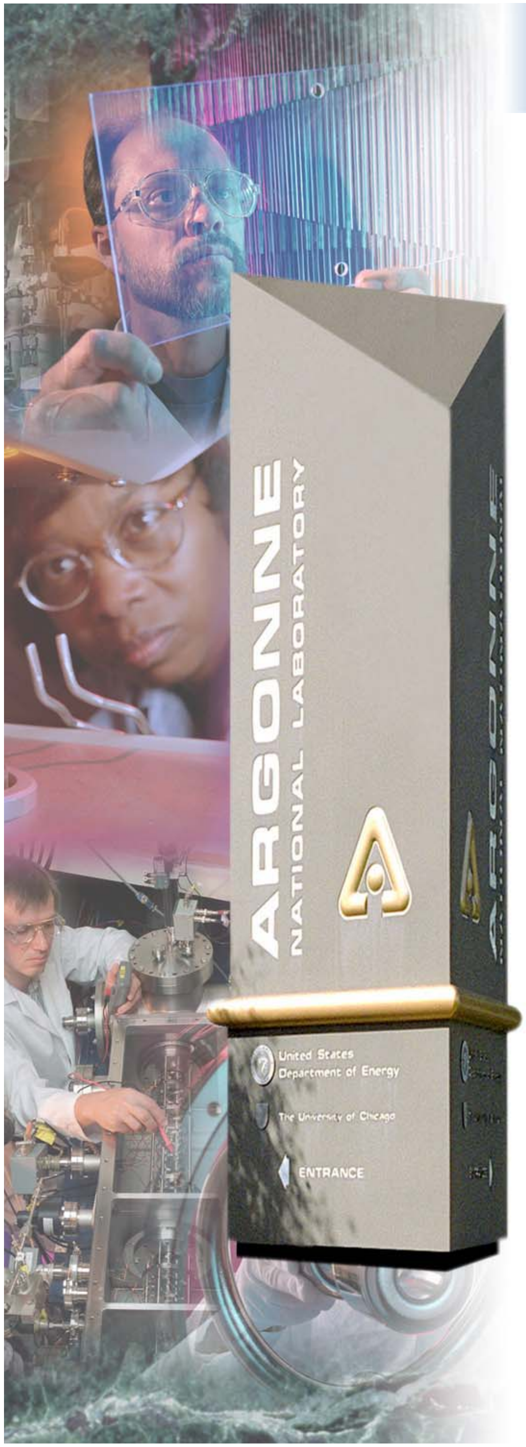

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Preliminary Assessment of Energy and GHG Emissions of Ammonia to H2 for Fuel Cell Vehicle Applications

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Center for Transportation Research

Argonne National Laboratory

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THE UNIVERSITY OF CHICAGO

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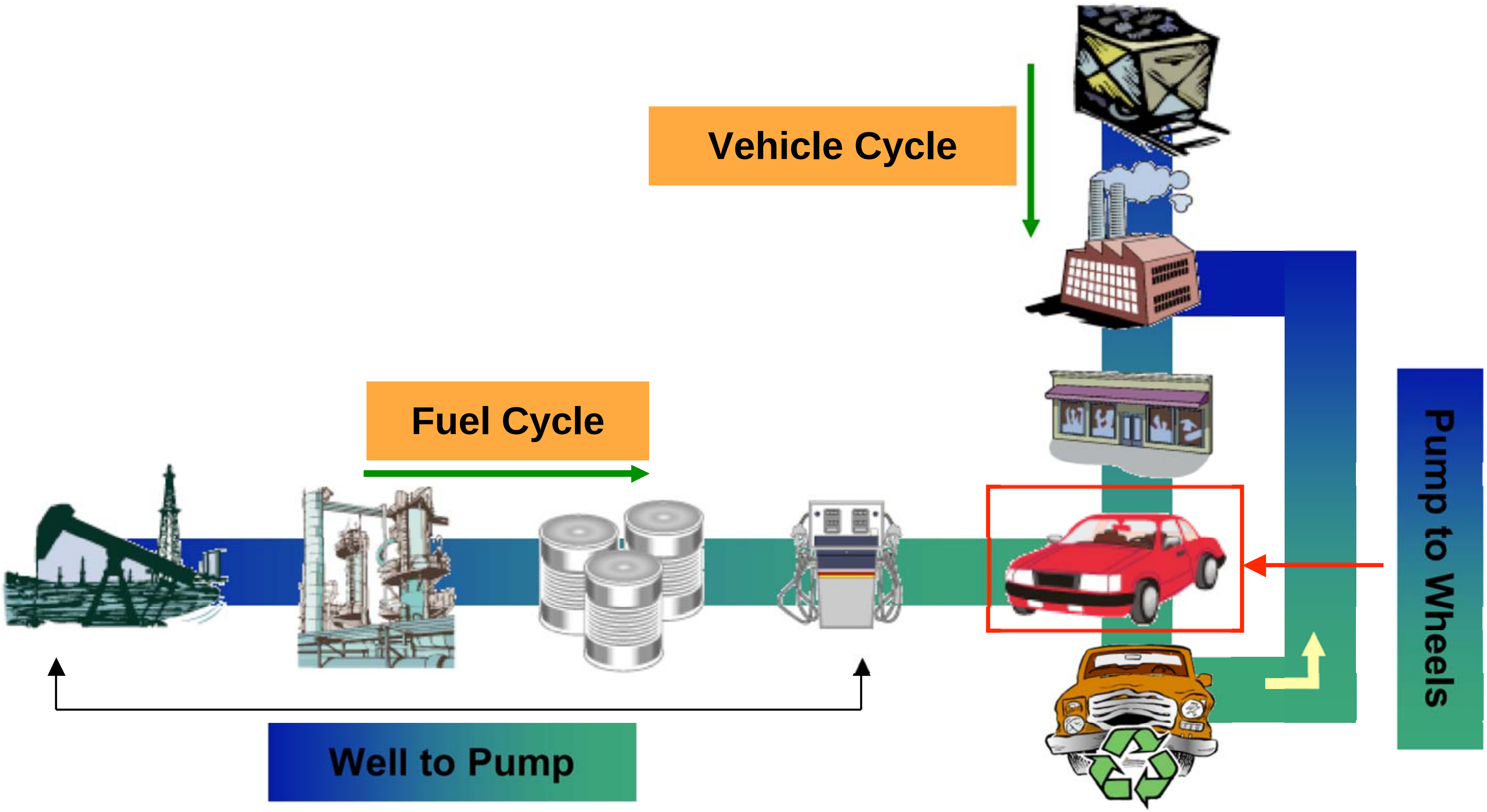
Well-to-Wheels Analysis of Vehicle/Fuel Systems Covers Activities for Fuel Production and Vehicle Use



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

- **Includes emissions of greenhouse gases**
  - CO_2, CH_4, and N_2O
  - VOC, CO, and NO_x as optional GHGs
- **Estimates emissions of five criteria pollutants**
  - VOC, CO, NO_x, SO_x, and PM_{10}
  - Total and urban separately
- **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***

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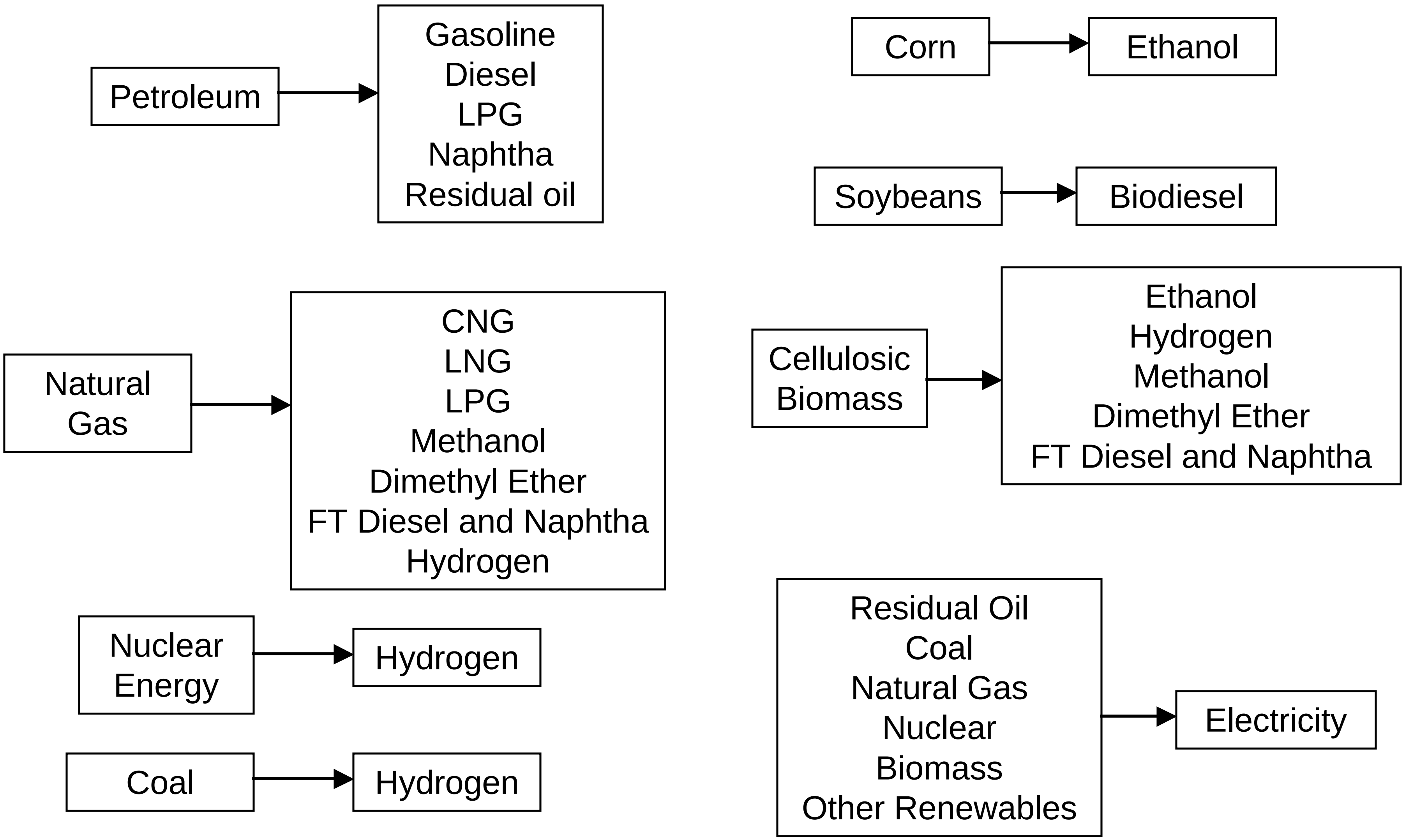
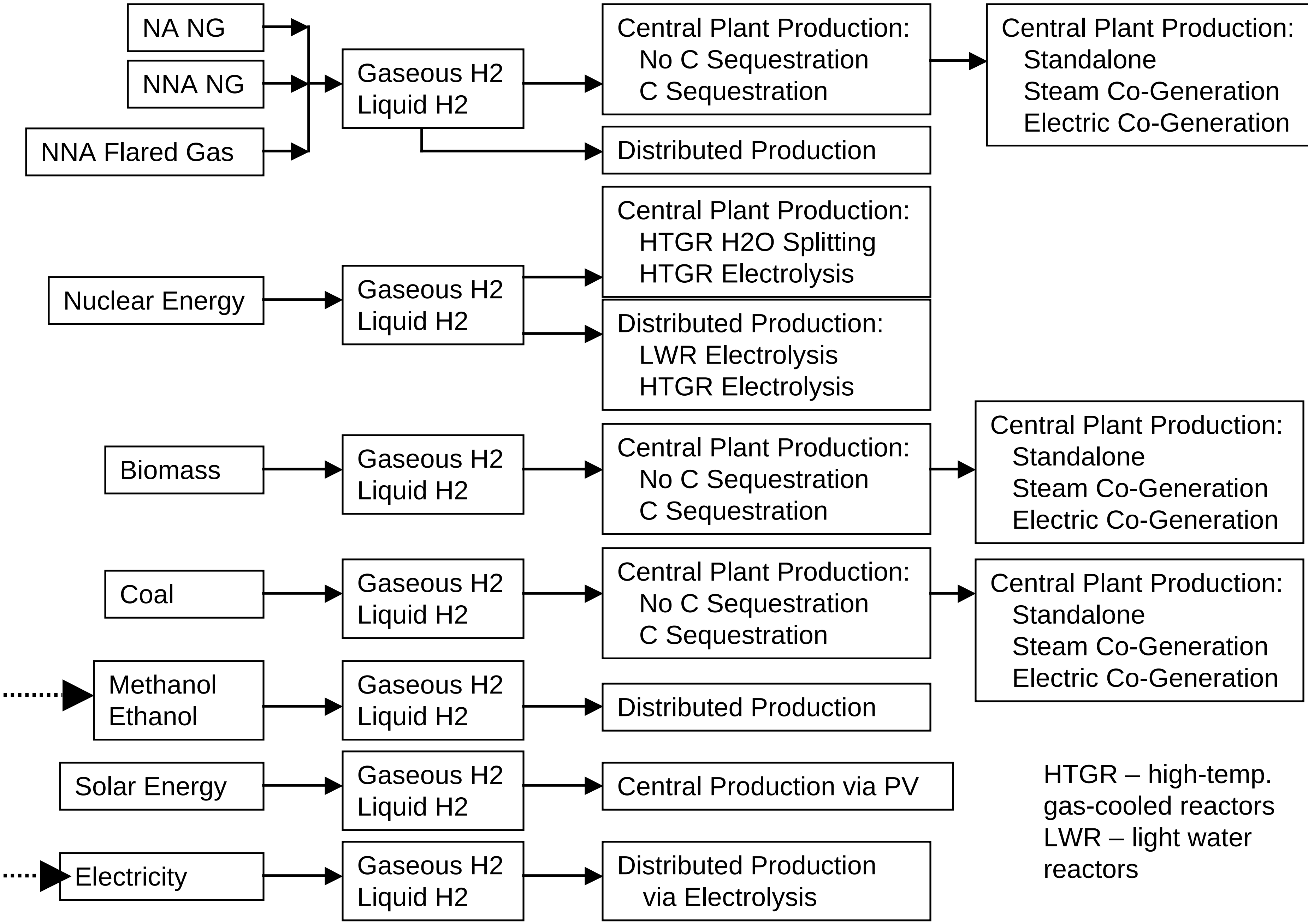
GREET Includes Transportation Fuels from Various Energy Feedstocks



GREET Includes a Varity of Hydrogen Production Pathways



HTGR – high-temp. gas-cooled reactors
LWR – light water reactors

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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

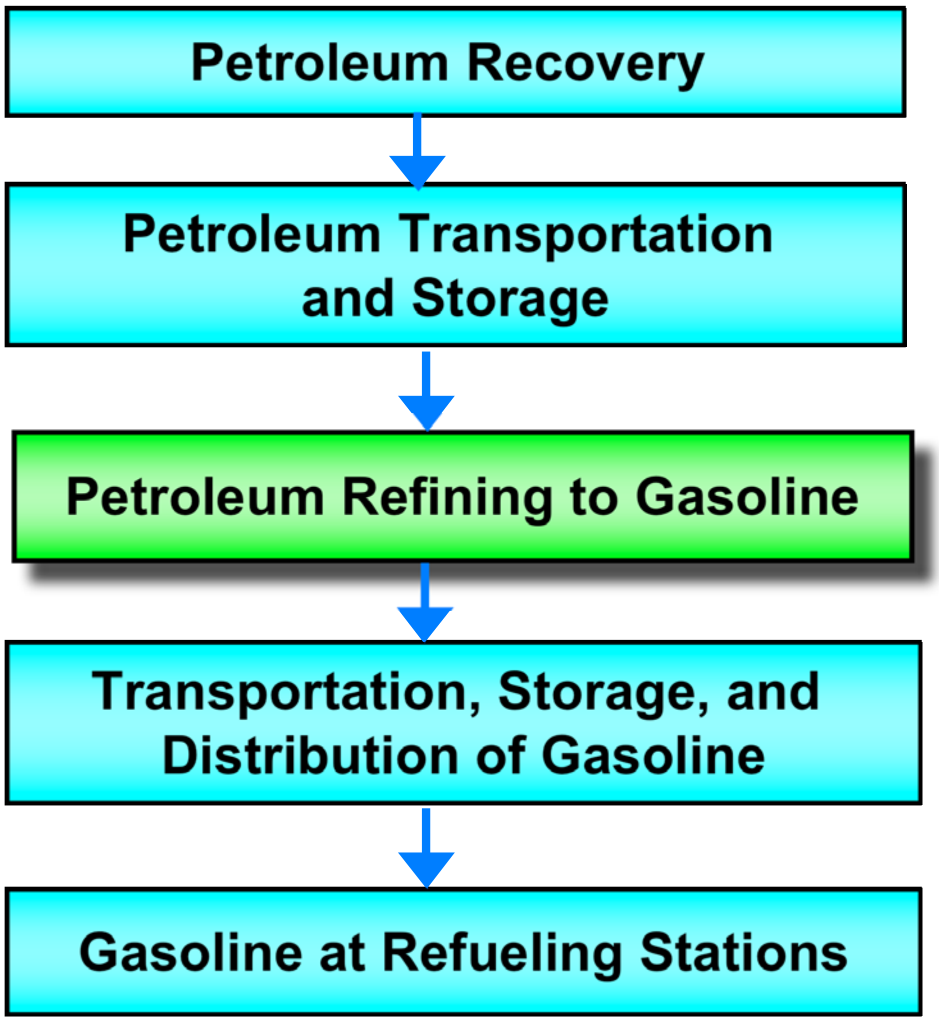
Battery-Powered Electric Vehicles
- U.S. generation mix
- California generation mix
- Northeast U.S. generation mix

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

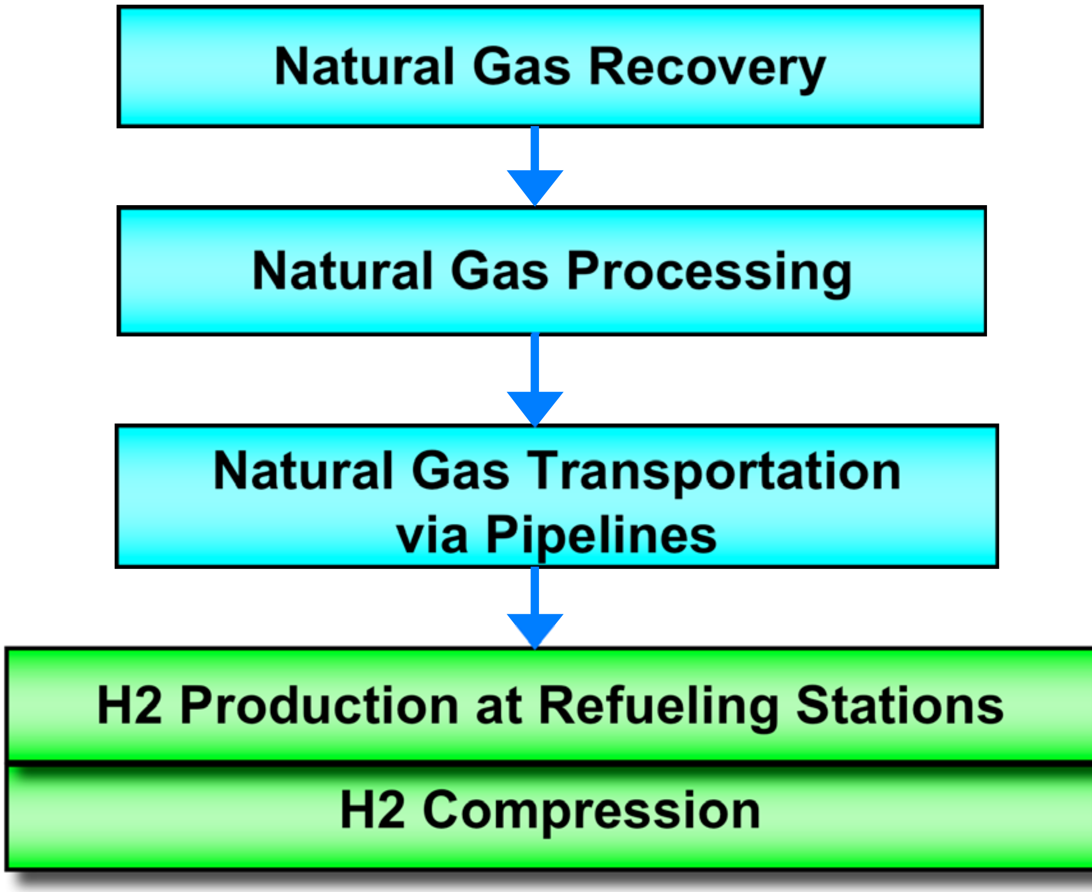
Compression-Ignition Direct-Injection Vehicles
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, and biodiesel

Spark-Ignition Direct-Injection Vehicles
- Conventional gasoline, federal reformulated gasoline, and California reformulated gasoline
- Methanol and ethanol

Petroleum Refining Is the Key Energy Conversion Step for Gasoline



Pathway of Producing H2 from Natural Gas at Refueling Stations



Pathway of Producing Hydrogen from Ammonia at Refueling Stations

Natural Gas Recovery

↓

Natural Gas Processing

↓

Natural Gas Transportation via Pipelines

↓

Ammonia Production

↓

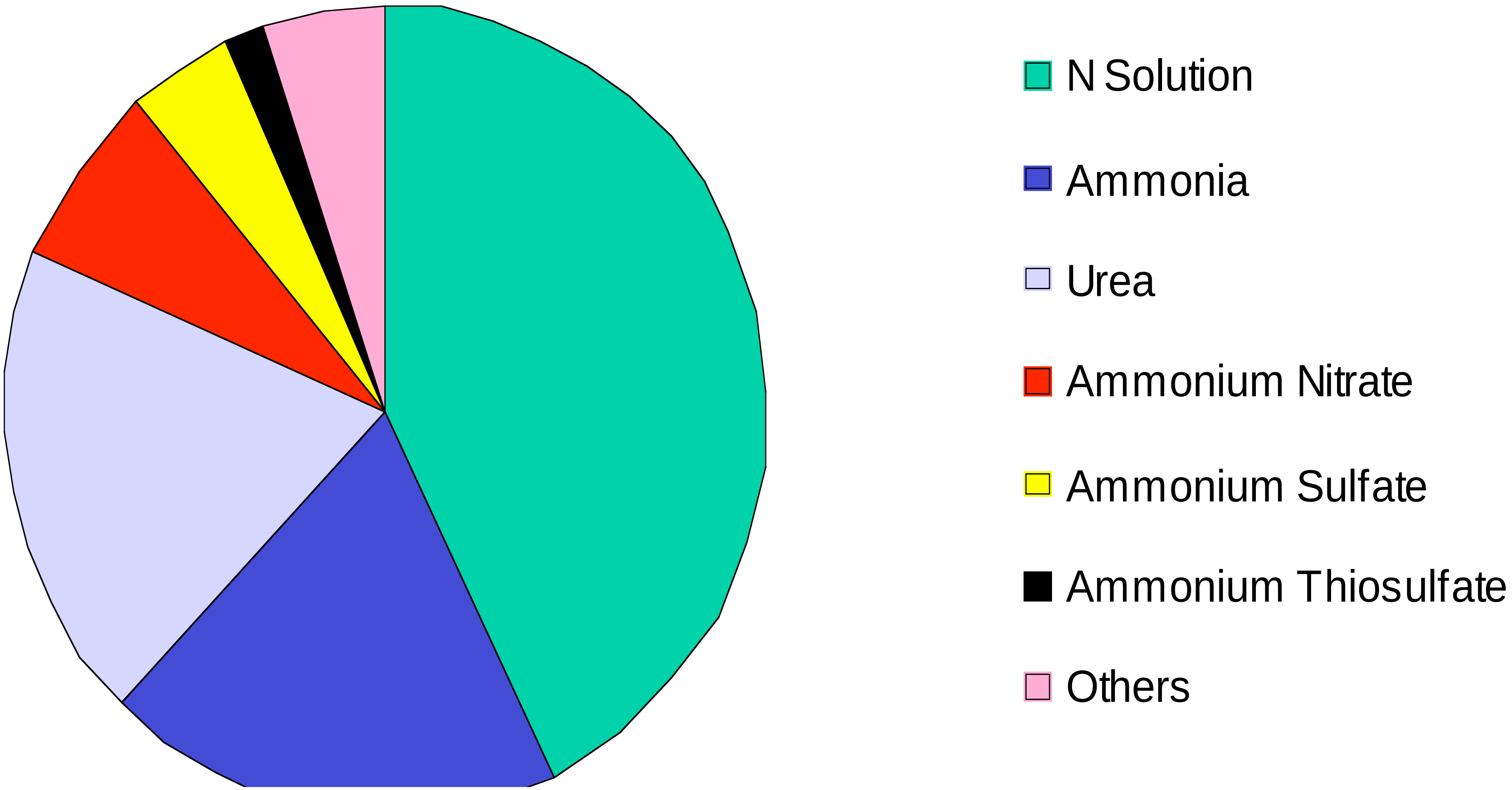
Ammonia Transportation

↓

H2 Production at Refueling Stations

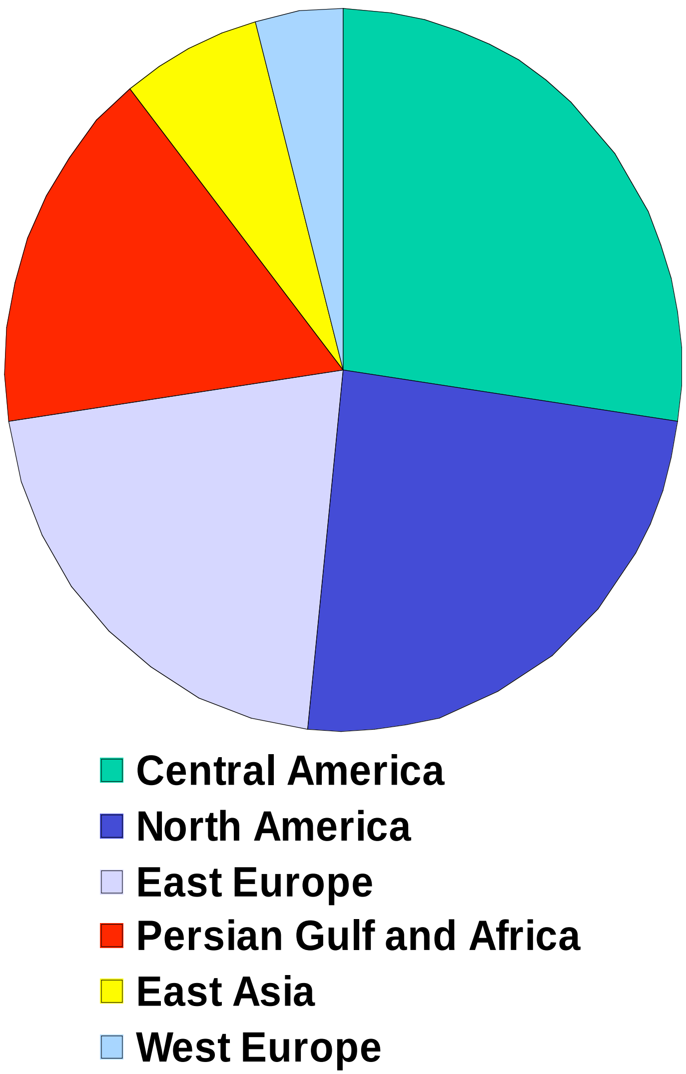
H2 Compression

In 2000, the U.S. Consumed 24.4 Million Tons of Nitrogen Fertilizer; Ammonia Fertilizer Accounted for ~20%

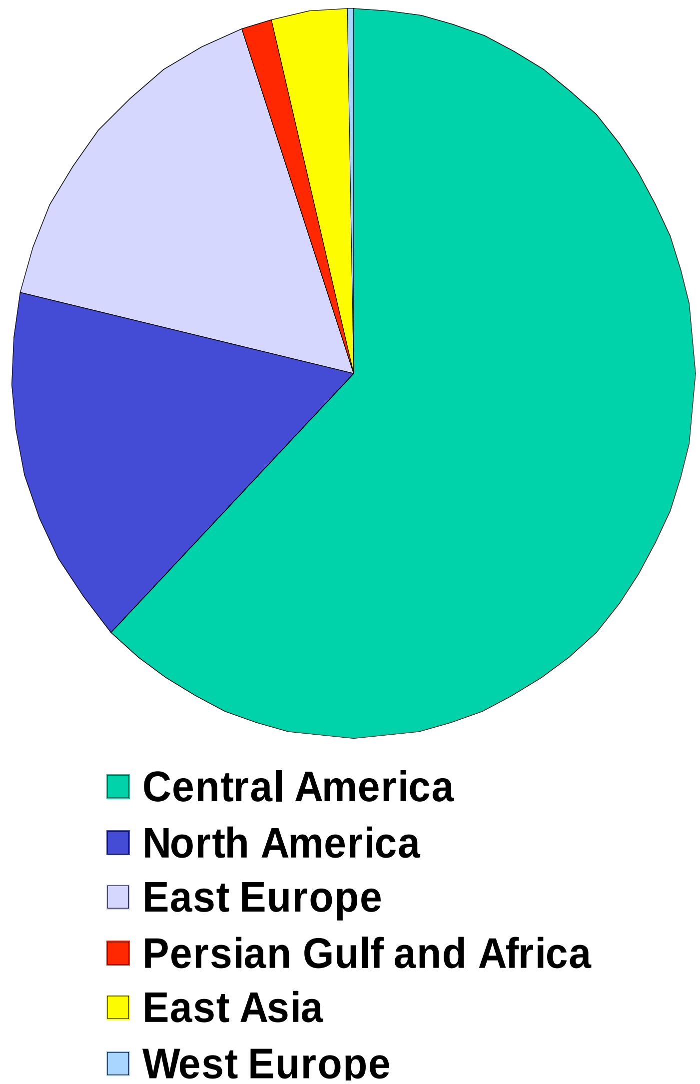


In 2001, the U.S. Imported ~60% of Its Nitrogen Fertilizer

The U.S. Imported 14.6 Million Tons of Its Nitrogen Fertilizer in 2001



The U.S. Imported 5.6 Million Tons of Ammonia Fertilizer in 2001



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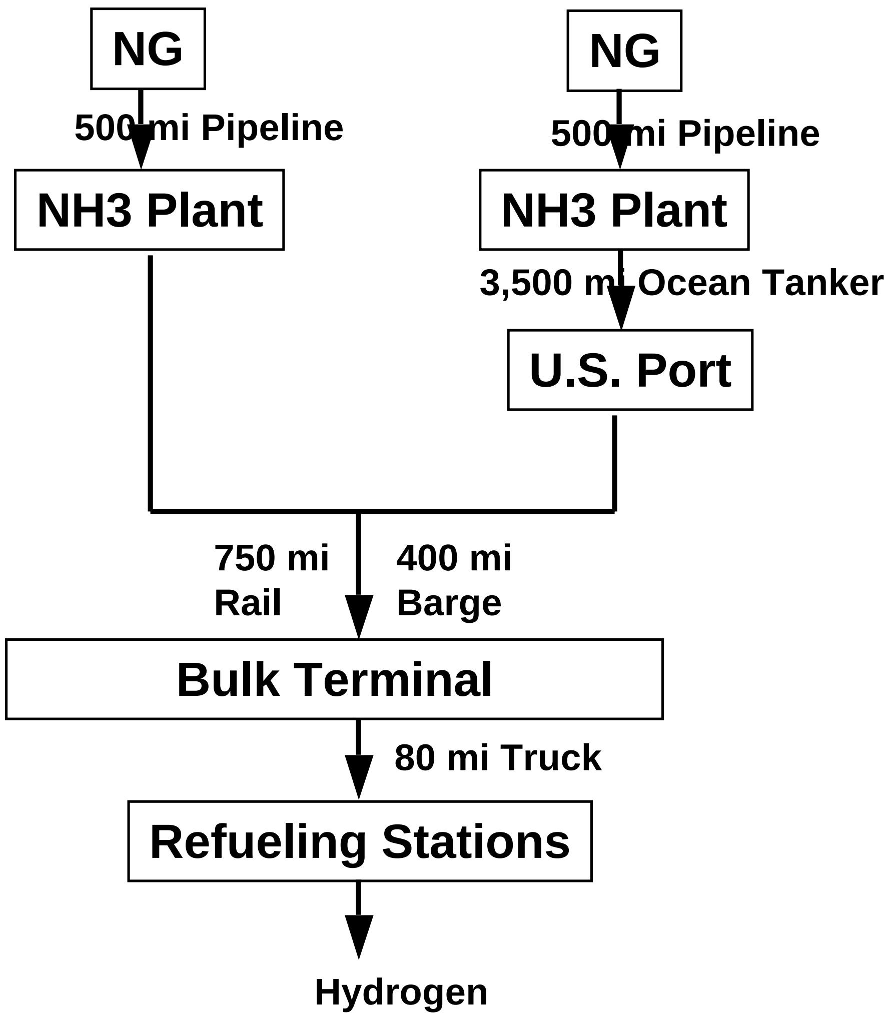
Ammonia Is Produced from Natural Gas

- Ammonia synthesis: $N_2 + 3H_2 \rightarrow 2NH_3$
- H_2 is produced from natural gas steam reforming
- Energy intensive for both natural gas steam reforming and ammonia synthesis
  - 26.4 million Btu of natural gas (LHV) per ton of ammonia produced
- Improvements in energy efficiency have been achieved through
  - Membrane syngas recovery
  - Waste heat generated steam-driven compressor
  - Ruthenium catalyst
  - CO_2 removal process

Ammonia Could Be Moved via Different Transportation Modes

- Ocean tanker for imported ammonia
- Rail
- Barge
- Truck from distribution centers to refueling stations
- Pipelines: not simulated in this analysis



Hydrogen Is Produced from Ammonia Through High-Temperature Cracking Process

- $2NH_3 \rightarrow N_2 + 3H_2$
- The "cracking" process requires temperature of 400 ^oC or above
- It is endothermic and requires about 19,700 Btu of energy per kg of H_2 produced
- Ammonia dissociation rate depends on temperature, pressure, catalyst type and reactor design. Literature shows wide range of conversion efficiency of stationary hydrogen reformers
- Key assumptions in this analysis
  - Process heat is provided by burning H_2 at refueling stations
  - Two ammonia utilization rates were simulated
    - ✓ *45%*
    - ✓ *99%: theoretical rate with improved catalyst and reactor design, multiple-pass, etc.*
- Process heat requirement could be reduced significantly from integrated heat recovery systems

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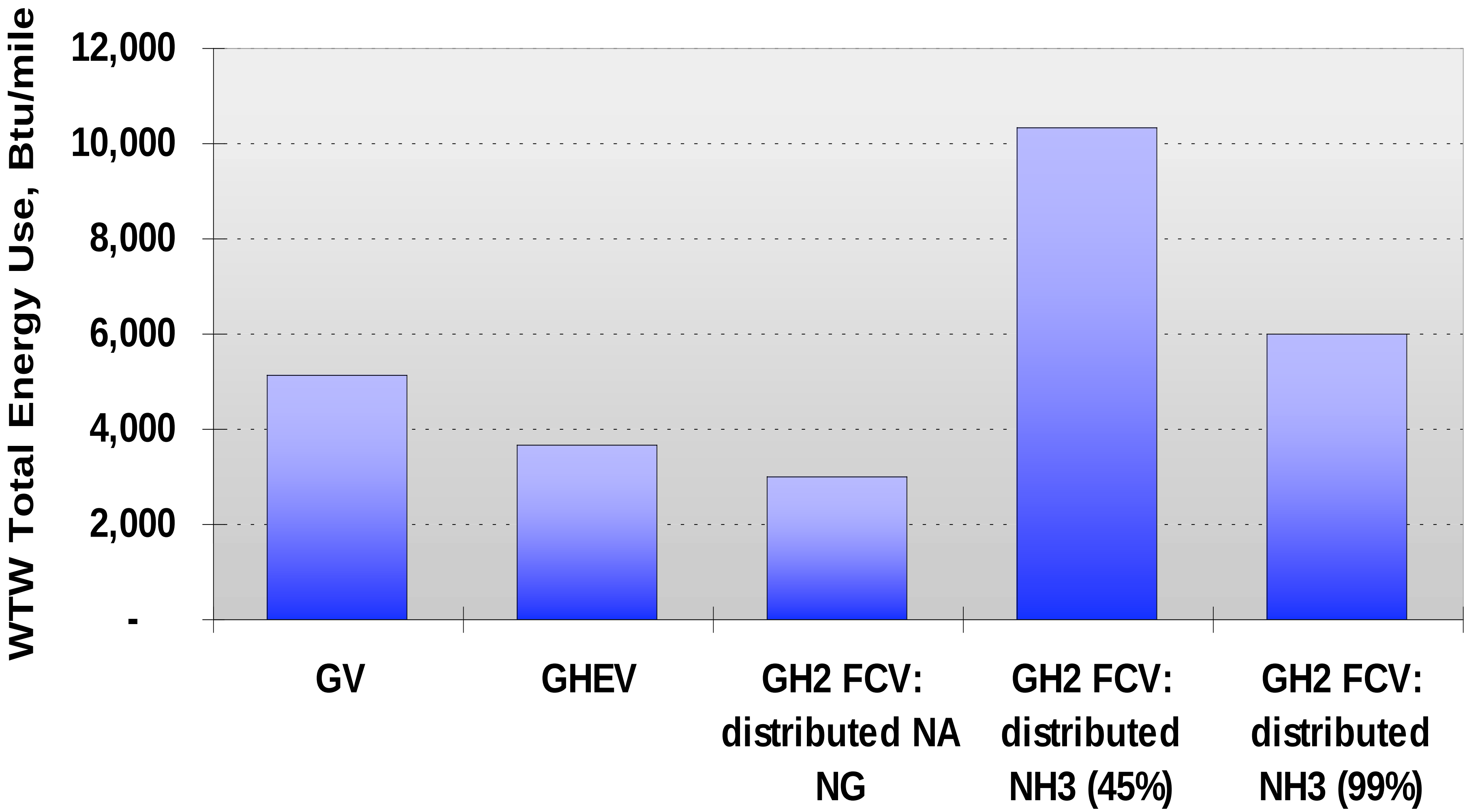
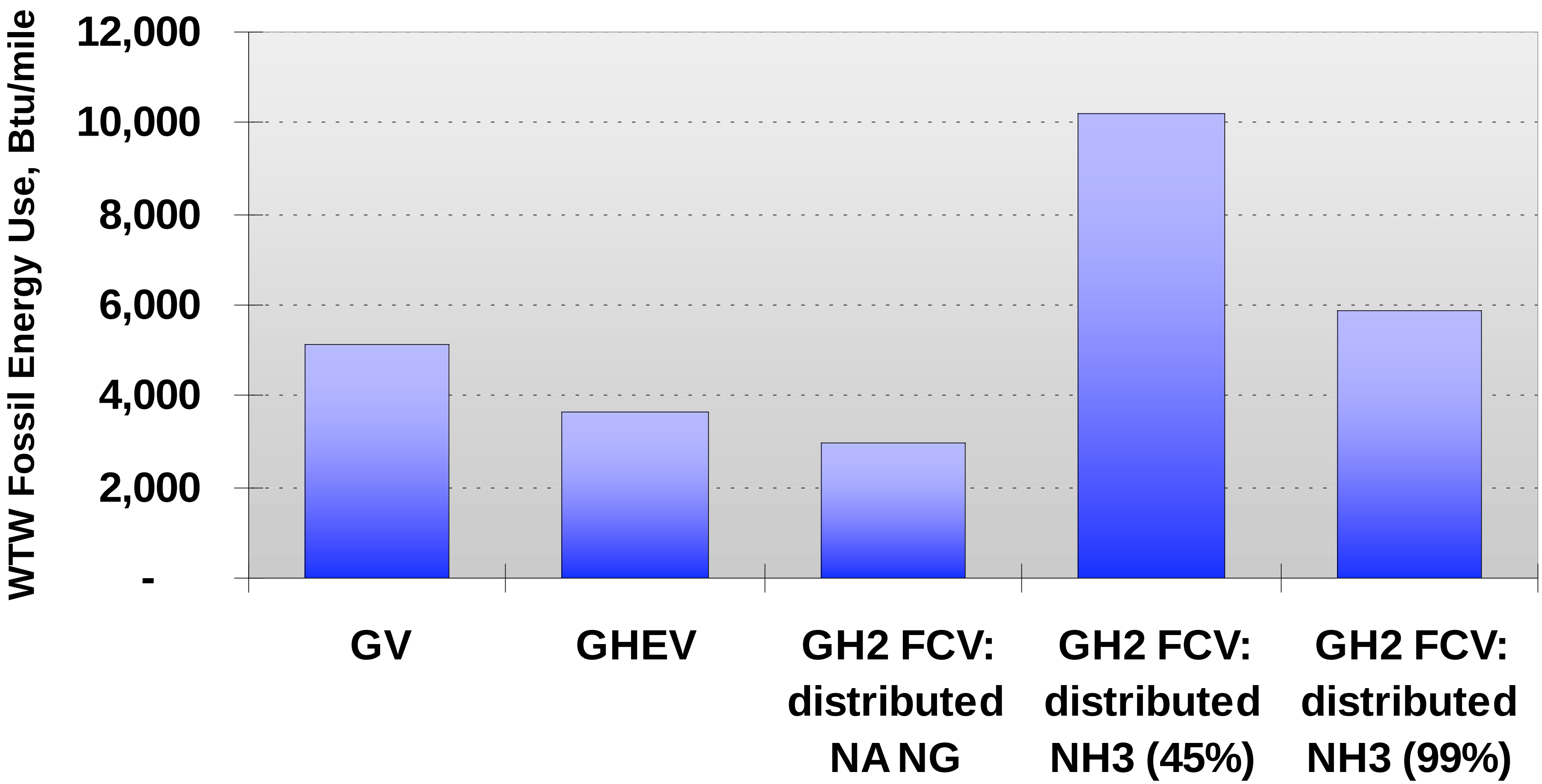
Five Vehicle/Fuel Options Are Compared in This Analysis

- Conventional gasoline vehicles (GV): 28 MPG fuel economy
- Gasoline hybrid electric vehicles (GHEV): 39 MPG fuel economy
- Gaseous H_2 fuel-cell vehicles (GH_2 FCV): 66 MPG fuel economy
  - Distributed NG SMR H_2 production
  - Distributed NH_3 to H_2 production with NH_3 utilization rate of 45%
  - Distributed NH_3 to H_2 production with NH_3 utilization rate of 99%

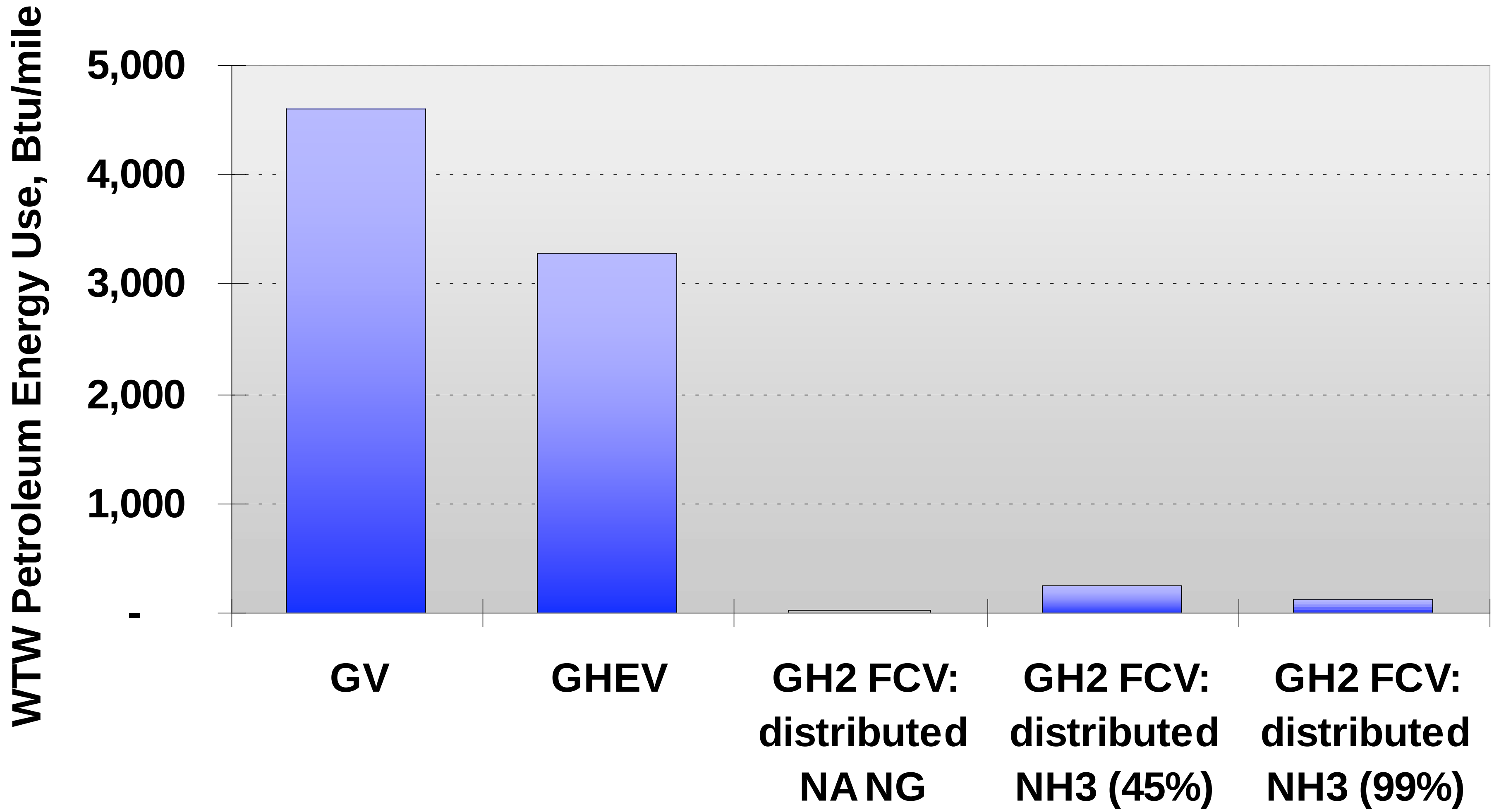
WTW Total Energy Use of Vehicle/Fuel Options



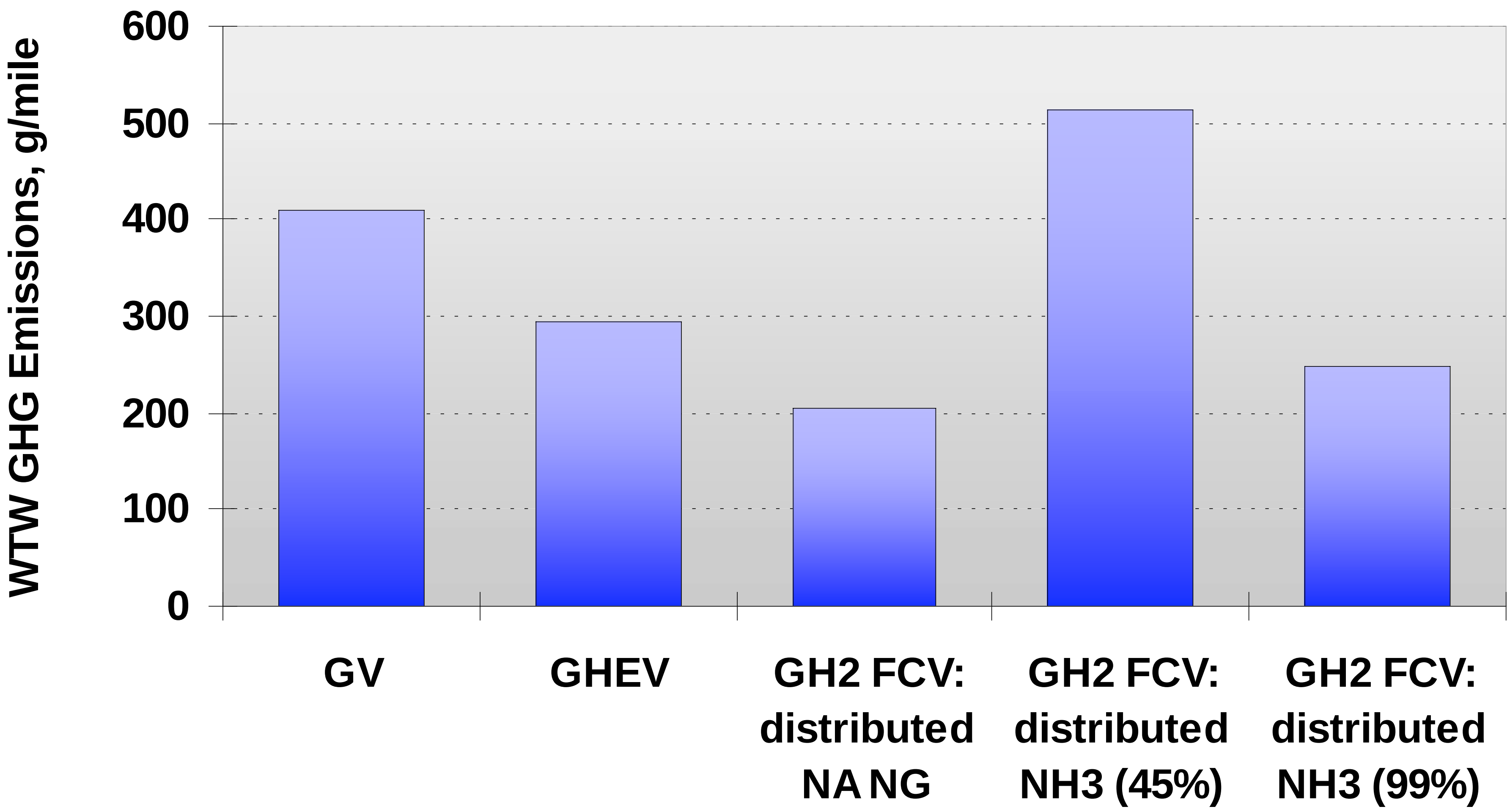
WTW Fossil Energy Use of Vehicle/Fuel Options



WTW Petroleum Use of Vehicle/Fuel Options



WTW Greenhouse Gas Emissions of Vehicle/Fuel Options



Concluding Remarks

Ammonia to H_2 production at refueling stations could help overcome H_2 transportation infrastructure,

But the pathway suffers from increased energy use and GHG emissions from efficiency losses of ammonia production and H_2 production