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

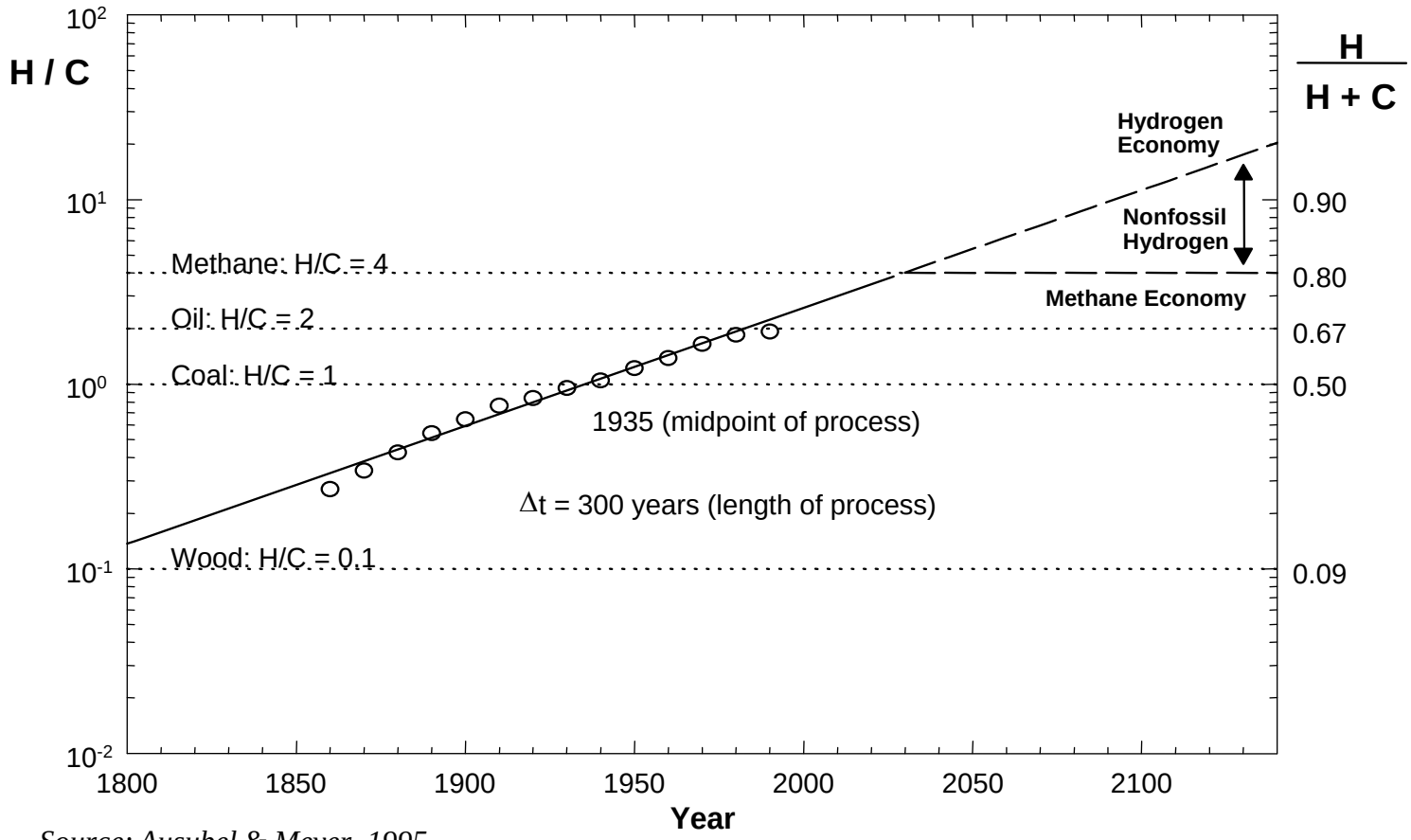
Fuel Cells and the "Hydrogen Economy"

- 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

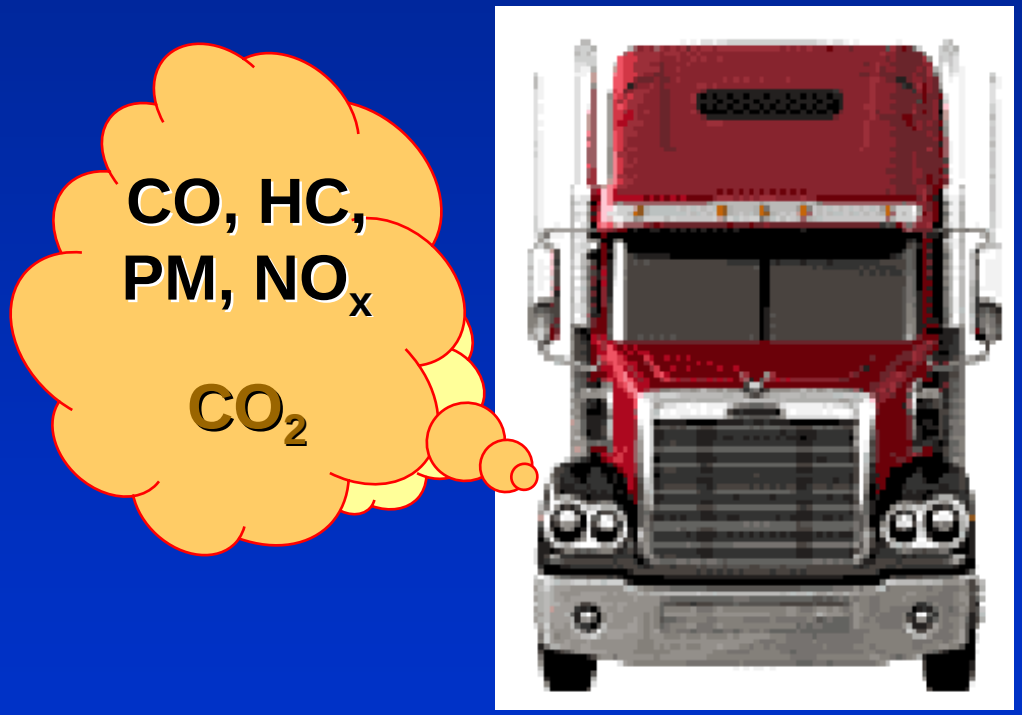
Hydrogen as a "Zero Emission" Fuel for Pollution Control

- 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

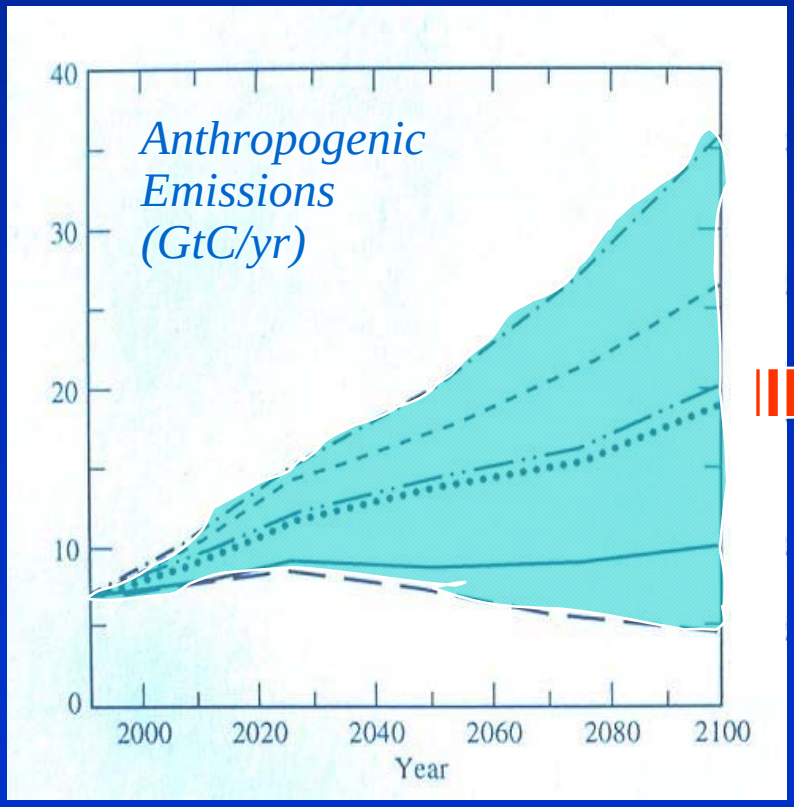
C-free
"ZEV"

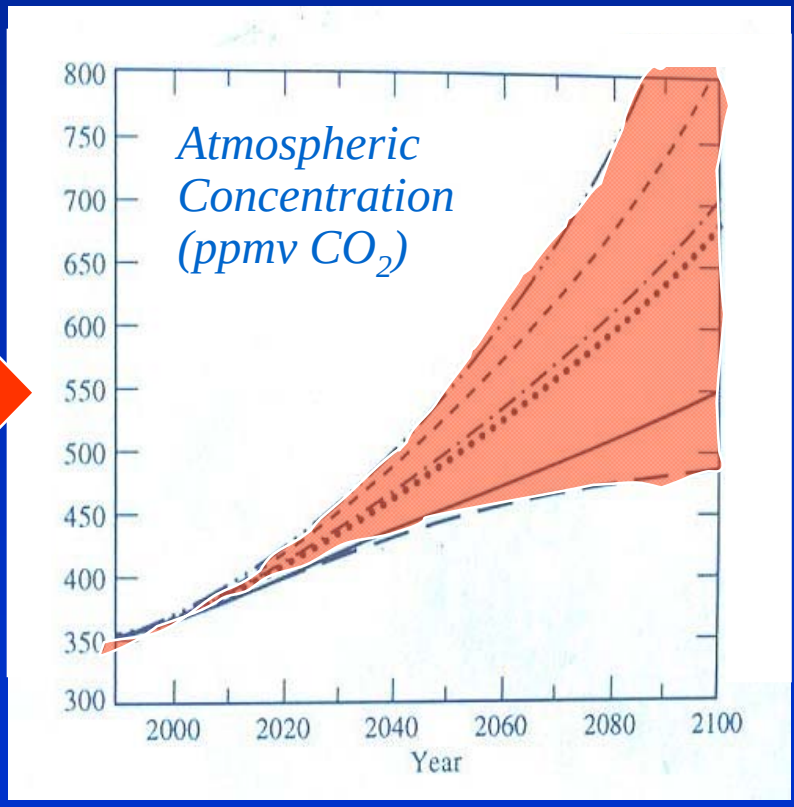
Caution: *Life cycle assessments might tell a different story*

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:

Reform: $CH_4 + H_2O \rightarrow 3H_2 + CO$

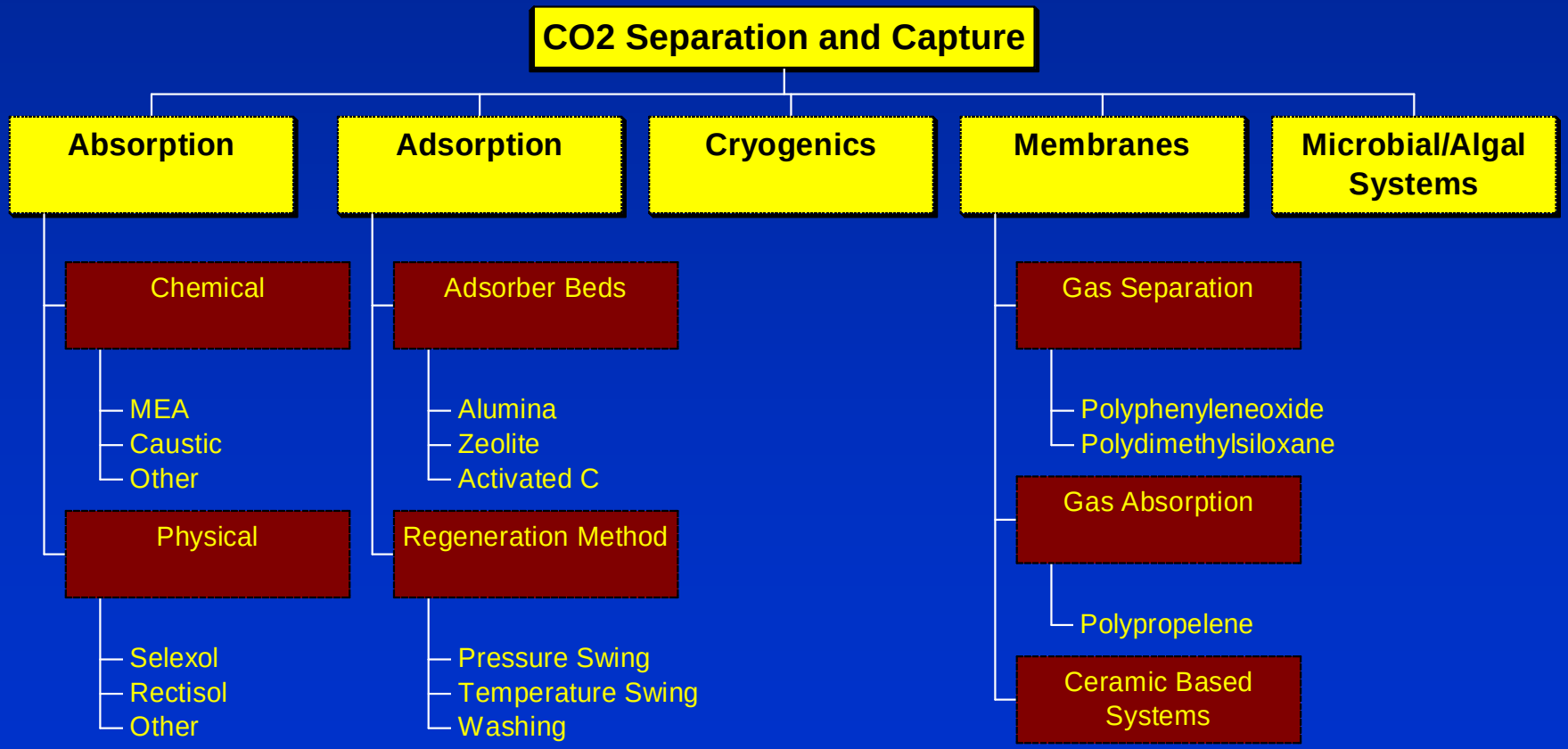
Shift: $CO + H_2O \rightarrow H_2 + CO_2$

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

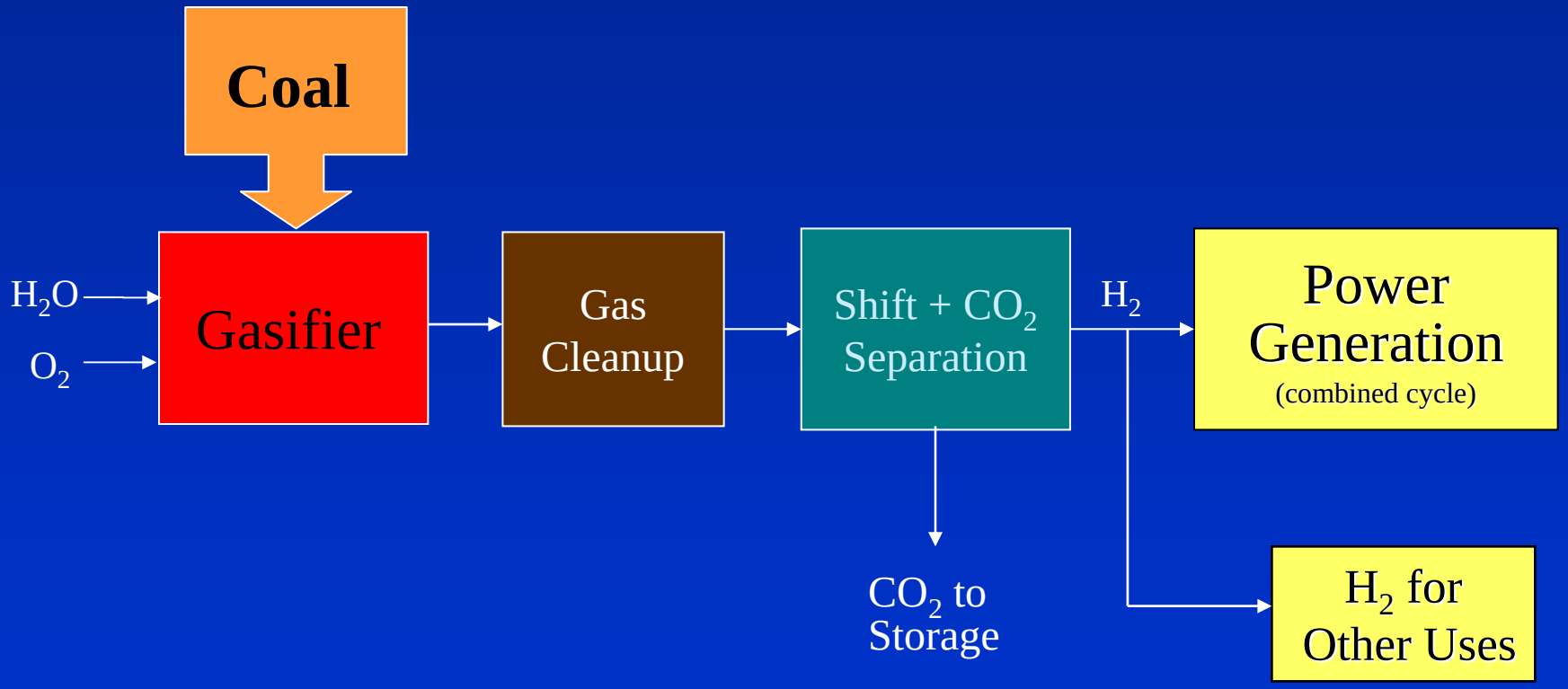
Storage Option	Worldwide Capacity (Order of Magnitude)
Deep Reservoirs	100s – 1000s GtC
Depleted Oil and Gas	100s GtC
Coal Seams	10s – 100s GtC
Terrestrial	10s GtC

Source: Herzog, 2000

One View of the Hydrogen Economy

Source: Statoil, 2001

Another View: Carbon-Free Hydrogen from Coal



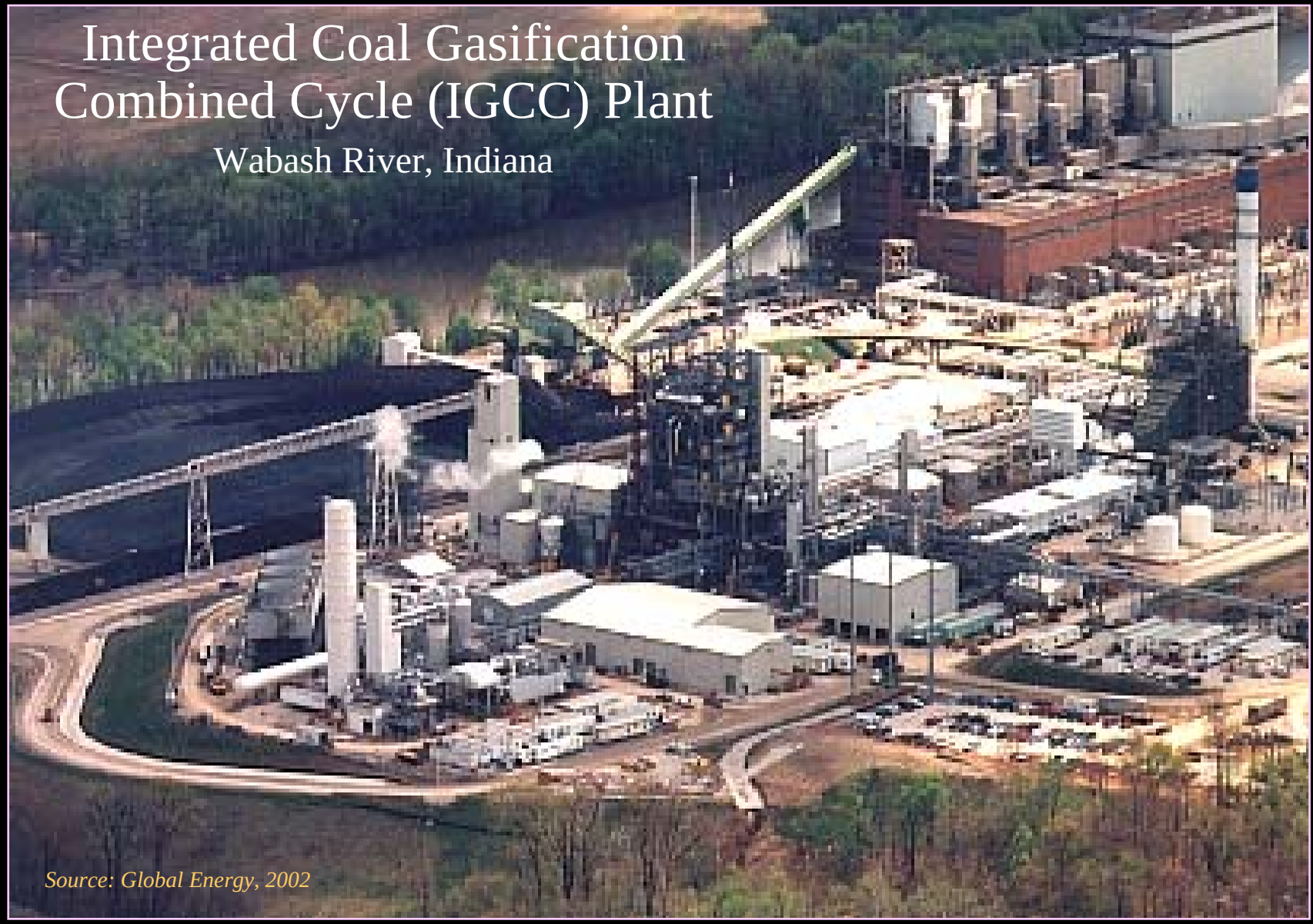
How Far-Fetched Is This?

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
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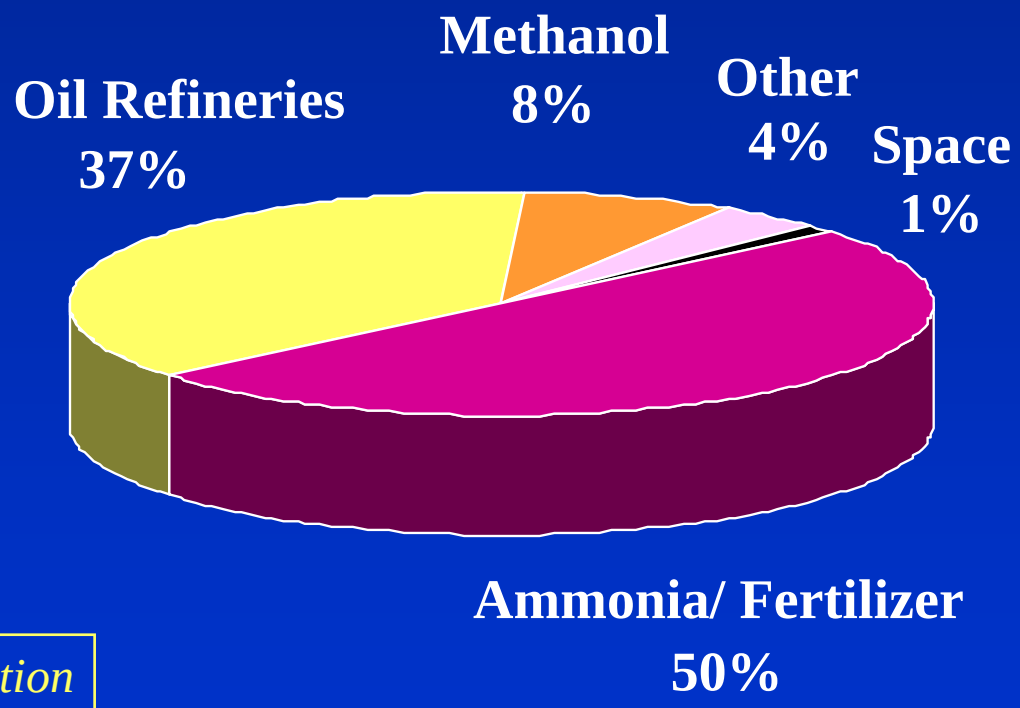
Current Uses of Hydrogen



World production
~ 40 Bscf/d

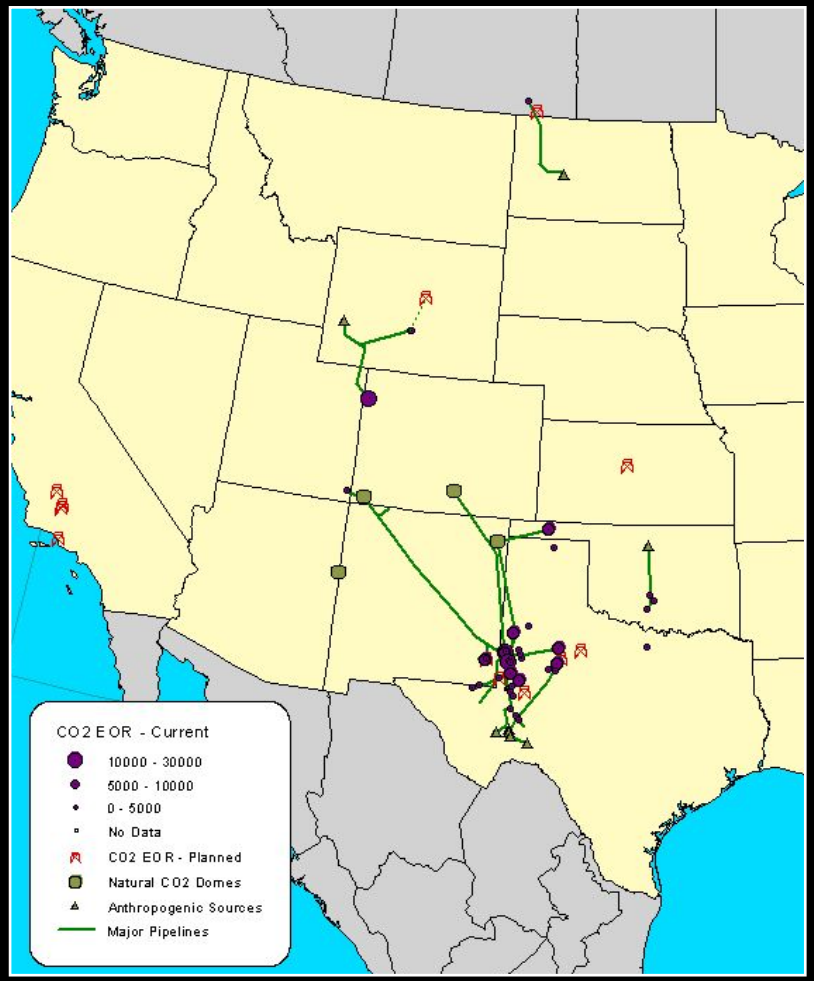
Source: IEA, 2001

Coke Gasification to Ammonia

Farmland Industries, Coffeyville, Kansas

Source: Chevron-Texaco

Existing CO_2 Pipelines for Enhanced Oil Recovery (EOR)

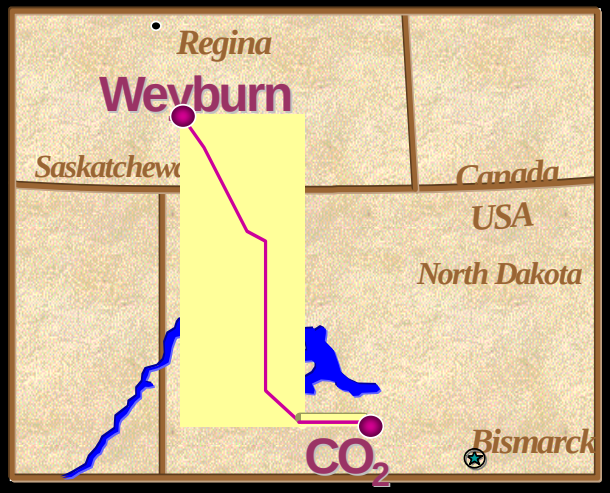


Source: USDOE/Battelle

Source: NRDC

Weyburn CO_2 Pipeline &Storage Project

CO_2 Storage with Enhanced Oil Recovery



Sources: USDOE; NRDC

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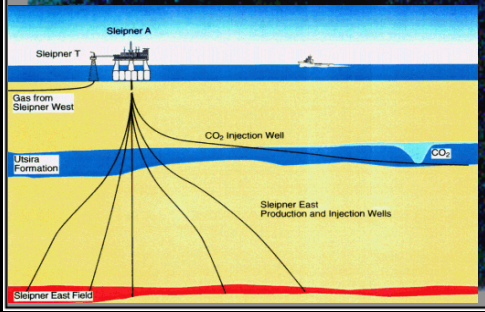
Geologic Sequestration of CO_2

(Sleipner Gas Field, North Sea, Norway)



Source: Statoil

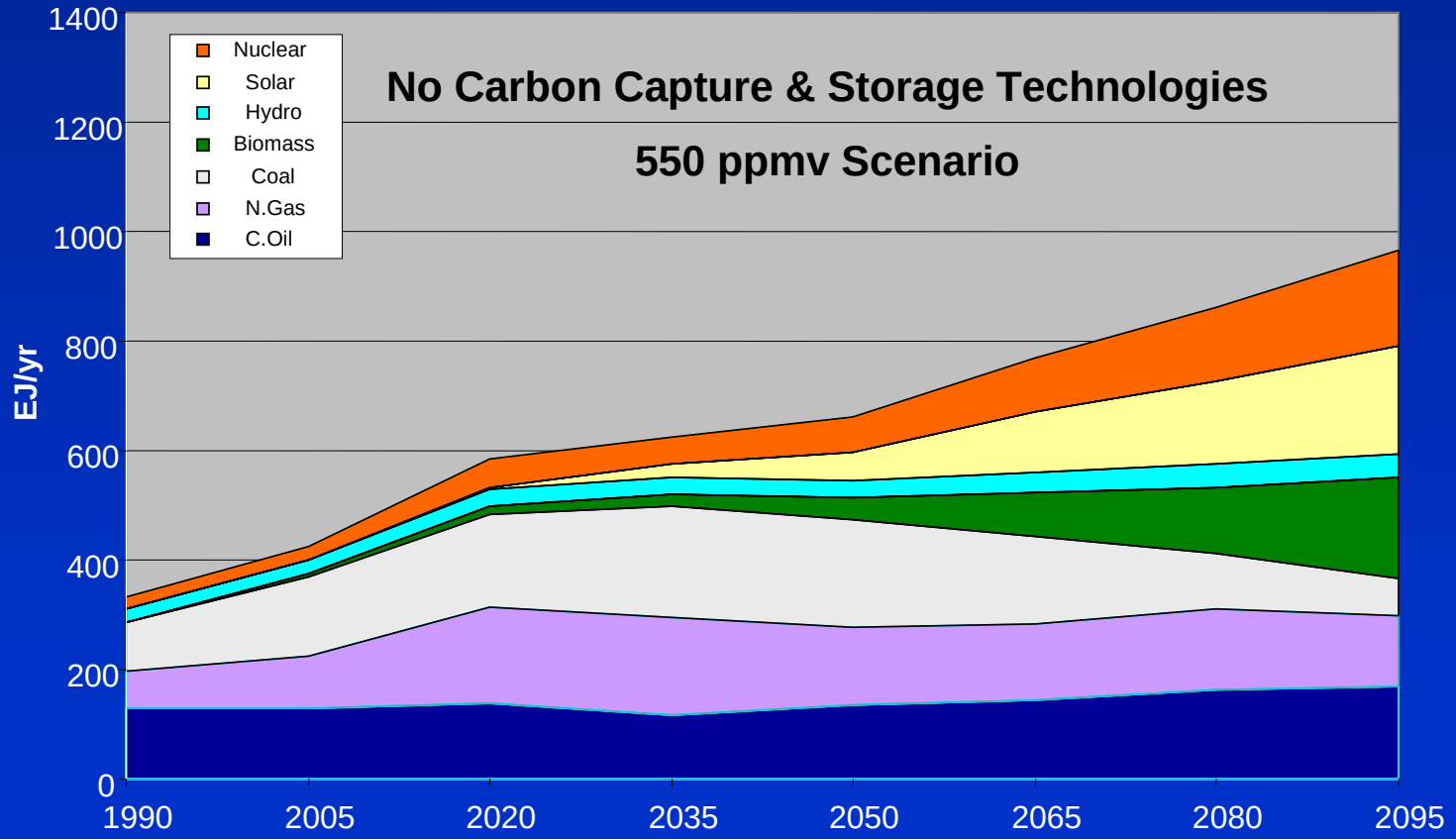
Carbon Sequestration R&D

- 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

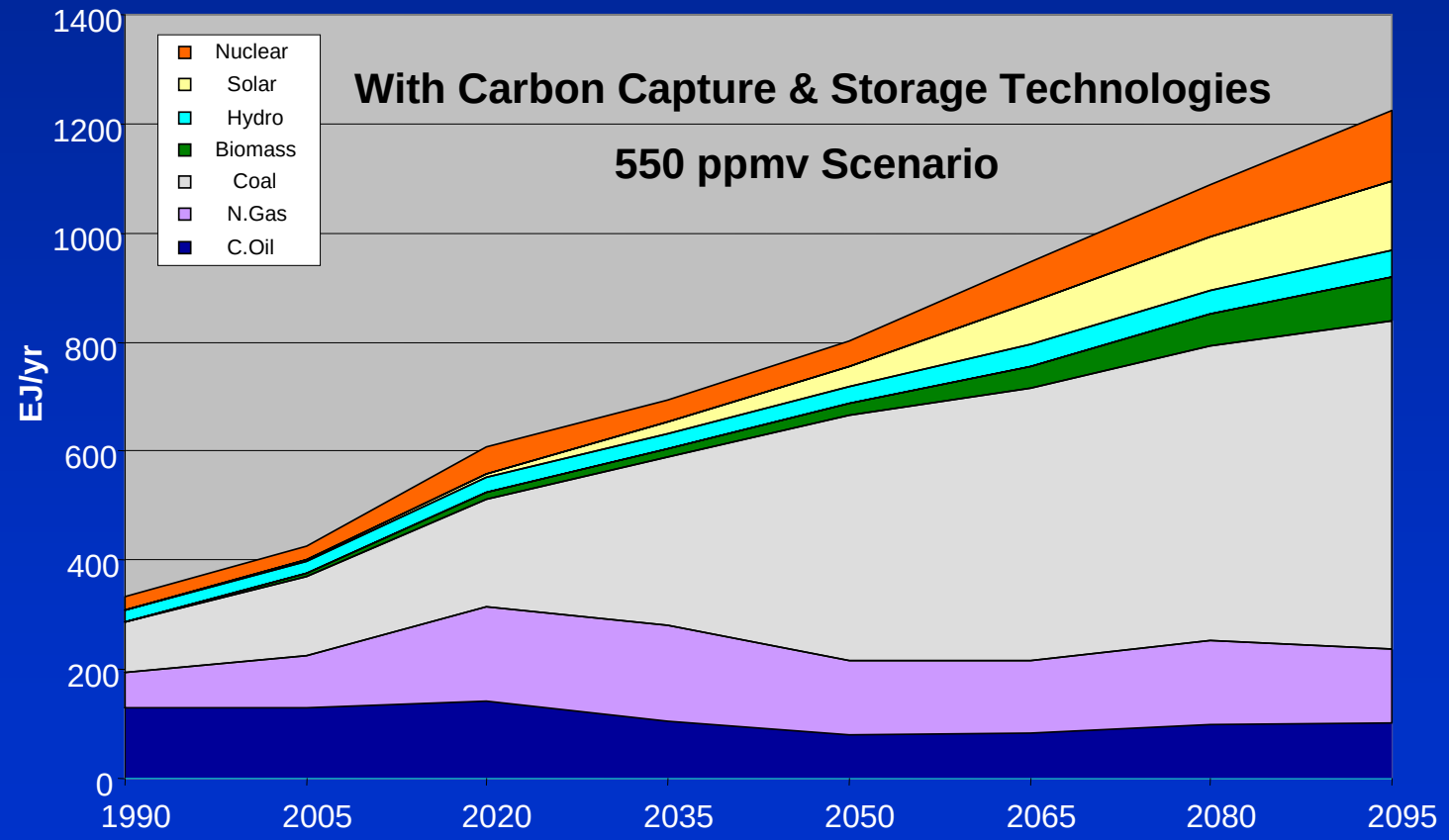
World Primary Energy w/o CCS



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

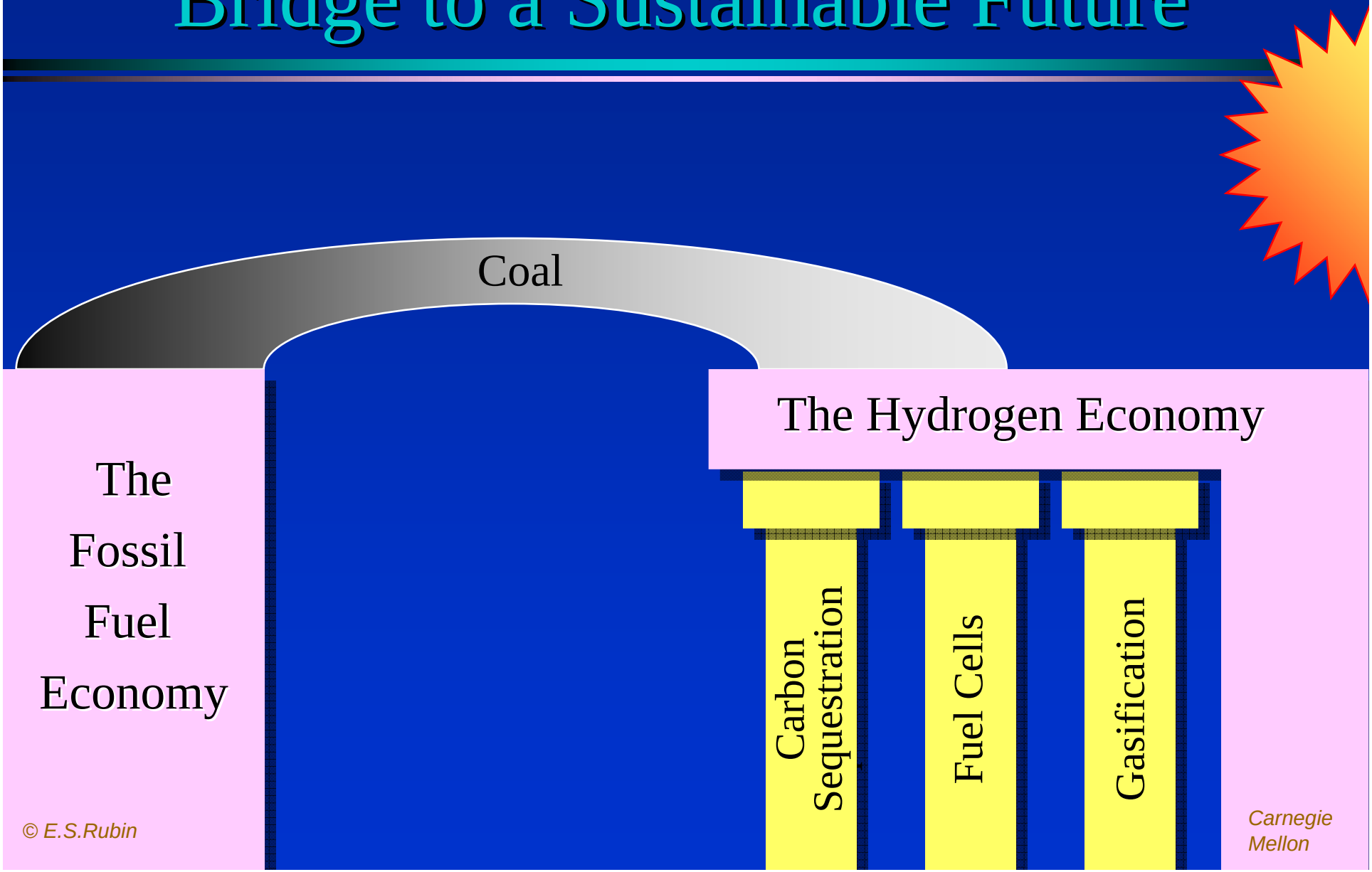
- Acceptance of carbon capture and storage as a viable method of CO_2 abatement
- The success of R&D efforts in lowering the costs of carbon capture, fuel cells, and other advanced power generation systems
- Development of infrastructure needed to support a hydrogen-based energy system
- Timing, magnitude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