What You Should Know About Energy

Part I: Electric Power

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... we have now sunk to a depth at which restatement of the obvious is the first duty of intelligent men.

-- George Orwell

Objective

To correct **misinformation and public misconceptions** about the safety, health effects, environmental impact, and economics of the major fuels and technologies for generating electric power

Outline

- Electric Power Overview
- Coal
- Nuclear
- Hydro
- Natural Gas
- Wind and Solar
- Next Generation Nuclear
- Conclusions

US Electric Power Sources

source	2011	2012	change
coal	42.3%	37.4%	-4.9%
natural gas	24.7%	30.4%	+5.7%
nuclear	19.3%	19.0%	-0.3%
hydro	7.8%	6.8%	-1.0%
wind	2.9%	3.5%	+0.6%
solar	0.04%	0.11%	+0.07%
total energy	4.10 PWh	4.05 PWh	-1.2%

data source: US Energy Information Administration

Coal

37.4% of US Electric Power in 2012

coal power plant, Monroe, Michigan

Worldwide Coal Burning Rate

8 billion tons/year
22 million tons/day
250 tons/second

- Coal use decreasing in US but rapidly increasing elsewhere
- One new major coal plant goes online per week in China
- 1200 new coal power plants currently planned worldwide

"The Toll from Coal"

Major study by Clean Air Task Force

- **13,200 fatalities/year** estimated in US in 2010 due to fine-particle coal pollution
  - **1,100 fatalities/month**
  - **36 fatalities/day**
- Down from 24,000/yr in 2004 study
  - Improved scrubber technology
- Global death rate *much* higher
  - One million per year estimated

1952 London Smog Disaster

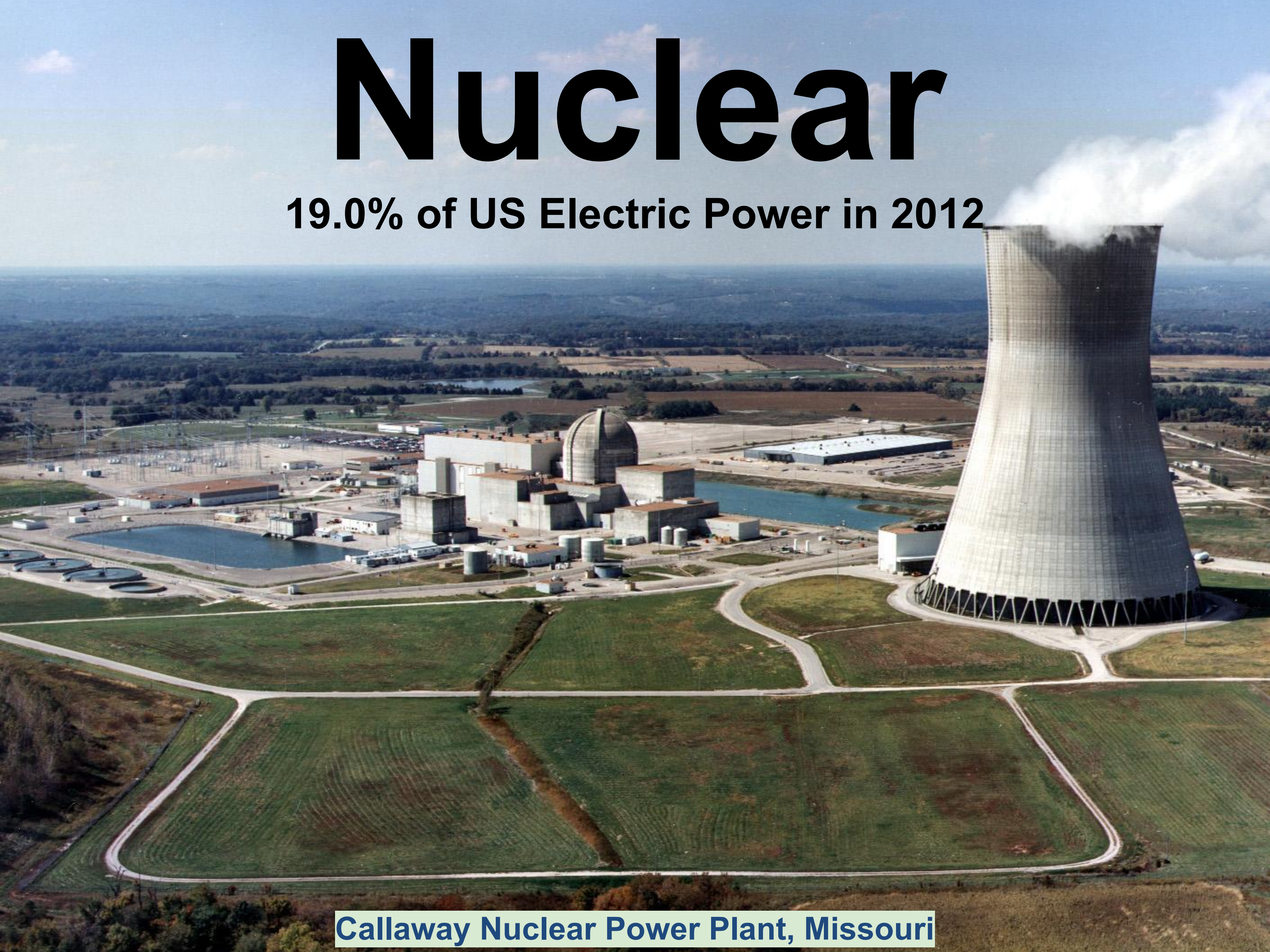
- Unusual cold causes more coal burning in homes for heat
- Temperature inversion occurs (air closer to ground cooler than air above it)
- Coal pollution trapped for five days
- Visibility severely reduced
- 100,000 people become ill
- **4,000 dead** within two weeks
- **12,000 eventual deaths** estimated

Coal Far Better than Nothing

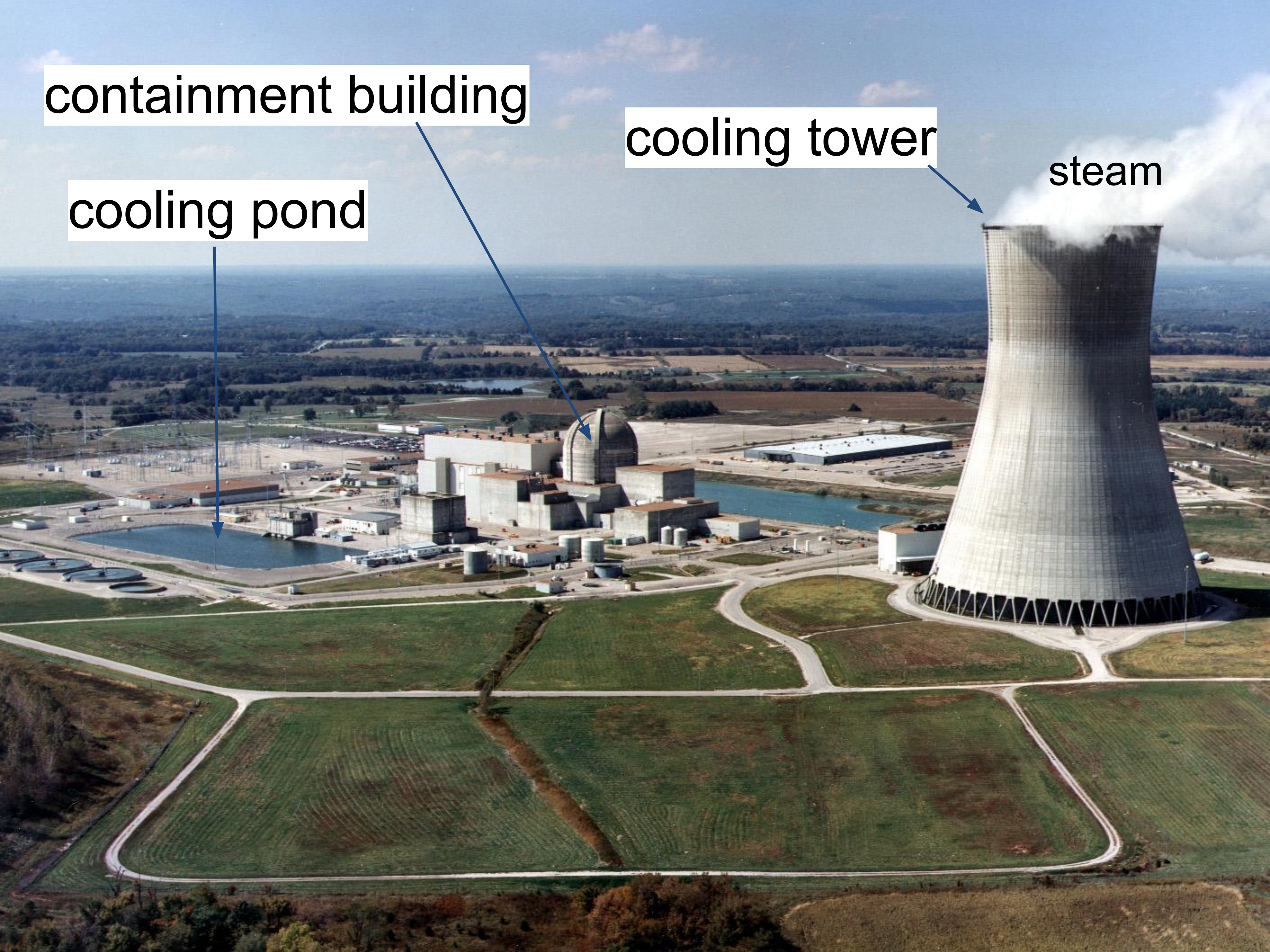
- Without reliable electric power, we would have a third-world standard of living
- Electricity from coal saves far more lives than coal pollution takes
- We cannot afford to shut down coal or drive the cost way up with regulation until we have an economical replacement

Nuclear

19.0% of US Electric Power in 2012



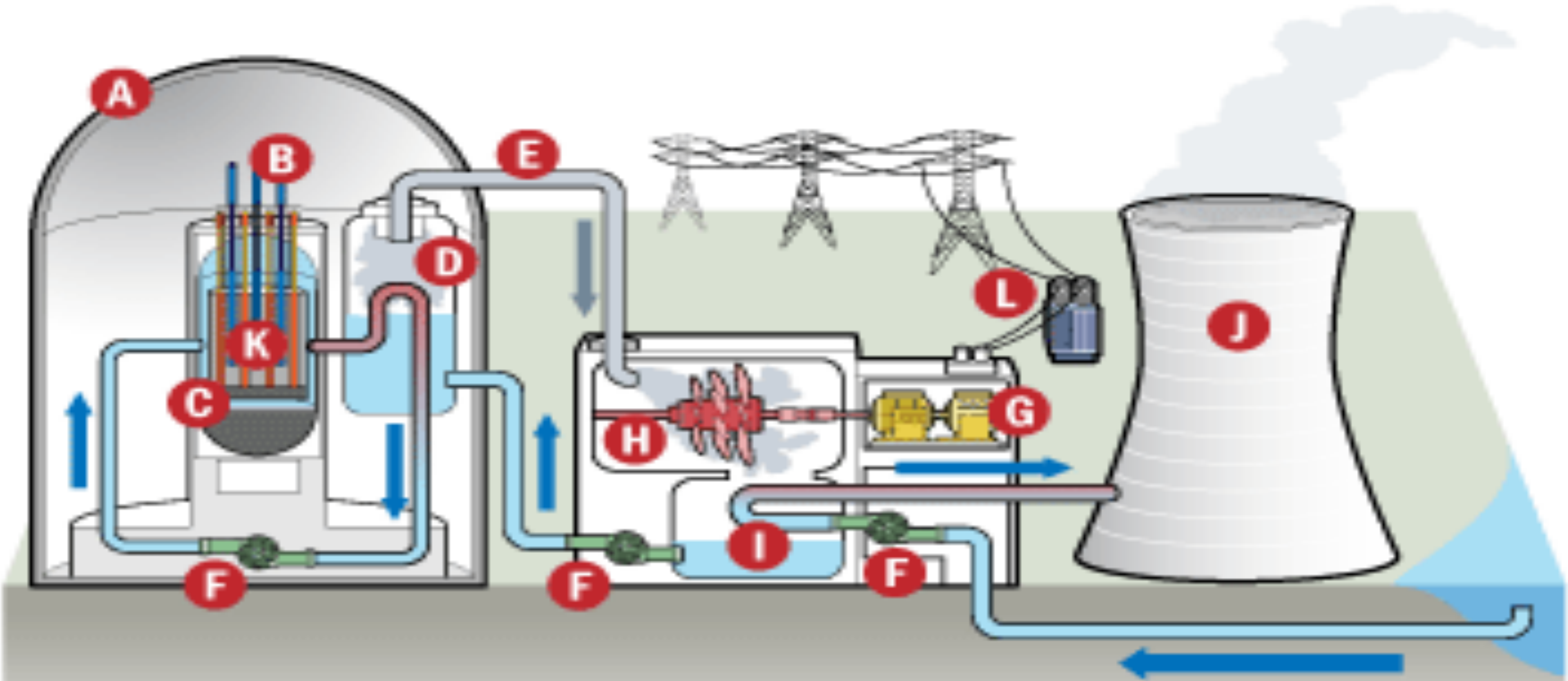
Callaway Nuclear Power Plant, Missouri


containment building
cooling tower
steam
cooling pond

Basic Facts about Nuclear Power Plants

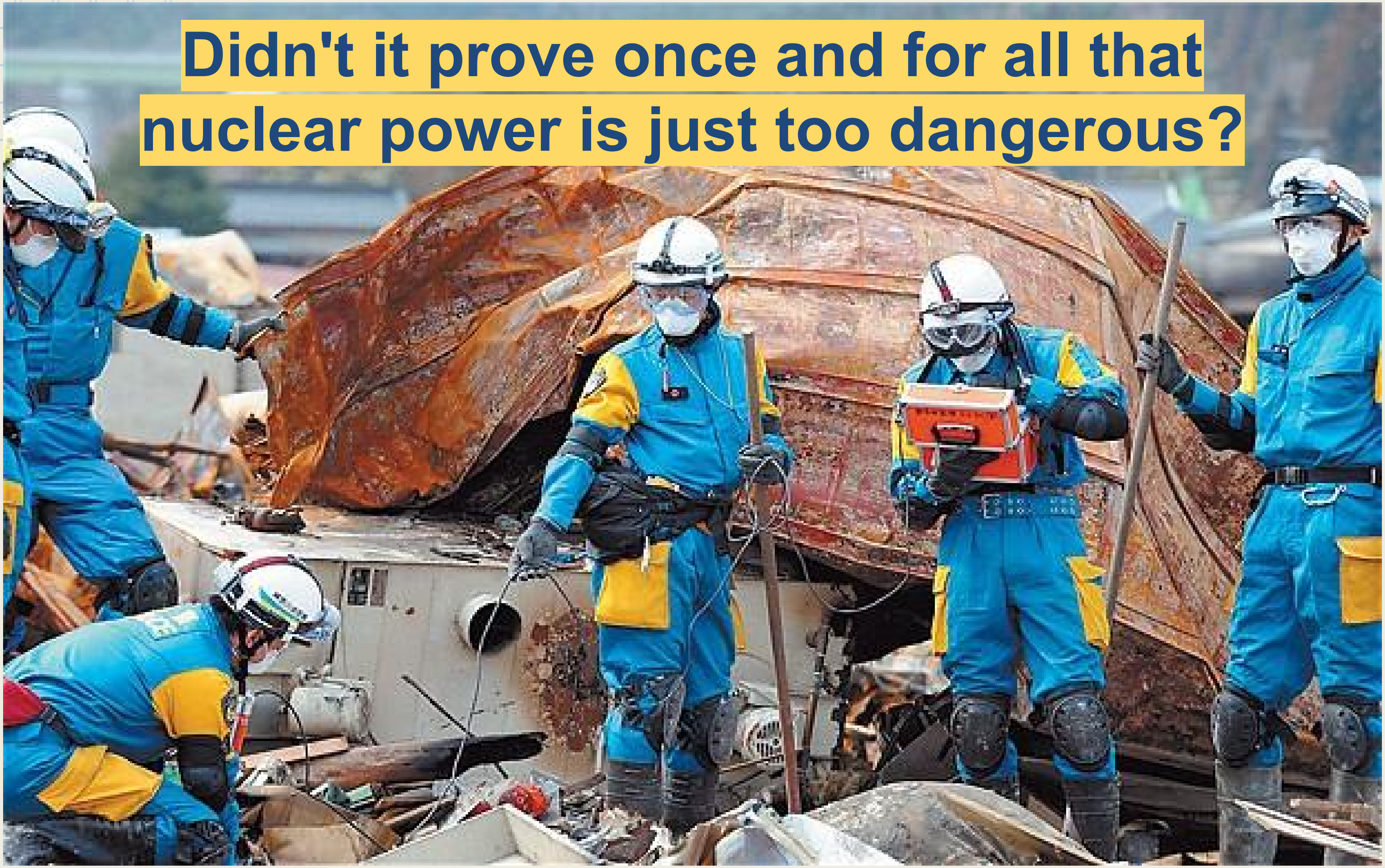
- A nuclear power reactor cannot possibly explode like a nuclear bomb
- Containment building has three-foot-thick wall nearly as strong as solid steel
- Cooling tower emits steam with no pollutants or radioactive substances
- All spent fuel from a plant since it started operating is stored safely at the plant
- **No emissions during normal operation**

Inside a Nuclear Power Plant



- A Containment Structure
- B Control Rods
- C Reactor
- D Steam Generator
- E Steam Line
- F Pump
- G Generator
- H Turbine
- I Cooling Water Condenser
- J Cooling Tower
- K Fuel Rods
- L Transformer

What about Fukushima?



Fukushima Facts

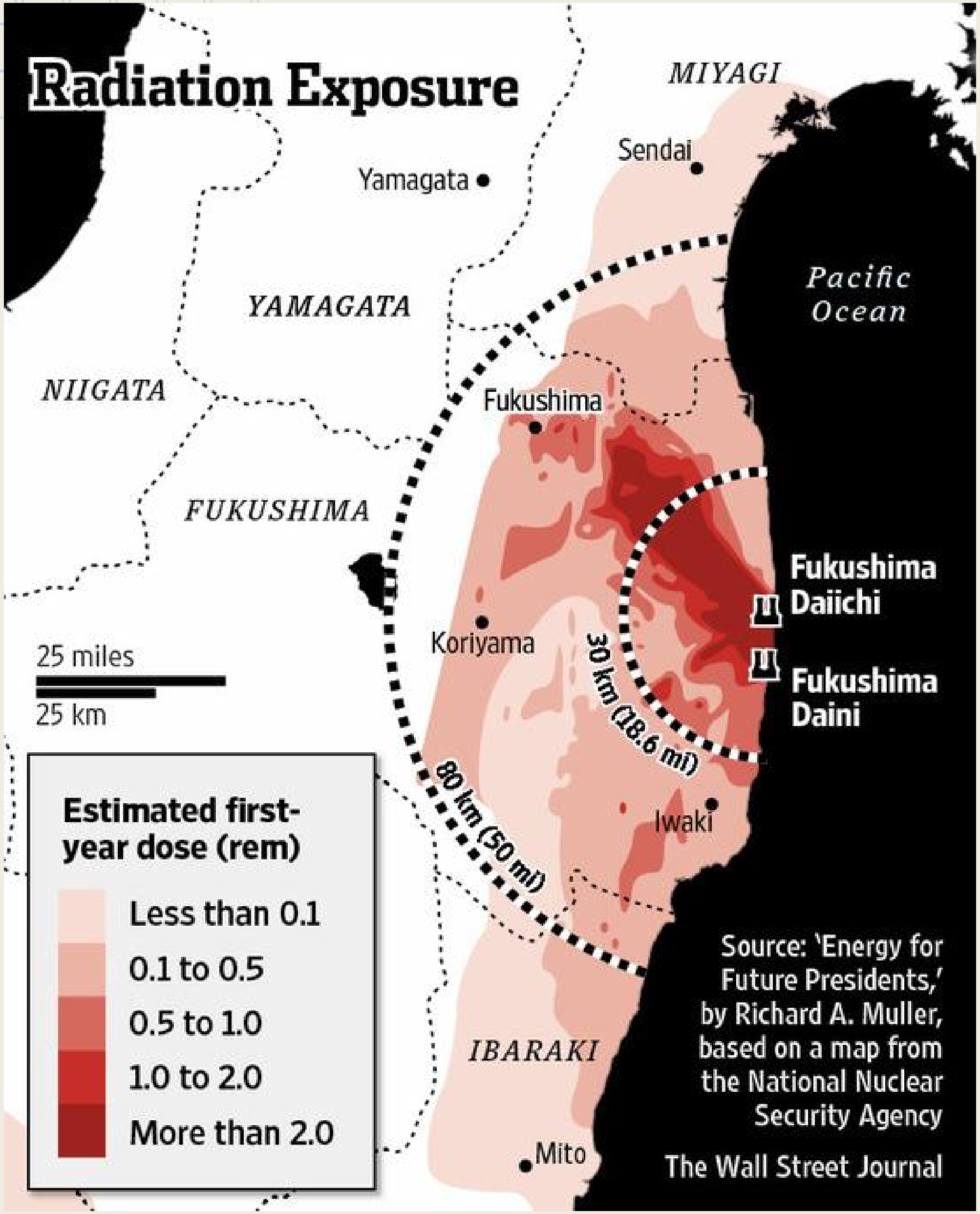
- **~20,000 deaths** due to 9.0 earthquake and 50-foot tsunami on March 11, 2011
- Three worker deaths at the nuclear plant (2 drowned, 1 hit by a crane)
- **Zero casualties caused by radiation** inside and outside the plant
- **Zero to 100 cancer deaths** projected in coming decades

source: American Nuclear Society, Special Committee on Fukushima

Radiation Exposure Basics

- ~1 Sv (sievert) short-term exposure causes radiation sickness, ~4 Sv causes death
- Avg American exposed to **6.2** mSv/yr from nature, medical procedures, etc.
- Denver gets extra **3** mSv/yr "Denver dose" (but has lower cancer rate than overall US)
- ICRP says evacuate at **1** mSv/yr above natural level (evacuate Denver?)

1 sievert = 1 Sv = 1000 mSv = 100 rem



"Denver dose" = 3 mSv/yr = 0.3 rem/yr

Fukushima Risk Assessment

World Health Organization press release:

28 FEBRUARY 2013 | GENEVA - A comprehensive assessment by international experts on the health risks associated with the Fukushima Daiichi nuclear power plant (NPP) disaster in Japan has concluded that, for the general population inside and outside of Japan, **the predicted risks are low and no observable increases in cancer rates above the baseline rates are anticipated.**

"Uninhabitable Nuclear Ghost Town"

Typical nuclear hysteria on the web

(visible damage NOT caused by nuclear plant!)

Uninhabitable Nuclear Ghost Town?

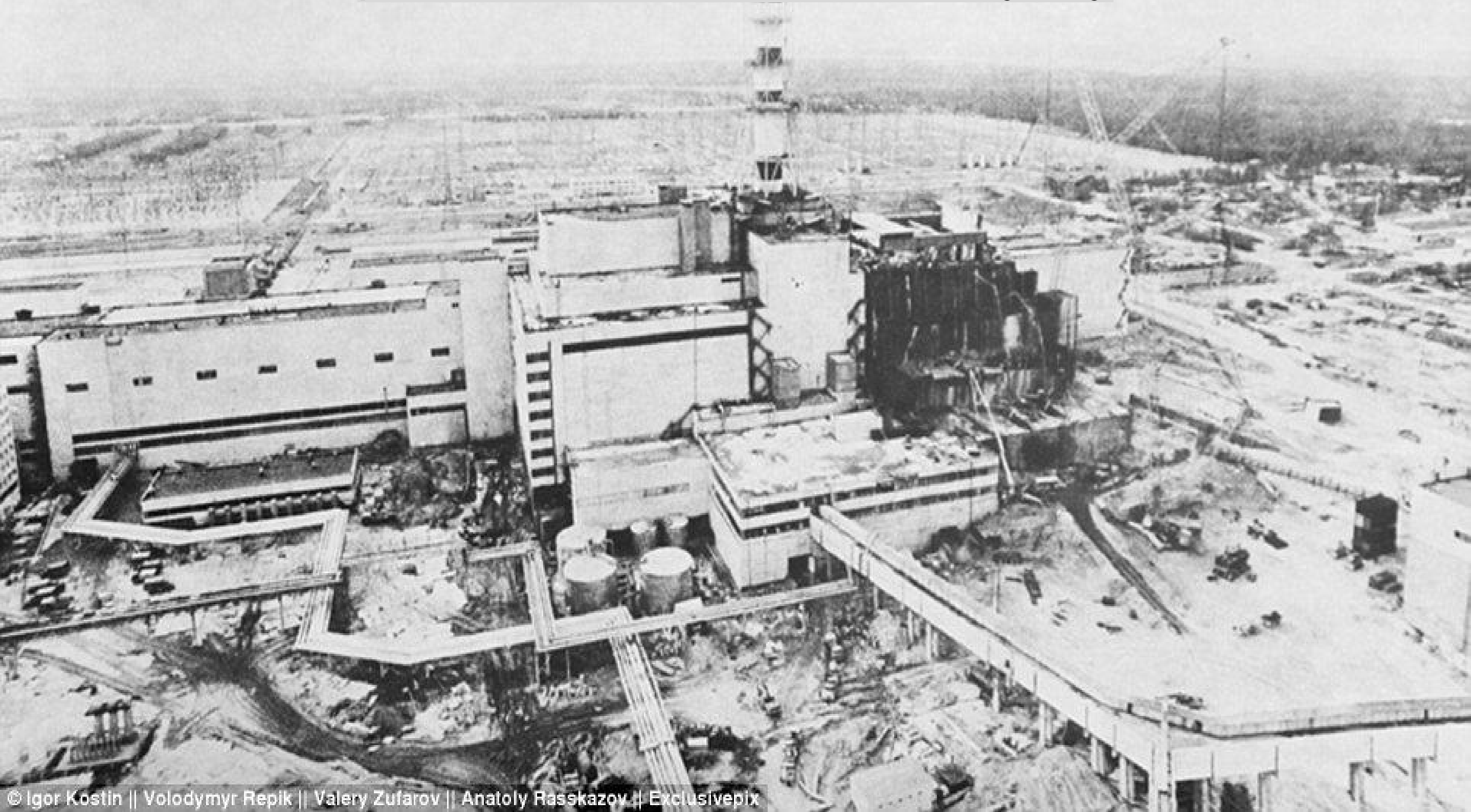
- Namie, Japan near Fukushima nuclear plant
- Highest radiation level ~220 mSv/yr
  - Guarapari, Brazil resort beaches have natural radiation of ~175 mSv/yr from the sand [link]
- Radiation levels now way down
  - Was likely below "Denver dose" within months
- Living there for many years will increase cancer risk negligibly if at all

Fukushima Alarmism

- Unscientific alarmist stories persist about global effects of Fukushima
- Fukushima released ~3.0E+16 Bq of radioactivity,[link] but
- The Pacific Ocean contains ~1.5E+22 Bq of natural radioactivity,[link] hence
- **Fukushima raised the radioactivity of the ocean by 2 millionths of its natural level** (i. e., raised the natural radioactivity by 1.000002 x)

What About Chernobyl?

No comparison with American nuclear power plants, but let's take a look anyway



Chernobyl Facts

- No containment structure or other basic safety features of US nuclear plants
- 64 deaths directly attributed to radiation (as of 2008)
- WHO projects 9,000 long-term cancer deaths,[link] other studies estimate more
- **Chernobyl casualty estimates relevant to Soviet nuclear power only**

Coal Disaster Equivalence

Fatalities due to emissions from coal power plants in the US alone occur at a rate of

- **One Fukushima every 1 to 3 days**
- **One Chernobyl every 9 months**

Global coal emissions cause as many fatalities as several Fukushima disasters *per day* -- with no news coverage!

Nuclear Meltdowns

After the 1979 TMI incident, anti-nuclear organizations and activists warned that radiation from a nuclear meltdown could kill *50,000* people *within weeks*.

The Fukushima meltdown (zero deaths) completely debunked those claims, yet it is often erroneously cited as a vindication of the anti-nuclear warnings.

Radioactive Emissions

The fly ash emitted by a coal power plant carries into the environment *100 times* more radiation than a nuclear power plant producing the same amount of energy.

--*Scientific American*, Dec 13, 2007

Yet the radiation from coal plants is far less dangerous than the particulates. Radiation from nuclear plants is negligible.

Nuclear Waste Disposal

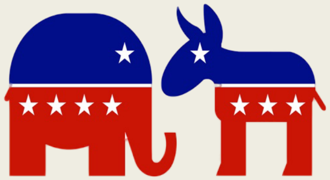
If the US went completely nuclear for *1,000 years,* the amount of land needed to dispose the spent fuel would be less than what is currently needed for the coal ash that accumulates in *one week*.

The widespread notion that nuclear waste disposal is an "unsolved problem" is a modern myth. The "unsolved problem" is irrational fear of spent nuclear fuel.

Politics of Nuclear Waste

Nearly all the spent nuclear fuel that has been generated by US commercial nuclear power since it started in the 1960s is still stored safely at the plants, where it has done no harm.

The reason it hasn't been moved to a permanent storage site is politics driven by misinformation.



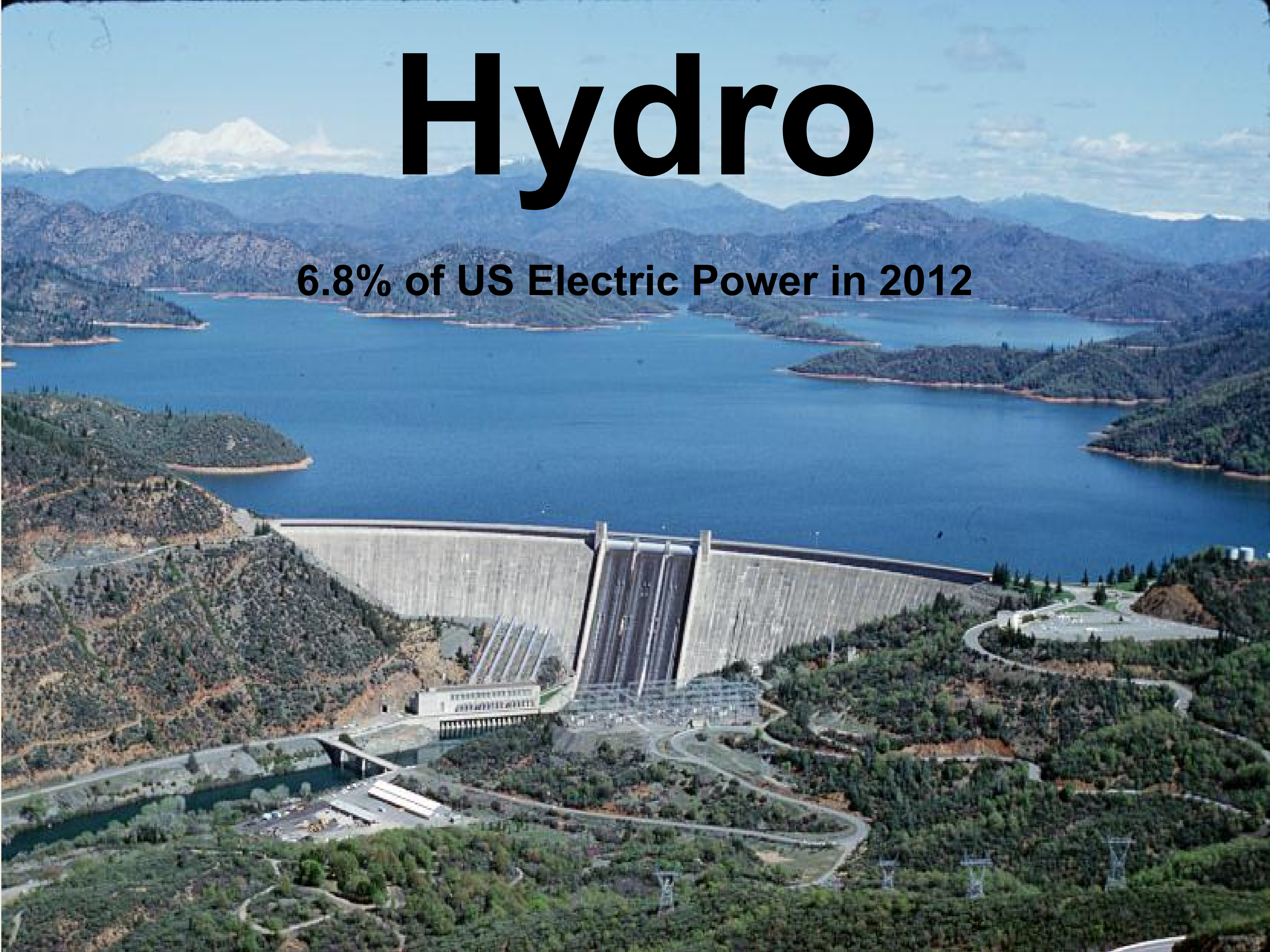
"Dangerous for Hundreds of Thousands of Years"

- Nuclear waste has a range of half-lives
  - Intensely radioactive elements decay rapidly
  - Elements with long half-lives have low radioactivity, and some are still usable fuel
- Toxic chemicals in coal ash (e.g., lead, mercury, arsenic, and asbestos) have an *infinite half-life* and are therefore *dangerous forever* (and, unlike nuclear waste, are dumped into the environment)

Dry Storage of Spent Nuclear Fuel

60,000,000 tons of coal saved

dry cask storage at decomissioned Connecticut Yankee nuclear power plant


Hydro
6.8% of US Electric Power in 2012

Dam Failures

- 1928 - Santa Clarita, California: 600 dead
- 1963 - Vajont Dam, Italy: 2000 dead
- 1979 - Morbi, India: up to 15,000 dead
- 1975 - Banqiao Reservoir, China: **171,000 dead** (within minutes or weeks, not decades later from cancer)

These were ***~20 times more deadly than Chernobyl*****.** A major earthquake can cause a dam failure. Should we abandon hydro?

Media Double Standard

Nuclear power is held to a much higher standard and level of scrutiny than any other source of energy.

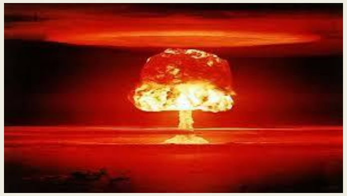
A complete lack of perspective in news coverage keeps the public from realizing that nuclear power is the safest and cleanest form of large-scale energy generation.

Academic Bias Against Nuclear Power

Mark Z. Jacobson

- Stanford Prof. of Civil and Environmental Eng.
- Published in top academic journals
- Author of textbooks on atmospheric modeling
- Testified before Congress several times
- Promotes aggressive use of wind power

Published a paper that counted the effects of hypothetical nuclear wars in the CO2 emissions of nuclear power[link]



Natural Gas

30.4% of US Electric Power in 2012

Metcalf Energy Center, San Jose, CA

Natural Gas

- Generates less than half as much CO2 per unit of energy as coal
- Hydraulic fracking recently brought cost down to less than coal
- Much cleaner than coal, but nowhere near as clean as nuclear power
- Good short-term economics, but not necessarily a good long-term solution
  - Proven reserves on the order of a century
  - Good bridge to long-term nuclear development

Advantages of Natural Gas over Coal

Coal: $C + O_2 \longrightarrow CO_2$

Gas: $CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$

- Natural gas (methane) produces less than half as much CO2 per kWh as coal, with no particulates, ash, sulfur, or other pollutants
- Combined-cycle (gas turbine + steam turbine) is more efficient (~55%) than coal steam cycle (~35%)

400MW (MEGAWATT) GAS TURBINE

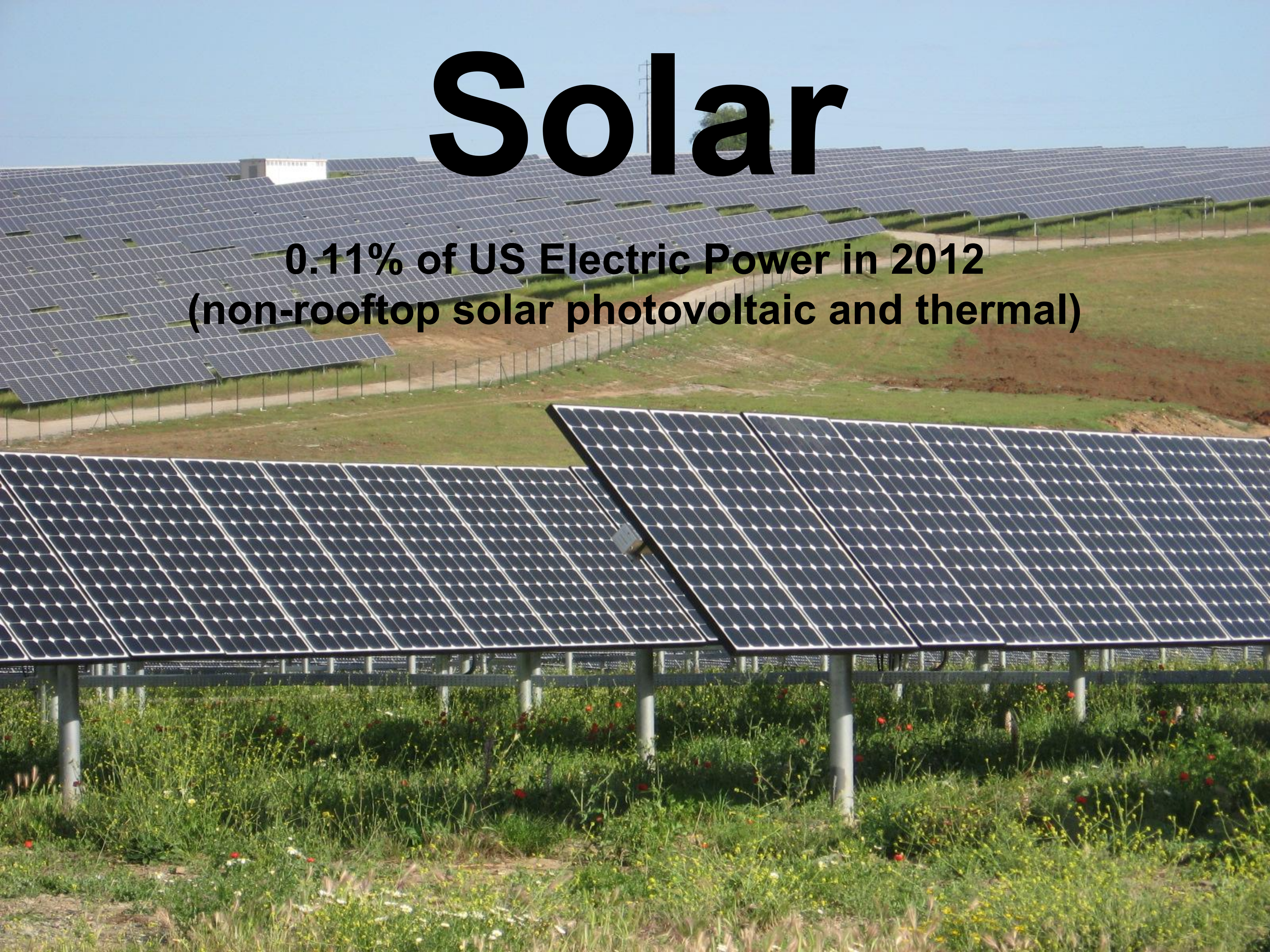
Steam Turbine in a Workshop

Wind

3.5% of US Electric Power in 2012

Wind Power

- Capacity factor ~15-40% (non-ideal winds)
- A wind farm of 1 GW *average* power takes *100-200 sq miles* of land (or water)
  - Land still usable for farming or other activities
  - Degraded natural views
  - ATC radar noise
- Power proportional to *cube* of wind speed
  - Power output sensitive to wind speed
  - Power output erratic in gusting wind
- More expensive than coal/gas (more later)
  - Many utilities forced to buy and pass along cost


Solar
0.11% of US Electric Power in 2012
(non-rooftop solar photovoltaic and thermal)

Solar Power

- Capacity factor ~10-28% (night, clouds, etc.)
- A solar farm of 1 GW *average* power takes *20-50 square miles* of land
  - Huge amounts of raw materials (concrete, steel, ...)
  - Huge amounts of toxic chemicals
  - ~40 x the land of a 1 GW nuclear plant
  - Can be put on buildings and over parking lots

- More expensive than coal/gas (more later)
  - Many utilities forced to buy and pass along cost
- Good for remote off-grid sites but not for large-scale energy production

Capacity Factor

Capacity ratings for wind and solar can be misleading. Capacity factor is the ratio of average generated power to peak rated power.

- **Wind** capacity factor ranges from **~15-40%**, depending on location wind consistency
- **Solar** capacity factor ranges from **~10-28%** depending on location, and accounting for night, sun angle, clouds, dirt, etc.
- **Nuclear** capacity factor **~90%**

Cost of Energy Conversion

Sunshine and wind are "free," but conversion to electricity is expensive in terms of

- Money
- Labor
- Land
- Raw materials
- Environmental degradation

Proponents emphasize the "free" part but seldom mention the high conversion costs.

Dispatchable vs. Contingent Power

Since load must be balanced on a continuous basis, units whose output can be varied to follow demand (dispatchable technologies) generally have more value to a system than those whose operation is tied to the availability of an intermittent resource.

-- US Energy Information Administration

Cost/kWh not directly comparable between dispatchable and non-dispatchable (contingent or intermittent) sources

Wind and Solar Power Not Dispatchable

- Large-scale energy storage not yet efficient and economically practical
- Wind/solar need near full-capacity backup when wind not blowing or sun not shining
- Capital cost of wind/solar farm is in addition to cost of dispatchable backup plant
- Backup power less efficient with partial or rapidly varying load, like a car in city traffic

Capital Cost and Marginal Fuel Cost

- Wind and solar power need full-capacity dispatchable backup power source
- Wind/Solar reduce marginal fuel cost but not capital cost of backup plant
- Nuclear fuel cost is very low, particularly for advanced molten-salt reactors
- Once a nuclear plant is built, wind/solar save very little on nuclear fuel cost -- their huge capital expense makes no economic sense

Cost of Non-Dispatchable Energy

The entire value of wind and solar energy is in reducing the fuel consumption and operating cost of the backup dispatchable energy source.

The total amortized capital cost of wind and solar energy should therefore be compared with the marginal fuel plus operating cost of the dispatchable backup.

Electric Power Costs

Projected costs in 2018, $/MWh

plant type	capital cost	fixed O&M	variable O&M + fuel	total cost
combined-cycle gas	15.8	1.7	48.4	67.1
advanced nuclear	83.4	11.6	12.3	108.4
wind	70.3	13.1	0.0	86.6
solar PV	130.4	9.9	0.0	144.3

source: US Energy Information Administration, "Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013" (selected fields from Table 1)

Electric Power Costs

Projected costs in 2018, $/MWh

plant type	capital cost	fixed O&M	variable O&M + fuel	total cost
combined-cycle gas	15.8	1.7	**48.4**	67.1
advanced nuclear	83.4	11.6	**12.3**	108.4
wind	70.3	13.1	0.0	**86.6**
solar PV	130.4	9.9	0.0	**144.3**

source: US Energy Information Administration, "Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013" (selected fields from Table 1)

Cost Comparison

non-dispatchable (total) / dispatchable (variable O&M + fuel)

- wind / gas = 86.6 / 48.4 = 1.8
- solar / gas = 144.3 / 48.4 = 3.0
- wind / nuclear = 86.6 / 12.3 = 7.0
- solar / nuclear = 144.3 / 12.3 = 12

Solar energy costs 12 x more than it can save in nuclear energy. Wind energy costs 7 x what it can save in nuclear energy.

Nuclear Power Plant Capital Costs

- Early nuclear plants cost ~$170M in early 70s and proved to be safe
- Plant cost increased more than 10x within 15 years (even after adjusting for inflation)
- Costs were driven up by excessive regulation and environmental obstructionism
- Inherent safety and low pressure of MSR/LFTR can dramatically reduce cost
- Standardization and modularization can also dramatically reduce capital cost
- New regulations needed for new designs

Load Following Ability

dispatchable power plant type	max change in 30 seconds	max ramp rate per minute
open-cycle gas turbine	20-30%	20%
combined-cycle gas	10-20%	5-10%
coal	5-10%	1-5%
nuclear	up to 5%	1-5%

Backup power plants respond slowly when the wind suddenly slows or the sun gets blocked by clouds. Open-cycle gas: fastest response but least efficient.

data source: "Nuclear Energy and Renewables," OECD NEA 2012

German Energy Debacle

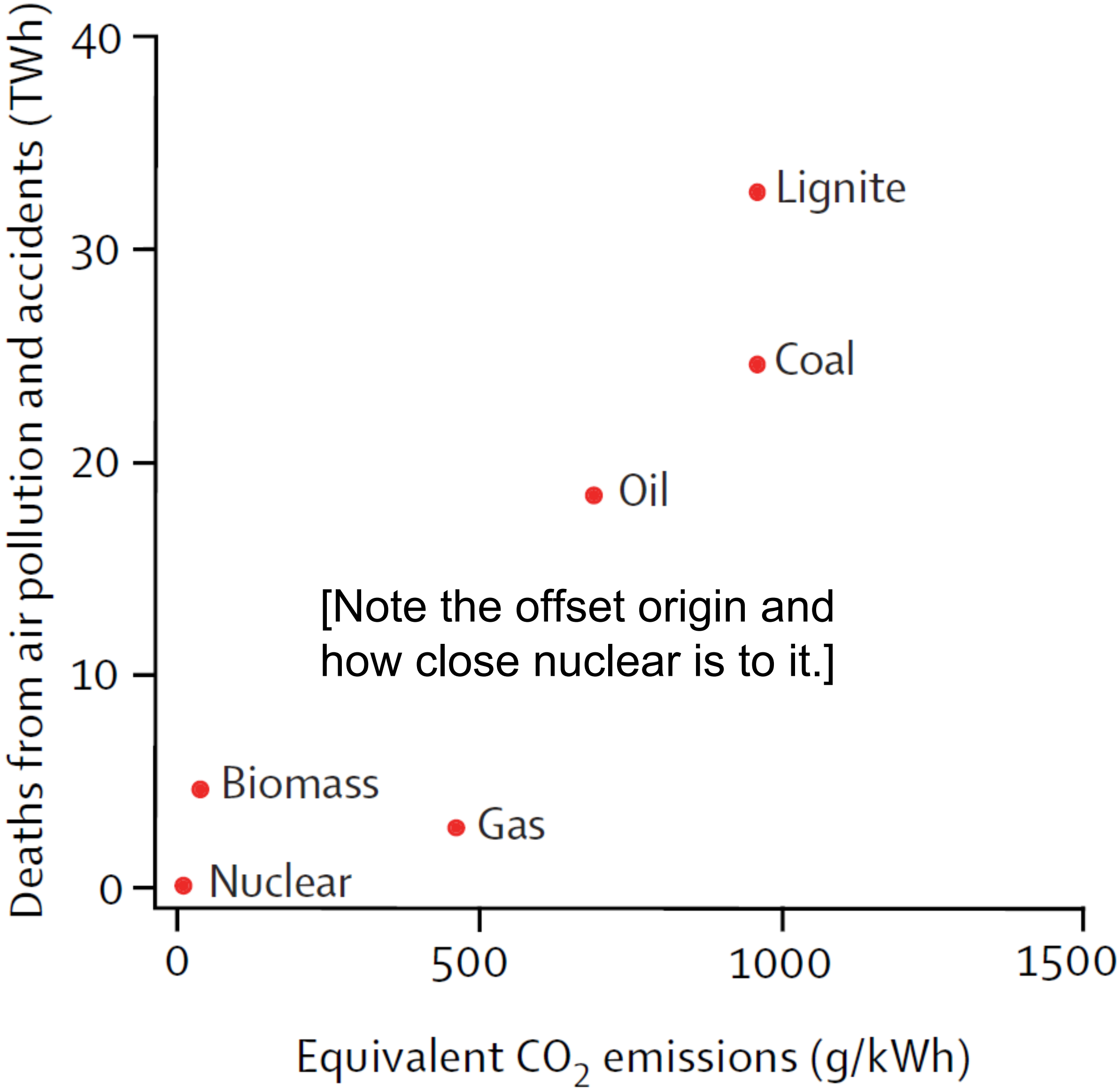
- After Fukushima, public pressure forced Germany to abandon nuclear power
    - 8 plants closed, all 17 to be closed by 2022
- Aggressive solar/wind program praised by environmentalists but
    - Costly in subsidies and utility rates
    - Solar+wind capacity factor < 5% days at a time
- **Increased dependence on gas/coal**
    - **27 new natural gas plants still due online**
    - **Now building/planning ~20 new coal plants**

Global Warming and Nuclear Power

The case for nuclear power is strong in terms of safety, environmental impact, and economics.

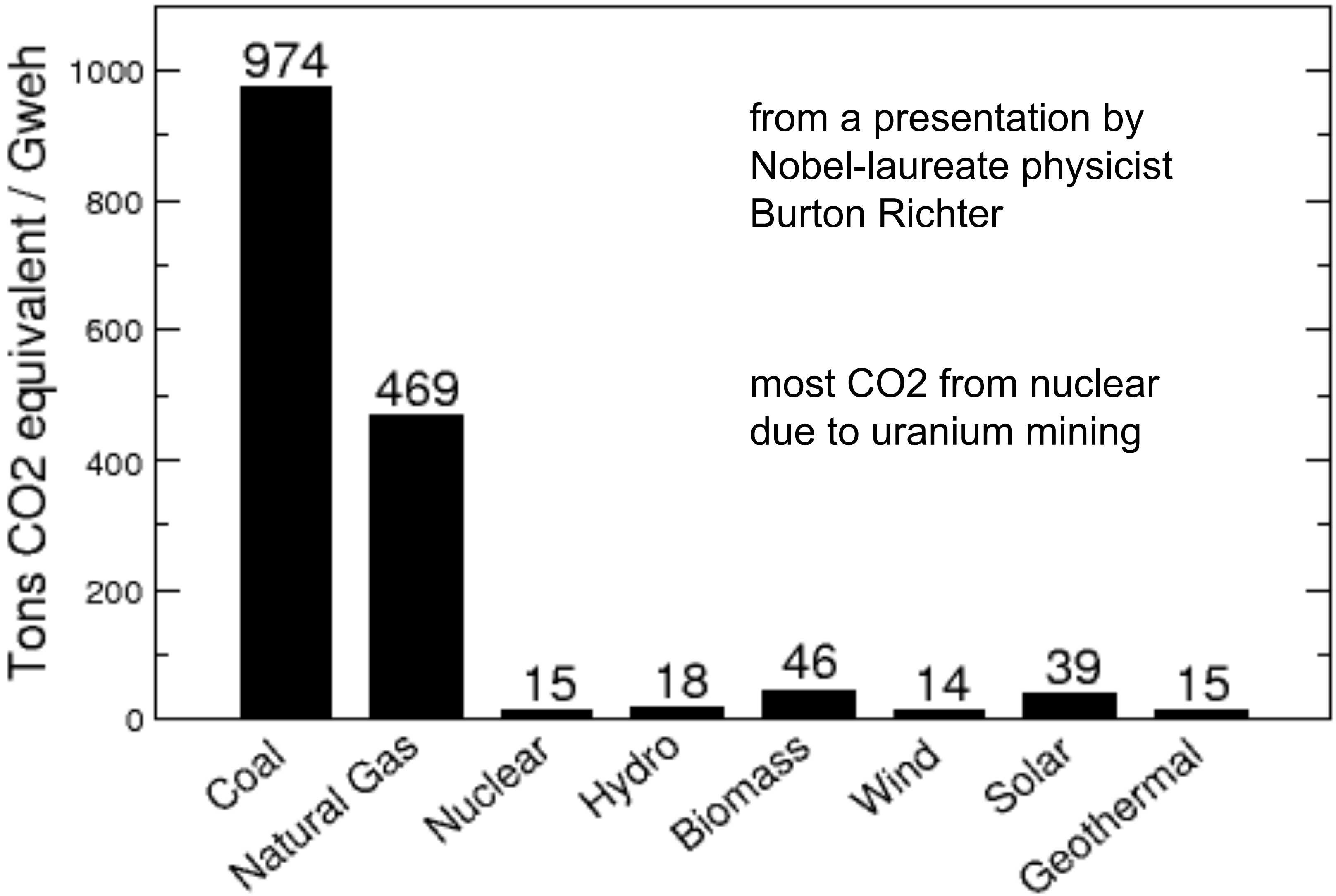
If human-caused global warming is a serious problem, the case for nuclear is stronger yet.

Both sides of the global warming debate can agree on nuclear power. Energy policy and planning need not depend on the outcome of any debate over global warming.



source: “Electricity Generation and Health,” *Lancet*, Sep 15, 2007, fig. 3

CO2 Emissions of Electric Power Sources



Greenhouse Gas Emissions

Question: What socio-political phenomenon is more responsible than anything else for the fact that our current rate of greenhouse gas emissions are as high as they are?

Answer: The post-TMI anti-nuclear hysteria that blocked the growth of nuclear power, forcing us to use carbon-based fuels (coal and gas) for over 2/3 of our electricity

Nuclear the Only Viable Solution to Global Warming

- 1200 new coal plants planned worldwide, and one goes online per week in China
- Wind/solar cannot even keep up with growth, let alone replace installed base
- Nearly all nuclear plants that are closed (or not built) are replaced with coal or gas
  - A natural gas plant produces as much CO2 as **30** nuclear plants of equal capacity
  - A coal plant produces as much CO2 as **60** nuclear plants of equal capacity

Who Benefits Most from Cheap Electricity?

- Wealthy don't worry about utility bills
- Middle class benefit from cheap electricity
- Poor benefit most from cheap electricity, especially destitute poor in third world

Many who claim to care about the less affluent want to deliberately drive up non-renewable energy prices to force conservation and to make renewable energy more competitive.

Energy Subsidies

Wind and solar power are heavily subsidized, as was nuclear, but not the same way:

- Nuclear power was a spinoff of military R&D on nuclear weapons
- Government did R&D on nuclear power, gave tax breaks for industry R&D
- Wind and solar subsidies have gone directly to consumers and utilities

Subsidies are more appropriate for R&D than for production, marketing, and sales

Subsidies and Mandates for Wind and Solar Power

- Direct payments or tax credits for installing rooftop solar panels
- Loan guarantees or tax breaks for equipment manufacturers (e.g., Solyndra)
- Direct payments or tax incentives for utilities to use wind or solar power
- Mandates for utilities to buy excess rooftop solar power at retail rates
- Mandates for utilities to use a certain percentage of renewable energy

Net Metering

- US law requires utilities to buy back excess rooftop solar power at retail rate
- Comparable to forcing grocery stores to buy home-grown produce at retail rate
- If required at all, buy back should be at wholesale rate (varies with demand)
- Buyback at retail rate forces utilities to pass along to other ratepayers the costs for grid infrastructure, labor, and overhead

Selective Optimism

Proponents of renewable energy are generally optimistic about the potential for future wind and solar technology advancements.

But apparently they think nuclear technology stopped advancing 50 years ago. They want to end nuclear power because a nuclear plant built 40 years ago had problems due to a natural disaster that killed 20,000 people.

Back to the Future of Nuclear Power

Imagine a new kind of nuclear power plant that:

- **cannot "melt down"** (the fuel is already liquid)
- **generates almost no waste** (< 1% of the tiny amount that current nuclear plants produce)
- **is based on proven technology** (from the 1960s)
- **uses fuel that will last thousands of years**
- **is unlikely to contribute to proliferation**
- **is simpler to build and operate than current nuclear plants** (operates at low pressure)

Molten-Salt Reactor Experiment

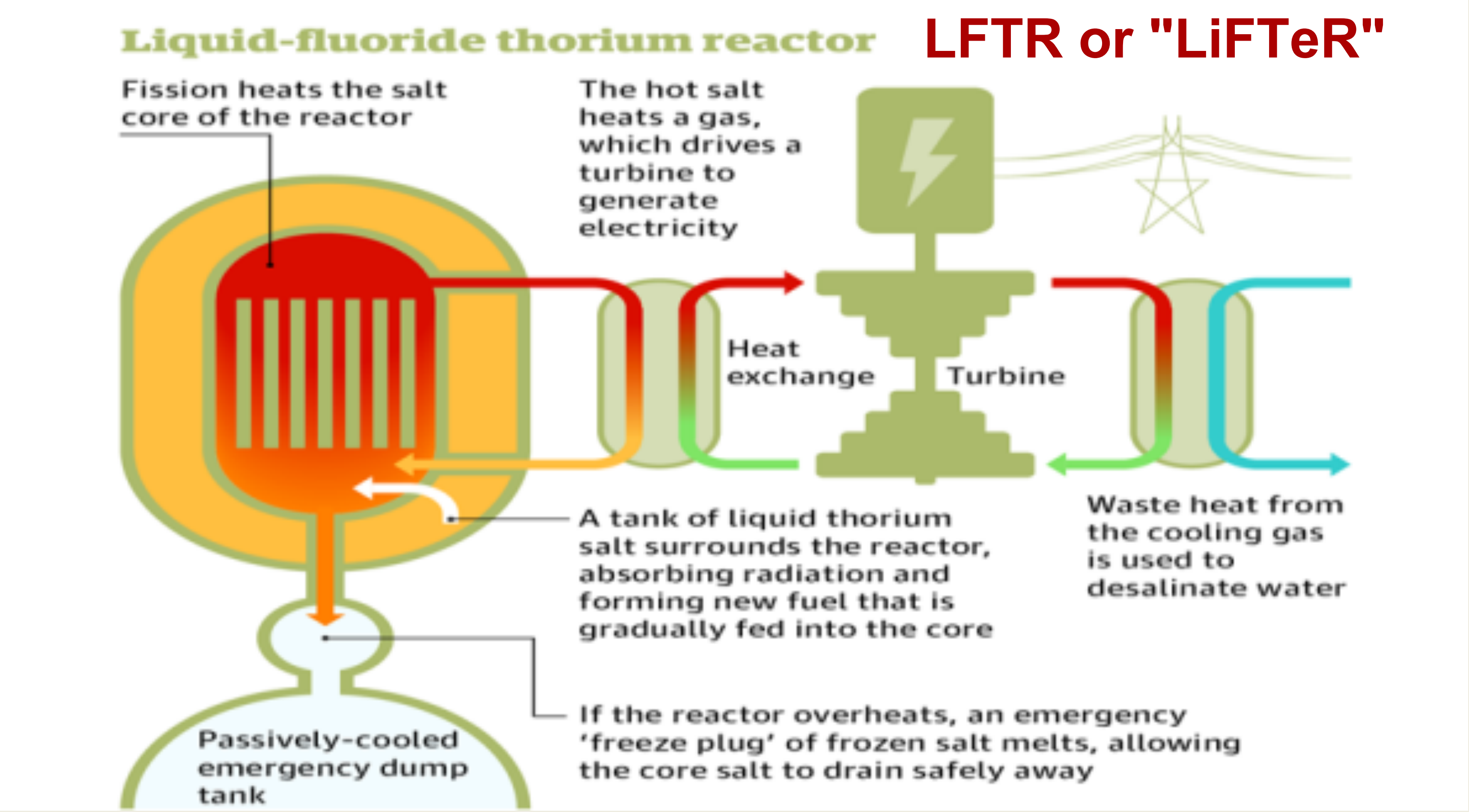
- MSRE at Oak Ridge National Lab, 1964-69
- Run by physicist Alvin Weinberg
- 13,000 hours (541 days) at full power
- Demonstrated feasibility of MSR

Weinberg saw this experiment as the start of an energy revolution, but the program was terminated under Nixon in 1974. Civilian nuclear research was subordinate to the military, and by that time the navy was committed to solid uranium fuel. Redirection of funds for political reasons also played a role.

One type of MSR is called the LFTR (next).

Liquid Fluoride Thorium Reactor

LFTR or "LiFTeR"



Thorium Energy Density

Average US energy consumption (including industrial) **per person per day**:

18 pounds of coal +
16 pounds of oil +
<u>10 pounds of natural gas</u>
= 44 pounds of carbon-based fuel

An amount of thorium about the size of a ping-pong ball can provide all the energy you will need for your entire lifetime.

Rediscovery of Thorium

Kirk Sorensen, former **NASA** nuclear engineer, rediscovered the MSR several years ago in the old literature and has started a company to develop it.

Thorium Energy Alliance has now held several annual conferences with many top scientists and engineers.

Advantages of Liquid Nuclear Fuel

Conventional solid nuclear fuel gets contaminated and must be discarded before **1%** of the fuel is consumed.

Liquid nuclear fuel can be chemically processed with the reactor online to add fuel and remove contaminants, allowing **~99%** of the fuel to be consumed, hence the tremendous efficiency and waste-reduction advantages.

Advantages of Low Pressure and High Temperature

- MSRs operate at atmospheric pressure
  - Conventional reactors at ~150x higher pressure
  - No massive pressure vessel needed
  - Less mechanical stress on components
  - Radioactive materials easier to contain
- MSRs operate at around 700 deg C
  - Conventional reactors operate at ~315 deg C
  - Higher temp means higher thermal efficiency > 45% compared to ~35% for conventional reactors

$$\text{Carnot efficiency limit} = 1 - T_{atm} / T_{reactor}$$

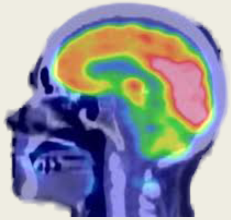
Passive Failsafe LFTR Design

- Low (atmospheric) operating pressure eliminates pressure vessel and reduces stress on components
- Thermal stability: fission reaction slows as reactor temperature rises (no control rods needed)
- No hydrogen or other chemicals that can burn or explode (as happened at Chernobyl and Fukushima)
- Large thermal safety margin due to high boiling point of molten salts (>1300 deg C)
- Simple freeze plug melts to safely drain fuel into a holding tank if reactor overheats
- **No power or moving parts required for safety or emergency cooling**

Valuable MSR Byproducts

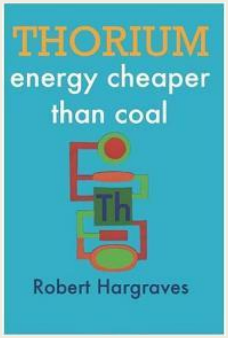
The high operating temperature can be used to economically desalinate seawater -- a major benefit in many parts of the world.

The radioisotope byproducts can be used for nuclear medicine -- and could be worth more than the energy produced.

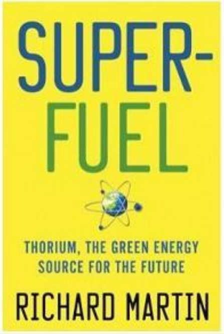


Recommended Books

Thorium: Energy Cheaper than Coal by Robert Hargraves (2012): excellent overview of energy technology and economics -- a must read for anyone interested in energy



Superfuel by Richard Martin (2012): informative history of nuclear technology and a vision for the future



Websites

- **EnergyFromThorium**.com - Kirk Sorensen's site with technical information, history, and a discussion forum
- **ThoriumEnergyAlliance**.com - Educational/Advocacy site operated by Thorium Energy Alliance, which runs the annual Thorium Energy Conference

Thorium MSR Projects

- Fuji MSR (molten-salt reactor) being developed by a consortium from Japan, US, and Russia
- Chinese Thorium MSR Project - startup budget of $350 million and staff of 750 planned by 2015
- Flibe Energy - Kirk Sorensen's company to develop small modular LFTRs, initially for military bases
- Thorium Energy Generation - Australian R&D company to develop LFTRs in joint venture with Czech Republic

Conclusions

- Conventional nuclear power is orders of magnitude safer and cleaner than coal
- Thorium-based nuclear power is orders of magnitude safer and cleaner yet
- Natural gas is much cleaner than coal but is nowhere near as clean as nuclear power
- Wind and solar power are NOT the answer for large-scale energy production
- Nuclear power is the best way to mitigate human-caused global warming

What I Hope You Remember

- Misinformation about energy is harming our economy *and* our environment
- Wind and solar power are not the answer to our large-scale energy needs
- Nuclear power is the real "green energy" and the clear solution for global warming
- **We could be on the verge of an energy revolution if we can overcome the ignorance**

Recommended Reading

- FAQ: Radiation from Fukushima "… even short distances from Japan, the Pacific will be safe for boating, swimming, etc."
- Ocean Radiation and the Fukushima Disaster "... dispel myths about Fukushima radiation that are prevalent on the internet."
- Snopes declares "Fukushima Emergency" story false "... any kind of release in Japan would be undetectable here, ..."
- Fossil fuels are far deadlier than nuclear power "Nuclear came out best, and coal was the deadliest energy source."
- The Hiroshima Syndrome "An important independent source of factual nuclear energy information."
- Green Energy Bust in Germany "... when you look beyond the cherry-picked hype, the results are dismal and disquieting."
- Germany's Energy Poverty: How Electricity Became a Luxury Good "Germany's aggressive and reckless expansion of wind and solar power has come with a hefty price tag for consumers, and the costs often fall disproportionately on the poor."

Next Time

How Nuclear Power can be used to Mass-Produce Economical Homegrown Fuel for Transportation

The End

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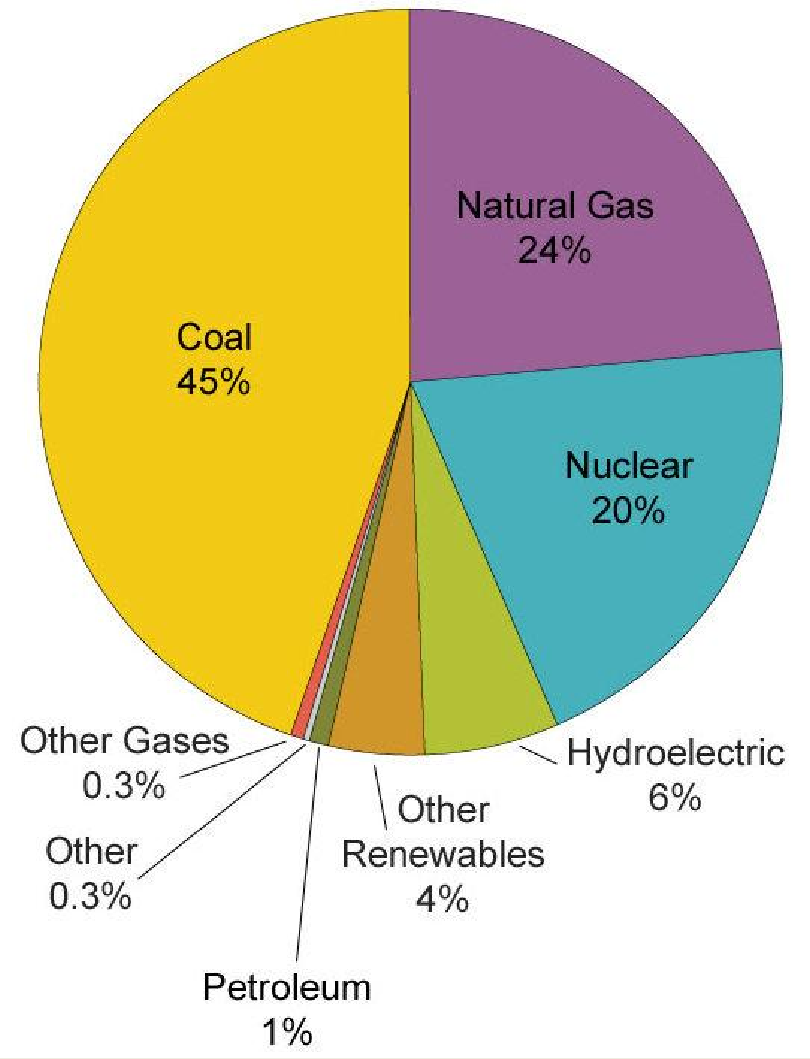
 Now please go out and educate the public. We need your help in fighting misinformation and ignorance about energy in general and nuclear power in particular.

backup slides

US Electric Power (2010)



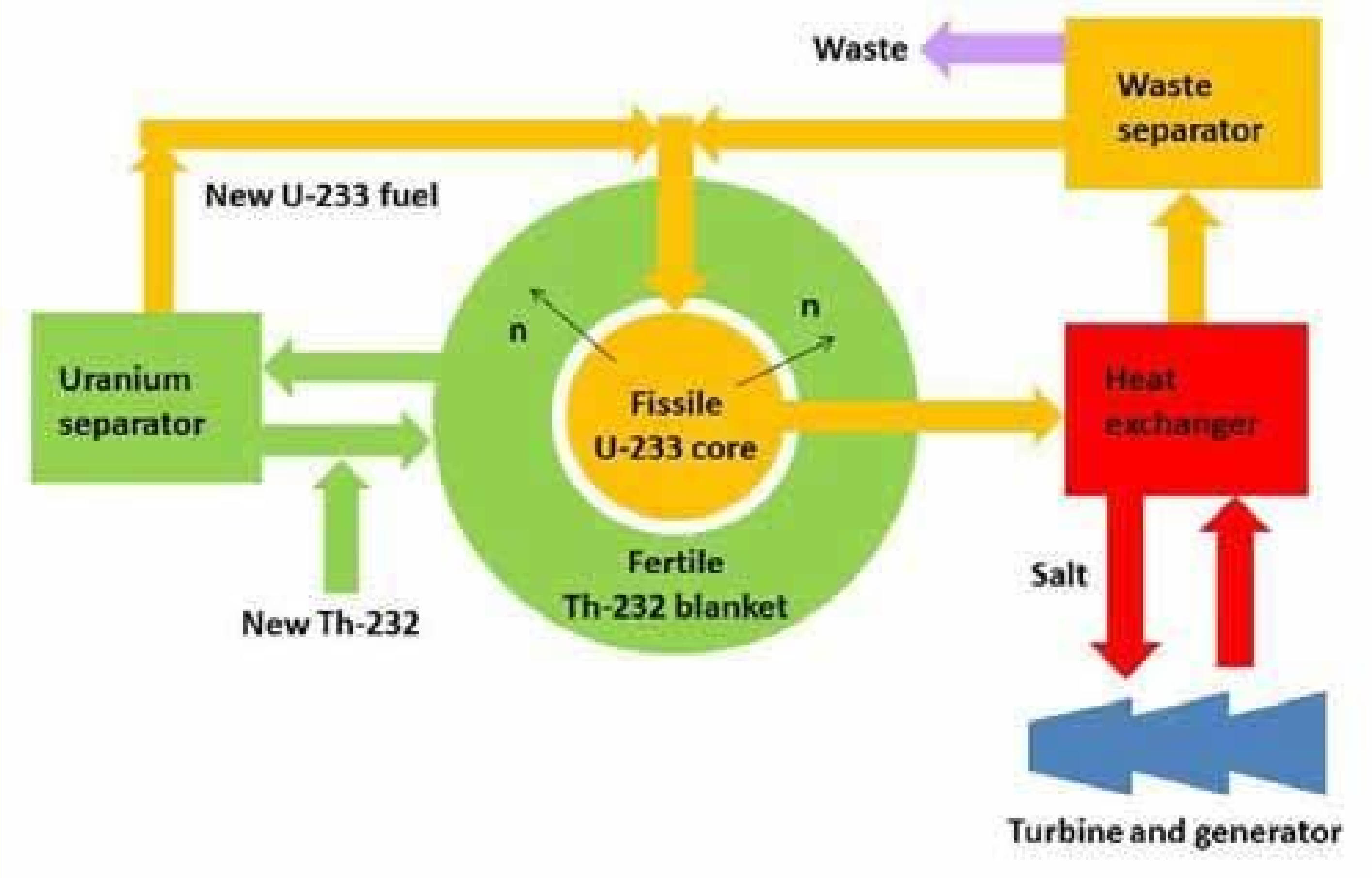
4.1 PWh total

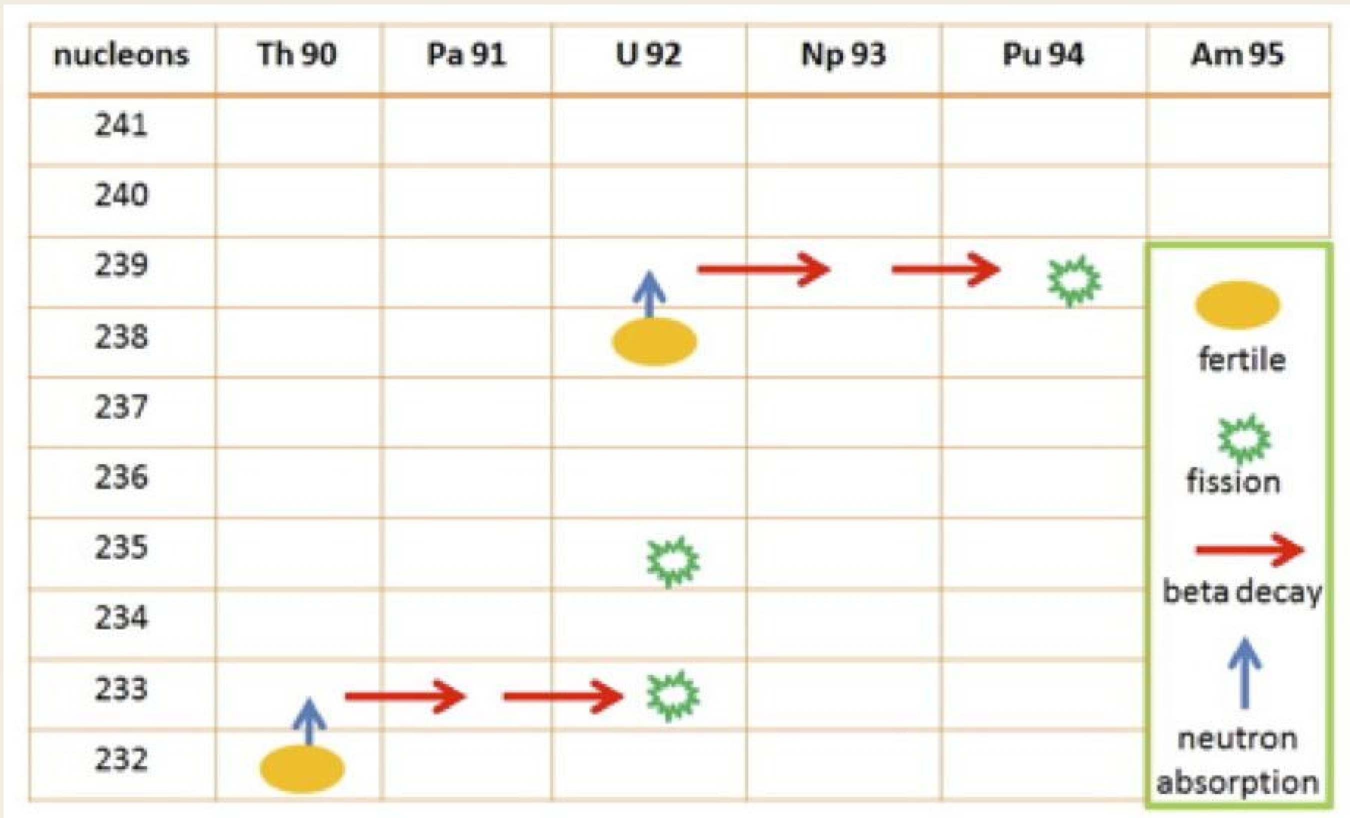
PWh: petaWatt-hour
peta = 10^{15}

source:
US Energy
Information
Administration

(Watt-hours are technically "energy," but electric "power" sounds better.)

CO2 Emissions: Germany vs. France


Waste
Waste separator
New U-233 fuel
n
n
Uranium separator
Fissile U-233 core
Heat exchanger
New Th-232
Fertile Th-232 blanket
Salt
Turbine and generator



neutrons transmute fertile thorium-232 to fissile uranium-233

Linear No-Threshold (LNT) Model

- Health effects of low-level radiation are difficult or impossible to measure
- LNT model: health effects of low-level radiation linearly interpolated from observable effects of high-level radiation
  - widely assumed by regulatory authorities
  - errs on the side of caution
  - defies common sense -- drinking 1 bottle of wine per week for a year is not as harmful as drinking 52 bottles in one night!

Thorium Energy Density

Average US energy consumption (including industrial) **per person per day**:

18 pounds of coal +
16 pounds of oil +
10 pounds of natural gas
= 44 pounds of carbon-based fuel

An amount of thorium about the size of a ping-pong ball can provide all the energy you will need for your entire lifetime.