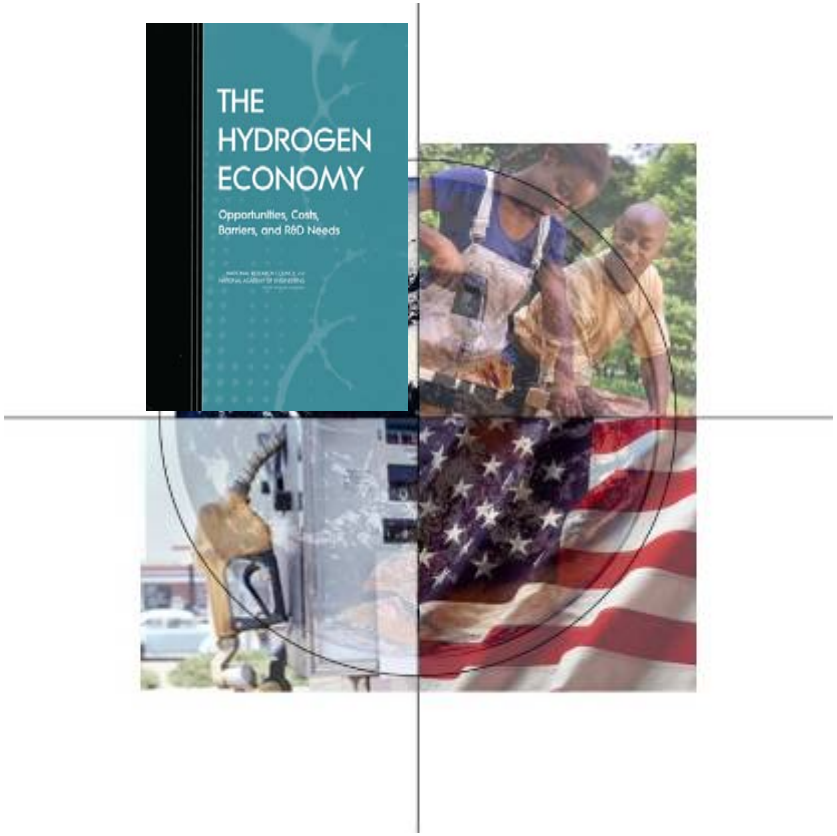
NETL Coal to Hydrogen Program



Hydrogen Separation and Purification Working Group

Laurel, Maryland
November 7, 2007

Dr. Daniel J. Driscoll
Senior Project Manager
Department of Energy
National Energy Technology Laboratory

National Energy Technology Laboratory

Presidential Initiatives for Hydrogen

- **$1.2 billion dollars**
- Addresses storage, delivery, and production from a variety of sources
- Aimed at future fuel cell vehicles

FutureGen

One billion dollar, 10-year project to create world's first coal-based, zero-emission electricity and hydrogen plant

President Bush, February 27, 2003

- **Produce lower cost hydrogen**
- **Produce electricity - nominally 275 MWe**
- **Sequester carbon dioxide**
- **Builds on DOE-sponsored Integrated Gasification Combined Cycle (IGCC) technology**

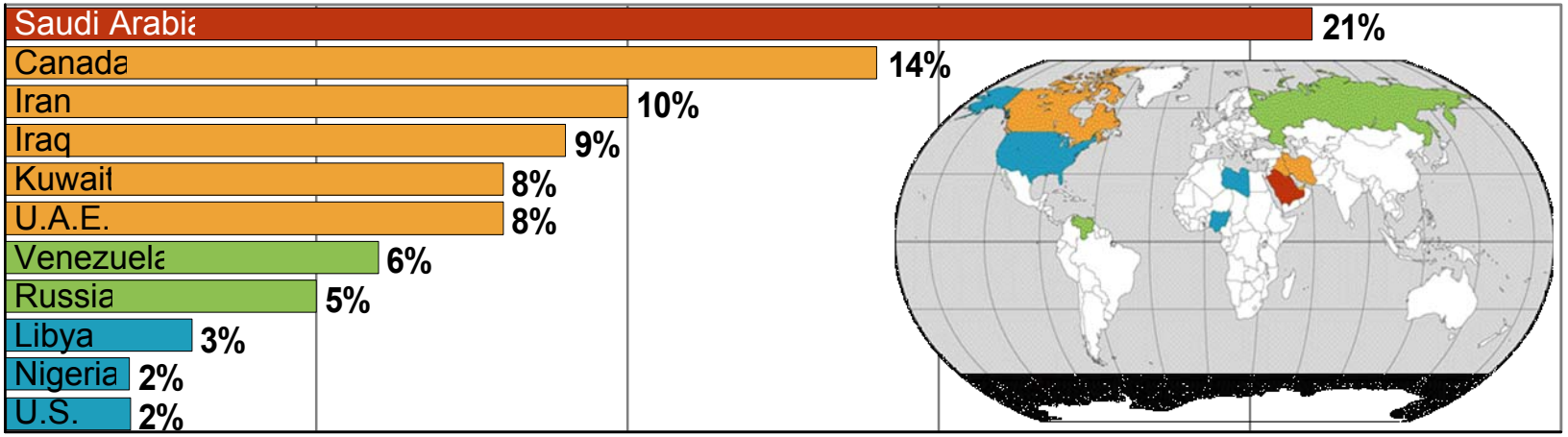
Interest Drivers for CTL

- **"Addicted to oil" – State of the Union address 2006**
- **US petroleum imports in 2005 exceeded $250 billion**
- **35% of energy consumption is from Oil [1]**
- **Daily world consumption is 84 million bbl/d – 20% higher than 1995 – expect 120 M by 2030**
- **World vehicle ownership at 700 M; – double by 2030 to 1.5 billion; – developing countries to triple**
- **96% of all energy used for transportation – largest demand for oil**
- **World oil supplies could peak between 2016 and 2037 [2]**
- **Oil resources not equitably distributed globally; coal more wide spread**
- **Concerns in: Energy security and Economic Development**
  - Oil availability supply issues
  - Infrastructure difficulties
- **Coal remains the most abundant fossil fuel in the world.**
- **Products produced from oil can be made from coal.**
- **Outside Activities:**
  - National Coal Council Report (March 2006) identified capacity to support production of 2.6 million bpd of liquid fuels from coal by 2025. See www.NationalCoalCouncil.org
  - Southern States Energy Board Report (July 2006) called for aggressive federal investment in CTL incentives "to encourage the private sector to step forward on a massive scale." See www.AmericanEnergySecurity.org
  - DOD Air Force Request for Interest in Military Alternative Fuels

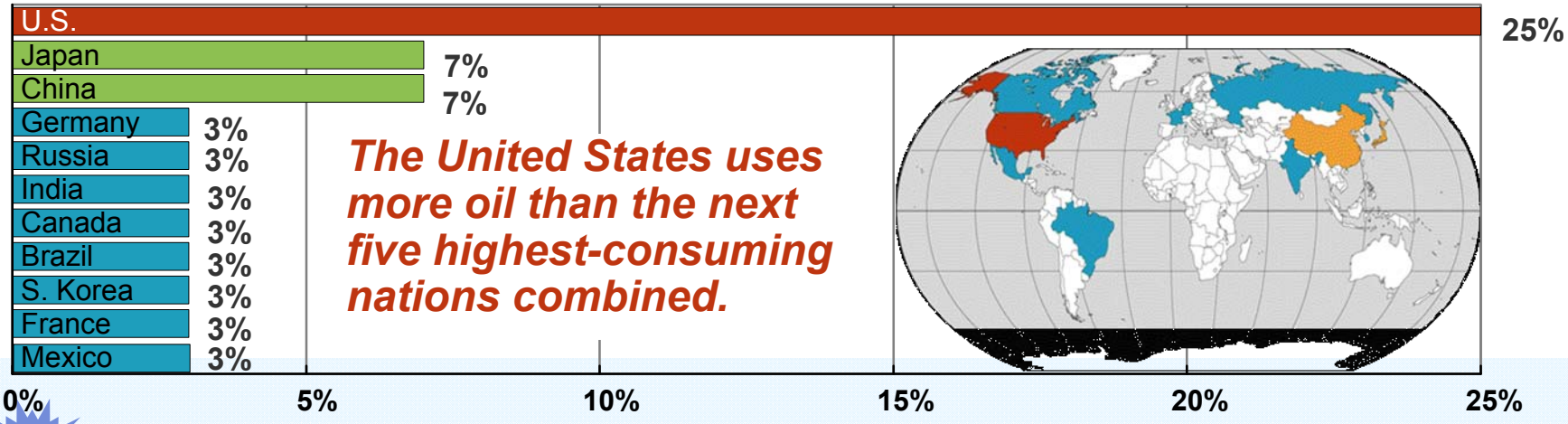
[1]Ref: World Coal Institute Report "Coal-to-Liquids" November 2006
[2]Ref: Hirsch, Robert, et, al., "Peaking of World Oil Production: Impacts, Mitigation, & Risk Management", NETL, February 2005

U.S. Dependence on Foreign Oil

Oil Reserves



Rate of Use



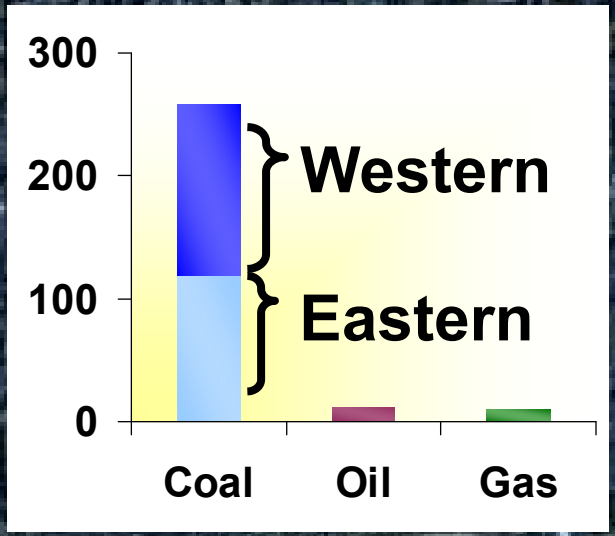
Updated July 2005. Source: International Energy Annual 2003 (EIA), Tables 1.2 and 8.1-O&GJ. Canada's reserves include tar sands.

Why Coal?

Coal Reserves are Abundant

- Provides over half Nation's electricity
- Abundant domestic reserves
- Low, relatively stable prices

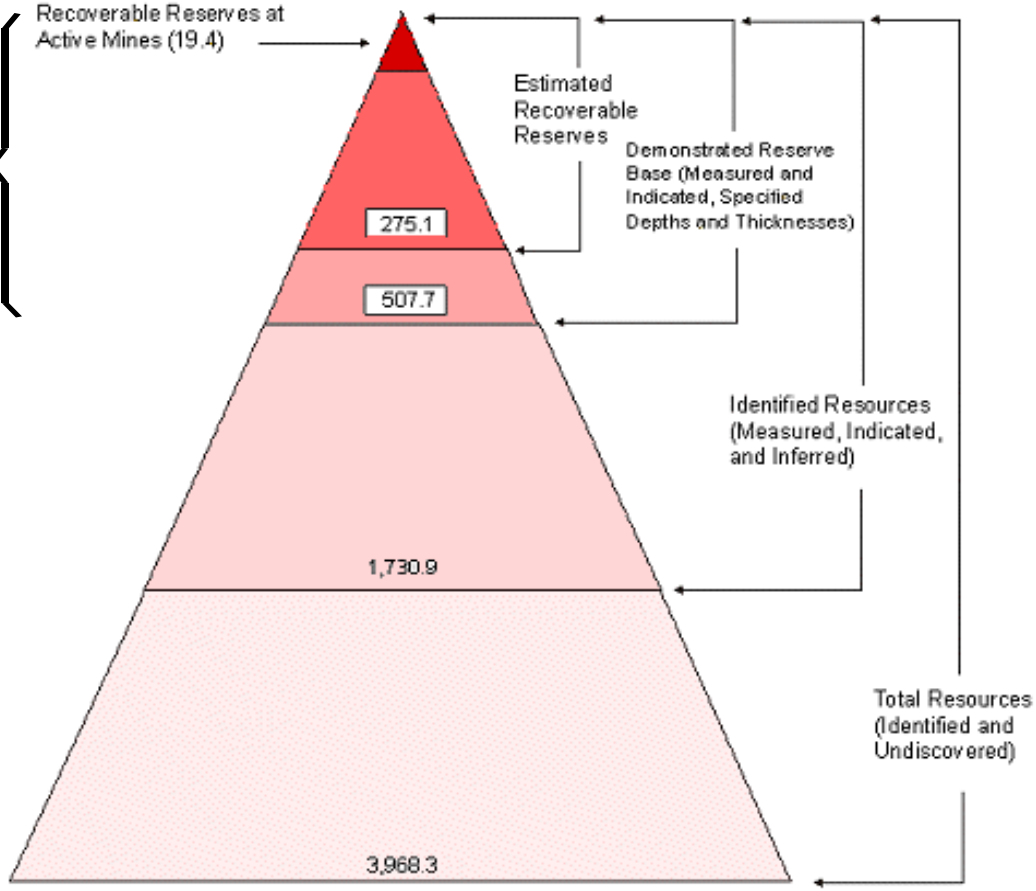
Years Supply at Current Production Rates



Delineation of U.S. Coal Resources and Reserves

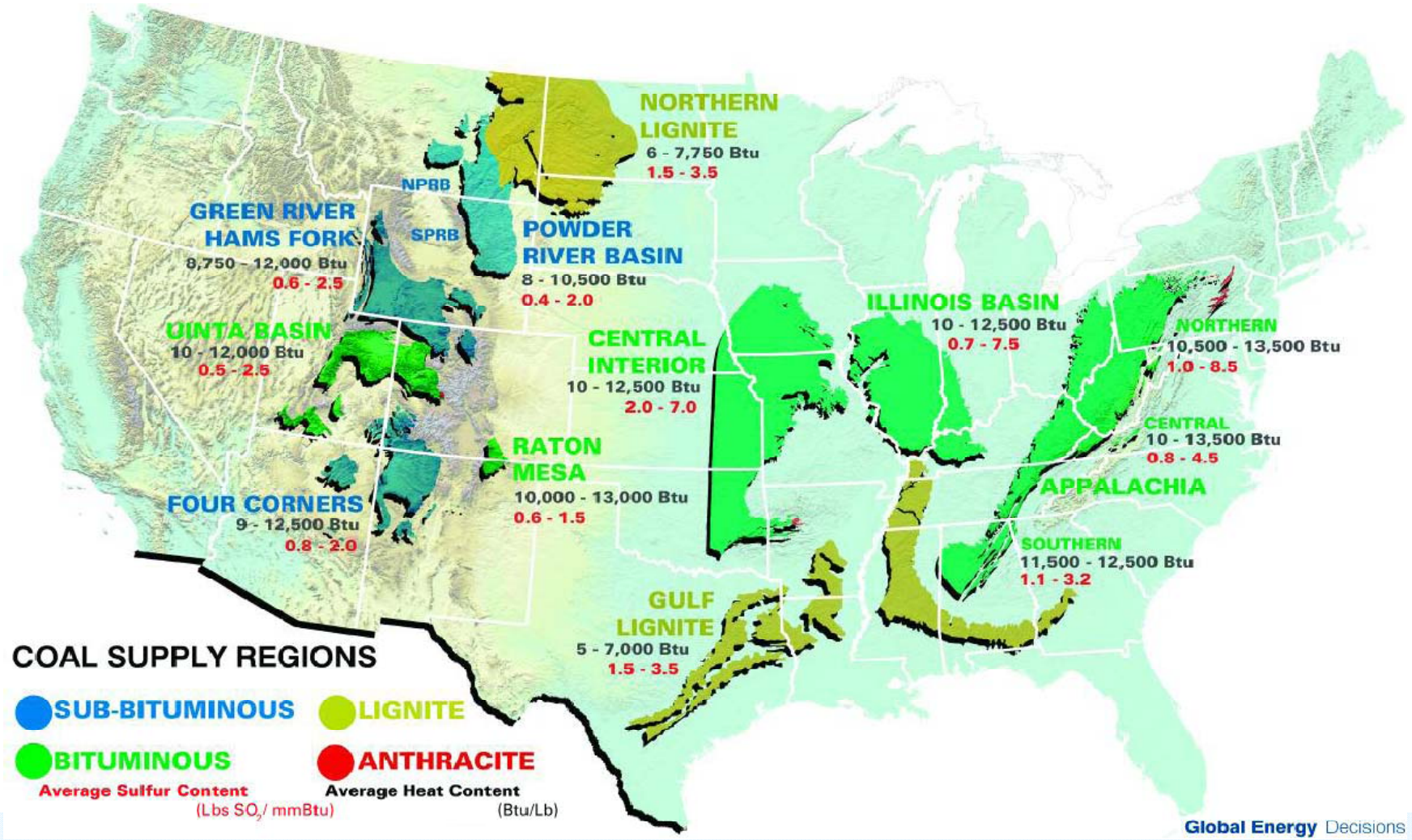
Sufficient reserve to meet projected demand for electricity and up to 4MMBPD CTL industry for over 100 years

1 ton of coal produces 2 barrels of liquid

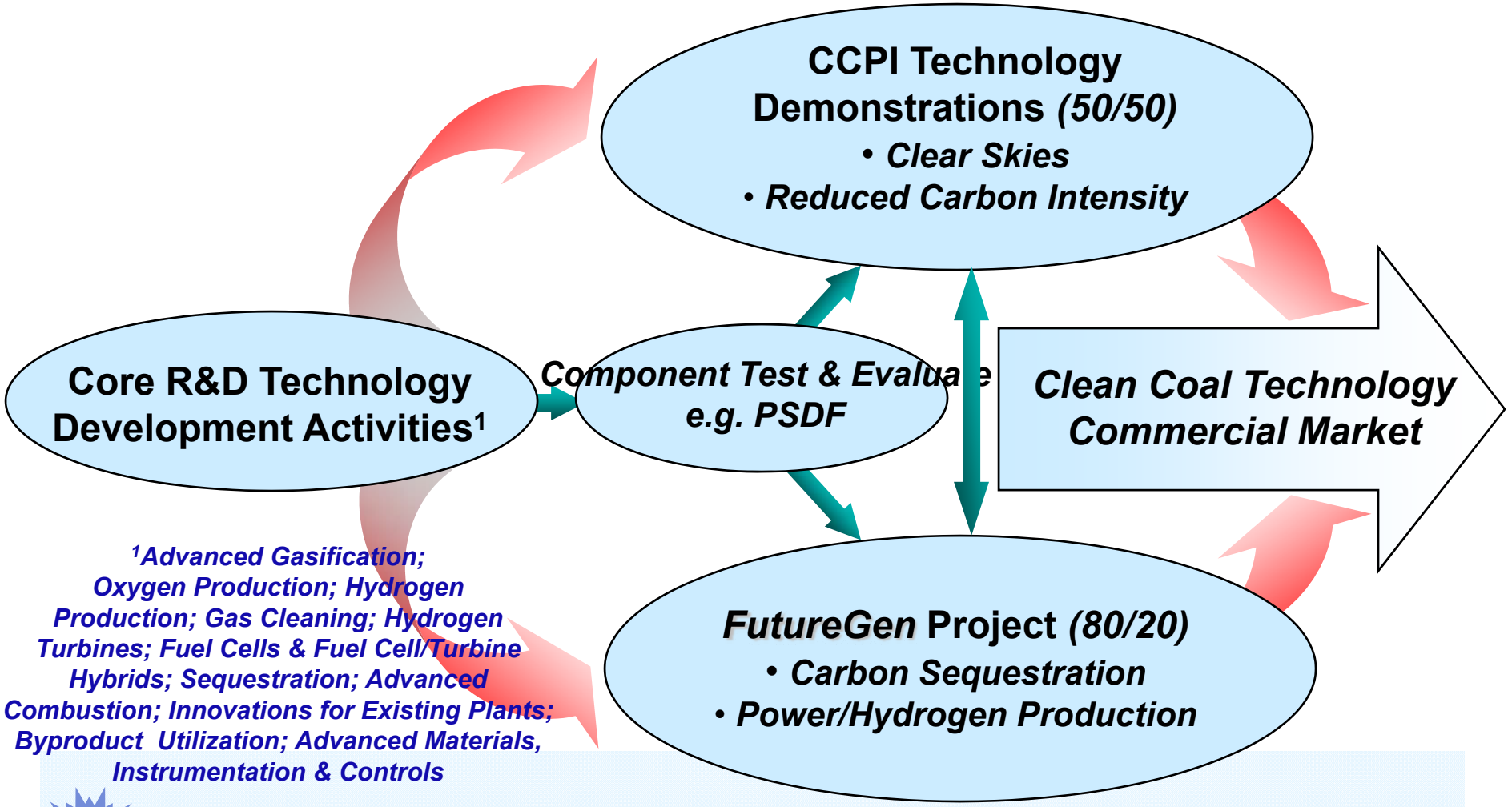


Source: EIA Coal Reserves Data 1997
http://www.eia.doe.gov/cneaf/coal/reserves/chapter1.html#chapter1a.html

U. S. Coal Resources Are Widely Distributed

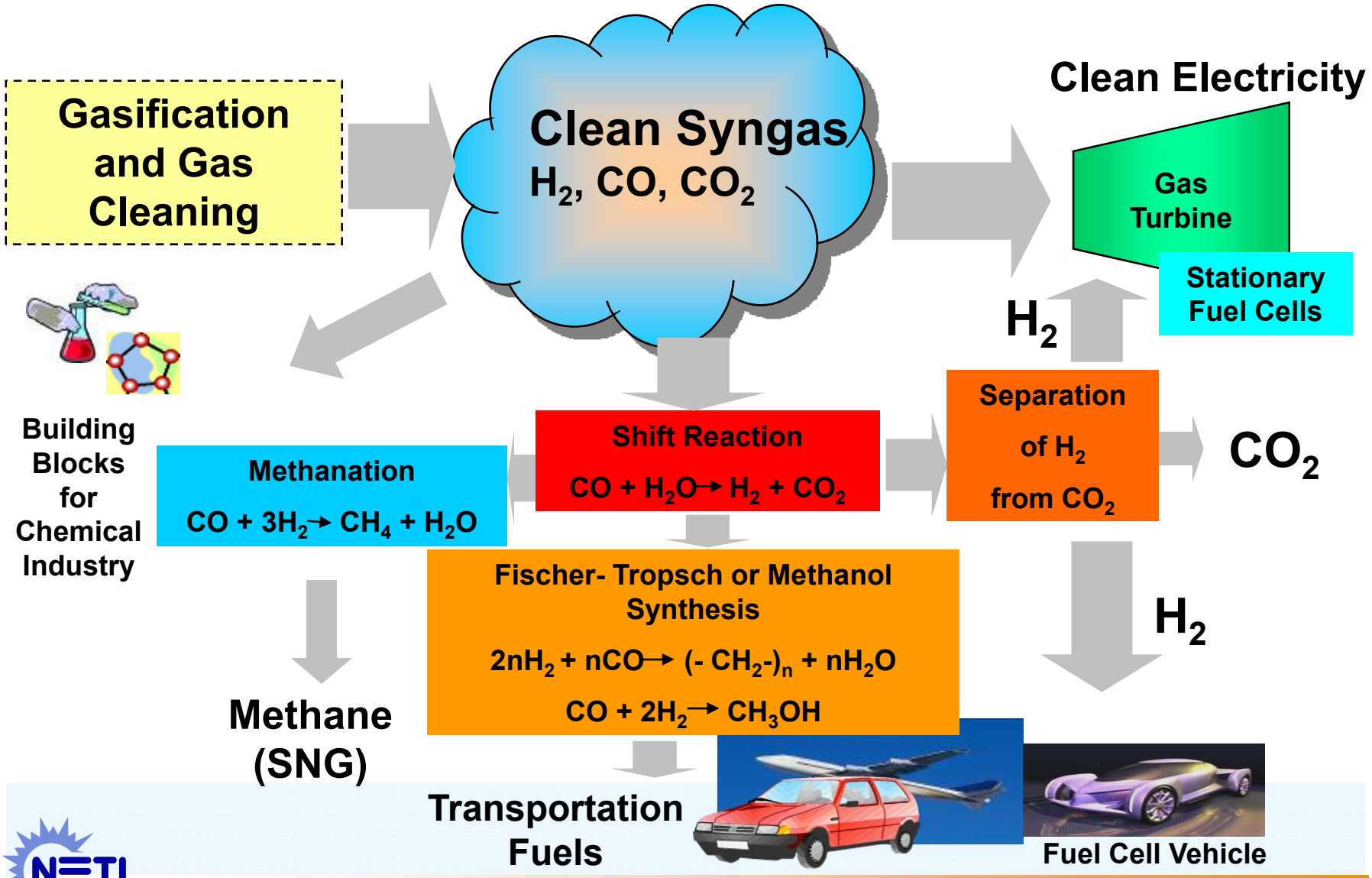


Office of Fossil Energy
Coal RD&D Program

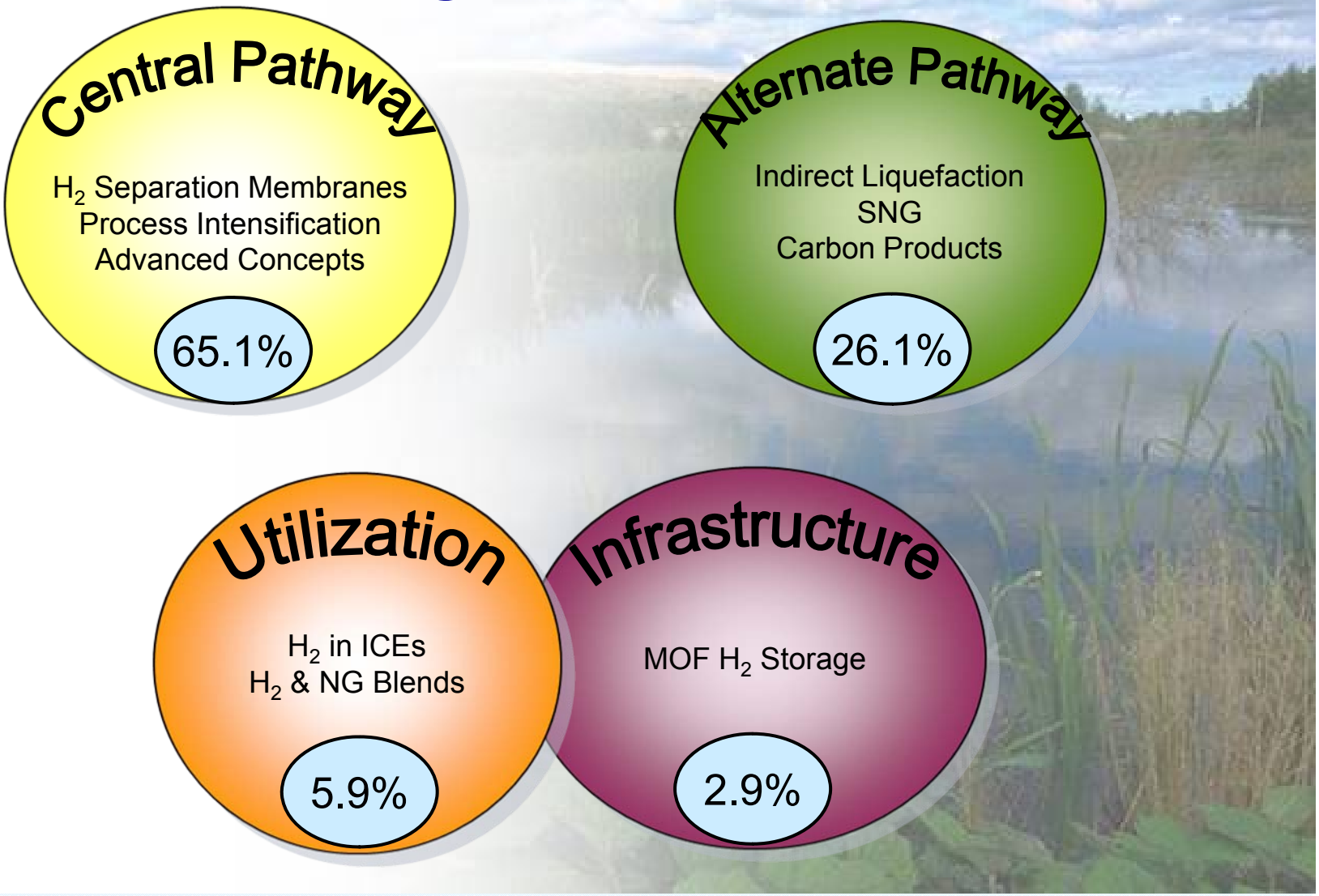


[1]Advanced Gasification; Oxygen Production; Hydrogen Production; Gas Cleaning; Hydrogen Turbines; Fuel Cells & Fuel Cell/Turbine Hybrids; Sequestration; Advanced Combustion; Innovations for Existing Plants; Byproduct Utilization; Advanced Materials, Instrumentation & Controls

Products from Coal Gasification Syngas

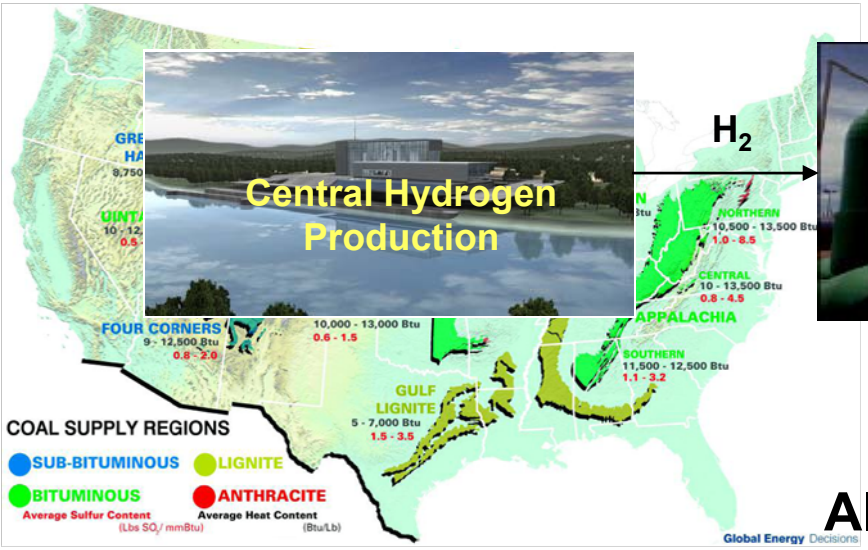


Hydrogen/Fuels from Coal Program Portfolio

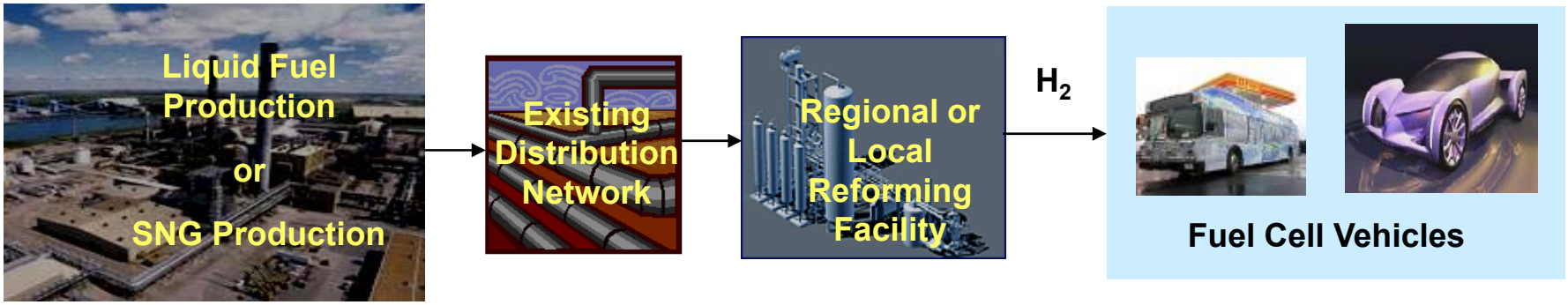


Hydrogen from Coal Strategies

Central Hydrogen Production

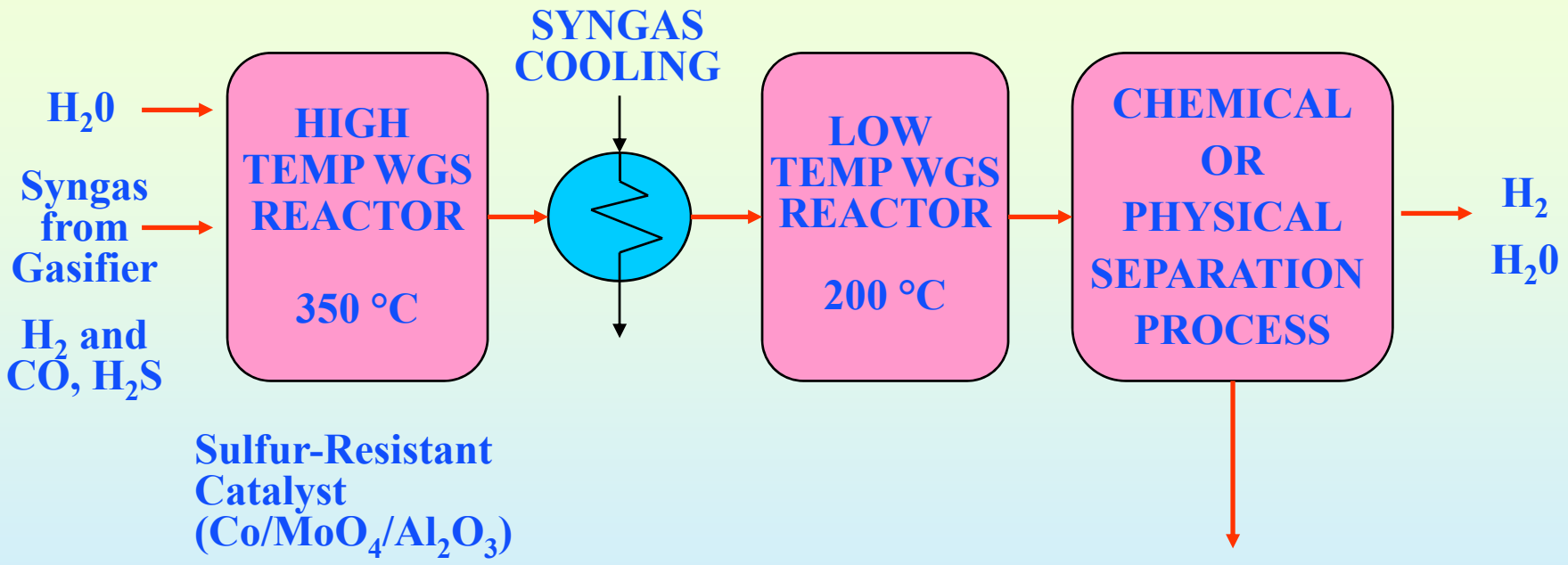


Alternate Production



Opportunities for Process Intensification

Water-gas shift $CO + H_2O \longrightarrow CO_2 + H_2$

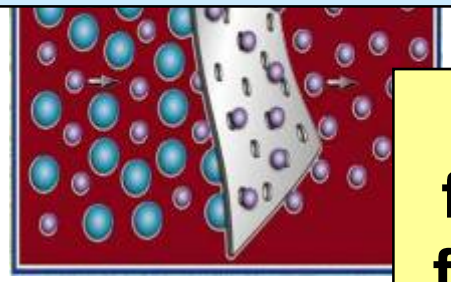


Technical Goals

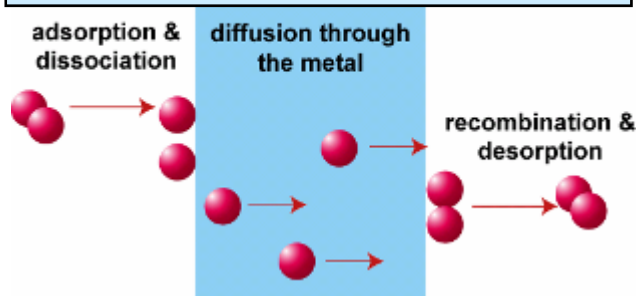
- Operation at high temperatures and pressures
- High conversion of CO
- Low steam/CO ratios
- Tolerant to S, Cl
- High stability, durability

Membrane-Based Hydrogen Separation

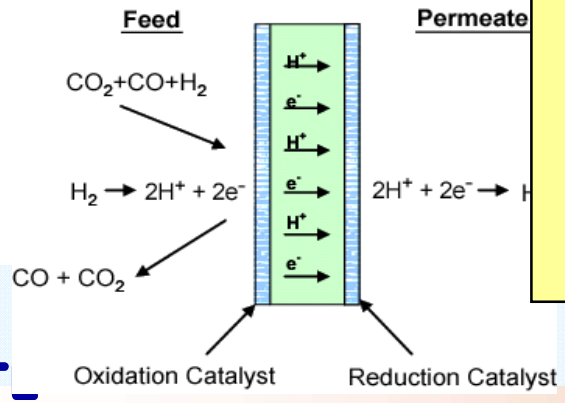
- **Micro Porous**



- **Dense Metallic**



- **Dense Ceramic**



Desired flux ~ 300 ft^3/ft^2-hr at 100 psi delta P with 99.99% purity and cost <$100/$ft^2$

Research Topics

Membrane materials and fabrication

Optimum diffusivity, flux, resistance, tolerance to impurities, temperature, pressure.

Large-scale production, cost.

Defect control and management

Fundamental knowledge base

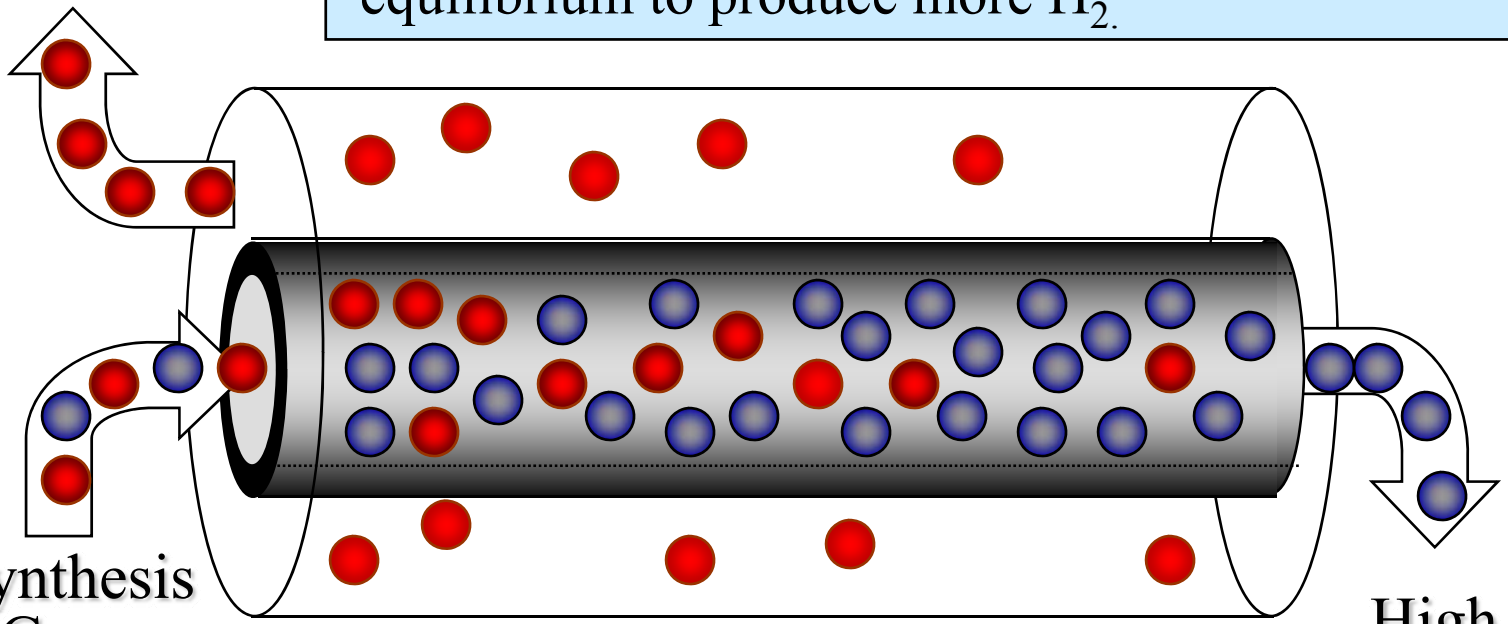
Mass transport, selectivity, kinetics

Membrane reactors

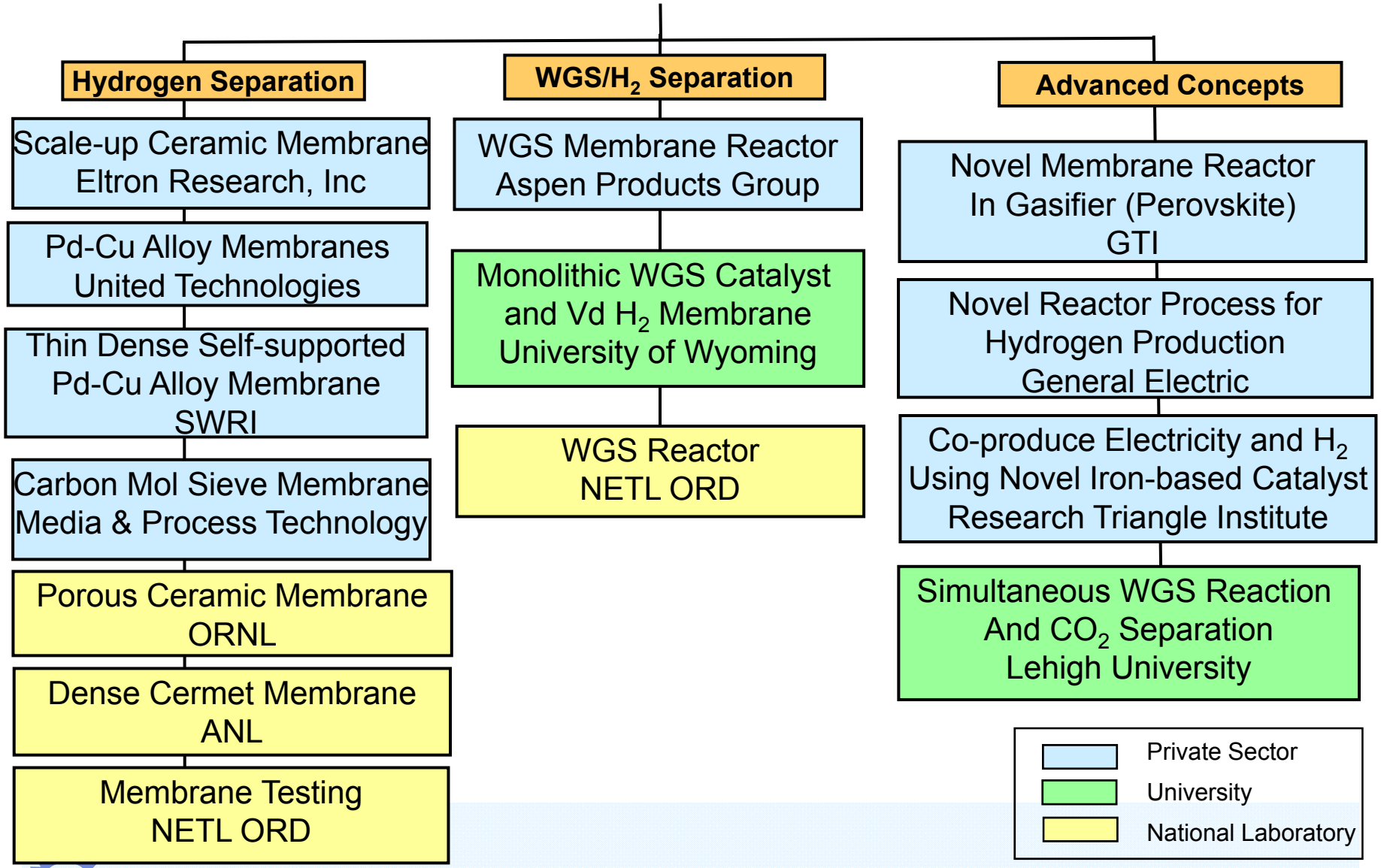
Seals, synergy versus challenges

Water-Gas-Shift Membrane Reactor Concept

- WGS Reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$
- High-T operation for favorable kinetics
- Membrane removes H_2 to "shift" unfavorable equilibrium to produce more H_2.



Hydrogen Central Production Pathway Projects



Hydrogen Central Production Pathway Projects Selections - Dec. 2006

Hydrogen Purification
- Praxair, CSM, Boothroyd-Dewhurst

Hydrogen Separation Membrane
- SWRI, CSM, CMU, TDA

Resistant Hydrogen Separation Membrane
- UTC, Power+Energy

"One Box" Process to Generate Low Cost Hydrogen
- MPT, USC, Pall, Southern

Process to Produce High-Purity Hydrogen
- OSU, Clear Skies Consulting, Consol

Composite Membranes
- WPI, Adsorption Research

Central Pathway
Selected Hydrogen Separation Membrane Projects

Eltron Research, Inc.

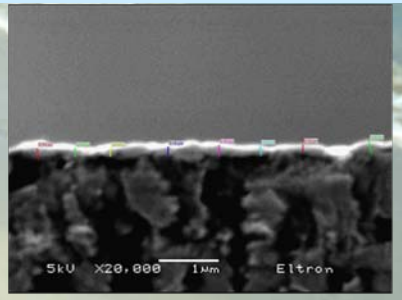
Novel ceramic/metal (cermet) membranes for the separation of hydrogen from coal derived syngas streams. Selectivity = 99.999%+

- Demonstrated wafer flux of 100 $ft^3/hr/ft^2$ at 100 psi and 420°C
- FY2007 testing showed hydrogen flow at 1.46 lb/day using a 63 cm^2 membrane, at 320 – 440 °C, with a trans-membrane pressure of 100 psi. Hydrogen flux ~ 150 $ft^3/hr/ft^2$
- Future engineering unit planned with H_2 production of 220 lbs/day with tubular membranes, at 400 psi
- Possible testing at FutureGen plant
- Eventual scale up to 4 tons/day.

Additional Participants: CoorsTek, Praxair, Noram Engineers and Constructors

1.3 lb/day separation unit

Cross-section of electro-deposited alloy catalyst on metal membrane



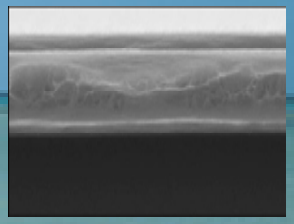
Central Pathway
Selected Hydrogen Separation Membrane Projects

Southwest Research Institute

New approach to produce metallic membranes for hydrogen separation- planar, self supporting thin films of Pd, Cu and a third transition metal (Ru)

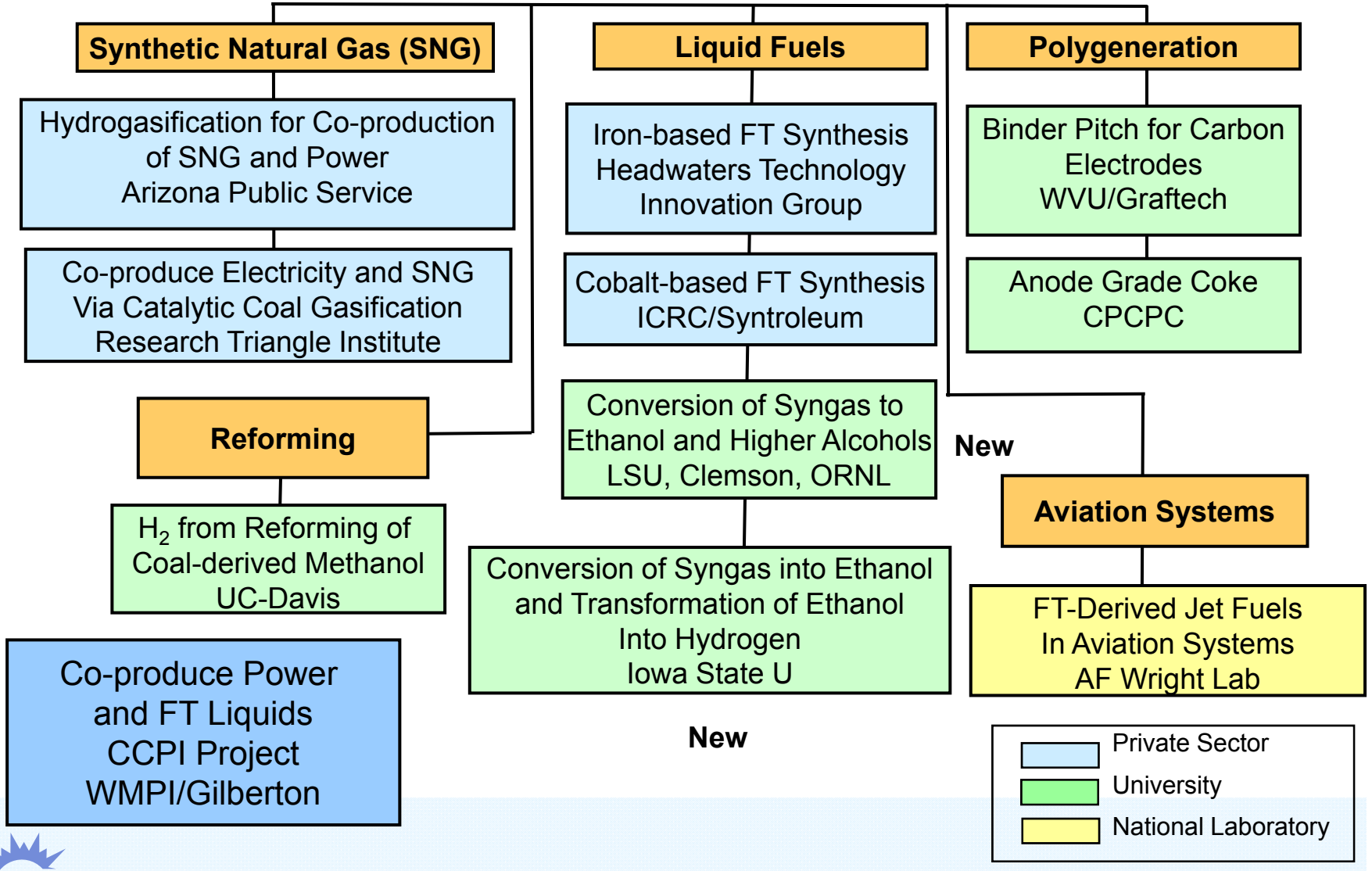
- Low cost, large surface area thin films via deposition on a removable substrate - target membrane thickness ~50% of existing membranes, or ~5 microns
- Recent tests on small membrane samples show flux rates of 242 $ft^3/hr/ft^2$ at 400 ^oC and 20 psi feed pressure
- Costs estimated to be ~$46/$ft^2$
- In Q3 FY 2007, test larger membrane- ~ 110 square inches- at 400 ^oC and 100-400 psi – with target purity of 99.95 % and flux rates >100 $ft^3/hr/ft^2$
- Other Participants- IdaTech, Colorado School of Mines

Membrane cross-section 10000X



SWRI membrane

Alternate H_2 Production Pathway Projects



CTL Research Activities

- **Headwaters Technology Innovation Group (HTIG) –** ($4.2M):
  - **Produce barrel quantities of coal-derived liquids using Iron-based FT synthesis in PDU-scale reactor.**
  - **Investigate primary and secondary wax/catalyst separation, hydrotreating and hydrocracking of neat FT liquid products, and hydrogen yield from product reforming.**
- **Status**:
  - **PDU planned at the Gas Technology Institute's (GTI) facility in Des Plaines, IL.**
  - **PDU fabrication and operation proposed to be done by HTIG.**
  - **HTIG will utilize their hydocracking facility to upgrade raw FT wax products.**

CTL Research Activities

- **ICRC – ($5M):**
  - **Produce gallon/barrel quantities of FT liquids from coal-derived syngas with Cobalt-based catalysts to be further processed into No. 2 diesel for small-scale testing as ultra-clean transportation fuel, evaluated as fuel for specialized vehicles for the military, and tested as feed to a reformer to produce hydrogen.**
- **Status:**
  - **Negotiating with two partners to produce lab and large scale quantities of FT liquids from "live" coal-derived synthesis gas.**

Nikiski AK FT Plant

Lab Scale CSTR

WMPI-Gilberton (DOE CCPI Project)

- Gasify anthracite waste (4,700 tons/day) to produce syngas using high pressure oxygen-blown gasifiers.
- Co-produce electric power (41MW) and steam together with 5,000 barrels per day of synthetic hydrocarbon liquid fuels via FT synthesis.
- A Shell gasifier and Rectisol™ process removes contaminants from the plant's effluent and concentrates CO_2 for sequestration.
- **Benefits-** If successful, technology may be applied throughout the U.S. enabling reclamation of coal wastes into high-cetane diesel fuel.

Shell SCGP Gasifier

Rationale for B-52 Testing

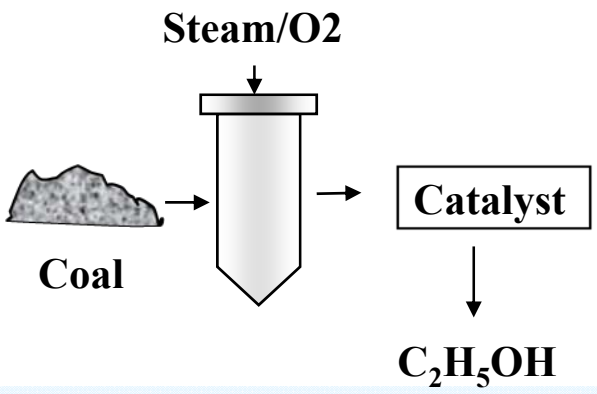
- **Decision to use B-52 for demo supported by:**
  - Safety
    - 8 Engines
    - Ability to isolate test fuel and feed only 2 engines
    - TF33 non-afterburning, less complex, subsonic flight envelope
  - Aircraft Available
    - Target aircraft selected to retire (no impact to test or operational fleet)
  - Successful Demonstrations:
    - Two engine test - 9/2006
    - Eight engine test with mixed jet fuel/FT fuel – 12/2006

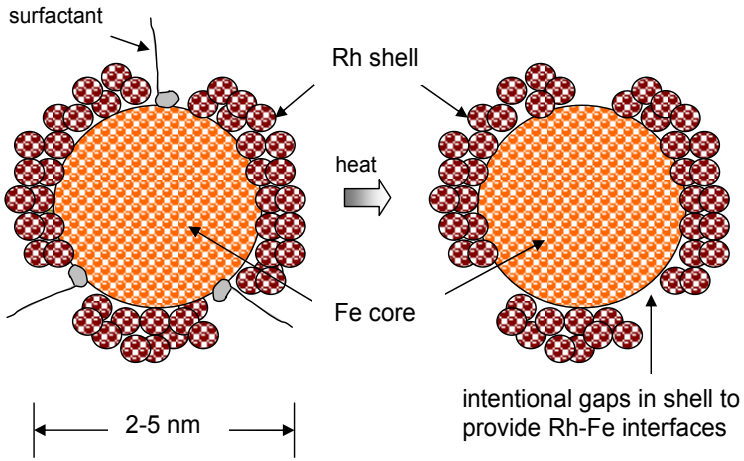
Request for Information Synthetic Fuel

- **DESC Request for Information (RFI)**
  - Issued May 30, 2006
  - Closed August 10, 2006 (initially set for July 31, 2006)
  - Responses received – 28 total (22 interested in production)
- **Objectives**
  - RFI PART I: Short-Term Objective (through 2011)
    - Identify responsible potential sources of synthetic fuel meeting the Fischer-Tropsch DRAFT specification
    - Determine feasibility of 200M USG requirement
      - 100M USG Air Force
      - 100M USG Navy
  - RFI PART II: Long-Term Objective (past 2011)
    - Investigate long-term prospects for the manufacture and supply of aviation synthetic fuels on a larger scale

LSU/Clemson/ORNL/ConocoPhillips

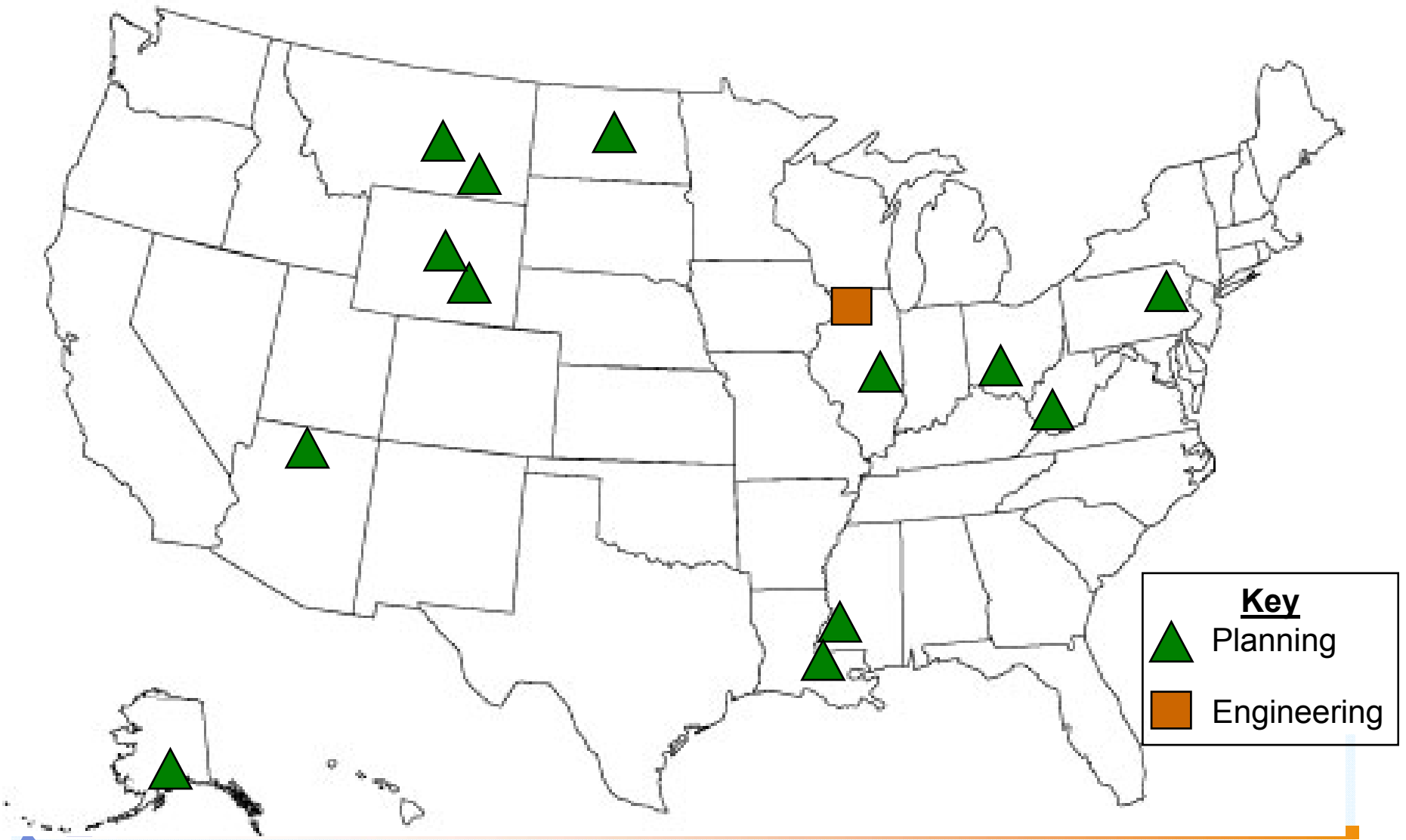
- Catalytic process for the synthesis of ethanol from coal-derived syngas
- Current yields – 5%
- Target yield – 45% (95% selectivity, 3 year life)





Core-shell nanostructured catalysts particles: Fe core-Rh shell.

Plants Under Consideration in the United States



Summary of CTL Projects in United States

State	Developers	Coal Type	Capacity (bpd)	Status
AZ	Hopi Tribe, Headwaters	Bituminous	10,000 – 50,000	Planning
MT	DKRW Energy (Roundup, MT)	Sub-bituminous/lignite	22,000	Planning
MT	State of Montana	Sub-bituminous/lignite	10,000 – 150,000	Planning
ND	Headwaters, GRE, NACC, Falkirk	Lignite	40,000	Planning
OH	Rentech, Baard Energy	Bituminous	2 plants, 35,000 each	Planning
WY	DKRW Energy (Medicine Bow, WY)	Bituminous	11,000	Planning
WY	Rentech	Sub-bituminous	10,000 – 50,000	Planning
IL	Rentech, (East Dubuque, IL)*	Bituminous	2,000	Engineering
IL	Unidentified Alexander County (Cairo, IL)	Bituminous	50,000	Planning
IL	American Clean Coal Fuels	Bituminous	25,000	Planning
PA	WMPI	Anthracite	5,000	Planning
WV	AEP Mountaineer	Bituminous	10,000	Planning
WV	Mingo County	Bituminous	10,000	Planning
MS	Rentech	Coal/petcoke	10,000	Planning
LA	Synfuel Inc.	Lignite	Not available	Planning

* will also co-produce fertilizer.

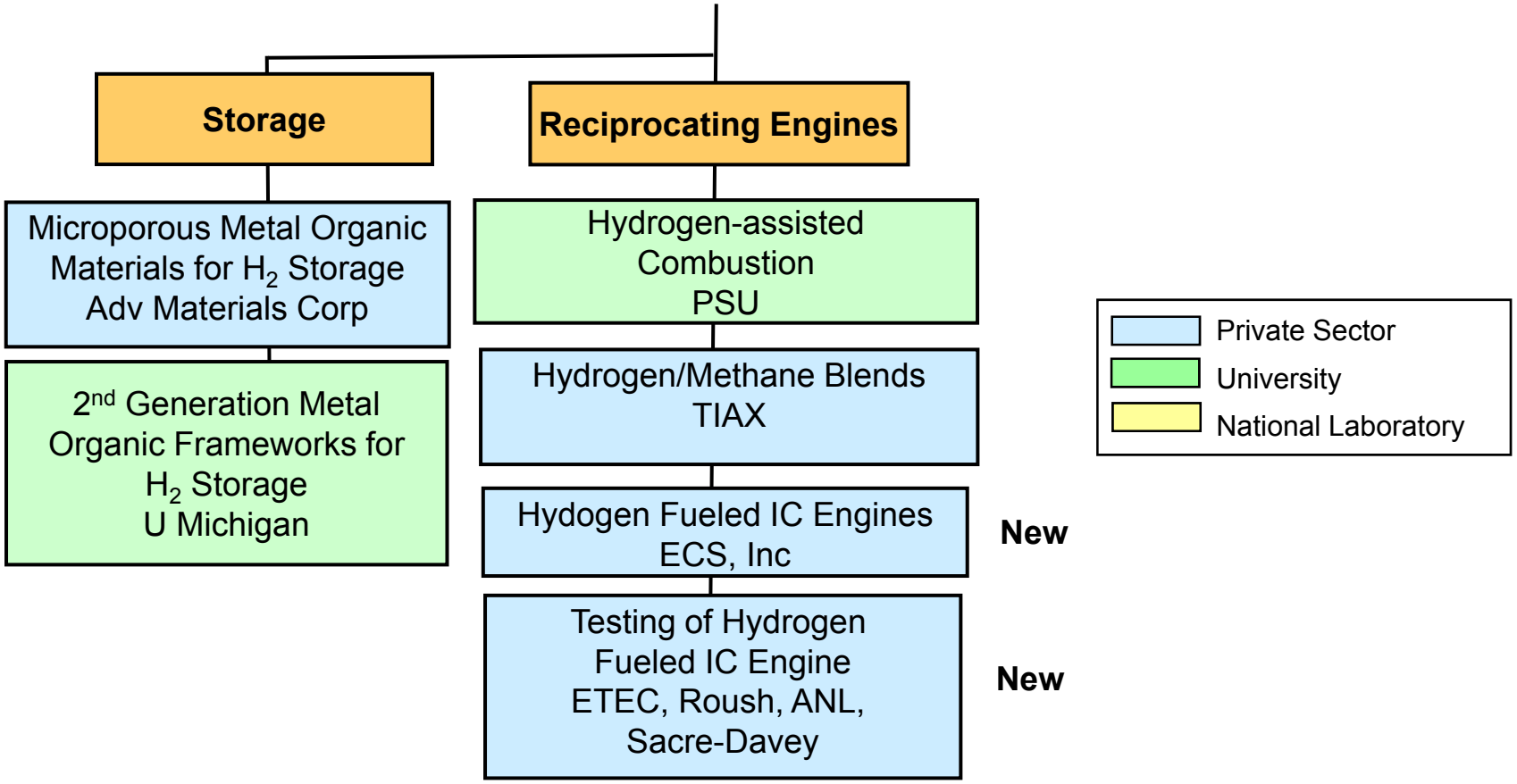
Existing and Potential CTL Projects

Ref: from Headwaters Inc. J.N. Ward Senate Briefing 1-19-07

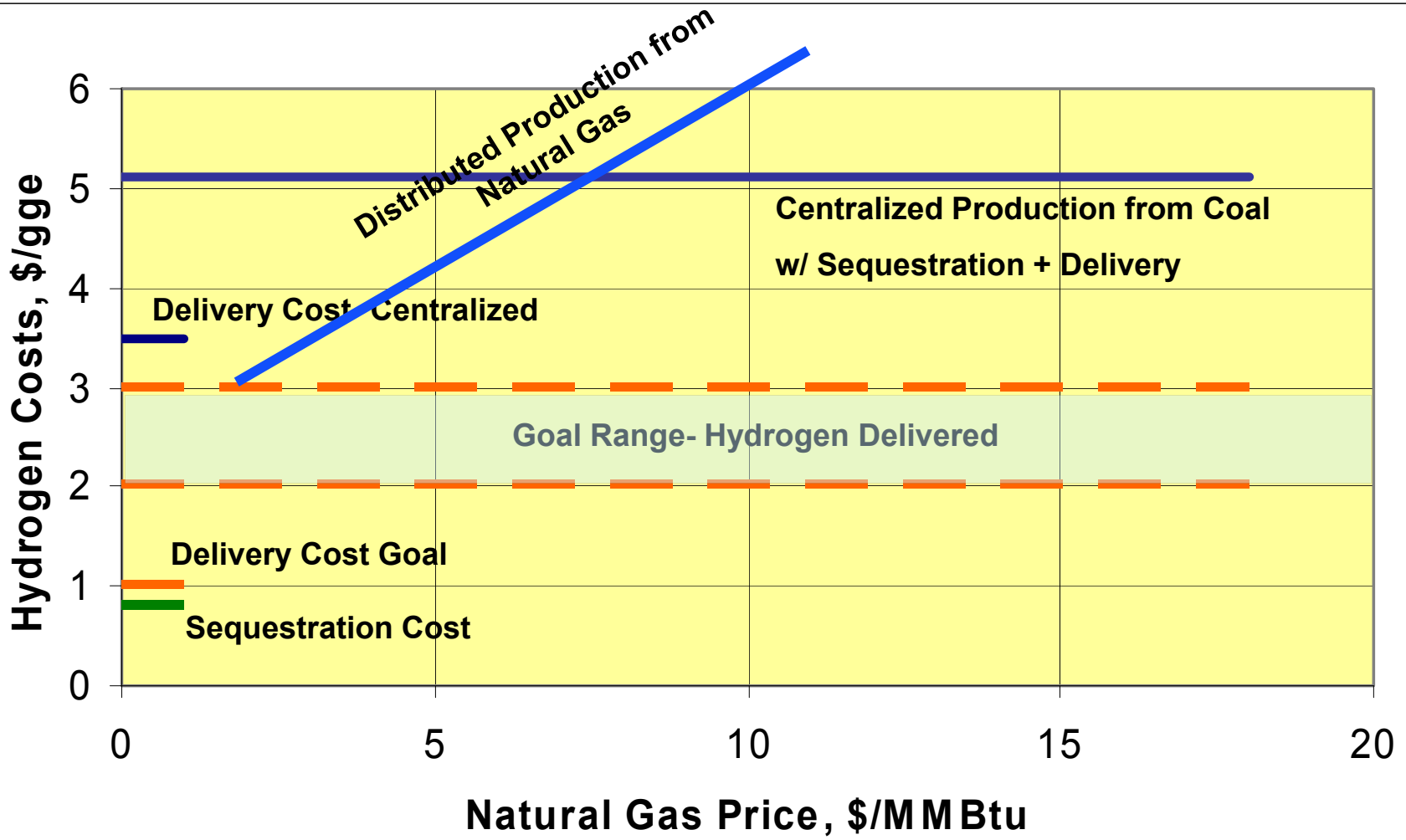
Summary of CTL World-Wide

Country	Owner/Developer	Capacity (bpd)	Status
South Africa	Sasol	150,000	Operational
South Africa	Sasol	80,000	Planning
China	Shenhua	20,000 (initially)	Construction – Operational in 2007
China	Lu'an Group	~3,000 to 4,000	Construction
China	Yankuang	40,000 (initially) 180,000 planned	Construction
China	Sasol JV (2 studies)	80,000 (each plant)	Planning
China	Shell/Shenhua	70,000 – 80,000	Planning
China	Headwaters/UK Race Investment	Two 700-bpd demo plants	Planning
China	Siemens	--	Planning
India	Oil India Ltd	Pilot plant	Operational & 2nd Planned
Indonesia	Pertamina/Accelon	~76,000	Construction
Australia	Anglo American/Shell	60,000	Planning
Philippines	Headwaters	50,000	Planning
New Zealand	L&M Group	50,000	Planning

Hydrogen Utilization and Storage Projects

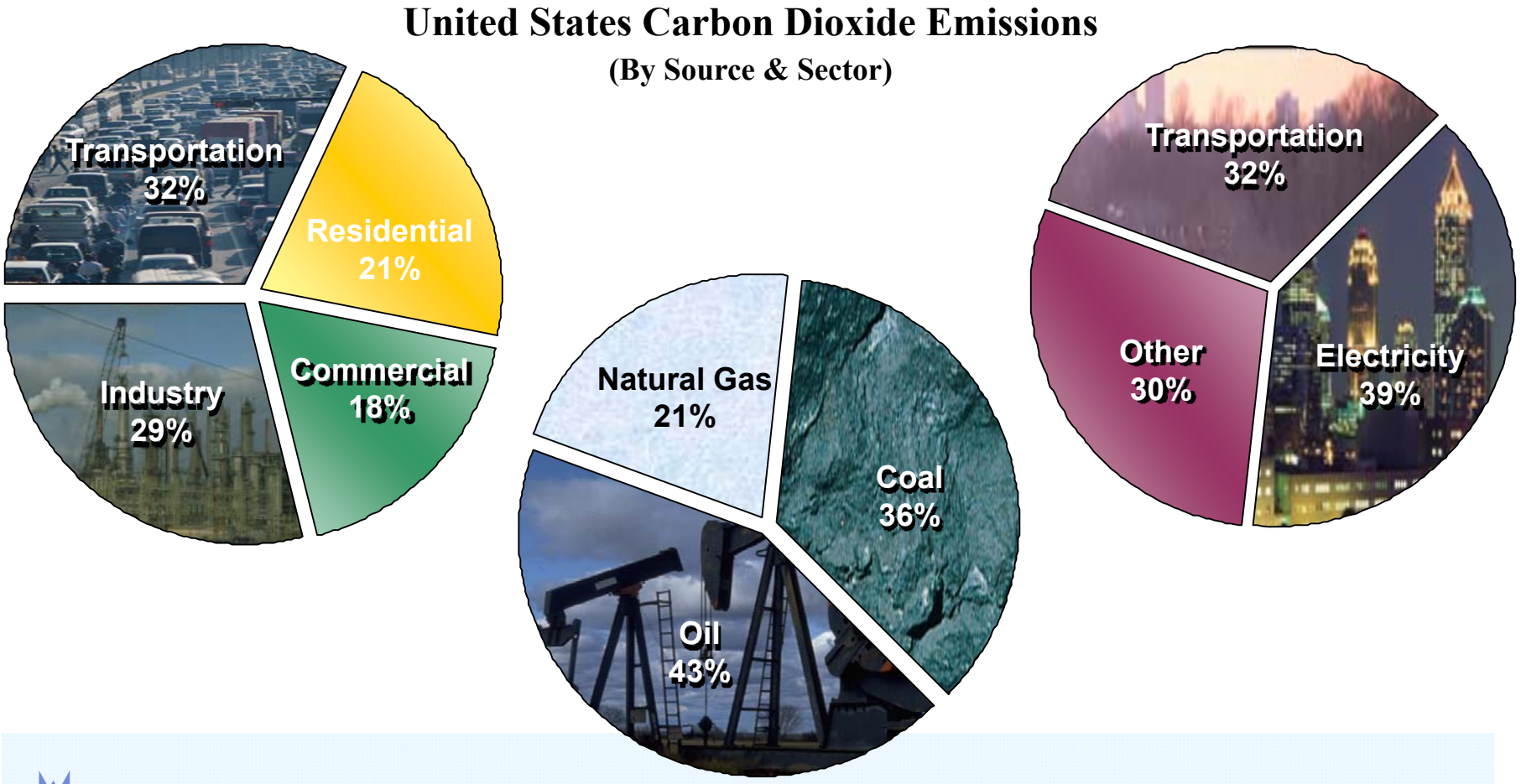


Hydrogen Production Costs from Natural Gas and Coal



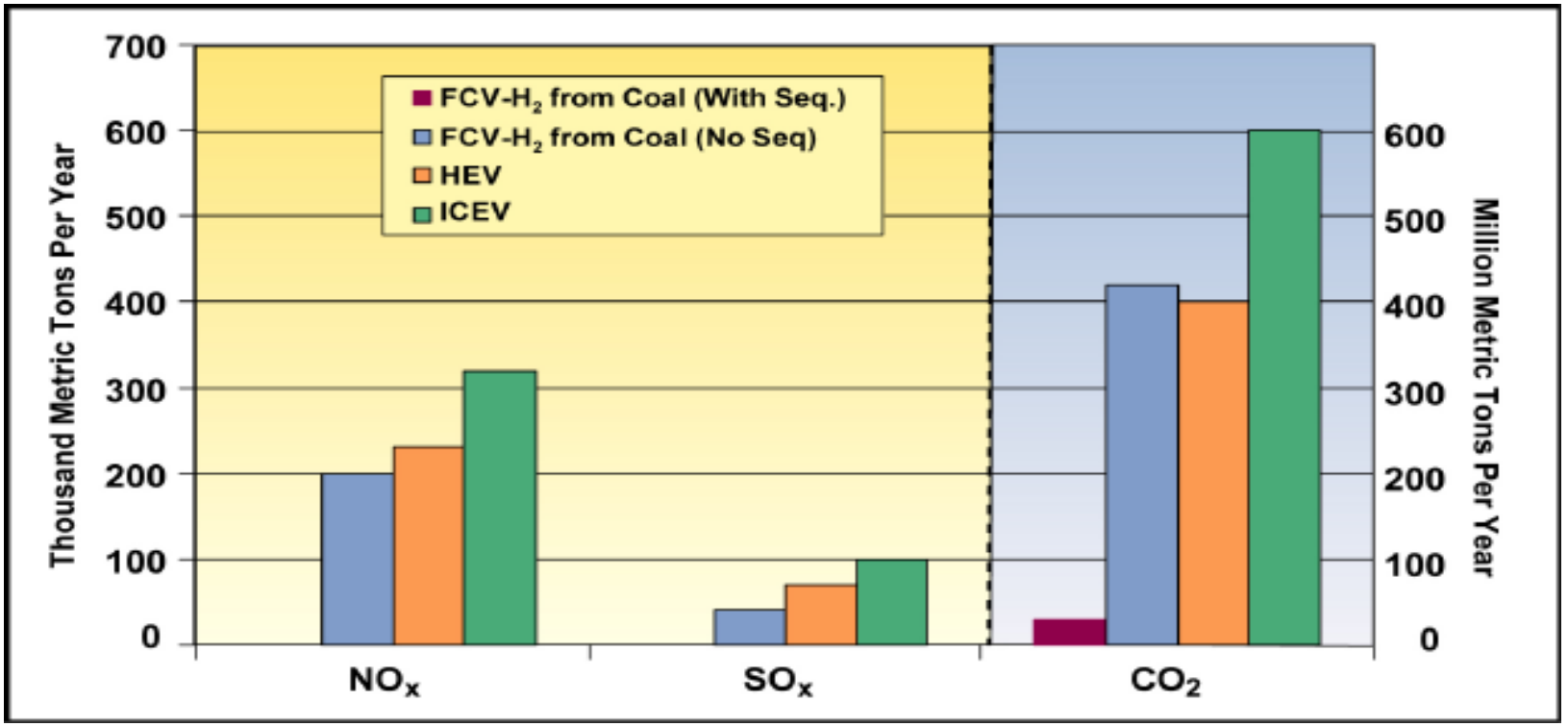
Source- DOE H2A Analysis Amended, http://www.hydrogen.energy.gov/well_wheels_analysis.html

All Fossil Fuels & Energy Sectors Contribute CO_2 Emissions



Projected Benefits - Hydrogen from Coal

Criteria Pollutants and CO_2 Emissions in 2025 from Hydrogen Use in Fuel Cell Vehicles Compared to Gasoline Use in Hybrid Electric and Internal Combustion Engine Vehicles (100 million vehicles)



Reference - Hydrogen from Coal Program RD&D Plan - External Draft for Review
http://www.netl.doe.gov/technologies/hydrogen_clean_fuels/index.html

Carbon Sequestration Options

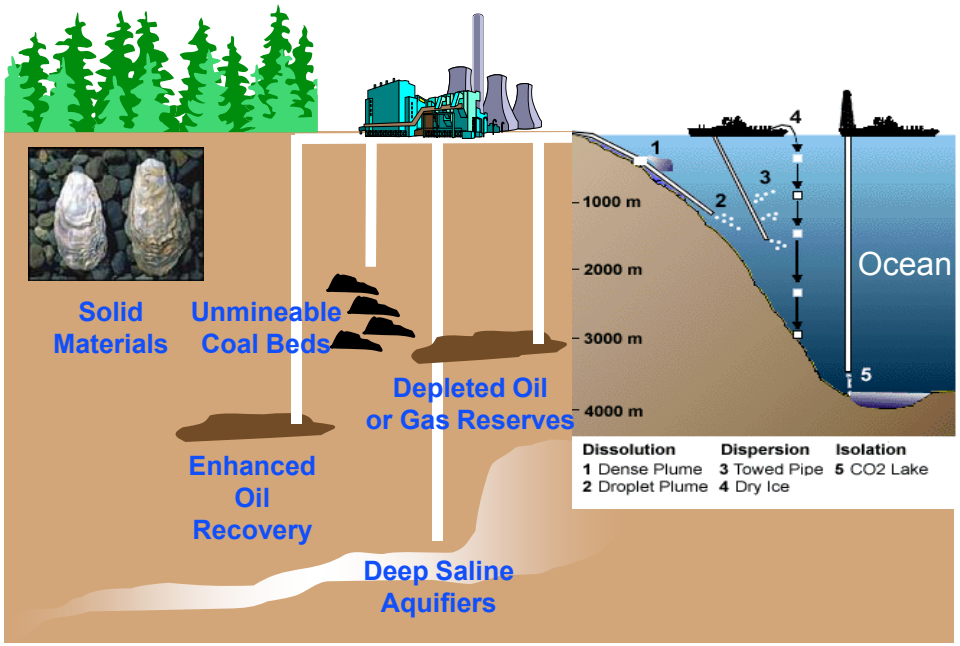
Capture and storage of CO_2 and other Greenhouse Gases that would otherwise be emitted to the atmosphere

Capture options:

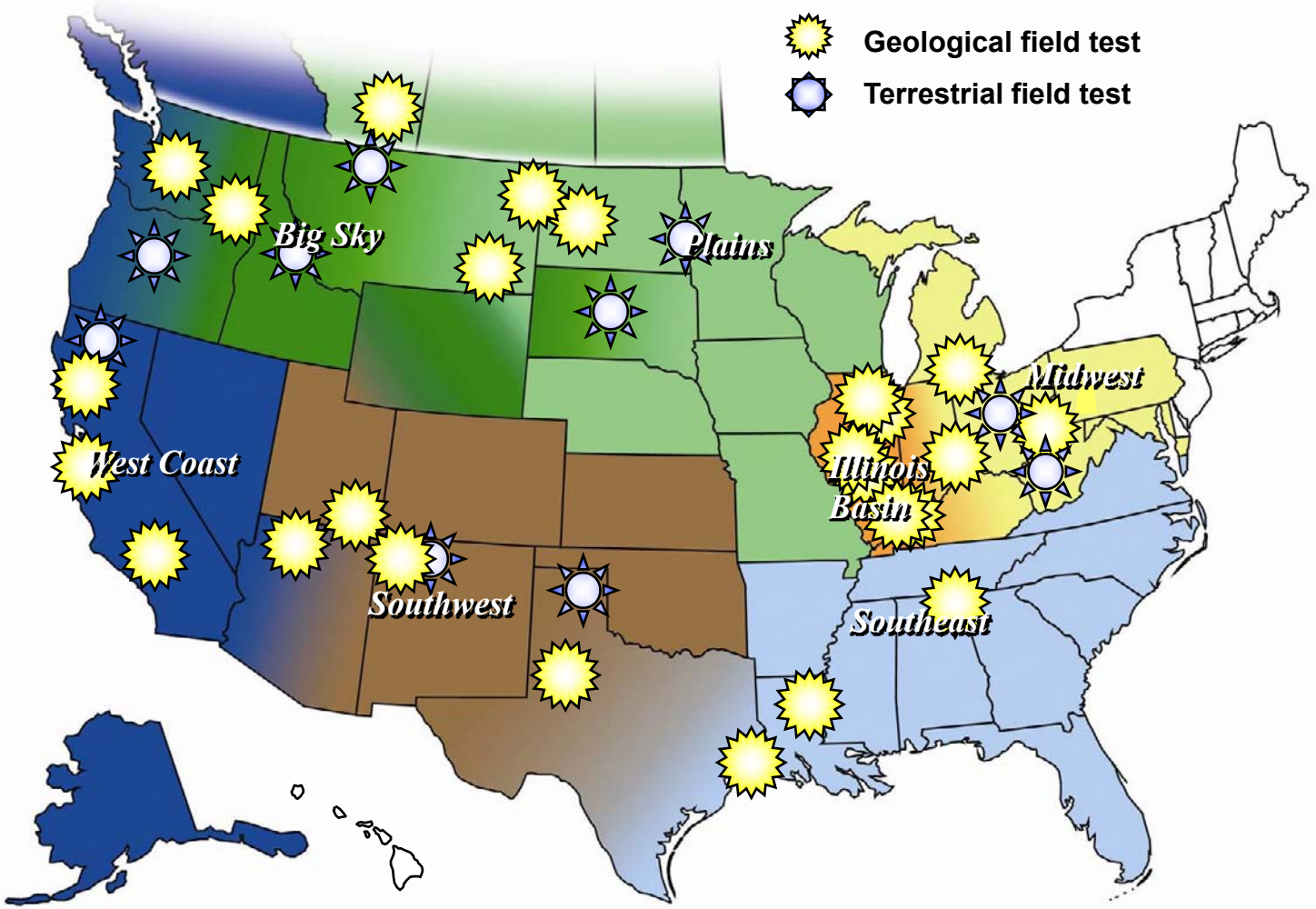
- Pre-combustion capture
- Post-combustion capture
- Oxygen-fired combustion
  - Chemical looping

Storage locations include:

- underground reservoirs
- dissolved in deep oceans
- converted to solid materials
- trees, grasses, soils, or algae

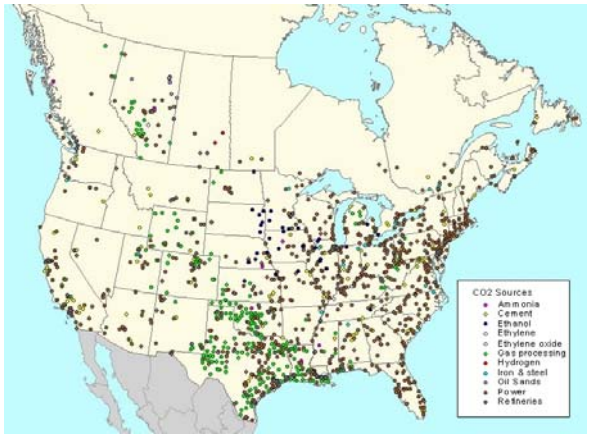


Regional Carbon Sequestration Partnerships
Field Validation Tests



Carbon Capture and Sequestration is Feasible

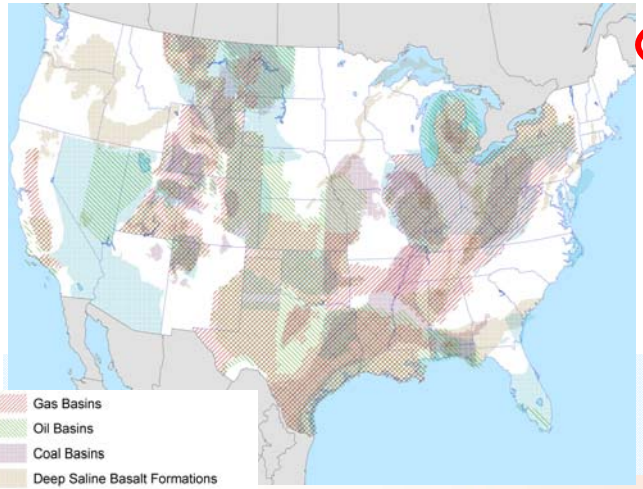
Adequate Capacity in U.S.



2,082 Large Sources (100+ $ktCO_2/yr$) with Total Annual Emissions = 3.8 $GtCO_2/yr$

- 1,185 electric power plants
- 447 natural gas processing facilities
- 154 petroleum refineries
- 53 iron & steel foundries
- 124 cement kilns
- 43 ethylene plants
- 9 oil sands production areas
- 40 hydrogen production
- 25 ammonia refineries
- 47 ethanol production plants
- 8 ethylene oxide plants

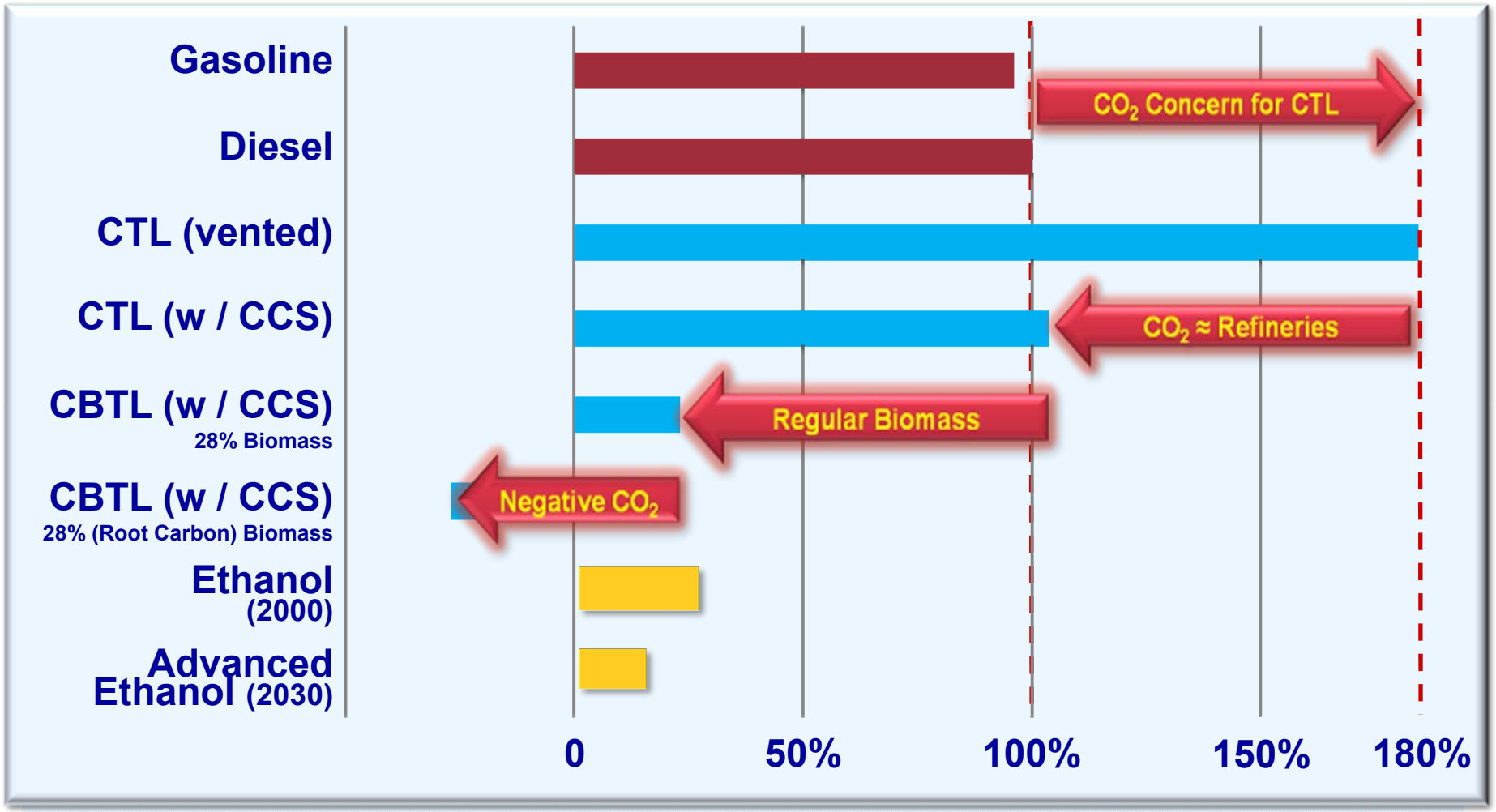
~ 1000 Years



3,800+ $GtCO_2$ Capacity within 330 US and Canadian Candidate Geologic CO_2 Storage Reservoirs

- 3,730 $GtCO_2$ in deep saline formations (DSF)
- **65 $GtCO_2$ in deep unmineable coal seams with potential for enhanced coal bed methane (ECBM) recovery**
- **40 $GtCO_2$ in depleted gas fields**
- 13 $GtCO_2$ in depleted oil fields with potential for enhanced oil recovery (EOR)

Greenhouse Gas Emission Rates for Fuel Production and Use



Coal / Biomass-to-Liquids May Beat Ethanol on CO_2 Emissions

Professor Robert Williams (Princeton), presentation to LERDWG meeting, April 18, 2007
Robert Williams Presentation to 5th Annual Conference on CCS, DOE/NETL, May 8–11, 2006

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