# Fuel Cells and the Environment:
## A Potential Path to Sustainability and the Hydrogen Economy

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# Outline of Talk

- Fuel cells and the "hydrogen economy"
- Environmental benefits and challenges
- The role of carbon sequestration
- A potential path to sustainability

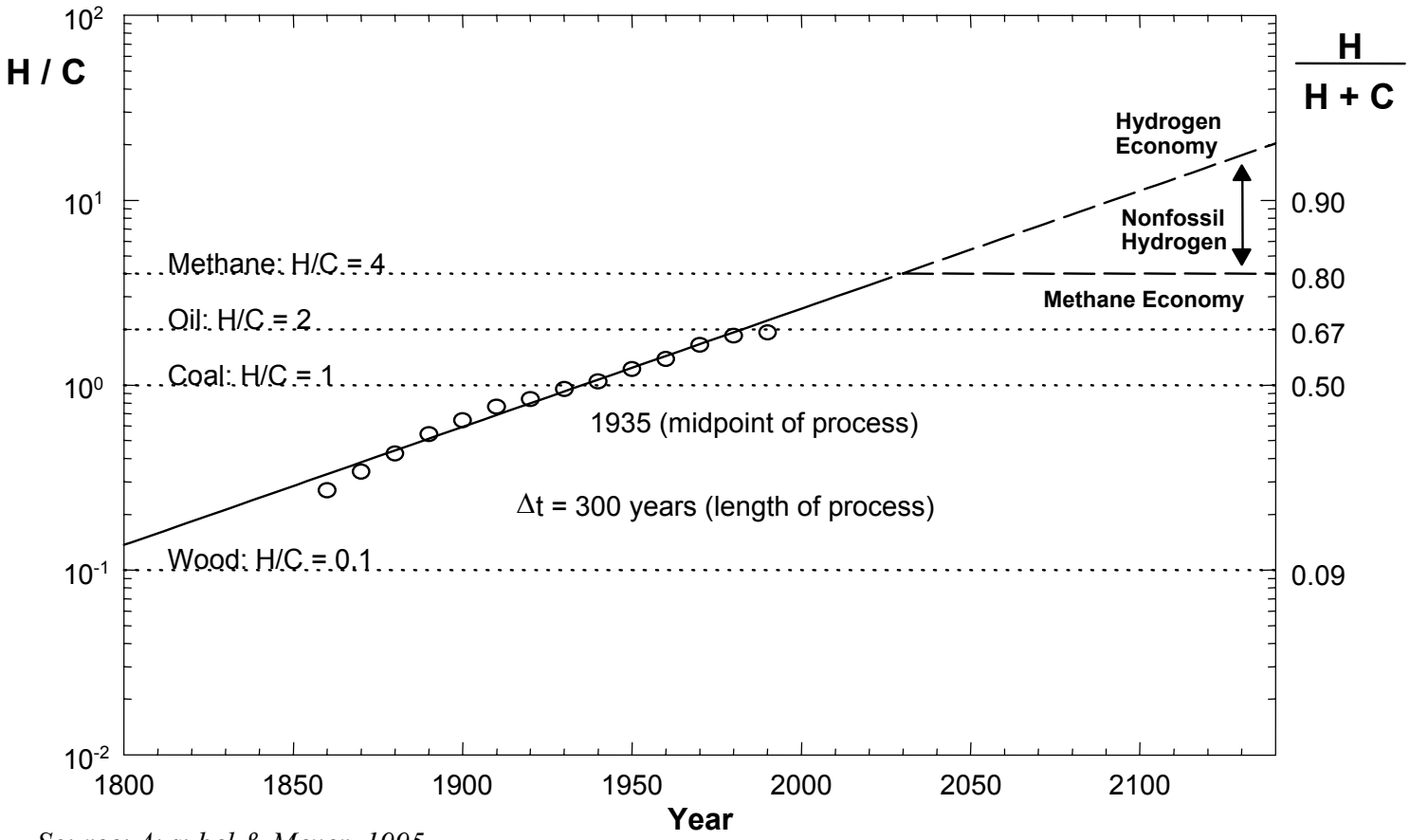
# Fuel Cells and the "Hydrogen Economy"

- Advanced fuel cells generating electricity from reactions of hydrogen and oxygen are intimately associated with the concept of a "hydrogen economy"

# Why the Interest in Hydrogen?

- Hydrogen as a clean end-use fuel (reducing emissions of conventional pollutants and greenhouse gases)
- Hydrogen as a national security asset (reducing oil imports and associated vulnerabilities)
- Hydrogen for sustainable development (replacing depleted fossil fuel resources over the next century and beyond)
- Hydrogen as "manifest destiny"

# Evolution of the World's Primary Fuel Mix




*Source: Ausubel & Meyer, 1995*

# Major Environmental Concerns Driving Interest in Fuel Cells and Hydrogen

*Near-term Issues:*

- Air pollutants affecting human health
  - Transportation sector (CO, HC, $NO_x$, Pb)
  - Other sectors ($SO_2$, $NO_x$, $PM_{10}$, Hg)

*Longer-term Issue:*

- Greenhouse gases affecting global climate
  - $CO_2$ emissions from fossil fuels
  - Other GHGs from human activities

# Hydrogen as a "Zero Emission" Fuel for Pollution Control

- Increasing stringency of automotive emission standards (esp. California ZEV requirements) helped promote substantial recent interest and investments in vehicles using $H_2$-powered fuel cells
- A wide array of public and private RD&D programs on $H_2$-powered vehicles (including SECA, FreedomCAR)
- *But many tough problems must be solved before fuel cells and $H_2$ can compete successfully with alternative transportation fuels and prime movers*

# Challenges of $H_2$ for Transportation

- Technology for $H_2$-powered Vehicles
  - Performance
  - Cost
  - Safety
  - Public Acceptance
- Infrastructure for $H_2$-powered Vehicles
  - Technology
  - Cost
  - Safety
  - Timing
  - Who will pay for it?

# Environmental Benefits of Fuel Cells: Reduced Vehicle Emissions


*Case 1:* Conventional Diesel Engine

# Environmental Benefits of Fuel Cells: Reduced Vehicle Emissions


*Case 2:* Fuel Cell w/ Hydrocarbon Fuel

# Environmental Benefits of Fuel Cells: Reduced Vehicle Emissions

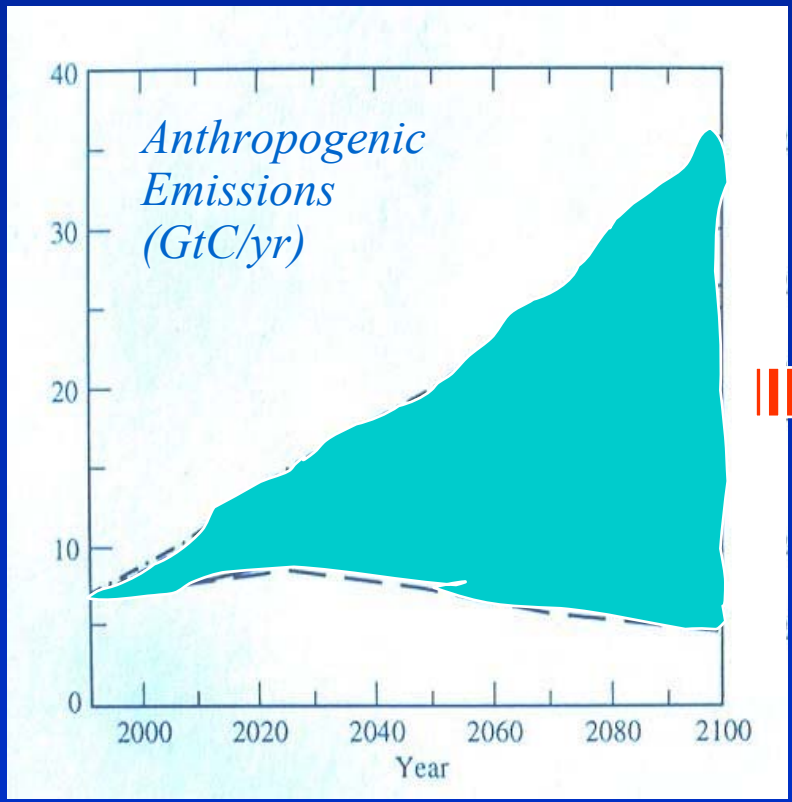
C-free
"ZEV"

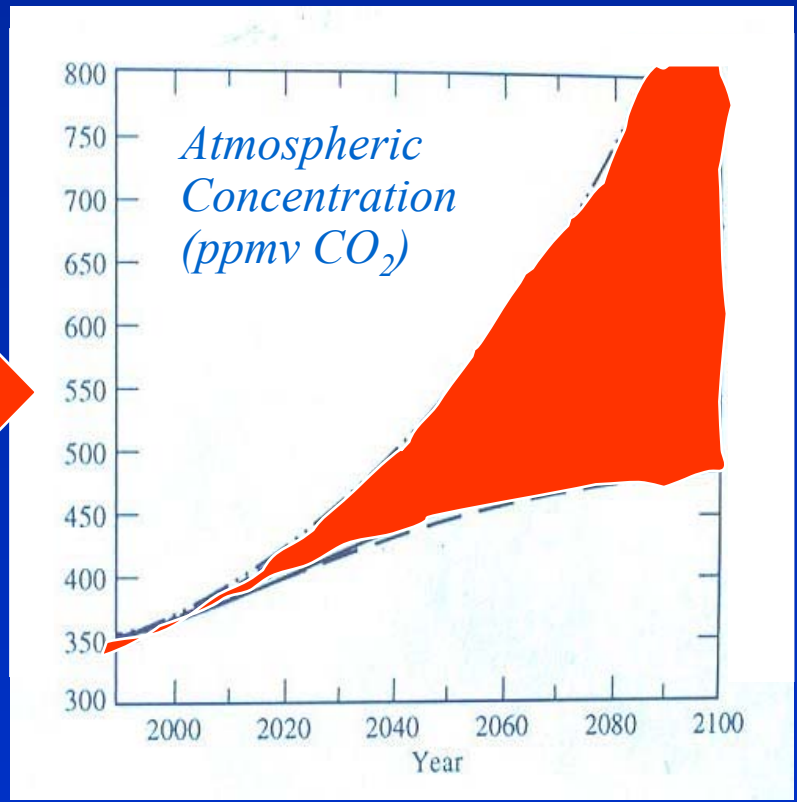

*Caution:* *Life cycle assessments might tell a different story*

*Case 3:* Fuel Cell w/ Hydrogen Fuel

# Why the Concern About $CO_2$?

*Projected increases in $CO_2$ levels drives the climate change issue*




*Source: IPCC, 1996*

# The Long-Term Goal of Carbon-Free Energy

- 1992 U.N. Framework Convention on Climate Change called for "stabilization of greenhouse gas concentrations in the atmospheric at a level that would prevent dangerous anthropogenic interference with the climate system"
- This implies a long-term need to drastically reduce $CO_2$ emissions, no matter what stabilization target is selected!
- *This will require major long-term changes in our energy system, with electricity and hydrogen playing critical roles as carbon-free energy carriers*

# Percentage of U.S. $CO_2$ Emissions by Energy Source and End-Use Sector

(Based on total $CO_2$ emissions of 5727 million metric tons in 2000)

| Energy Source | End-Use Sectors | | | | |
|---|---|---|---|---|---|
| | **Residential** | **Comm'l** | **Industry** | **Transport** | **Total** |
| Petroleum | 1.8 | 0.9 | 5.6 | 32.2 | **40.4** |
| Natural Gas | 4.7 | 3.2 | 6.7 | 0.7 | 15.2 |
| Coal | 0.1 | 0.1 | 2.1 | - | 3.2 |
| Electricity | 13.5 | 13.0 | 15.4 | 0.1 | **41.9** |
| **Total** | **20.1** | **17.1** | **29.8** | **33.0** | 100.0 |

*Source: DOE/IEA, 2002*

# But Is $H_2$ Really Carbon-Free?

- Zero $CO_2$ emissions at the tailpipe or stack does not necessarily mean carbon-free energy
- Must look at how hydrogen is produced, and evaluate all emissions over the full life cycle (fuel cycle)

# The Production of Hydrogen

- *The Dream Scenario:* $H_2$ produced from electrolysis of water using electricity produced from clean renewable energy (solar, wind):

$$H_2O + \text{elec} \rightarrow H_2 + \tfrac{1}{2} O_2$$

- *The Current Reality:* Most $H_2$ is made by steam reforming of natural gas:

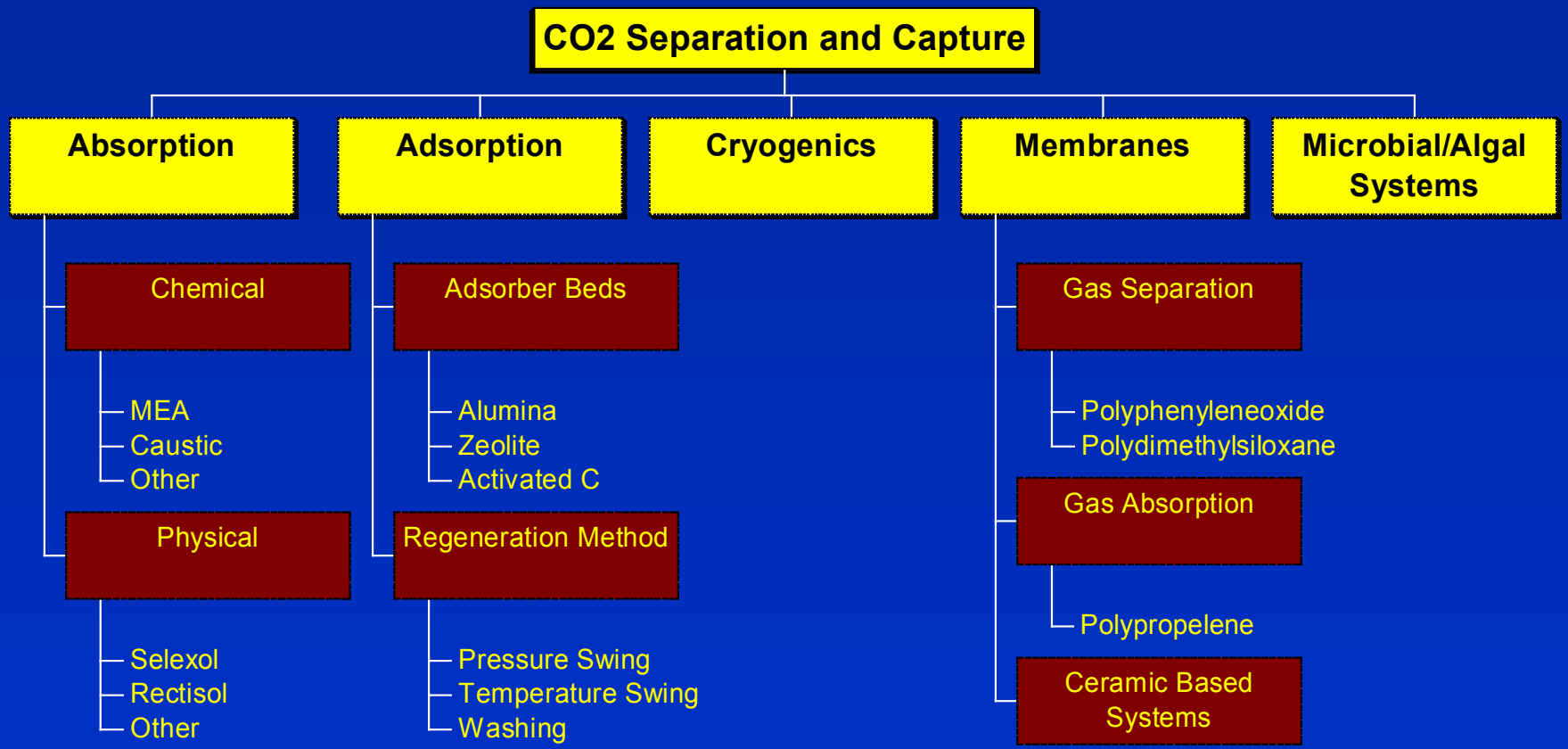
$$\underline{\textit{Reform}}: \quad CH_4 + H_2O \rightarrow 3H_2 + CO$$
$$\underline{\textit{Shift}}: \quad CO + H_2O \rightarrow H_2 + CO_2$$

Result: 5.5 tons $CO_2$ emitted per ton $H_2$ produced

# Enter Carbon Sequestration

- Until recently, the term "carbon sequestration" referred to the natural uptake of $CO_2$ by trees and other biomass (terrestrial sequestration)
- Today this term also includes the capture and storage of $CO_2$ from power plants and other industrial processes
- Carbon capture and storage (CCS) technology potentially can allow fossil fuels to be used with little or no emissions of $CO_2$ to the atmosphere

# Many Ways to Capture $CO_2$



# Potential Options for $CO_2$ Storage

- Geologic Sequestration
  - Depleted oil and gas wells
  - Unmineable coal seams
  - Deep saline reservoirs
- Terrestrial Sequestration
- Mineralization
- Ocean Sequestration
- Other Novel Concepts

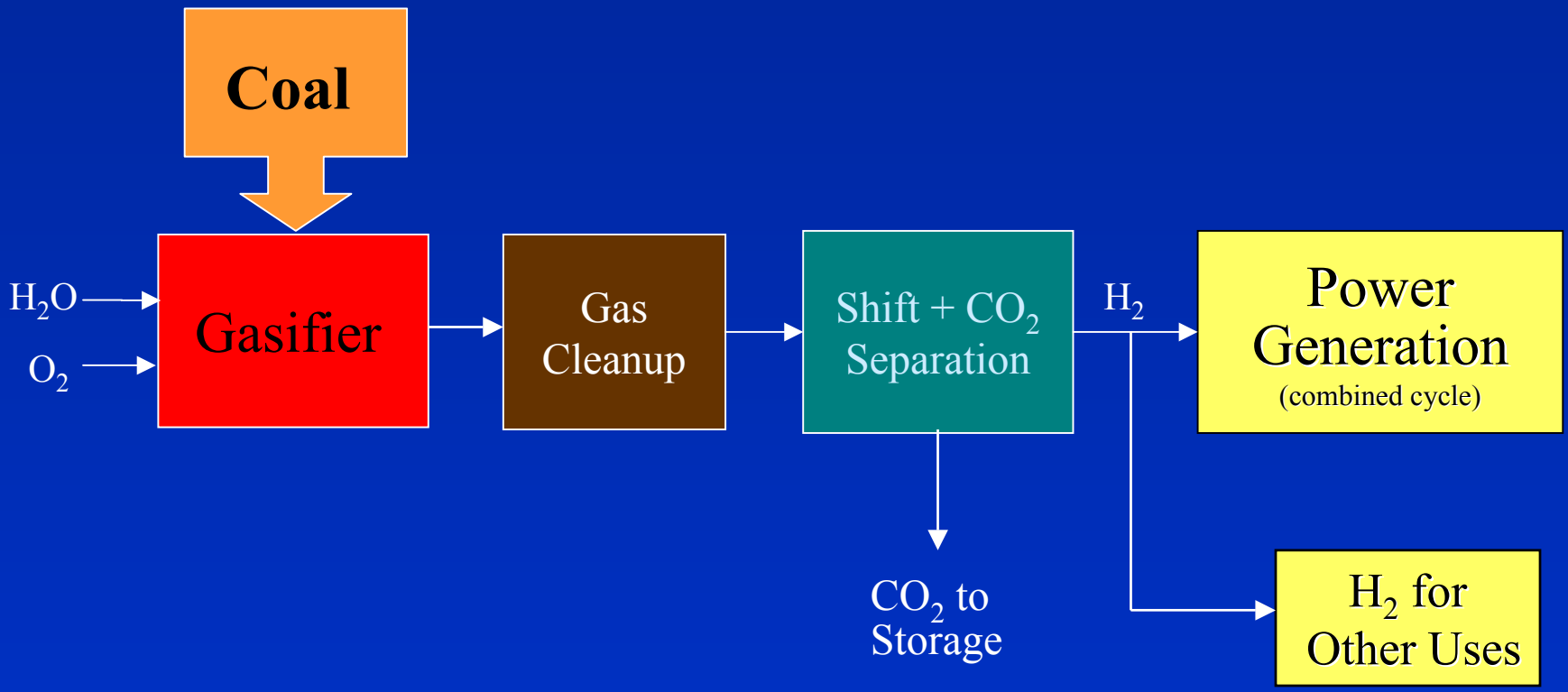
# Carbon Storage Capacity

| Storage Option | Worldwide Capacity (Order of Magnitude) |
|---|---|
| Deep Reservoirs | 100s – 1000s GtC |
| Depleted Oil and Gas | 100s GtC |
| Coal Seams | 10s – 100s GtC |
| Terrestrial | 10s GtC |

*Source: Herzog, 2000*

# One View of the Hydrogen Economy

# Another View: Carbon-Free Hydrogen from Coal



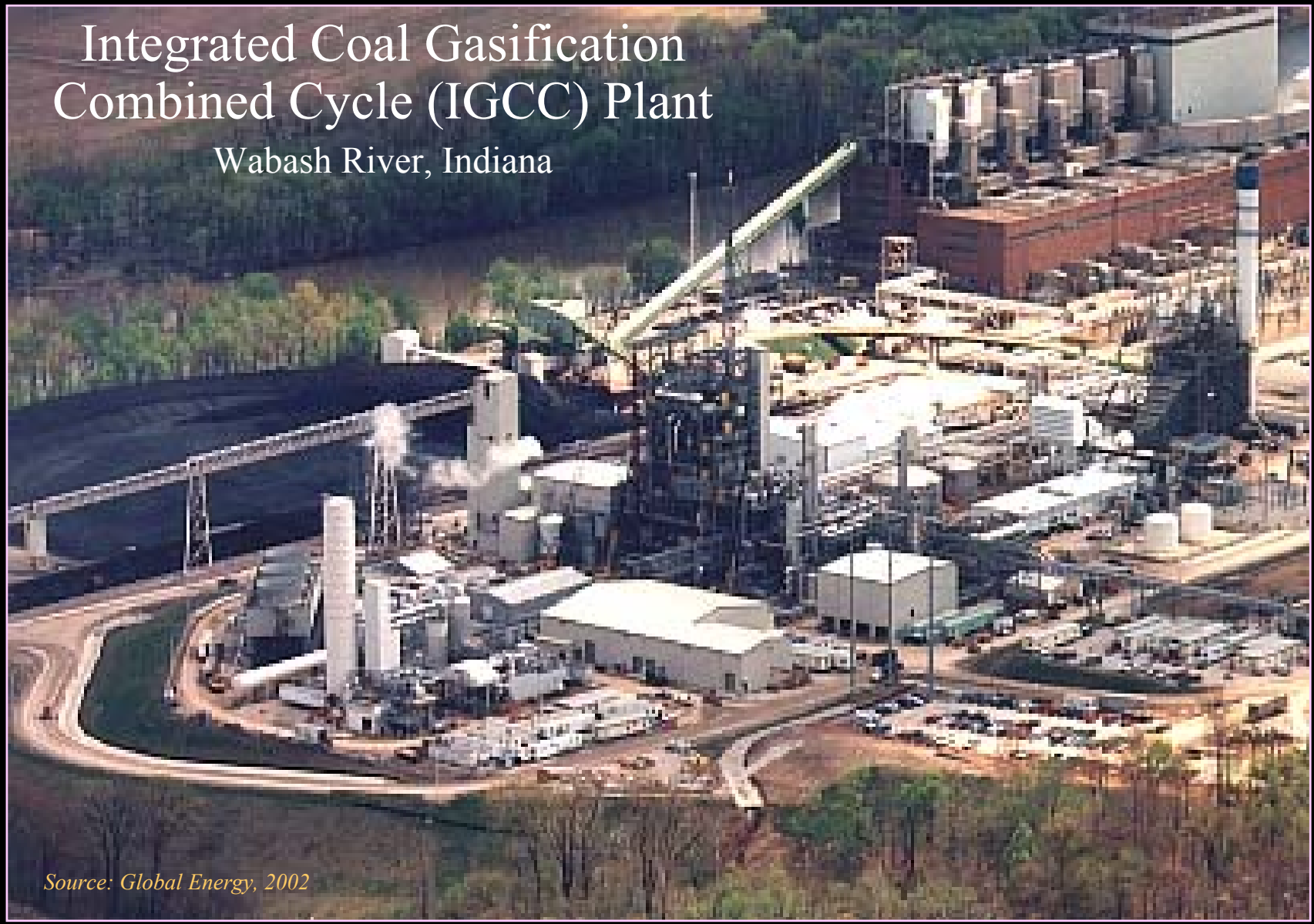
# How Far-Fetched Is This?

*Many of the pieces already exist commercially:*

- Gasification of coal and other feedstocks is a commercial technology used extensively in world industry (including power generation applications)
- Hydrogen production today is a well-developed, commercially-proven industry
- $CO_2$ capture technology also is used commercially today in a variety of process industries
- $CO_2$ injection and storage in geologic formations has been widely used for enhanced oil recovery and disposal of acid gases; several large-scale sequestration projects are now underway

# Integrated Coal Gasification Combined Cycle (IGCC) Plant

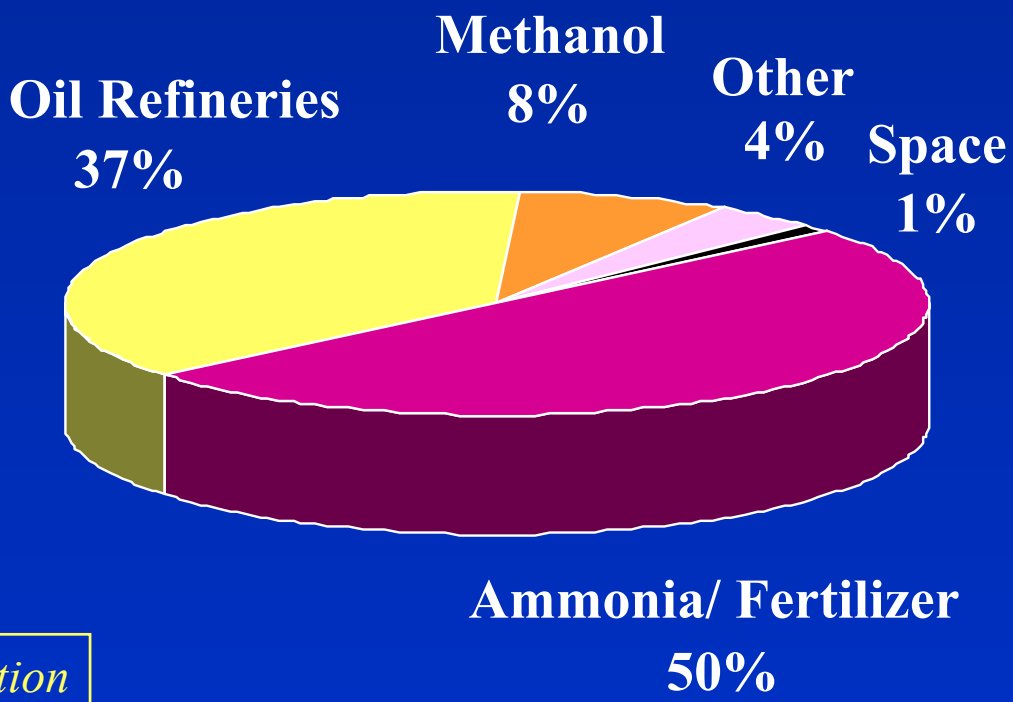
Wabash River, Indiana



*Source: Global Energy, 2002*


30 MMSCF/D Hydrogen Plant
BOC/Bulwer Island
Brisbane,Australia
Source: Chevron-Texaco
Carnegie Mellon

# Current Uses of Hydrogen

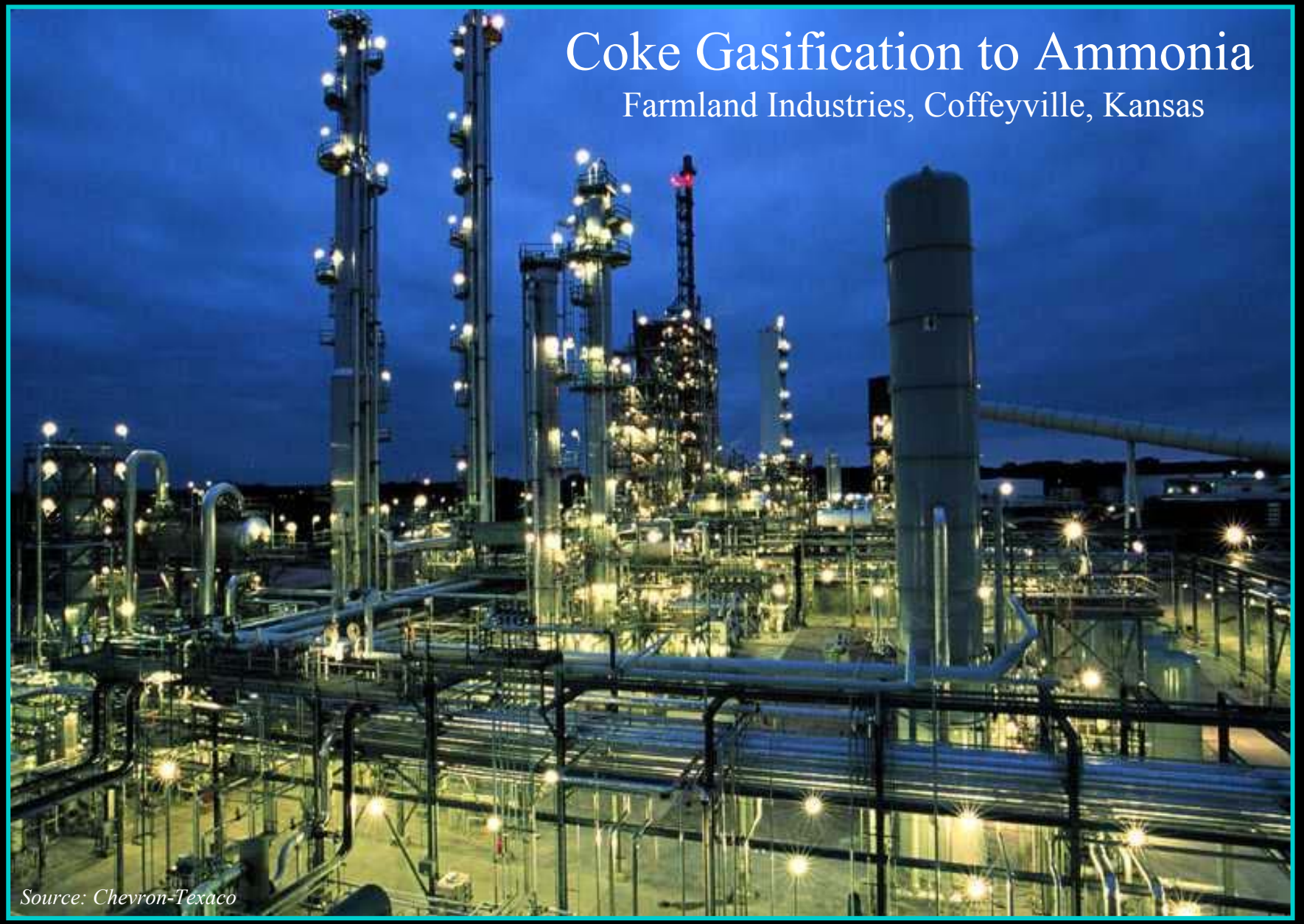



*World production*
*~ 40 Bscf/d*

*Source: IEA, 2001*

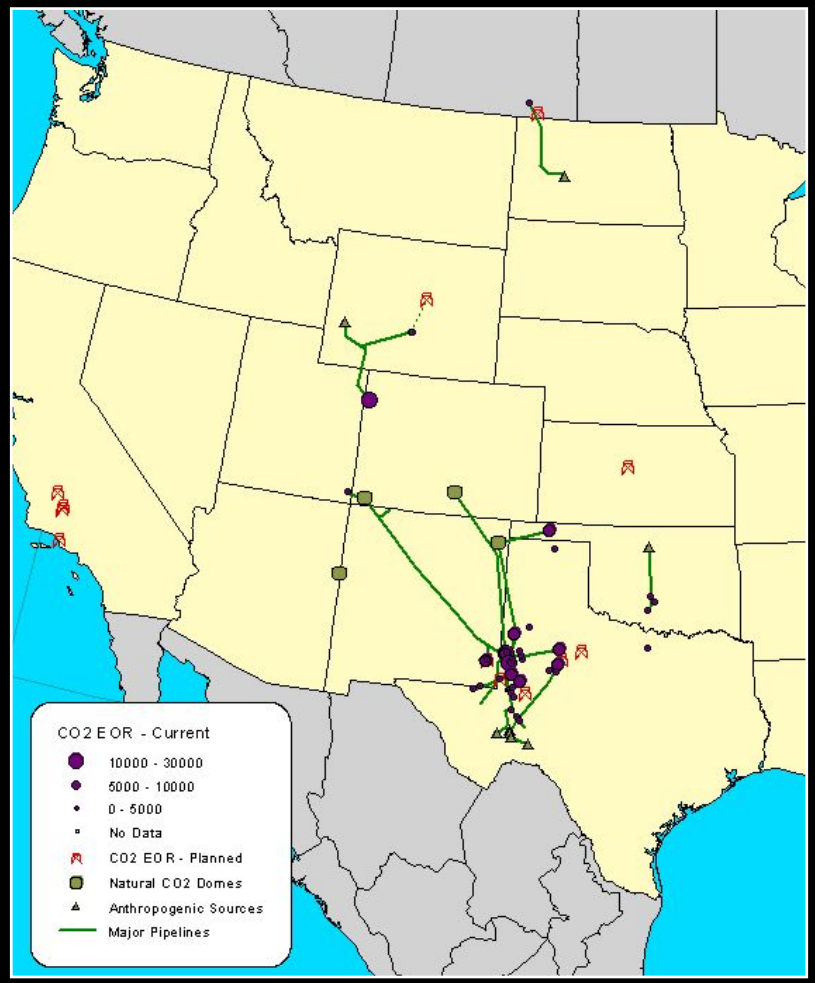
# Coke Gasification to Ammonia

## Farmland Industries, Coffeyville, Kansas



*Source: Chevron-Texaco*

# Existing $CO_2$ Pipelines for Enhanced Oil Recovery (EOR)

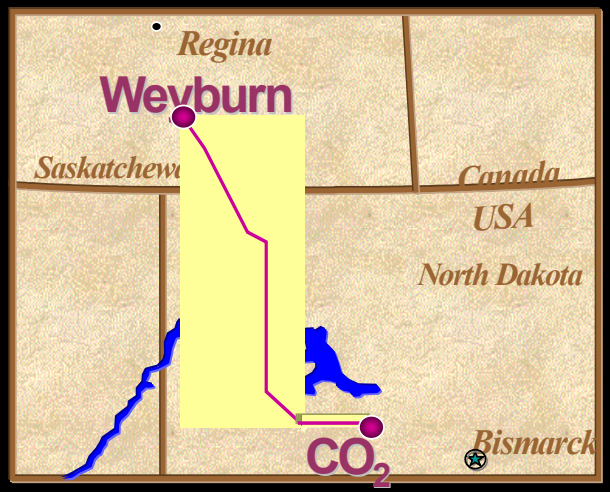



*Source: USDOE/Battelle*


*Source: NRDC*


# Weyburn $CO_2$ Pipeline &Storage Project

## $CO_2$ Storage with Enhanced Oil Recovery



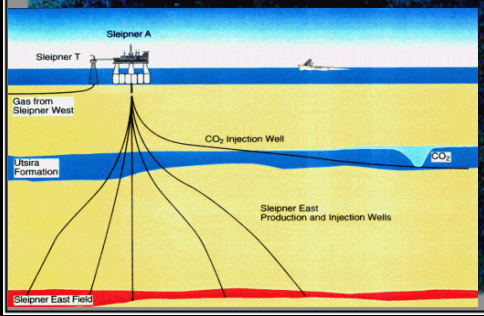

*Sources: USDOE; NRDC*


*E.S.Rubin*

*Carnegie Mellon*

# Geologic Sequestration of $CO_2$

(Sleipner Gas Field, North Sea, Norway)




*Source: Statoil*

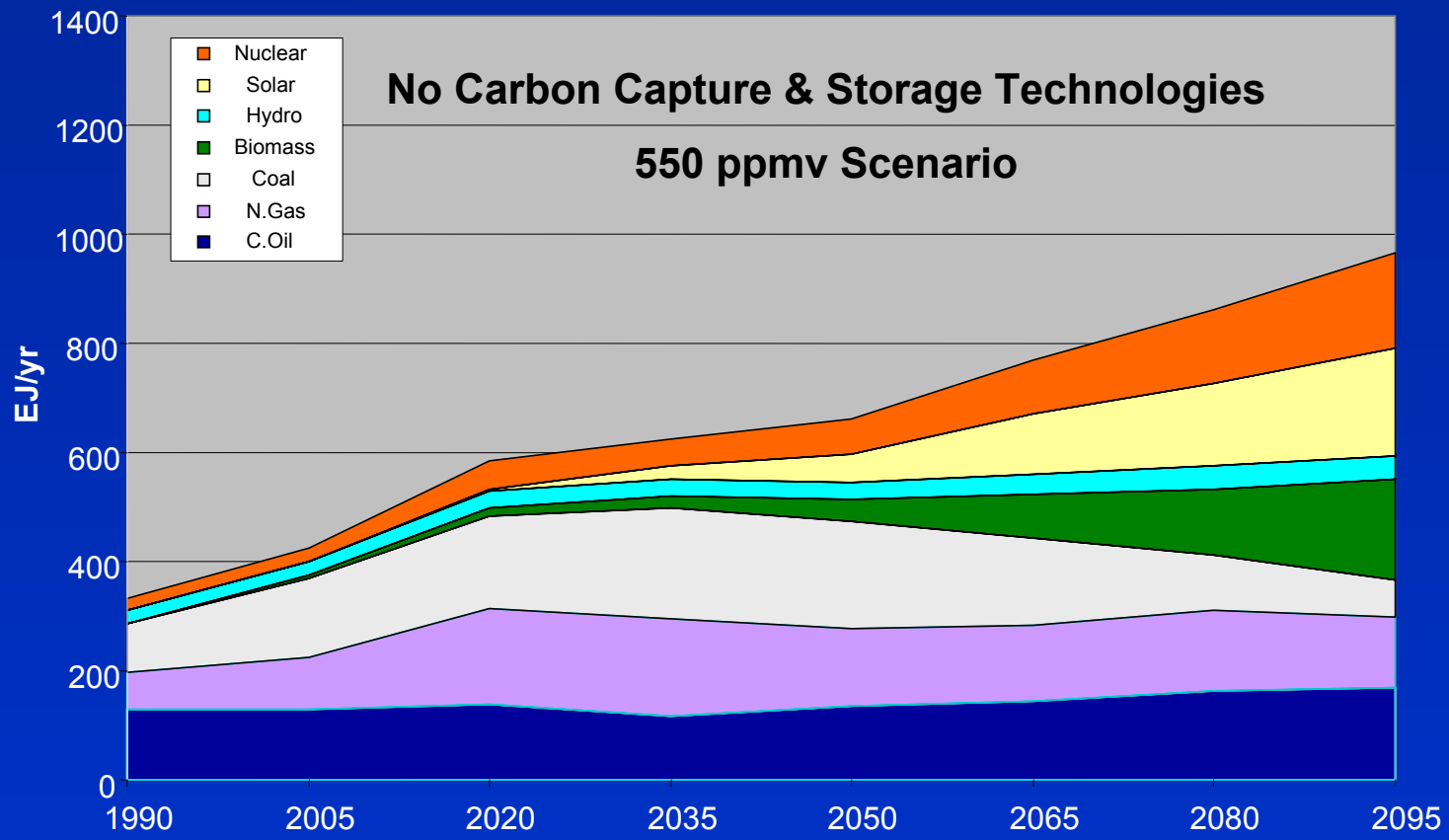
# Carbon Sequestration R&D

- Goals are to develop and demonstrate improved, lower-cost and effective methods of $CO_2$ capture and storage
- Major R&D programs underway worldwide, led by both government and industry, e.g.,:
  - U.S. Department of Energy
  - International Energy Agency
  - $CO_2$ Capture Project
  - Canadian Clean Power Consortium
  - ... and many others

*What difference could these efforts make?*

# The Potential Role of CCS in a Carbon-Constrained World

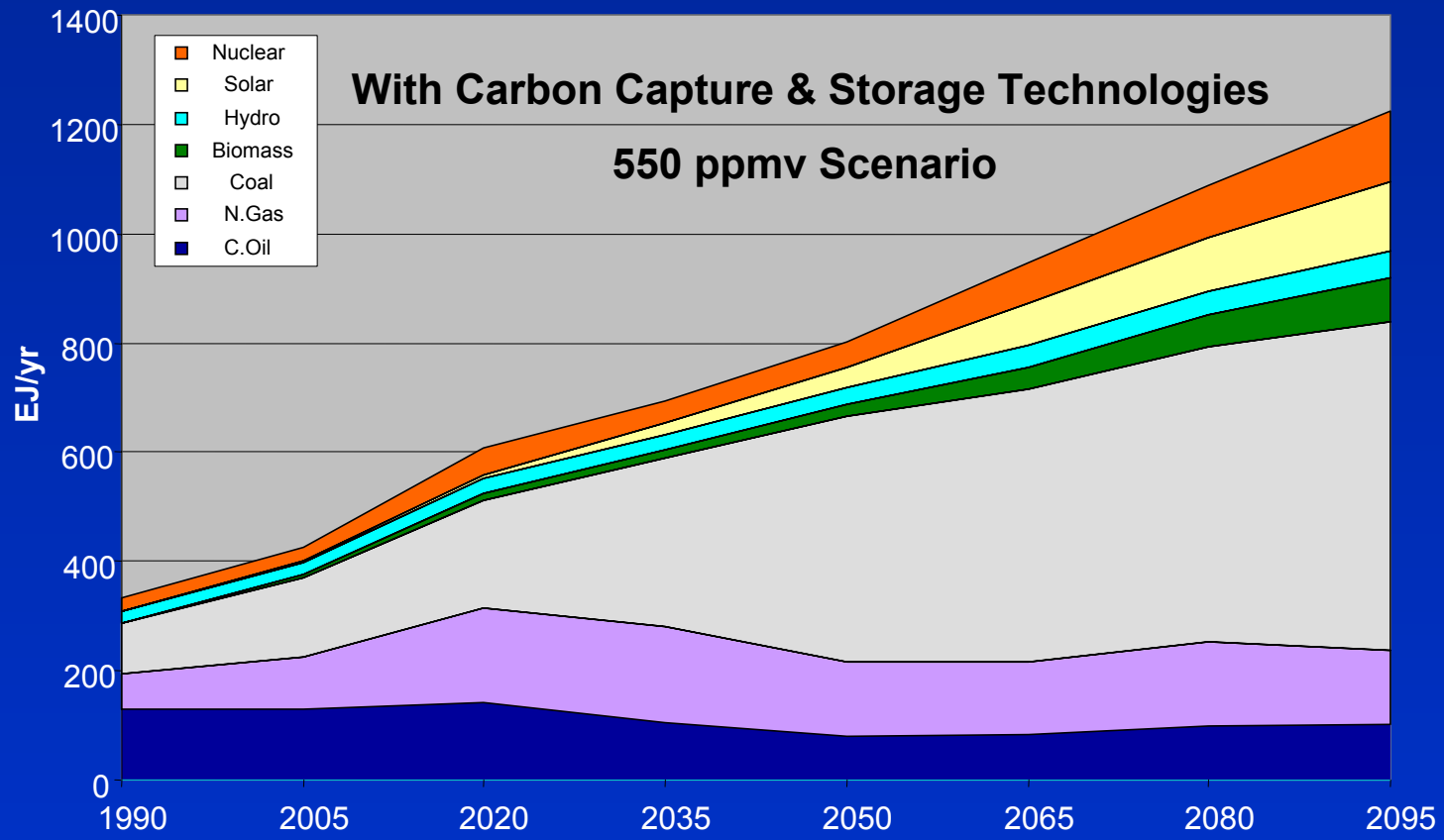
*World Primary Energy w/o CCS*




*Source: USDOE, 1999*

# The Potential Role of CCS in a Carbon-Constrained World

*World Primary Energy with CCS*




*Source: USDOE, 1999*

# Many Issues Yet to be Resolved

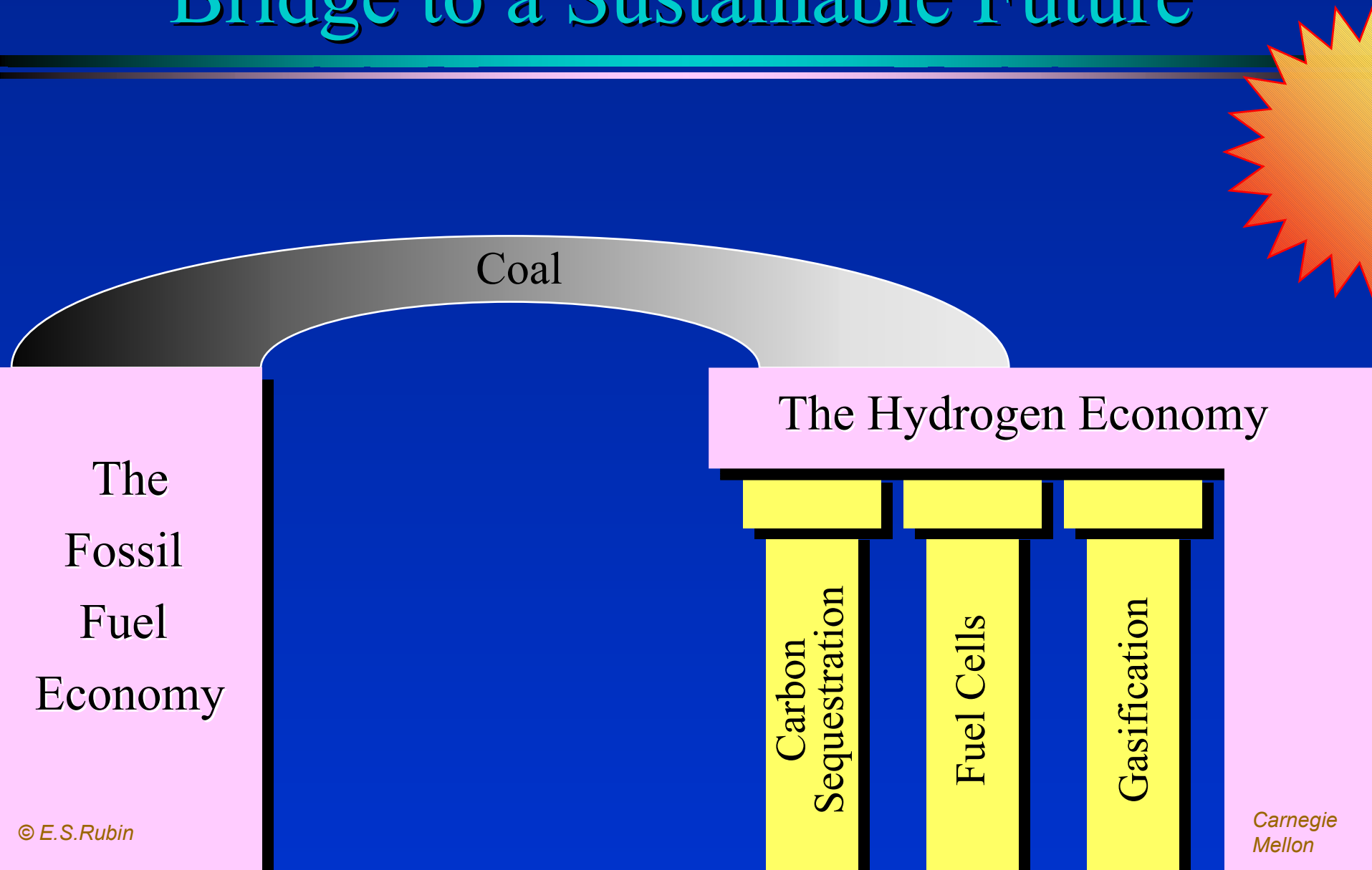
- Acceptance of carbon capture and storage as a viable method of $CO_2$ abatement
- The success of R&D efforts in lowering the costs of carbon capture, fuel cells, and other advanced power generation systems
- Development of infrastructure needed to support a hydrogen-based energy system
- Timing, magnitude and nature of future emission constraints for greenhouse gases

# Conclusions

- A future "hydrogen economy" is by no means assured; a host of technical, economic and political challenges remain to be overcome before this could happen
- BUT, if societal concerns about climate change and sustainability become increasingly important, the use of hydrogen could grow in the decades ahead
- In this picture, fuel cells — together with carbon sequestration and gasification technology — could play a major role in plowing a "zero emissions" path to a sustainable future (ultimately based on cost-effective renewable energy technology)

# *Envisioning the future: a potential path to sustainability*

# Bridge to a Sustainable Future



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