U.S. Department of Energy
Energy Efficiency and Renewable Energy

# DOE's Hydrogen Production and Delivery Infrastructure Program


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**The Transition to Alternative Fuels: What That Means for Transportation, Homes, Businesses and Communities,**

**UC Irvine Center for Urban Infrastructure,**

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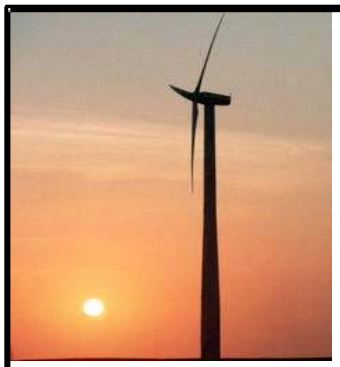
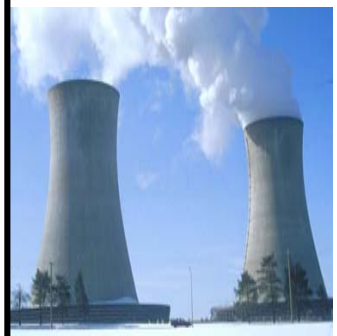
# Why Hydrogen?



Biomass

Hydro
Wind
Solar



Nuclear

Oil

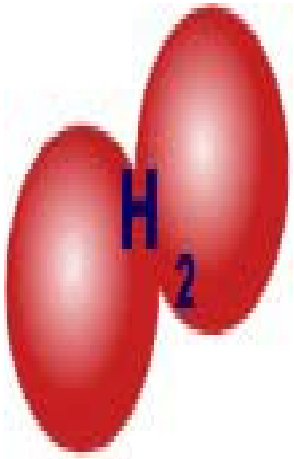
Coal

Natural
Gas

Sequestration

## National Energy Security

SOURCE: DIVERSE DOMESTIC RESOURCES




## The Environment

ZERO/NEAR ZERO GHG and other EMISSIONS

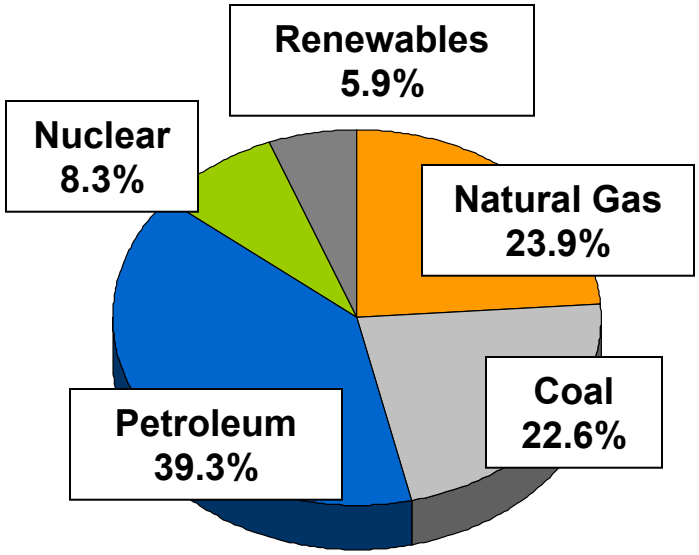
**Transportation**

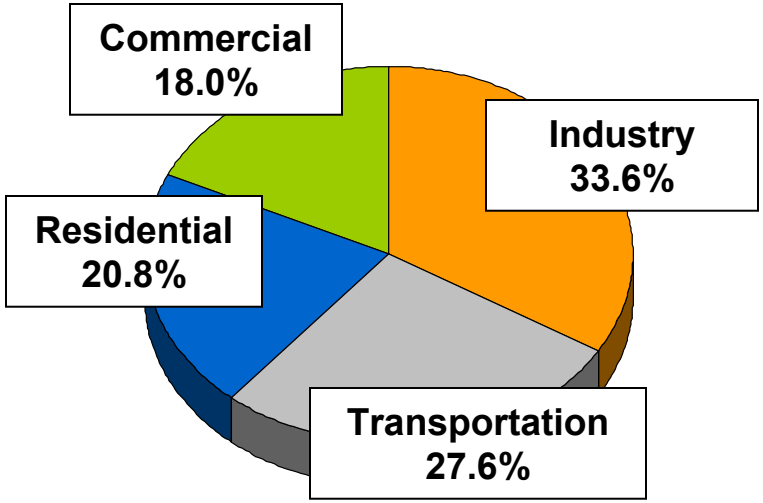
**Distributed Generation**

# Outline

- U.S. Energy Use
- Hydrogen Production Feedstock/Process Options
- Hydrogen Delivery Options
- Transition and End Analysis

# U.S. Energy Use



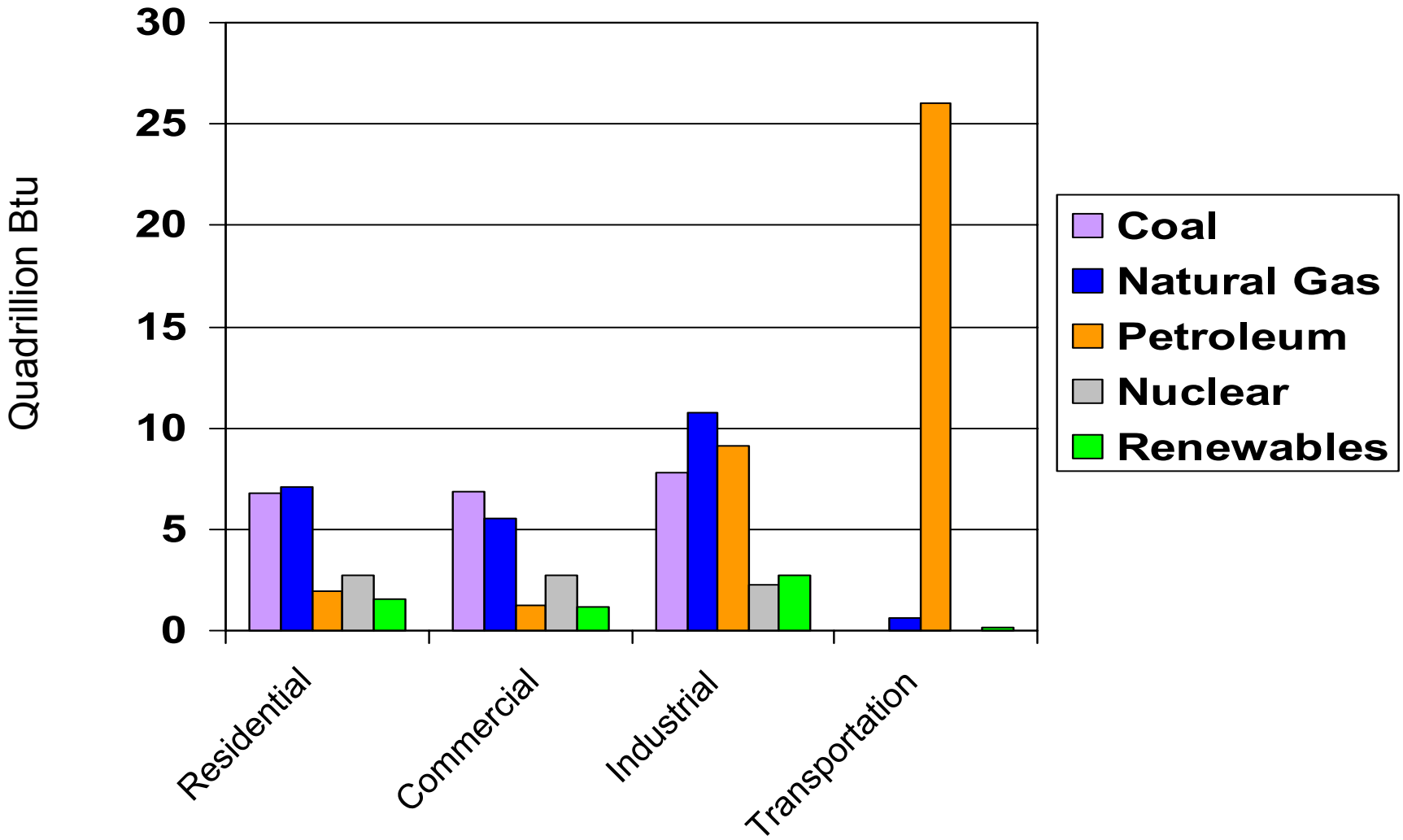




**2001 U.S. Energy Use**

**97 Quads**

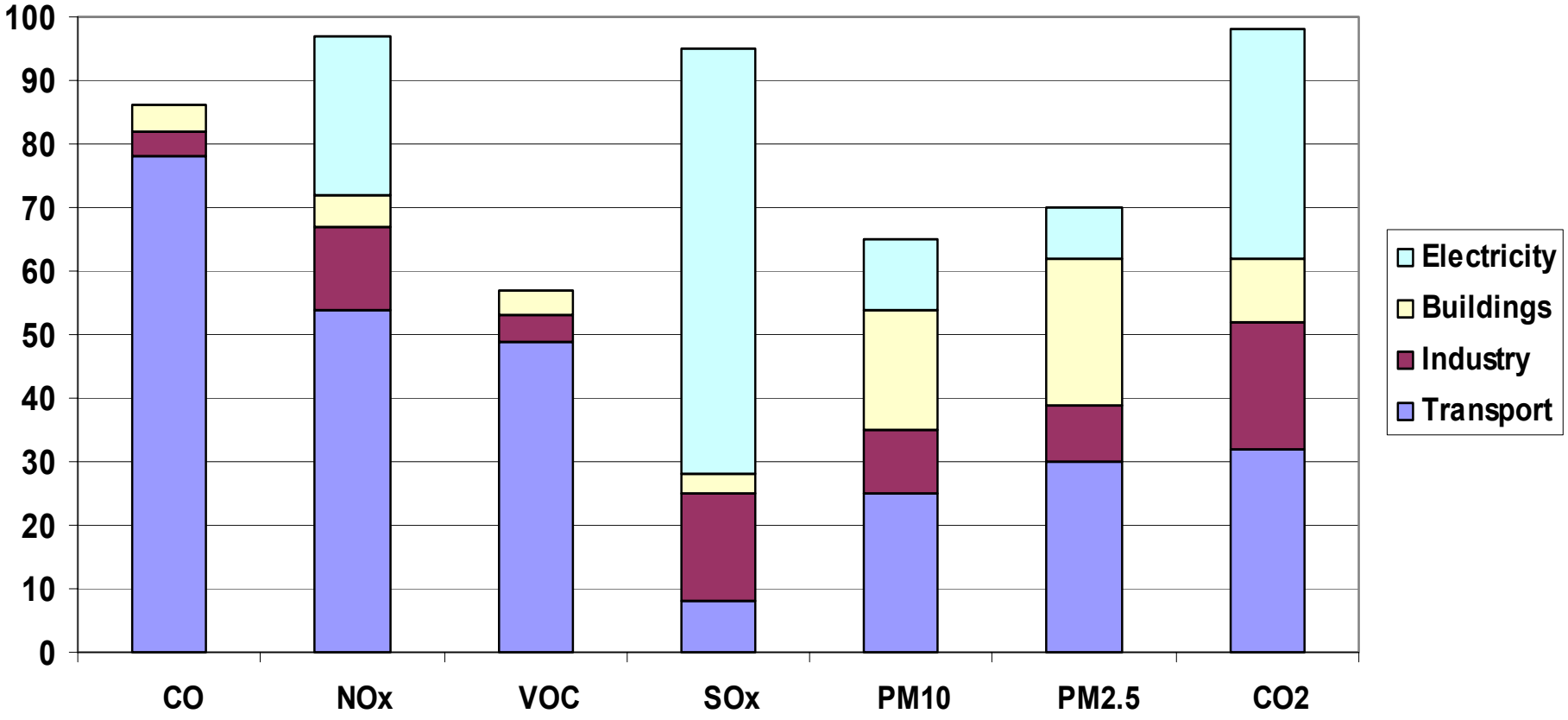
Source: Annual Energy Review, U.S. Department of Energy, Energy Information Administration, 2001

# U.S. Sector Energy Use by Source




Source: Annual Energy Review, U.S. Department of Energy, Energy Information Administration, 2001.

# 1998 U.S. Energy-Linked Emissions as Percentage of Total Emissions



# Office of Hydrogen, Fuel Cells and Infrastructure Technologies Program

*Develop and validate fuel cells and hydrogen production, delivery, and storage technologies for transportation and stationary applications.*

- Dramatically reduce dependence on foreign oil.
- Promote the use of diverse, domestic, and sustainable energy sources.
- Reduce carbon and criteria emissions from energy production and consumption
- Increase the reliability and efficiency of electricity production by utilizing distributed fuel cells

# Hydrogen Production Goal

*Research and develop low-cost, highly efficient hydrogen production technologies from diverse domestic sources, including fossil, and renewable resources.*

Target: Cost of delivered hydrogen is equivalent on an energy basis to the cost of untaxed gasoline

**$1.50/kg of Hydrogen in 2010**

# Production Feedstock/Process Options

## Coal

- Supply: 5,780 Quads recoverable reserves
- Process options: central production from gasification
- Cost: Current: $0.90-1.80/kg
  Projected: $0.50-1.10/kg
- Requires sequestration and near-zero other emissions

# Production Feedstock/Process Options

## Natural Gas

- Supply:
  - 188 Quads proven reserves
  - Currently importing 15% of our needs
- Process Options
  - Central Reforming
    - Cost: Current: $0.60-1.00/kg  Projected: $0.40-$0.90/kg
    - Requires sequestration
    - Lowest cost current route
  - Distributed Reforming
    - Cost: Current: $4.00-$6.00/kg  Projected: $1.50-$3.00/kg
    - Lowest cost current route for delivered hydrogen
    - Very sensitive to NG price
    - GHG emissions unavoidable

# Production Feedstock/Process Options

## Biomass

- Supply
  - 6-10 Quads/yr. currently possible
  - Could be much more with biotech advancements
- Feedstock Cost and Infrastructure are Key Issues
- Central Production Process Options
  - Gasification
    - Cost: Current $2.00-$4.00/kg Projected: $1.00-$3.00/kg
  - Fermentation
    - Relatively unexplored
  - Anaerobic Fermentation Methane Hydrogen
    - Agriculture, MSW or industrial sites
    - Existing biomass “collection” infrastructure
    - Co-Gen power and hydrogen possible
    - Sensitive to scale of operations and required distribution infrastructure

# Production Feedstock/Process Options

## Biomass

- Central/Distributed Process Options
  - Trades hydrogen delivery costs for liquid carrier costs plus reforming
  - Fermentation → Ethanol → Hydrogen
    - Fungible transition from ethanol fuel
    - Cost ??
  - Gasification → Syngas → Methanol (Ethanol) → Hydrogen
  - Pyrolysis → Bio-Oil → Hydrogen
  - Sugar Hydrogenation → Sugar Polyols (e.g., Sorbitol)→ Hydrogen

# Production Feedstock/Process Options

## Water: Electrolysis

- Distributed and central production
- Requires non-GHG emitting clean power: wind, solar, geothermal, hydroelectric, nuclear, fossil with sequestration
- Supply:
  - Essentially unlimited
  - Need purified water

# Production Feedstock/Process Options

- Distributed Electrolysis
  - Cost: Current: $4.00-$8.00/kg  Projected: $2.50-4.50/kg
  - Electricity cost is the driver/controlling
  - Eliminates hydrogen delivery costs and infrastructure
- Central Electrolysis
  - Cost: need better analysis
  - Enables more efficient use of intermittent renewables
  - Enables more efficient use of off peak power availability
  - High temperature steam electrolysis may be more efficient
  - Requires hydrogen delivery

# Production Feedstock/Process Options

## Water: Photolytic Production

- Supply: Unlimited
- Central Production Utilizing Photosynthetic Organisms (Algae)
  - Cost: Current ~$200/kg Projected: <$5.00/kg
  - Requires breakthroughs in biotechnology and systems engineering
  - Land area requirements or ocean operations
- Central or Distributed Direct Photoelectrochemical Production
  - Cost: Current: N/A Projected: <$3.00/kg
  - Requires breakthroughs in materials
  - Intermittent: diurnal cycle
  - The ultimate system if successful: renewable, unlimited, <u>simple</u>

# Production Feedstock/Process Options

## High Temperature Thermochemical Water Splitting

- Process Options
  - High temperature (500-1000 C) central production utilizing advanced nuclear energy heat source (or other source) and S-I or CaBr (or other) cycles
  - Ultra-high temperature (1000-3000 C) water splitting chemical cycles utilizing concentrated solar energy
  - Direct water splitting
- Unproven Chemical Cycles
- Materials Issues

# Other Considerations

- Sequestration Needed for Coal and NG Feedstock
  - Risk
  - Sufficient sequestration capacity
- Brownfield vs. Greenfield Central Production
  - Building expansions of existing hydrogen production (e.g. large SMR facilities for petroleum and ammonia)
  - Adding on to future coal IGCC power plants
- Refinery/Biorefinery
  - Adding biomass feedstock to NG hydrogen and power plants
  - Adding hydrogen to existing and emerging biorefineries
    - Sugar based corn wet and dry mills
    - Cellulosic sugar based ethanol/product biorefineries
    - Biomass gasification power/product biorefineries
    - MSW and future animal waste biogas power operations

# Other Considerations

- Co-Gen Power Parks
  - Power and hydrogen swing operations
  - Local to large
  - Options include: biomass; coal; NG; reversible electrolysis with wind, solar, hydro, etc.
- Multiple H2 Production Options: Good Yet Challenging
  - Diversity of feedstock and process helps enable energy security
  - Can’t afford to build multiple production and delivery infrastructures

*Commercialized routes should be synergistic and fungible*

# OHFCIT Hydrogen Delivery Goal

**Gaseous**

- Pipeline
- Truck
- Onsite reforming

**Liquid $H_2$ & Chem. Carriers**

- Liquid $H_2$
  - Truck
  - Rail
- Hydrides
- Other Carriers

**Develop *hydrogen fuel delivery* technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power.**

# Delivery Options

- End Game
  - Pipelines
  - Other as Needed
    - Breakthrough hydrogen carriers
    - Truck: HP gas & liquid hydrogen
  - Electrolysis and Distributed Reforming of NG, Renewable Liquids (Ethanol, etc.)
- Transition
  - Electrolysis and Distributed Reforming of NG, Gasoline, Renewable Liquids (Ethanol, etc.)
  - Truck: HP Gas & Liquid Hydrogen
  - Regional Pipelines
  - Breakthrough Hydrogen Carriers

# Barriers

- Lack of Infrastructure Options Analysis
- High Capital Cost of Pipelines
- High Cost of Compression
- High Cost of Liquefaction
- Lack of Cost Effective Carrier Technology

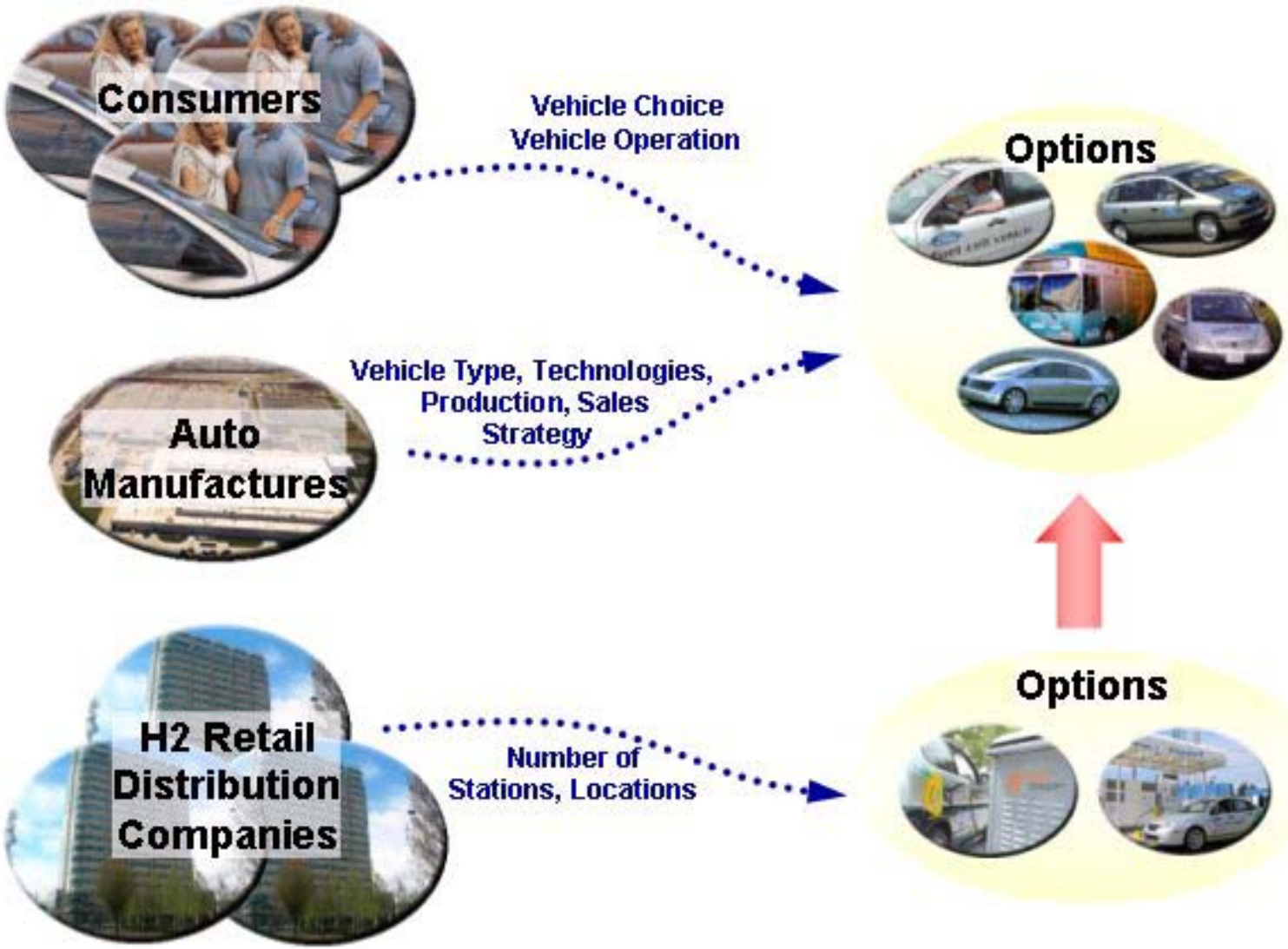
# The Transition

- Transition to a hydrogen economy is a large-scale, long-term, high-risk endeavor. Much of the potential benefit will accrue to society generally. It will involve enormous societal investment:
  - in physical and human capital
  - in long-lived infrastructure
  - in institutions and laws
- Costs and benefits of the hydrogen economy will extend well beyond the direct costs and benefits of the hydrogen system itself, and will depend on:
  - the technologies for hydrogen production, distribution and use
  - how these technologies are deployed over time and geographically, to create an energy system
  - the energy sources utilized
  - external factors (e.g., competing energy sources and technologies)
  - the value of externalities (e.g., climate change).
- The hydrogen economy will be a complex system:
  - many components
  - will interact with the rest of the economy
  - will face external threats and competition

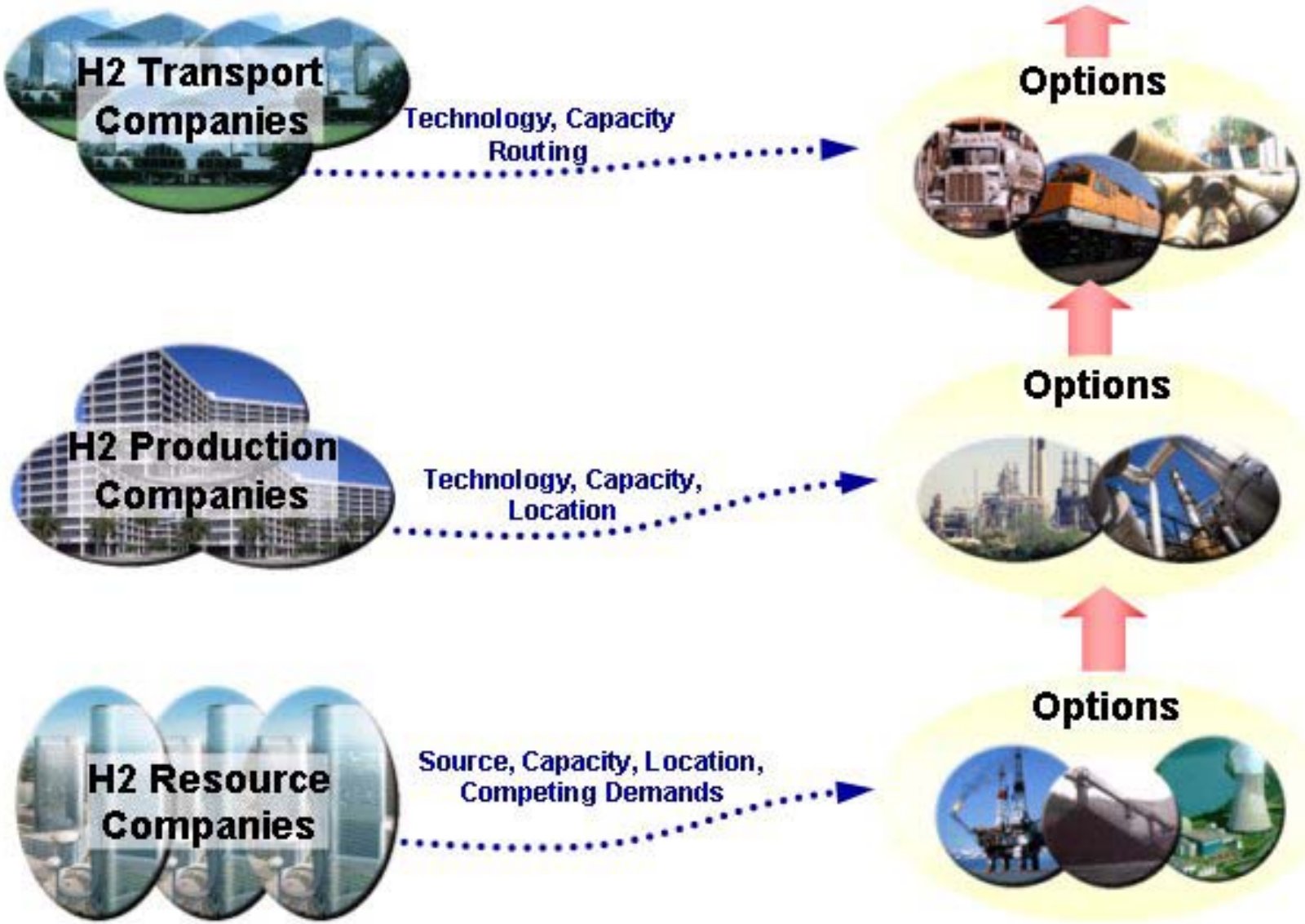
# Development of a H2 Infrastructure Shows Typical Characteristics of a CAS

- Many participants interacting in complex and non-linear ways
  - Resource industries -- Hydrogen retailers
  - Hydrogen producers -- Vehicle producers
  - Hydrogen distributors -- Consumers
  - Environmentalists -- Regulators, etc.
- Actions of some participants depend on actions of others in difficult-to-predict ways
  - Hydrogen delivery and distribution network could precede the advanced hydrogen-powered vehicles; or the reverse could occur
- Conditions in the environment in which the infrastructure is developing can lead to dramatically different end results
  - Success or failure of new technology or subsystem or in implementing a regulation/policy could affect success/failure of overall process
- H2-based transportation system will evolve as a series of steps, missteps and movement in different directions, not smoothly

# A Hydrogen CAS Model May Include (1)



# A Hydrogen CAS Model May Include (2)



# Agent-Based Modeling in H2 Infrastructure Development

- Allows study of ups and downs of system development, not just end game
- Can determine magnitude of fluctuations in the system
  - How far will system swing in one direction or another before it corrects itself or possibly collapses
- Can identify areas of stability, oscillation, or instability in parameters that affect hydrogen infrastructure development
  - Ability to treat the non-linearities in this type of complex adaptive system
- Can serve as an integrating tool to allow stakeholders to develop specific plans for a hydrogen transition
  - Types, quantities, locations and timing of infrastructure investments

# Transition Questions

- In what scenarios (under what conditions) will the hydrogen economy succeed?
- How do individual technologies affect the transition to and functioning of the system?
- How do alternative energy sources affect the transition to and functioning of the system?
- How will the evolution of the system over time and geographically affect costs and benefits?
- What is the role for policy in the transition and maintenance of the hydrogen economy?
- What are the costs and benefits (including the global macroeconomic effects) of a hydrogen economy?

# Conclusions

- Transportation is where H2 will put ”pedal to the metal”
- DOE’s program goals are ambitious ($1.50/kg)
- Many barriers must be overcome (technical, economic, behavioral)
- H2 supply, demand and infrastructure will co-evolve
- Hydrogen will interact with other energy markets and technologies in difficult-to-predict ways
- Transition strategies are critical and will impact outcome in difficult-to-predict ways
- Societal and policy issues (e.g., public/political acceptance of nuclear power, carbon taxes, import fees, etc.) are critical, as are other aspects of this complex system