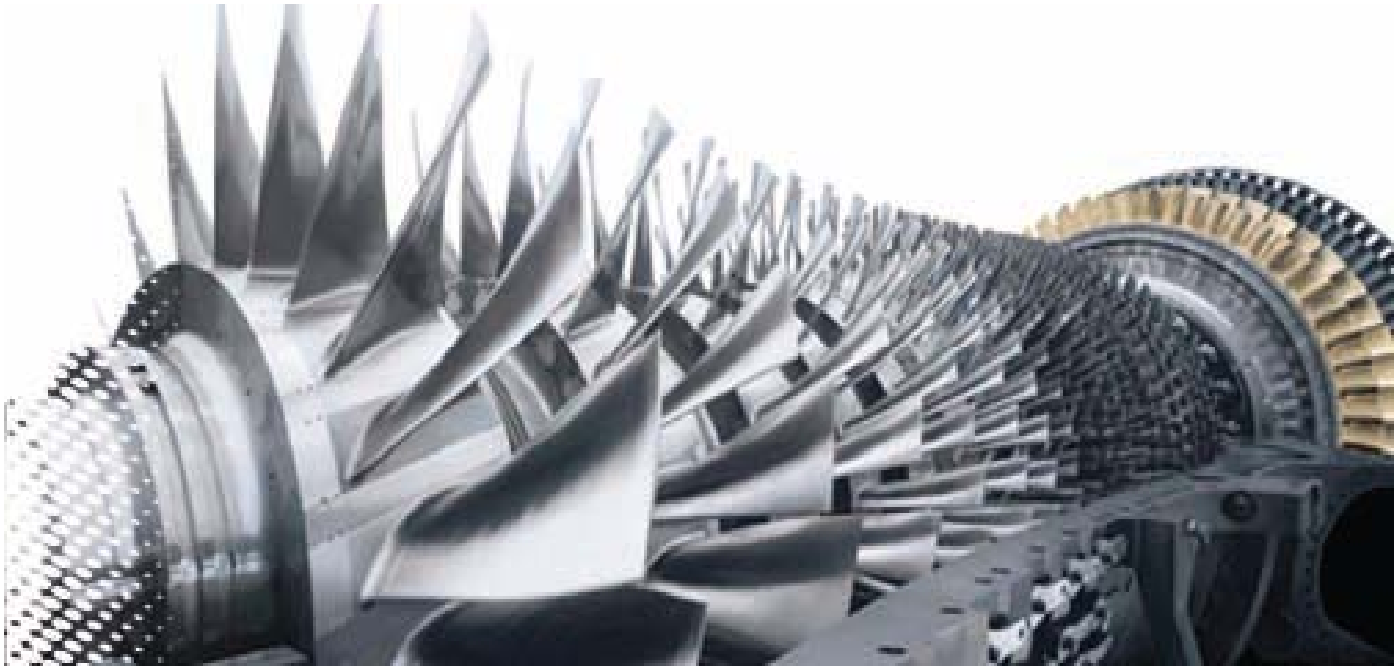
NATIONAL ENERGY TECHNOLOGY LABORATORY

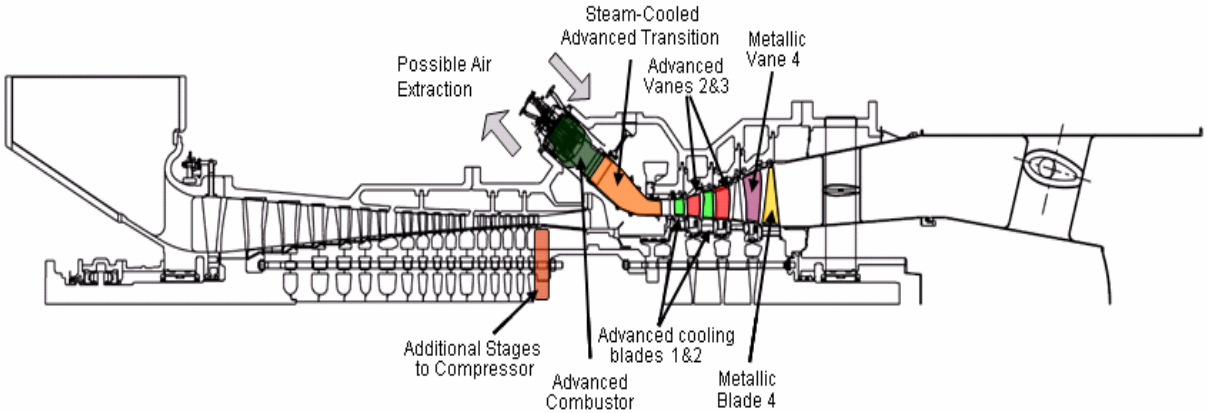


H_2 Turbines for Clean, Efficient, CCS Power Systems

Richard A. Dennis
Turbine Technology Manager

Presentation Overview

- **NETL Overview and budget**
- **Program Drivers**
- **Goals**
- **Status of Hydrogen Turbine Projects**
  - Technology issues
- **Summary**



National Energy Technology Laboratory

- Only DOE national lab dedicated to fossil energy
- One lab, five locations, one management structure
- 1,200 Federal and support-contractor employees
- Research spans fundamental science to technology demonstrations

Alaska

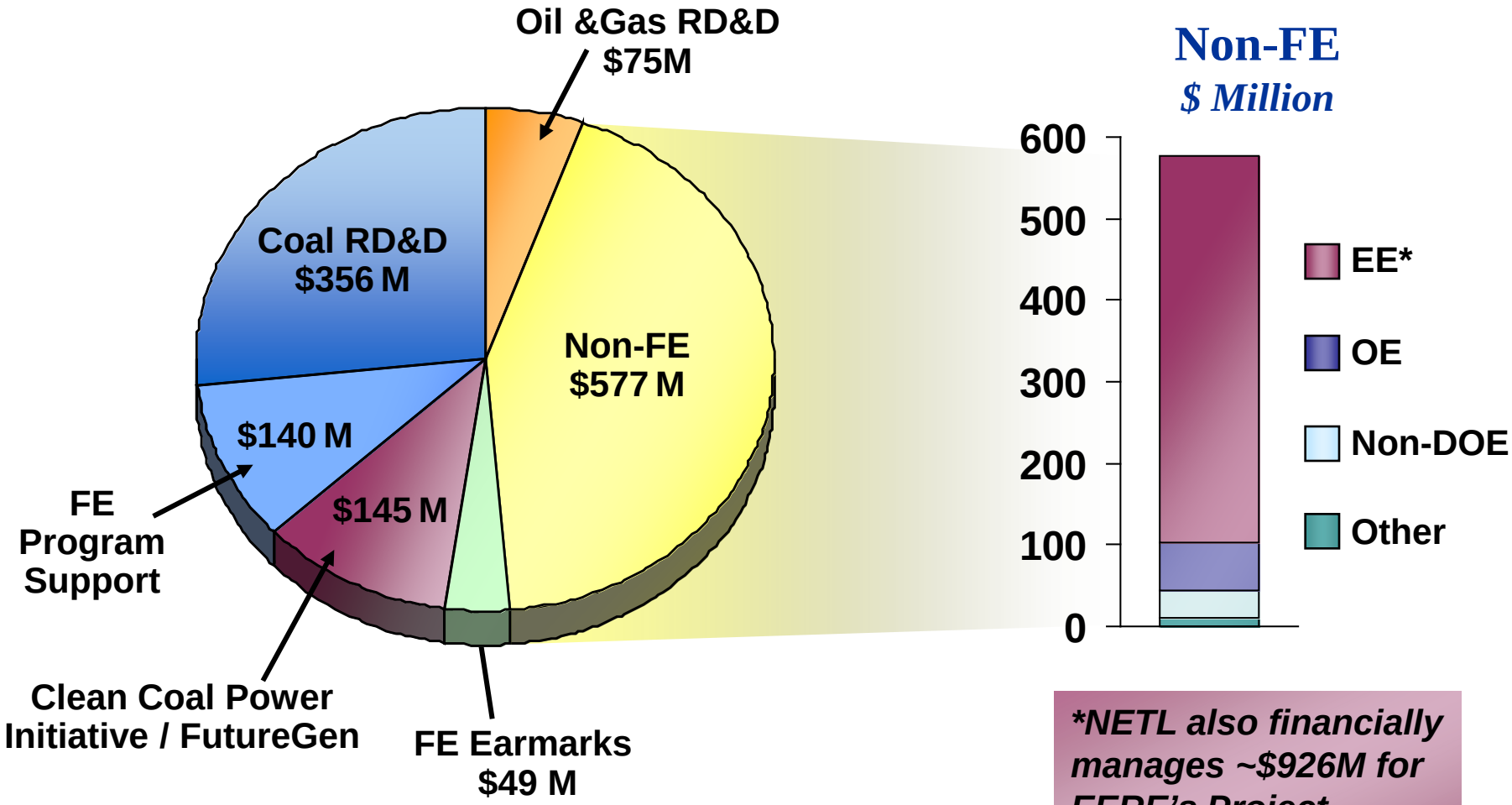
Houston

Oregon

Pennsylvania

West Virginia

NETL FY 2008 Budget: $2.27 Billion



**NETL also financially manages ~$926M for EERE's Project Management Center*

Fossil Energy Stimulus Summary

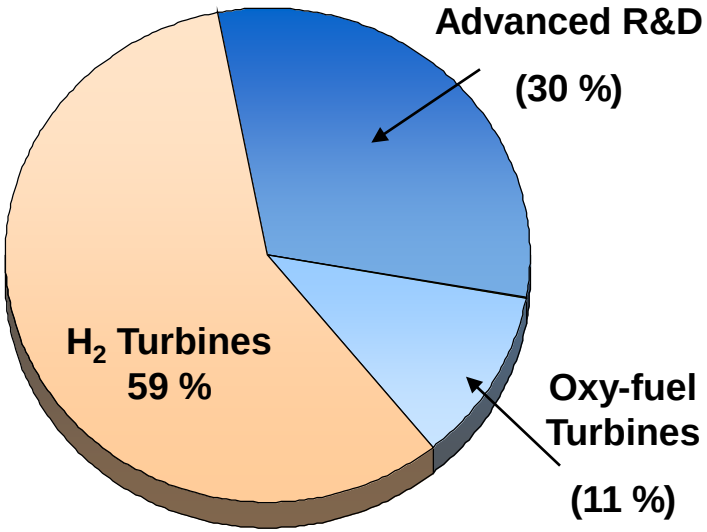
Implemented in FY 2009

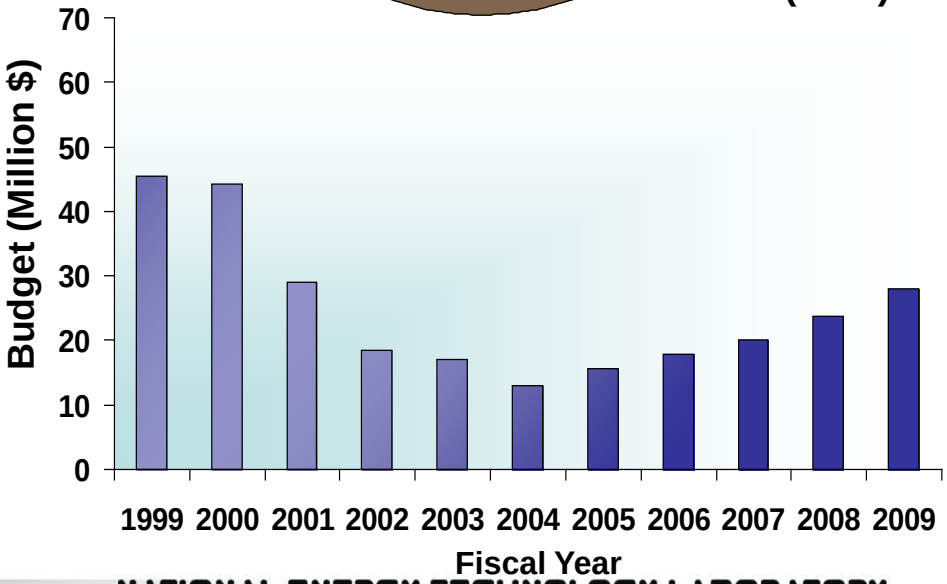
	Funding Amount
Fossil Energy ($ in Thousands)	
Fossil Energy Research and Development	$1,000,000
Clean Coal Power Initiative – Round 3 FOA	$800,000
Industrial Carbon Capture Solicitation	$1,520,000
Geologic Formation Site Characterization (RCSP)	$50,000
Geologic Sequestration Training & Research	$20,000
Program Direction	$10,000
Total, Fossil Energy	$3,400,000

FE Advanced Turbine Budget / Projects

FY 09 Budget $28M

- **Hydrogen Turbines ($16,177 k)**
  - Adv. H2 GT Development (GE)
  - Adv. H2 GT (Siemens)
  - Catalytic Comb. for H2 (PCI)
  - Micro-mixing for H2 (Parker)
- **Oxy-fuel turbine ($3,227 k)**
  - Oxy-Fuel Combustor (CES)
  - Oxy-fuel Turbine (Siemens)
- **Advanced Research ($8,597 k)**
  - UTSR (Various Universities)
  - Systems Studies (NETL)
  - Combustion & Materials (NETL)
  - HX Analysis (Ames Lab)
  - H2 combustion (LBNL)





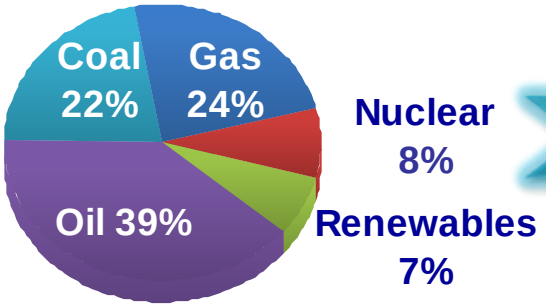
FE Advanced Turbine

Technology Area/Budget Line Funding ($000's)			
Key Activity /Component	**FY 2008** (3) **Enacted**	**FY2009** (2) **Enacted**	**FY2010 CBR**
1.0 **Advanced Turbines** (1,4)	**25,000**	**28,000**	**31,000**
1.1 H_2 turbines (59%)	15,895	16,177	TBD
1.2 Ox-fuel turbines (11%)	1,816	3,227	TBD
1.3 Adv turbine R&D (31%)	7,288	8,597	TBD
Total	**25,000**	**28,000**	**31,000**

Advanced Turbine Program Drivers

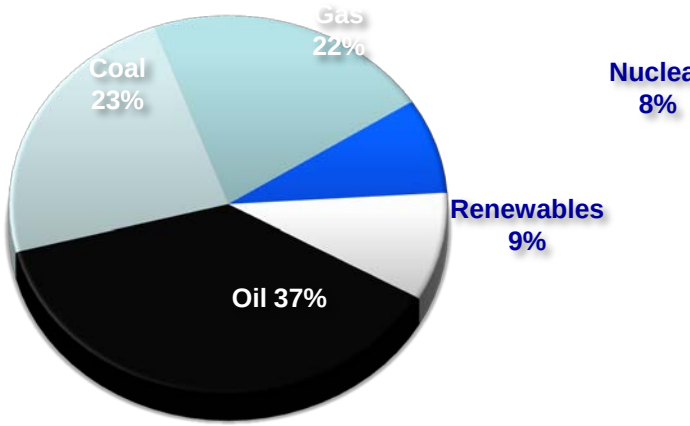
Energy Demand Today

101 QBtu / Year
85% Fossil Energy



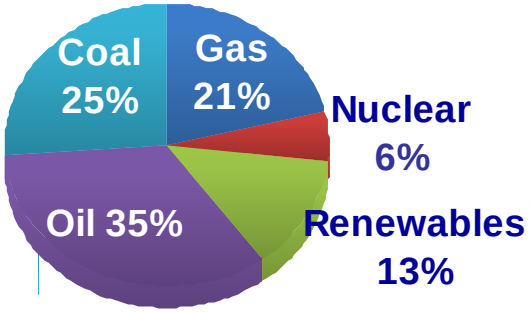
Energy Demand 2030

113 QBtu / Year
82% Fossil Energy



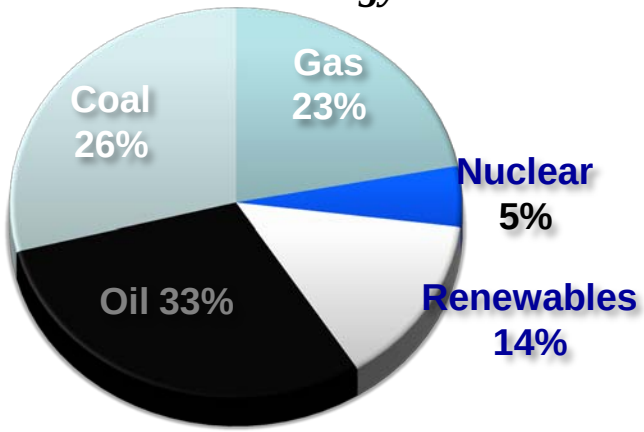
United States

469 QBtu / Year
81% Fossil Energy



World

681 QBtu / Year
80% Fossil Energy

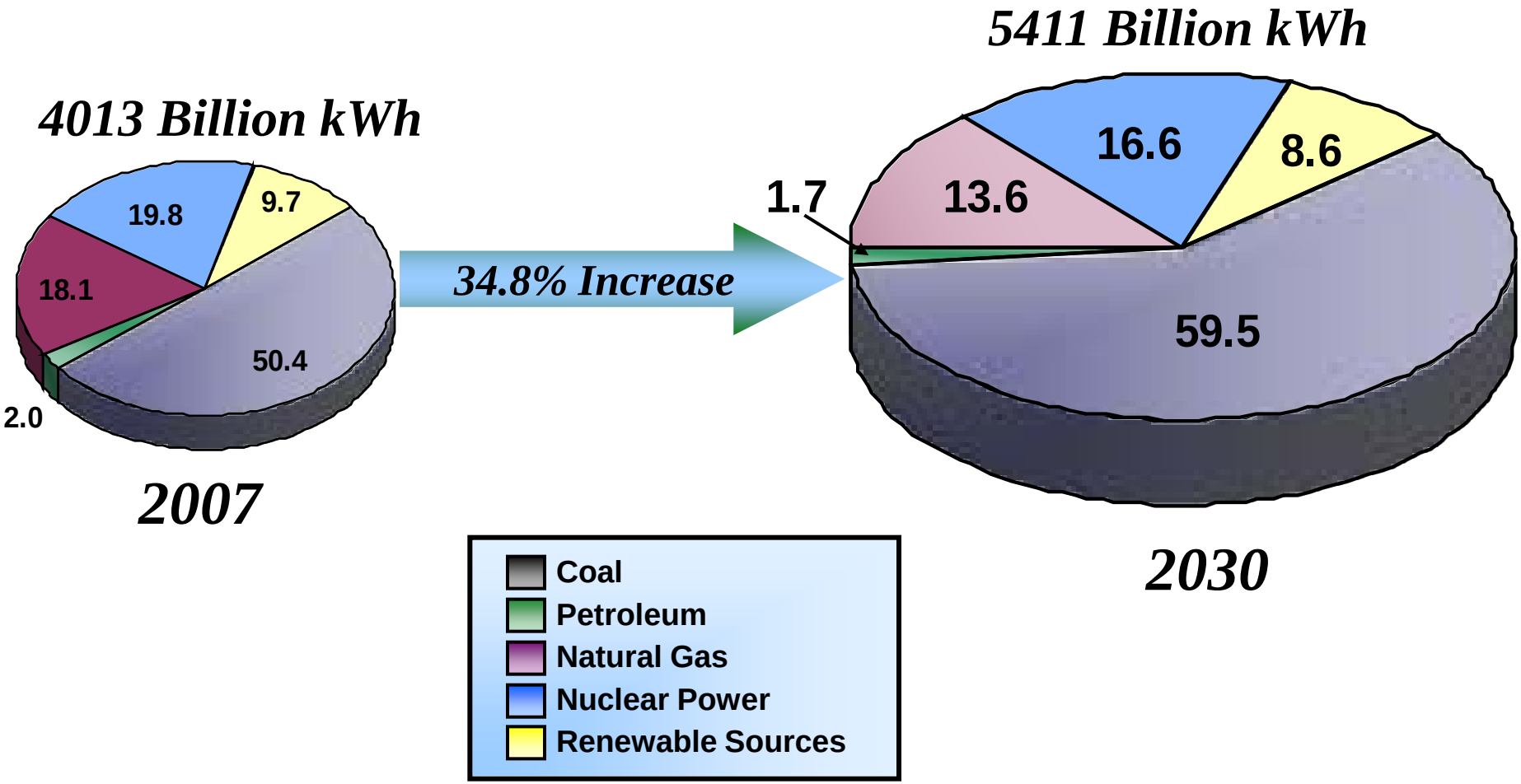


U.S. data from EIA, Annual Energy Outlook 2009 Early Release, years 2008 and 2030; World data from IEA, World Energy Outlook 2008, years 2006 and 2030

U.S. Electrical Generation by Fuel Type

Coal Remains a Dominate Source as Demand Grows

(2008 Data)



U.S. Electrical Generation by Fuel Type

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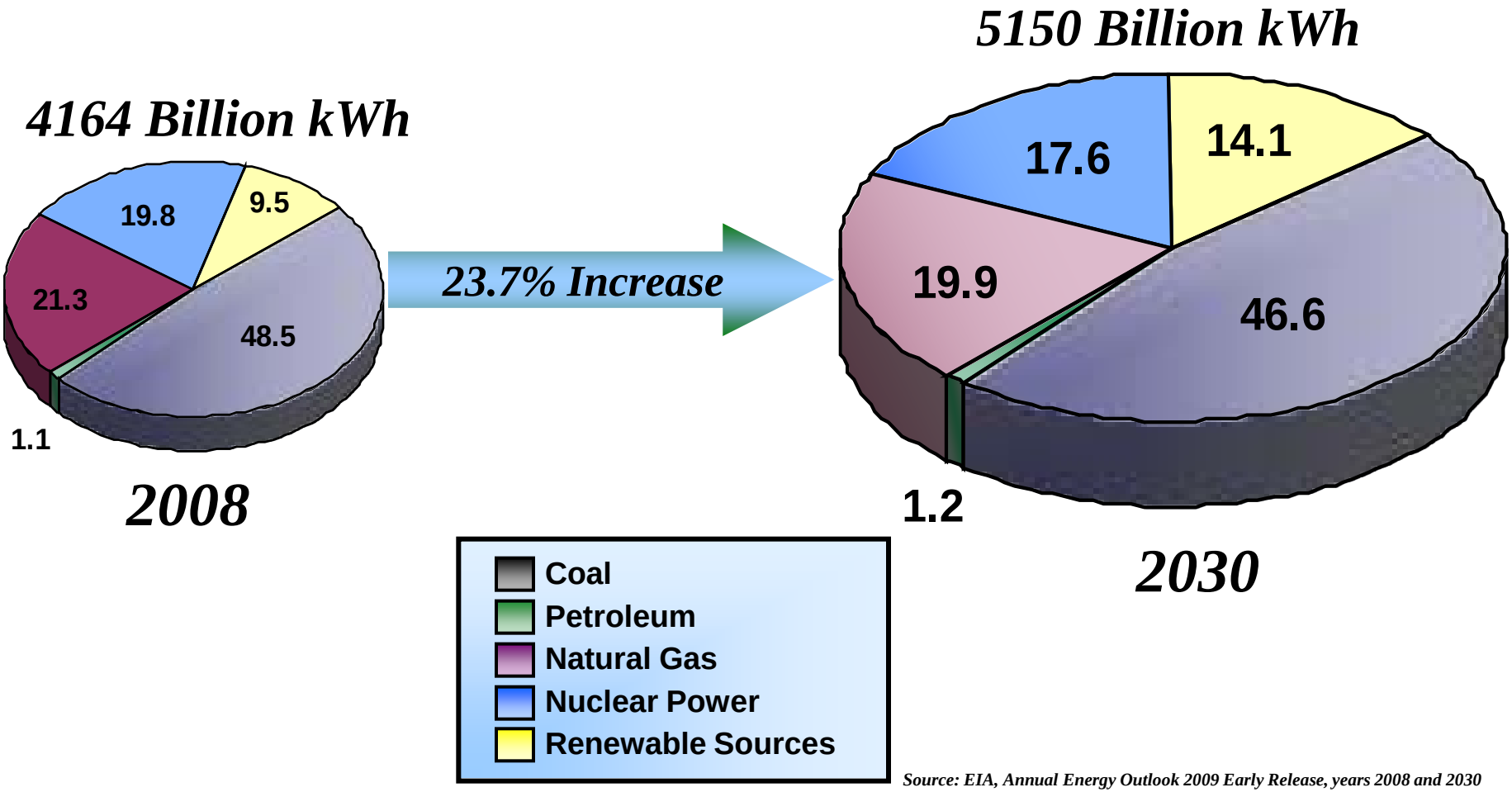
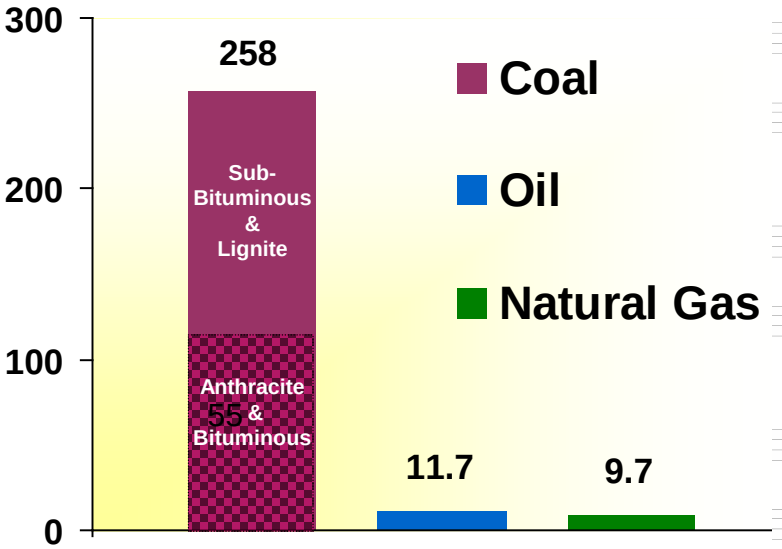


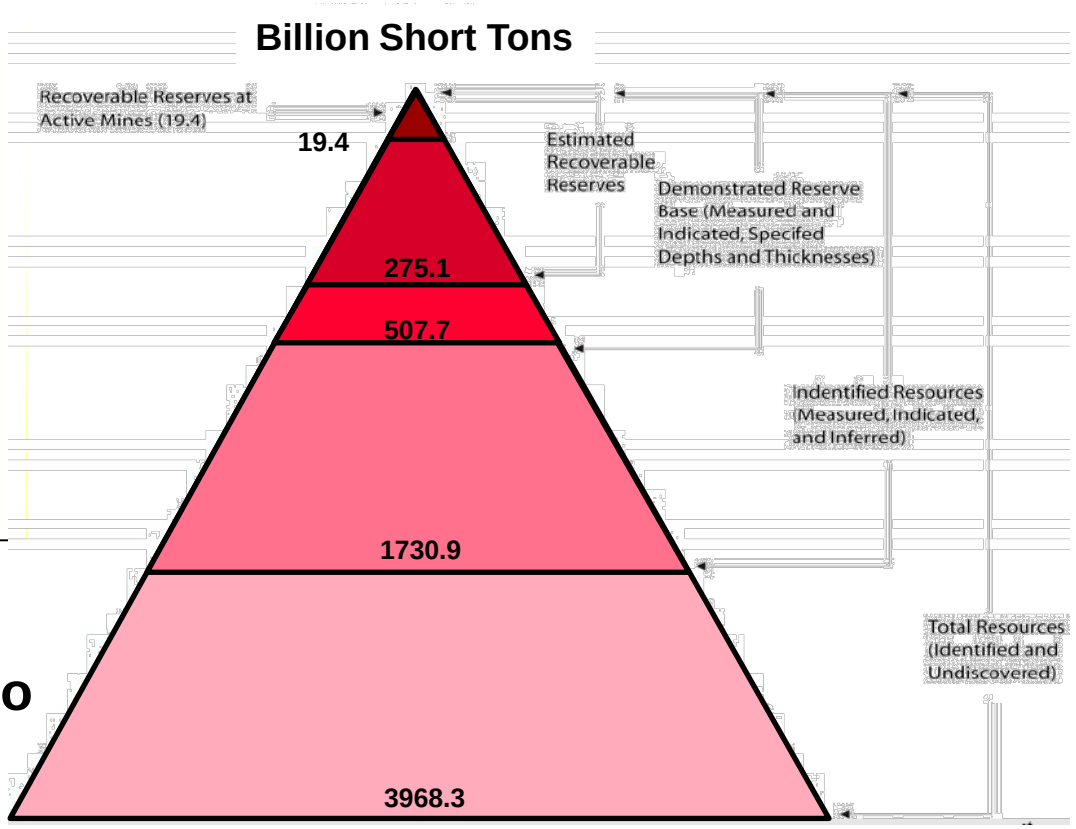
Source: EIA, Annual Energy Outlook 2009 Early Release, years 2008 and 2030

U.S. has a 250 Year Supply of Coal at Current Demand Levels!

Coal Provides Nearly Half of U.S. Electricity



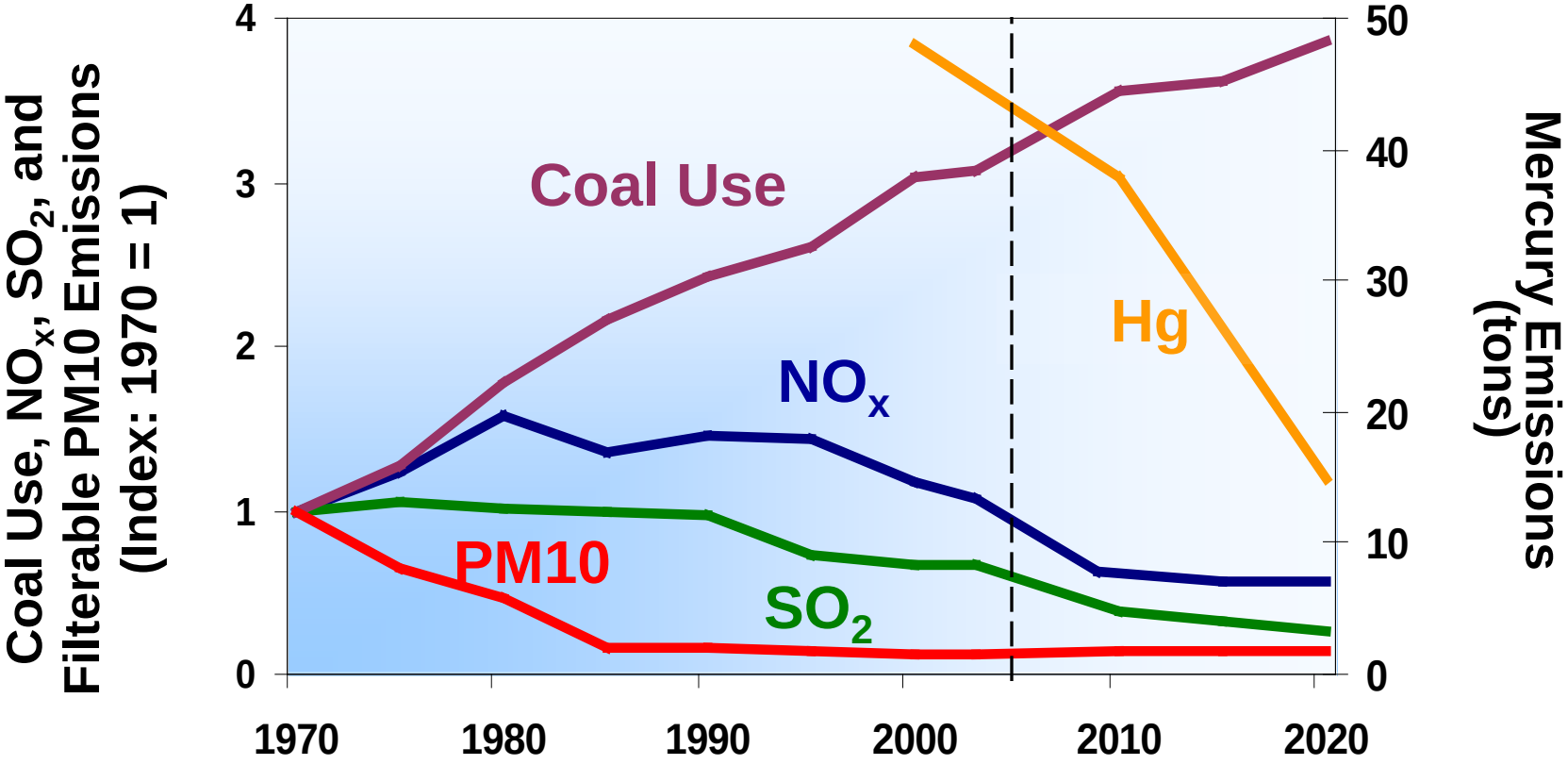
U.S. Fossil Fuel Reserves / Production Ratio



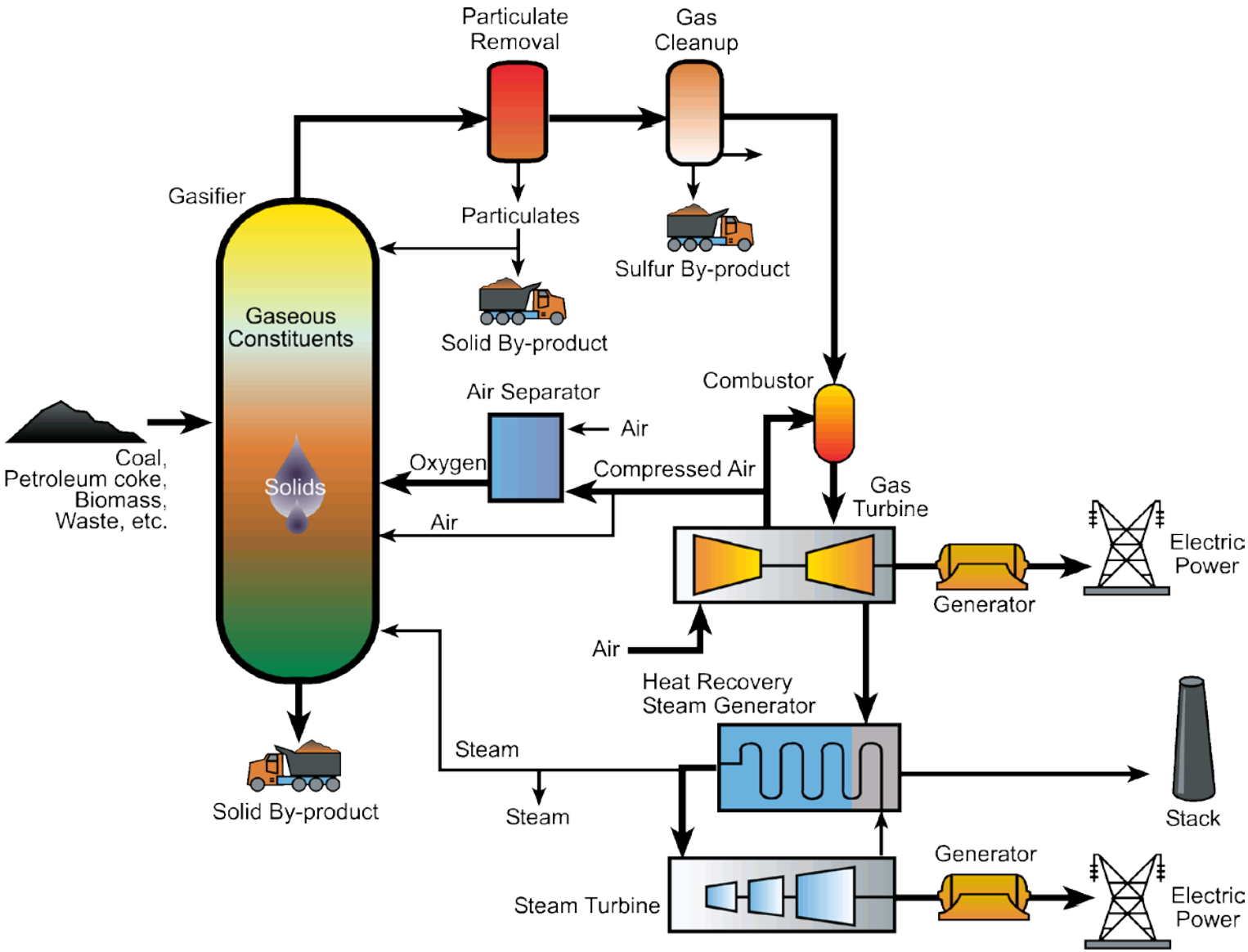
Sources: BP Statistical Review, June 2004, - for coal reserves data – World Energy Council; EIA, Advance Summary U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, September 22, 2004 - for oil and gas reserves data
Pyramid figure: NRC – "COAL: Research and Development to Support National Energy Policy", Summer 2007

Annual U.S. Air Emission Trends and Projections

Coal-Fired Power Generation Emissions Dramatically Reduced



Integrated Gasification Combined Cycle (IGCC)



Environmental Performance - IGCC Vs PC

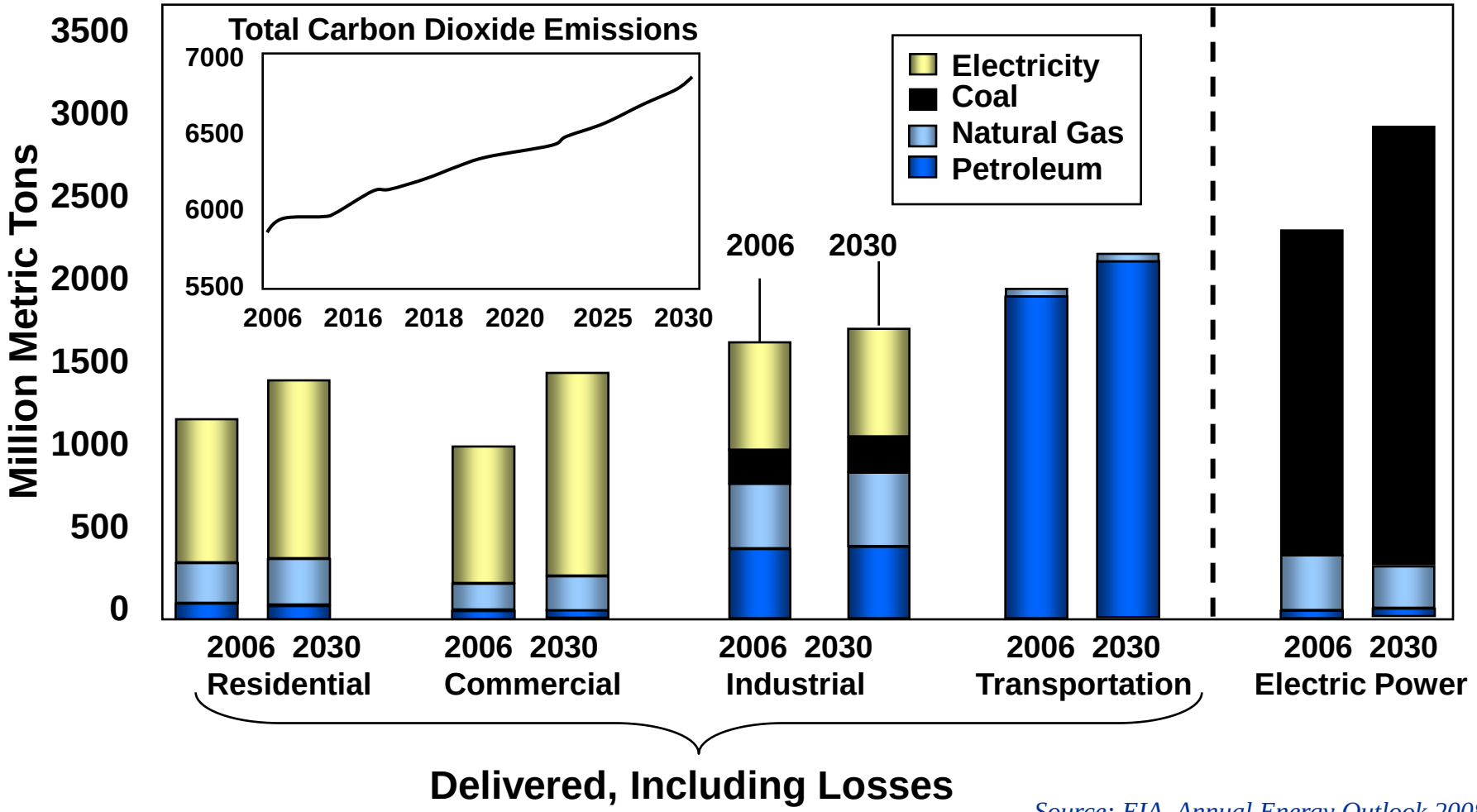
IGCC is significantly Cleaner

Tons of Emissions from Comparable 600 MW Coal Based Power Plants

	Carbon Monoxide (CO)	Nitrogen Oxides (NOx)	Sulfur dioxide (SO2)	Mercury (Hg)	Fluorides (as HF)	Sulfuric Acid Mist	Particulates (as PM10)
Super Critical Pulverized Coal Plant	3,169	1,859	3,961	0.03	23	264	475
Integrated Gasification Combined Cycle	564	1,396	1,117	0.01	0.50	26	199
	2,605	**463**	**2,844**	**0.02**	**22.50**	**238**	**276**
Percent Reduction	**82.2%**	**24.9%**	**71.8%**	**66.7%**	**97.8%**	**90.2%**	**58.1%**

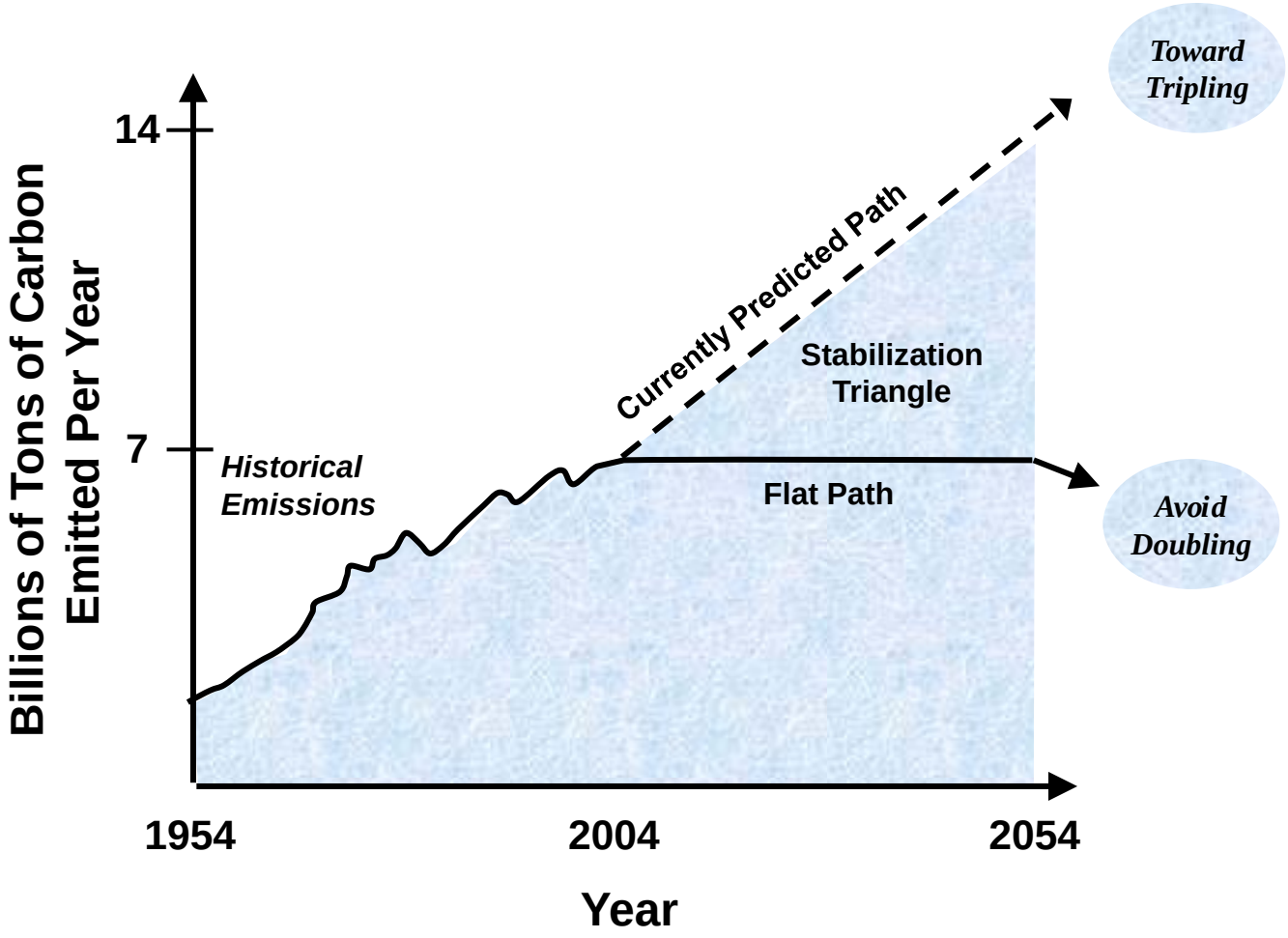
Reference: Wisconsin Dept. of Natural Resources, air pollution control operation permit 03-RV-166, Elm Road Generating Station, issued January 14, 2004 Table 1, page 3 (Pitt # 8 coal)

U.S. CO_2 Emissions by Fuel and Use



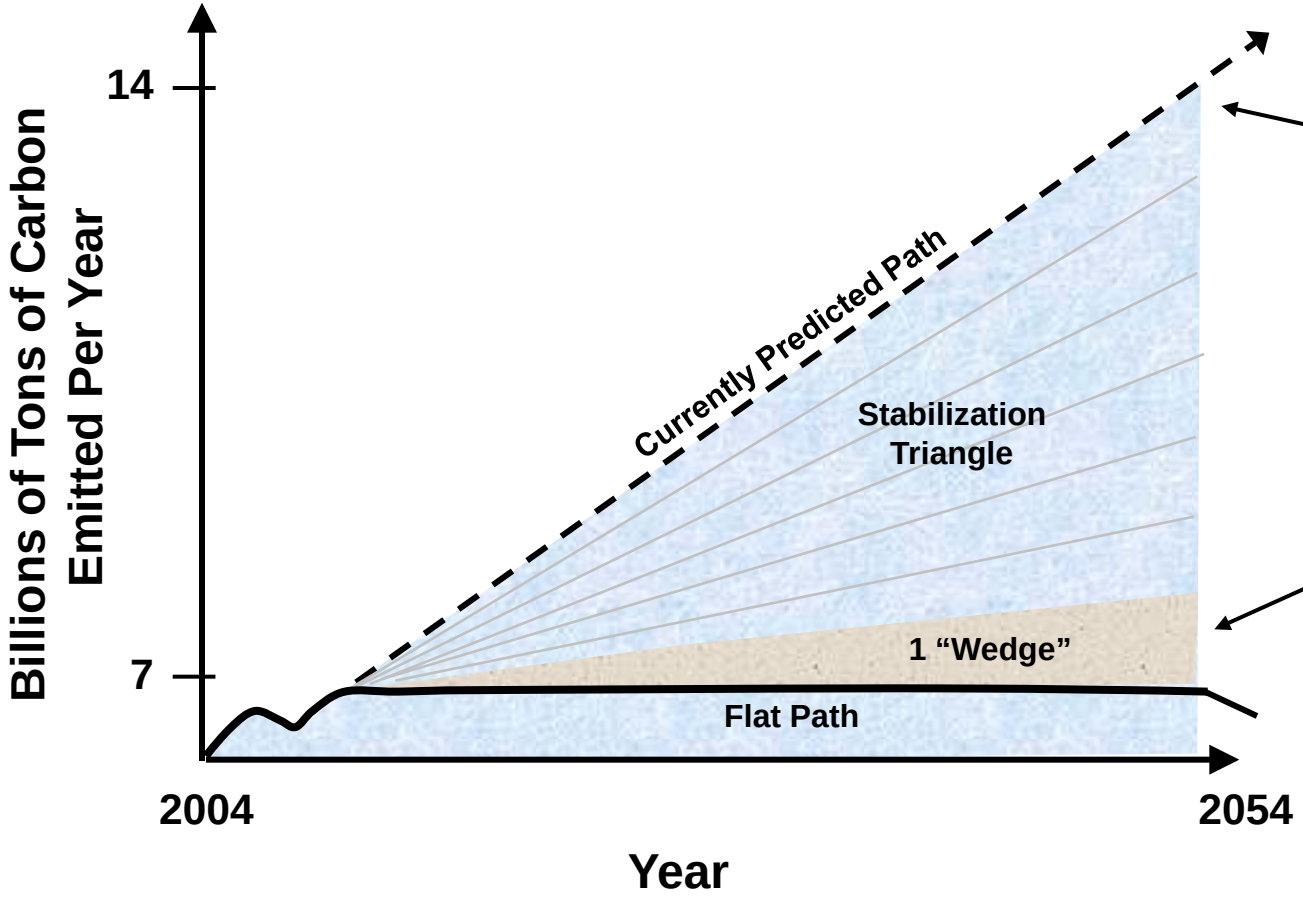
Source: EIA, Annual Energy Outlook 2008

Historical Carbon Emissions with Two Potential Pathways for the Future



Source: R. Socollow, R. Hotinski, J.B. Greenblatt, and S. Pacala.

Stabilization Wedges



7 Wedges are needed to build the stabilization triangle.

1 Wedge avoids 1 billion tons of carbon emissions per year by 2054.

Source: R. Socollow, R. Hotinski, J.B. Greenblatt, and S. Pacala.

Potential Stabilization Wedges

Options to reduce carbon emissions by 25 GtC over 50 yrs.[1]

Potential Wedge Option	Level of Effort
•Efficient vehicles	•Increase MPG from 30 to 60 for 2 billion cars
•Efficient buildings	•Reduce emissions by ¼ in all buildings / appliances by 2054
•Efficient base load coal plants	•Produce twice today's coal power at 60% vs. 40% efficiency (32 % today's average)
•Base load coal w/CCS	•Introduce CCS at 800 GW of coal plants (compared to 1060 GW existing coal)
•Wind power for coal	•Add 2 M 1-MW peak windmills (50 times current capacity)
•PV power for coal	•Add 2000 GW peak (700 times current capacity)

Ref (1):Pacala and Socolow, Science, Vol. 305, August 13, 2004

Technological Carbon Management Options

Reduce Carbon Intensity	Improve Efficiency	Sequester Carbon
• Renewables • Nuclear • Fuel Switching	• Demand Side • Supply Side	• Capture & Store • Enhance Natural Processes

All options needed to:

- **Supply energy demand**
- **Address environmental objectives**

DOE Office of Fossil Energy (FE) Advanced Power Systems Goals

- **2010:**
  - 45-50% Efficiency (HHV)
  - 99% SO_2 removal
  - NOx< 0.01 lb/MM Btu
  - 90% Hg removal
  - $1600 / kW ($2007)
- **2012: - Carbon Capture**
  - 90% CO_2 capture
  - <10% COE increase for IGCC
  - <35 % COE increase in PC
- **2015**
  - Multi-product capability
  - 60% efficiency (w/o CCS)

DOE FE programs:

- **Advanced Turbines**
- **Gasification**
- **Advanced Research**
- **Fuel Cells**
- **Innovations for Existing Plants**
- **Sequestration**
- **Fuels from Coal**

Turbine Program Contribution to APS Goals

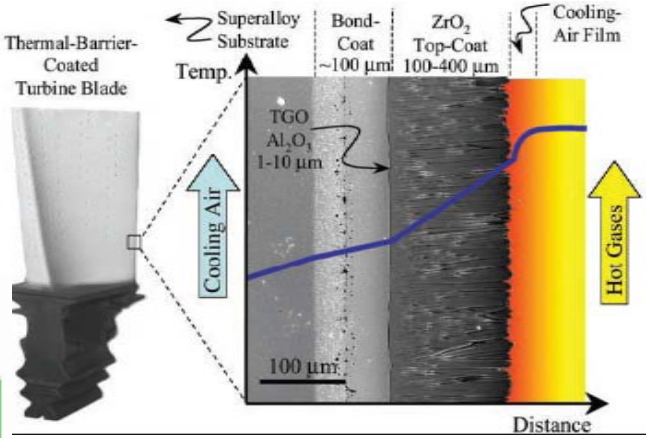
Predicted in FY 2006

- **2010 Contribution to Goals**
  - Efficiency: 2 – 3 % pts. improvement in CC
  - Cost: ~ 20 % reduction in CC capital cost
  - Emissions: 2 ppm NO_x (@15 % O_2) in GT exhaust
- **2012 Contribution to Goals**
  - Maintain 2010 performance with hydrogen fuels.
- **2015 Contribution to Goals**
  - Efficiency
    - H_2 turbine w/ 3 – 5 % pts. improvement in CC
  - Emissions
    - H_2 Turbine IGCC with 2 ppm NO_x (@15 % O_2)
    - Oxy-fuel turbine near zero emissions

R&D Areas Advance Turbine Performance

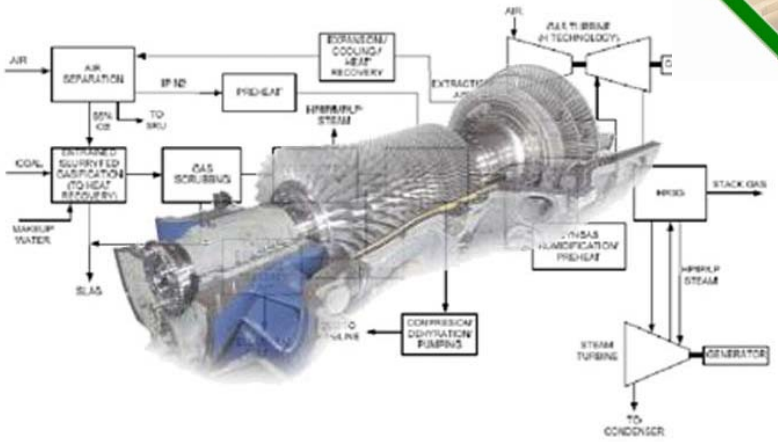
Combustion

Materials

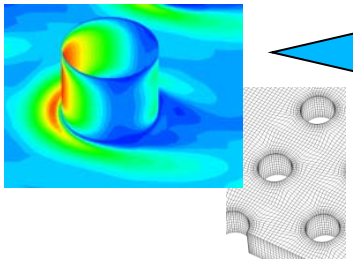


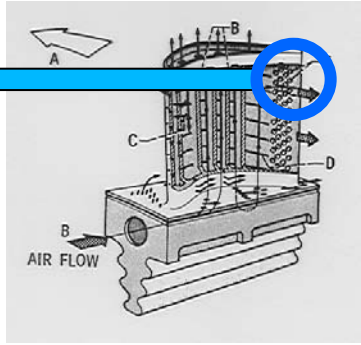
Cost
Power
Efficiency
Emissions

System Design



Aerodynamics & Heat Transfer

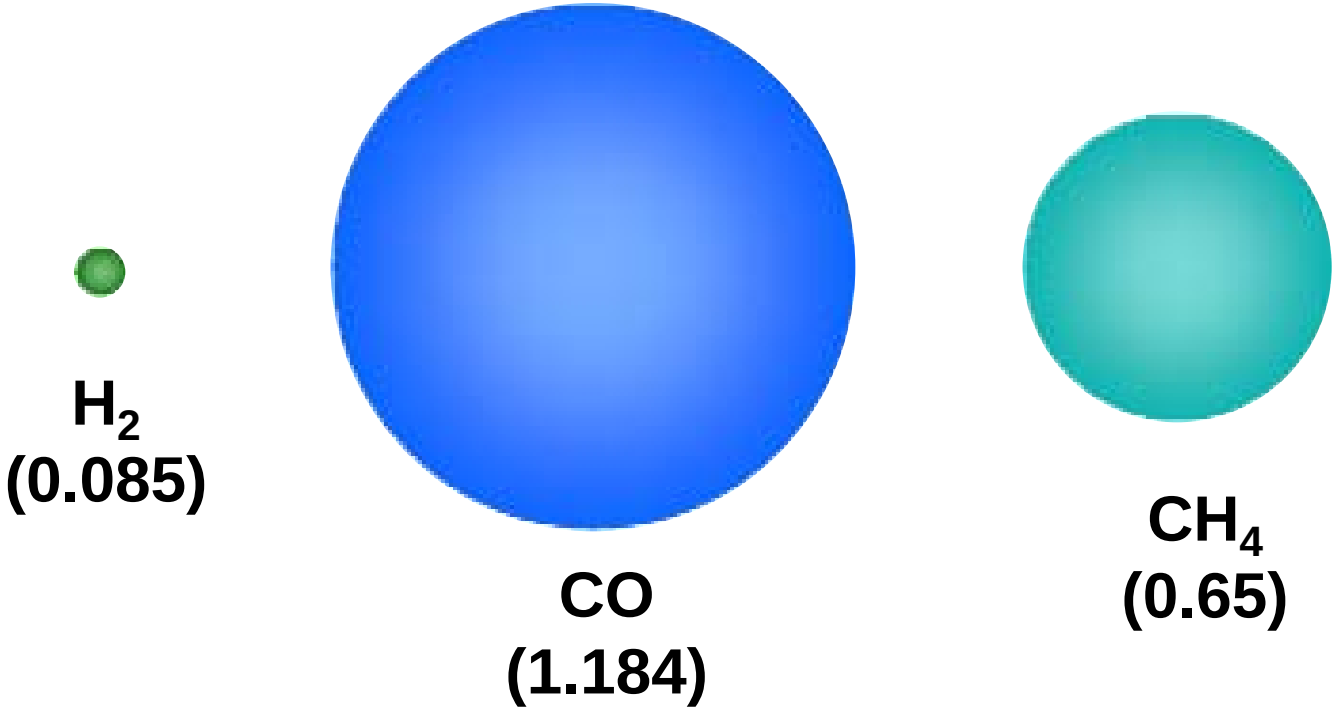




Physical Properties of Hydrogen and Impact on Combustion

Density (kg/m^3)

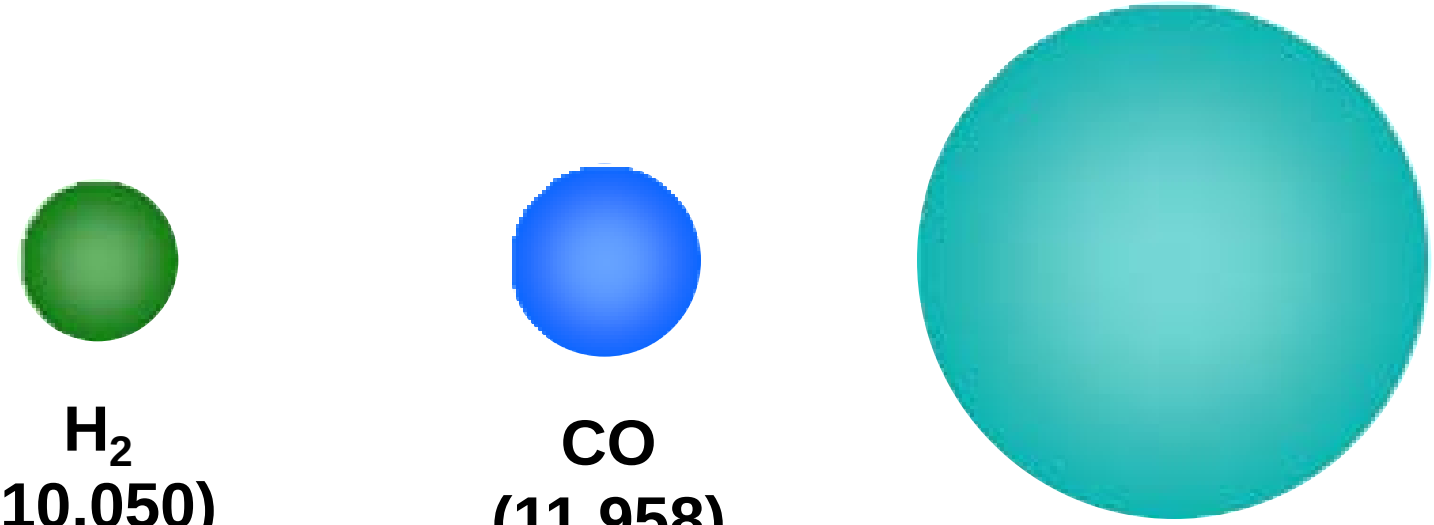
Hydrogen Has a Very Low Density



At 1.013 bar and 15 C

Energy Density (kJ/m^3)

Hydrogen Has a Low Energy Density



H_2
(10,050)

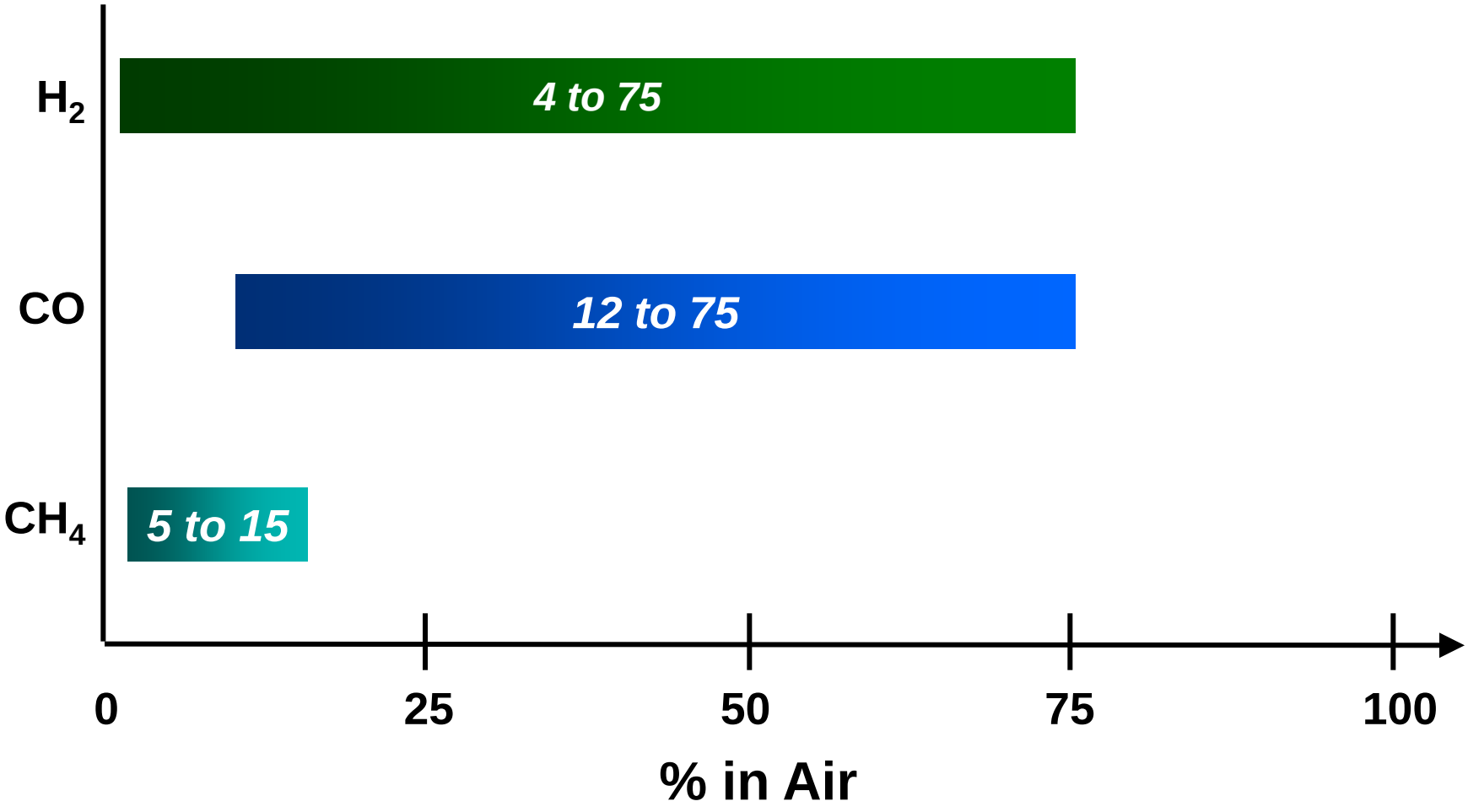
CO
(11,958)

CH_4
(32,560)

At 1 atm. 25 C

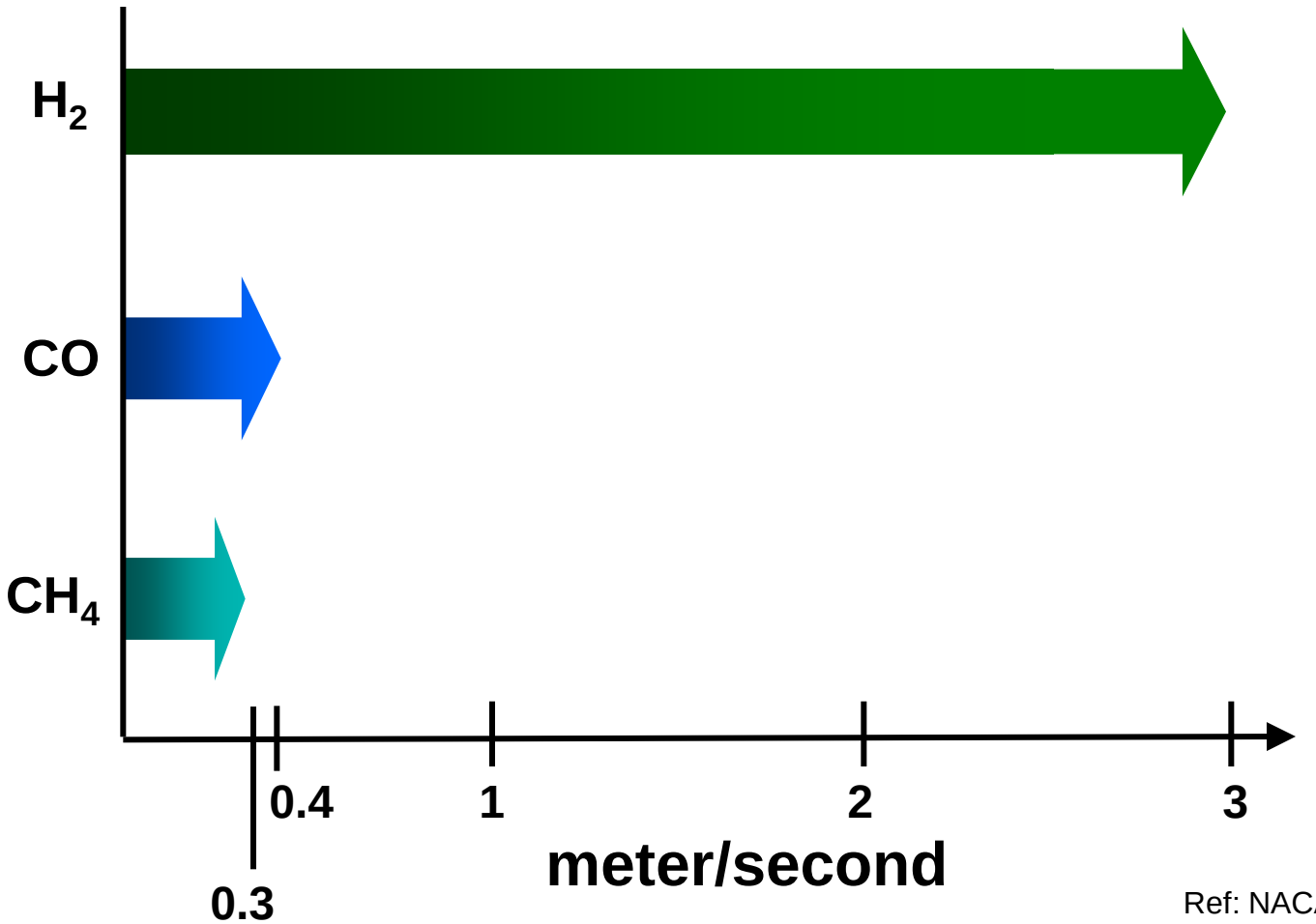
Flammability Limits In Air

Hydrogen Has Broad Flammability Limits



Laminar Flame Speeds

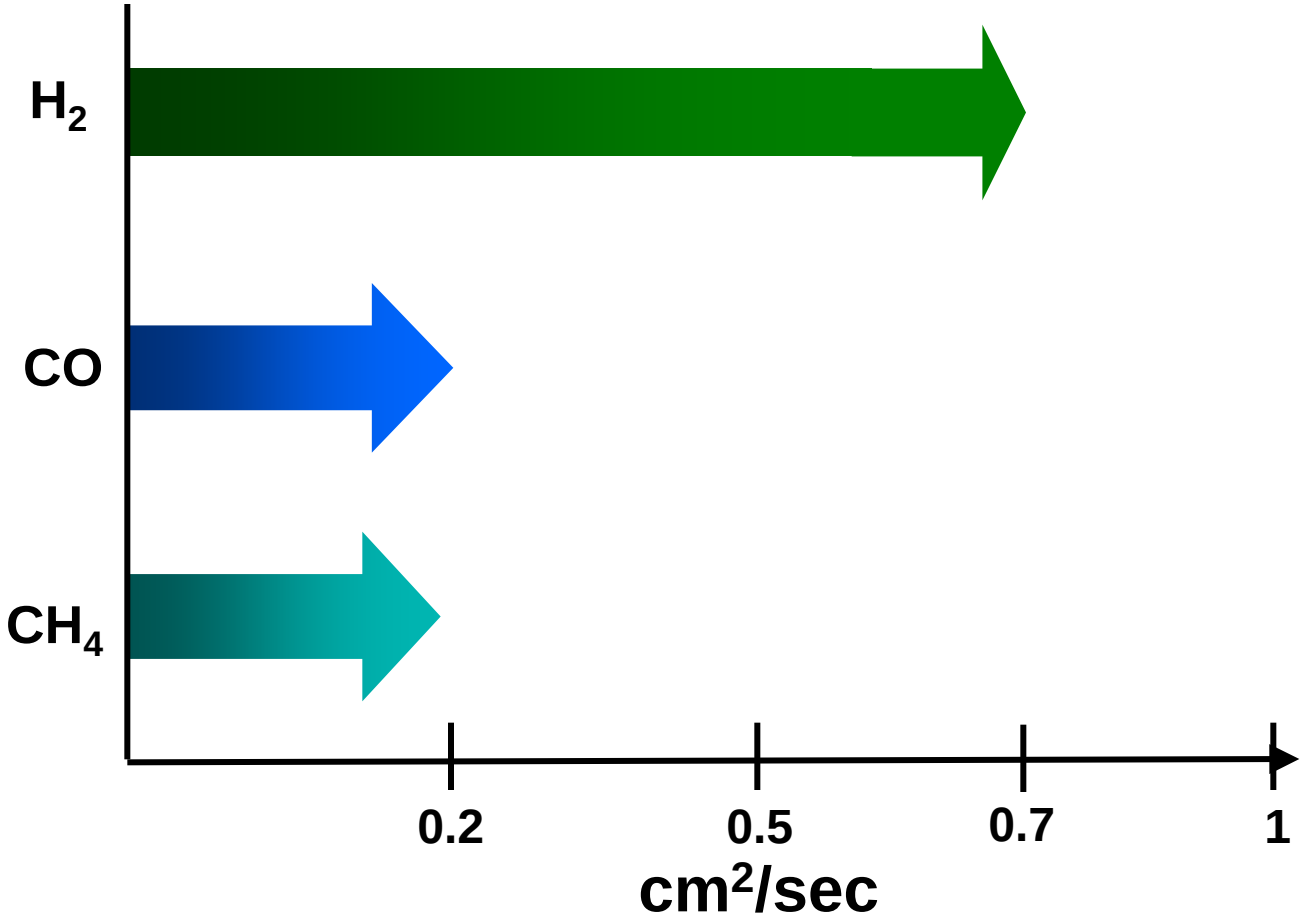
Hydrogen Burns Ten Times as Fast as Methane



Ref: NACA Report 1300

Diffusivity in Air

In Air Hydrogen Diffuses Over Three Times as Fast



Ref: Vargaftik, N. B., Vinogradov, Y. K., and Yargin, V. S. (1996) *Handbook of Physical Properties of Liquids and Gases*, 3rd Ed., Begell House, Inc., New York.

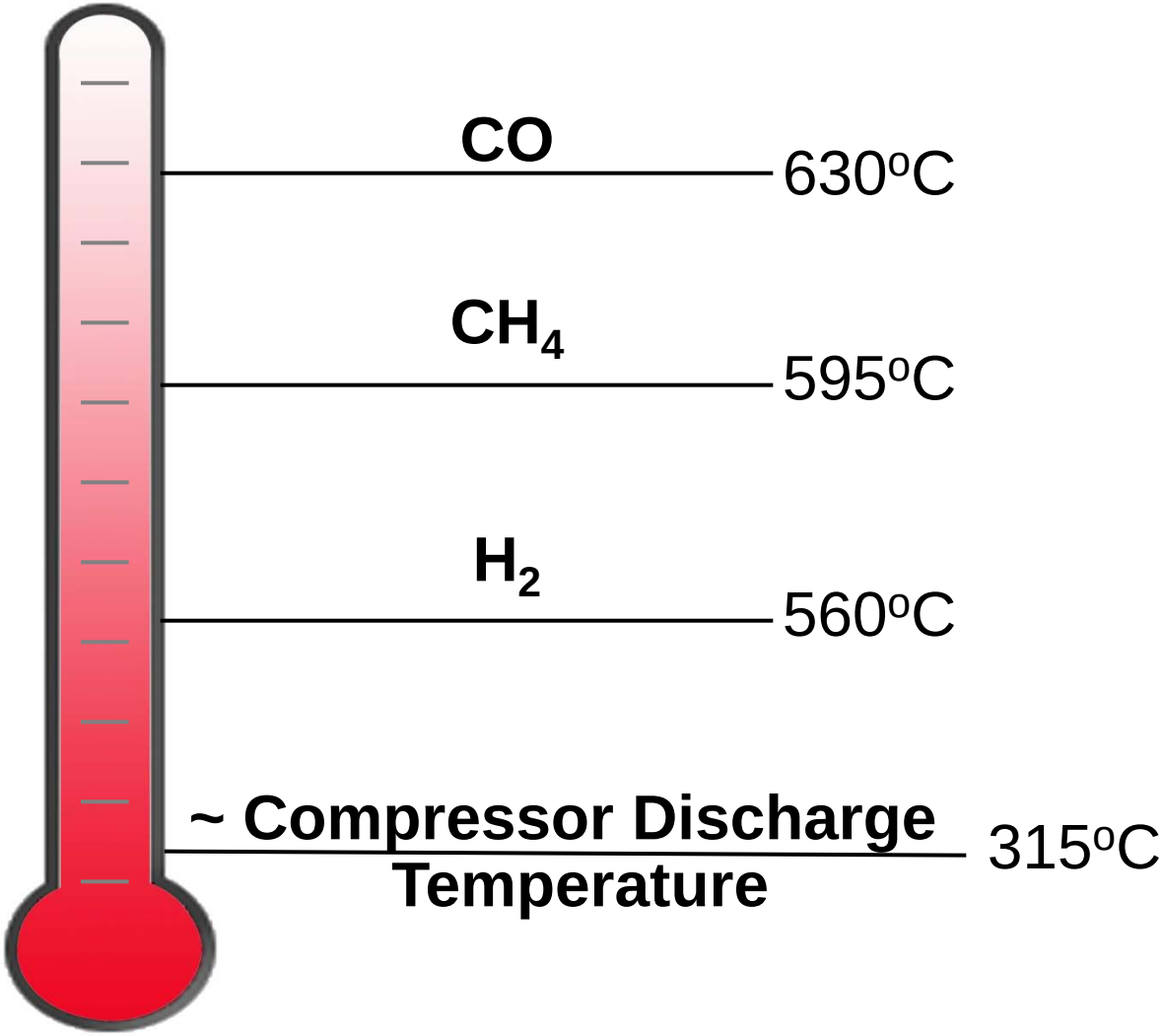
Minimum Ignition Energy (mJ)

- CO …….. 0.3 [2]
- CH_4…….. 0.3 [1]
- H_2…….. 0.017 [1]
- Coffee…….... 160 [1]

References

1. Babrauskak, V. (2003) Ignition Handbook, Fire Science Publishers, Issaquah WA
2. Berufsgenossenschaften, Richtlinien Statische Elektrizität, ZH1/200 (1980), Bonn

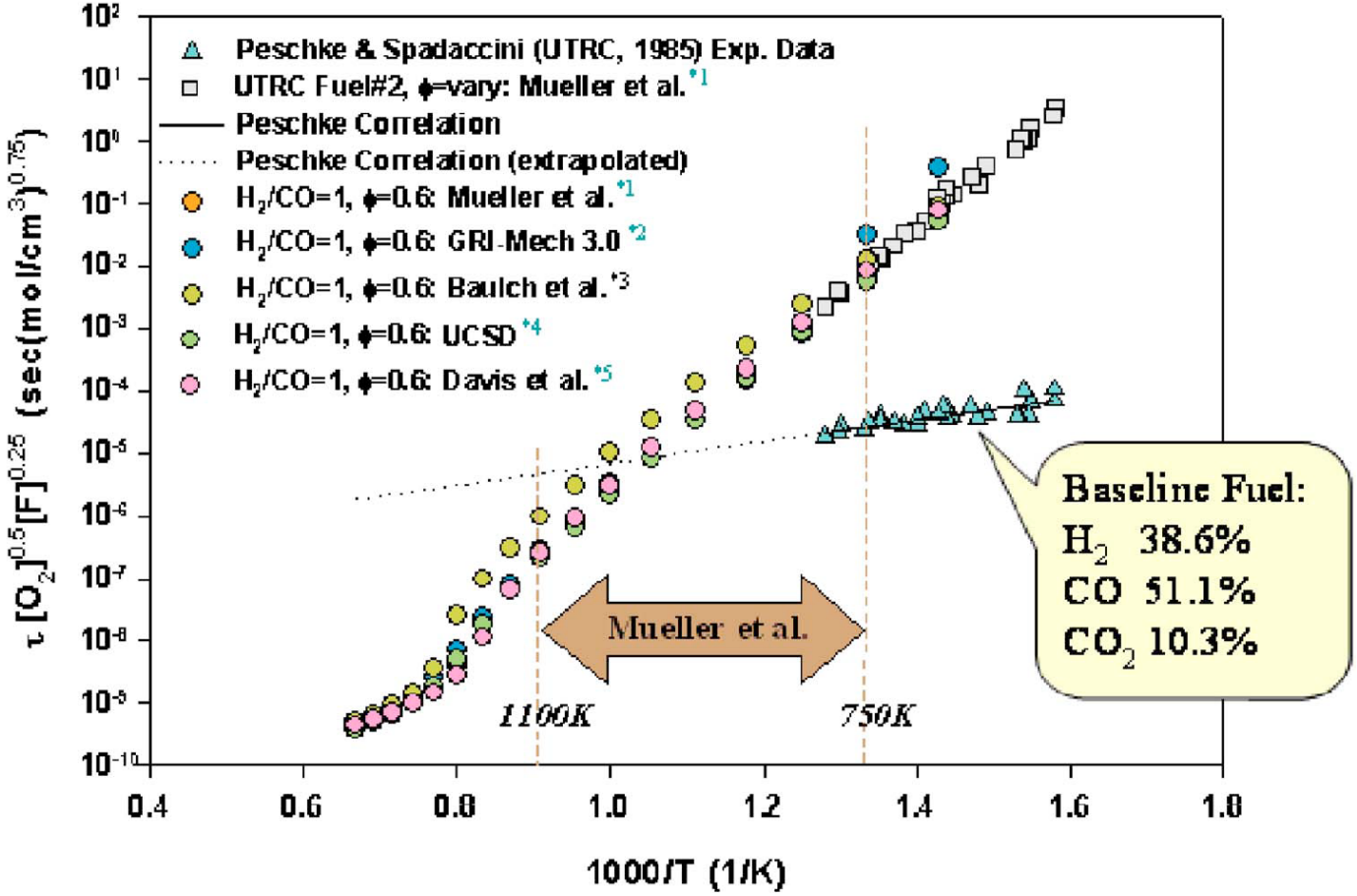
Auto Ignition Temperature



H_2 Properties Impacts Turbine Combustion

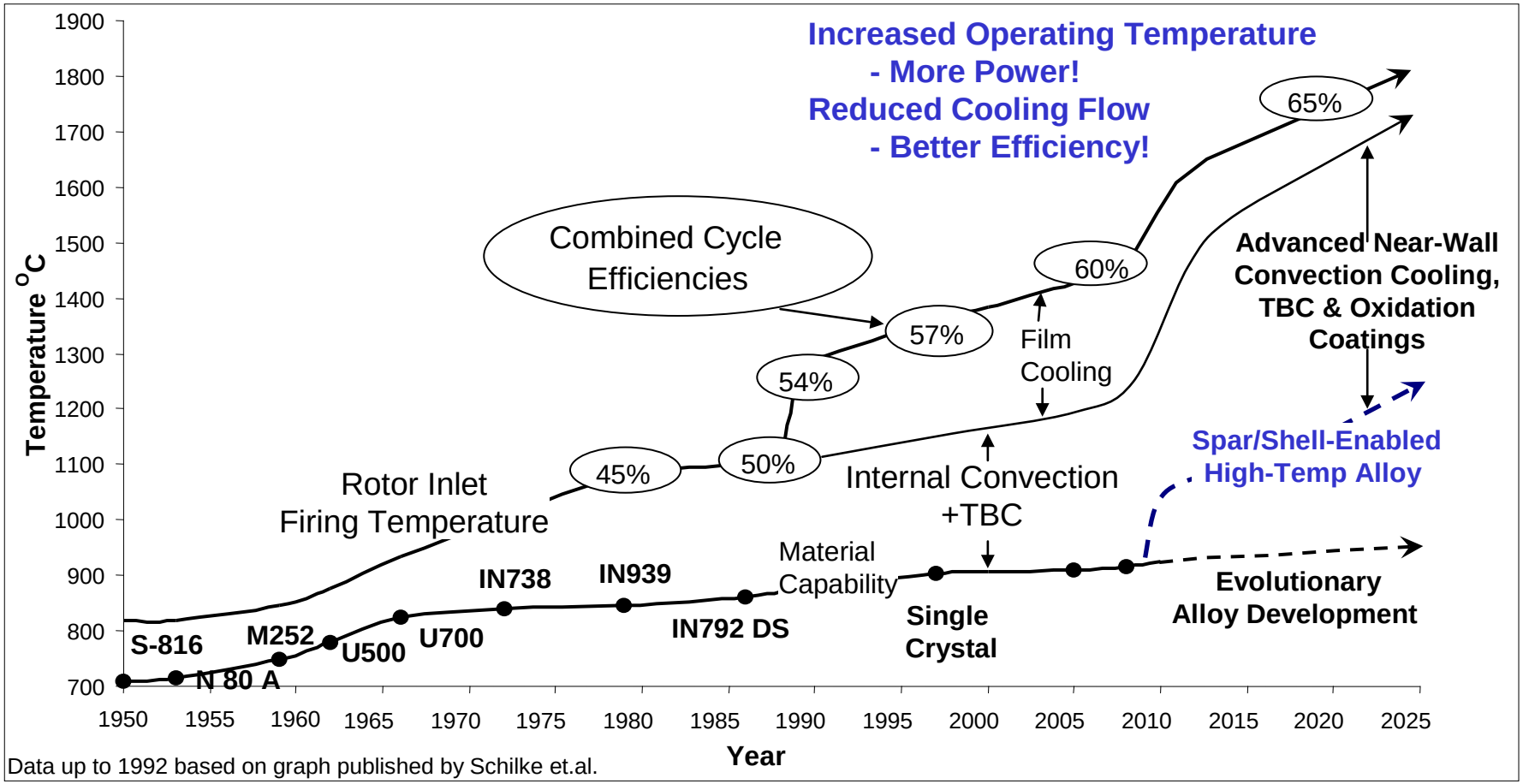
- **Low density of hydrogen (7.6 X< natural gas (NG))**
  - Reduces momentum of injected fuel to promote mixing
- **Low energy density (3.2 x< NG)**
- **H_2 has broad flammability limits 4 – 75 % versus 5 – 15 % for NG in air**
  - H_2 more likely to combust in undesirable locations
- **Laminar flame speed of H_2 ten times faster than NG**
  - Promoting flash back and flame holding
- **H_2 diffuses three times as fast as NG in air**
- **Minimum ignition energy 17 times lower than NG**

Kinetic Models vs. Experiments
Autoignition of Hydrogen Fuels



Ref: Fuel Flexibility Influences on Premixed Combustor Blowout, Flashback, Autoignition and Stability, T. Lieuwen et al, J.Eng. GT Power, Jan 2008, Vol 130

Turbine Inlet Temperature Key to Efficiency



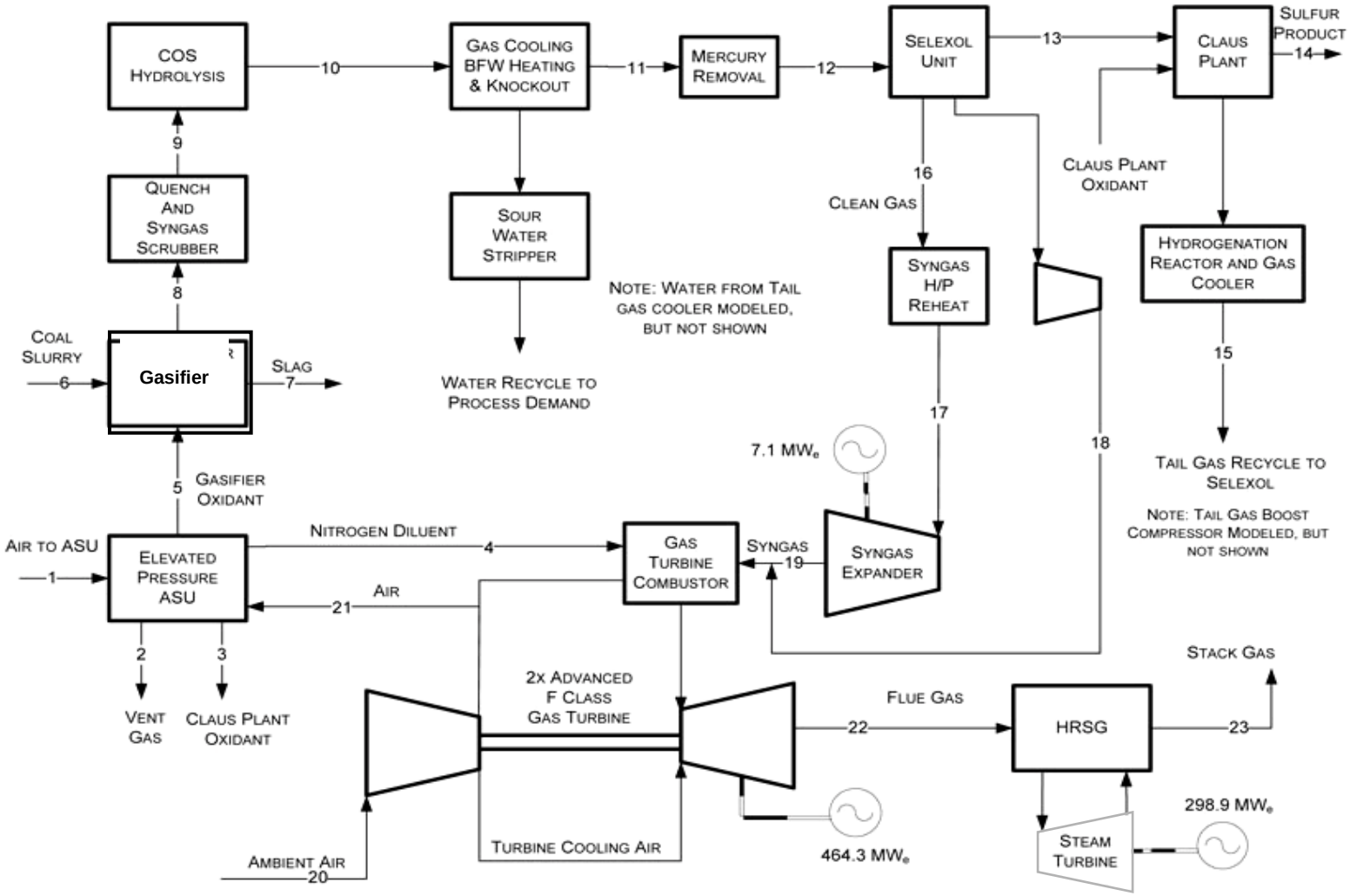
Data up to 1992 based on graph published by Schilke et.al.

Status of H_2 Turbine Projects

GE and Siemens

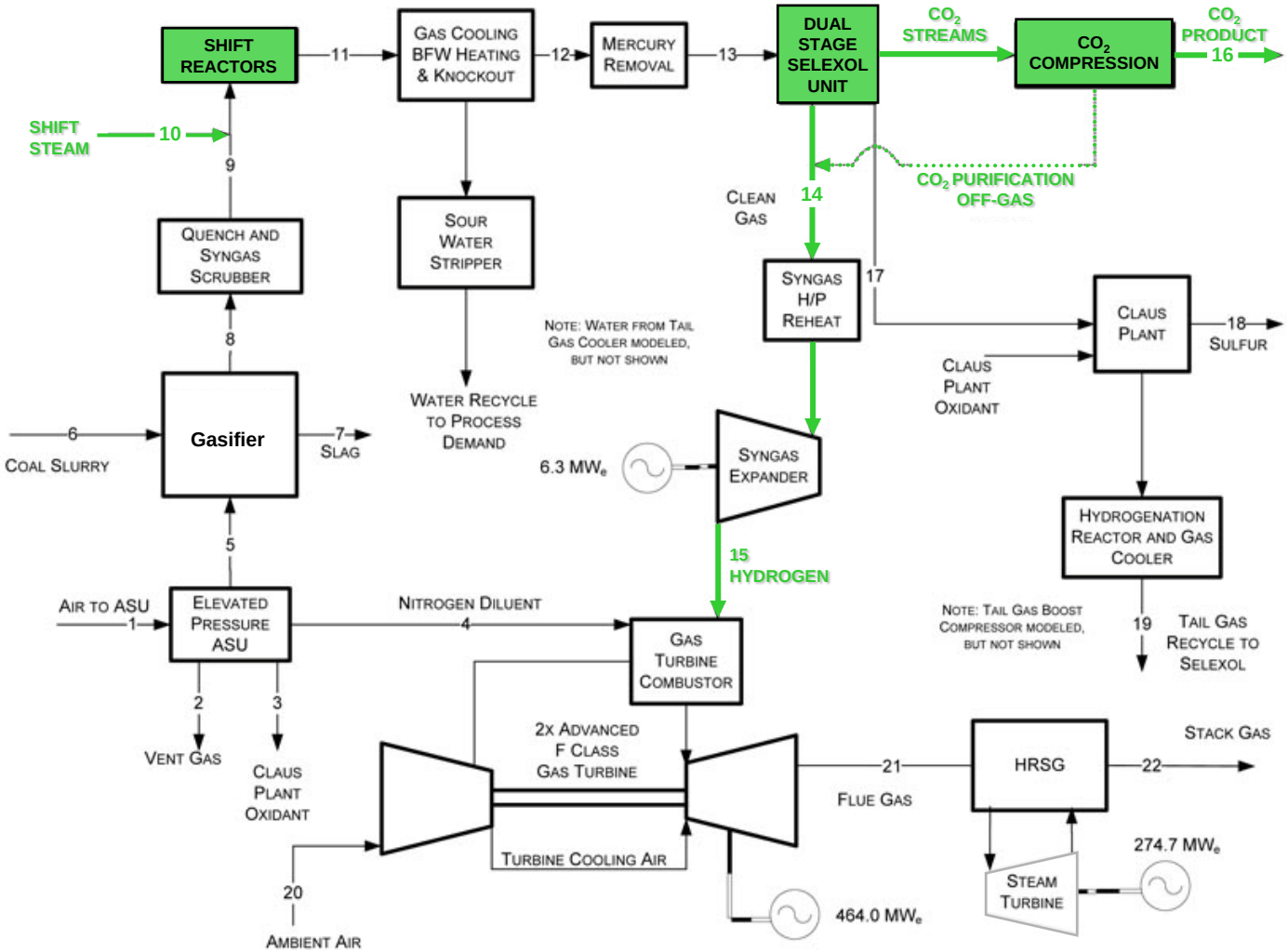
- **Combustion**
  - Conducted full can testing of generation 1 concepts (GE)
    - **100% syngas w/ single digit NOx at F-class conditions**
    - **Promising operability NG, 100% H_2, and H_2-N_2 fuels**
  - Adv. nozzle designs released for manufacturing (SE)
- **Turbine**
  - Completed aero/mech testing of latter stage bucket (GE)
  - Row 1 blade core w/ adv. cooling produced (SE)
- **Materials**
  - Initial tests on metallic and TBC with significant increases in corrosion resistance & TBC spallation life (GE)
  - TBC tests carried out on a Laser rig for advanced high temperature low conductivity coatings (SE)

Nominal IGCC System



Nominal IGCC System with CO_2 Separation

Changes from the Non-Separation Case Shown in Green



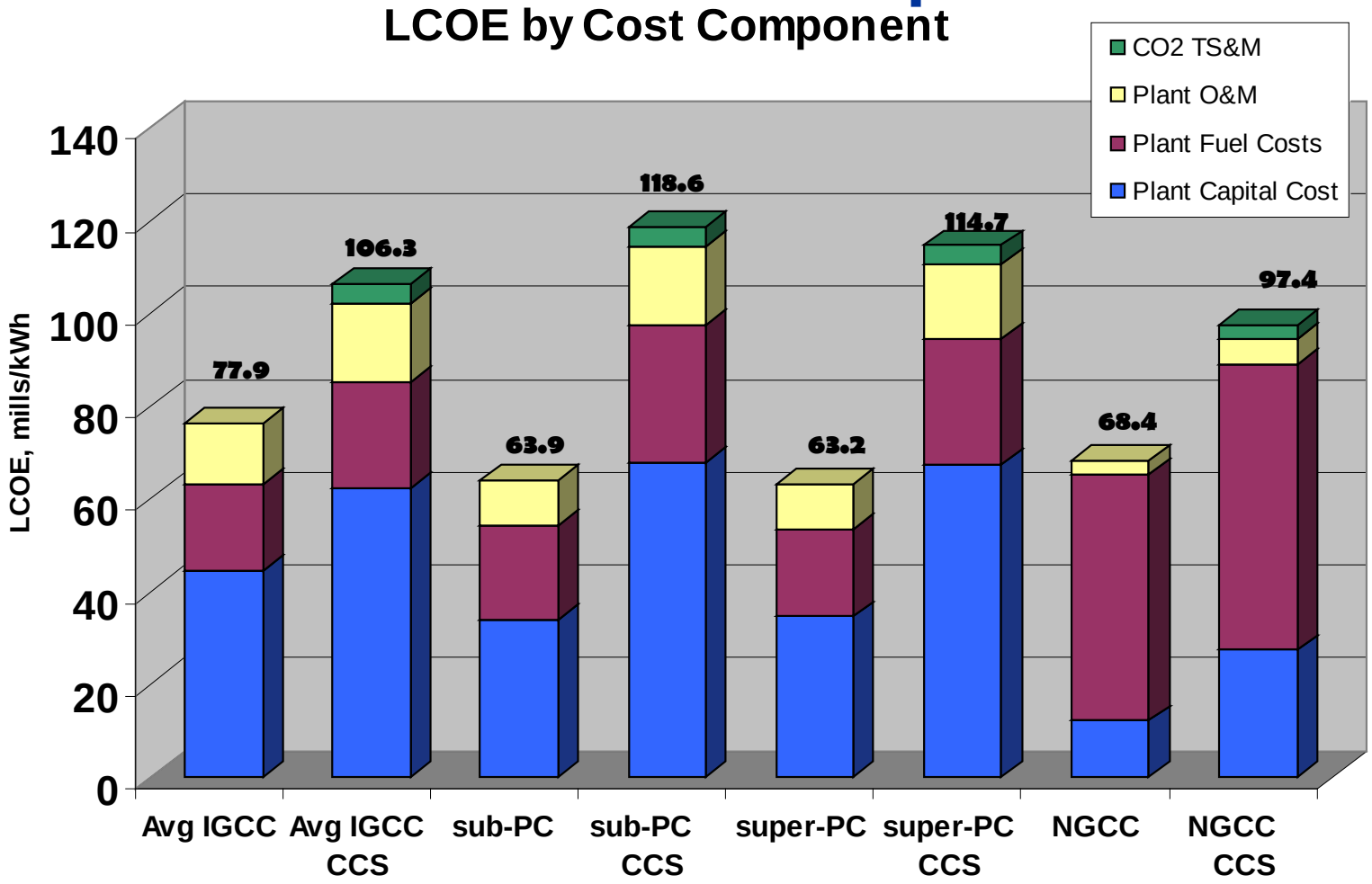
Summary of Changes When Capturing CO2

IGCC to IGCC with carbon capture

- **Higher capital cost (31 %) and COE (27 %)**
- **Auxiliary power increases by 45 % (59 MW)**
- **46 % increase in auxiliary power for CO2 compression (27.4 MW)**
- **Steam use degrades steam turbine output by 8 % (24 MW)**
- **Net power reduced by 85 MW**
- **Net plant efficiency reduced by 5.7 % points**
- **2 % increase in coal consumption (~ 117 TPD)**

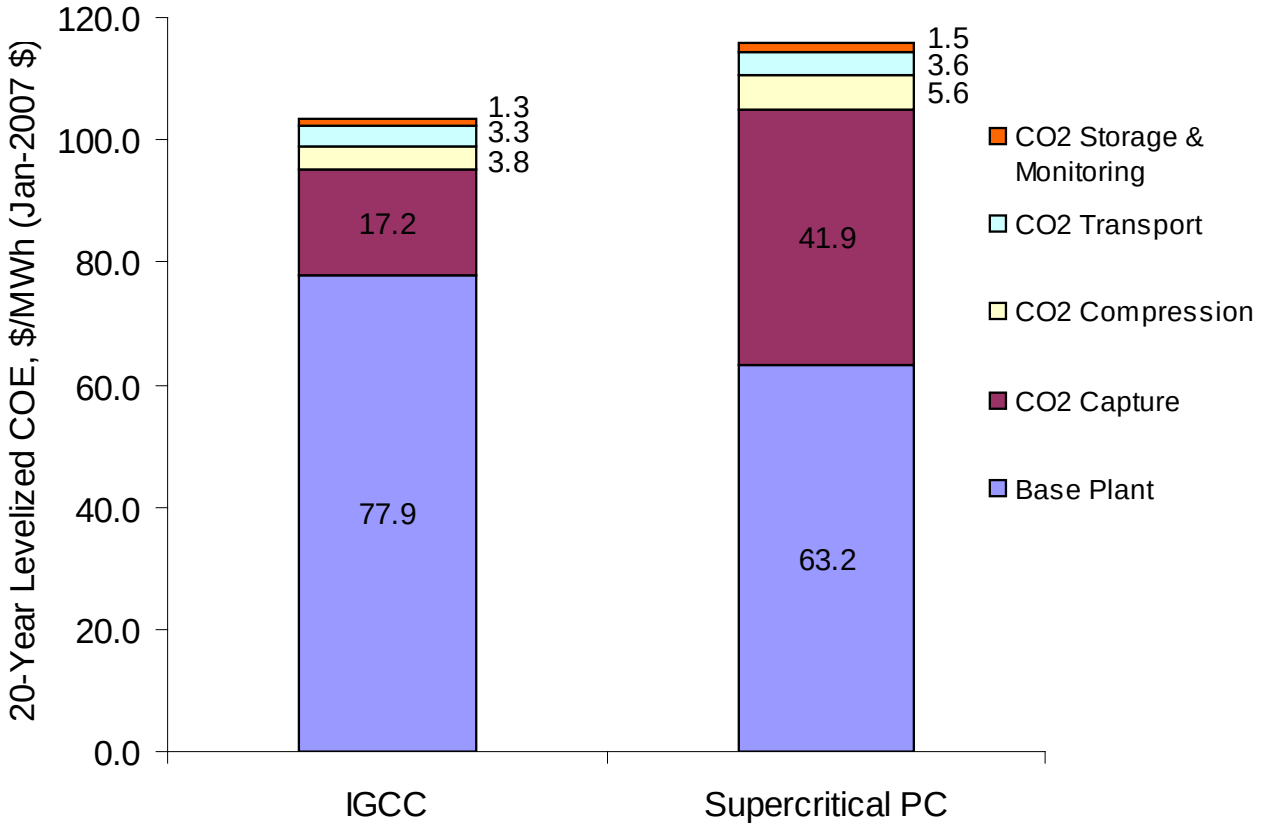
Reference: Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, J. Klara, May 2007, Final Report DOE NETL

Cost of Electricity for Fossil Fuel Power Plants That Capture CO2



January 2007 Dollars, Coal cost $1.80/10^{6}Btu, Gas cost $6.75/10^{6}Btu
CCS = Carbon capture and sequestration
TS&M = transport, storage, and monitoring

Impact of CCS on COE



Summary

- **Coal is projected to be a major energy resource for the U.S. and the world**
- **Effective CO2 management will require a multi facetted approach**
- **For new coal plants IGCC is the best approach for CO_2 capture**
  - CO_2 capture and geologic sequestration is a viable option for reducing carbon intensity
  - IGCC creates new pathways for energy production, lower emissions and higher efficiency
- **DOE's Turbine program is addressing opportunities for IGCC with CO_2 capture**
  - Excellent progress in efficiency, power output materials and combustion with reduced emissions
- **On track to meet program goals**

Questions and Discussion