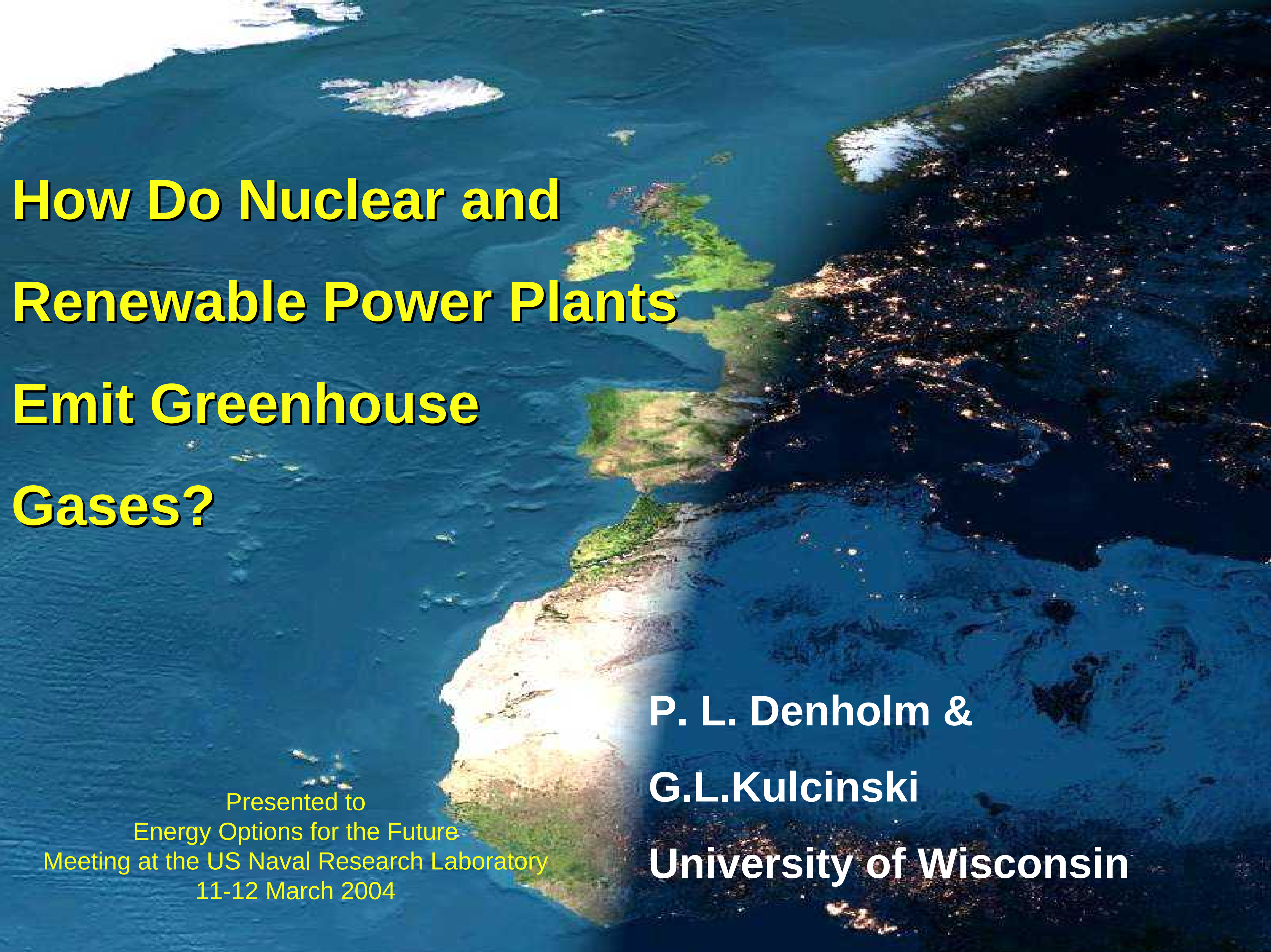


# How Do Nuclear and Renewable Power Plants Emit Greenhouse Gases?

P. L. Denholm &
G.L.Kulcinski
University of Wisconsin

Presented to
Energy Options for the Future
Meeting at the US Naval Research Laboratory
11-12 March 2004

# Past Statements About Greenhouse Gas Emissions Can Be Misleading!

**"Nuclear power is a zero-carbon energy source"**

**Nuclear News, Dec 1997**

**"Wind, photovoltaics, and improved energy efficiency produce no carbon at all."**

**Wisconsin State Journal, July 26, 1998**

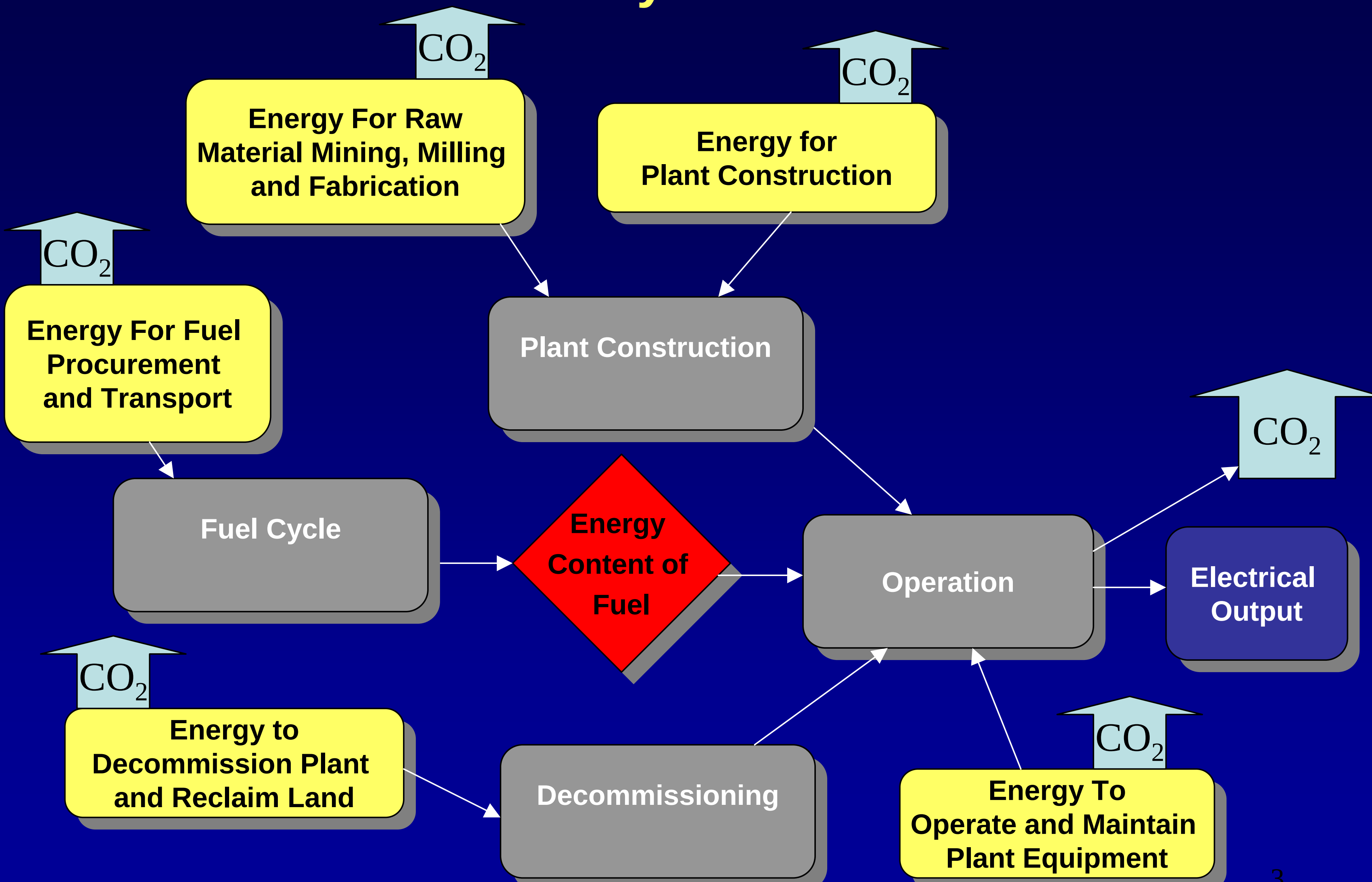
**"Additional governmental support of clean, carbon-free wind energy is an idea that few would disagree with."**

**The Christian Science Monitor. April 1, 1993**

**"Nuclear power produces electricity without emitting any greenhouse gases."**

**The Washington Times, Nov 6, 1997**

# Life-Cycle Analysis Considers All Stages of the “Fuel Cycle”



# Six Different Electrical Power Plants Were Considered

| Power Source | Facility Used |
|---|---|
| Coal | El-Bassioni, NUREG/CR-1539, 1980 |
| Natural Gas | 2 x 1 combined cycle,Cass County,MO |
| Fission | Bryan, ORNL, TM-4515, 1974 |
| Fusion | 2 tokamaks (Aries-RS, UWMAK-I) |
| Wind | Buffalo Ridge Wind Farm, Southwestern MN |
| Photovoltaic | Big Horn Center, Silverthorne, CO, Roof Unit |

# There are Two Methods to Measure Energy Input to Power Plants

*Process Chain Analysis (PCA)*

$\frac{\text{unit mass}}{GW_e \text{ or } GW_e y}$ X

| *Material* | *GJ/tonne* |
|---|---|
| Aluminum | 207 |
| Concrete | 1.4 |
| Copper | 131 |
| Stainless Steel | 53 |
| Vanadium | 3711 |
| Rocket Fuel ($LH_2$) | 460 |
| Rocket Fuel ($LO_x$) | 10 |
| Titanium (for lunar mining equipment) | 444 |

→ $\frac{GJ}{GW_e \text{ or } GW_e y}$

*Input/Output (I/O)*

$\frac{\text{"service"}}{GW_e \text{ or } GW_e y}$ X $\frac{\$}{\text{unit "service"}}$ X

| *Commodity* | *Energy Intensity (GJ/1977$)* |
|---|---|
| New Construc. | 32 |
| Elect. Utility | |
| Auto Repair | 23 |
| Railroad | 49 |
| Paving | 192 |

# REFERENCE NATURAL GAS PLANT

<u>Operating Assumptions:</u>

Gas Turbine ($\eta$ = 50%)

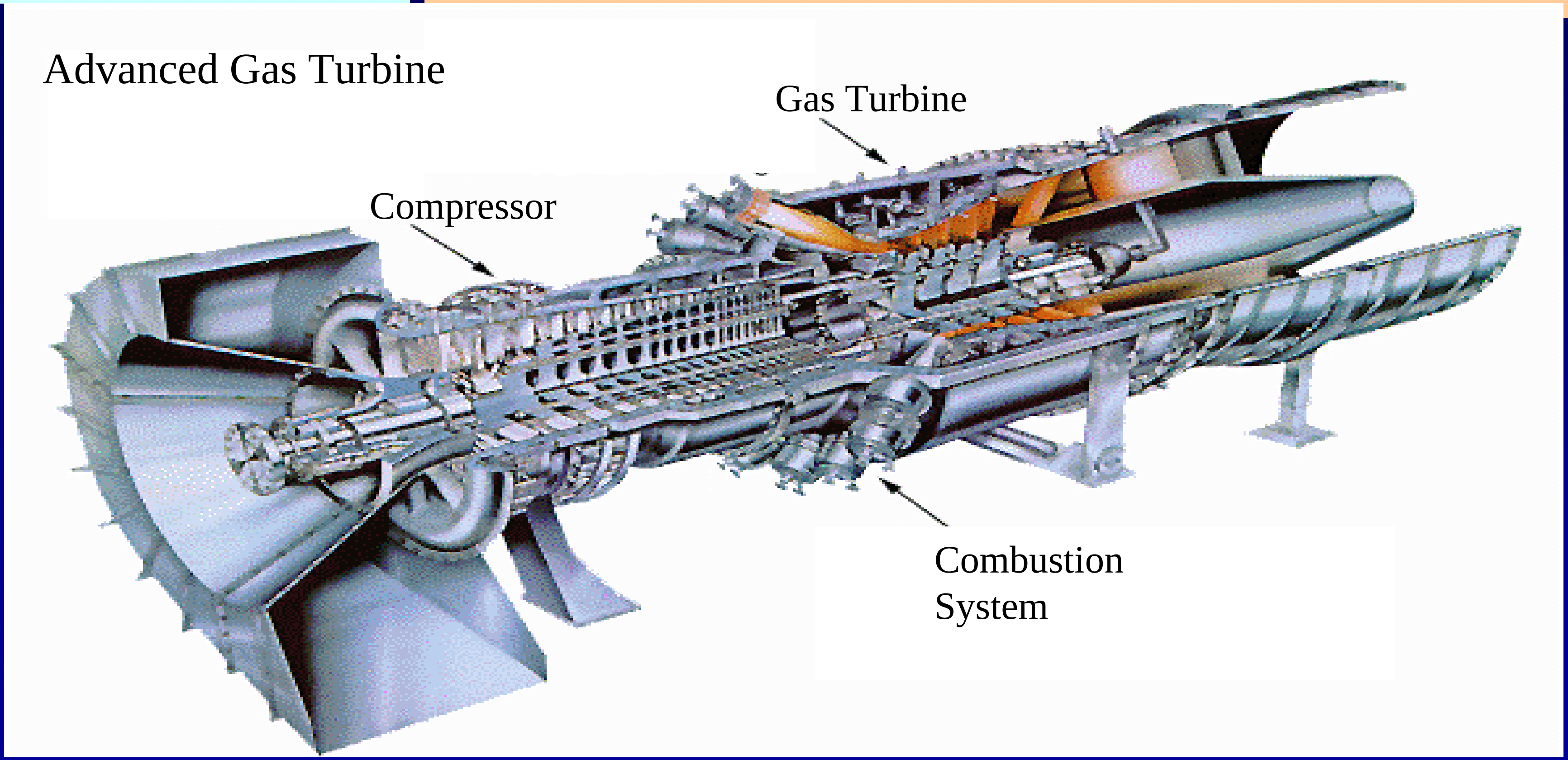
Plant Capacity = 80%

Gross Electrical Power Output: 450 $MW_e$ total from 3 turbines

Annual Electrical Energy Output: 11,352,960 $GJ_e$ (3,153 $GW_eh$)

Annual Natural Gas Input = 22,705,920 $GJ_{th}$ ($6 \times 10^8$ $m^3$*)

*1020 BTU/$ft^3$ (38 MJ/$m^3$)



# Example of Process Chain Analysis

| GAS PLANT - MATERIALS | | | |
|---|---|---|---|
| | **Mass (a.i)** | **Energy Req.** | **Energy Totals** |
| **Element or Alloy** | **Tonnes of Material** | **GJ/Tonne of Material** | **GJ** |
| Chromium (High C Fe Cr) | 0.32 | 82.9 | 27 |
| Concrete | 29,660 | 1.4 | 40,876 |
| Copper (Refined) | 4 | 130.6 | 479 |
| Iron | 73 | 23.5 | 1,718 |
| Carbon Steel (castings) | 135 | 34.4 | 4,632 |
| High Alloyed Steels | 1,392 | 53.1 | 73,948 |
| Manganese | 17 | 51.5 | 864 |
| Molybedenum (FeMo) | 0.17 | 378.0 | 65 |
| Plastic | 15 | 54.0 | 820 |
| Silicon | 3.8 | 158.6 | 608 |
| Vanadium (FeV) | 0.51 | 3,711.2 | 1,885 |
| **Total** | **31,300** | | **125,923** |

# Example of Input/Output Analysis

| GAS PLANT - EQUIPMENT | | | | |
|---|---|---|---|---|
| **Description** | **Budgeted Cost** | **I/O Intensity (GJ/$)** | **I/O Description** | **Energy Invested (GJ)** |
| Combustion Turbines | $ 64,785,903 | 0.008799 | Turbines & turbine generator sets | 570,073 |
| Transformers | $ 3,873,556 | 0.016821 | Power, distribution, & specialty transformers | 65,158 |
| Steam Generator | $ 2,905,066 | 0.012112 | Motors & generators | 35,187 |
| Pumps | $ 3,820,757 | 0.009963 | Pumps & compressors | 38,067 |
| Condensers | $ 1,507,187 | 0.011140 | Refrigeration & heating equipment | 16,791 |
| Electrical Equipment | $ 6,888,277 | 0.012056 | Electrical industrial apparatus | 83,048 |
| Noise Attenuation | $ 261,400 | 0.006809 | Other repair & maintenace construction | 1,780 |
| Road upgrades | $ 500,000 | 0.009275 | Maintenance & repair of highways & streets | 4,638 |
| Pipeline & Header Interconnect | $ 6,811,000 | 0.006176 | Installed Pipeline | 42,064 |
| | | | | **856,804** |

# $CO_2$ Emissions are Calculated from Both Electrical and Thermal Inputs

## *Electrical*

| 1996 U.S. Electrical Distribution | |
|---|---|
| Coal | 56.5% |
| Hydro | 10.7 |
| Nuclear | 21.9 |
| Oil | 2.2 |
| Natural Gas | 8.7 |

X

| kg $CO_2$ / MWh | |
|---|---|
| Coal | 974 |
| Hydro | 3.1 |
| Nuclear | 17 |
| Oil | 726 |
| Natural Gas | 484 |

→ **0.605** $\frac{\text{tonnes } CO_2}{\text{MWh}}$

## *Thermal*

(example)

$\frac{\text{Unit of Fuel}}{\text{tonne structural steel}}$

X

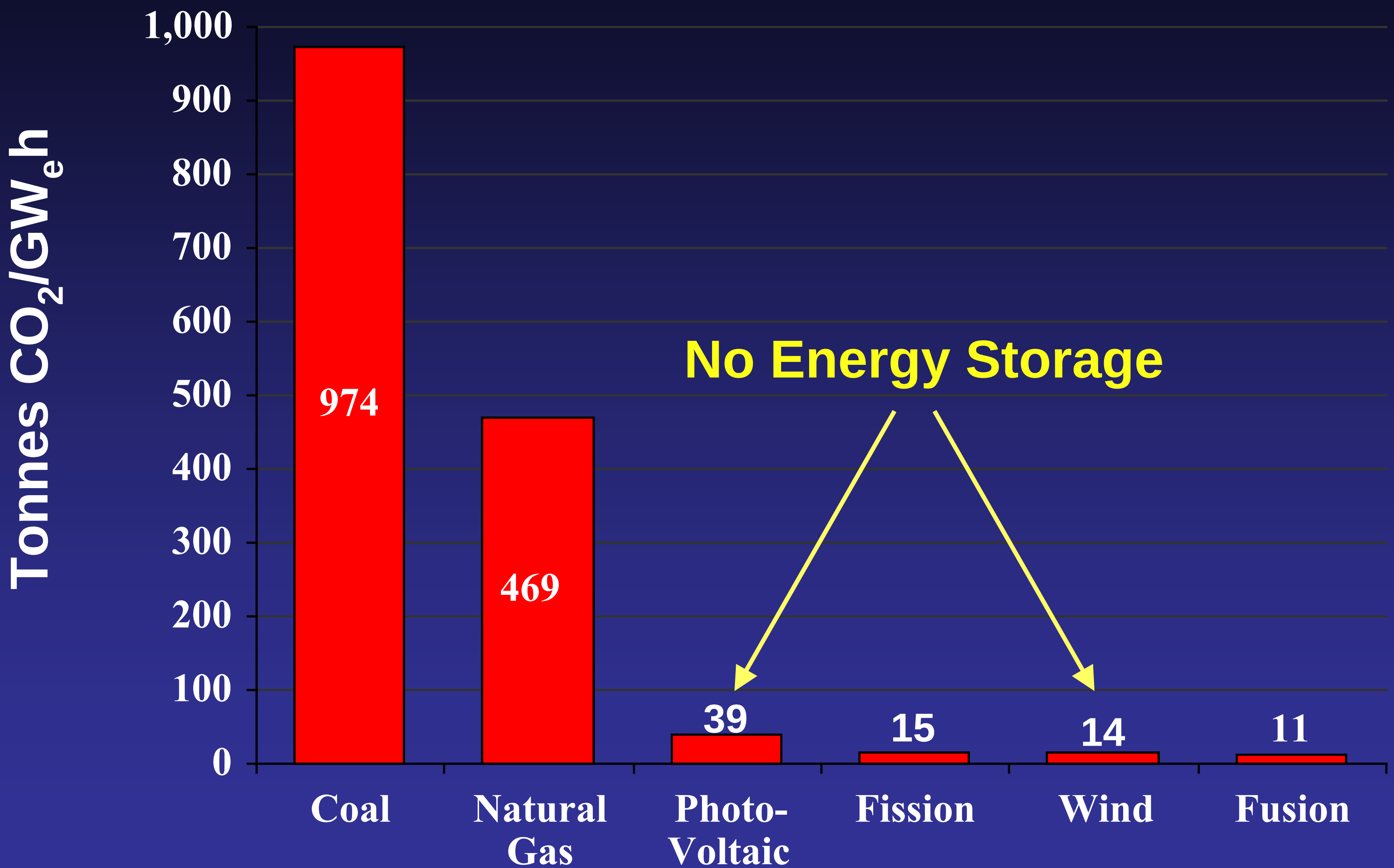
| Energy Intensity | |
|---|---|
| Coal | 23 GJ/tonne |
| Petroleum | 0.13 GJ/gal |
| Natural Gas | 0.001 GJ/ft$^3$ |
| Diesel | 0.15 GJ/gal |
| ... | ... |

X

| kg $CO_2$ / $GJ_{th}$ | |
|---|---|
| Coal | 93 |
| Petroleum | 69 |
| Natural Gas | 51 |
| Diesel | 72 |
| ... | ... |

→ **1.5** $\frac{\text{tonnes } CO_2}{\text{tonnes structural steel}}$

# Relative to the $CO_2$ Emissions of Coal and Natural Gas, Those from Nuclear and Renewables are Low, But Not Zero

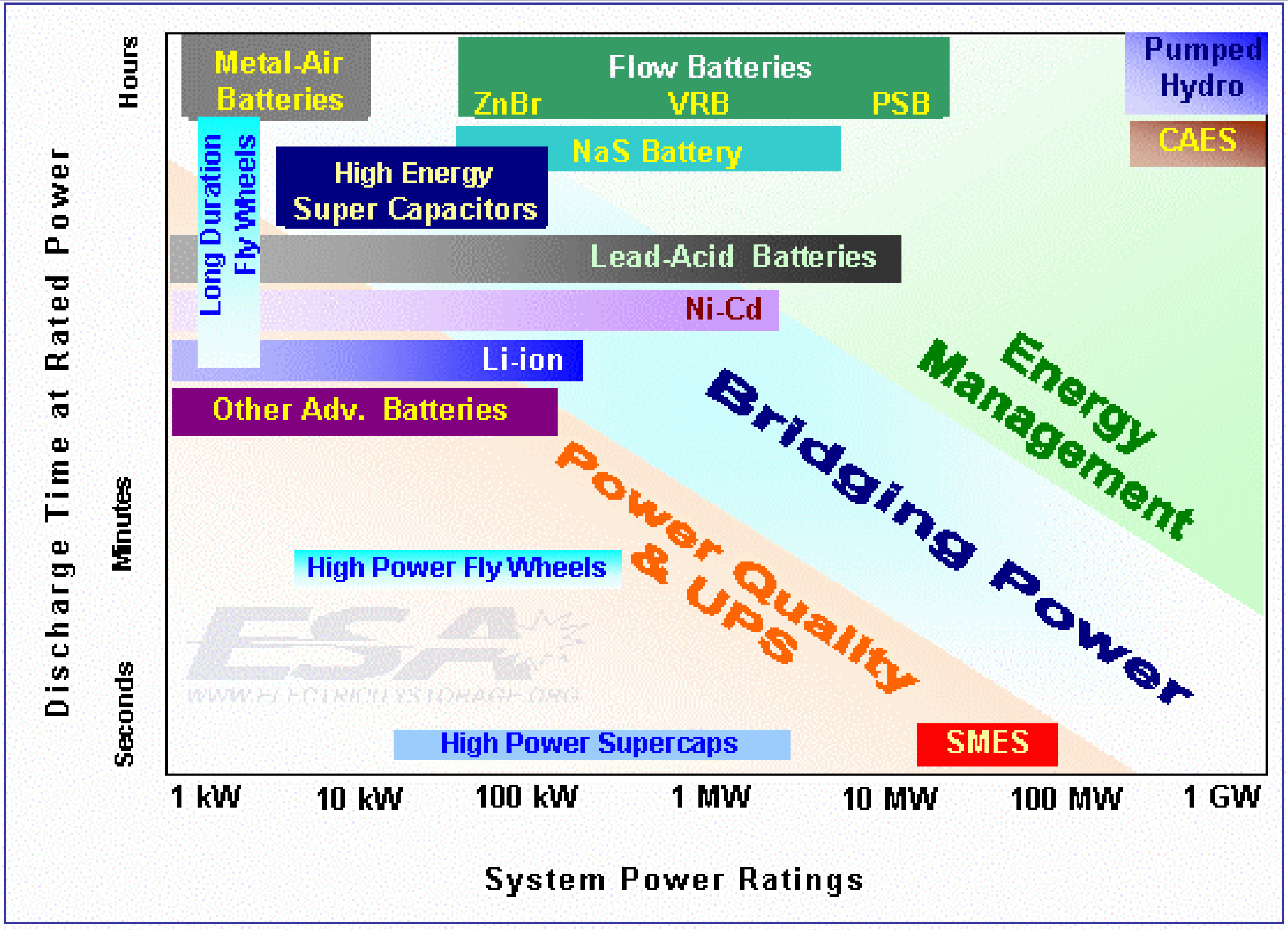



After Paul Meier-Univ. of Wisconsin-2001

## The GHG Comparison Between Base-Loaded Systems and Intermittent Renewables is Not Complete

- “The wind doesn’t always blow and the sun doesn’t always shine”
- Large hourly fluctuations in wind output (up to 100% per hour) places tremendous stress on generation systems
- Coupling to energy storage units would provide level “playing field” to compare intermittent sources to base-load sources

# Available Storage Technologies



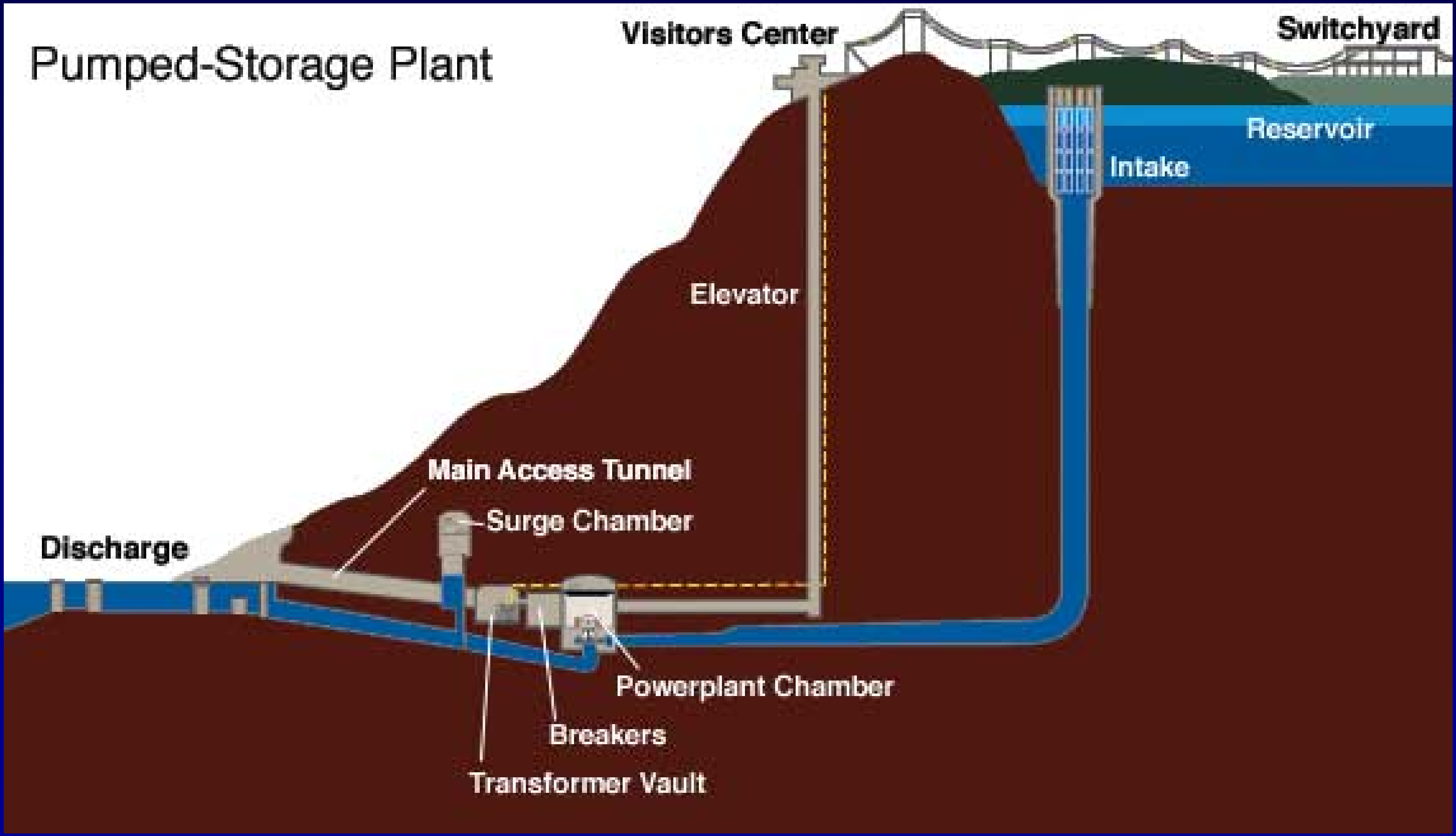

Source: Electricity Storage Association

# Utility-Scale Storage Technologies Analyzed in This Work

- Pumped Hydro Storage (PHS)

- Compressed Air Energy Storage (CAES)
- Battery Energy Storage Systems (BESS)
  - Lead Acid
  - Flow Batteries:
    - Vanadium (VRB)
    - Regenesys-Na Bromide/ Na Polysulphide (PSB)

# Pumped Hydro



# Pumped Hydro Characteristics

- Dominate technology world-wide ~100,000 MW (>99% of utility scale storage)

- U.S. PHS exceeds 18,000 MW at 36 facilities
  Sizes from ~200 MW to 2100 MW

# CAES Characteristics

- Hybrid storage/generation technology - consumes natural gas

- 2 Facilities Worldwide, 400 MW total
- Plans for 3 facilities in U.S. including 2700 MW plant in Ohio (model for this study)

- Requires large storage cavern in hard rock or salt dome
- Many places in the U.S. have appropriate geology, including Midwest

# Compressed Air Energy Storage (CAES)

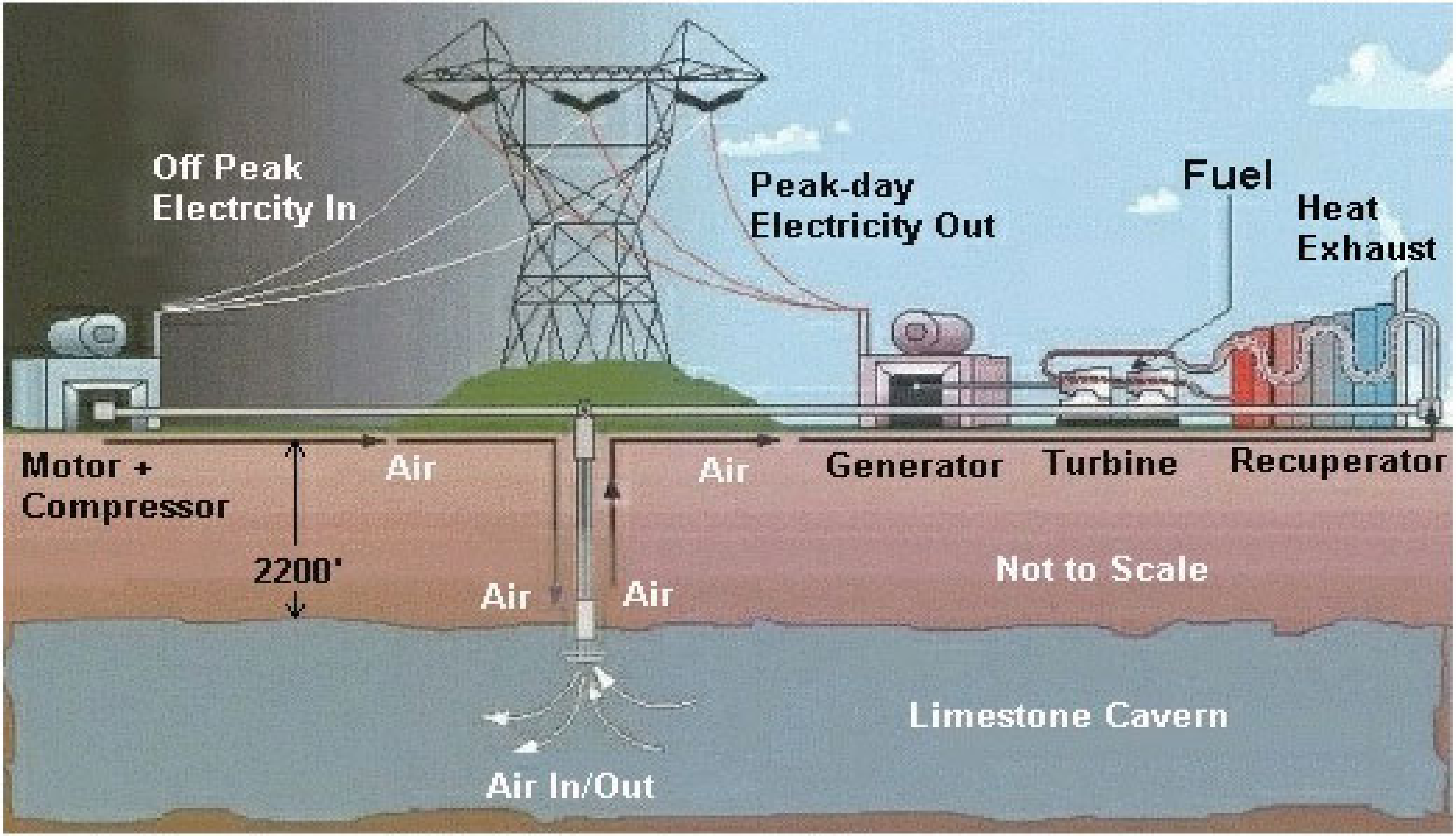



Photo Courtesy of CAES Development Company

# Batteries: Finally Ready?

- A number of large battery farms world wide primarily for power quality

- Lead-Acid has been dominant technology

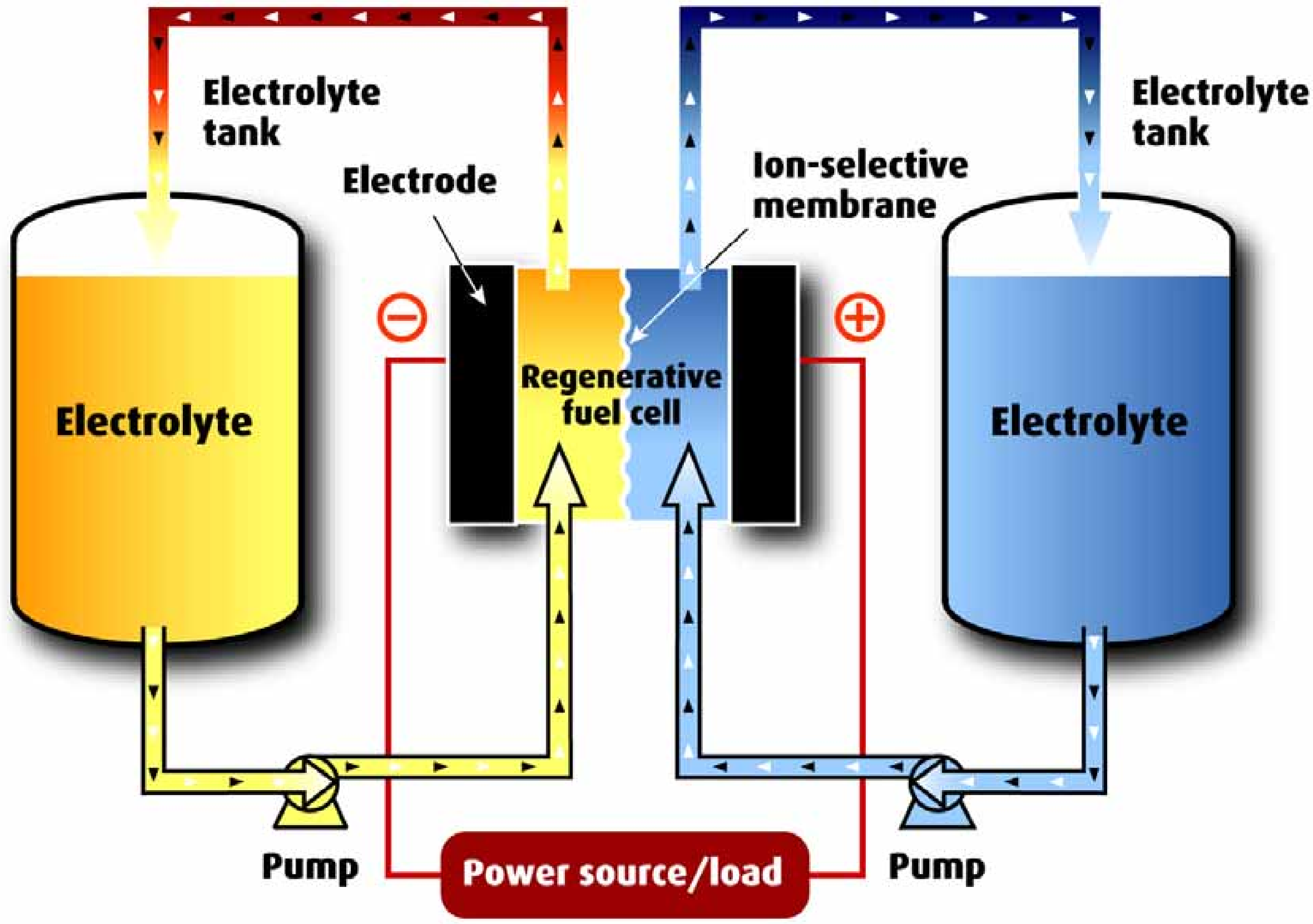
- New technologies finally competitive, partially as a result of USABC

# Flow Battery Characteristics

- Liquid electrolyte (Flow) batteries are promising for stationary application
- Longer life, greater efficiency than Pb-Acid
- Capital cost competitive with Pb-Acid

- Three competing electrolytes
- Zinc-Bromine
- Regenerative Fuel Cells:
  - Vanadium Redox
  - Regenesys Na Bromide/Na Polysulphide

# Flow Batteries



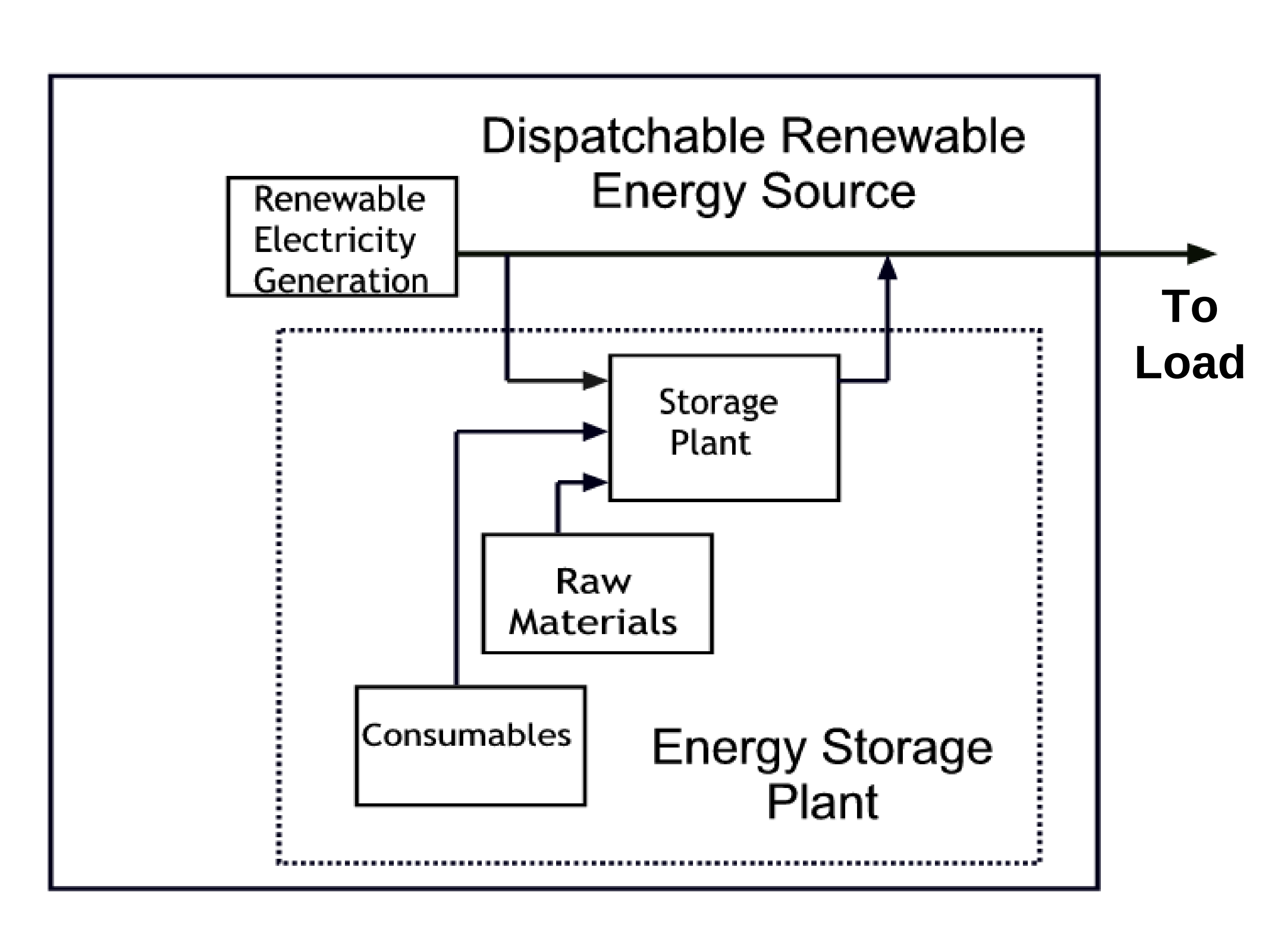
# Flow Batteries

**TVA's 15MW 120 MWh Regenesys Project**
**Courtesy Regenesys**

# Likely Renewable-Storage Scenarios

- Wind – PHS
- Wind - CAES
- Solar PV – Battery

# System Analysis: What does a Dispatchable Renewable System Look Like?



# Analysis Example: Wind - PHS

| **Energy and GHG Emissions associated with Wind Generated Electricity with and without Pumped Hydro Storage** | | |
|---|---|---|
| | System w/o Storage | System with Storage |
| Total energy produced by wind farm ($GWh_e$) | 1,530 | 1,530 |
| Energy lost to storage ($GWh_e$) | 0 | 111 |
| Total energy input into system $GJ_t$ | 239,720 | 306,153 |
| System EPR ($GWh_e$/ $GWh_t$) | **23** | **16** |
| | | |
| Emissions rate (tonnes $CO_2$ equiv./ $GWh_e$) | **14** | **20** |

# Example Analysis: Wind - CAES

| GHG Emissions associated with Wind Generated Electricity with and without Compressed Air Energy Storage | | |
|---|---|---|
| | System w/o Storage | System with Storage |
| Total energy produced by wind farm ($GWh_e$) | 61,320 | 61,320 |
| Energy delivered to CAES ($GWh_e$) | 0 | 17,170 |
| Energy Produced by CAES | 0 | 23,361 |
| Total energy produced by system ($GWh_e$) | 61,320 | 67,511 |
| Total Emissions (tonnes $CO_2$ equiv.) | 769,800 | 6,564,313 |
| Emissions rate (tonnes $CO_2$ equiv./ $GWh_e$) | 12.5 | 109 |

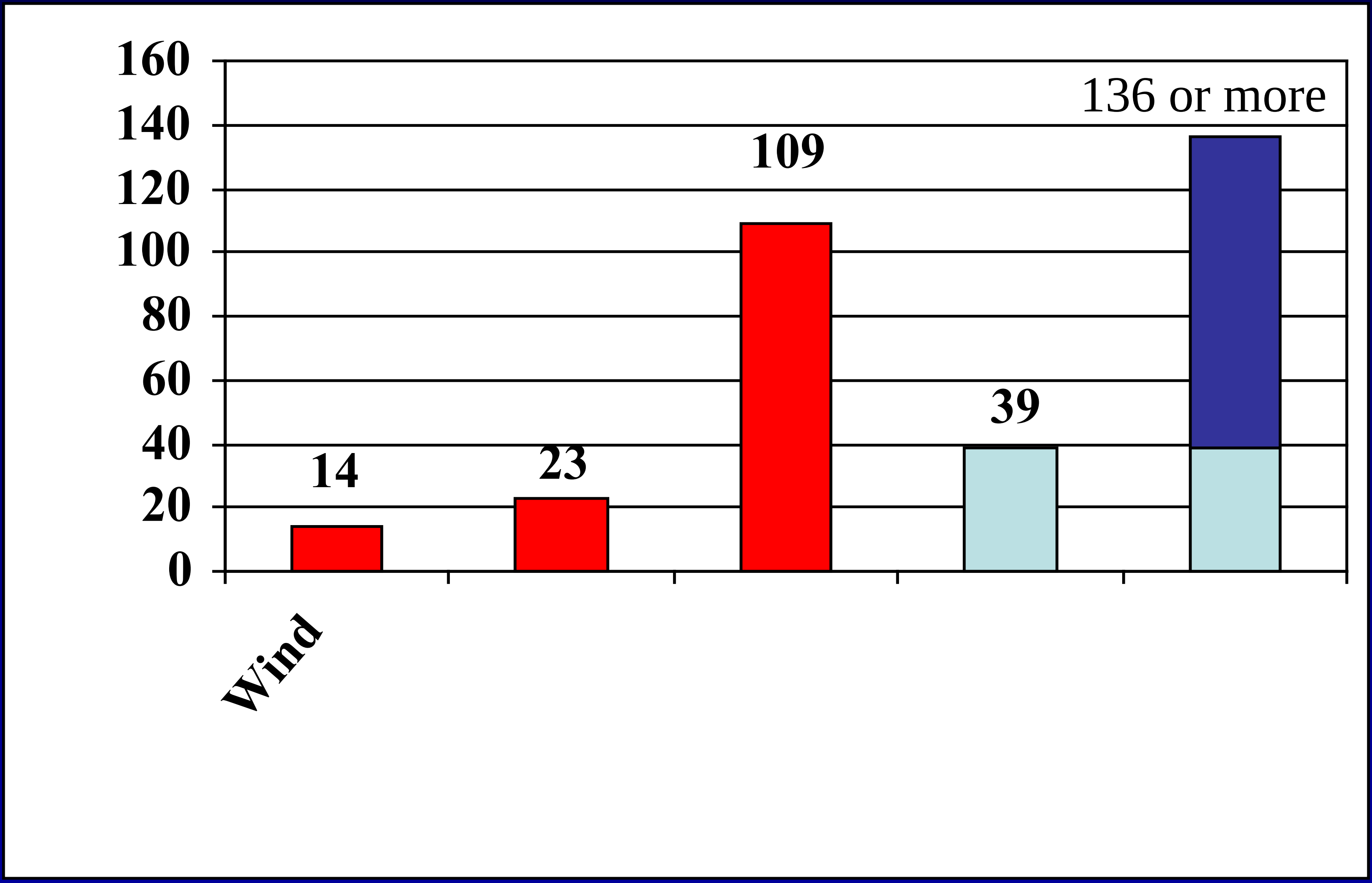
# Preliminary Results

•PHS  and CAES have very low construction related energy requirements and emissions

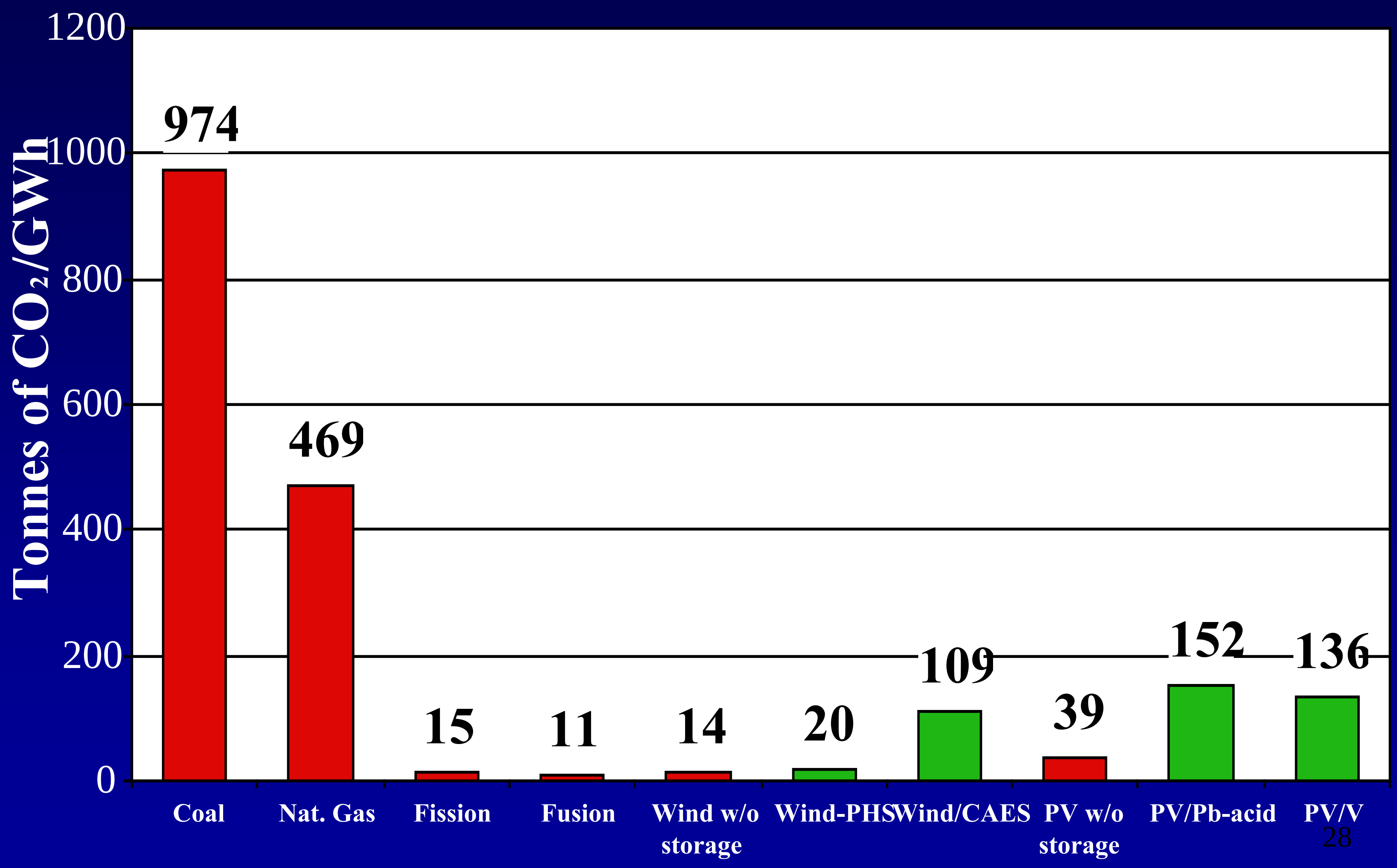
•Batteries have significant construction related energy requirements and emissions

•CAES is a significant point source of GHG emissions with considerable life-cycle emissions resulting from gas transport

# Results: Energy Storage Can Makes a Considerable Difference on GHG Emissions



# The Inclusion of Energy Storage Makes a Considerable Difference for Renewables

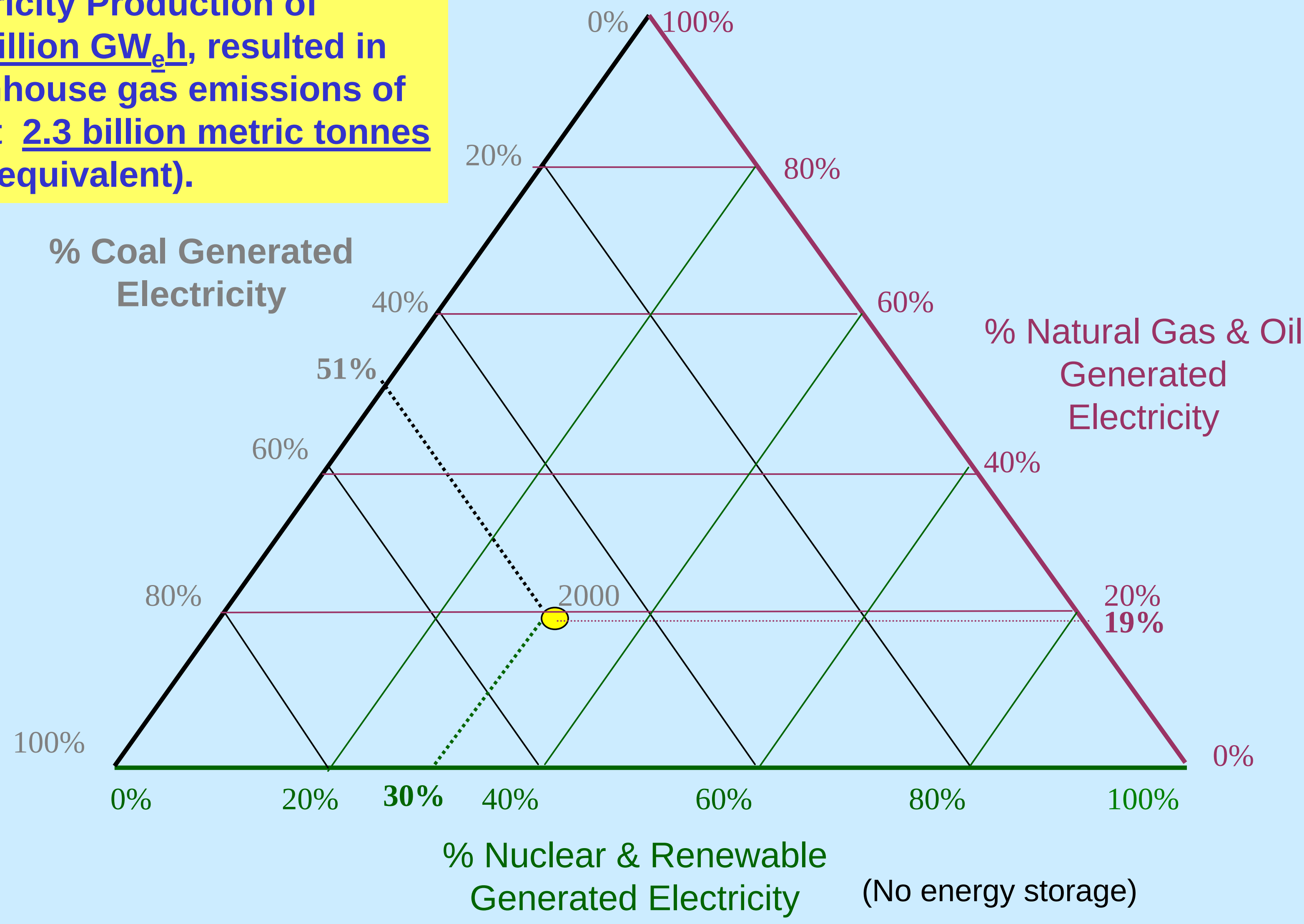


# Conclusions for Base Loaded Renewable Systems

- **The addition of energy storage to make renewables “dispatchable” increases the GHG emissions by factors of 50% to over 700%.**
- **The coupling of PHS with wind produces GHG emissions slightly high than nuclear systems but still 20-50 times lower than fossil fuels.**
- **The addition of energy storage batteries to PV systems increases the GHG emissions to ≈ 1/3 that of natural gas systems.**

What Fuel Mix Would it Take to Achieve Policy Goals Such as the Kyoto Accord?

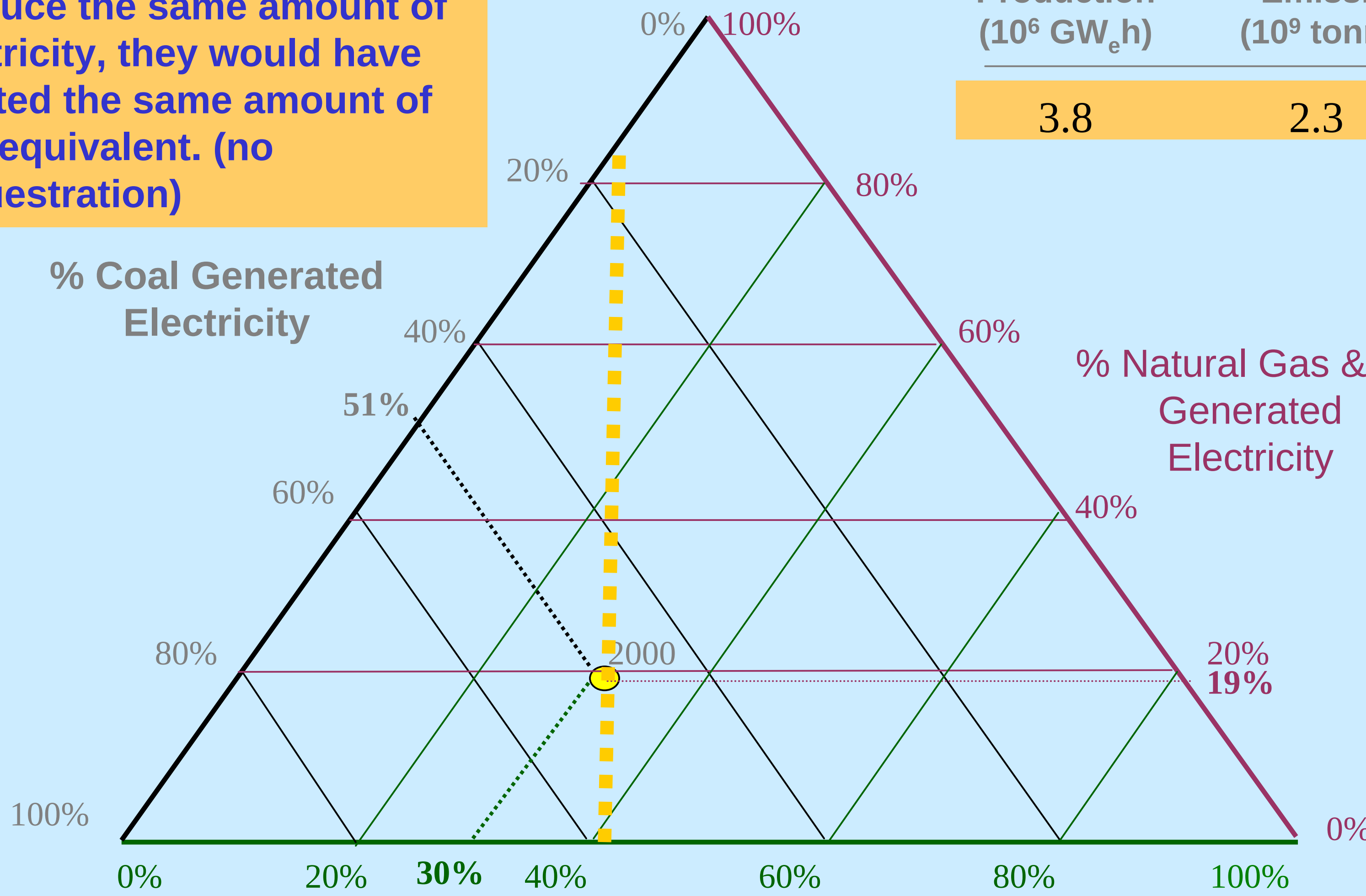
**Using this mixture of technologies, 2000 U.S. Electricity Production of <u>3.8 million $GW_eh$</u>, resulted in greenhouse gas emissions of about <u>2.3 billion metric tonnes</u> ($CO_2$-equivalent).**



# What Fuel Mix Would it Take to Achieve Policy Goals Such as the Kyoto Accord?

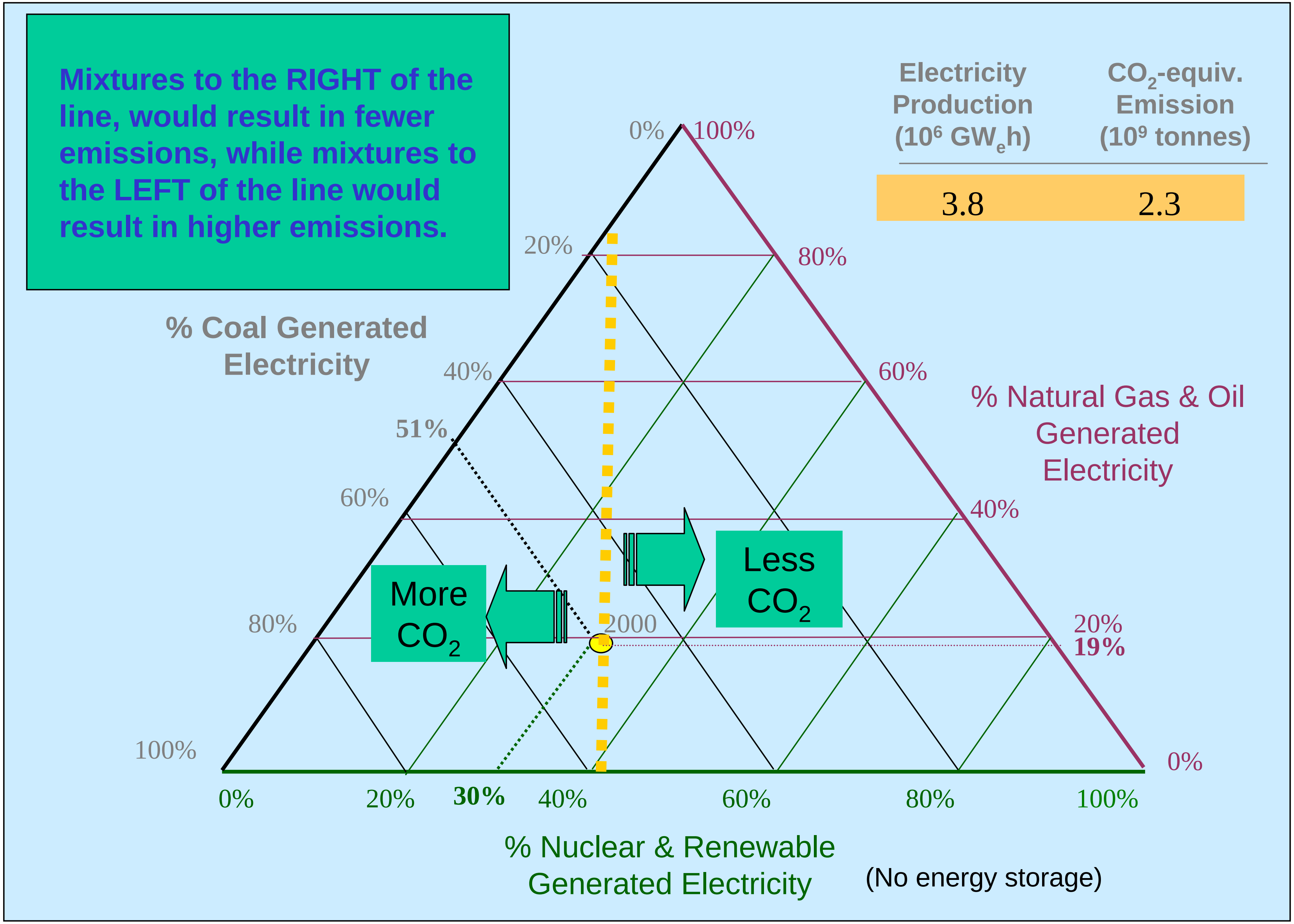
**If the following "mixtures" could have been used to the produce the same amount of electricity, they would have emitted the same amount of $CO_2$ equivalent. (no sequestration)**

| Electricity Production ($10^6$ $GW_eh$) | $CO_2$-equiv. Emission ($10^9$ tonnes) |
|---|---|
| 3.8 | 2.3 |

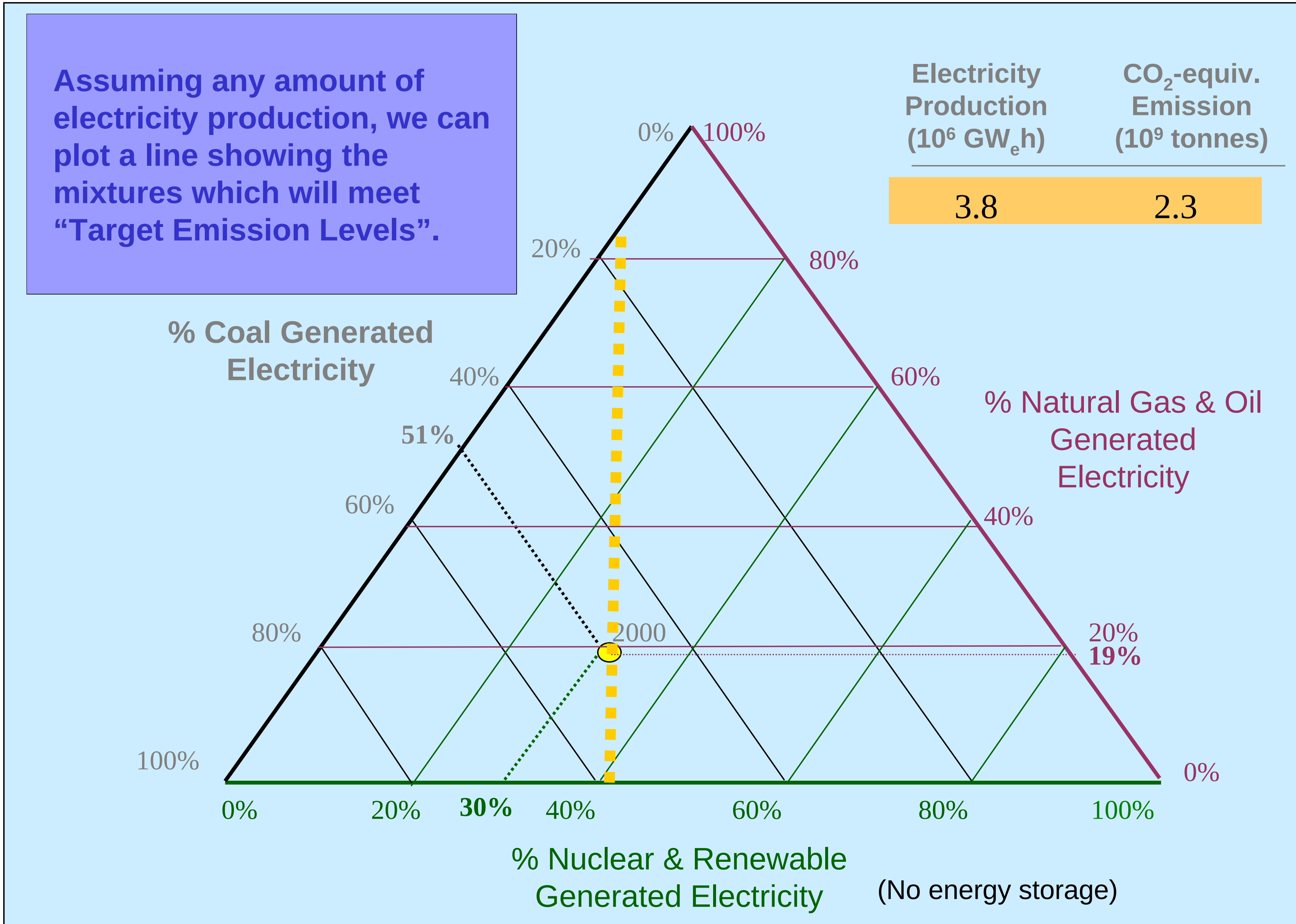



(No energy storage)

# What Fuel Mix Would it Take to Achieve Policy Goals Such as the Kyoto Accord?



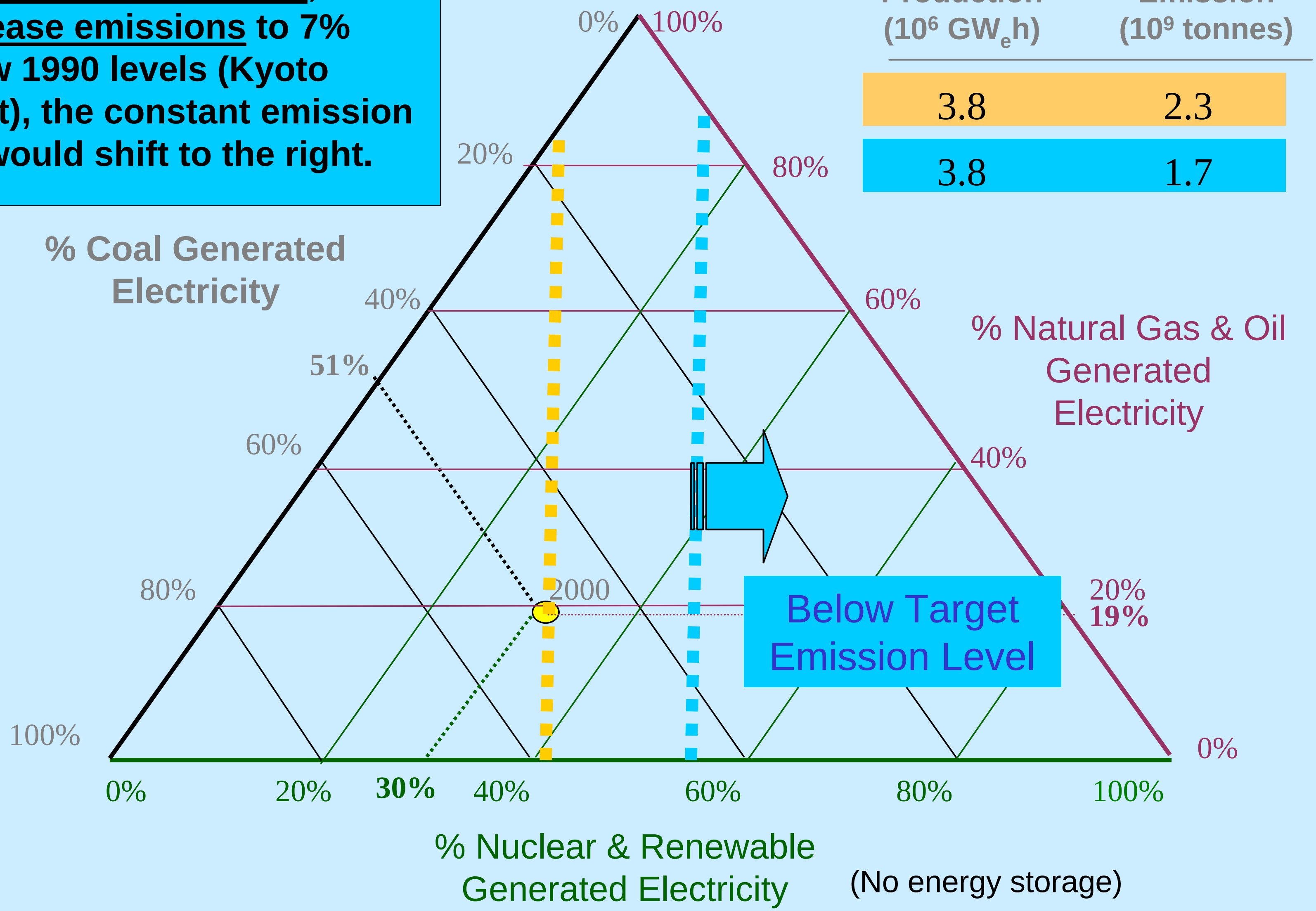
# What Fuel Mix Would it Take to Achieve Policy Goals Such as the Kyoto Accord?



# What Fuel Mix Would it Take to Achieve Policy Goals Such as the Kyoto Accord?

**To <u>maintain the same electricity consumption</u>, but <u>decrease emissions</u> to 7% below 1990 levels (Kyoto target), the constant emission line would shift to the right.**

| Electricity Production ($10^6$ $GW_e h$) | $CO_2$-equiv. Emission ($10^9$ tonnes) |
|---|---|
| 3.8 | 2.3 |
| 3.8 | 1.7 |

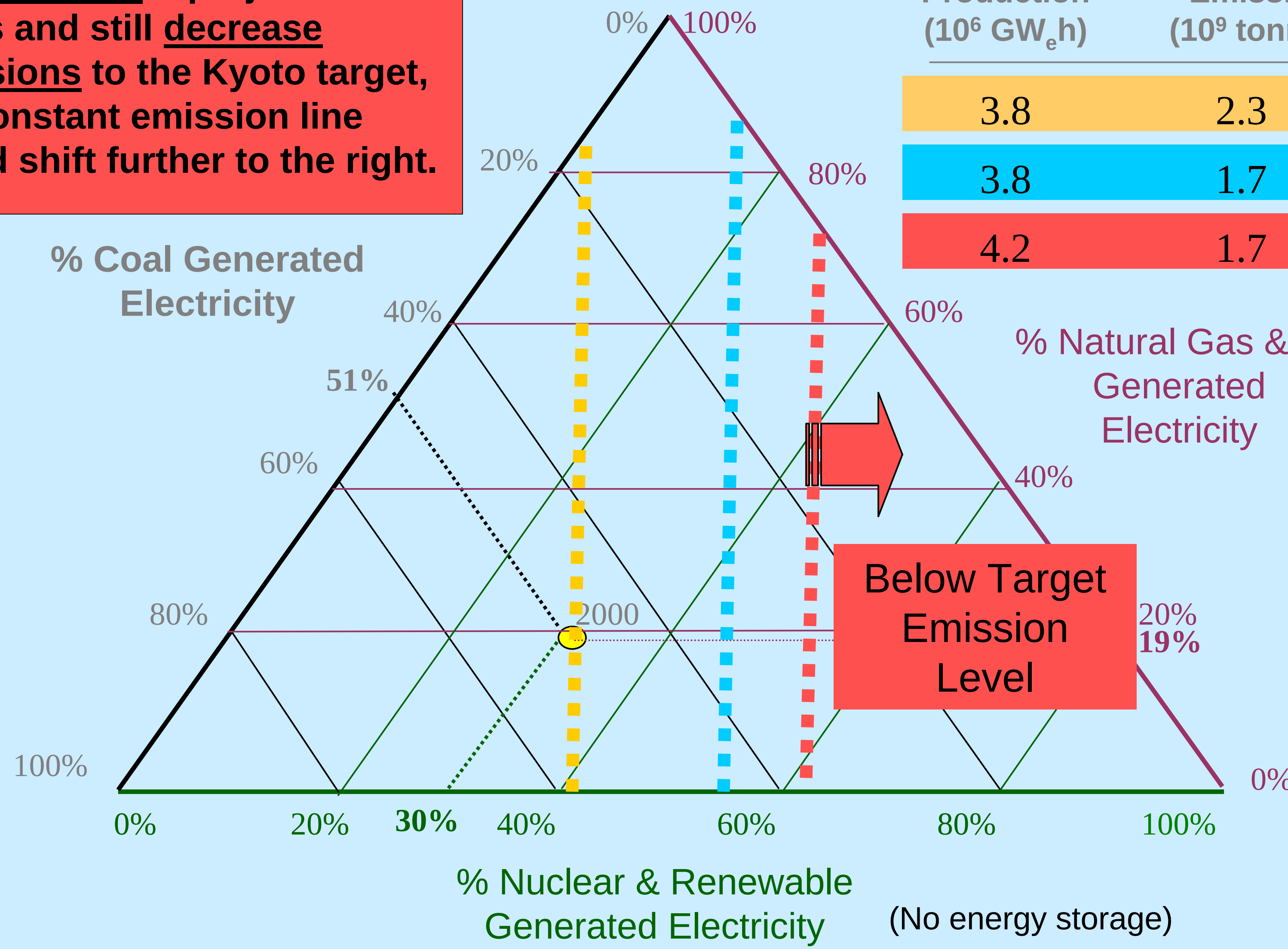



(No energy storage)

# What Fuel Mix Would it Take to Achieve Policy Goals Such as the Kyoto Accord?

**To <u>increase electricity consumption</u> to projected 2010 levels and still <u>decrease emissions</u> to the Kyoto target, the constant emission line would shift further to the right.**

| Electricity Production ($10^6$ $GW_eh$) | $CO_2$-equiv. Emission ($10^9$ tonnes) |
|---|---|
| 3.8 | 2.3 |
| 3.8 | 1.7 |
| 4.2 | 1.7 |




(No energy storage)

# Policy Implications

- The use of a triangular energy diagram can be used to quickly determine the fuel mixtures needed to satisfy greenhouse gas emission limits
- Various greenhouse gas emission values for fossil fuels, nuclear, and renewables can be substituted in the triangular energy diagram to account for sequestration, energy storage, etc.