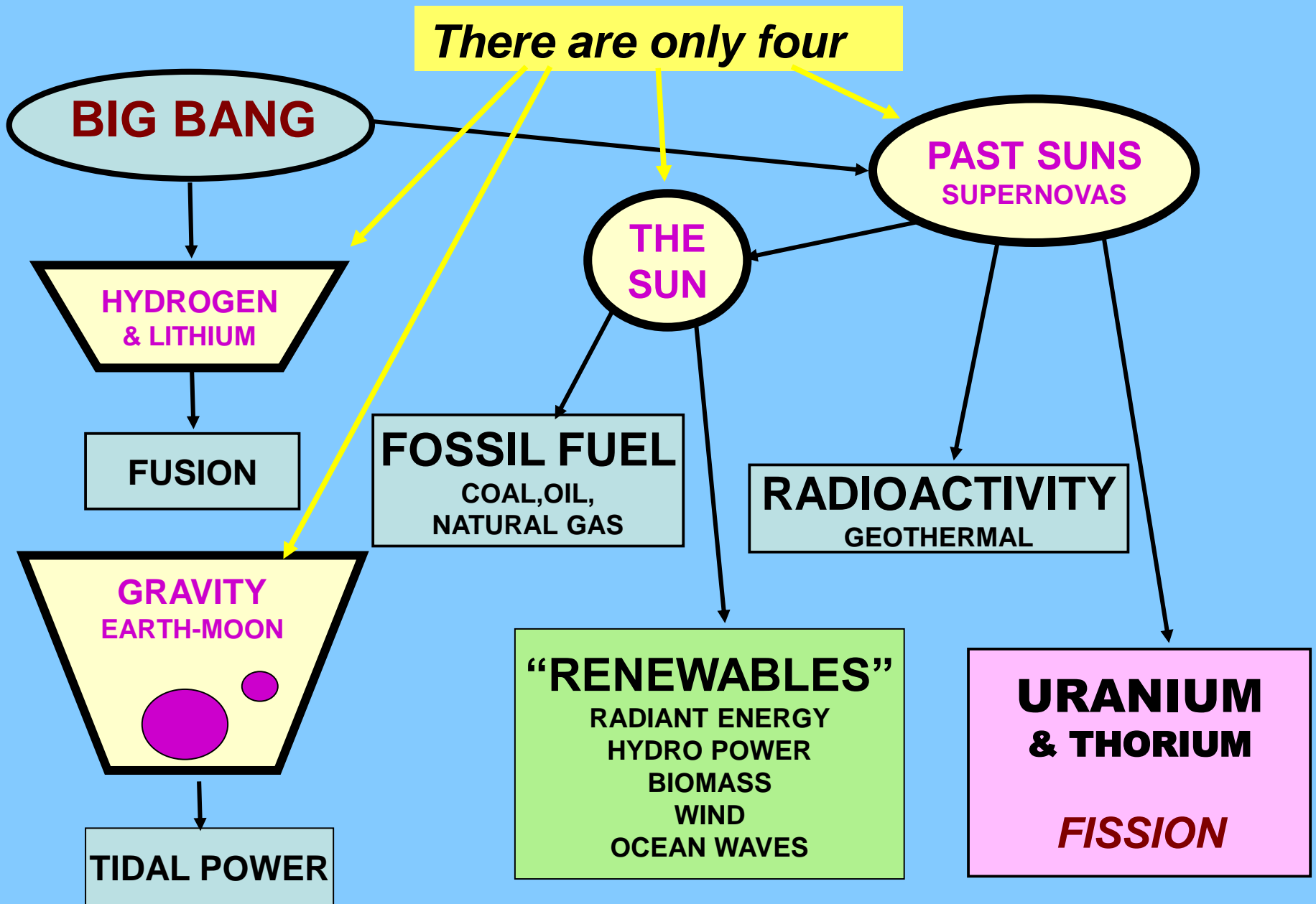


# **NUCLEAR POWER IN THE ENERGY PICTURE**

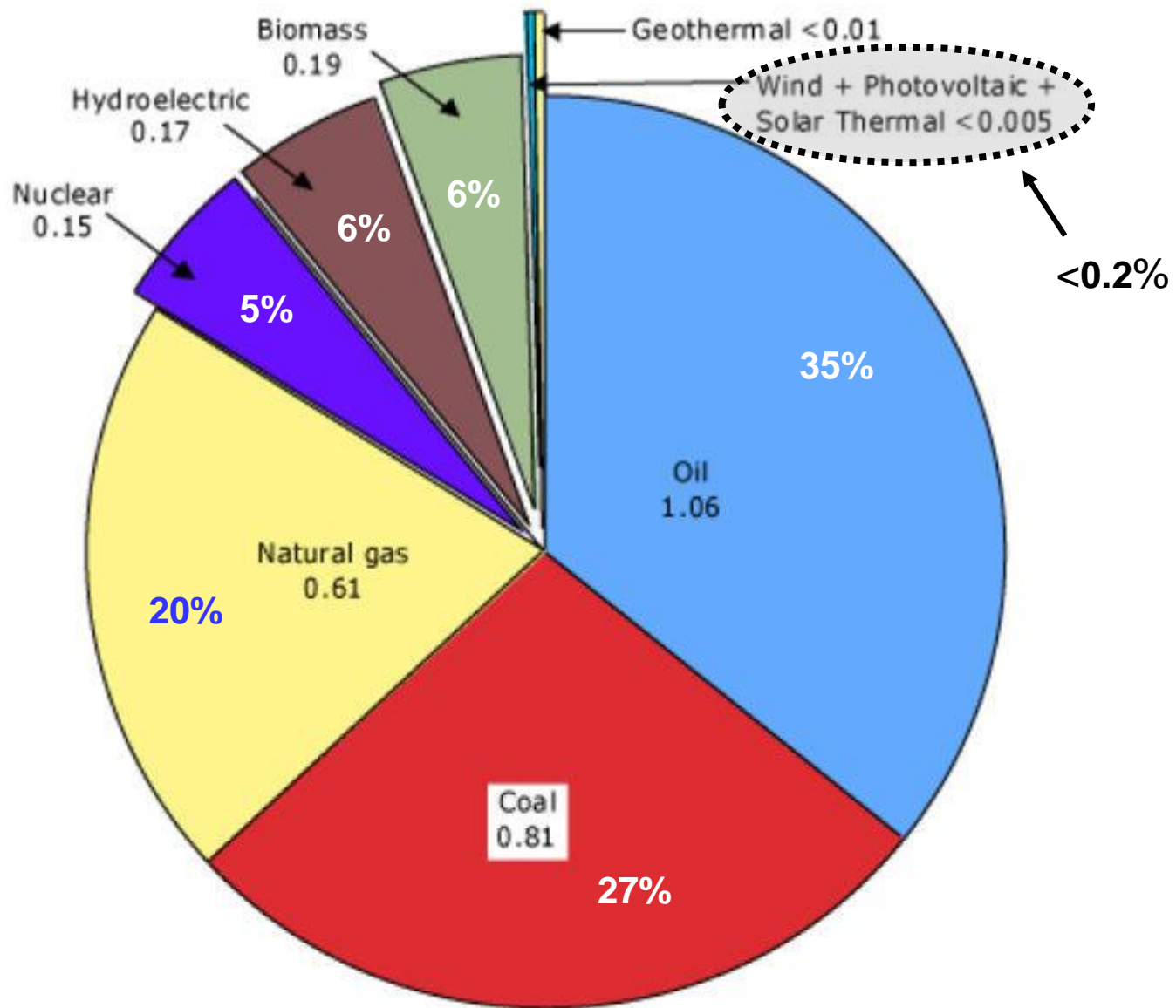
George S. Stanford  
Reactor Physicist, retired

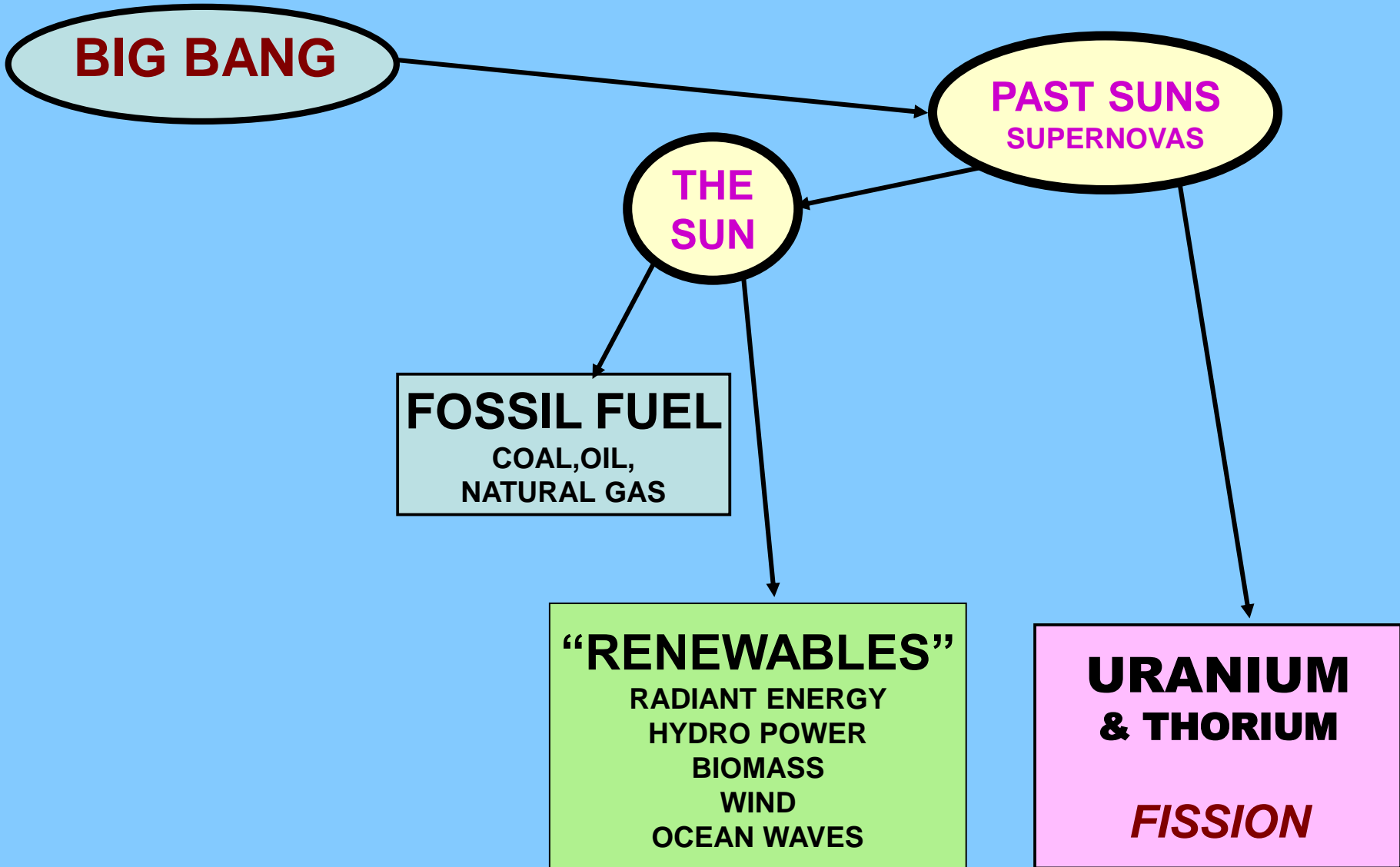
April 2010

# SOURCES OF ENERGY



# Global sources of energy in 2006





# NUCLEAR POWER

- Can come from **FISSION** (splitting) of heavy nuclei

**or**

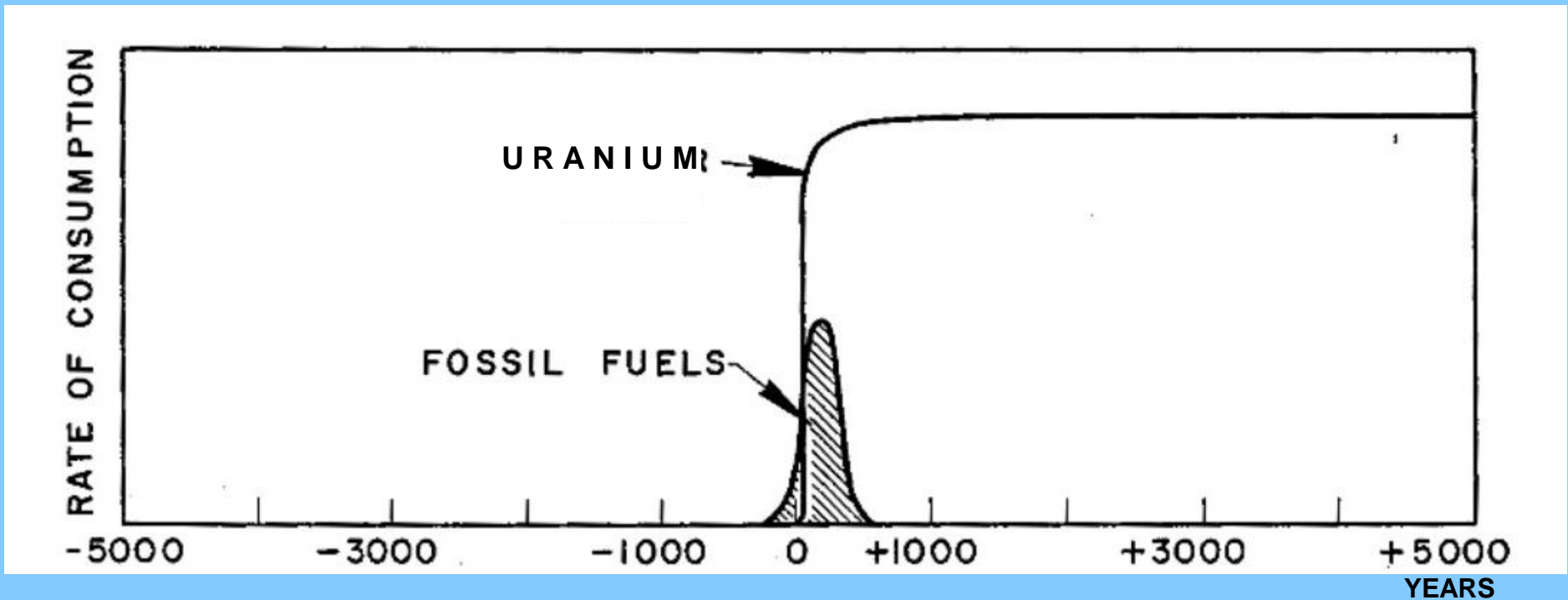
- From **FUSION** (combining) of light nuclei.

\* \* \* \*

*Fusion* power is far in the future, if ever.

For now, “nuclear power” means  
power from *fission*.

# A 10,000-YEAR PERSPECTIVE



Relative magnitudes of possible fossil-fuel and nuclear-energy consumption seen in time perspective of minus to plus 5000 years.

# DOES “RENEWABLE” MEAN *RENEWABLE?*

- **NO!**
- **ENERGY USED IS ENERGY GONE.**
- **THE SUN WILL EVENTUALLY RUN OUT OF FUEL.**
- **THE EARTH’S INTERIOR WILL EVENTUALLY COOL DOWN.**

# **“RENEWABLE” MEANS *INEXHAUSTIBLE***

And INEXHAUSTIBLE means . . .

- **that it will keep coming (we think) as long as we need it . . .**



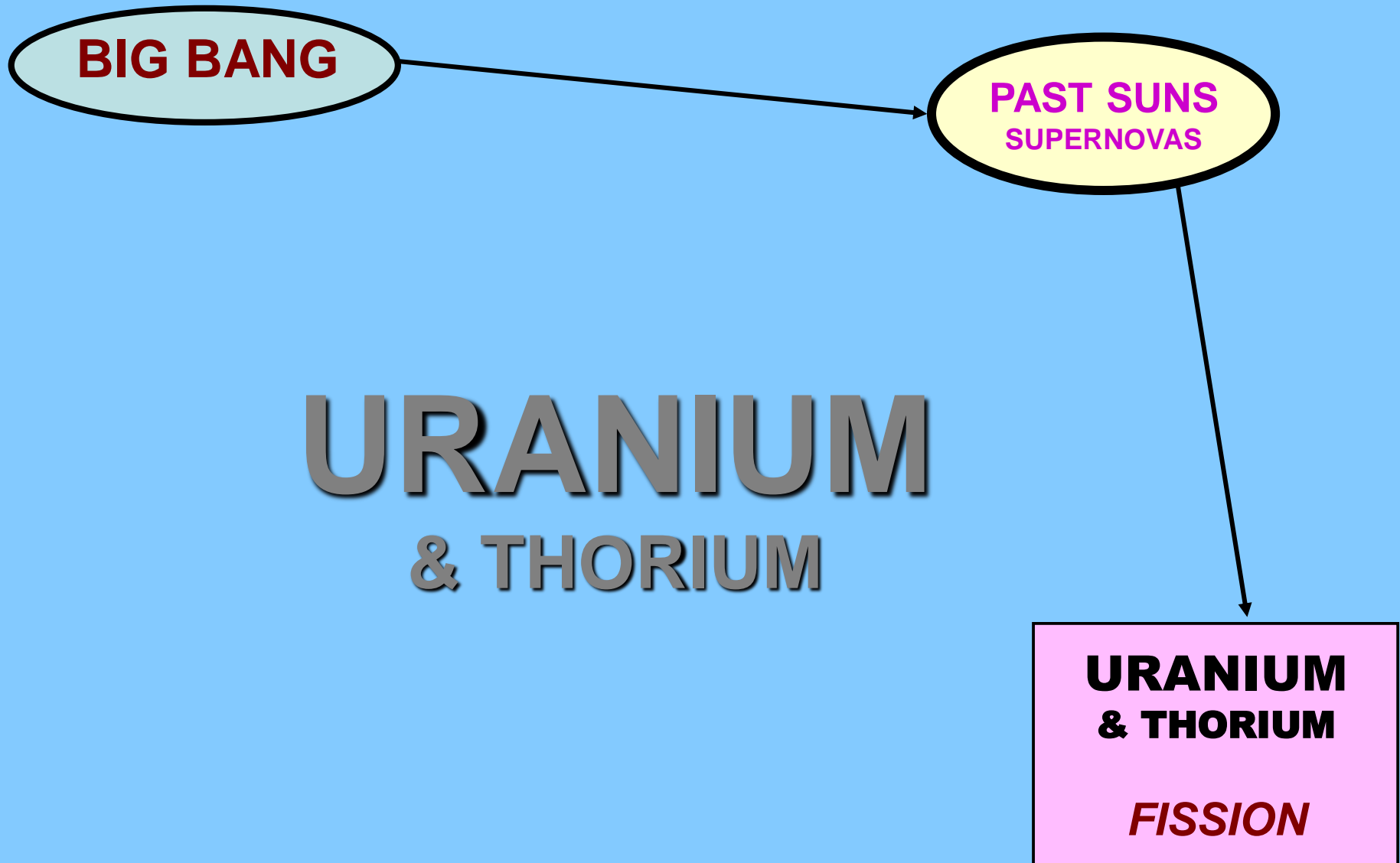
***. . . but not necessarily as abundantly as we want it.***

- **The wind doesn't always blow when we want it to.**
- **The Sun doesn't always shine.**
- **The Sun's energy is spread thin.**
- **Geothermal energy is usually hard to get to.**
- **Biomass for energy takes up crop land and drives up fuel prices.**
- **Hydropower sources are limited.**

**Well, is there an  
inexhaustible energy  
source without the  
above limitations?**

**YES – it's . . .**

# Fission





## **THE THREE-MILE ISLAND POWER PLANT**

**The reactors are in the small cylindrical buildings.**

**Water vapor comes from Unit 2's cooling towers.**

**Unit 1 was shut down by the 1979 accident.**

# PERIODIC TABLE

1 <b>H</b>																	2 <b>He</b>
3 <b>Li</b>	4 <b>B</b>											5 <b>B</b>	6 <b>C</b>	7 <b>N</b>	8 <b>O</b>	9 <b>F</b>	10 <b>Ne</b>
11 <b>Na</b>	12 <b>Mg</b>											13 <b>Al</b>	14 <b>Si</b>	15 <b>P</b>	16 <b>S</b>	17 <b>Cl</b>	18 <b>Ar</b>
19 <b>K</b>	20 <b>Ca</b>	21 <b>Sc</b>	22 <b>Ti</b>	23 <b>V</b>	24 <b>Cr</b>	25 <b>Mn</b>	26 <b>Fe</b>	27 <b>Co</b>	28 <b>Ni</b>	29 <b>Cu</b>	30 <b>Zn</b>	31 <b>Ga</b>	32 <b>Ge</b>	33 <b>As</b>	34 <b>Se</b>	35 <b>Br</b>	36 <b>Kr</b>
37 <b>Rb</b>	38 <b>Sr</b>	39 <b>Y</b>	40 <b>Zr</b>	41 <b>Nb</b>	42 <b>Mo</b>	43 <b>Tc</b>	44 <b>Ru</b>	45 <b>Rh</b>	46 <b>Pd</b>	47 <b>Ag</b>	48 <b>Cd</b>	49 <b>In</b>	50 <b>Sn</b>	51 <b>Sb</b>	52 <b>Te</b>	53 <b>I</b>	54 <b>Xe</b>
55 <b>Cs</b>	56 <b>Ba</b>	57 <b>La</b>	72 <b>Hf</b>	73 <b>Ta</b>	74 <b>W</b>	75 <b>Re</b>	76 <b>Os</b>	77 <b>Ir</b>	78 <b>Pt</b>	79 <b>Au</b>	80 <b>Hg</b>	81 <b>Tl</b>	82 <b>Pb</b>	83 <b>Bi</b>	84 <b>Po</b>	85 <b>At</b>	86 <b>Rn</b>
87 <b>Fr</b>	88 <b>Li</b>																

89  
**Ac**  
(227)

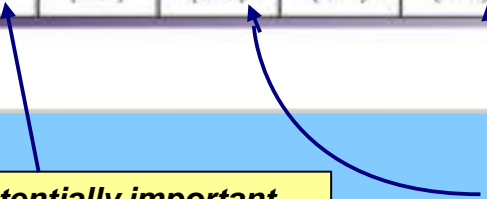
## ACTINIDES

Thorium    Protactinium    Uranium    Neptunium    Plutonium    Americium    Curium    Berkelium    Californium    Einsteinium    Fermium    Mendeleevium    Nobelium    Lawrencium

90 <b>Th</b> (232)	91 <b>Pa</b> (231)	92 <b>U</b> (238)	93 <b>Np</b> (237)	94 <b>Pu</b> (244)	95 <b>Am</b> (243)	96 <b>Cm</b> (247)	97 <b>Bk</b> (247)	98 <b>Cf</b> (251)	99 <b>Es</b> (252)	100 <b>Fm</b> (257)	101 <b>Md</b> (258)	102 <b>No</b> (259)	103 <b>Lr</b> (260)
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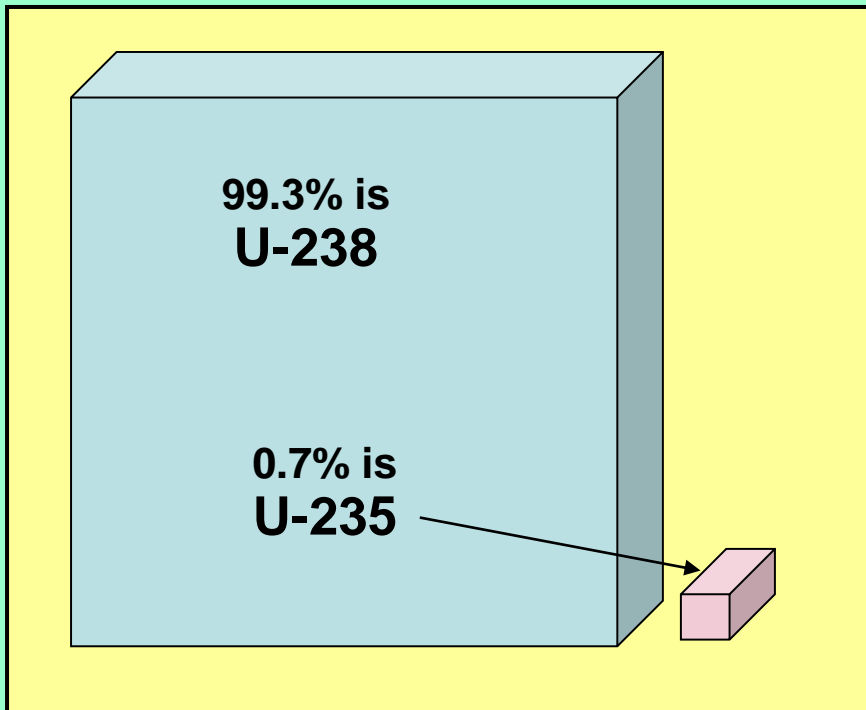
Potentially important

Most important now

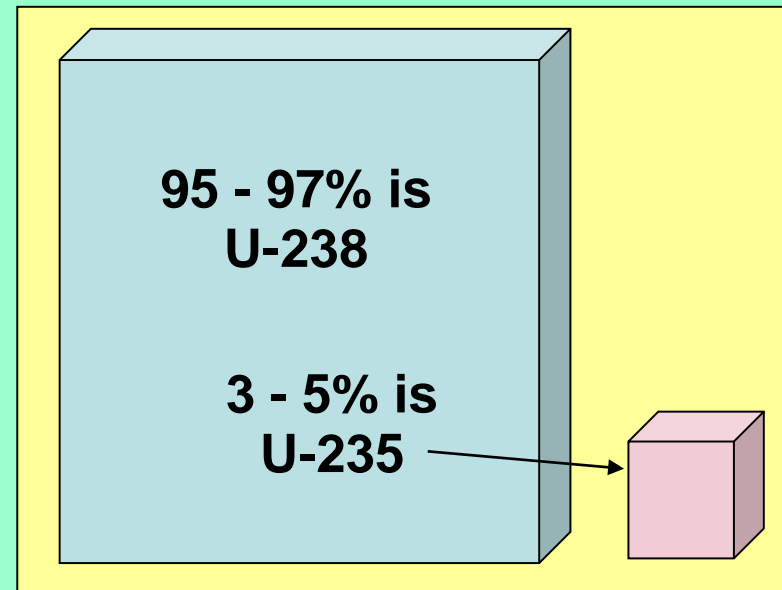


# URANIUM HAS TWO MAIN ISOTOPES

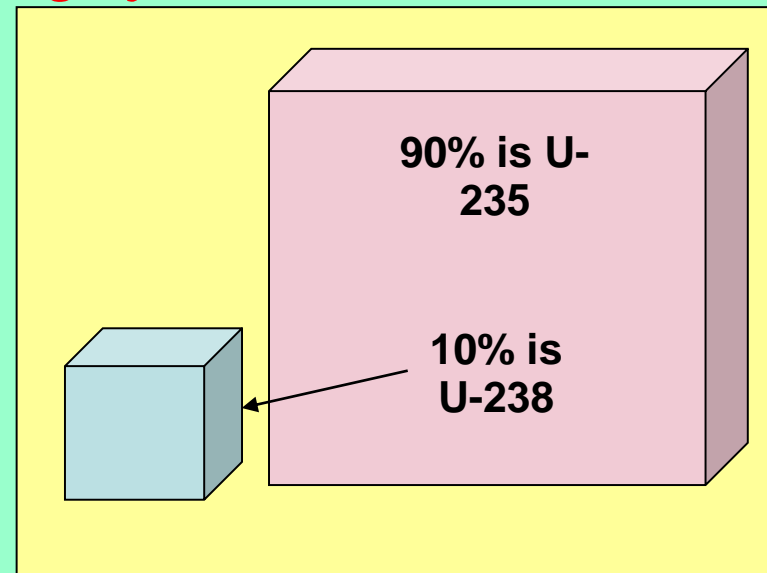
## *Natural uranium*



## *Low-enriched uranium for LWR fuel*



## *Highly enriched uranium for weapons*



# FISSIONABLE NUCLEI

## ***FISSILE NUCLEUS***

- Fissions readily
- Fission induced by thermal neutrons
- Odd-number actinide
- U-233, U-235, Pu-239, Pu-241, . . .

## ***FERTILE NUCLEUS***

- Fission sometimes induced by a fast neutron
- **Becomes fissile upon absorption of one neutron**
- Even-number actinide
- Th-232, U-238, Pu-240, Pu-242, . . .

# TWO KINDS OF REACTOR

## **THERMAL REACTOR**

*Neutrons are slow ("thermal")*

- Virtually all of today's reactors use thermal neutrons
- And most of them are **LWRs** (*Light-Water Reactors*)
  - Moderated and cooled by light water (H<sub>2</sub>O)
  - Fuel: uranium that is **enriched to 3–5% fissile\***

\* The fissile is U-235, mainly, but sometimes helped by Pu-239)



# TWO KINDS OF REACTOR

## **FAST REACTOR**

*(It's the neutrons that are fast)*

Needed for resource utilization

*The wave of the future*

- Fuel can be derived from used LWR fuel
- Startup fuel is uranium **enriched to ~20% fissile**
  - \* The fissile is Pu from used LWR fuel
- Not moderated
- Cooled by liquid metal (e.g. Na or Pb)
- Once fueled, a ton of heavy metal\*\* per year keeps it running.
  - \*\* The “heavy metal” can be any mixture of actinides, from thorium on up

# **NUCLEAR POWER TODAY COMES ALMOST ENTIRELY FROM THERMAL REACTORS**

## **•THERMAL REACTOR**

**Neutrons are slow (“thermal”)**

**Many varieties**

- Most are LWRs
  - Moderated by light water (H<sub>2</sub>O)**
  - Uranium: enriched to 3–5% U<sup>235</sup>****
- We’ll use the LWR as typical of thermal reactors**

# CURRENT FUEL CYCLE (U.S.)

is an **OPEN CYCLE**: once-through  
("throw-away")

- uses < 5% of the energy in the fuel

- uses < 1% of the energy in the mined U

  - vast energy in DU "tails"

  - (>10 times US coal reserves)*

# NEUTRON ECONOMY

*Neutrons are valuable*

Thermal reactor gives 2.2 neutrons per fission.  
That's enough to keep the reaction going, in spite of competition from

- Leakage out of the core
- Absorption by non-fuel material
- Non-fission capture by fuel nuclei
  - e.g.  $\text{U-238} + \text{n} \rightarrow \text{Pu-239}$
- **but there are not enough neutrons to breed more fissile than is used.**

# PLUTONIUM

- In an LWR, by the end of the fuel's lifetime some 60% of the energy is coming from fissions in plutonium.
- But thermal reactors cannot breed more fissile than they consume -- *there aren't enough neutrons.*

# FAST FISSION

Fast fission releases more neutrons per breakup. Therefore:

Fast reactors can be run as

- **breeders**
  - produce more fissile than they consume
- or **burners**
  - consume more fissile than they create
- or **neither** (*break-even mode*)
  - create just enough fissile to keep themselves going

# NUCLEAR POWER

## ADVANTAGES:

***Safe*** -- safety record second to none

***Environmentally friendly:***

- No atmospheric pollution
- No greenhouse-gas emissions
- Easily managed waste

- More -

# NUCLEAR POWER

## Advantages -- 2

***Renewable*** – just as inexhaustible as the other “renewables”

***Reliable*** – available day and night, rain and shine, hot weather and cold.

***Abundant*** – there’s more uranium than we’ll ever use.

***Cheap*** – economically competitive now, even without a carbon tax.



# NUCLEAR POWER

## MAIN DOWNSIDE:

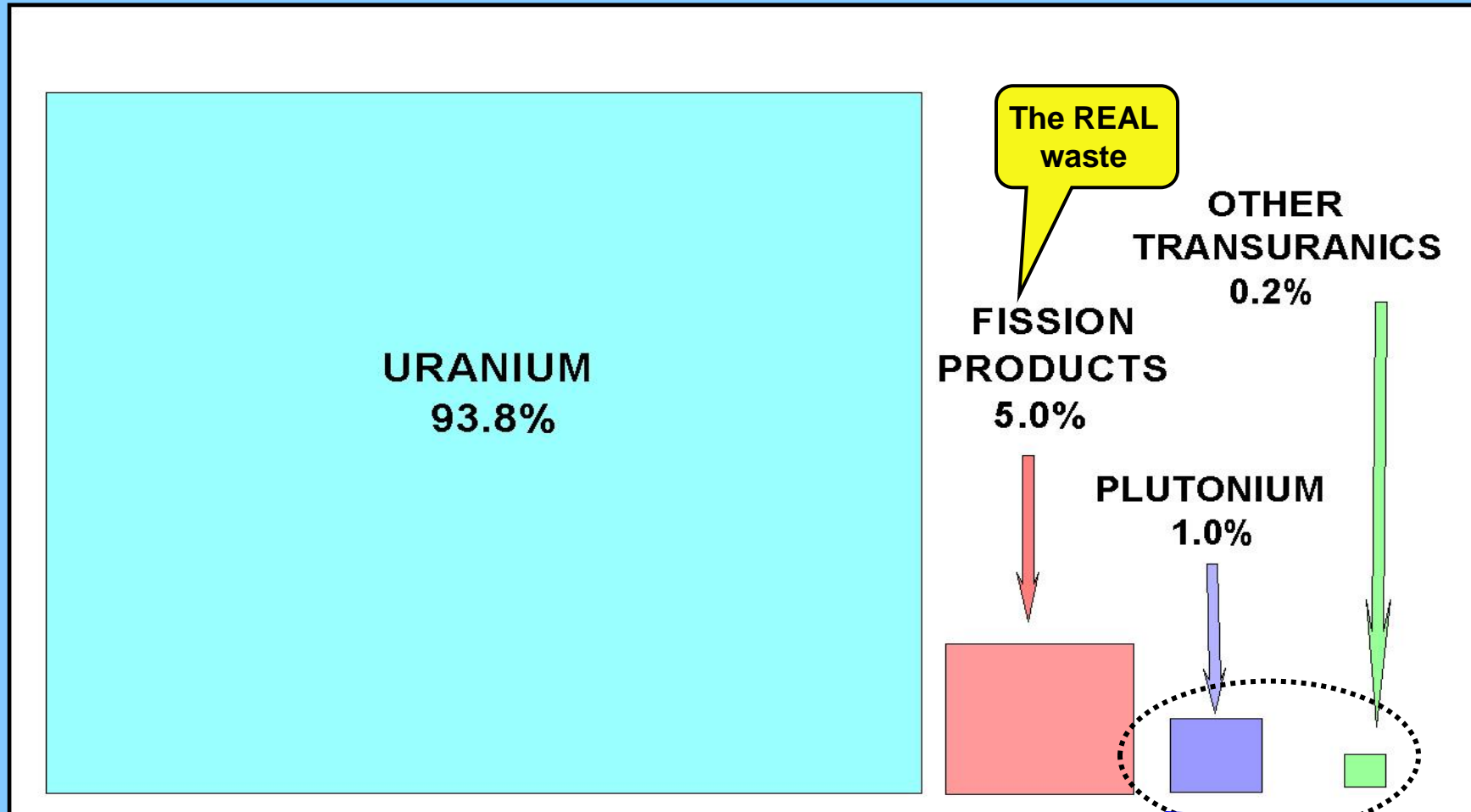
Proliferation potential

**Some of the technology is applicable to weapons**

**BUT: *Nuclear power is here to stay*, and we'd better manage it as well as we can.**

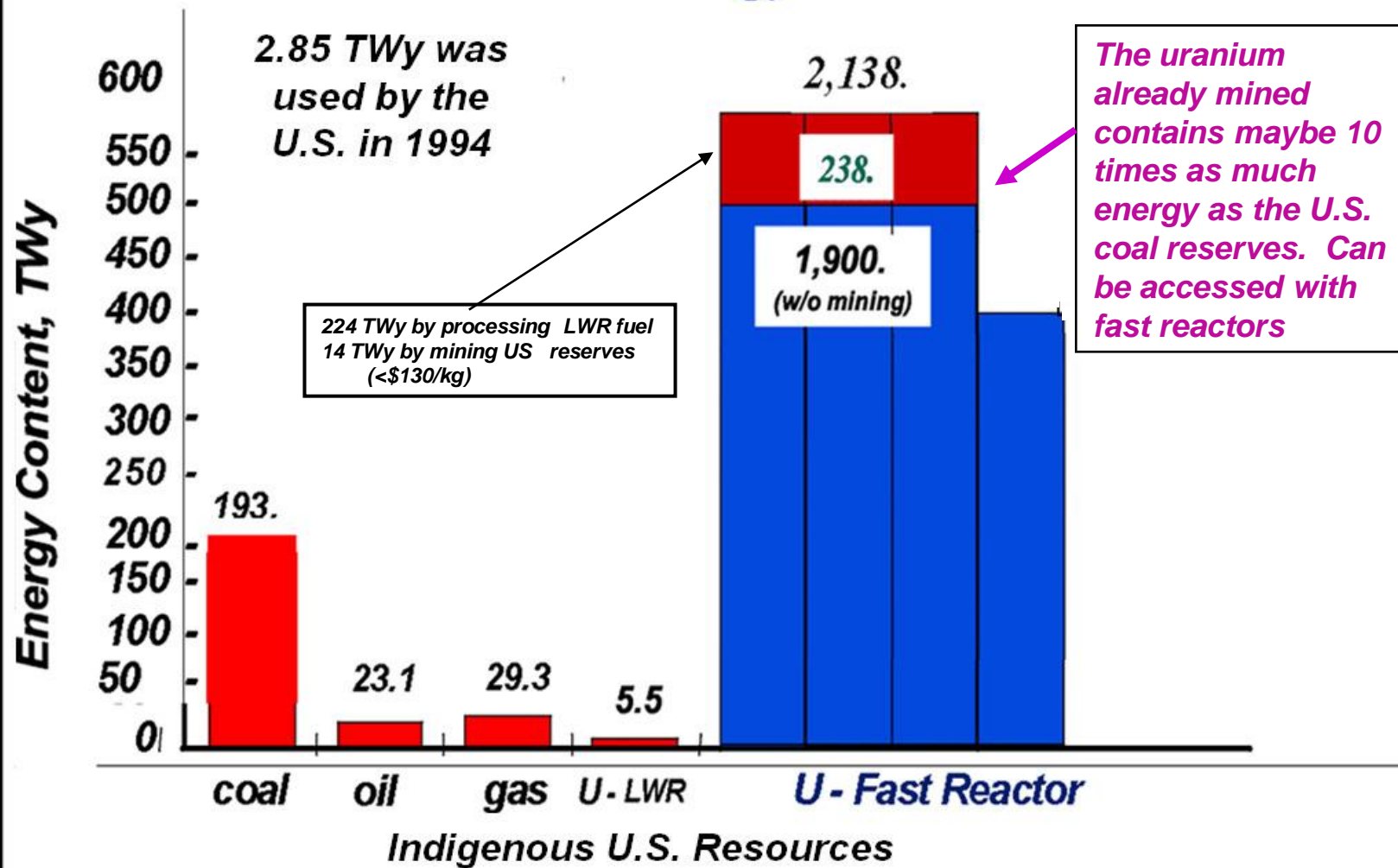
# USED LWR FUEL

*All of it is now treated as waste, but it's not*



*With this portion consumed (in fast reactors),  
dangerous activity is gone in 300 years*

# United States Energy Resources



Energy estimates for fossil fuels are based on "International Energy Outlook 1995", DOE/EIA-0484(95). The amount of depleted uranium in the US includes existing stockpile and that expected to result from enrichment of uranium to fuel existing LWRs operated over their 40-y design life. The amount of uranium available for LWR/Once Through is assumed to be the reasonably assured resource less than \$130/kg in the US taken from the uranium "Red Book". This figure courtesy of C. Boardman.

# ACTINIDE-CONSUMING REACTOR SYSTEM

1000 MWe power plant



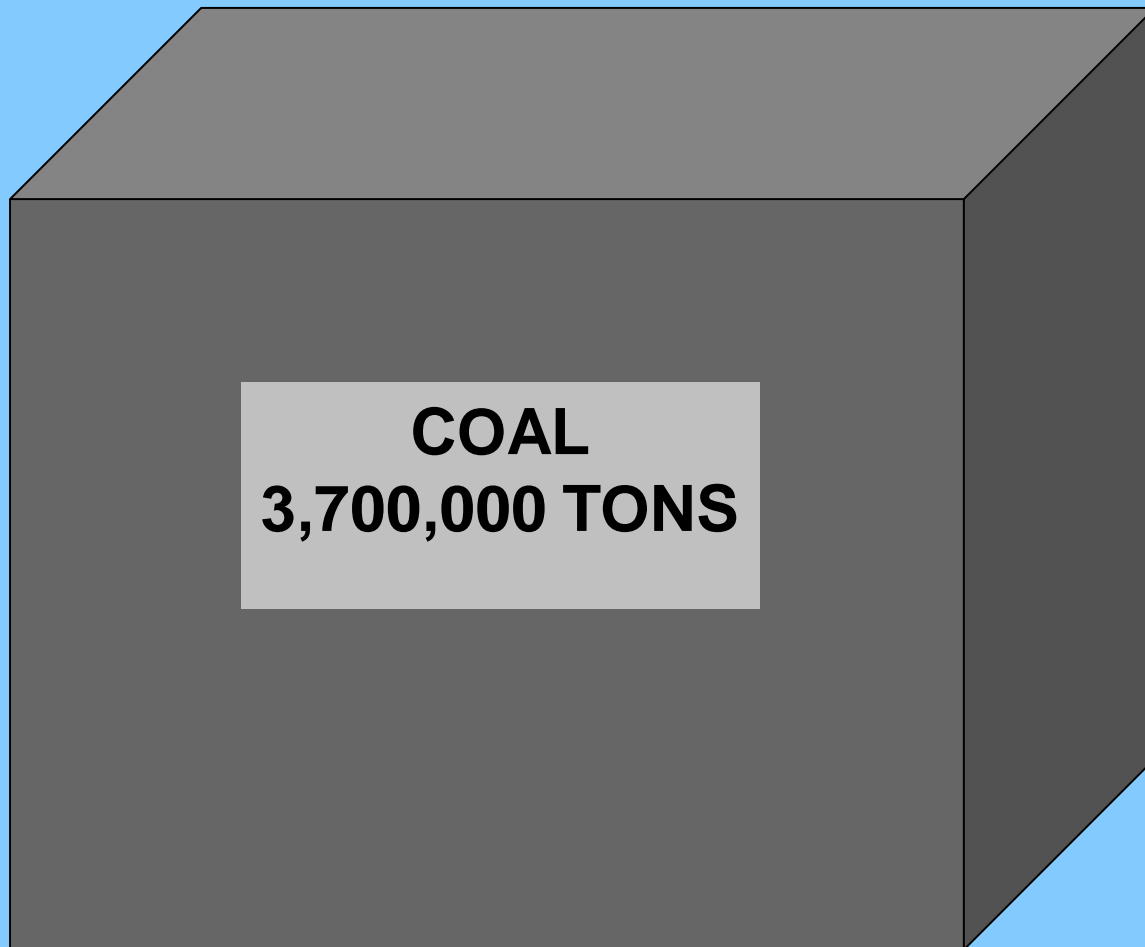
***Eventually:***

***NO LOOSE PLUTONIUM -- ANYWHERE!!***

***NO MORE ENRICHMENT OF URANIUM – EVER!!***

# ANNUAL FUEL REQUIREMENT FOR A 1,000-MWe PLANT

*Drawn to scale*



**COAL**  
**3,700,000 TONS**

**FAST REACTOR**  
**1 TON OF U**

**THERMAL REACTOR**  
**150 TONS OF U**

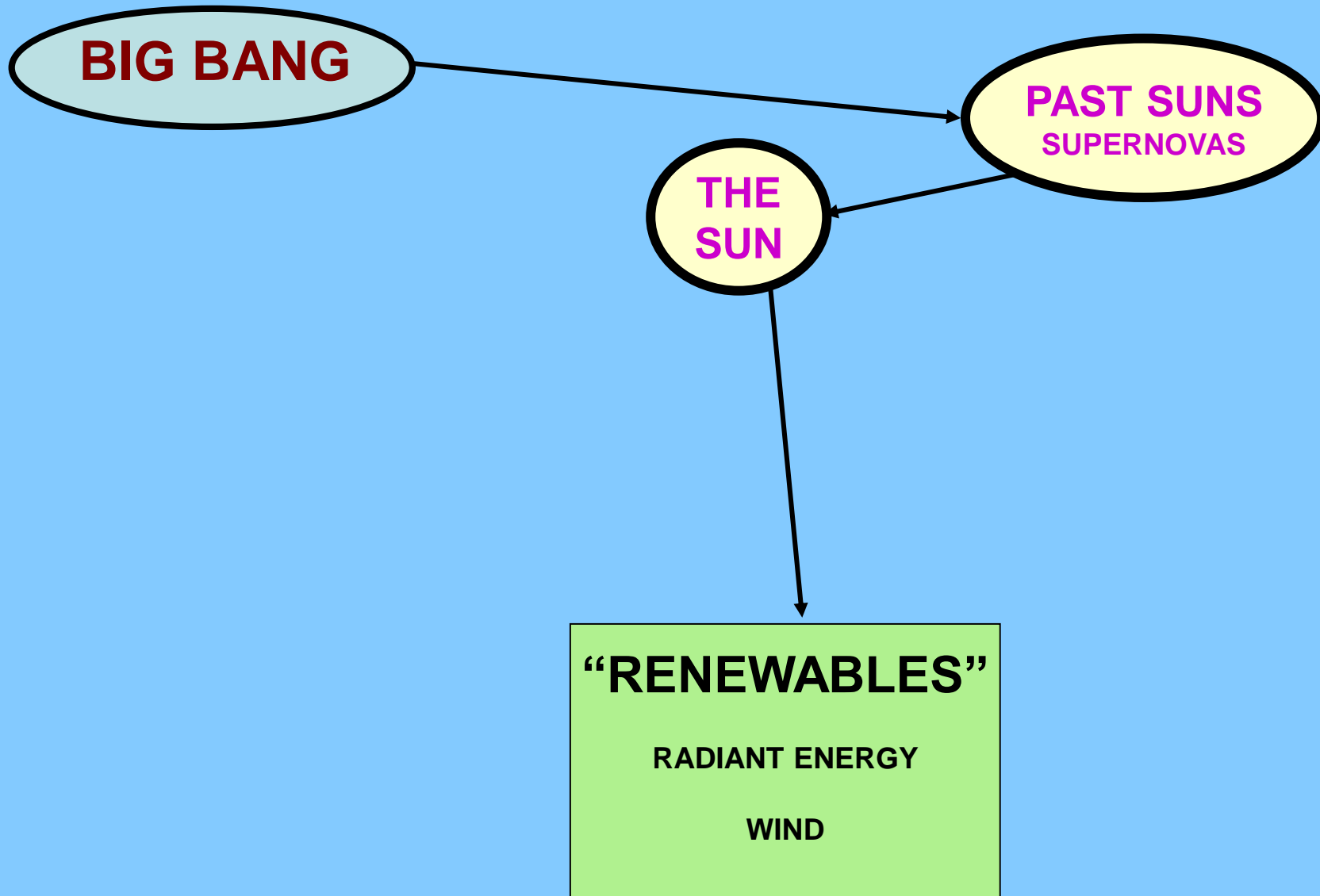


## Germany has perfected coal strip mining



**45,500-ton German Krupp earth mover, can mine 76,455 cubic meters (100,000 large 40 cu. yd. dump trucks) per day**

# Renewables



# Palm Springs, CA



Picture of the Wind Farm, Palm Springs, California. This wind farm on the San Gorgonio Mountain Pass in the San Bernadino Mountains contains more than 4000 separate windmills and provides enough electricity to power Palm Springs and the entire Coachella Valley.







Washington Monument  
and 5-MW windmill  
to scale.



**Pouring Concrete for the Base of a Windmill**

# **PROBLEMS with Solar & Wind**

- **INTERMITTENCY**
- **COST**
- **ENVIRONMENTAL IMPACT**

# INTERMITTENCY

- Wind & solar are good for jobs that are not time-urgent, like pumping water, charging batteries, and extracting oil from shale. BUT:
- When the wind **doesn't blow** or the sun **doesn't shine**, we still need power.
- That power has to come from  
**COAL - OIL - NATURAL GAS - NUCLEAR**
- The **fossil + nuclear** capacity has to be able to meet the peak demand.
- **THUS THE RENEWABLE CAPACITY WILL BE DUPLICATED**, or there will be sporadic brownouts and blackouts.

**The backup capacity for  
WIND POWER  
will mainly be NATURAL GAS,  
to cope with the rapid, unpredictable  
changes.**

## **POINT TO REMEMBER**

### **INTERMITTENT RENEWABLE CAPACITY**

**(wind, solar, tidal)**

### **WILL BE DUPLICATED**

**by something reliable**

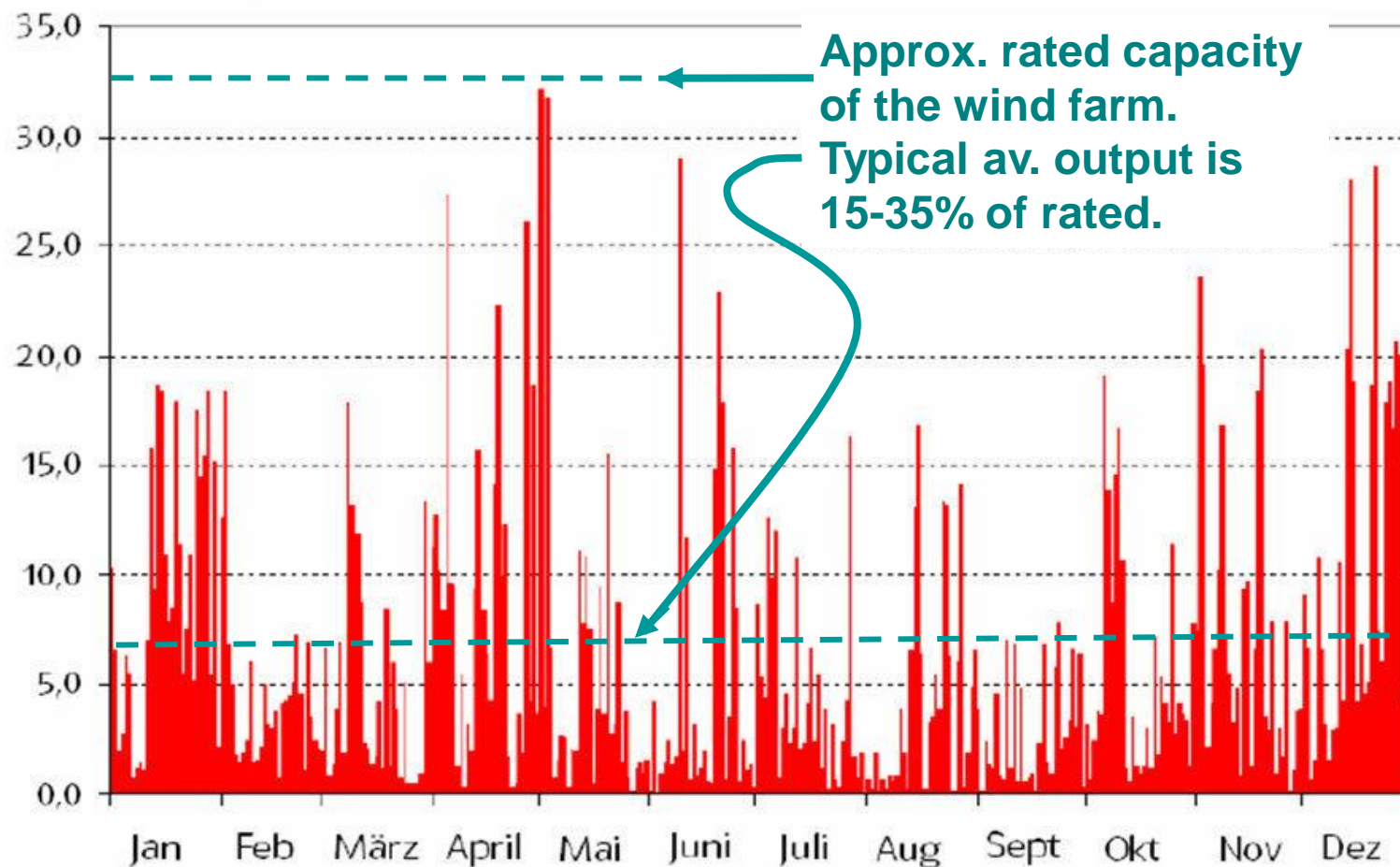
**(nuclear, coal, natural gas,  
hydro, or geothermal)**

**or there will be sporadic brownouts  
and blackouts**

# INTERMITTENCY

## ONE YEAR OF OUTPUT, GERMAN WIND FARM

**Annual share of daily wind power [%] in respective daily peak demand in E.ON-grid in Germany**



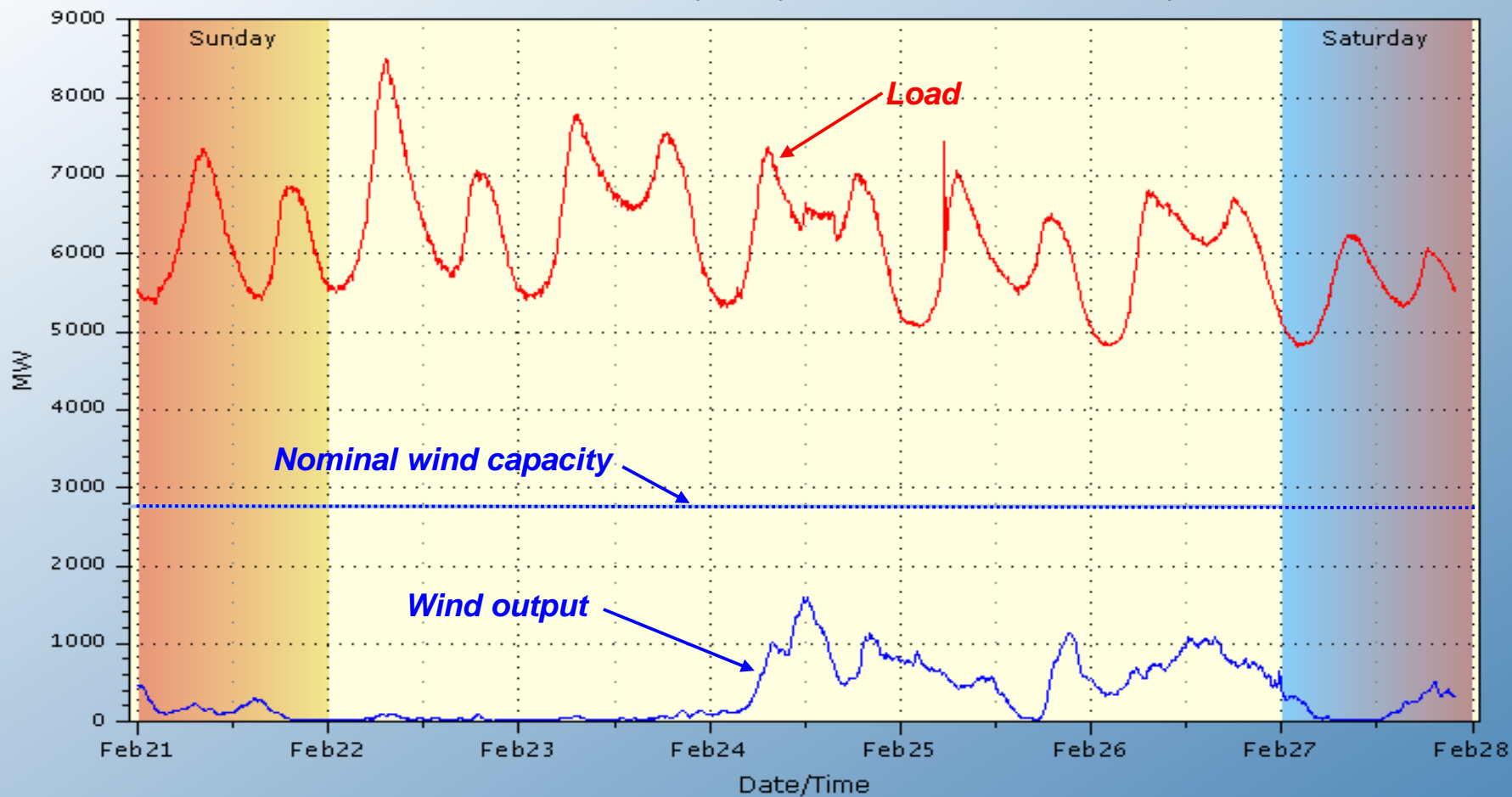
Source: UCTE, 2004, [11].



# Bonneville Power Administration

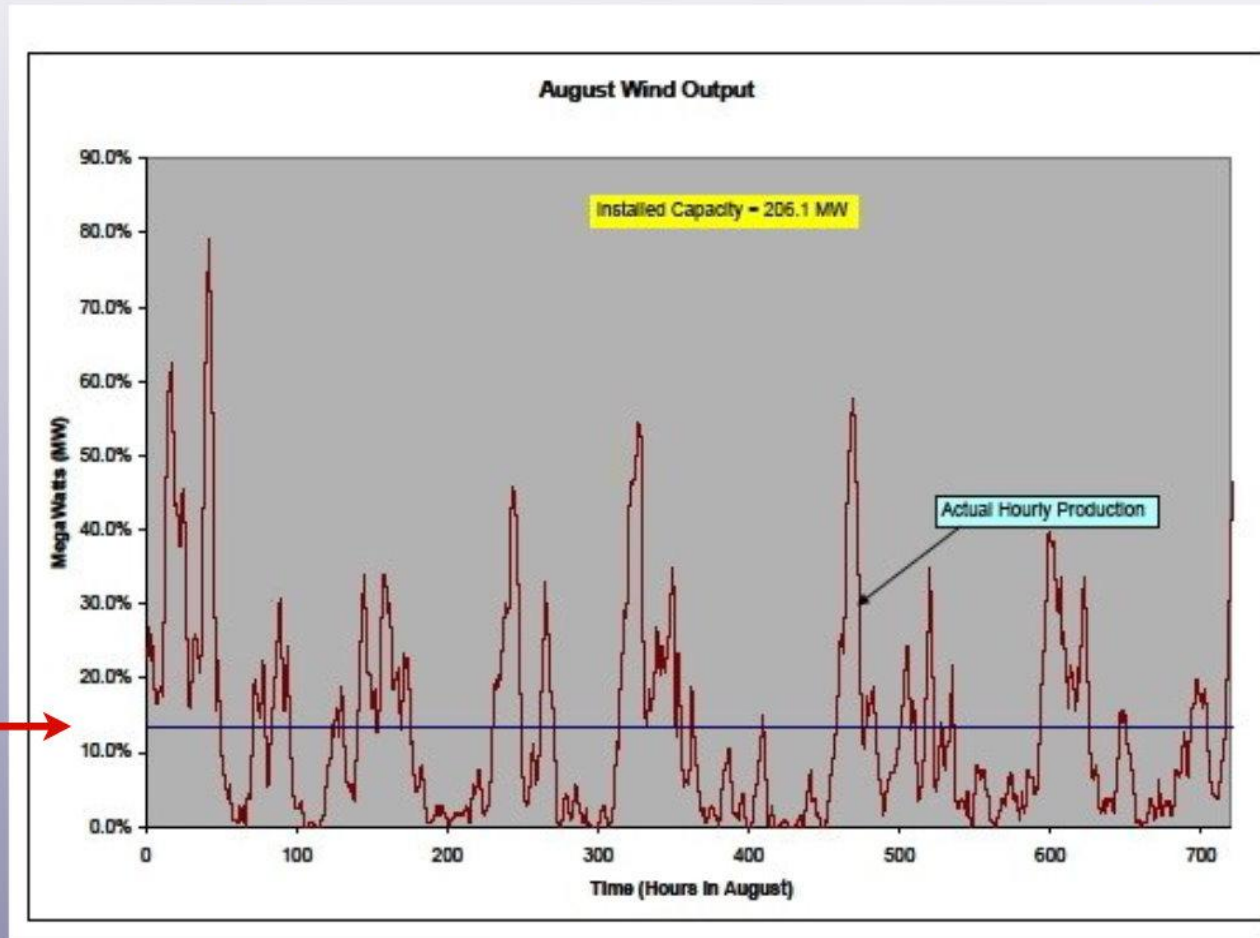
## Feb 21 – 28, 2010

BPA Balancing Authority Load & Total Wind Generation, Last 7 days  
21Feb2010 - 28Feb2010 (last updated 27Feb2010 22:01:35)



Based on 5-min readings from the BPA SCADA system for points 45583, 79687  
Balancing Authority Load in Red, Wind Generation in Blue; Installed Wind Capacity=2780 MW  
BPA Technical Operations (TOT-OpInfo@bpa.gov)

## Sample Data from Ontario Power Authority



**Note:**  
Average Output  
was only 13.5%  
of Rated Capacity.

Observe wide variability across this one month time period.





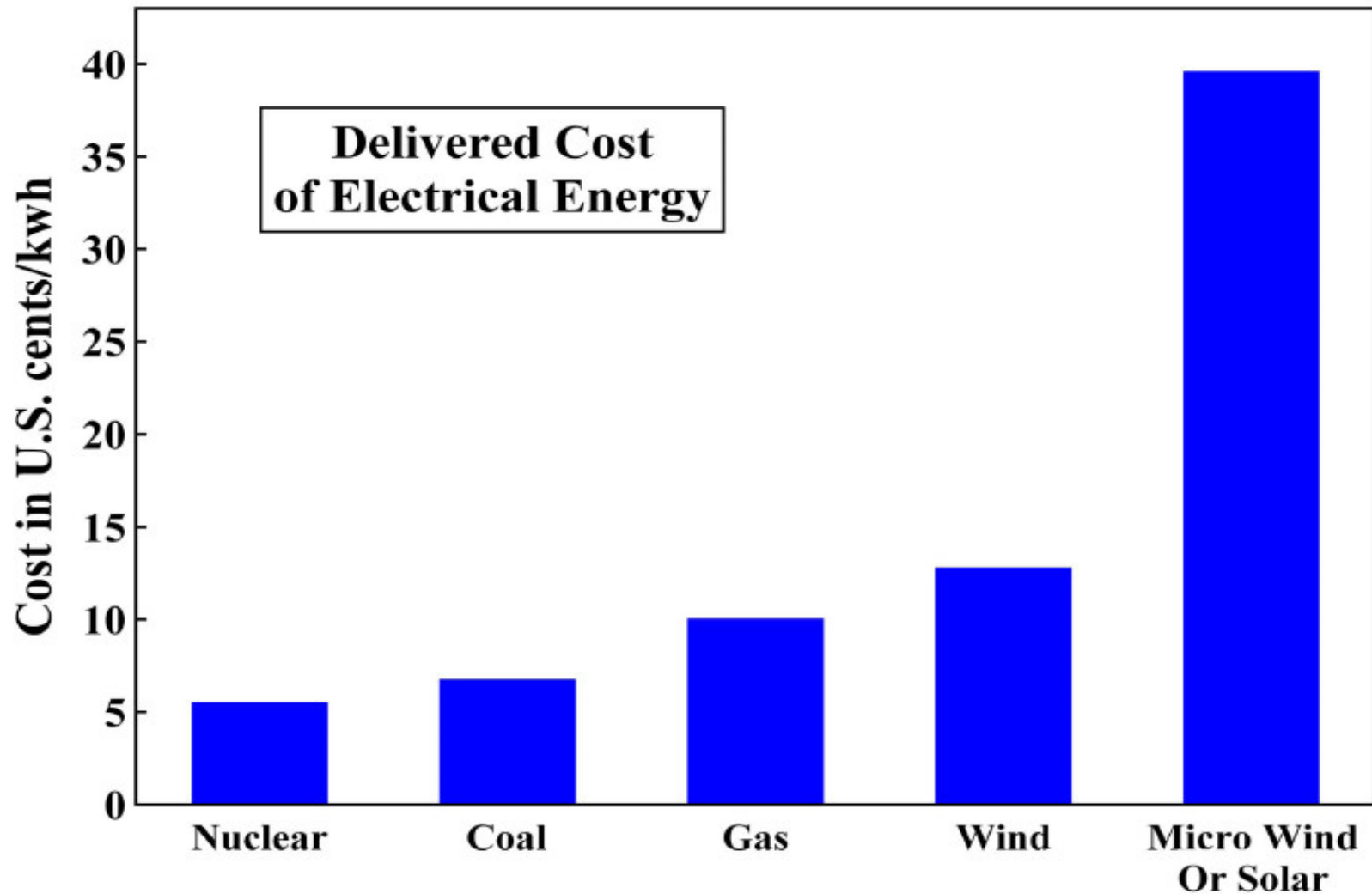
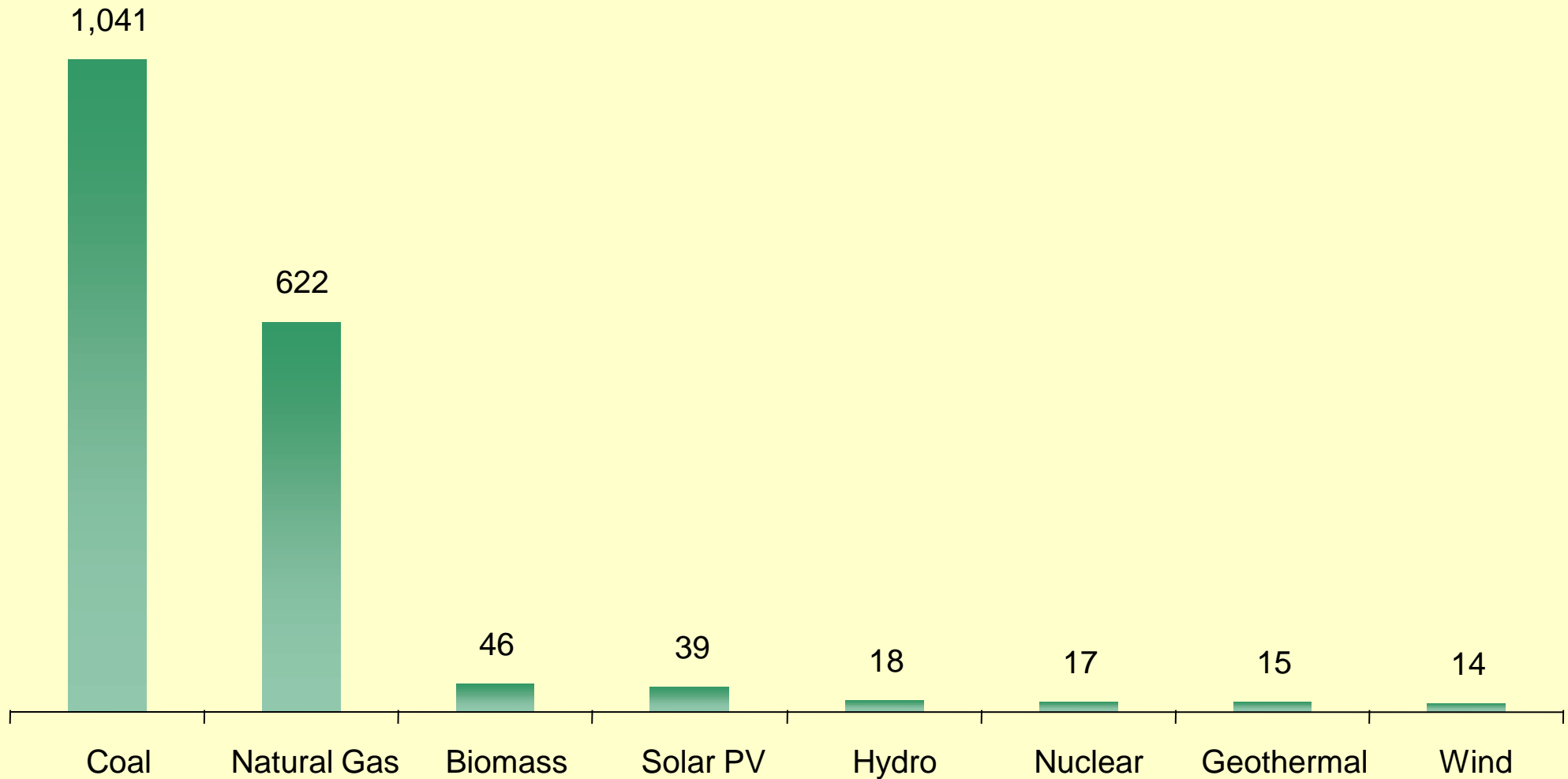


Figure 26: Delivered cost per kilowatt hour of electrical energy in Great Britain in 2006, without CO<sub>2</sub> controls (126). These estimates include all capital and operational expenses for a period of 50 years. Micro wind or solar are units installed for individual homes.

# Comparison of Life-Cycle Emissions

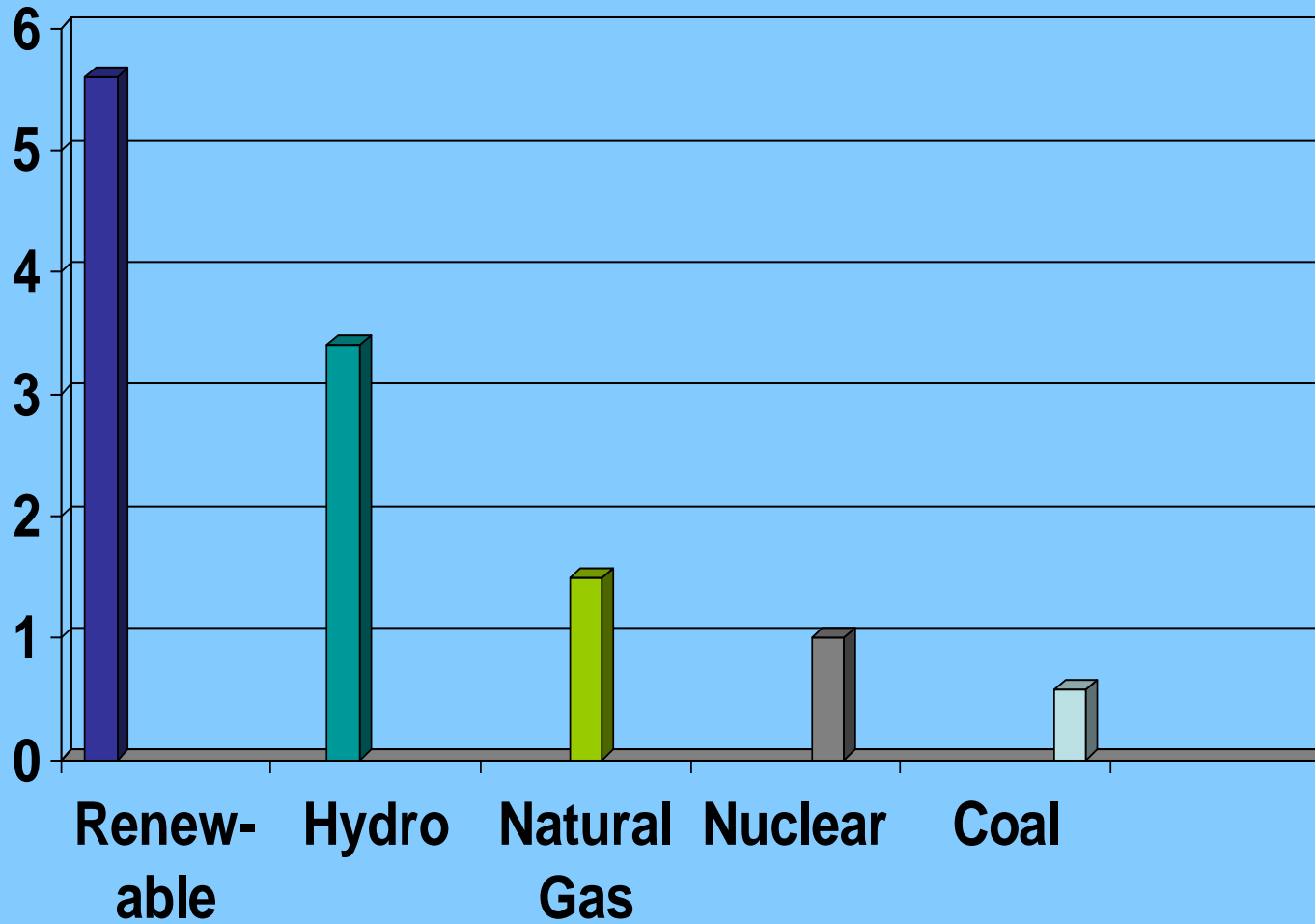
## Tons of Carbon Dioxide Equivalent per Gigawatt-Hour



Source: "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," Paul J. Meier, University of Wisconsin-Madison, August 2002.

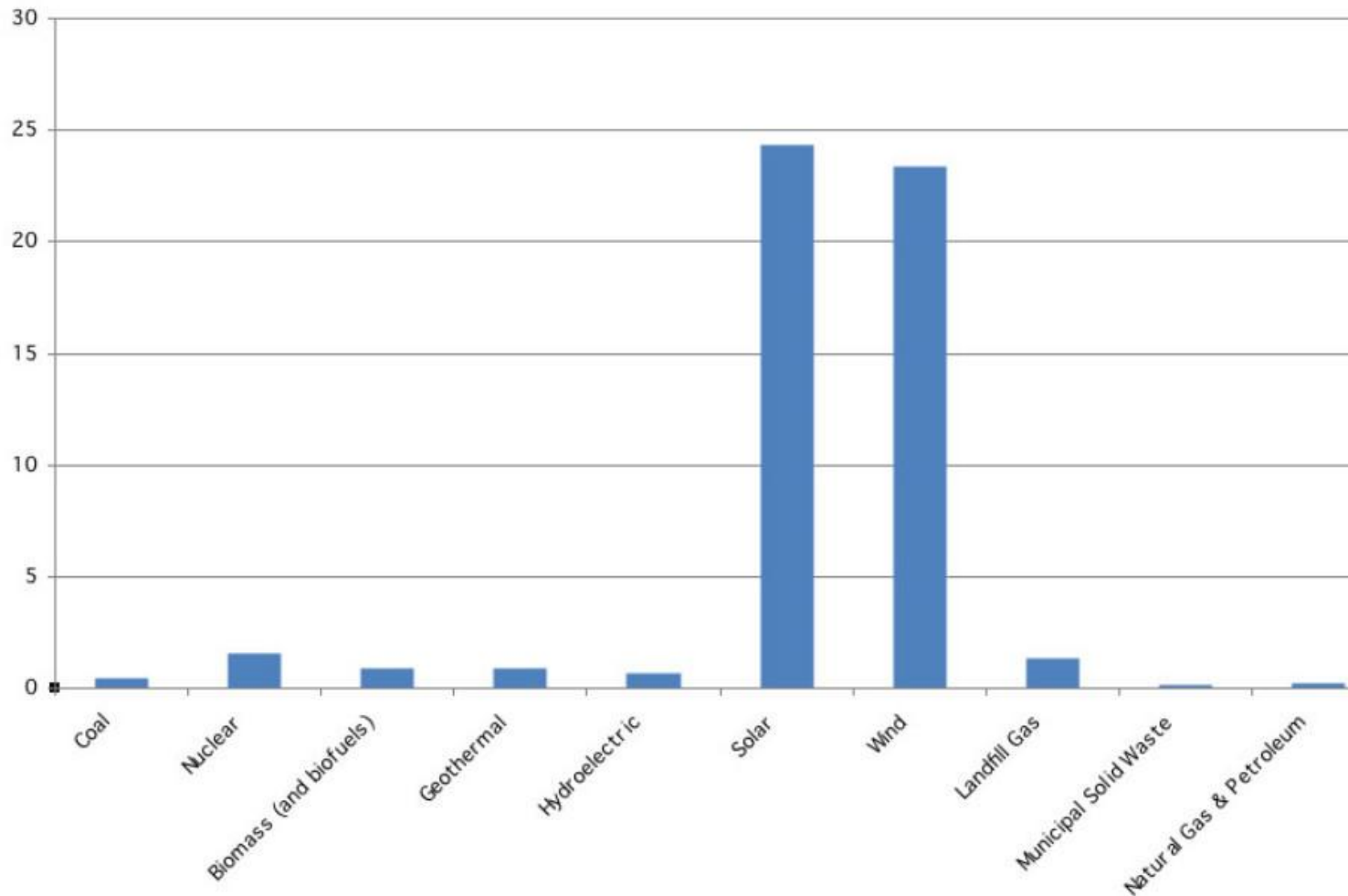
# RELATIVE SUBSIDIES, 1950-2006

PER UNIT OF ENERGY DELIVERED IN 2006



## Subsidies for Electricity Production by Generating Fuel, FY 2007

(2007 Dollars per Megawatt-hour)



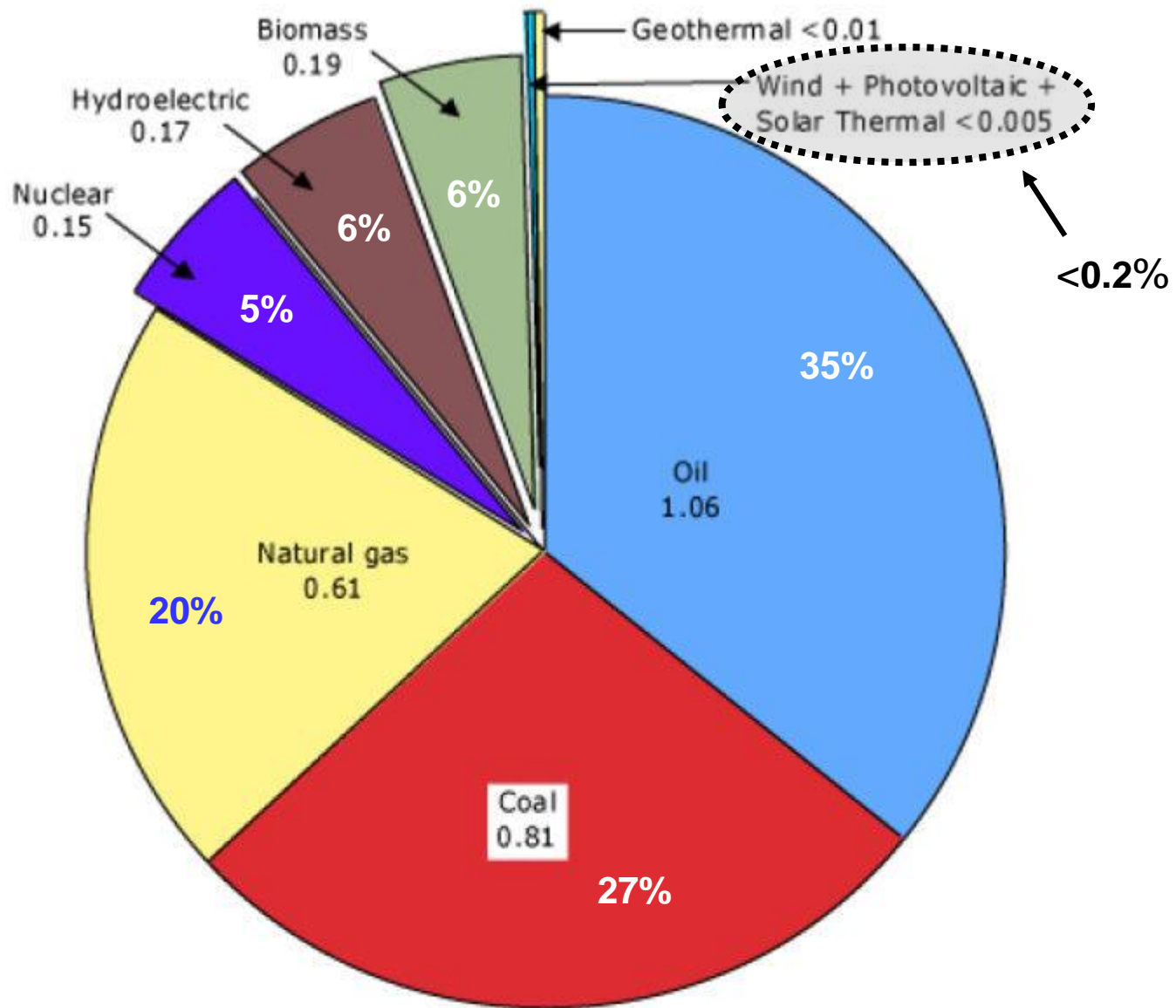
Source: Energy Information Administration,  
Federal Financial Interventions and Subsidies in Energy Markets, 2007,  
Table ES5

**IER** INSTITUTE FOR  
ENERGY RESEARCH

<http://www.instituteforenergyresearch.org/2008/07/30/energy-subsidies-study/>



# Global sources of energy in 2006



# BOTTOM LINE - 1

**Near term,**

- there will be increasing global demand for **enriched uranium**

**Near term and longer term,**

- there will be increasing global demand for **recycled fuel**

**The process will be managed badly  
or it will be managed well,  
BUT IT WON'T GO AWAY**

# BOTTOM LINE - 2

On balance, the U.S. fast reactor

Metal fueled

Sodium cooled

• **IFR**

with pyrometallurgical recycling

**IS THE BEST TECHNOLOGY FOR THE JOB**

**What is needed is a commercial-scale demo  
to establish cost and tie up some  
technological loose ends**

**END**