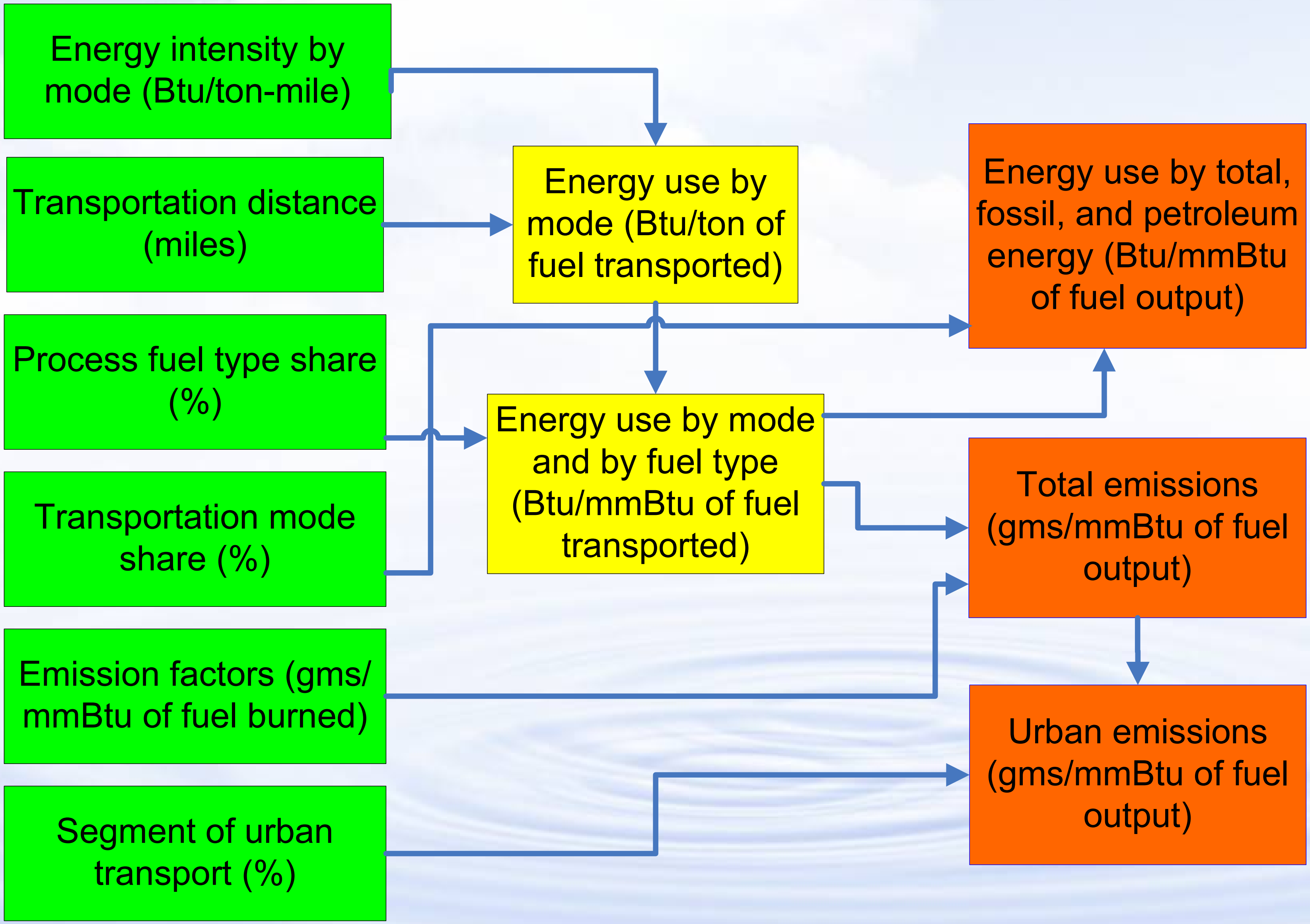


HTGR – high-temp. gas-cooled reactors

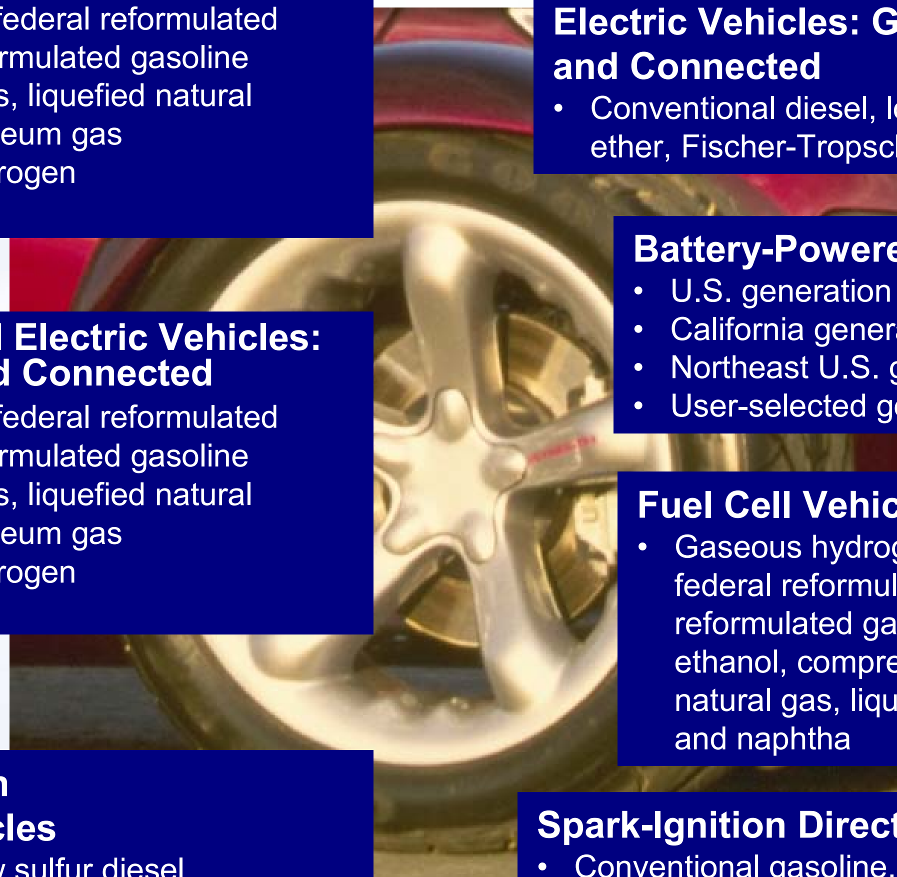
Calculation Logic for a Given WTP Production Activity in GREET



Calculation Logic for a Given WTP Transportation Activity in GREET



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

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

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

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

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

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

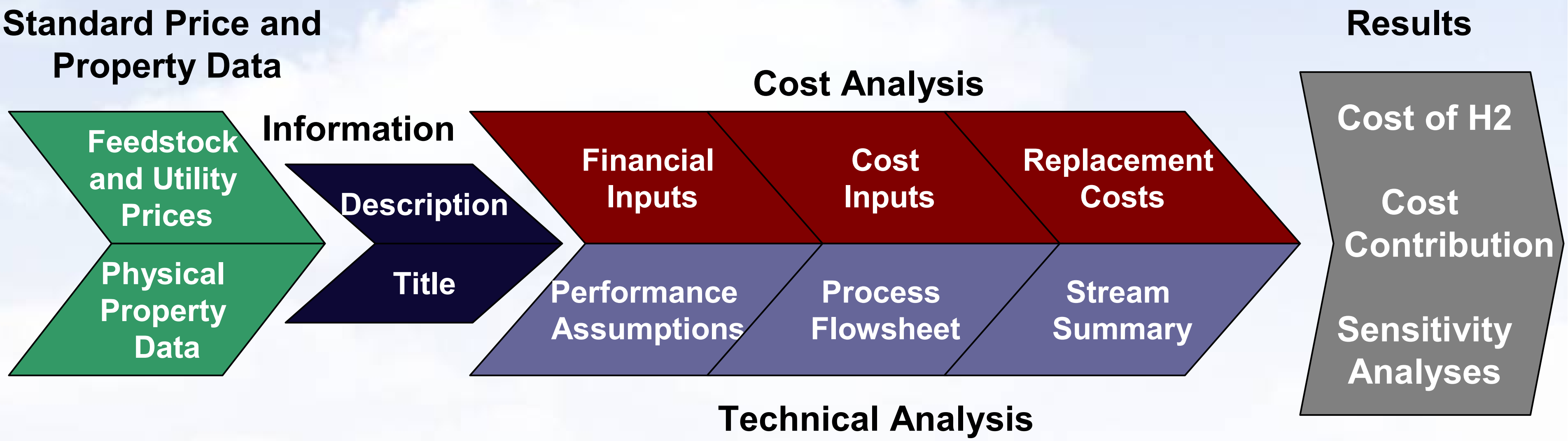
- **Purpose**
  - ❖ Improve transparency and consistency of analyses
  - ❖ Improve understanding of the differences among analyses
  - ❖ Seek better industry validation
  - ❖ Analysis portfolio development
  - ❖ Provide research direction

- **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)

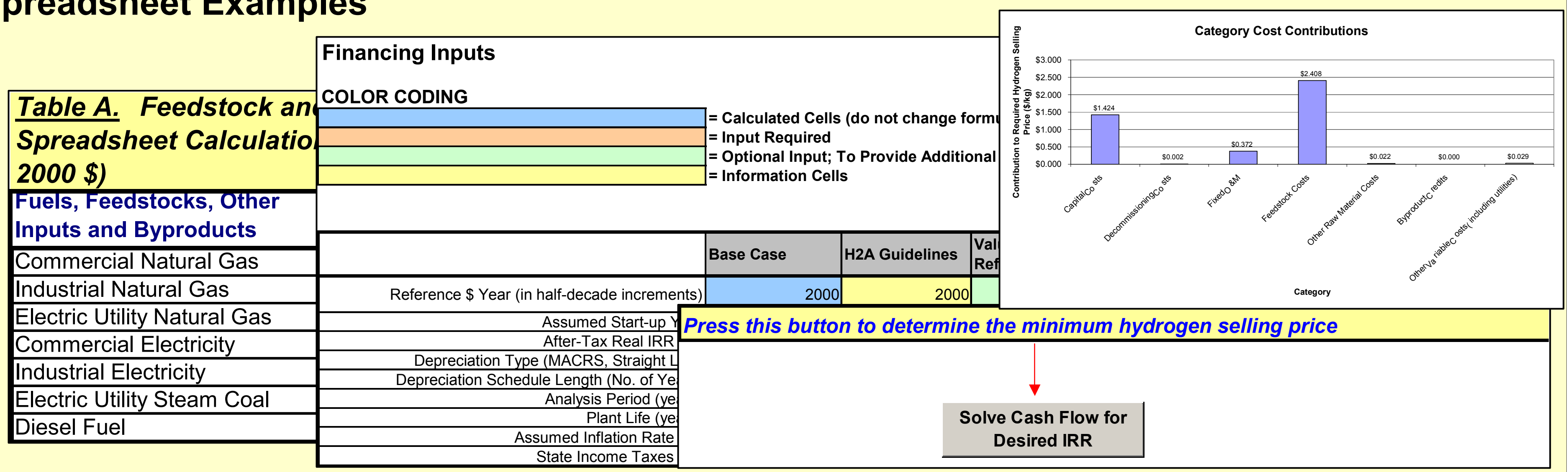
H2A Model Description

- 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



Spreadsheet Examples



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

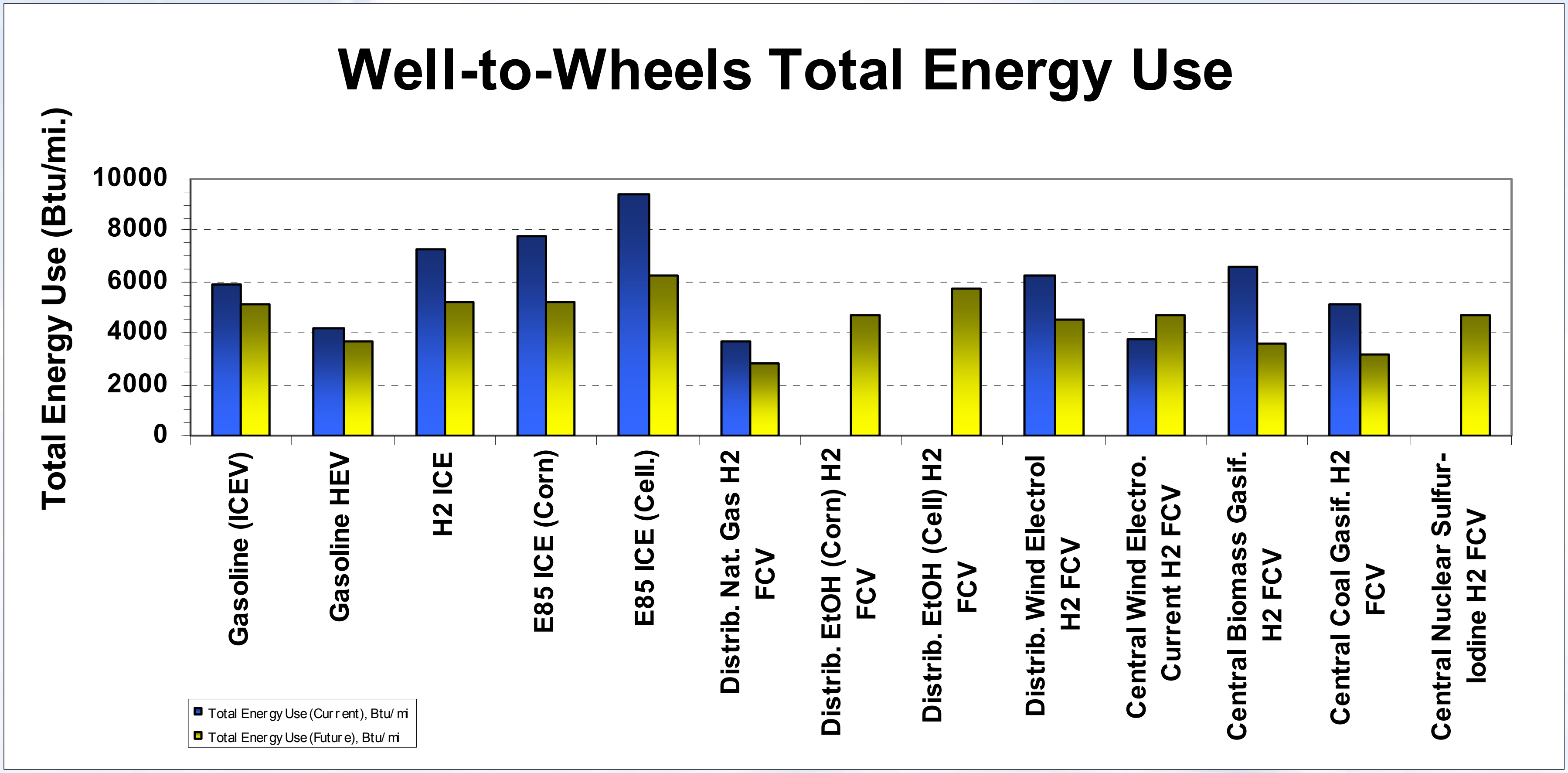
- Electrolysis (one option)
- Electricity not necessarily produced as an intermediary, options being pursued include:
  - Gasification of biomass
  - Reforming of renewable liquids
  - Photoelectrochemical
  - Photobiological
  - Thermochemical (solar and nuclear)

Coal

- Only with carbon capture & sequestration
- Gasification process produces hydrogen directly
- Electricity not produced as an intermediary

WTW Analysis Results

Well-to-Wheels Total Energy Use

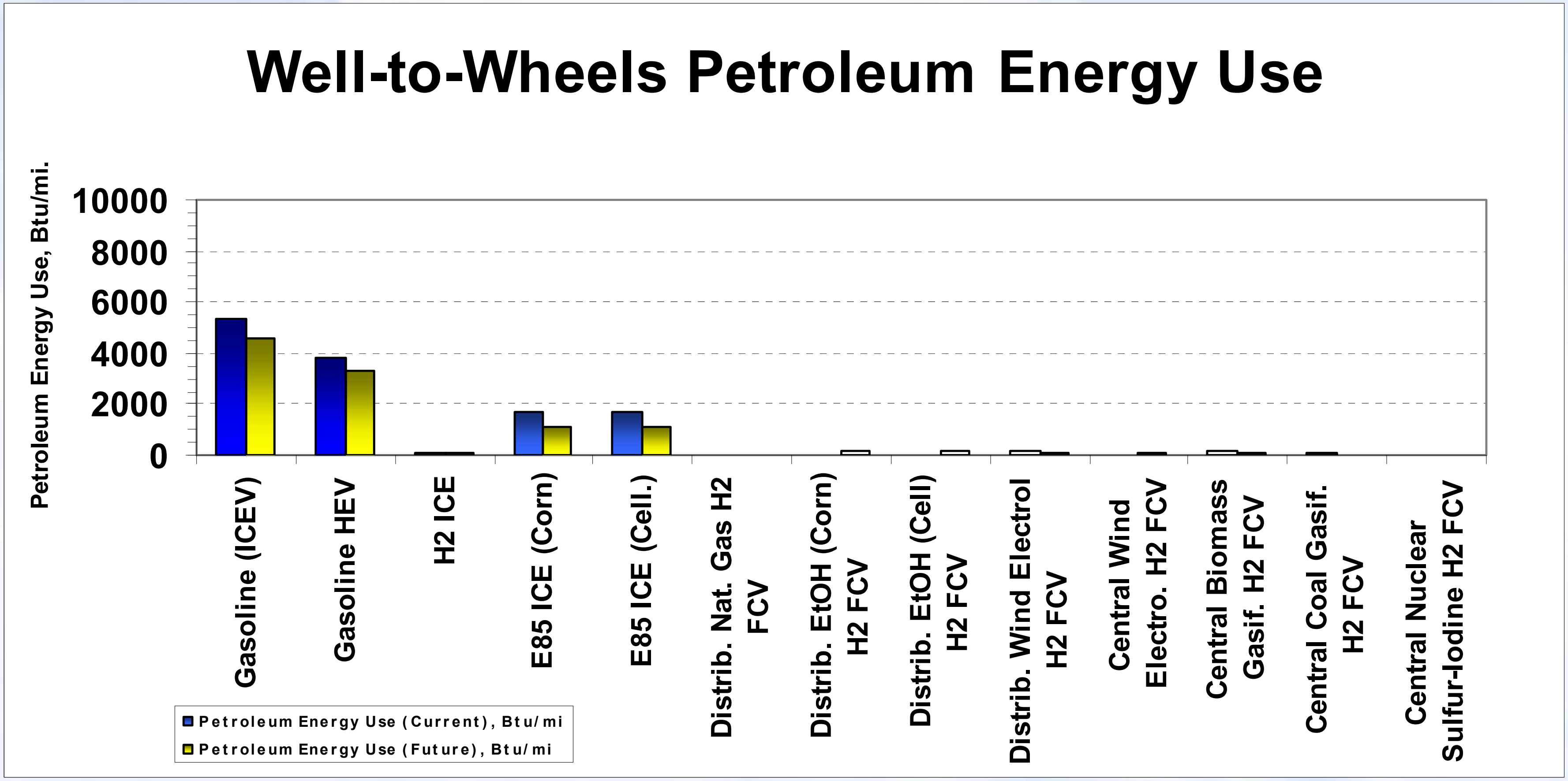


Vehicle Fuel Economy used in the analysis:

Fuel Economy, mpgge	Gaso. ICE	Gaso.HEV	E85 ICE	H2 ICE	FCV HEV
2005	24	34	24	29	57
2015	28	39	28	34	66

Sources: H2A and GREET models

Well-to-Wheels Petroleum Energy Use



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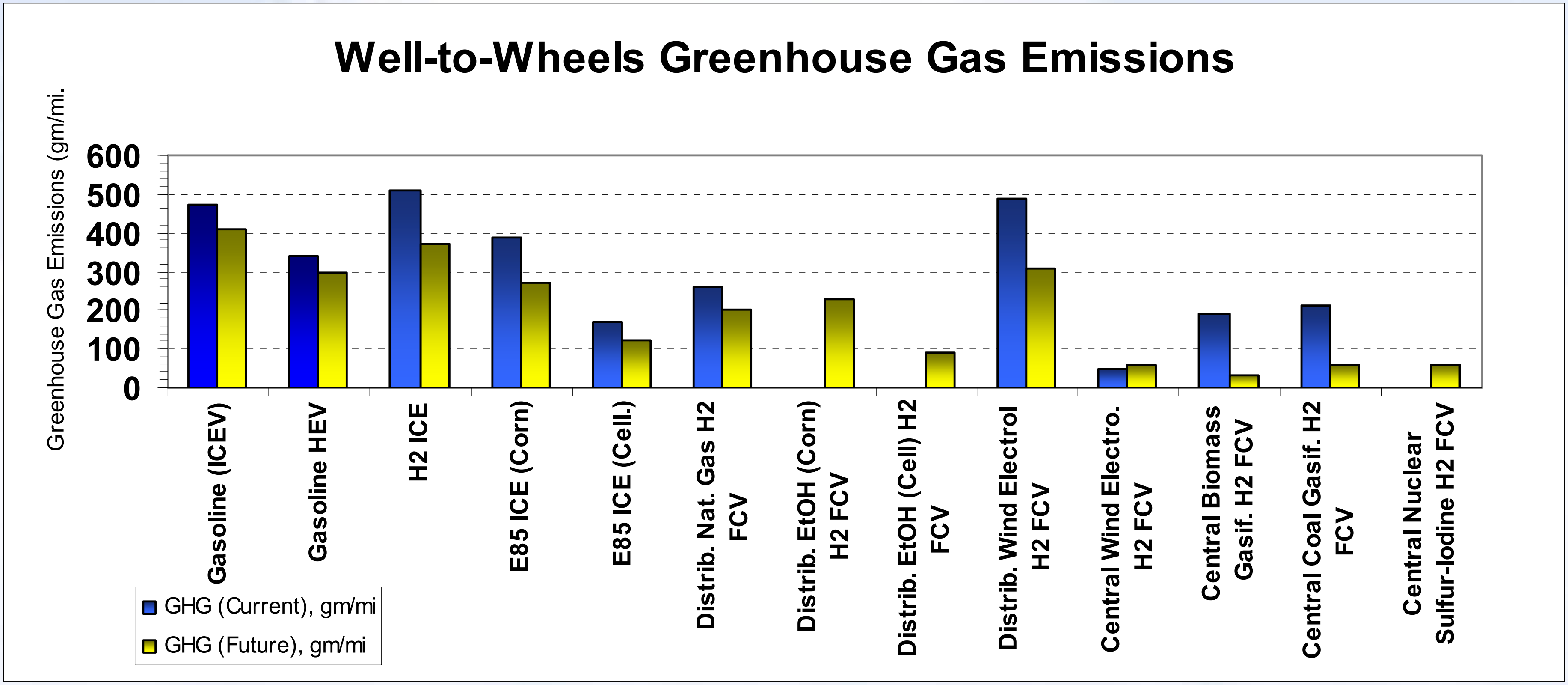
Sources: H2A and GREET models

Well-to-Wheels Greenhouse Gas Emissions



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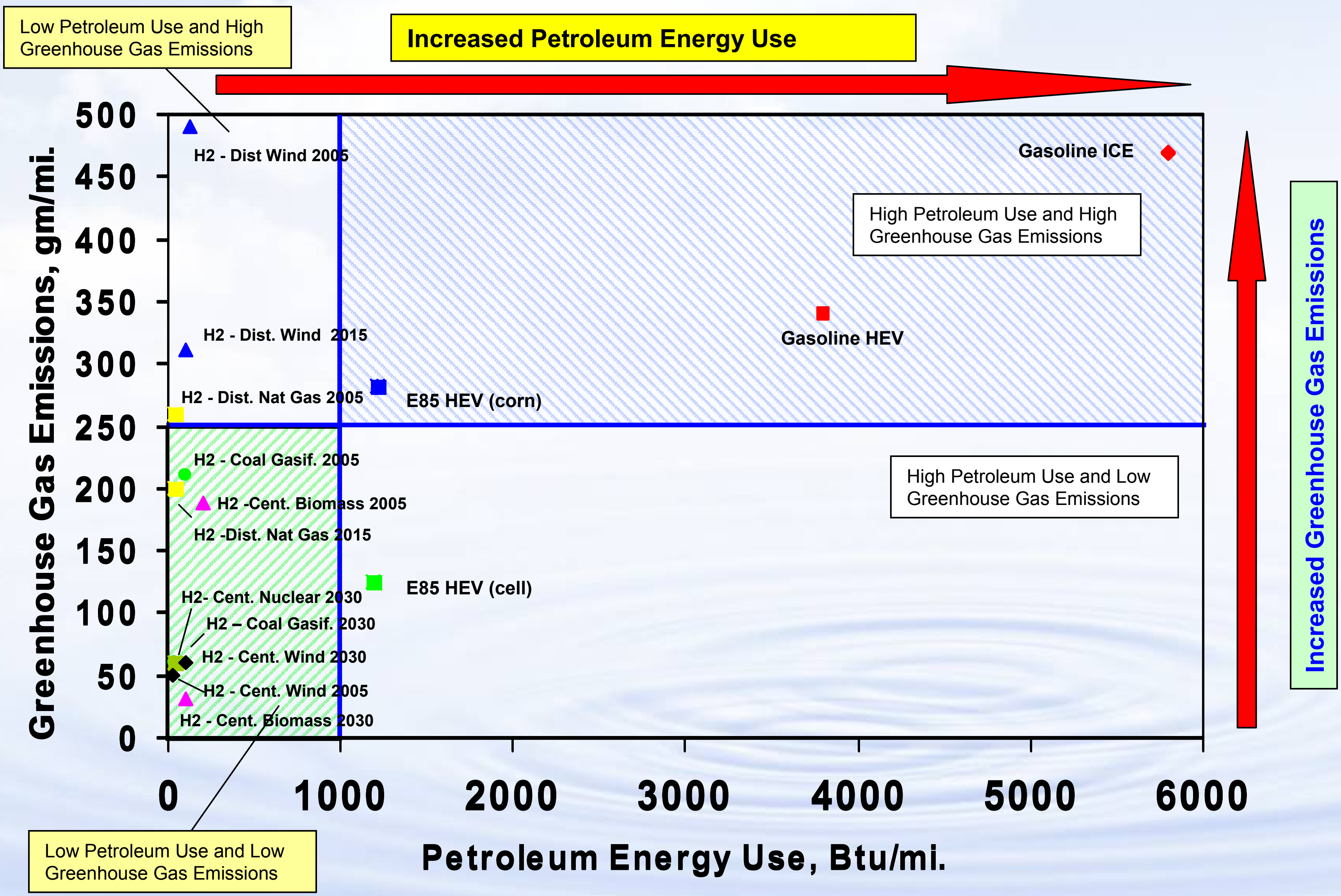
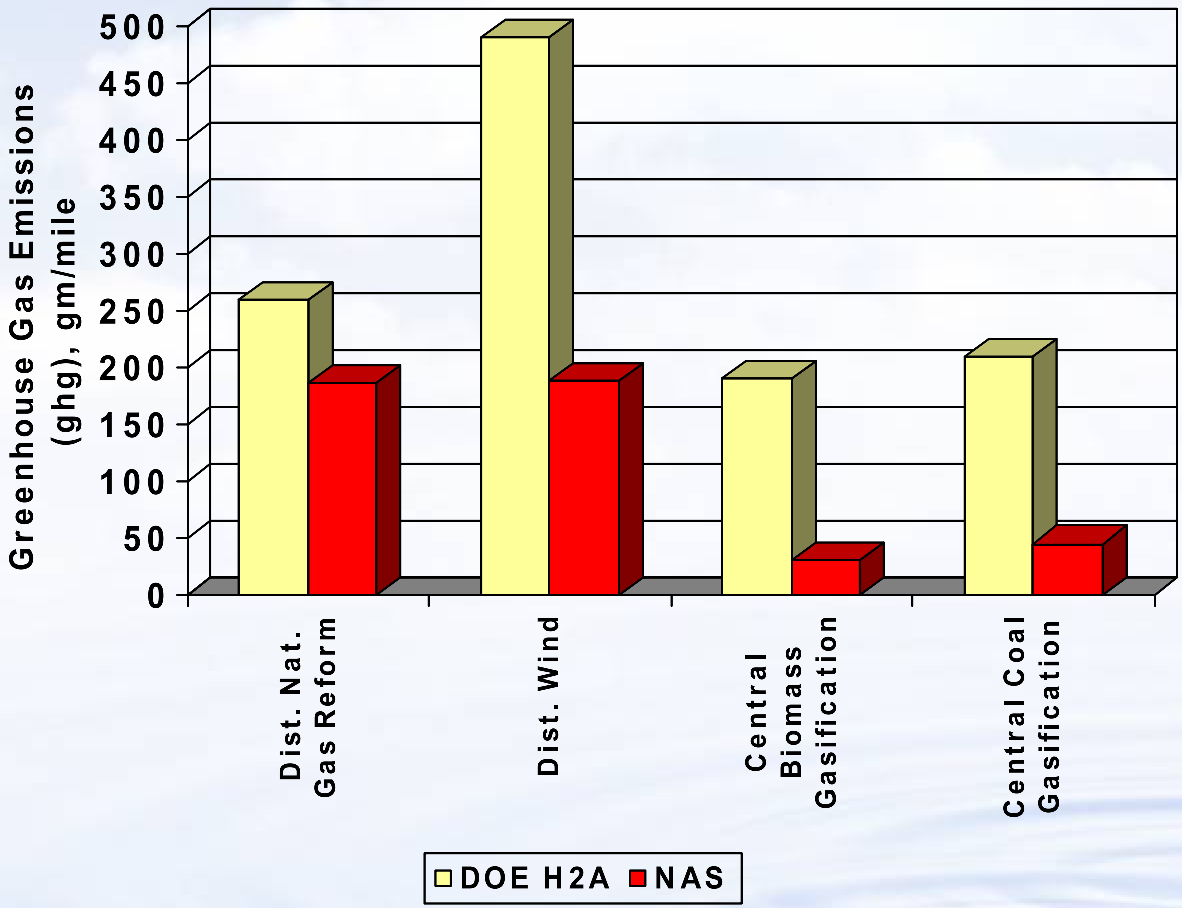
Fuel Economy, mpgge	Gaso. ICE	Gaso.HEV	E85 ICE	H2 ICE	FCV HEV
2005	24	34	24	29	57
2015	28	39	28	34	66

Sources: H2A and GREET models

GHGs vs. Petroleum Energy Use for Technologies



Comparison of DOE and NAS Greenhouse Gas Emissions (GHG) for the Current Case

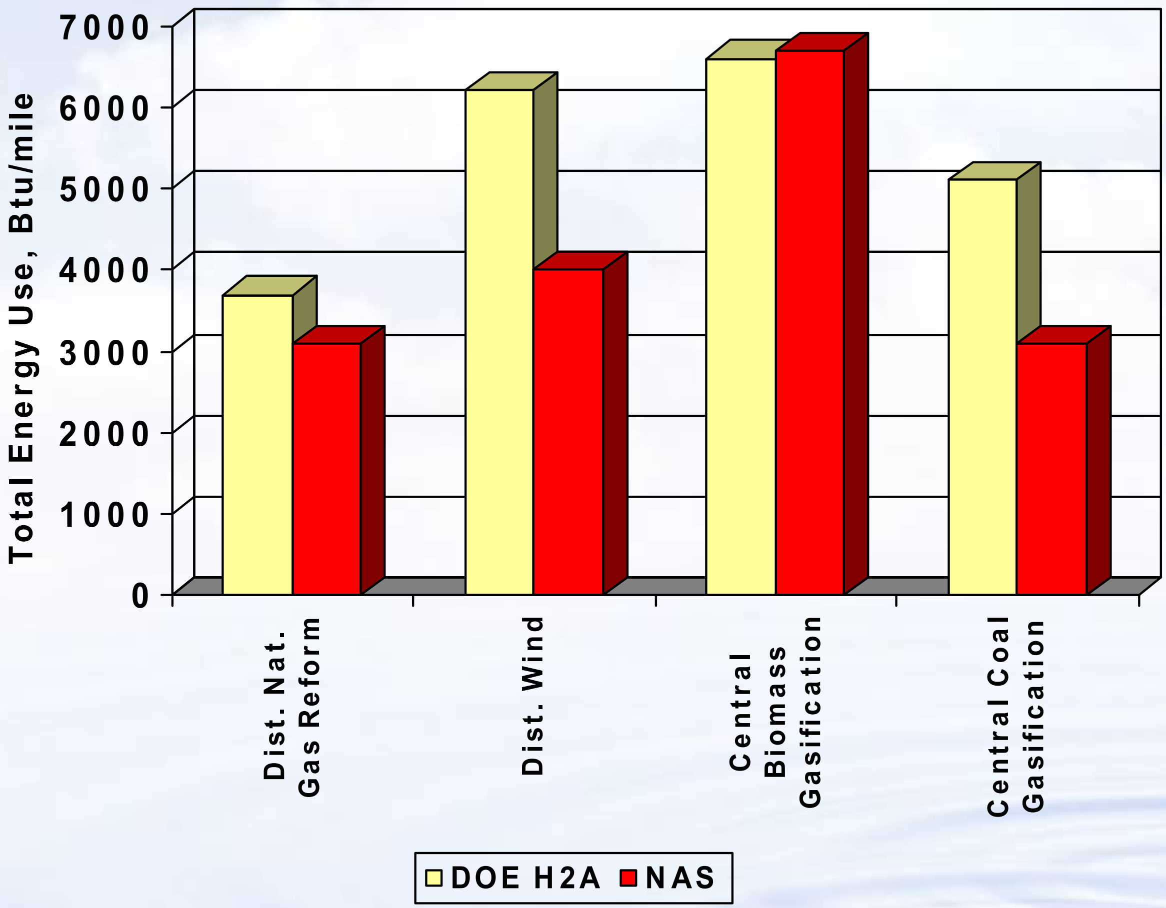


Differences and Assumptions

- 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



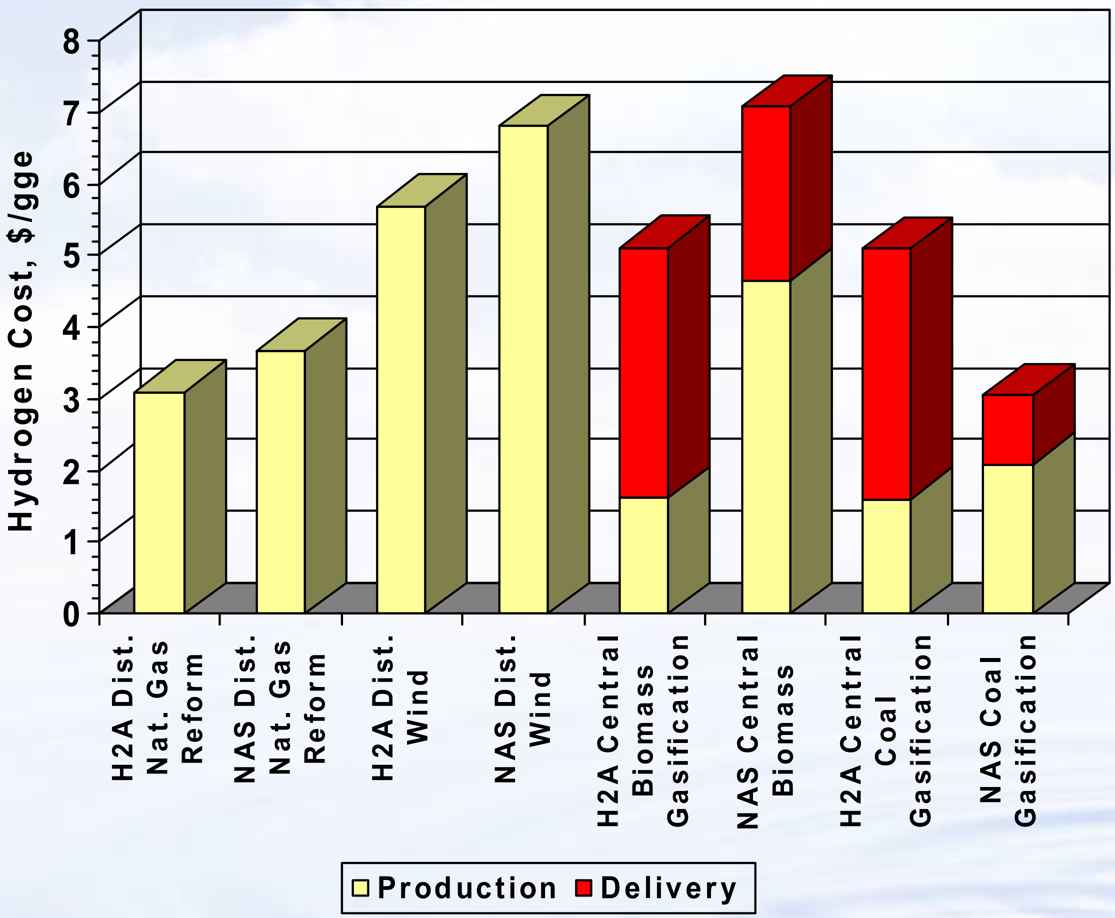
Differences and Assumptions

- 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



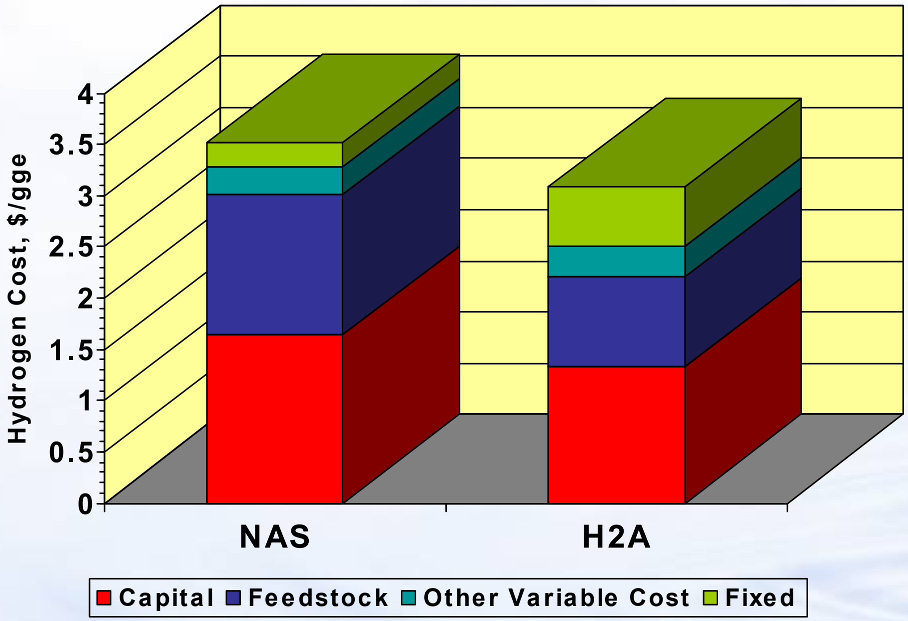
Differences and Assumptions

- 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

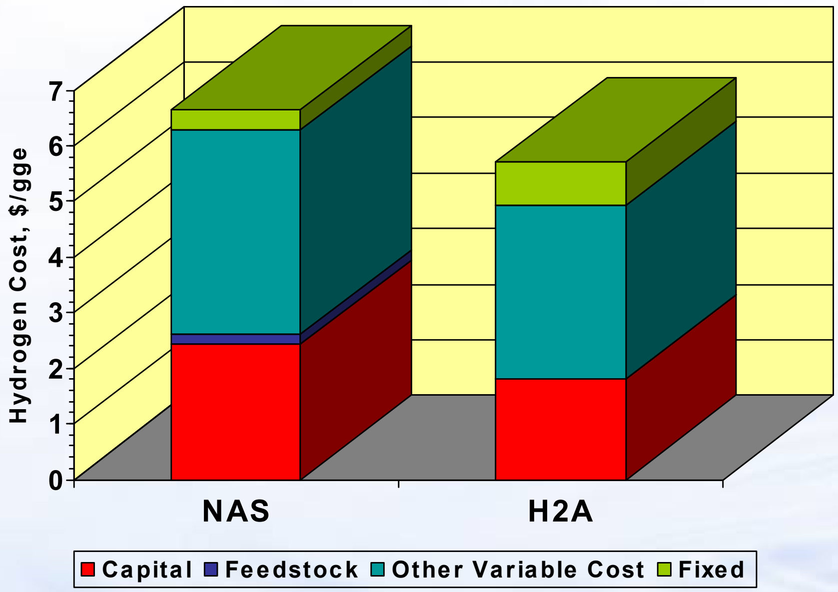
Cost Elements	**NAS H2 cost, $/kg.**	**DOE H2A Model H2 cost, $/kg**
Production		
Capital	1.64	1.33
Feedstock	1.37	0.88
Other variable	0.27	0.30
Fixed	0.23	0.58
Total	**3.51**	**3.09**



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

Comparison of NAS and DOE H2A Hydrogen Production from Distributed Wind Electrolysis

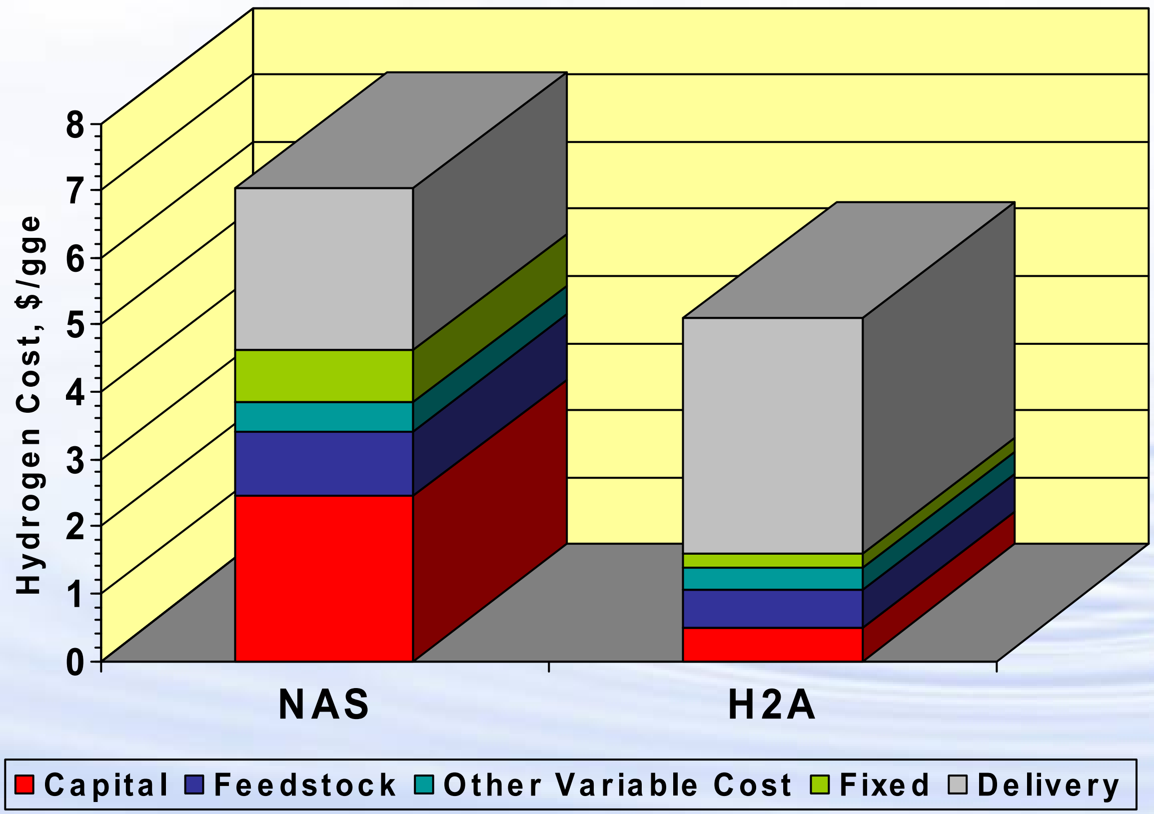
Cost Elements	NAS H2 cost, $/kg.	DOE H2A Model H2 cost, $/kg
Production		
Capital	2.44	1.80
Feedstock	0.17	0.02
Other variable	3.68	3.10
Fixed	0.35	0.80
Total	**6.64**	**5.72**



Key Factor	H2A Dist. Wind Electrolysis Assumption	NAS Distributed Wind Electrolysis Assumption	Impact on the hydrogen cost
Hydrogen production rate	1,500 kg/day	480 kg/day	The lower rate increases the plant production cost due to economies of scale.
Electricity price	$0.052/kWhr	$0.07/kWhr	The higher electricity price will increase the cost of the hydrogen product.
Electrolyzer cost	$780/kW	$1228/kW	The higher electrolyzer cost will increase the cost of the hydrogen product.

Comparison of NAS and DOE H2A Hydrogen Production from Biomass Gasification

Cost Elements	NAS H2cost, $/kg.	DOE H2A Model H2 cost, $/kg
Production		
Capital	2.44	0.52
Feedstock	0.98	0.58
Other variable	0.44	0.31
Fixed	0.77	0.21
Total	**4.63**	**1.62**
Delivery	2.42	3.50
Total delivered H2	**7.05**	**5.12**

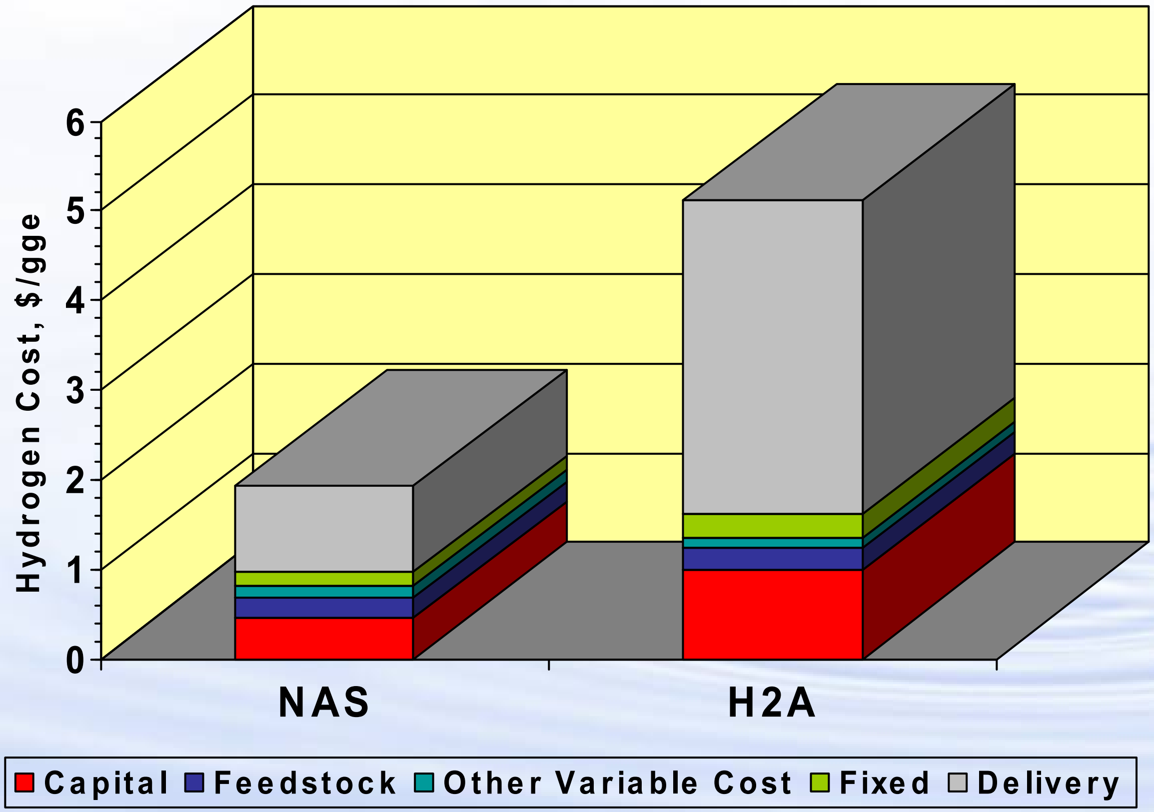


Comparison of NAS and DOE H2A Hydrogen Production from Biomass Gasification

Key Factor	NAS Study Assumption	H2A Assumption	Impact on the hydrogen cost
Gasifier Type	Shell High Pressure Oxygen Blown Gasifier	Batelle Indirectly Heated, Low Pressure (without oxygen)	The Shell gasifier type has a significantly higher capital cost than the Batelle
Gasifier Operating Pressure, psia	1515	40	Higher pressure increases the equipment cost of the Shell gasifier.
Source of process oxygen	Cryogenic Air Separation Unit (ASU)	None	The need for the ASU for the Shell gasifier adds significant capital cost.
Hydrogen production rate	24,000 kg/day	155,000 kg/day	The lower rate will increase the plant production cost due to economies of scale.
Spare gasifier vessels	1	0	The spare, high pressure gasifier vessel will increase the capital cost and the cost of hydrogen.
Feedstock cost	$53/dry ton	$38/dry ton	The higher feedstock cost will increase the cost of hydrogen
Feedstock usage factor	15.1 kg of biomass/kg of hydrogen	13.6 kg of biomass/kg of hydrogen	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.

Comparison of NAS and DOE H2A Hydrogen Production from Coal Gasification

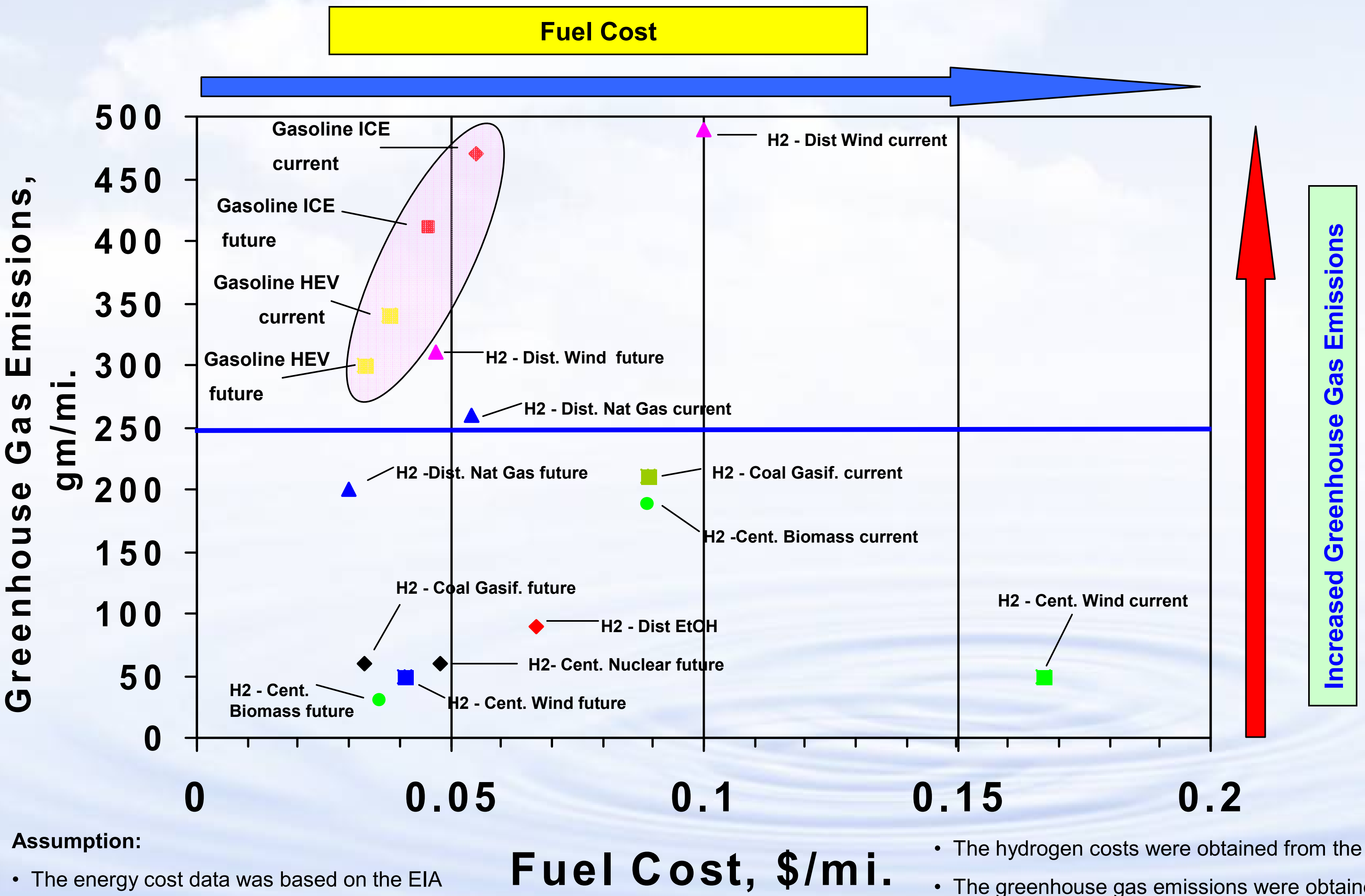
Cost Elements	**NAS H2cost, $/kg.**	**DOE H2A Model H2 cost, $/kg**
Production		
Capital	0.46	1.00
Feedstock	0.21	0.24
Other variable	0.14	0.11
Fixed	0.15	0.27
Total	**0.96**	**1.62**
Delivery	0.96	3.50
Total delivered H2	**1.92**	**5.12**



Comparison of NAS and DOE H2A Hydrogen Production from Coal Gasification

Key Factor	H2A Coal Gasification Assumptions	NAS Coal Gasification Assumptions	Impact on the hydrogen cost
Gasifier Type	Texaco High Pressure Oxygen Blown Gasifier	Texaco High Pressure Oxygen Blown Gasifier	Not applicable
Gasifier Operating Pressure, psia	1515	1515	No difference
Source of process oxygen	Cryogenic Air Separation Unit (ASU)	Cryogenic Air Separation Unit (ASU)	No difference
Hydrogen production rate	308,000 kg/day	1,200,000 kg/day	The lower rate of the H2A coal gasifier increases the plant production cost due to economies of scale.
Spare gasifier vessels	1	1	No difference
Feedstock cost	$30/tonne	$32/tonne	The higher feedstock cost increases the cost of hydrogen of the H2A coal gasifier.
Feedstock usage factor	7.8 kg of coal/kg of hydrogen	6.5 kg of coal/kg of hydrogen	The higher feedstock usage factor increases the hydrogen cost for the H2A gasification.

GHGs vs. Fuel Cost for Technologies

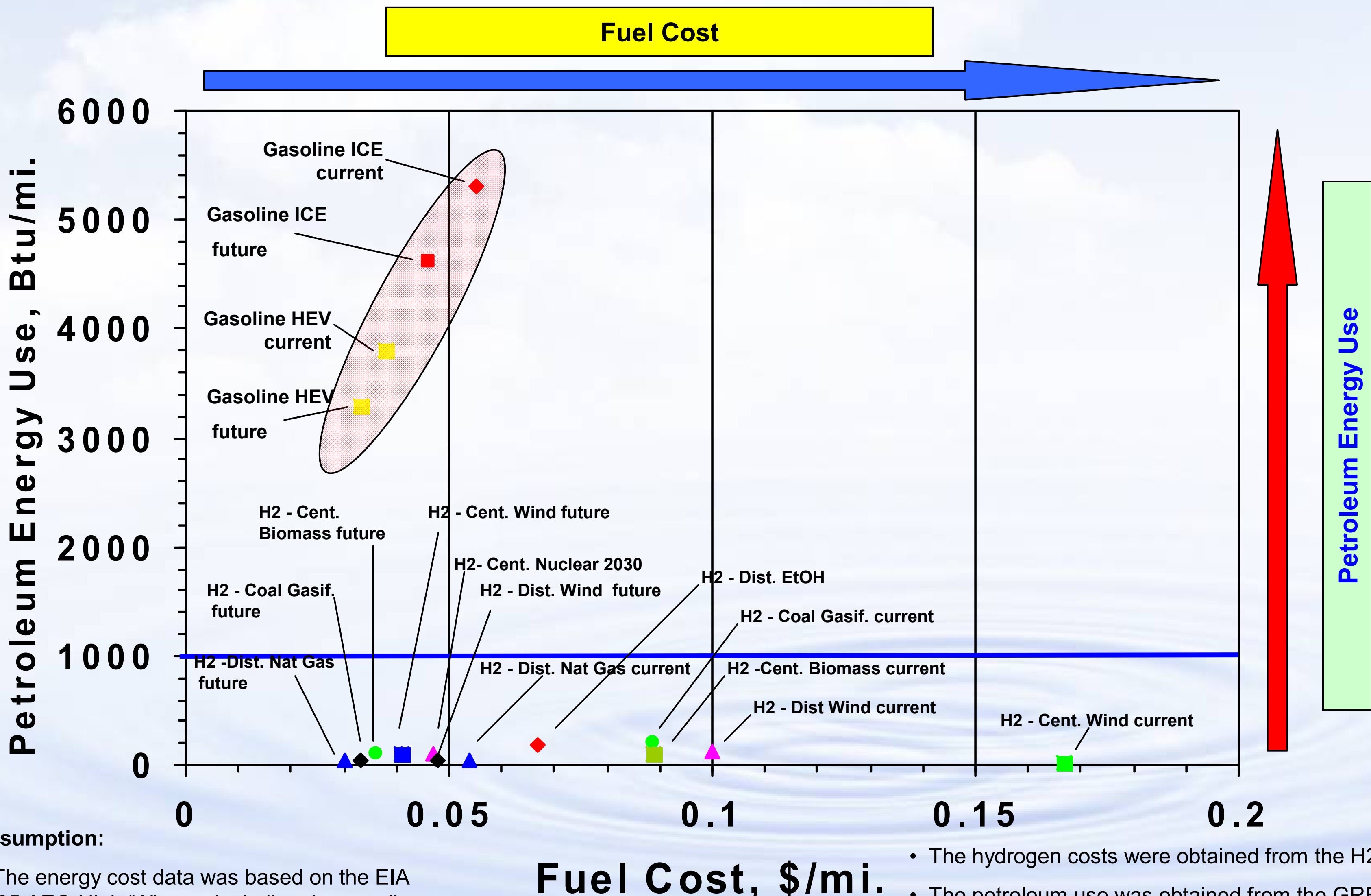


Assumption:

- 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 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.

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

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Backup

Well-to-Wheels Analysis: Hydrogen Pathways
Distributed Ethanol Reforming

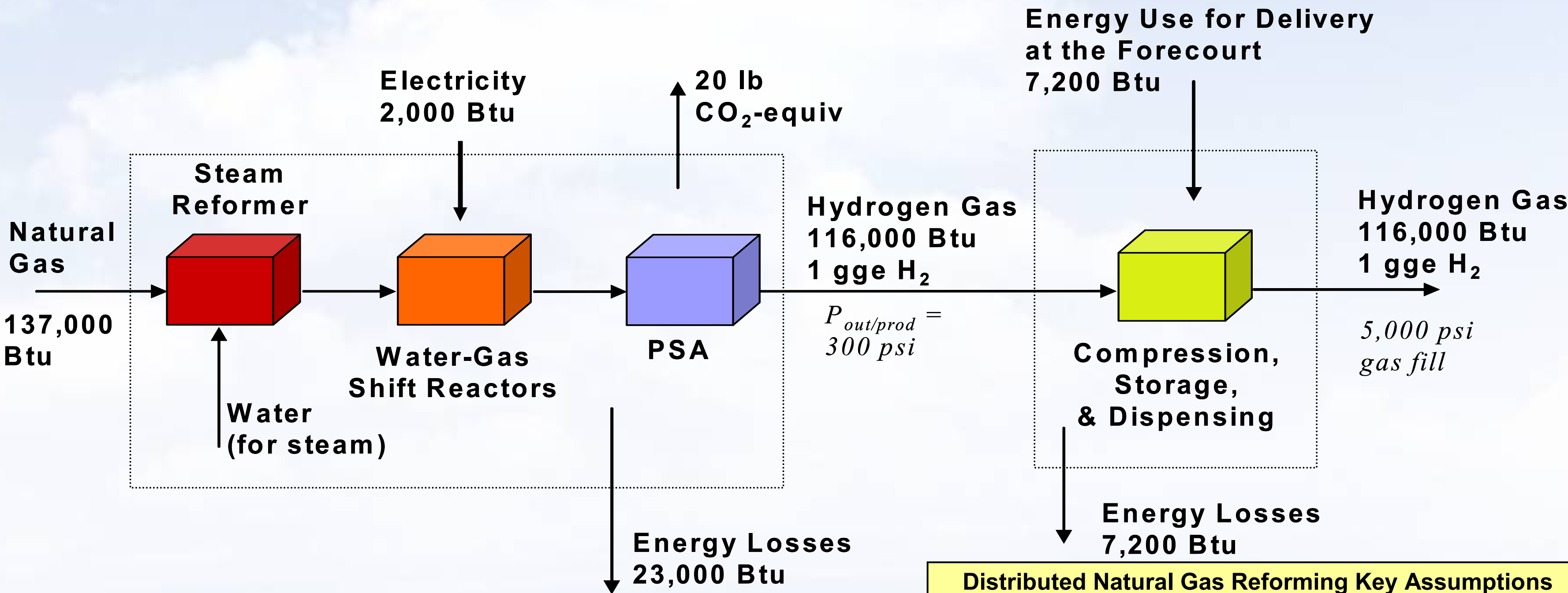
Well-to-Wheels Energy and Greenhouse Gas Emissions Data			
	Gasoline ICE Vehicle	Gasoline Hybrid Electric Vehicle	Distributed Ethanol Reformer - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	5740
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	190
Well-to-Wheels Greenhouse Gas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

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



Well-to-Wheels Energy and Greenhouse Gas Emissions Data				
	Gasoline ICE Vehicle	Gasoline Hybrid Electric Vehicle	Current Distributed SMR FCV	Future (2015) Distributed SMR FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	3,700	2,800
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	40	40
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	260	200
Cost of Hydrogen ($/gge, Delivered)			3.10	2.00

Source: NREL and ANL

Distributed Natural Gas 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 SMR.
3. Costs include hydrogen production, compression, storage and dispensing to the vehicle.
4. Natural gas feedstock price for current and future cases based on 2015 industrial gas ($5.24/MM Btu LHV) by DOE's EIA Energy Outlook 2005 High A case. Price is in 2005$.
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

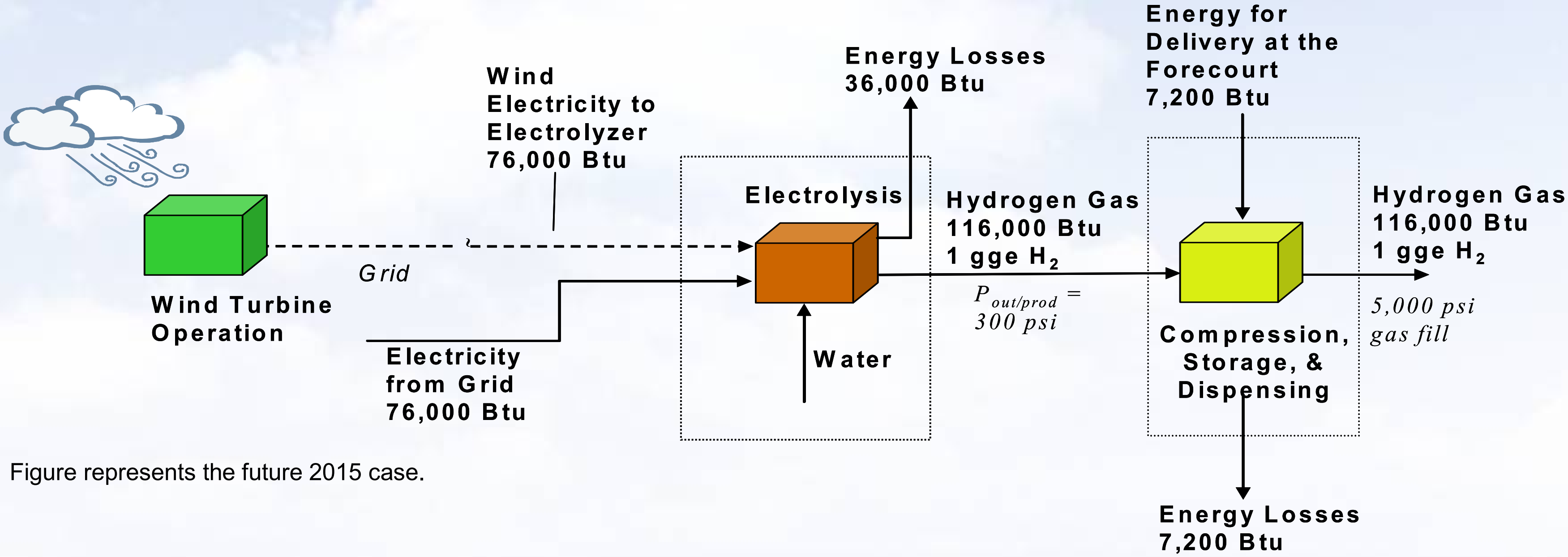


Figure represents the future 2015 case.

Well-to-Wheels Energy and Greenhouse Gas Emissions Data				
	Current (2005) Gasoline ICE Vehicle	Current (2005) Gasoline Hybrid Electric Vehicle	Current (2005) Distributed Electrolysis Using Wind/Grid - FCV	Future (2015) Distributed Electrolysis Using Wind/Grid - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	6,200	4,500
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	130	100
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	490	310
Cost of Hydrogen ($/gge, Delivered)			5.70	3.10

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

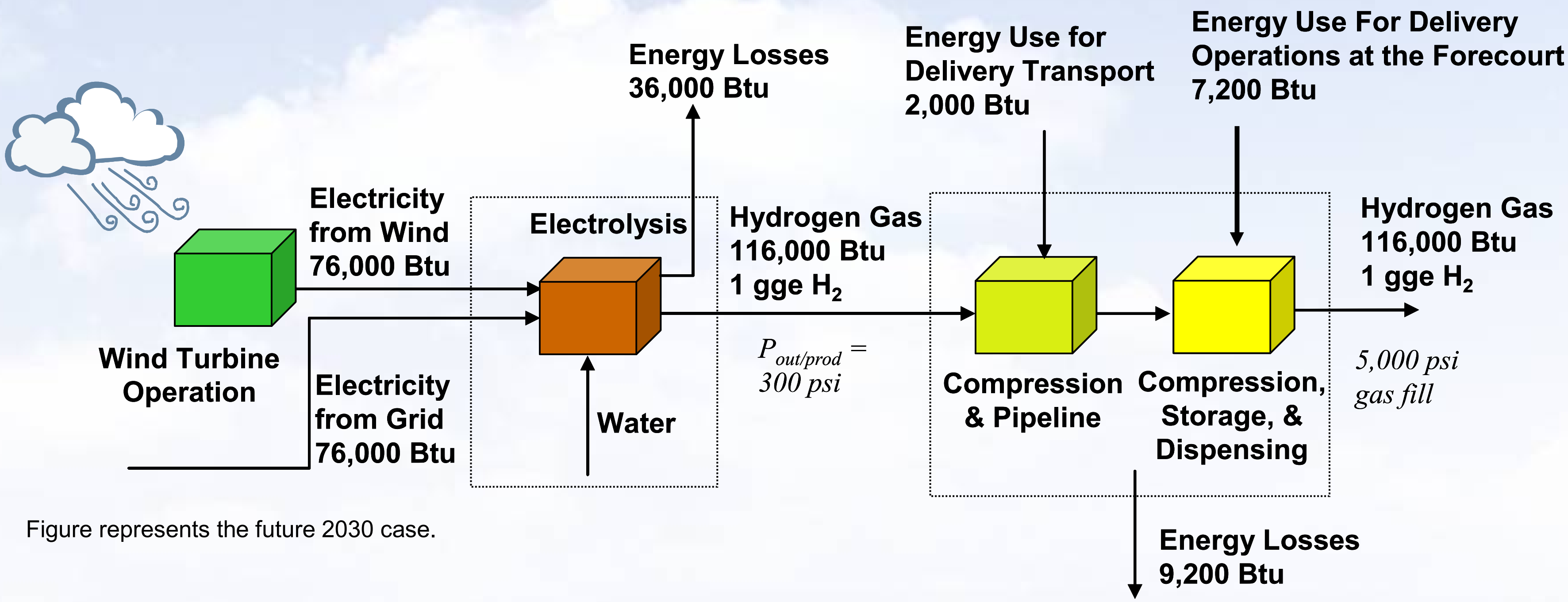


Figure represents the future 2030 case.

Well-to-Wheels Energy and Greenhouse Gas Emissions Data				
	Current (2005) Gasoline ICE Vehicle	Current (2005) Gasoline Hybrid Electric Vehicle	Current (2005) Central Electrolysis Using Wind - FCV	Future (2030) Central Electrolysis Using Wind/Grid - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	3,800	4,700
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	20	100
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	50	50
Cost of Hydrogen ($/gge, Delivered)			9.50	2.70

Source: NREL and ANL

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.

Well-to-Wheels Analysis: Hydrogen Pathways

Centralized Hydrogen Production from Coal

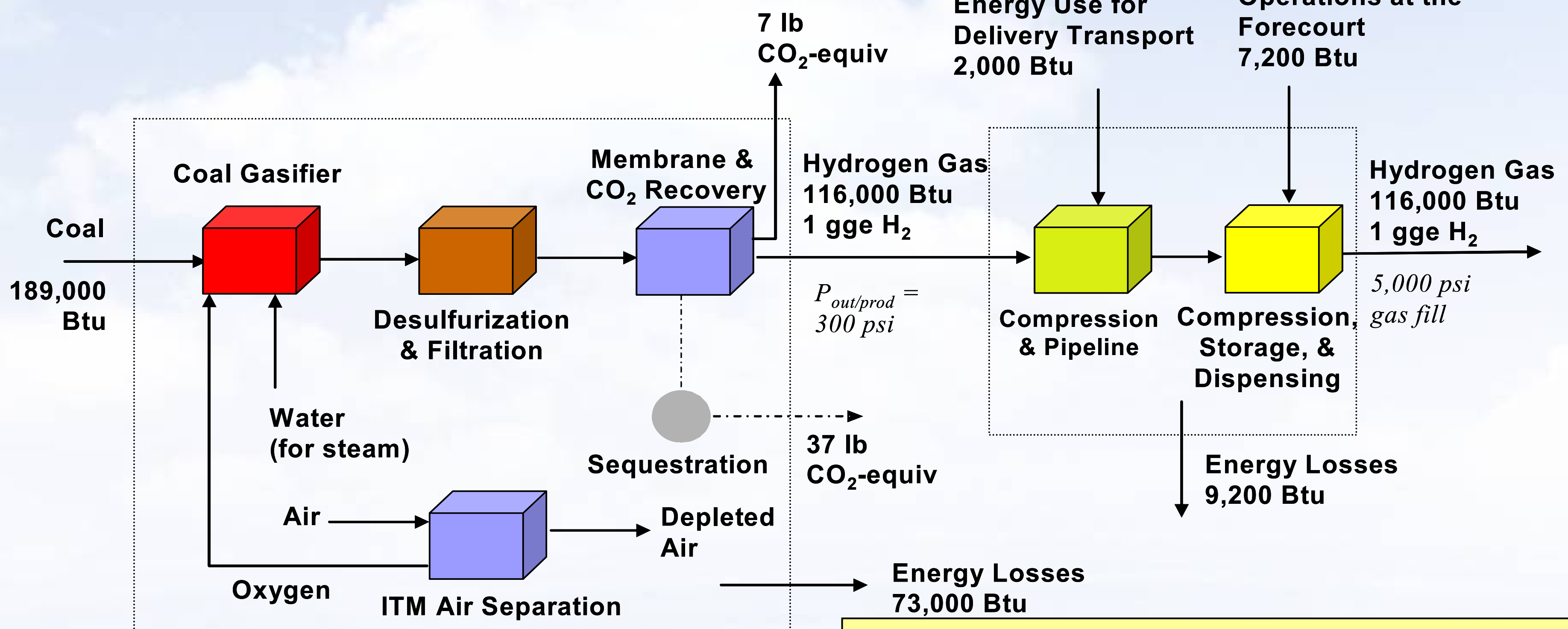


Figure represents the future 2030 case.

Well-to-Wheels Energy and Greenhouse Gas Emissions Data				
	Current (2005) Gasoline ICE Vehicle	Current (2005) Gasoline Hybrid Electric Vehicle	Current (2005) Coal with Sequestration - FCV	Future (2030) Coal with Sequestration - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	5,100	3,200
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	100	40
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	210	60
Cost of Hydrogen ($/gge, Delivered)			5.10	2.20

Central Coal Key Assumptions

1. Coal feedstock prices are based on 2015 projections for electric utility steam coal of $26.70/ton. Price is in 2005$.
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.

Centralized Hydrogen Production from Biomass

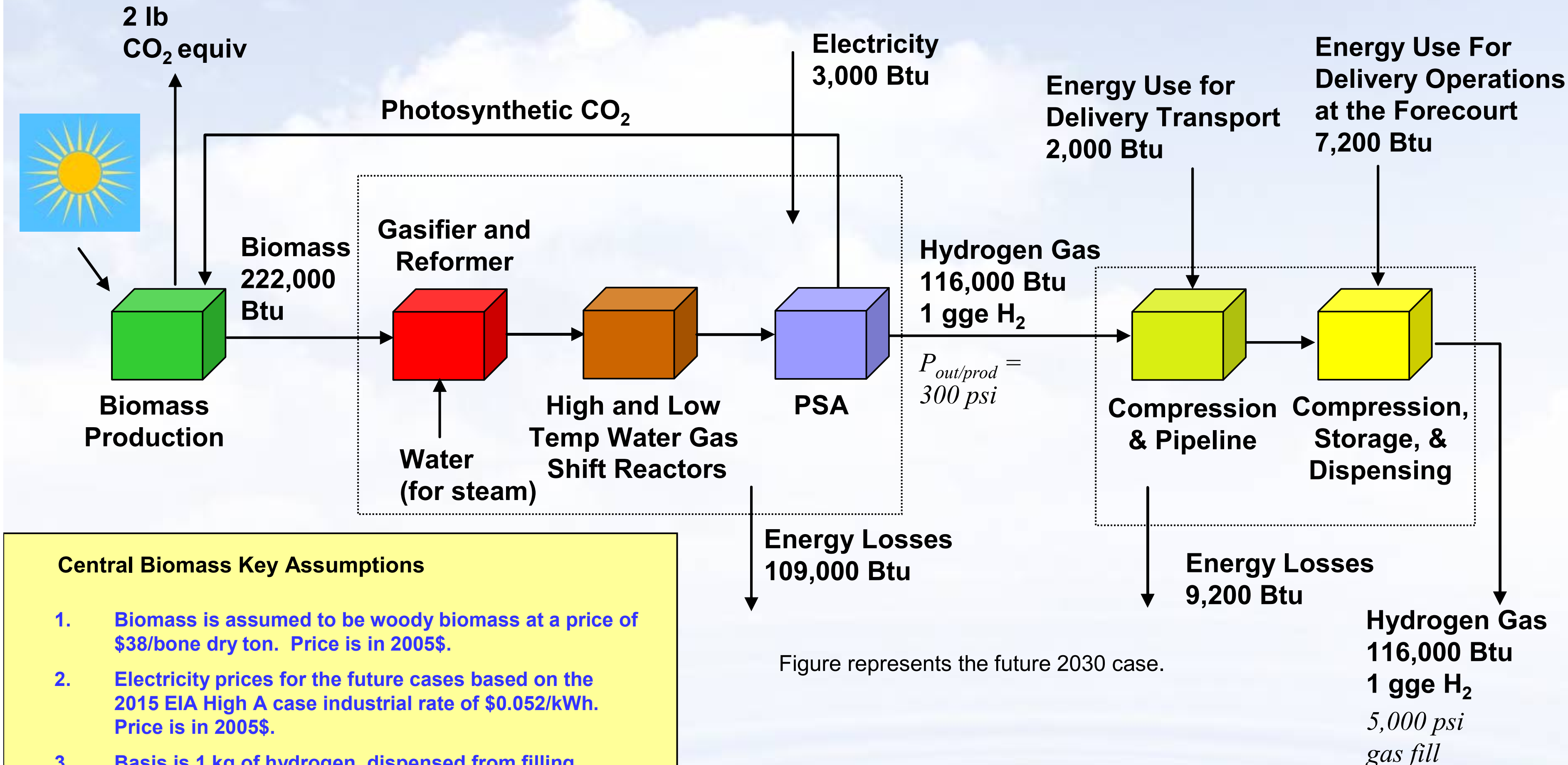


Figure represents the future 2030 case.

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

	Current (2005) Gasoline ICE Vehicle	Current (2005) Gasoline Hybrid Electric Vehicle	Current (2005) Biomass Gasification - FCV	Future (2030) Biomass Gasification - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	6,600	3,600
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	200	100
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	190	30
Cost of Hydrogen ($/gge, Delivered)			5.10	2.40

Centralized Hydrogen Production from Nuclear Sulfur-Iodine Process

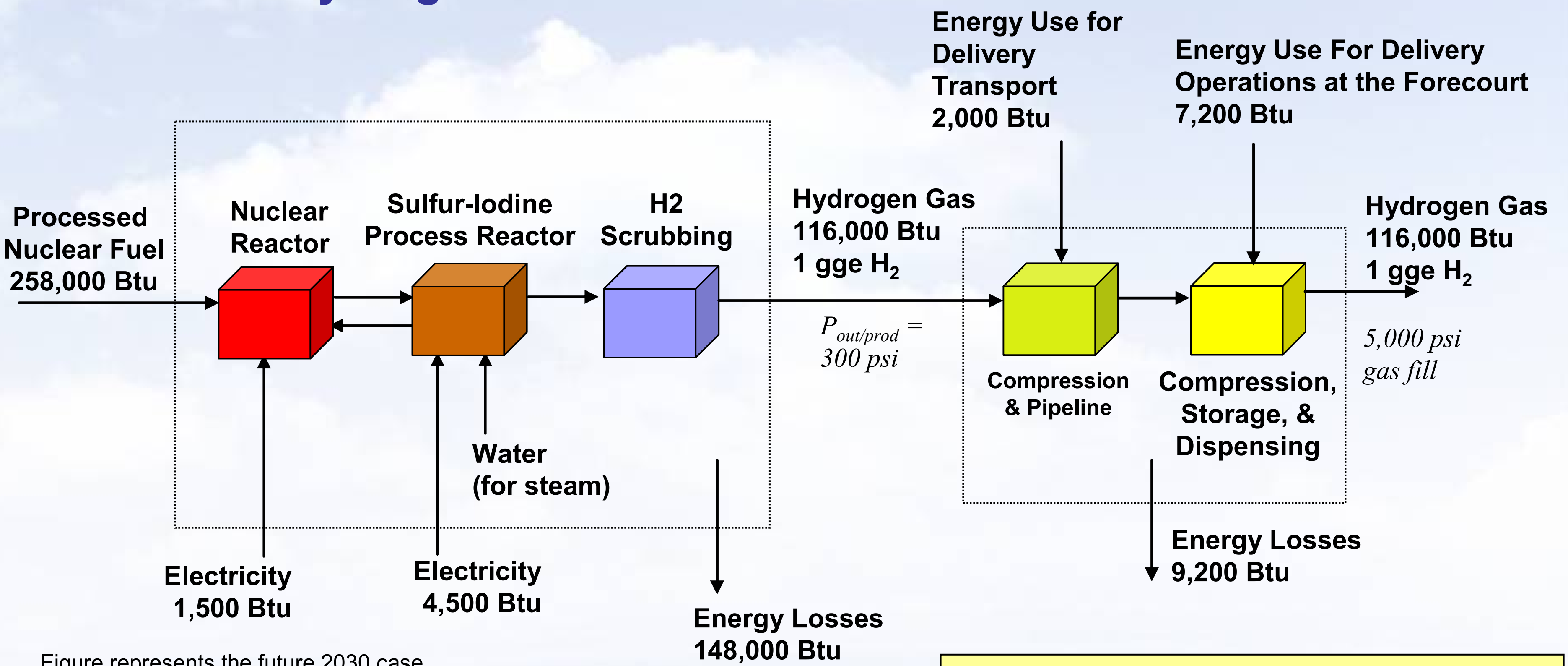


Figure represents the future 2030 case.

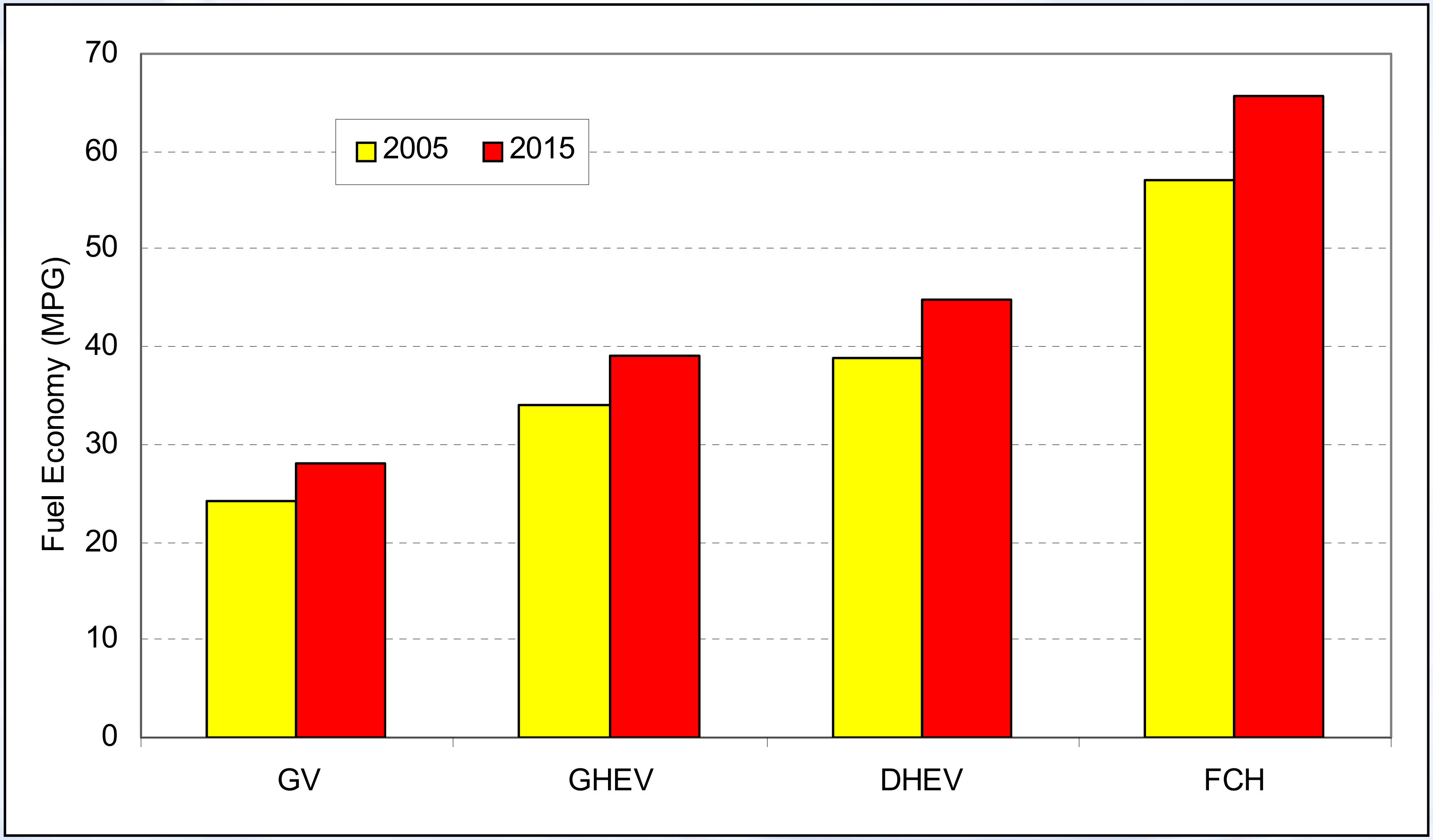
Well-to-Wheels Energy and Greenhouse Gas Emissions Data			
	Current (2005) Gasoline ICE Vehicle	Current (2005) Gasoline Hybrid Electric Vehicle	Future (2030) Nuclear Sulfur Iodine - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	4,700
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	40
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	60
Cost of Hydrogen ($/gge, Delivered)			3.20

Source: NREL and ANL

Central Nuclear Key Assumptions

1. Nuclear Fuel Cycle cost of $9.3/MWh – based on U308@$38/lb, enriched@$55/SWU (separative work unit).
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 768,000 kg/day.
4. Hydrogen delivery from the central site in the future case is by pipeline at $1.00/kg.
5. The levelized capital cost is $1.30/kg of hydrogen.
6. The operating capacity factor is 90%.

DOE WTW Analysis Effort: Pump-to-Wheels (PTW) Fuel Economy Assumptions



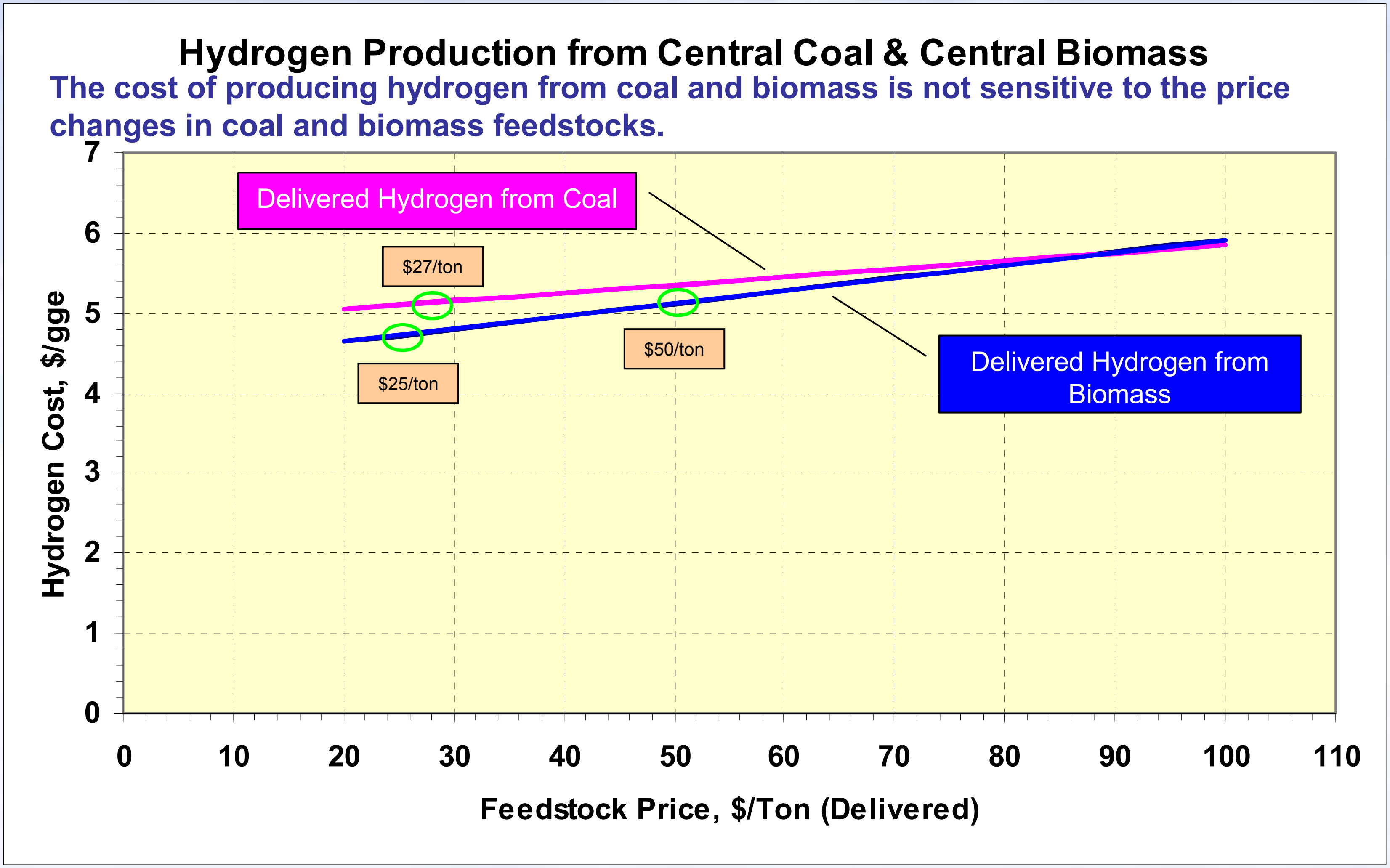
Legend:

GV – Gasoline ICE

GHEV – Gasoline Hybrid Electric Vehicle

DHEV – Diesel Hybrid Electric Vehicle

FCH – Fuel Cell Hybrid Electric Vehicle



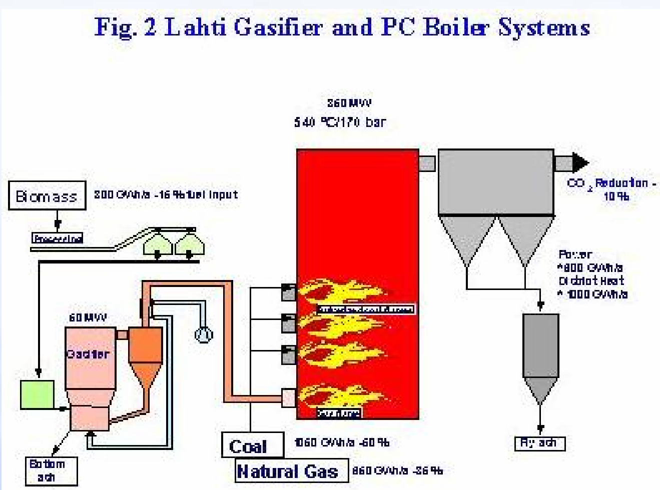
Notes:

- 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

Commercial Biomass-to-Liquids Plant, Choren Industries, Freiberg Germany, 2007: 200 mt/d biomass, 2010: 2,000 mt/d biomass

300 ton/day gasifier Burlington Electric, VT



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

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

Source: NREL