# Current Status and Future Prospects of Nuclear Energy Worldwide
# (세계 원자력의 현황과 전망)

Presentation at KAIST
January 25, 2019

Yoon Il Chang (장윤일)
Argonne Distinguished Fellow, ANL
KAIST 원자력 및 양자공학과 초빙교수

# Richard Rhodes
# Nuclear Renewal: Common Sense About Energy

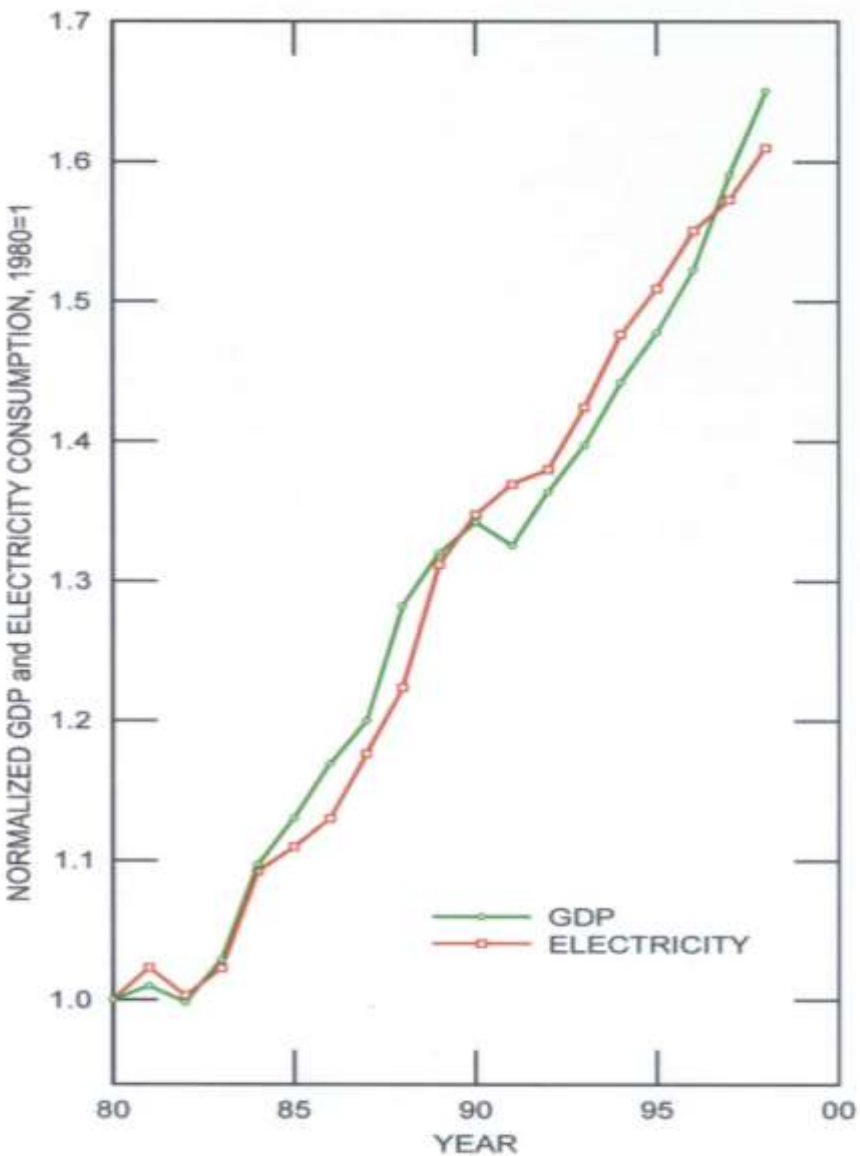
"Satisfying human aspiration is what our species invents technology to do. Some Americans, secure in comfortable affluence, may dream of a simpler and smaller world. However noble such a dream appears to be, its hidden agenda is elitist, selfish, and violent. Millions of children die every year for lack of adequate resources – clean water, food, medical care – and the development of those resources is directly dependent on energy supplies. The real world of real human beings needs more energy. With nuclear power, that energy can be generated cleanly and without destructive global warming. Whether it will be or not depends on leadership and public education. Where nuclear power is concerned, in both departments the United States has a long way to go."

# Outline

- Worldwide Energy (Electricity) Demand
- Current Status of Nuclear Energy Worldwide
- Why Nuclear Energy?
- Leadership
- Public Education

# Electricity is Engine of Economic Growth

- Over 20 years (1980-2000), the per capita GDP and electricity growth rate was identical in the U.S. on an annual basis or cumulatively.
- Electricity consumption is about 40% of the total energy (about 30% transportation and 30% others).

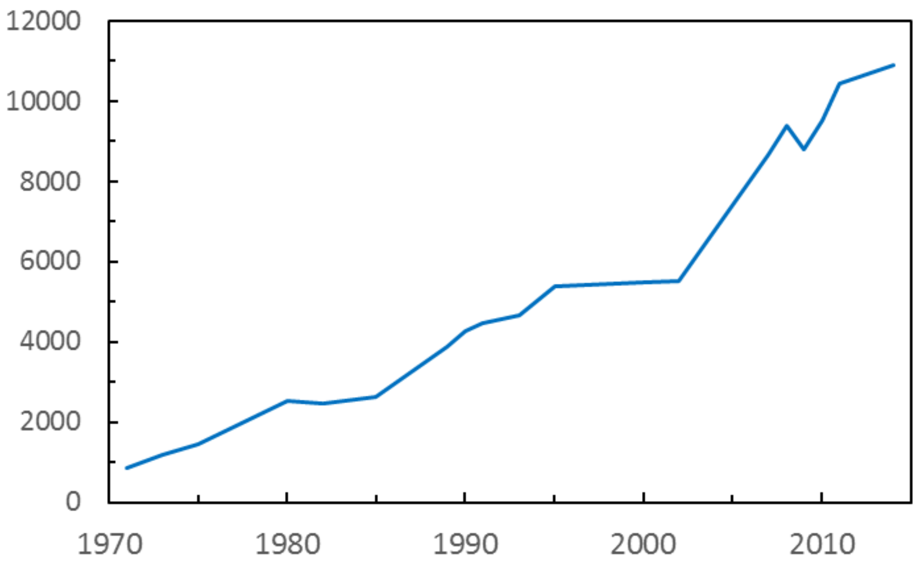



U.S. Electricity Consumption and GDP Trends

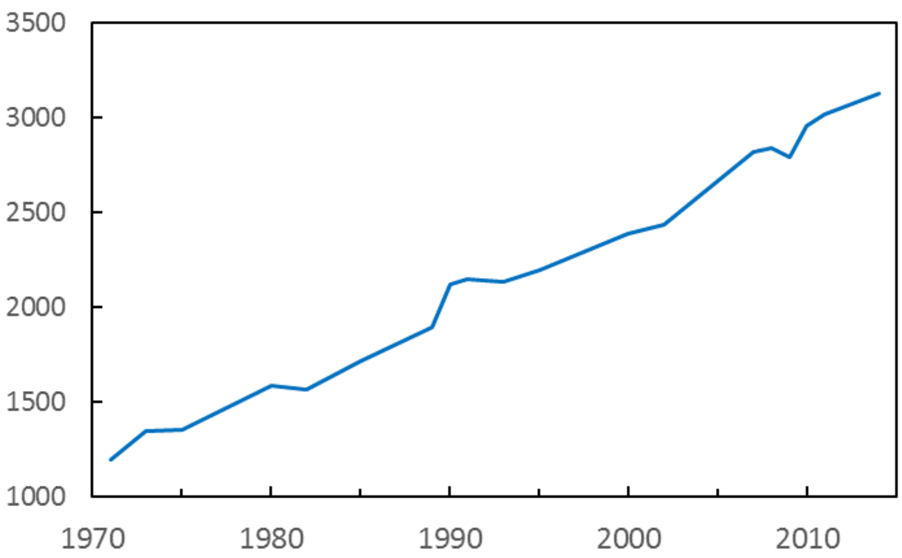
# Worldwide Data 1965- 2014

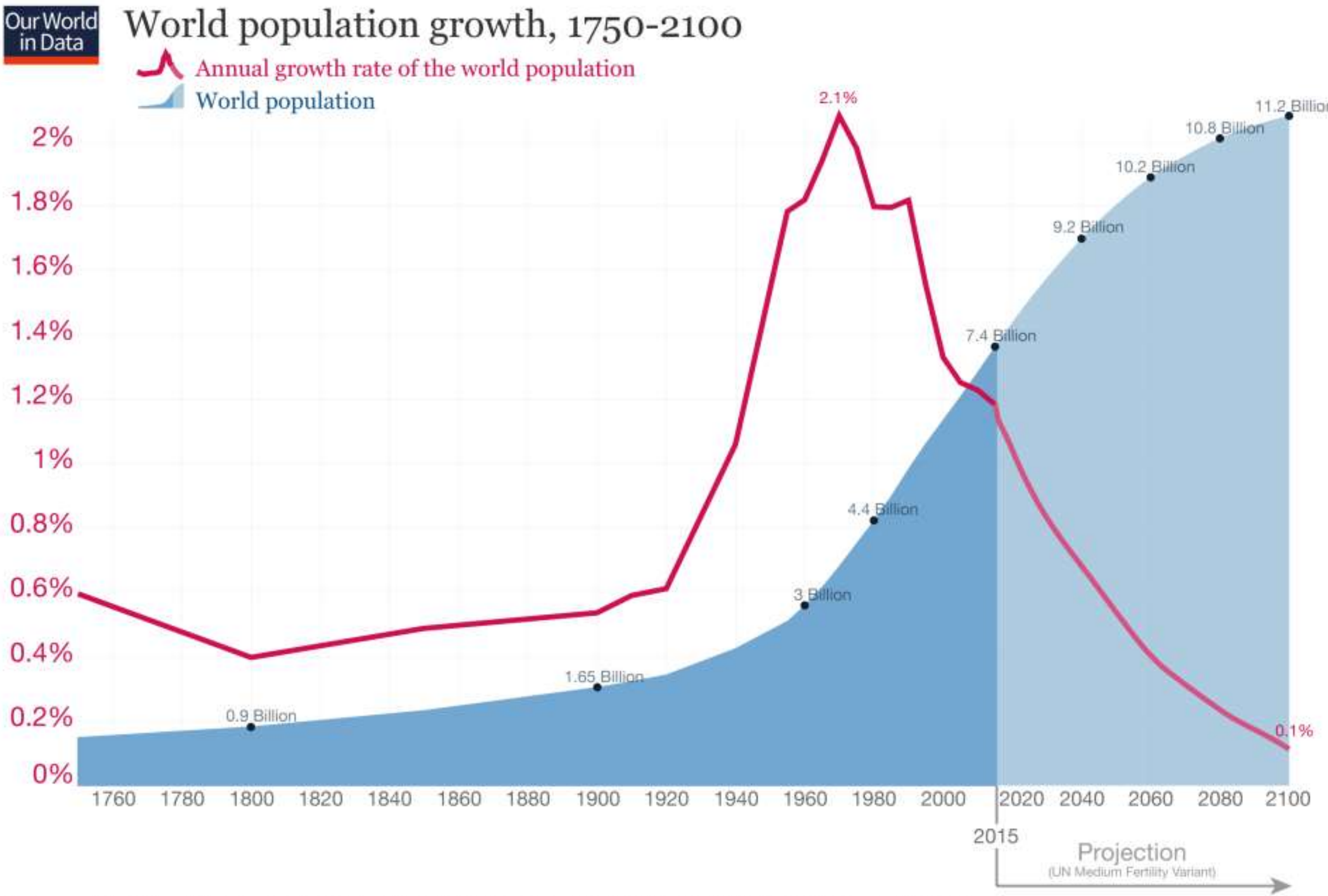
- Worldwide data on per capita GDP and per capita electricity show continuous growth in the last 50 years.
- It appears this linear growth will continue at least through 2050 and far beyond.

Worldwide per capita GDP
(U.S. $)




Worldwide per capita electricity
(kWhr)





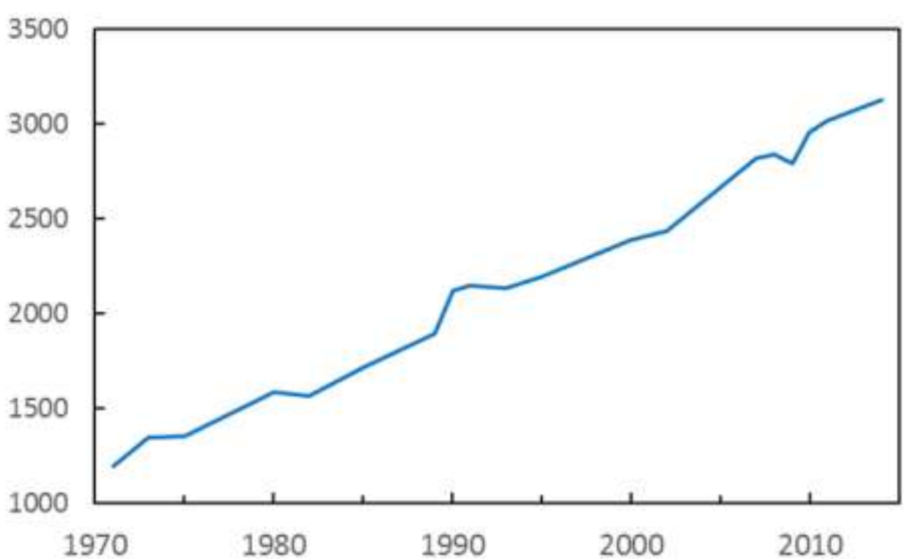

Data sources: Up to 2015 OurWorldInData series based on UN and HYDE. Projections for 2015 to 2100: UN Population Division (2015) – Medium Variant.
The data visualization is taken from OurWorldinData.org. There you find the raw data and more visualizations on this topic.

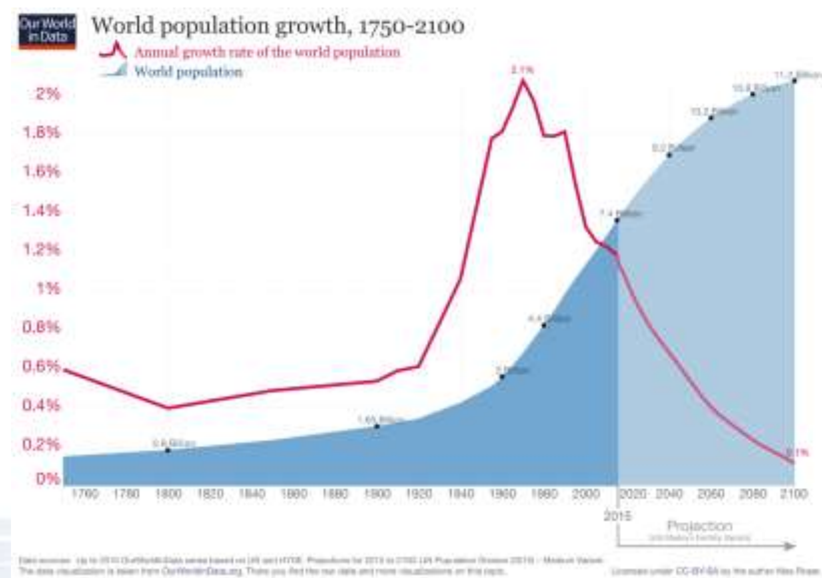
Licensed under CC-BY-SA by the author Max Roser.

# Plausible Electricity Demand Growth in Long Term

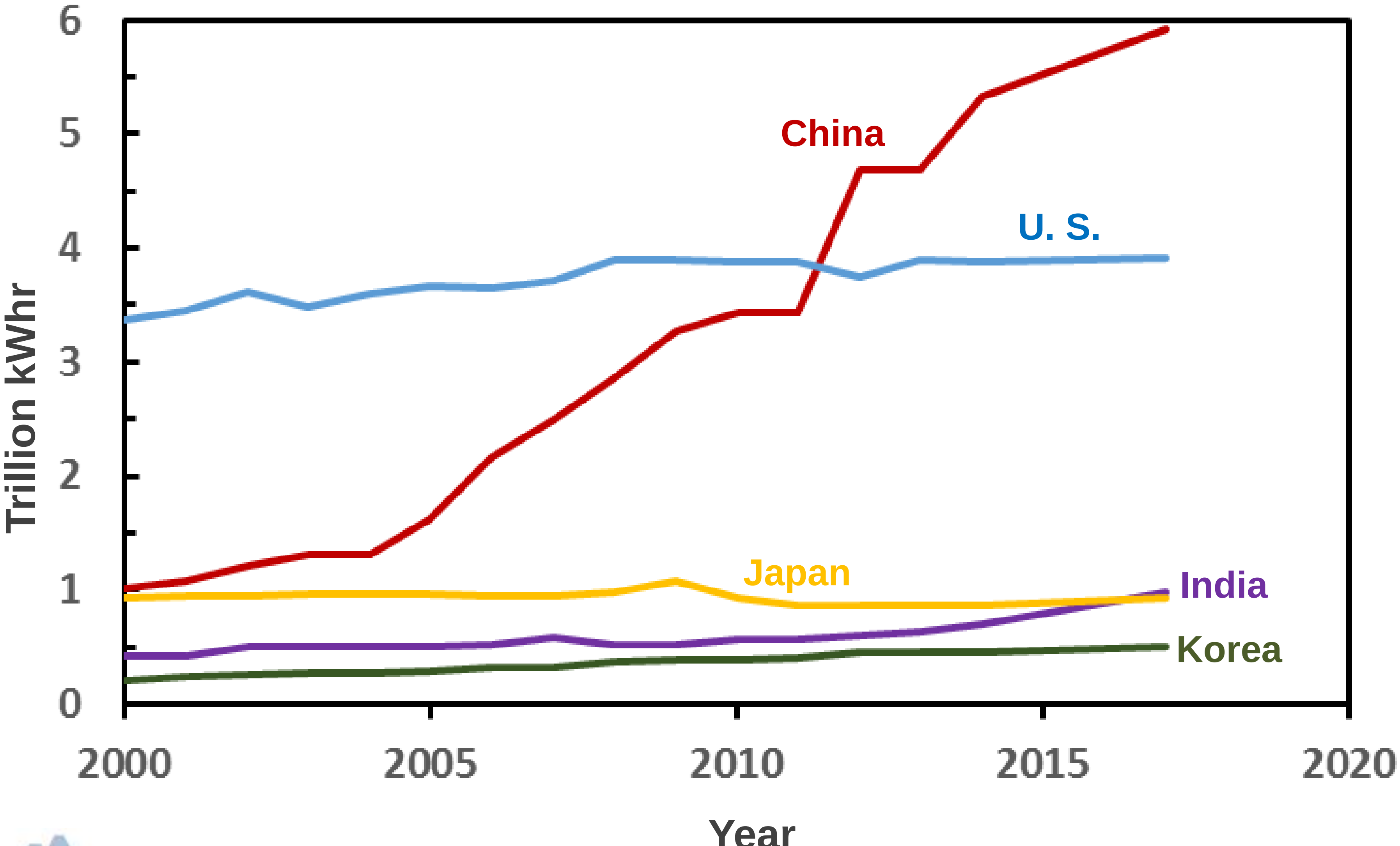
| | 2015 | 2050 | 2100 |
|---|---|---|---|
| Per Capita Electricity | 1 | 2.1* | 2.7** |
| Population Growth | 1 | 1.3 | 1.5 |
| Total Electrical Energy | 1 | 2.7 | 4.1 |

*Linear growth **Equivalent to 80% of Korea in 2015

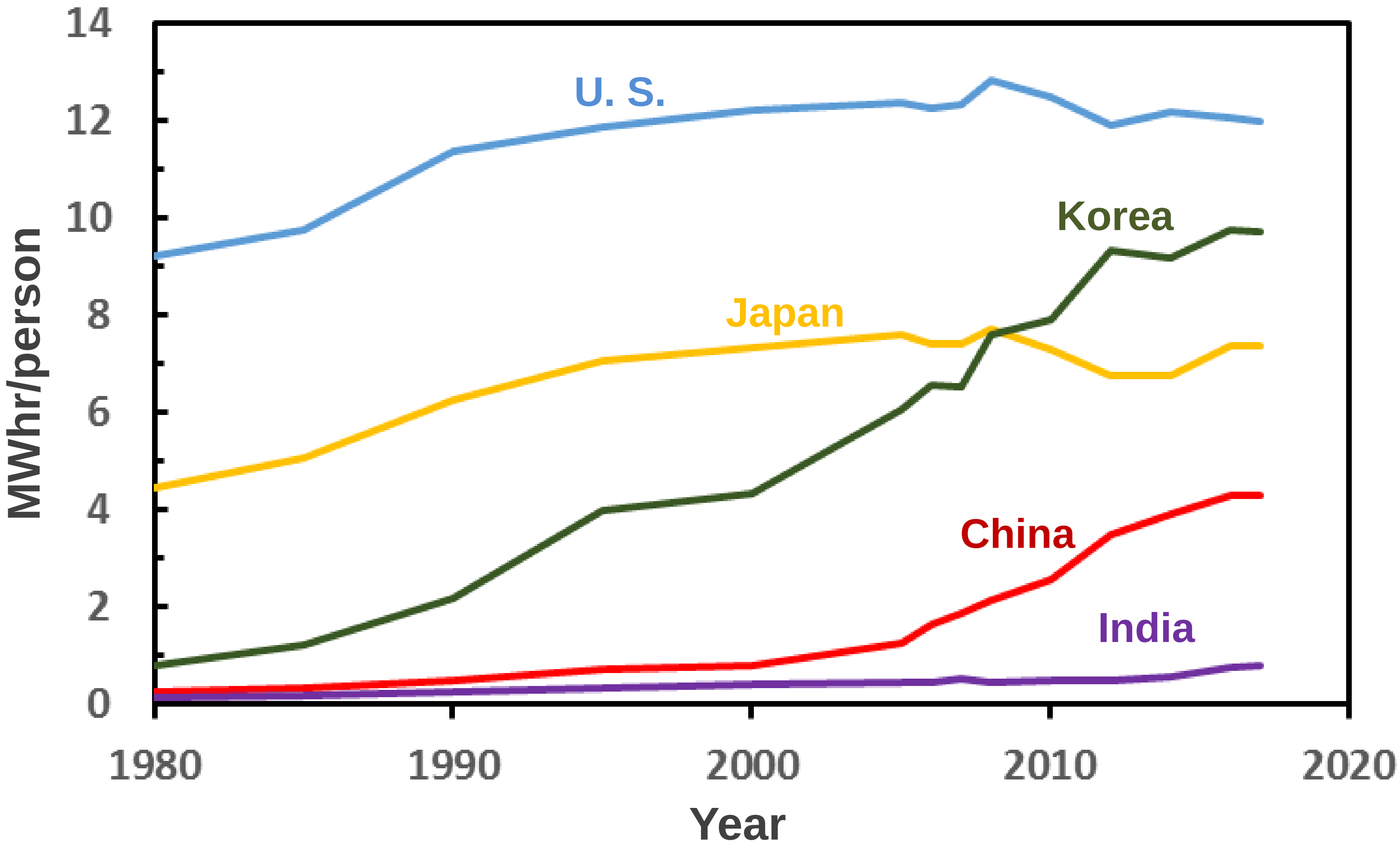


# Electricity Consumption per Year



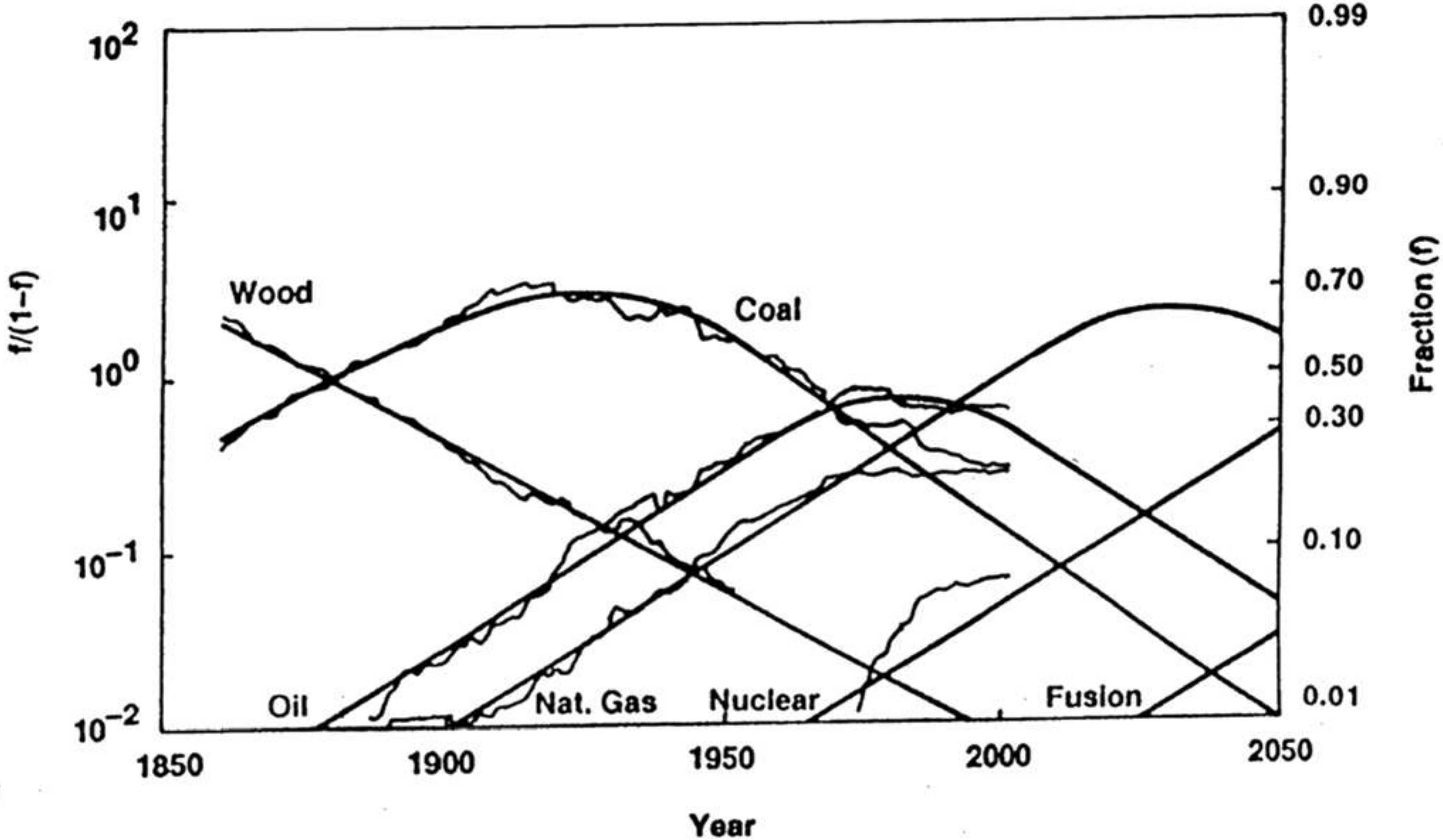
# Per Capita Electricity Consumption

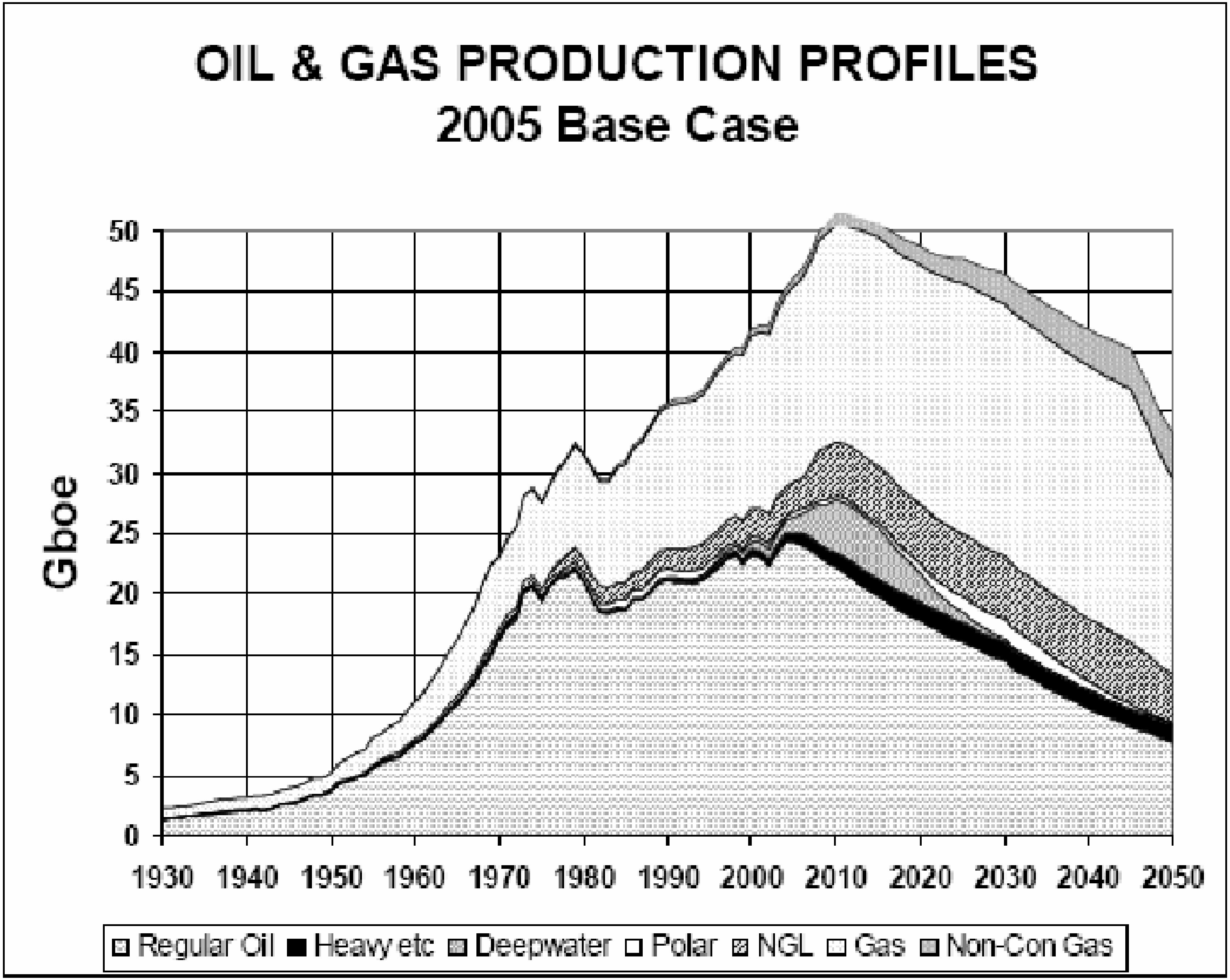


# Electricity Options for Future

- Lilienthal, "For the near- and long-term future, the energy we now have and can count on, from all sources, is not enough. …it has never been enough, and it will never be enough…"
- Given such a high electricity demand growth, we cannot afford to pick and choose.
- The world will demand absolutely all energy sources mankind can muster for electricity: coal, natural gas, oil, nuclear, hydro, solar, wind, biomass, etc.
- Only nuclear has capability to deliver multiples of the current consumption level with no air pollutants/greenhouse gases, and least amounts of construction commodities and land usage.

# World Primary Energy Substitution Model (Source: Marchetti)




OIL & GAS PRODUCTION PROFILES
2005 Base Case
Gboe
50
45
40
35
30
25
20
15
10
5
0
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Regular Oil
Heavy etc
Deepwater
Polar
NGL
Gas
Non-Con Gas

# Trend of U.S. Electricity by Fuel type (% Total)

| | 1973 | 1980 | 1990 | 2000 | 2010 | 2017 |
|---|---|---|---|---|---|---|
| Coal | 45.5 | 50.7 | 52.5 | 51.7 | 44.8 | 29.9 |
| Nat. Gas | 18.3 | 15.1 | 12.3 | 16.2 | 24.2 | 32.1 |
| Nuclear | 4.5 | 11.0 | 19.0 | 19.8 | 19.6 | 20.0 |
| Petroleum | 16.9 | 10.7 | 4.2 | 2.9 | 0.9 | 0.5 |
| Hydro | 14.8 | 12.2 | 9.5 | 7.1 | 6.2 | 7.4 |
| Renewables | 0.1 | 0.2 | 2.1 | 2.1 | 4.4 | 9.6 |
| - Biomass | | | 1.5 | 1.6 | 1.7 | 1.6 |
| - Wind | | | 0.1 | 0.1 | 2.3 | 6.3 |
| - Geothermal | 0.1 | 0.2 | 0.5 | 0.4 | 0.4 | 0.4 |
| - Solar | | | | 0.01 | 0.03 | 1.3 |

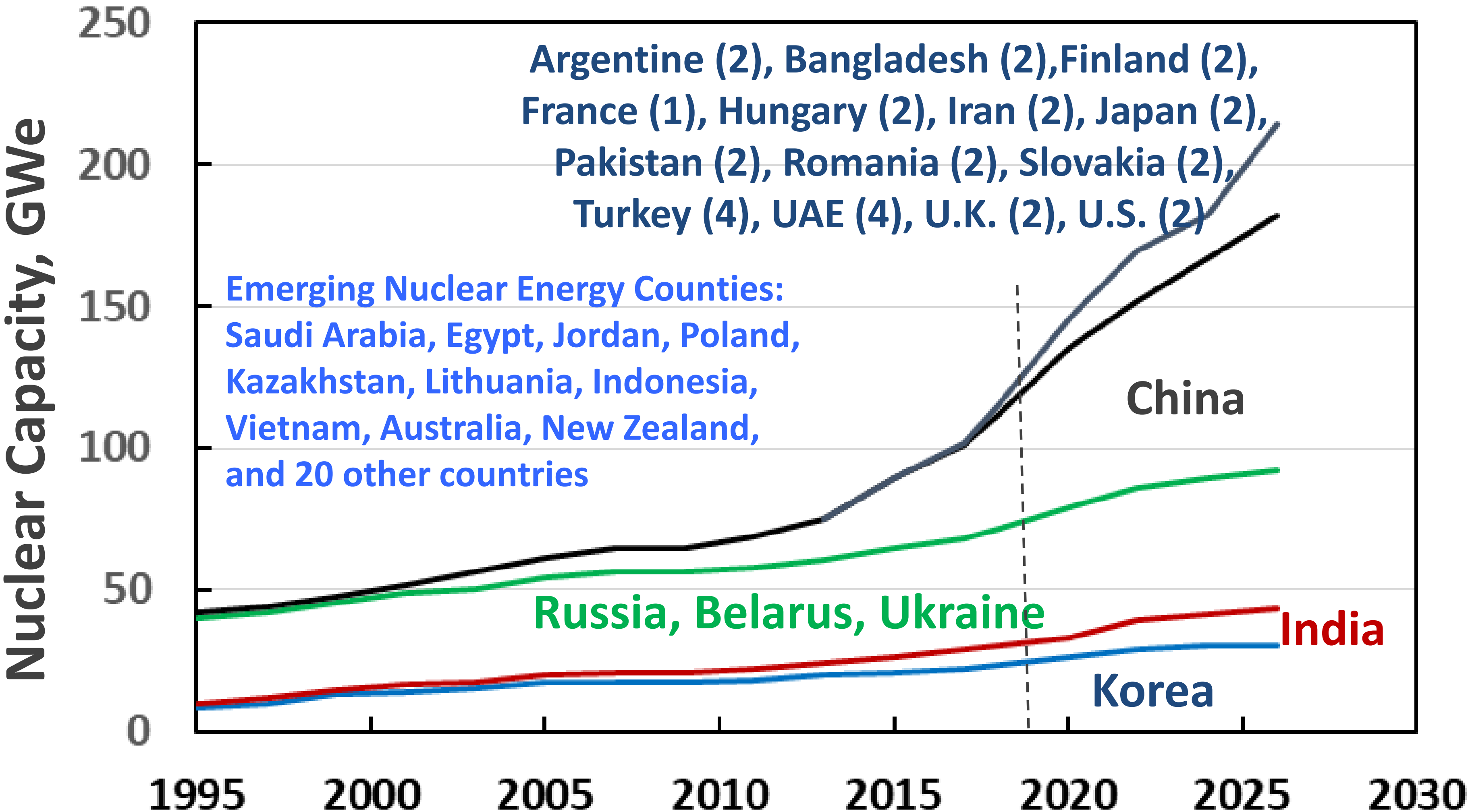
# U.S. Capacity Factor by Fuel Type (2009)

| Fuel Type | C.F. % |
|---|---|
| Nuclear | 90.5 |
| Geothermal | 71.5 |
| Biomass | 66.0 |
| Coal | 63.1 |
| Gas (Combined Cycle) | 44.7 |
| Hydro | 29.4 |
| Wind | 27.8 |
| Solar | 23.5 |
| Gas (Steam Turbine) | 13.3 |
| Oil | 7.4 |

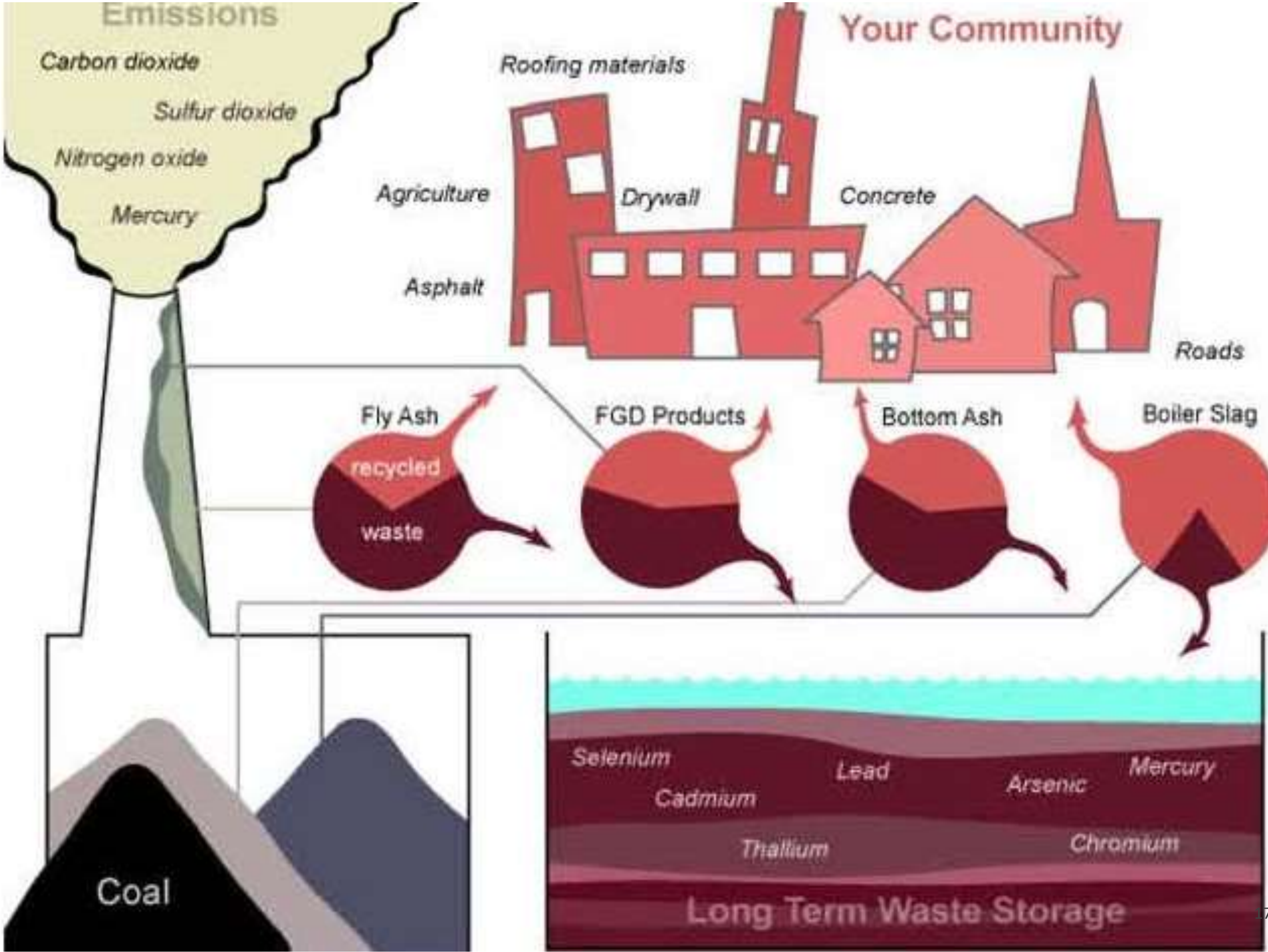
# Worldwide Nuclear Capacity (2018)

| Country | Number | GWe | % Electricity |
|---|---|---|---|
| U.S.A. | 99 | 102 | 20 |
| France | 58 | 63 | 72 |
| Japan | 42 | 40 | 2 |
| China | 44 | 41 | 3 |
| Russia | 35 | 26 | 17 |
| Korea | 24 | 22 | 30 |
| Canada | 19 | 14 | 16 |
| Ukraine | 15 | 13 | 52 |
| U.K. | 15 | 9 | 20 |
| Germany | 7 | 10 | 13 |
| Others (26) | 95 | 61 | |
| Total | 453 | 401 | 14 |

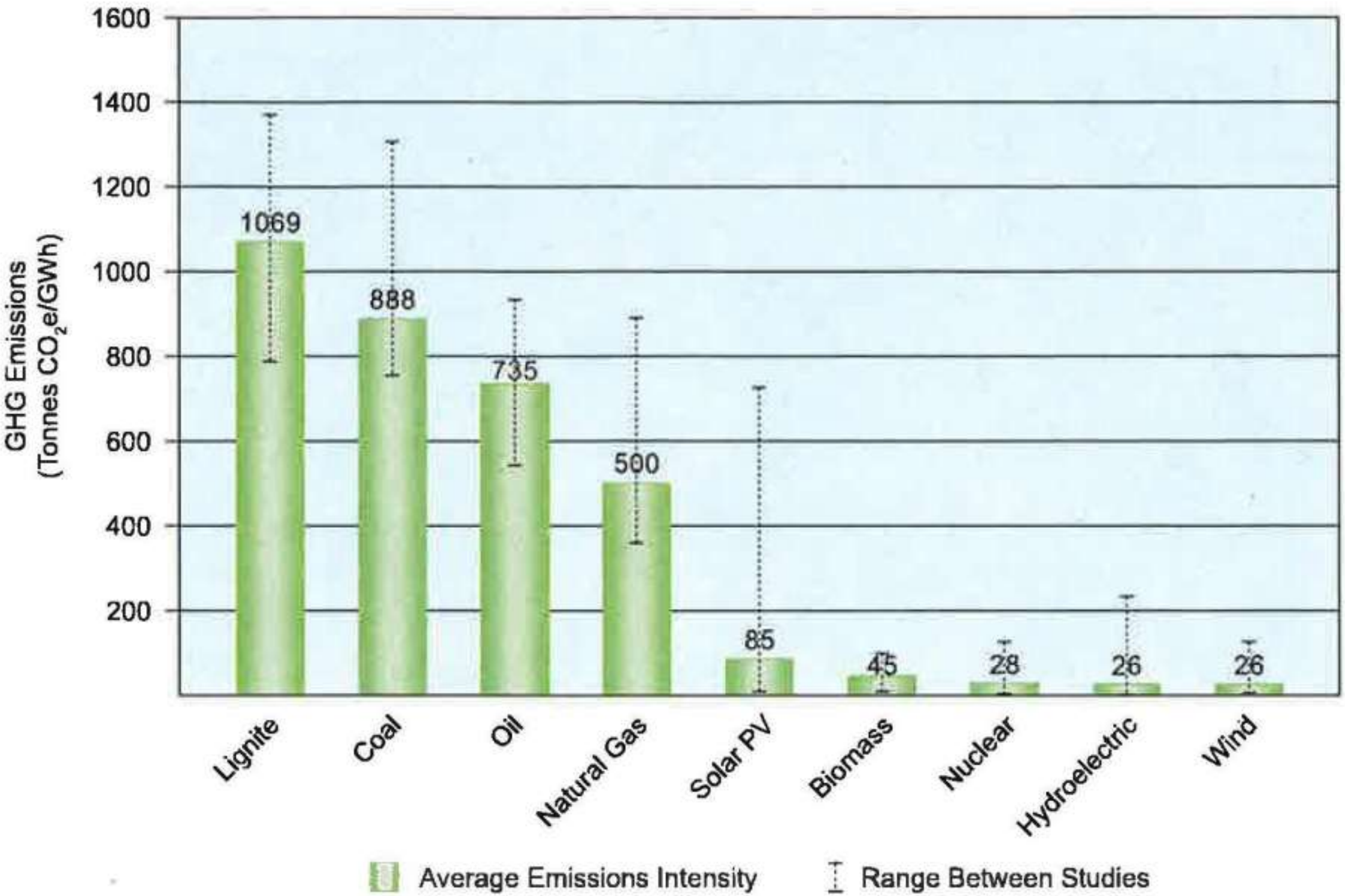
# Recent Nuclear Plants and New Constructions - Nuclear Renaissance -



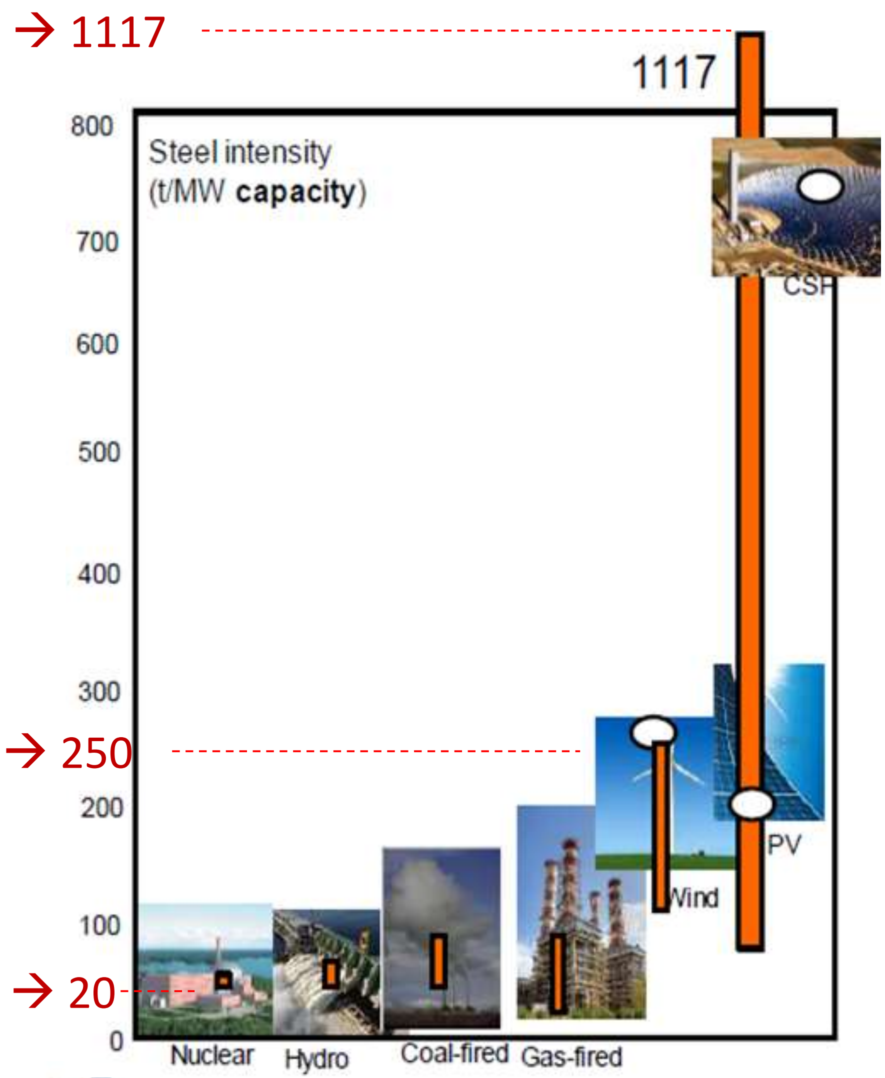
# 1 T Fission = 3.5 million T Coal Combustion



# $CO_2$ Emission per Electricity Generation

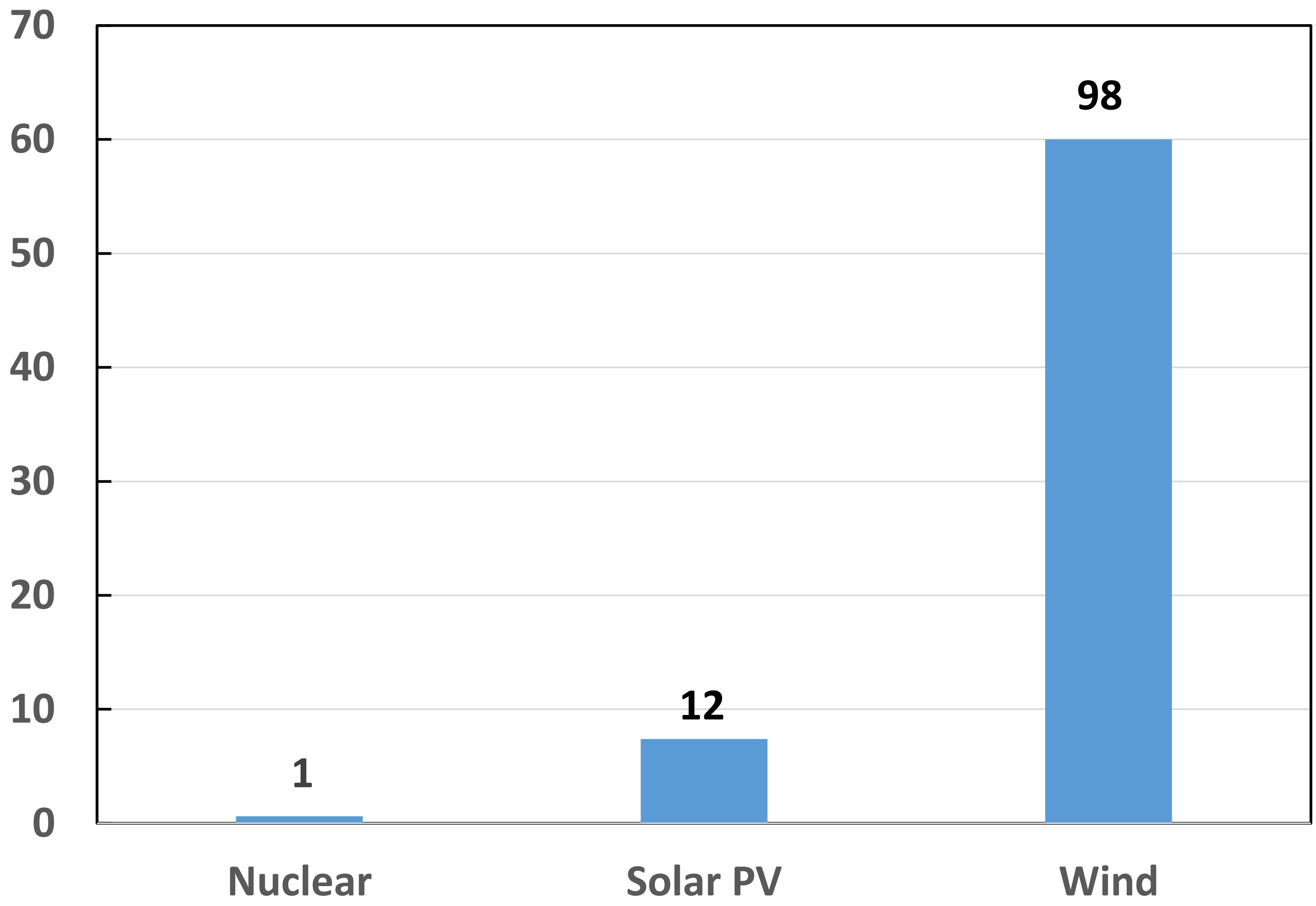


# Materials Tension: the Hidden Flaw in the «Renewable Alone » Dream




Latest wind turbine generation 6 MW with rotor >150m
1500 t of steel - permanent magnet with 1 ton of Rare Earths Nd, Dy, Sm, Gd, or Pr

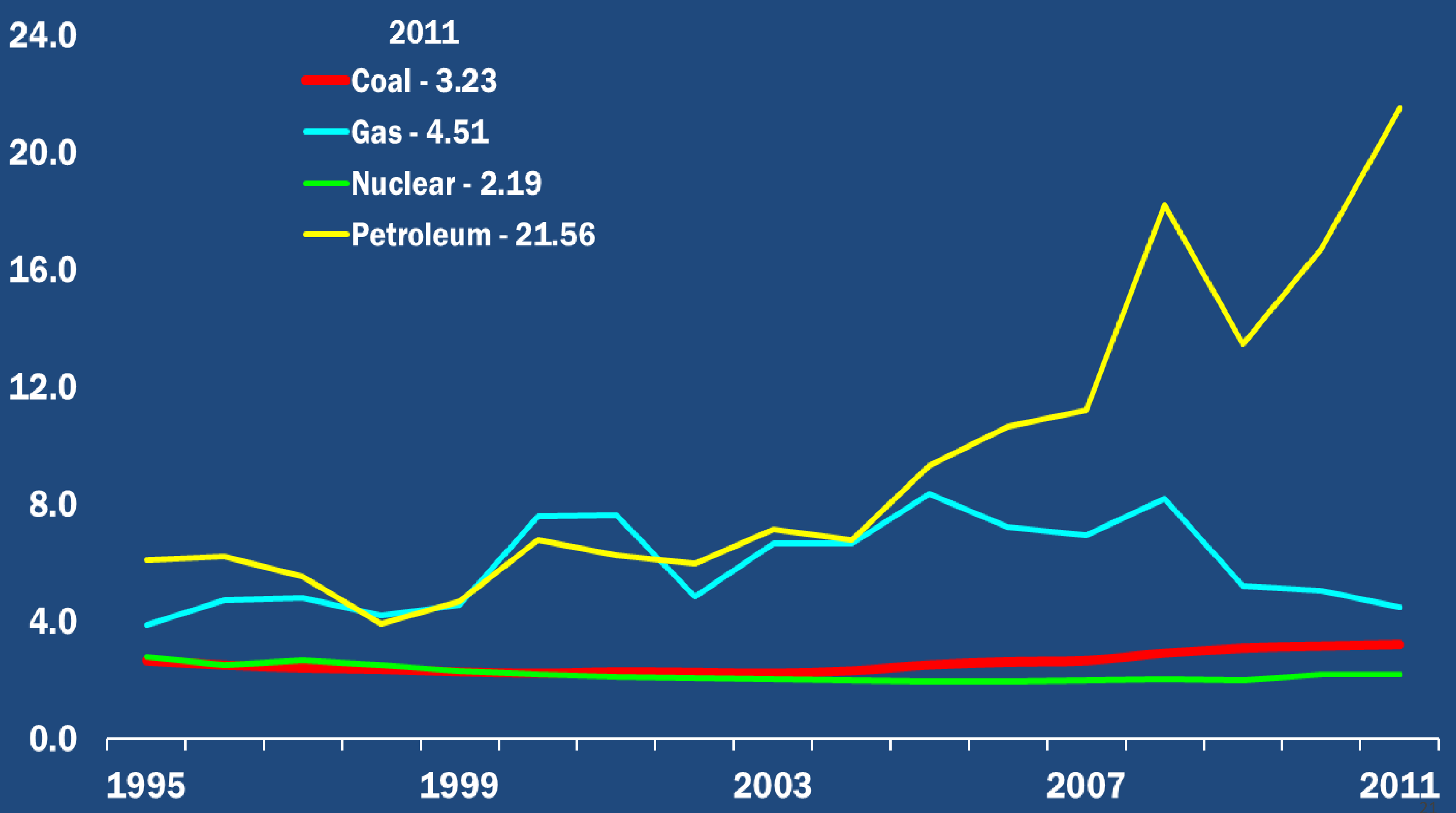
# Land Use by Electricity Source, Acres/MW Capacity



# Nuclear Electricity Price is Low and Stable

## U.S. Electricity Production Costs

**1995-2011, *In 2011 cents per kilowatt-hour***

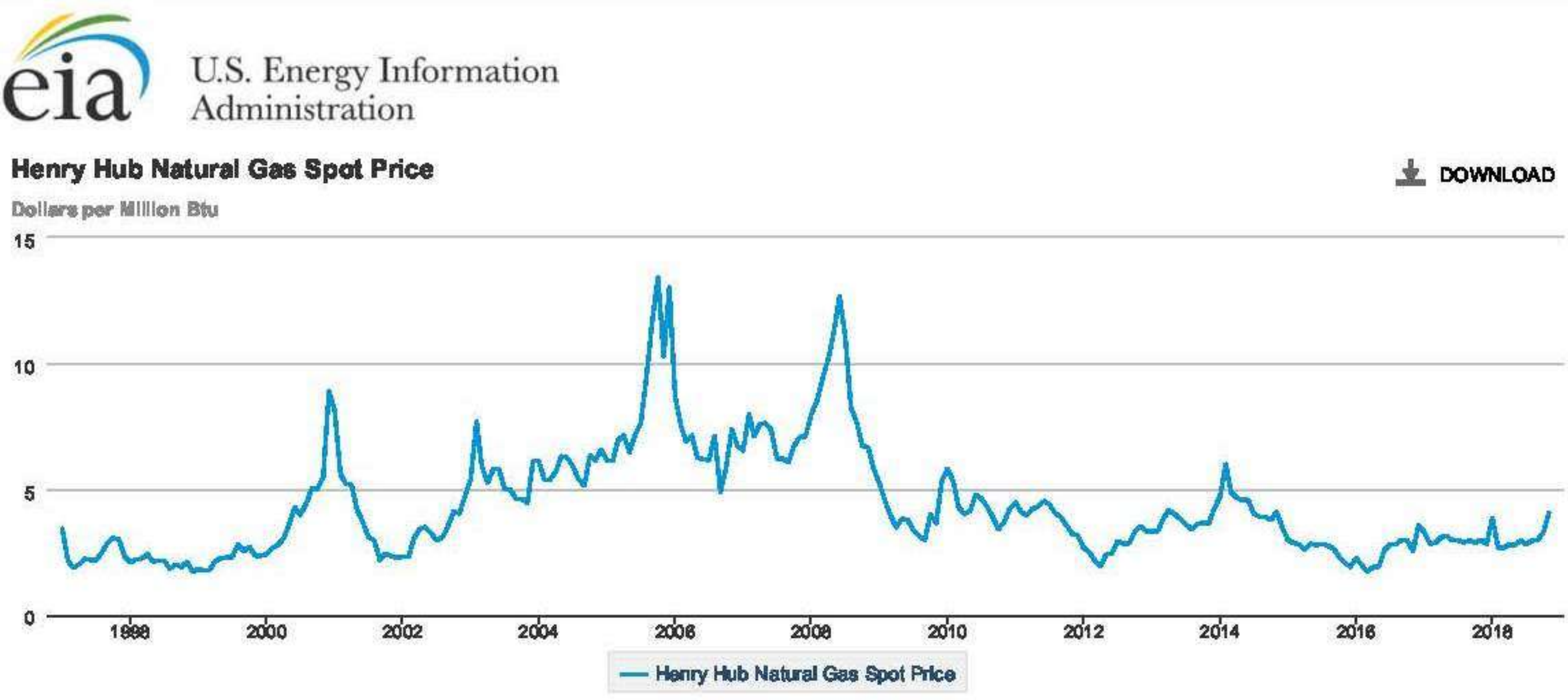


# 한국의 전력 발전 단가

| | 발전 단가 | |
|---|---|---|
| | KRW/kWh | Relative |
| 원자력* | 53 | 1 |
| 화력 (LNG) | 185 | 3.5 |
| 풍력 | 182 | 3.4 |
| 태양광 | 243 | 4.6 |

***원자력 발전 단가에는 사용후연료 처분 비용과 제염 해체 비용이 포함되며 이 비용은 정부와 원자력환경공단에서 관리하는 기금에 적립되고 있음**

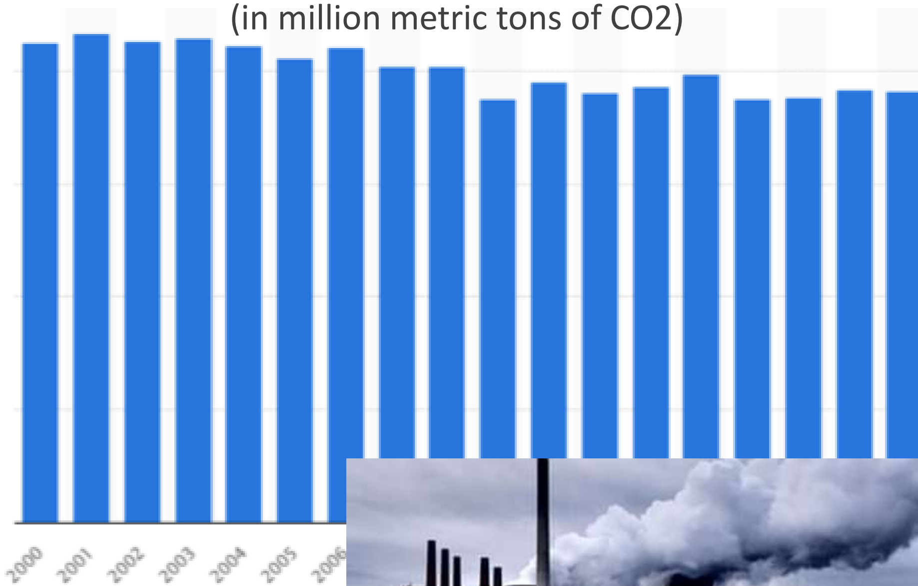
# Natural Gas Price Volatility



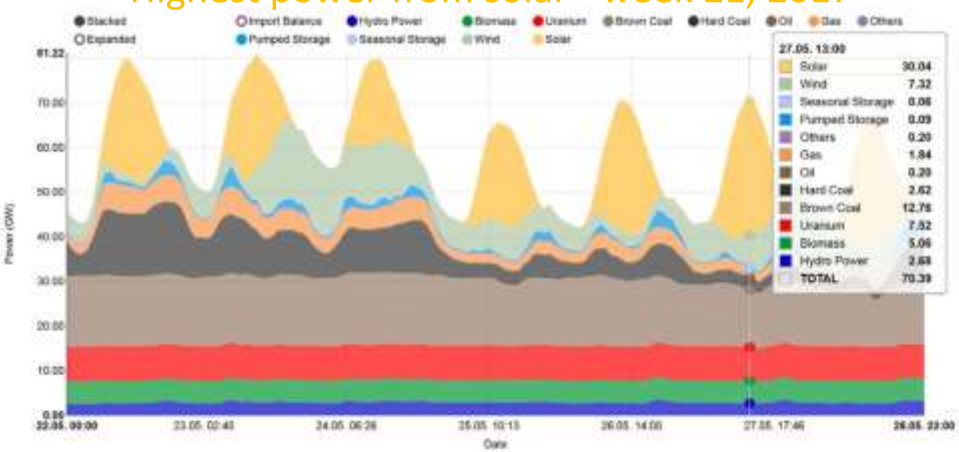
# Case Study of Germany Renewables

- Germany invested $181 billion (~200조원 ) in 34 GWe wind and solar in last 5 years, but essential no change in $CO_2$ emission.
- Peaks and valleys in electricity can be managed because Germany is a net exporter and peaks are absorbed into a larger market base.
- In a closed system, a major load management problem.

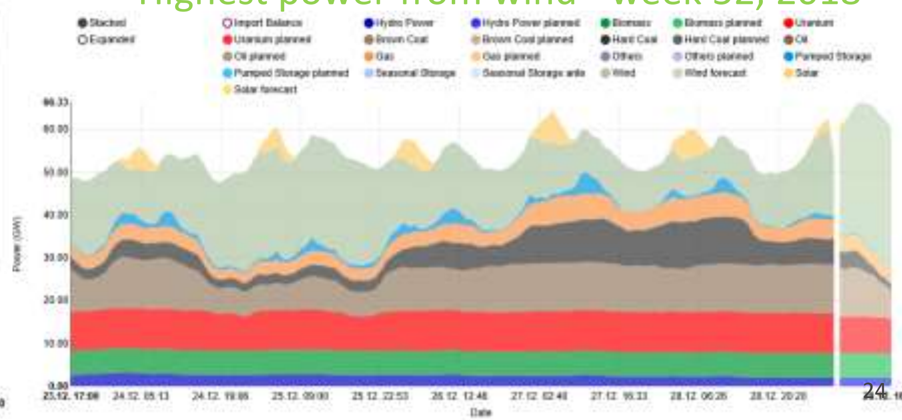
Carbon Dioxide emissions in Germany from 2000-2017
(in million metric tons of CO2)




Highest power from solar - week 21, 2017



Highest power from wind - week 52, 2018

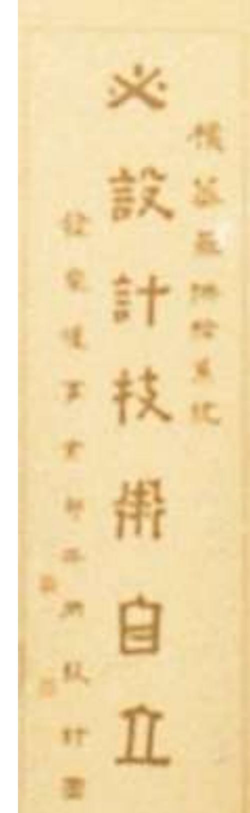


# Nuclear Development Requires Leadership

- All successful nuclear deployments required a strong national and international leadership:
  - Eisenhower's Atoms for Peace initiative opened door for peaceful use and created International Atomic Energy Agency.
  - U.S., France, UK, Japan, Germany and so on all had a strong government leadership role in the development stage.
  - Centrally planned economies: Russia, China, etc.
- Developed nations have to fully exploit nuclear energy so that under-developed nations can enjoy the benefit of conventional resources.
- Export market is very competitive and a strong Government support is absolutely required.

# Success Story of Korea

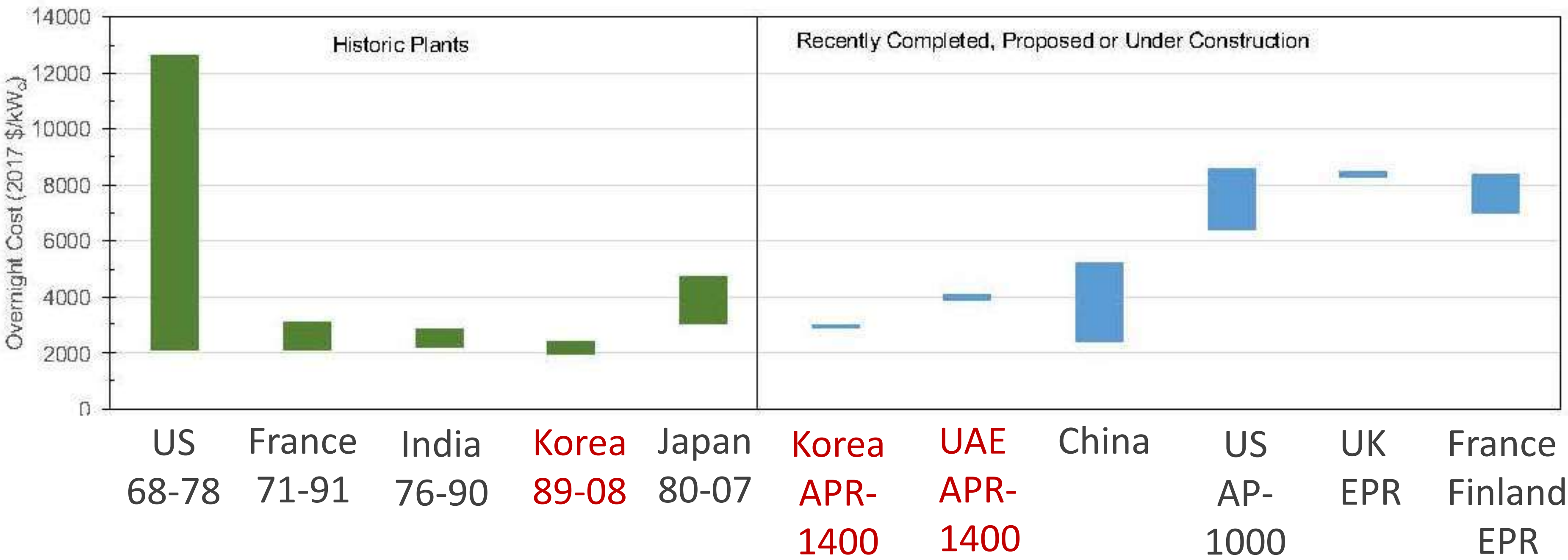
- The 1986 decision of Combustion Engineering (CE) for Hanbit-3 and -4 led to eventual reactor technology transfer of the CE's System 80 design and subsequent standardization of OPR-1000 and APR-1400.
- During 1987-1996, more than 200 KAERI staff were assigned at CE for a joint design of Hanbit-3, which started commercial operation in 1995 as planned.
- If any other vendor was selected, the technology transfer would not have occurred. And there was a narrow time window since CE was sold to ABB in 1990 and later the nuclear part was merged with Westinghouse in 2000.




# Korea Has Merged as a Leader in Nuclear

- Korea with 24 reactors operating and 5 under construction is the 5th in the world, following U.S., France, Russia and China. (China only recently overpassed Korea.)
- Exported 4 APR-1400 to UAE and the commissioning is in the near future – Potential for additional export opportunities.
- Received U.S. Nuclear Regulatory Commission approval of APR-1400 Design Certification in 2018 (only non-U.S. reactor licensed in U.S.) – Potential for U.S. market.

# Reactor Construction Costs Around the World*




*Source: The Future of Nuclear Energy in a Carbon-Constrained World, An Interdisciplinary MIT Study, 2018

# Nuclear Export Opportunities

- APR-1400 has a best chance to succeed in the emerging export opportunities, if supported by a cohesive national policy and financial support.
- Russia is negotiating export of 35 reactors in 11 countries: Rosatom subsidy of 20-50% underbid.
- China is also aggressively seeking export to Pakistan, Argentine, Romania, Iran, UK and other countries: State bank finance of $6.5billion in Pakistan, $15 billion in Argentine, and CGN holds 33% of Hinkley Point C project in UK.
- APR-1400 is technically the strongest, but cannot succeed without a proactive Government support in the current competitive export market environment.

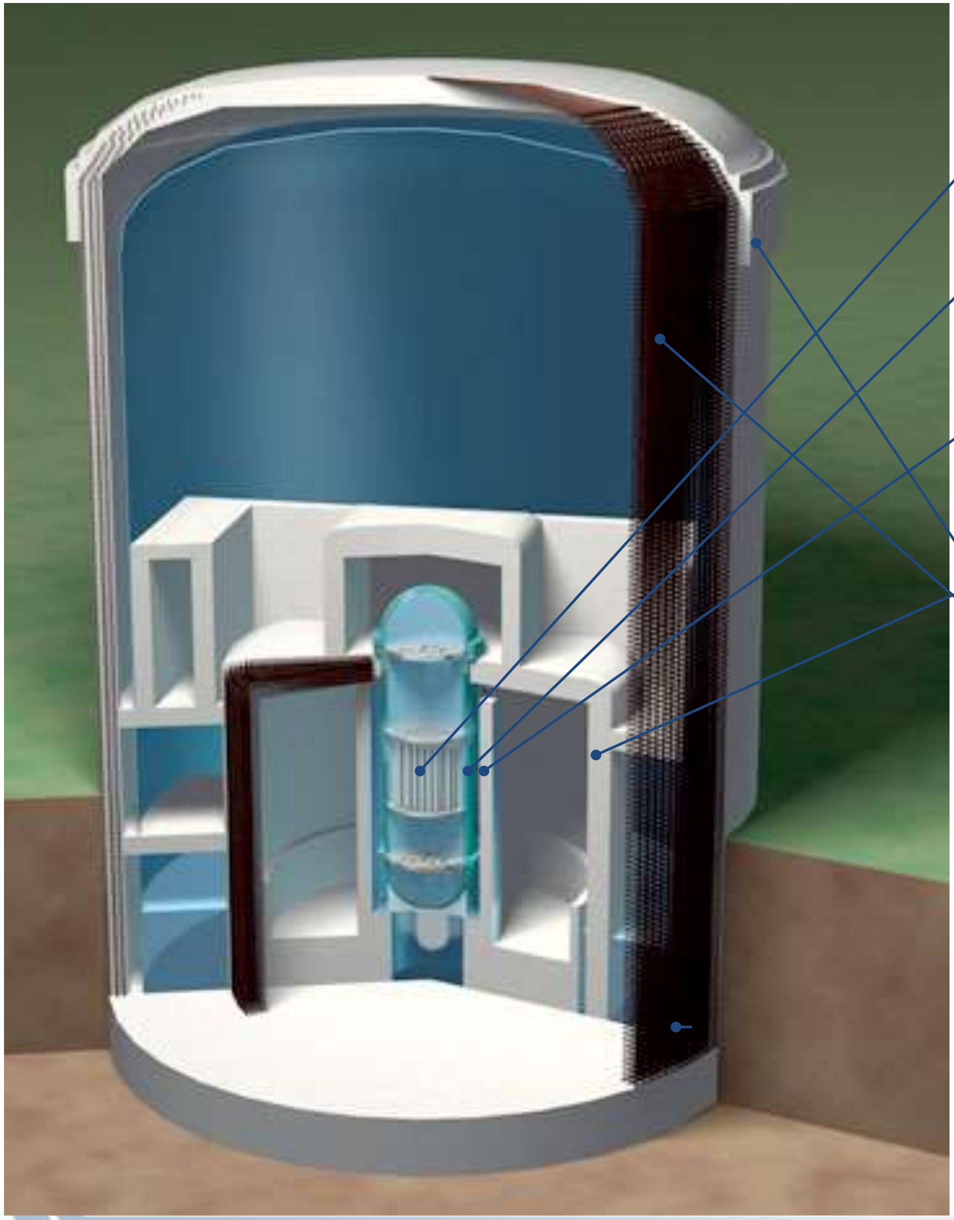
# Public Education is Prerequisite for Long-Term Nuclear

- Nuclear energy cannot be deployed without the support of the general public.
- The public fear may stem from:
  - Not distinguishing nuclear energy and nuclear weapons (the term ‘nuclear energy’ is preferred than ‘nuclear power’)
  - Fear of reactor safety and invisible radiation
  - Misinformation from anti organizations
- Public education is everyone’s responsibility.

# Common Myths about Nuclear Energy (근거 없는 믿음)

- Myth 1: 원자력은 친환경적이 아니다
- Myth 2: 원자력은 경제성이 없다
- Myth 3: 원자력은 안전성이 없다
- Myth 4: 원자력에서 나오는 방사선은 위험하다
- Myth 5: 사용후 핵연료 폐기 해결책이 없다

# Myth: Reactor Safety?



1차 방어: 연료봉

2차 방어: 압력용기 10-20cm 강철

3차 방어: Bio Shield
120cm 콘크릿 + 7cm 강철

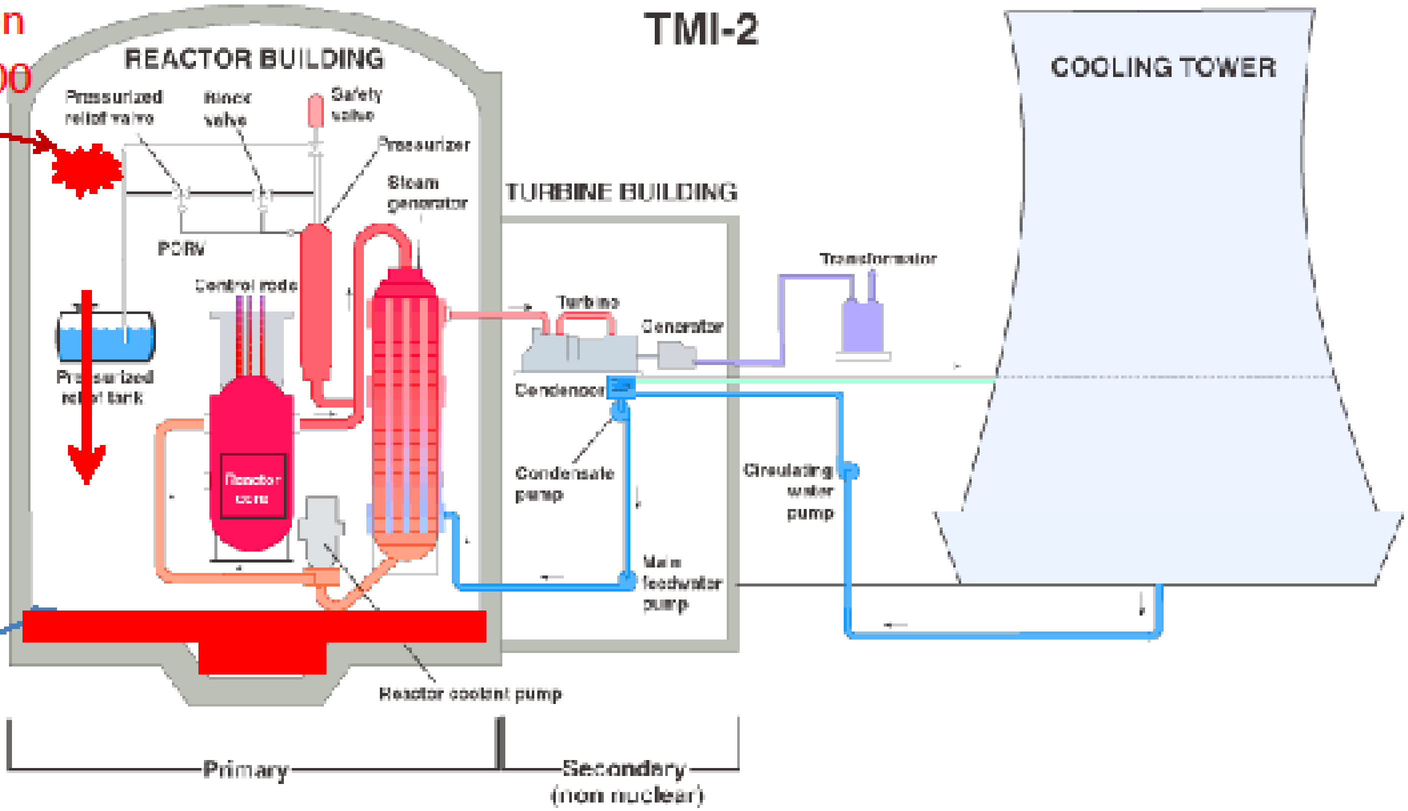
4차 방어: Dry Well 150cm 콘크릿

5차 방어: Containment Building
4cm 강철
90cm 콘크릿

전체: 21 - 31 cm 강철
360 cm 철근 콘크릿

# TMI-2 Accident in 1979 (PWR type = Korean type)

Hydrogen
Deflagration
28psig 13:00



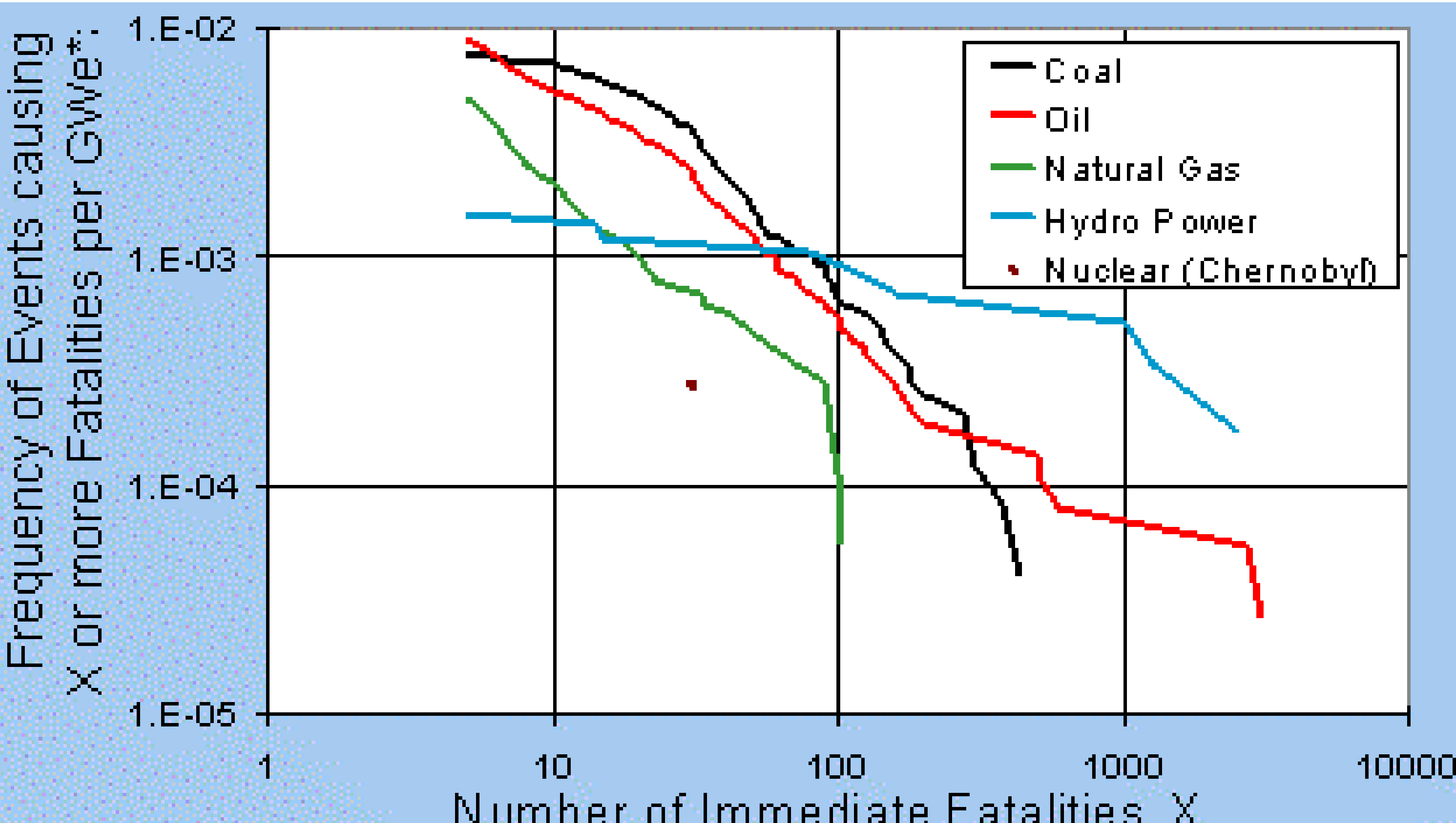

~3M deep
water
1000R/hr
@ 2 yr

Average dose to people within 10 miles radius was 0.08 mSv, with no more than 1 mSv to any single individual.

# 사고 사망률 비교

- 자동차, 비행기, 원자력 발전소 중 사고사 확률이 가장 높은것?
- 자동차 사고 (미국): 매년 37,000 명 사망
- 비행기 사고 (전세계): 연 평균 850명 (10년 통계)
- 원자력 발전 사고 (전세계): 지난 30년 동안 전무
  – 33년전 Chernobyl 사고 (1986년): Steam Explosion으로 방사능 유출, 42명 사망
  – 1979년 Three Mile Island 사고: 원자로는 폐기 되었지만 방사능 유출은 거의 없었음
  – 2011년 일본 Fukushima 사고: 지진, 쓰나미로 20,000 이상의 사망자가 생겼지만 원자로 방사선 노출로 인한 사망자는 전무 (만약을 대비해 오염지역 대피)

# Risk Comparisons



# Myth: 한국의 원자로 사고 피해?

- Fukushima 사상자 (15,896 사망, 6,157 부상, 2,537 행방불명)는 일본 역사상 가장큰 지진과 쓰나미 때문, 원자로 사고 피해자는 전무!
- 지진 Richter Scale 의 맹점:
  - Fukushima 9.0 대 포항/경주 5.4-5.8
  - 지진폭: $10^{9.0}/10^{5.4}$ = 4,000: $10^{9.0}/10^{5.8}$ = 1,600
  - 파괴력: $4000^{1.5}$ = 250,000: $1600^{1.5}$ = 64,000
  - 5.5 정도는 캘리포니아에 매년 2,3회 오는 지진
- 한국의 지진은 일본과 대비해 하늘과 땅 차이이지만 원자로는 일본과 비슷한 내진 설계가 되어있어 지진 피해는 불가능하다!
- Fukushima의 6기의 원자로와 부근 4기의 원자로 지진 피해는 하나도 없었고 쓰나미로 인해 원자로 3기의 Diesel generator oil tank 가 쓸려내려 갔음

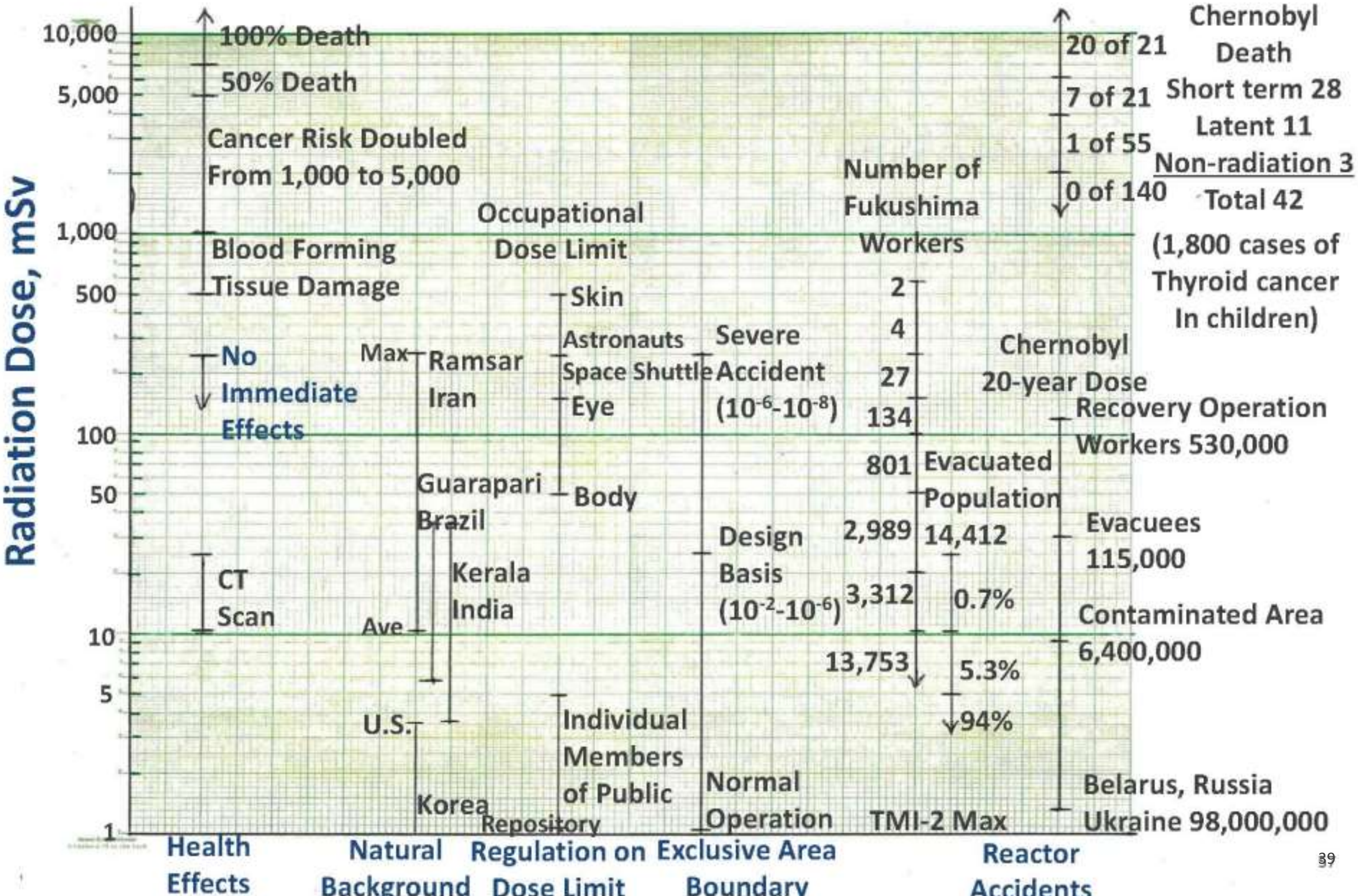
# Myth: Radiation Danger?
# Natural Background Radiation (U.S.)

| 방사선 종류 | mSv/year |
|---|---|
| Radon in air (라돈 가스) | 2.0 |
| Medical X-rays (엑스레이) | 0.4 |
| Food and Water (음식, 물) | 0.4 |
| Terrestrial (지표) | 0.3 |
| Cosmic Rays (코스믹 레이) | 0.3 |
| Consumer Products (일상품) | 0.1 |
| Mining and farming (광업,농업) | 0.02 |
| Nuclear Power Plants (원전) | 0.00009 |
| Total (합계) | ~3.5 |

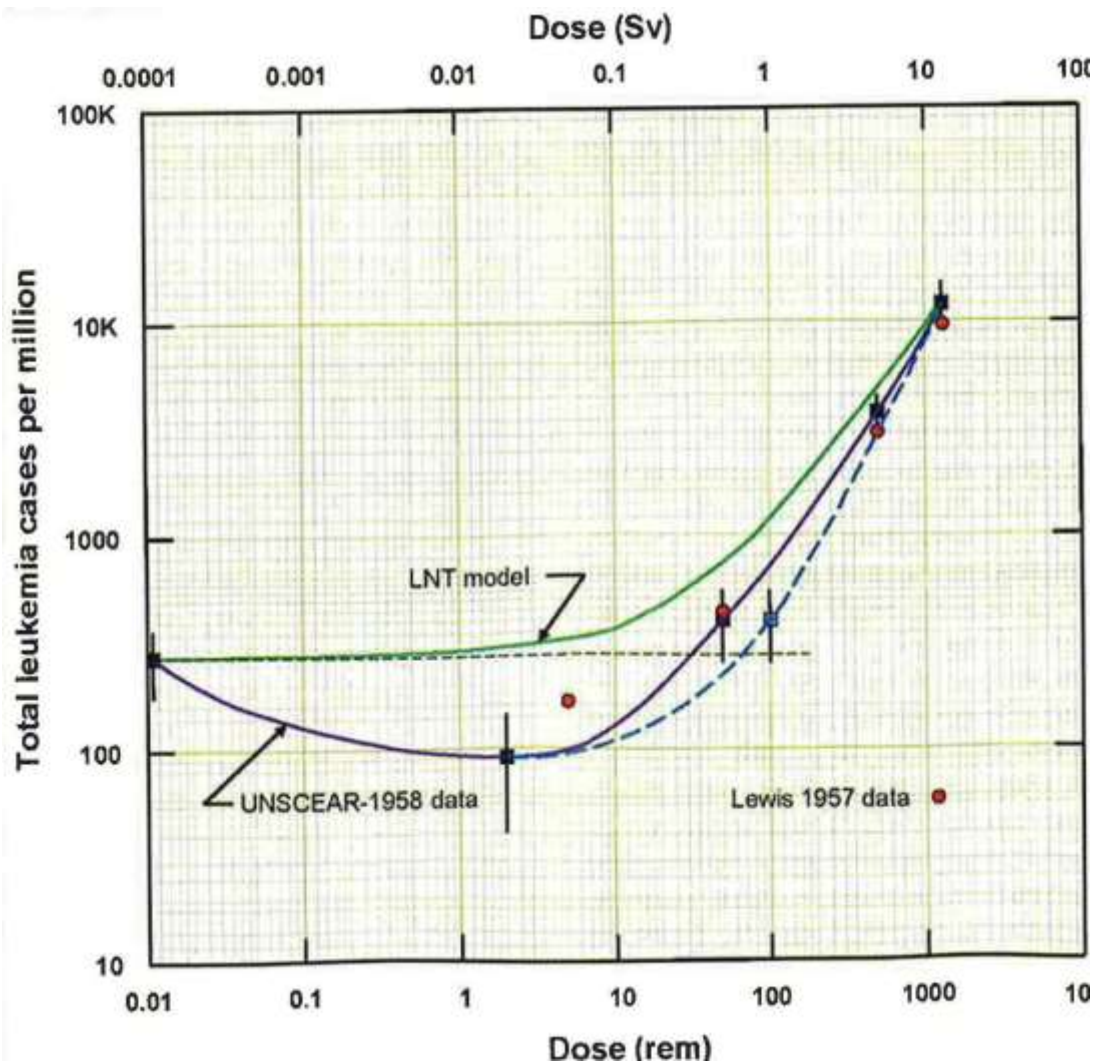
# Radiation Dose from Various Sources (mSv/yr or mSv/event )

| | |
|---|---|
| Radionuclides in body (i.e. potassium) | 0.39 |
| Building materials (concrete) | 0.03 |
| Drinking water | 0.05 |
| Eye glasses (containing thorium) | 0.06-0.11 |
| Coast to coast airplane ride | 0.05/event |
| Chest X-ray | 0.05-0.2/event |
| CT (head and body) | 10-25/event |
| Banana (one) | 0.0001 |

# Radiation Dose Chart



# Radiation Hormesis?

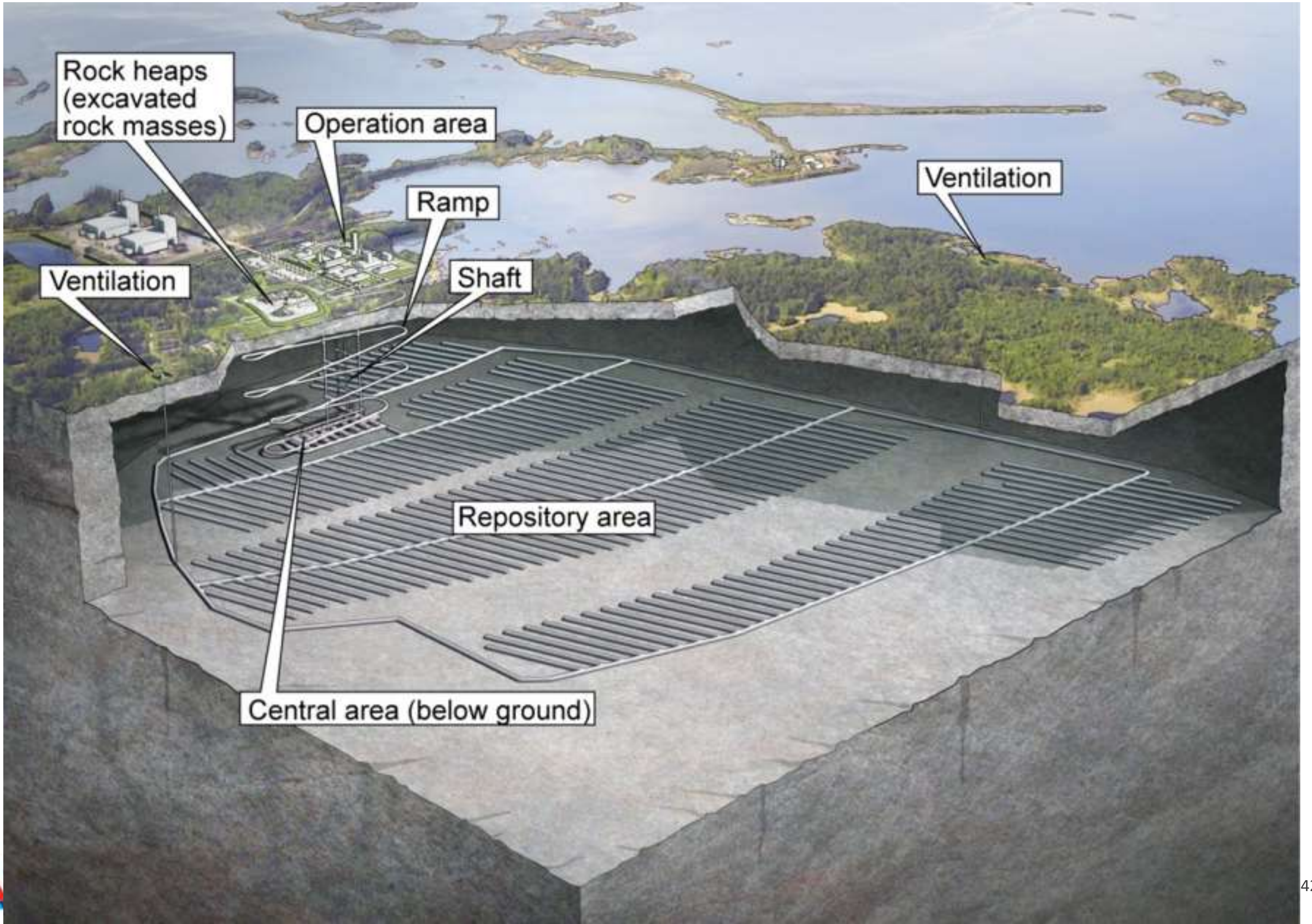



Leukemia Incidence from 1950 50 1957 among Hiroshima survivors

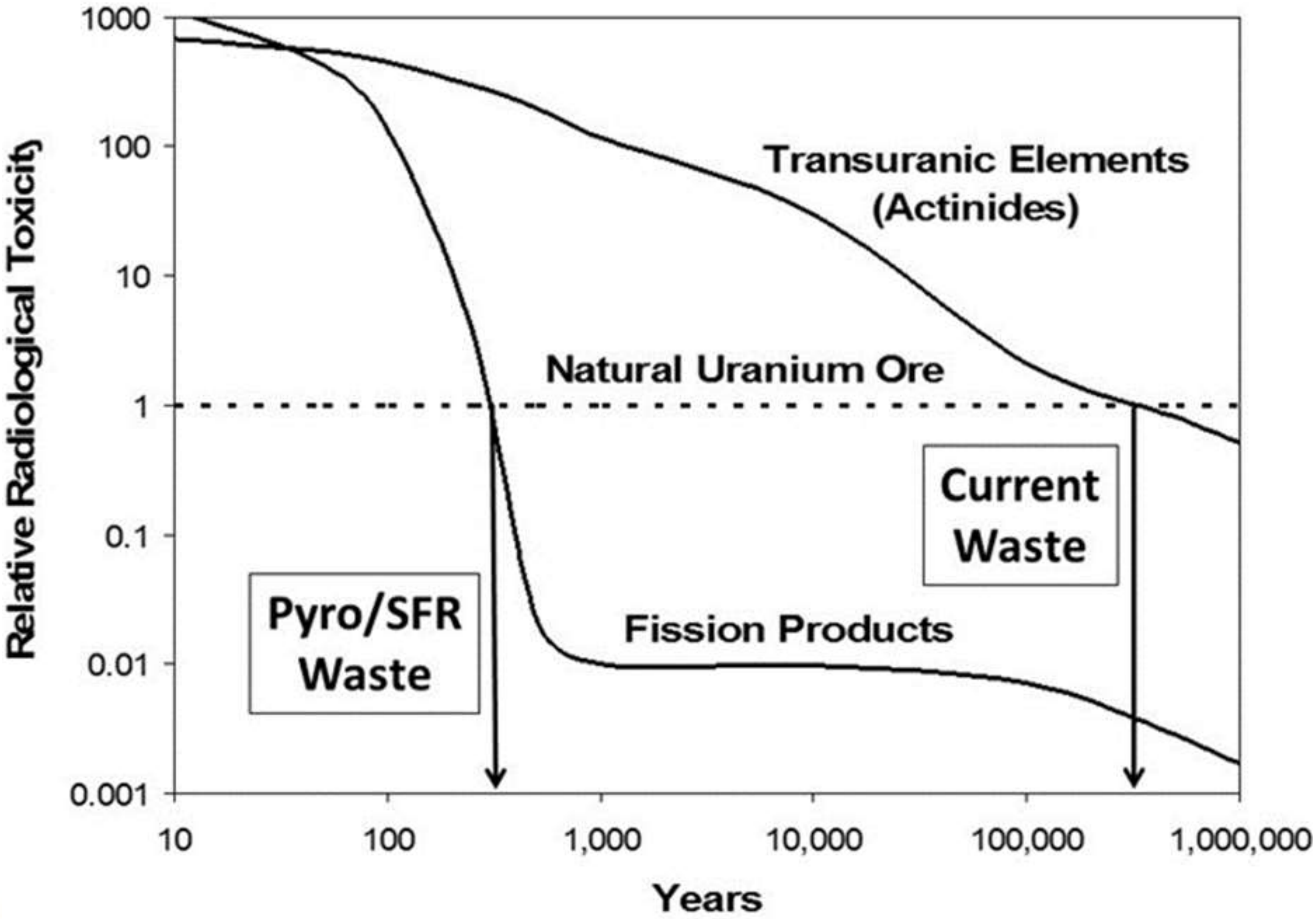
# Myth: Spent Fuel (High Level Waste) Management?

- The public views adequate nuclear waste management as a critical linchpin in further development of nuclear energy. Nuclear energy has been utilized over a half century without a definite solution to the back end of the fuel cycle. Examples of metaphors:
  - "Building a house without a toilet!"
  - "A plane taking off without its landing gear!"
- Volume is so small, direct disposal is a viable approach. Sweden has successfully implemented this approach.
- However, pyroprocessing spent fuel and burning long-lived actinides in Sodium-cooled Fast Reactors reduces effective lifetime of nuclear waste from ~300,000 years to ~300 years making waste disposal an easy task.

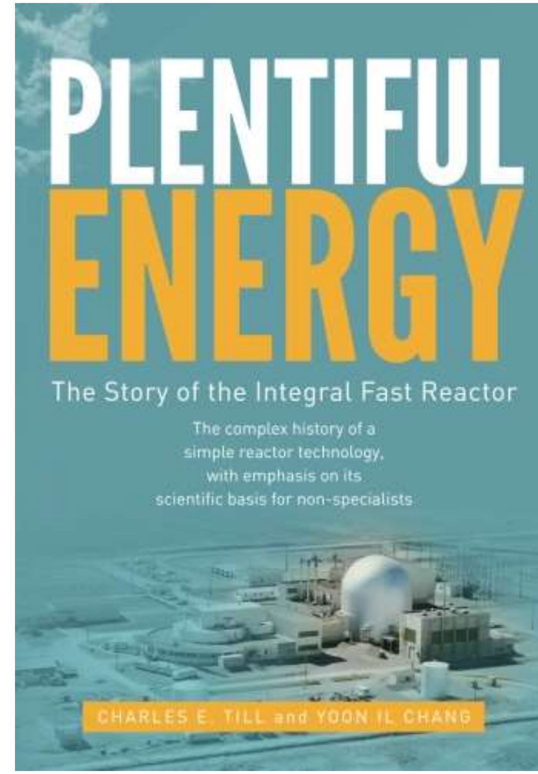
# Direct Disposal in Sweden
# (500m Deep in 1.9 Billion Years Old Rock)



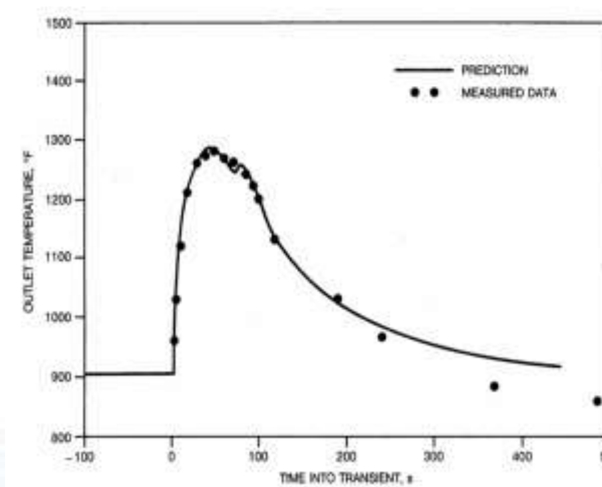
# Radiological Toxicity of LWR Spent Fuel



# Next-Generation Nuclear




- Sodium-cooled Fast Reactor and pyroprocessing (aka Integral Fast Reactor, or IFR) have been developed at Argonne National Laboratory in the 80s and 90s based on EBR-II (1964-94).
- Commercial reactors use only 0.6% of uranium, the rest in tailings and spent fuel. IFR can recycle all extending uranium resource by a factor of 170, making nuclear essentially inexhaustible.
- Pyroprocessing is a revolutionary technology processing spent fuel for recycle of long-lived actinides – waste management solution.
- Inherent safety demonstrated in the landmark EBR-II tests in 1986.



# Unique Opportunity for Korea

- KAERI's Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) project was launched in 2012 in collaboration with Argonne National Laboratory under a Strategic Partnership Project Agreement with technology transfer approval by the U.S. Government: Planned design approval in 2020 and construction completion by 2028.
- Conventional energy resources are explored from the earth or nature, but nuclear energy is created by the brain power. This is a critical juncture for Korea to take a leadership role for demonstrating the next-generation nuclear technology and assume the international leadership role for our future generations.
- If Korea foregoes this opportunity, China and India, who have aspirations for the IFR technology will surpass Korea sooner or later.