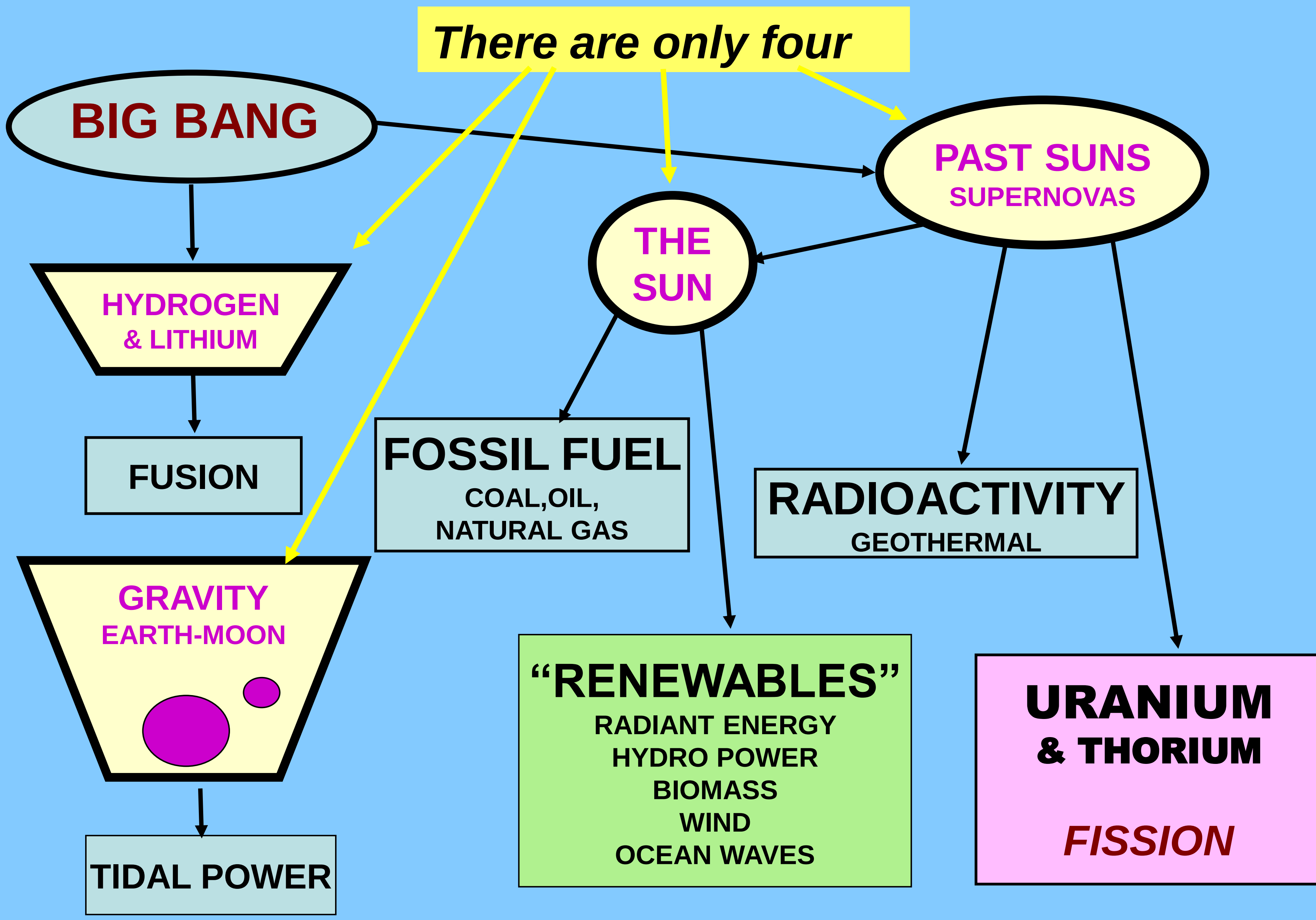
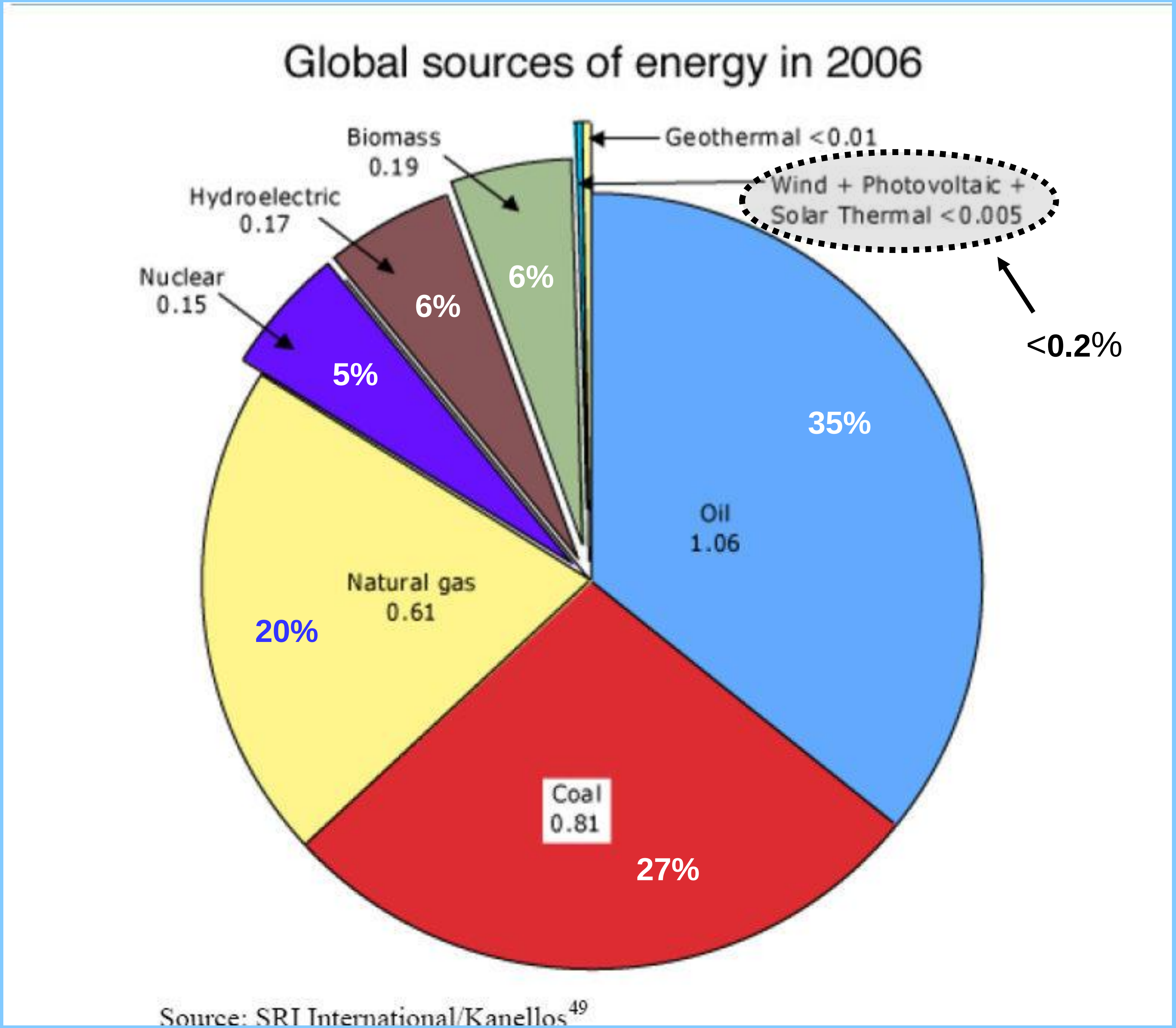
NUCLEAR POWER
IN THE
ENERGY PICTURE

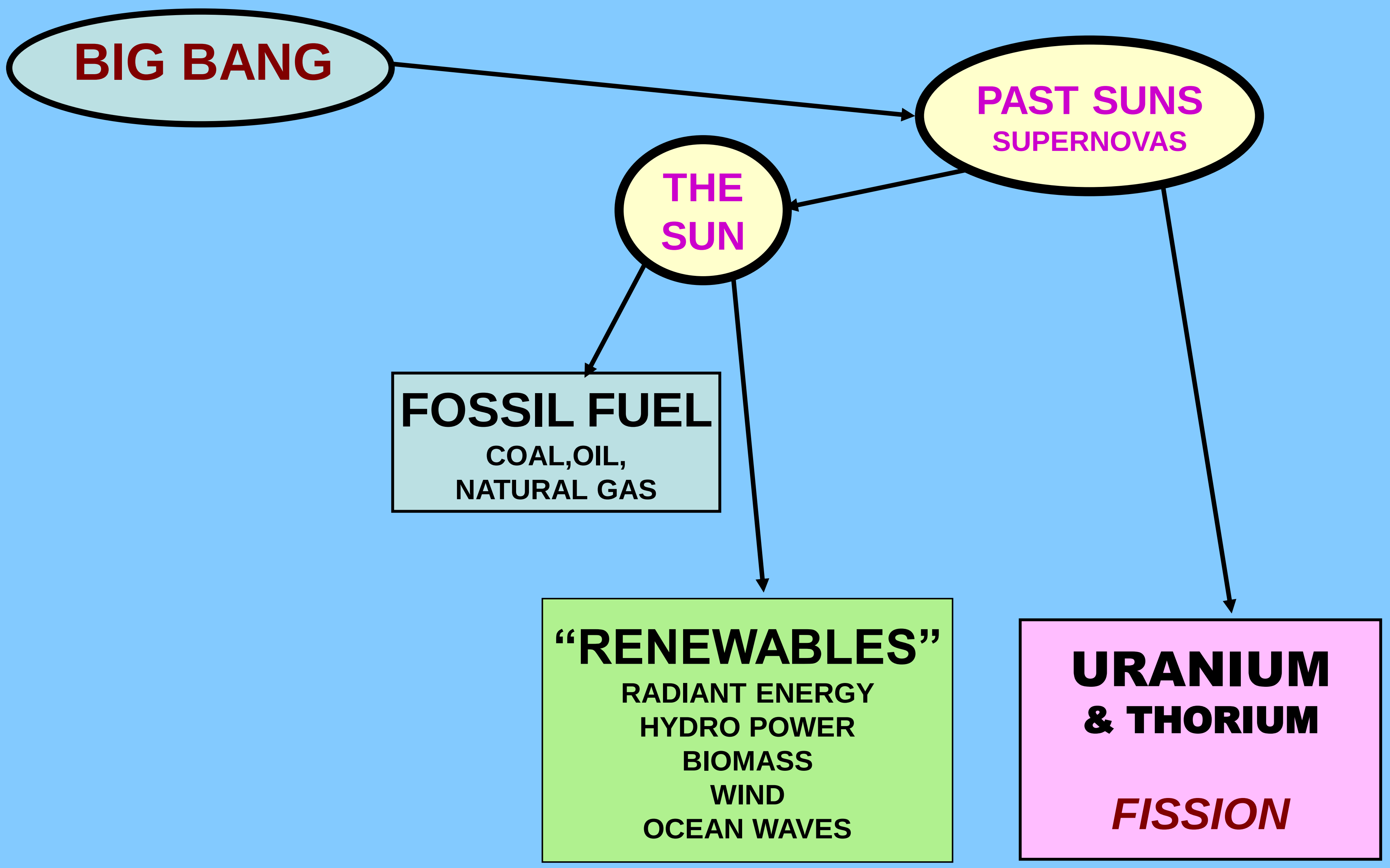
George S. Stanford
Reactor Physicist, retired

April 2010

SOURCES OF ENERGY




Global sources of energy in 2006
Biomass
0.19
Geothermal <0.01
Wind + Photovoltaic +
Solar Thermal <0.005
Hydroelectric
0.17
Nuclear
0.15
6%
6%
5%
<0.2%
35%
Oil
1.06
Natural gas
0.61
20%
Coal
0.81
27%
Source: SRI International/Kanellos[49]


BIG BANG
PAST SUNS
SUPERNOVAS
THE SUN
FOSSIL FUEL
COAL,OIL,
NATURAL GAS
"RENEWABLES"
RADIANT ENERGY
HYDRO POWER
BIOMASS
WIND
OCEAN WAVES
URANIUM
& THORIUM
FISSION

NUCLEAR POWER

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

or

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

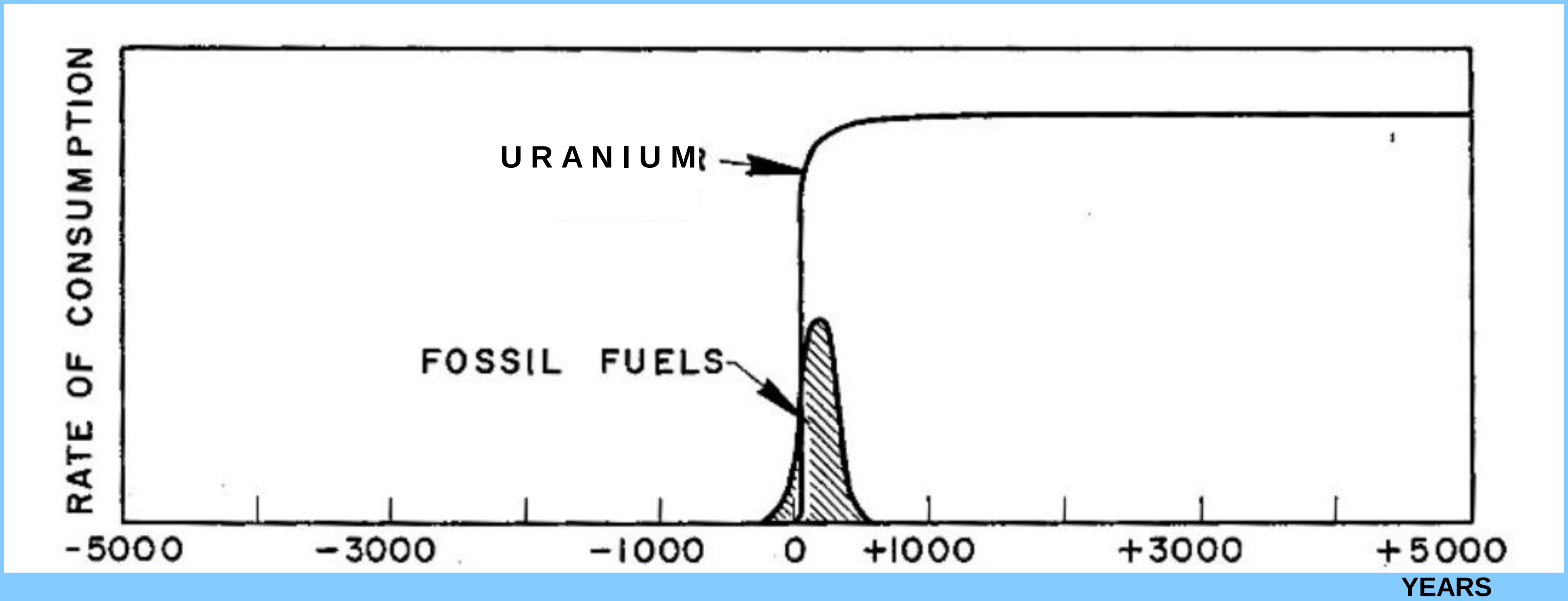
***   *   *   ***

***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 . . .**

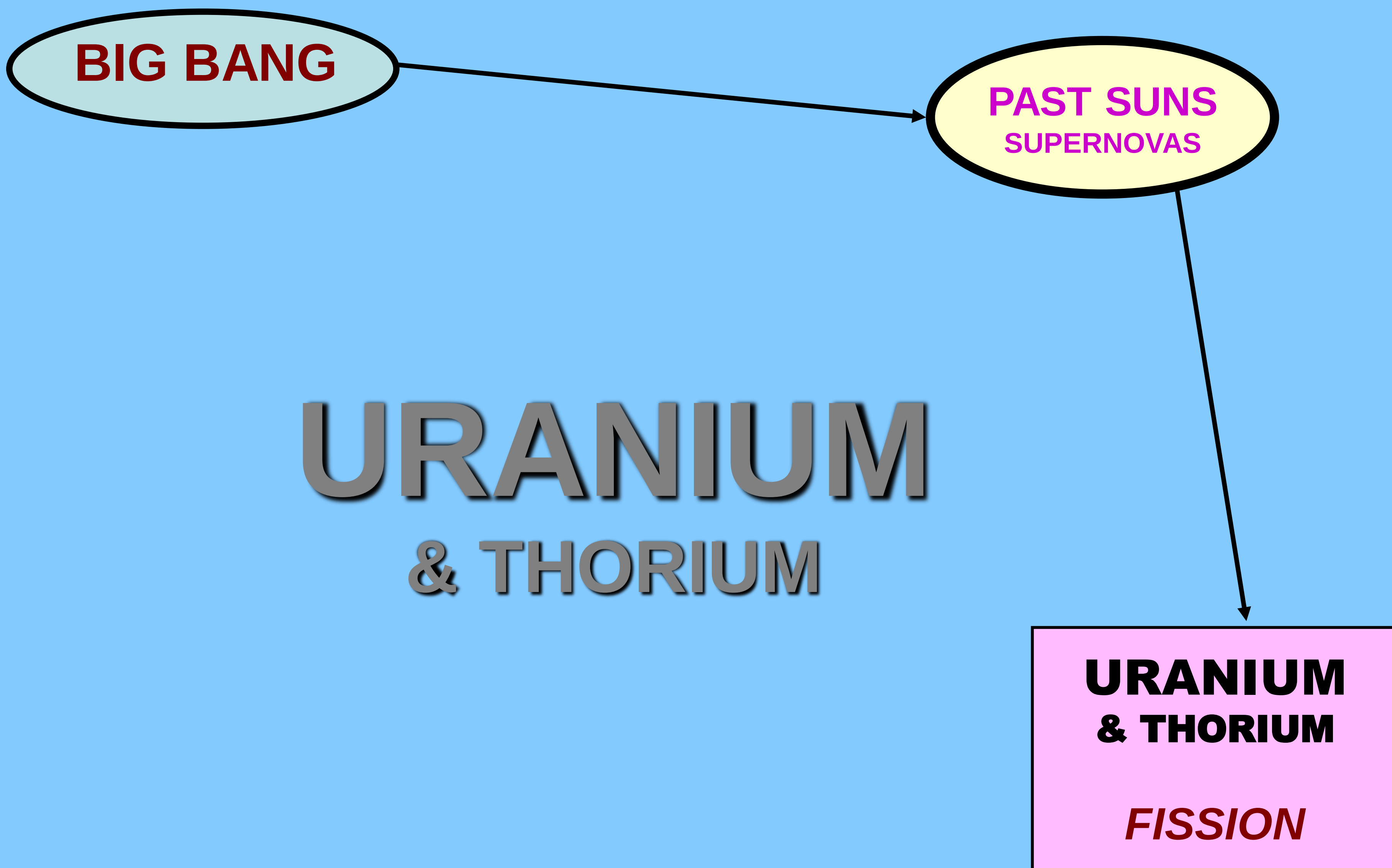
. . . but not necessarily as abundantly as we want it.

- **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?

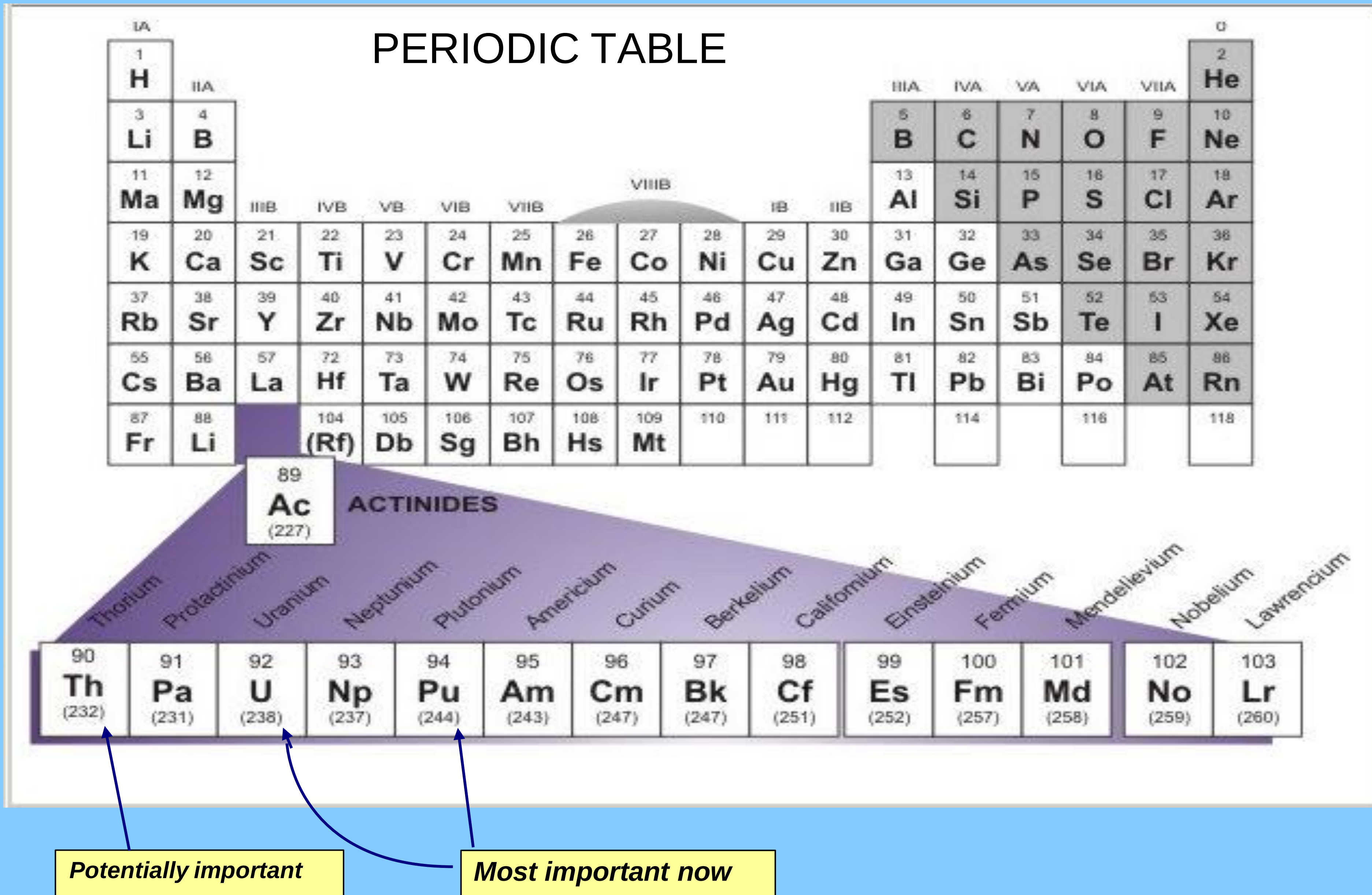
YES – it's . . .

Fission


BIG BANG
PAST SUNS
SUPERNOVAS
URANIUM
& THORIUM
URANIUM
& THORIUM
FISSION

THE THREE-MILE ISLAND POWER PLANT

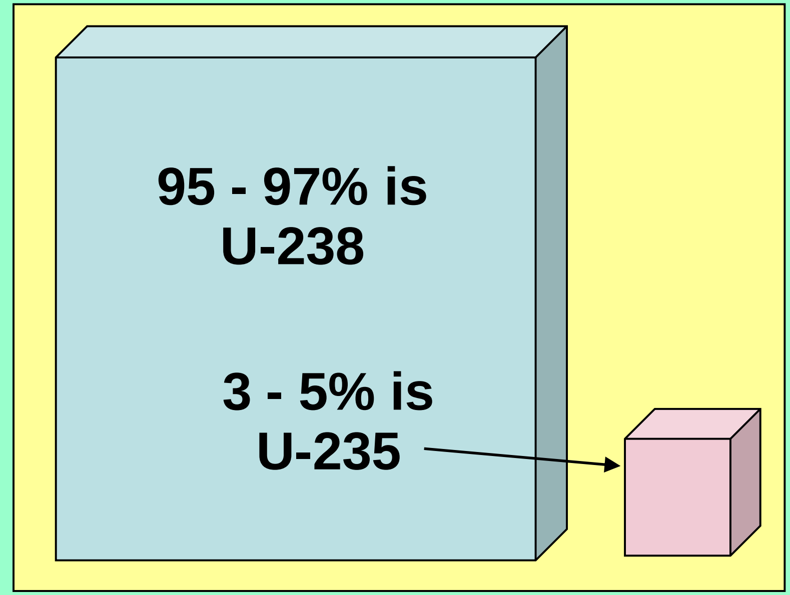
The reactors are in the small cylindrical buildings.
Water vapor comes from Unit 2's cooling towers.
Unit 1 was shut down by the 1979 accident.



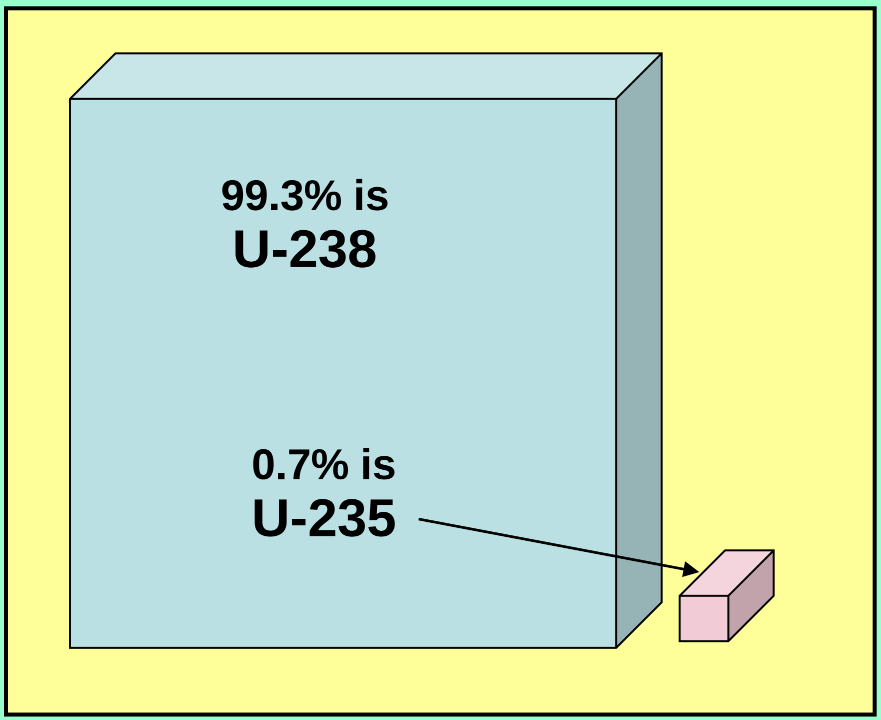
PERIODIC TABLE
IA
IIA
IIIB IVB VB VIB VIIB VIIIB IB IIB
IIIA IVA VA VIA VIIA
0
1 H
2 He
3 Li 4 B
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Ma 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 57 La 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Li 104 (Rf) 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 111 112 114 116 118
89 Ac (227)
ACTINIDES
Thorium Protactinium Uranium Neptunium Plutonium Americium Curium Berkelium Californium Einsteinium Fermium Mendelevium Nobelium Lawrencium
90 Th (232)
91 Pa (231)
92 U (238)
93 Np (237)
94 Pu (244)
95 Am (243)
96 Cm (247)
97 Bk (247)
98 Cf (251)
99 Es (252)
100 Fm (257)
101 Md (258)
102 No (259)
103 Lr (260)
Potentially important
Most important now

URANIUM
HAS TWO MAIN ISOTOPES

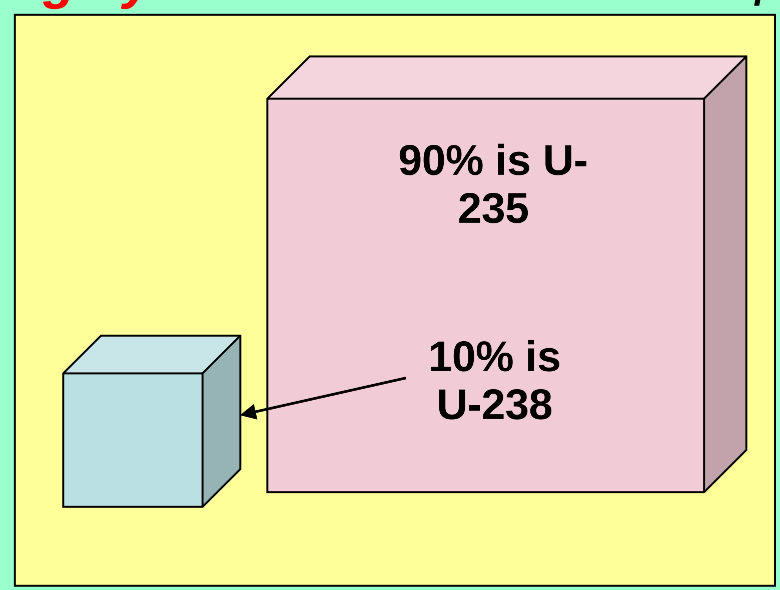
***Low-enriched uranium** for LWR fuel*



Natural uranium



***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_2O)**
  - **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_2O)**
    - **Uranium: enriched to 3–5% U235**

- **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. U-238 + n $\rightarrow$ 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:

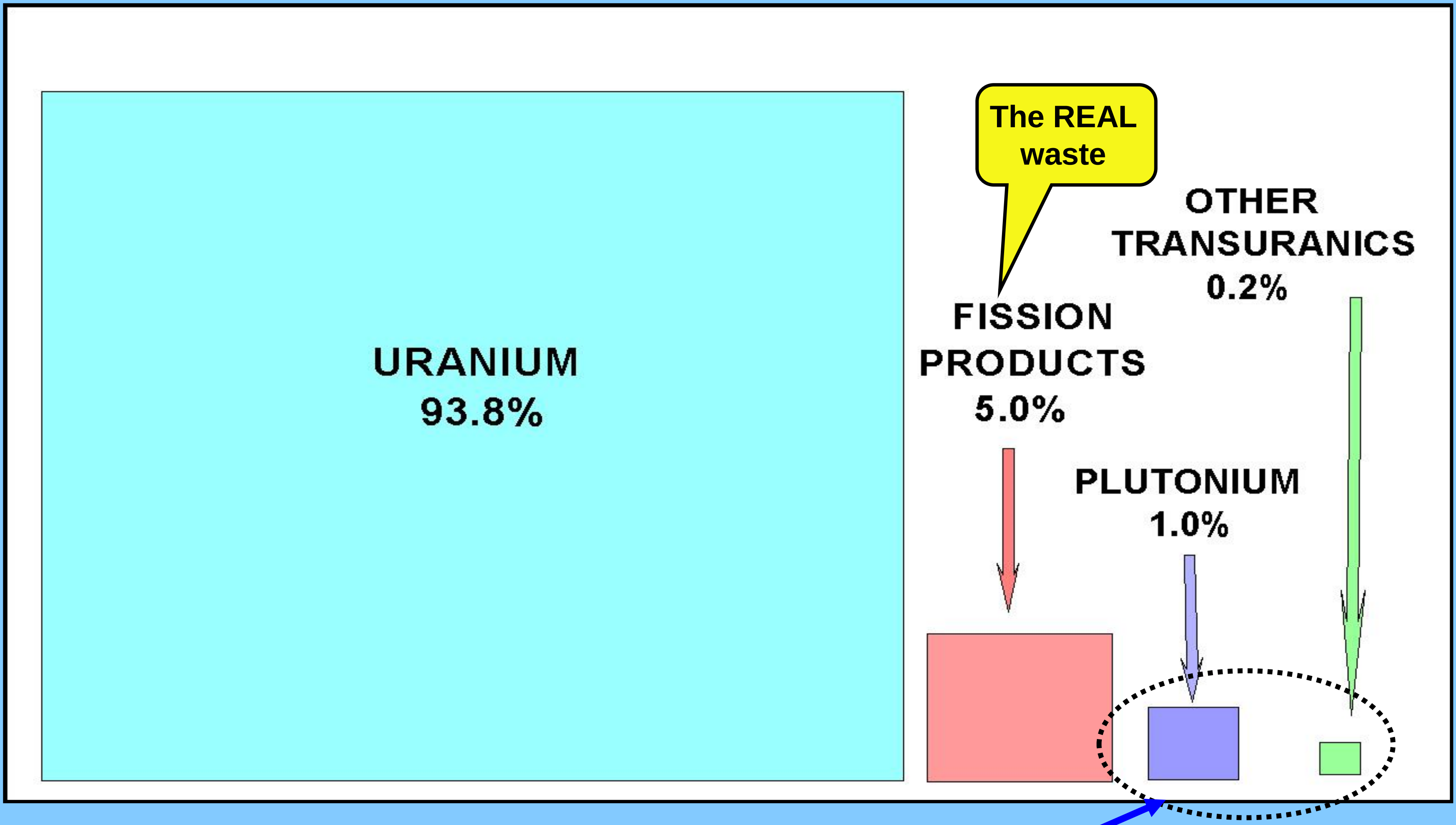
Proliferation potential

Some of the technology is applicable to weapons

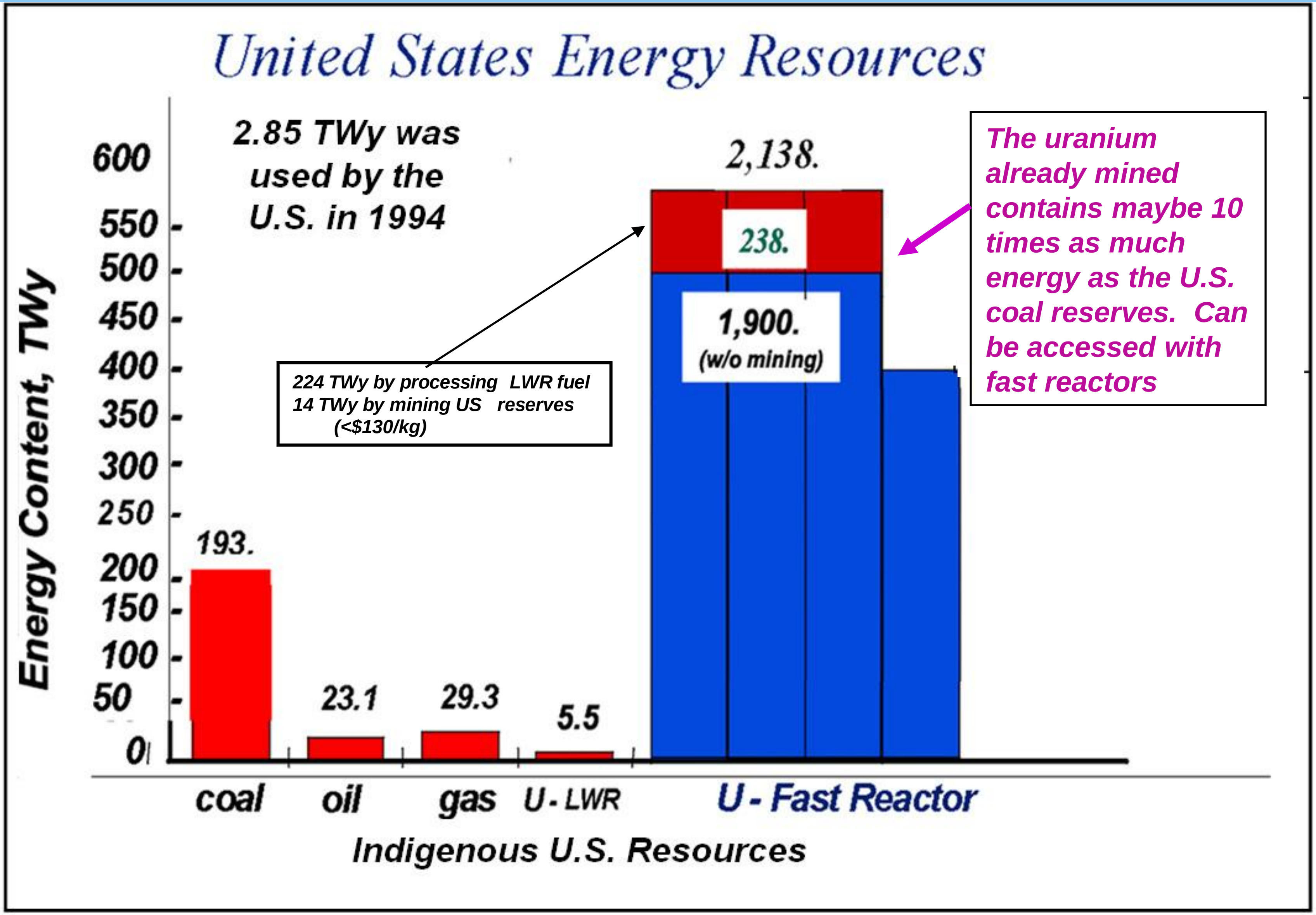
BUT: *Nuclear power is here to stay*, and we'd better manage it as well as we can.

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



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

U-238 in
1 ton per year

Energy out

FP out
1 ton per year

In the power plant:

- A fast reactor
- A facility to extract the fission products and make new fuel elements

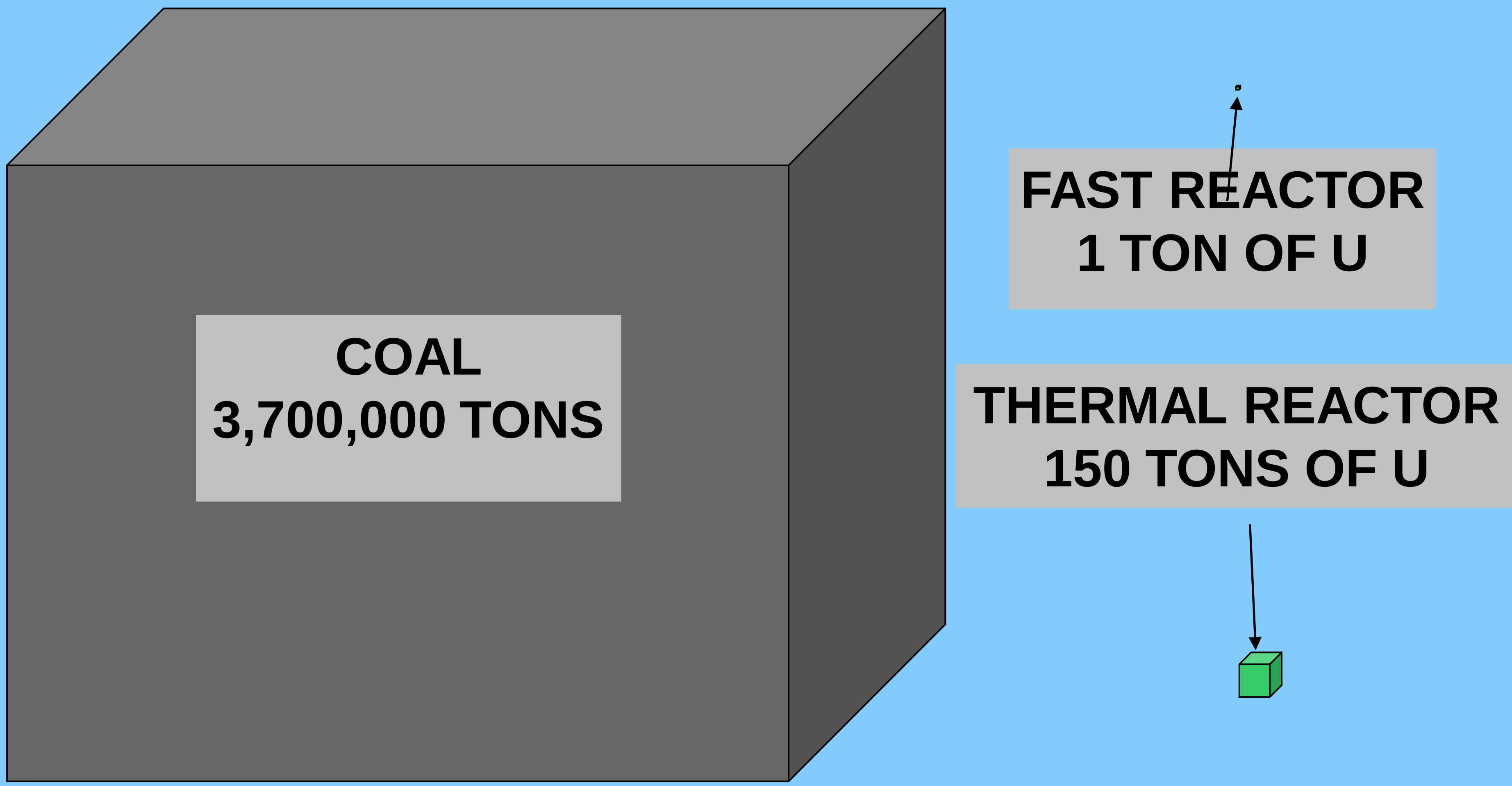
***Eventually*:**

NO LOOSE PLUTONIUM -- ANYWHERE!!

NO MORE ENRICHMENT OF URANIUM – EVER!!

ANNUAL FUEL REQUIREMENT FOR A 1,000-MWe PLANT

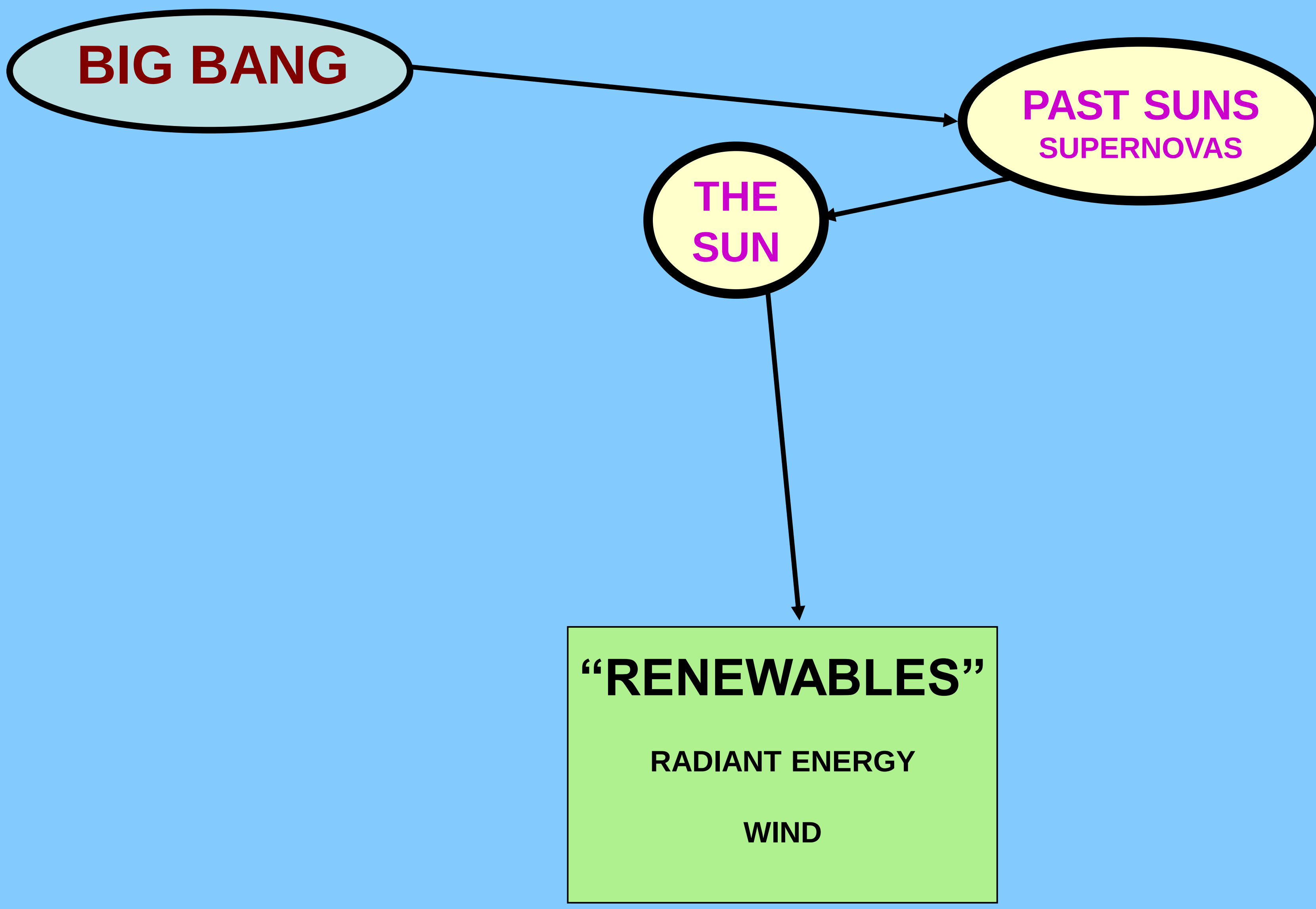
Drawn to scale



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


BIG BANG
PAST SUNS
SUPERNOVAS
THE SUN
"RENEWABLES"
RADIANT ENERGY
WIND

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

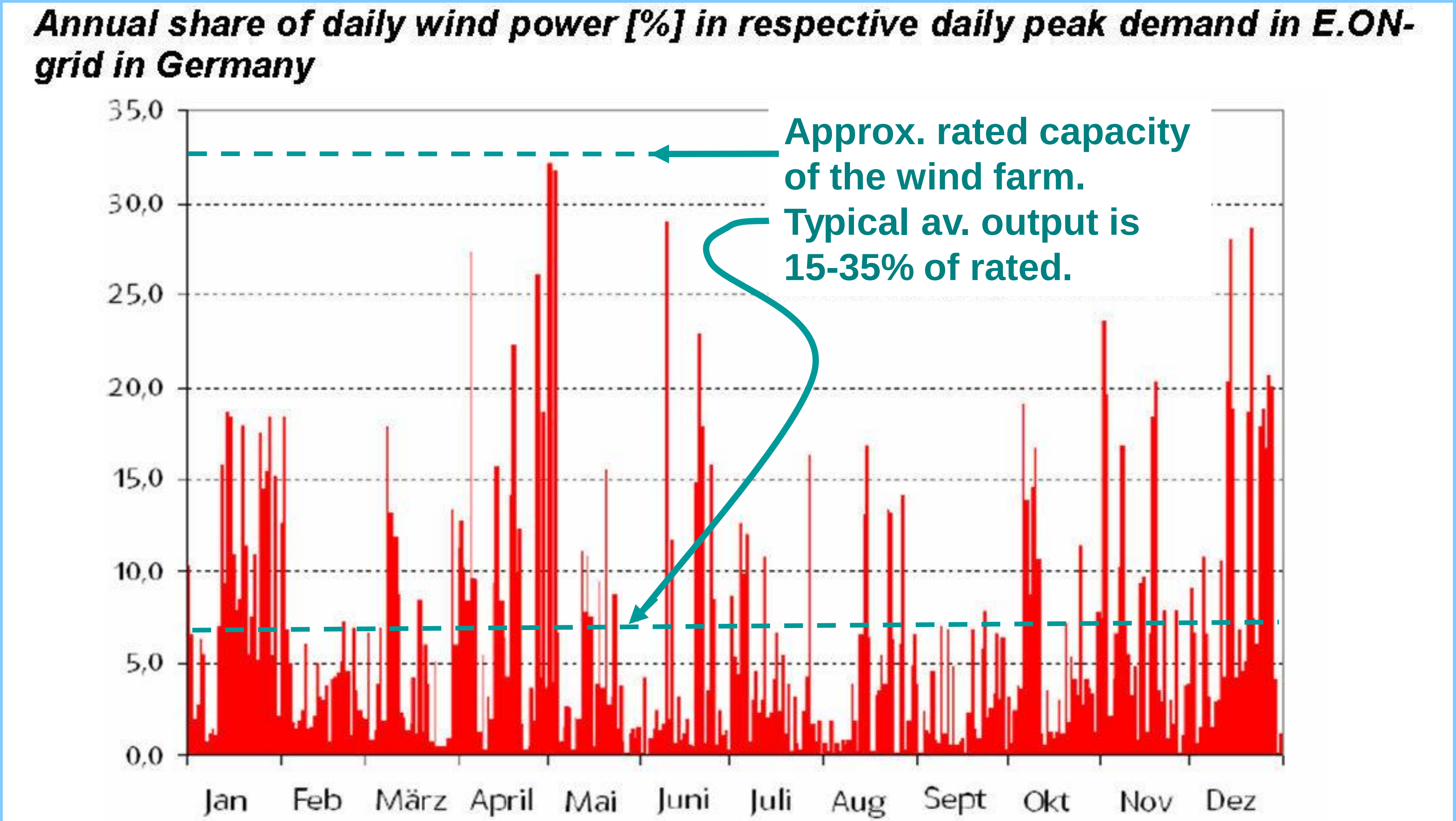
by something reliable

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

or there will be sporadic brownouts and blackouts

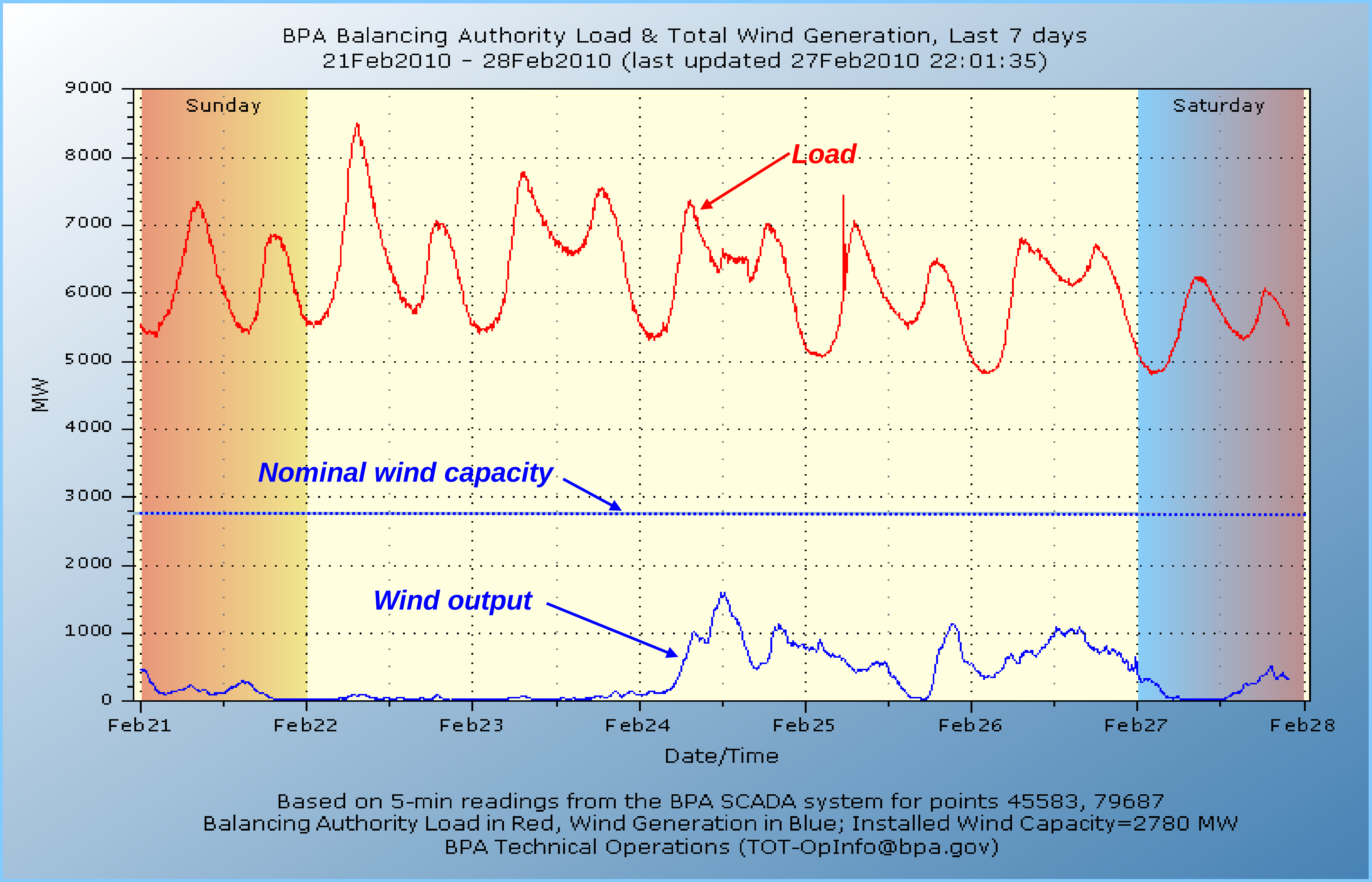
INTERMITTENCY

ONE YEAR OF OUTPUT, GERMAN WIND FARM

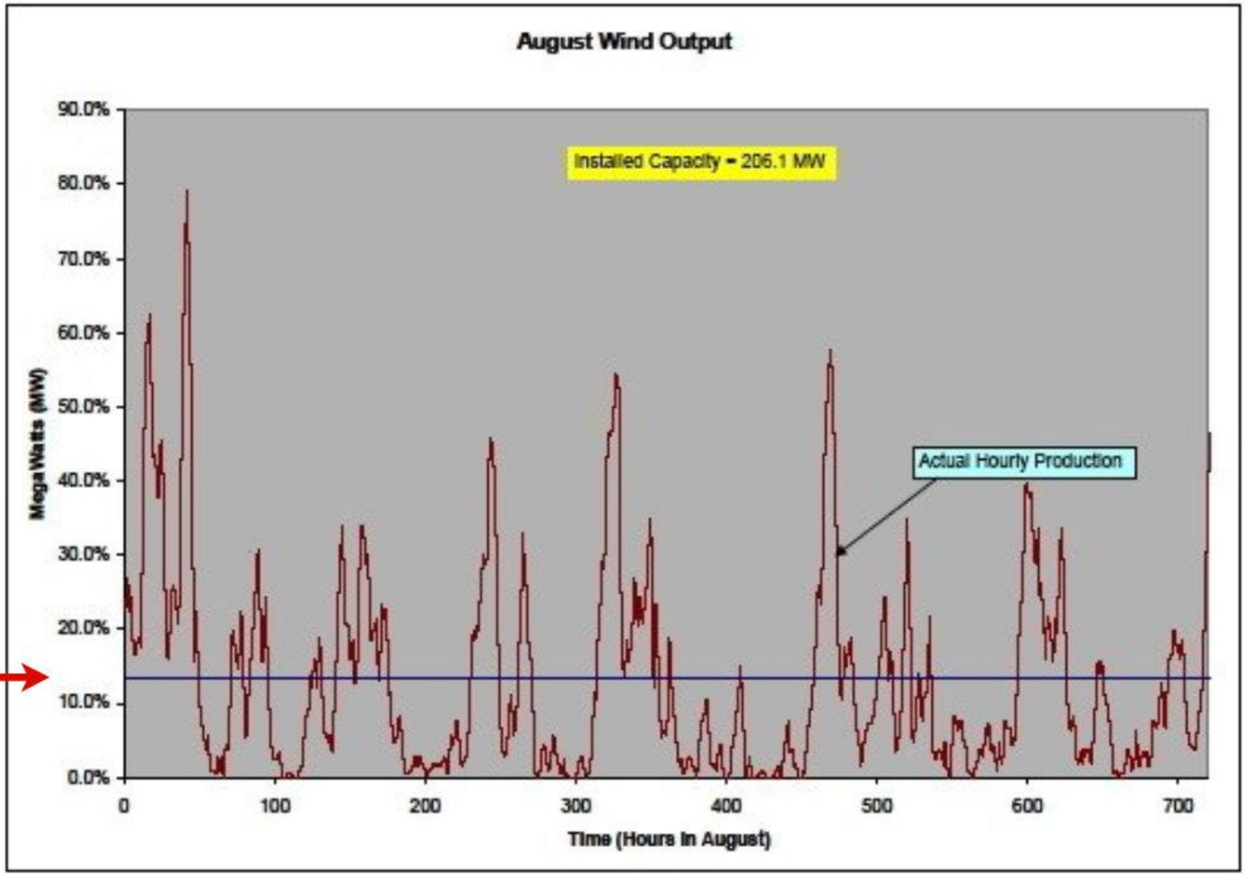


Source: UCTE, 2004, [11].

Bonneville Power Administration
Feb 21 – 28, 2010



Sample Data from Ontario Power Authority



Note:
Average Output was only <u>13.5%</u> of Rated Capacity.

Observe wide variability across this <u>one</u> <u>month</u> time period.

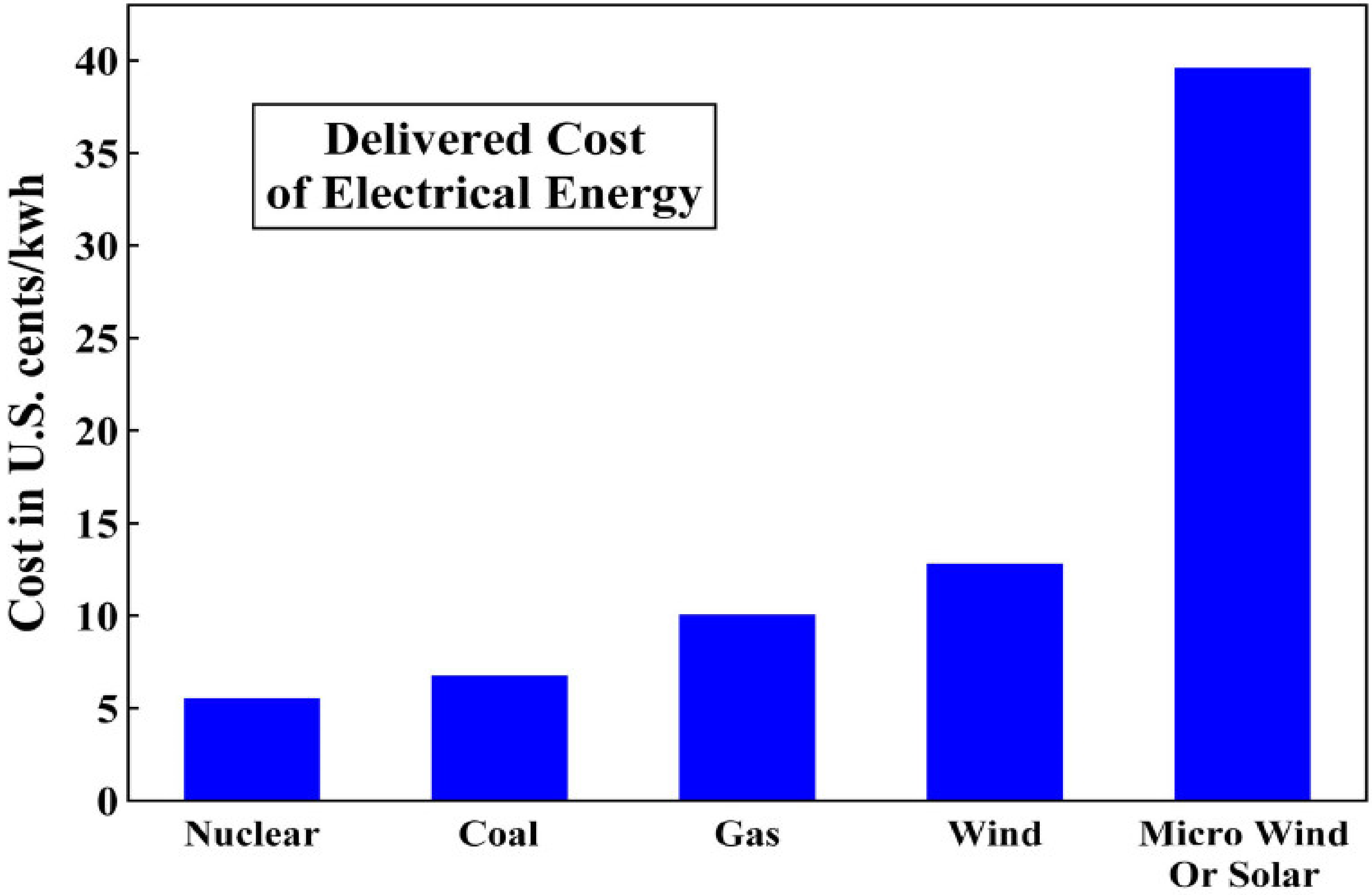
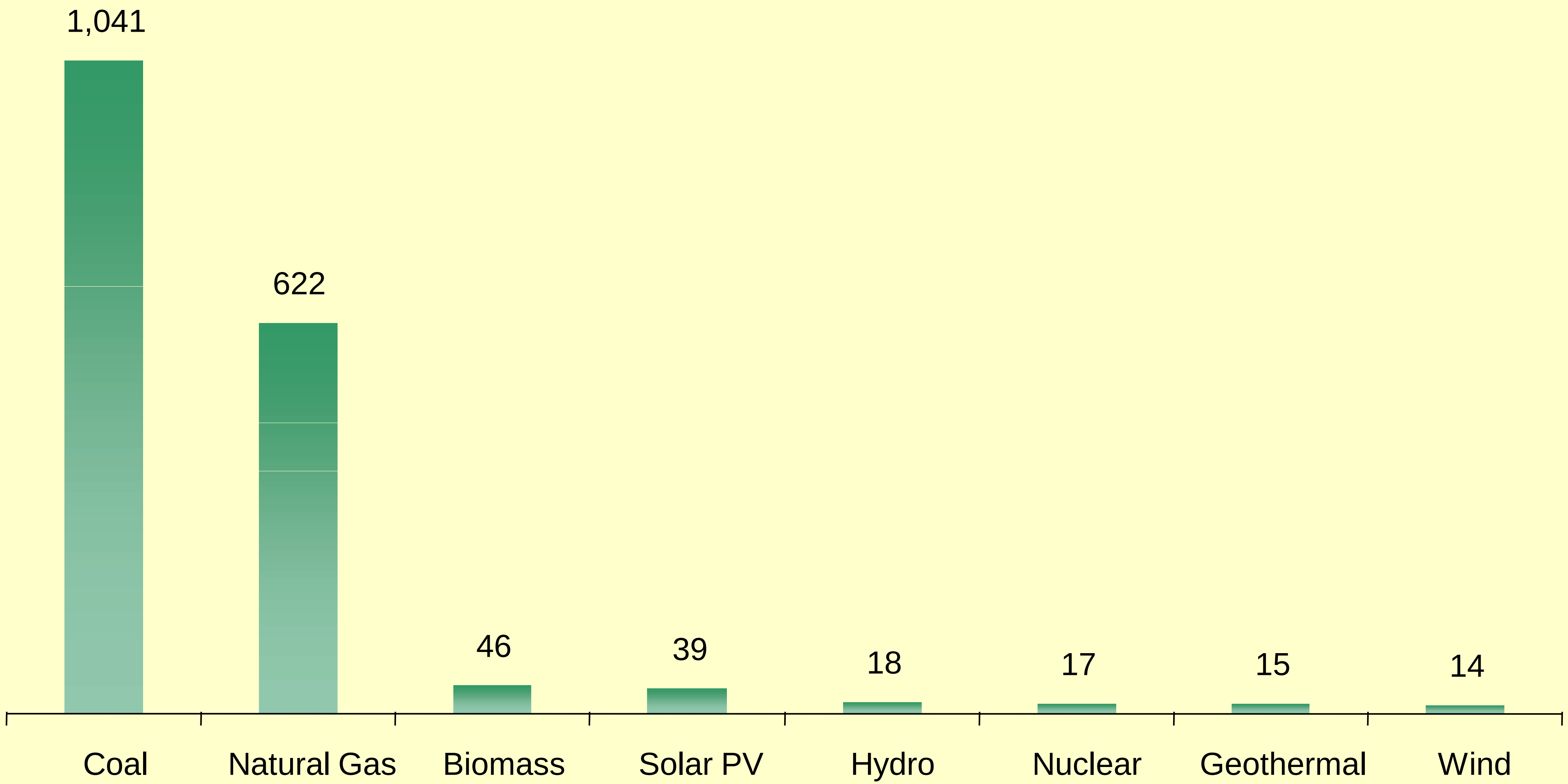


Figure 26: Delivered cost per kilowatt hour of electrical energy in Great Britain in 2006, without CO_2 controls (126). These estimates include all capital and operational expenses for a period of 50 years. Micro wind or solar are units installed for individual homes.

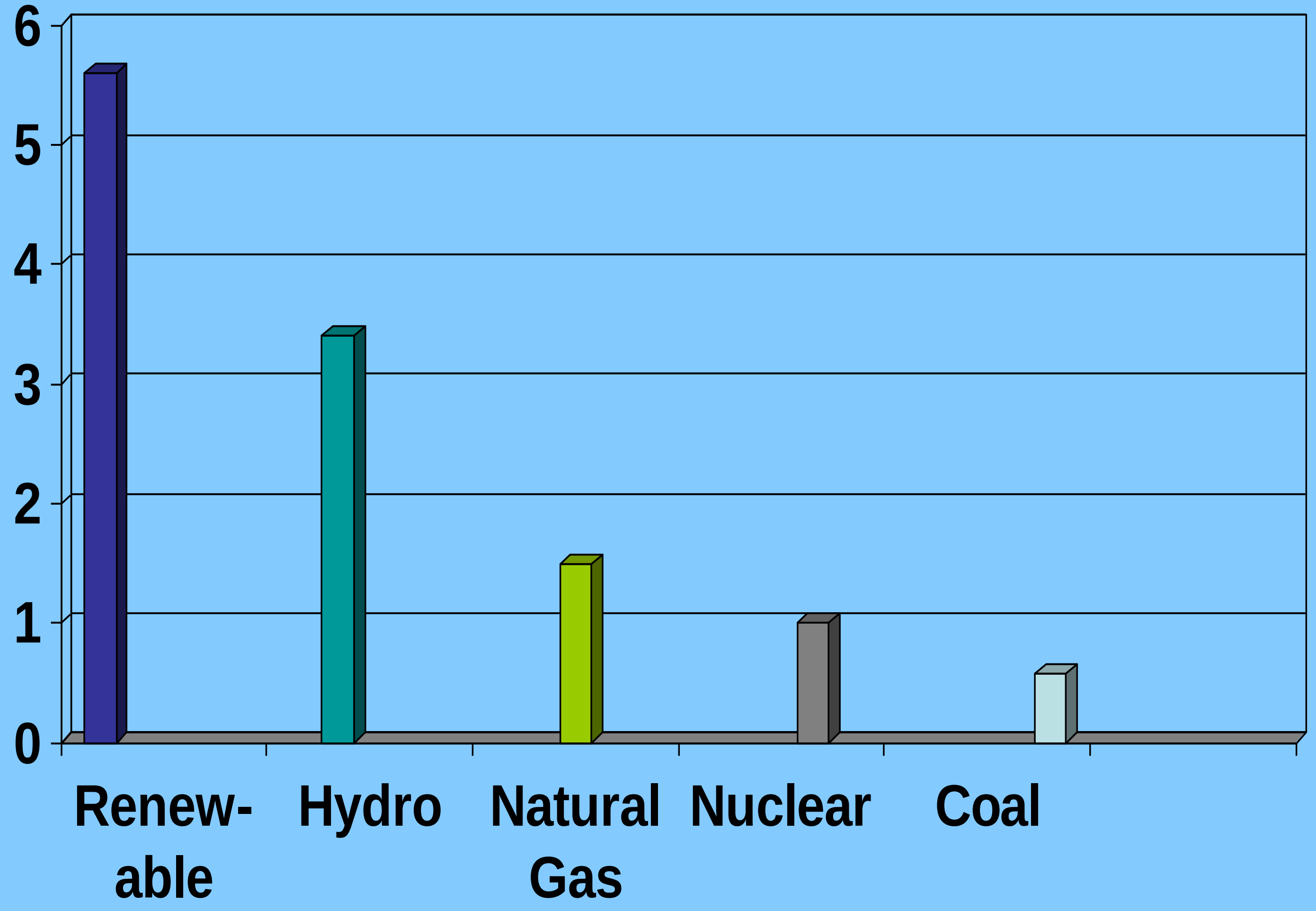
Comparison of Life-Cycle Emissions
Tons of Carbon Dioxide Equivalent per Gigawatt-Hour



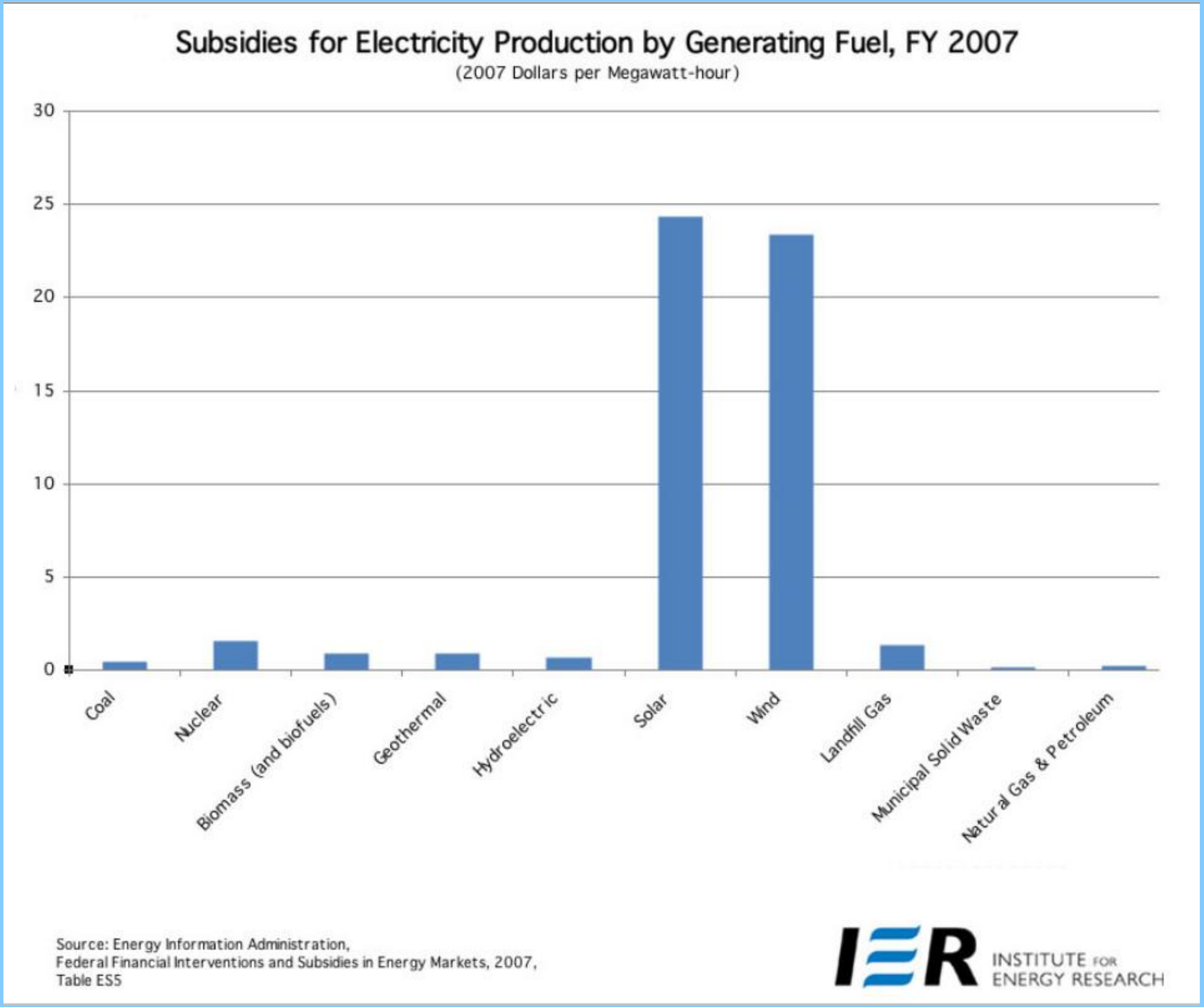
Source: "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," Paul J. Meier, University of Wisconsin-Madison, August 2002.

RELATIVE SUBSIDIES, 1950-2006

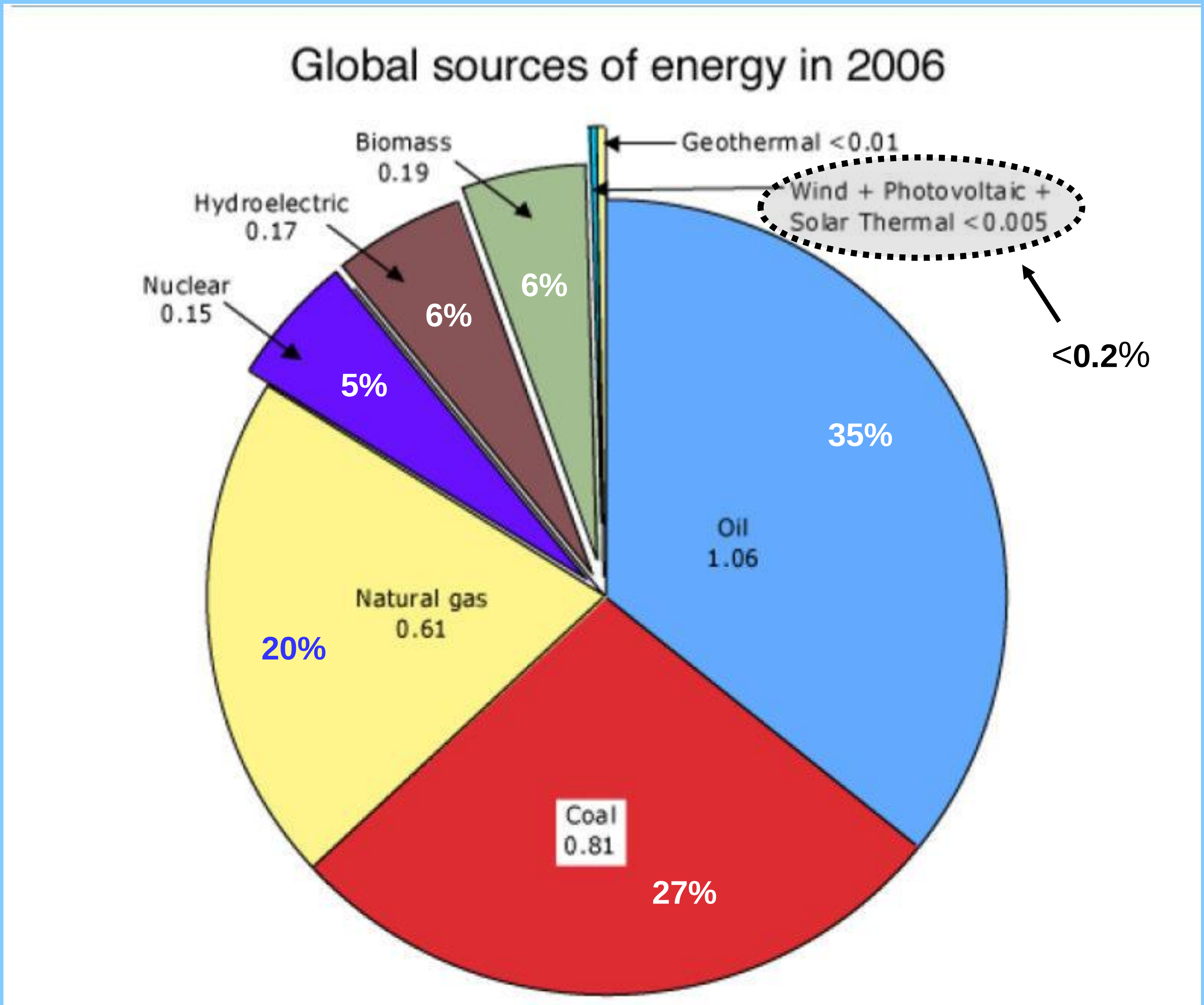
PER UNIT OF ENERGY DELIVERED IN 2006



<http://www.world-nuclear-news.org/newsarticle.aspx?id=22796>



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



Source: SRI International/Kanellos[49]

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