Will Thorium Save the world?

Nasser Kalantar-Nayestanaki,
KVI-CART, University of Groningen

Wetenschap in de wijk

Amsterdam, The Netherlands

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Some slides borrowed from Drs. S. Brandenburg, J.L. Kloorsterman, A. Plompen, and M. Fujiwara

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The Problem

- Increasing energy consumption
- Increasing climatic problems
- Decreasing energy reserves

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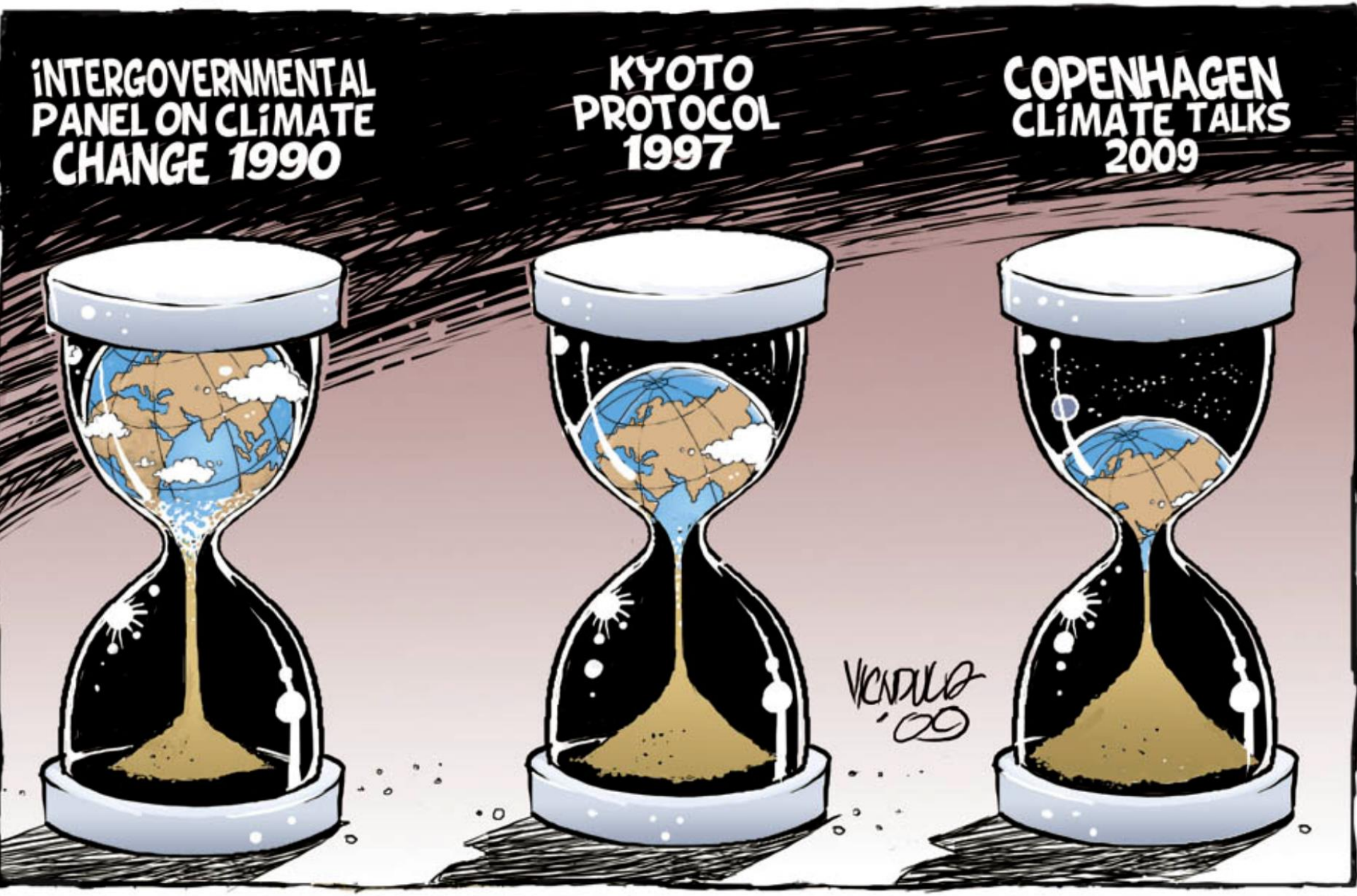
The Solution

?


INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 1990
KYOTO PROTOCOL 1997
COPENHAGEN CLIMATE TALKS 2009
VENDULA '09

40% reduction of greenhouse gases in 2030 compared to 1990

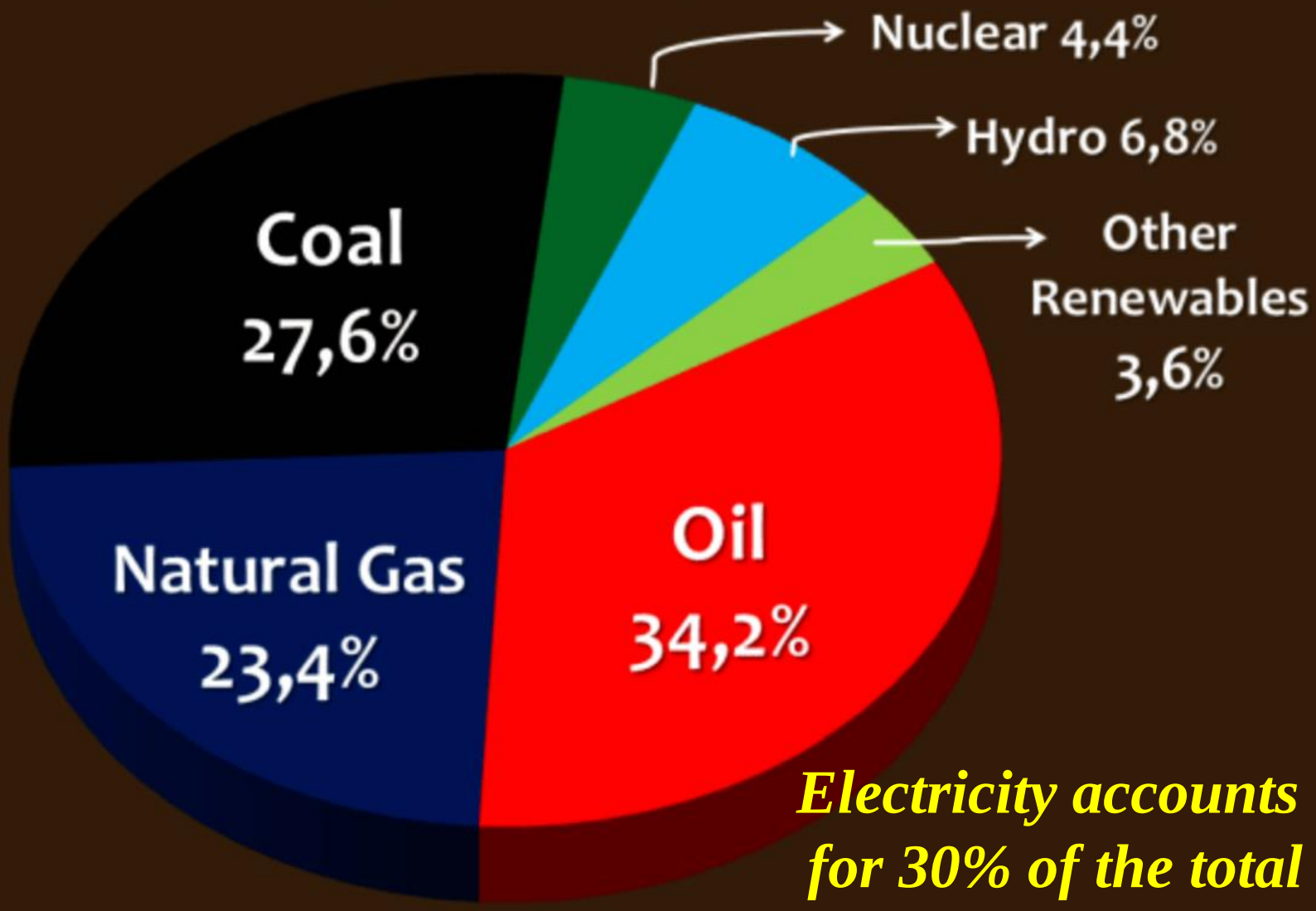
Max. 2º C increase in temperature
Shoot for 1.5º C

The challenges for energy

- **Societal**
  - **Safety**
  - **Waste management**
  - **Proliferation**
- **Technical**
  - **Efficient fuel use**
  - **Minimum CO_2 emission**
- **Economical**
  - **Costs**

World Energy Consumption by Sources

(%, end of 2017)

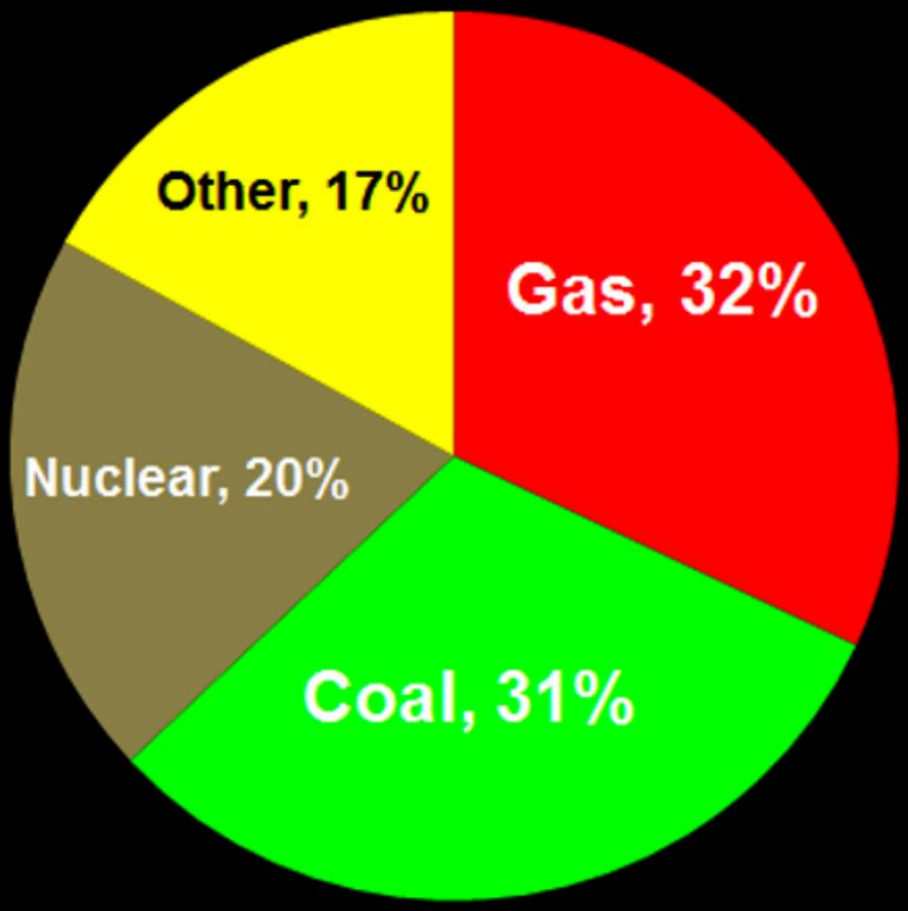


Electricity accounts for 30% of the total

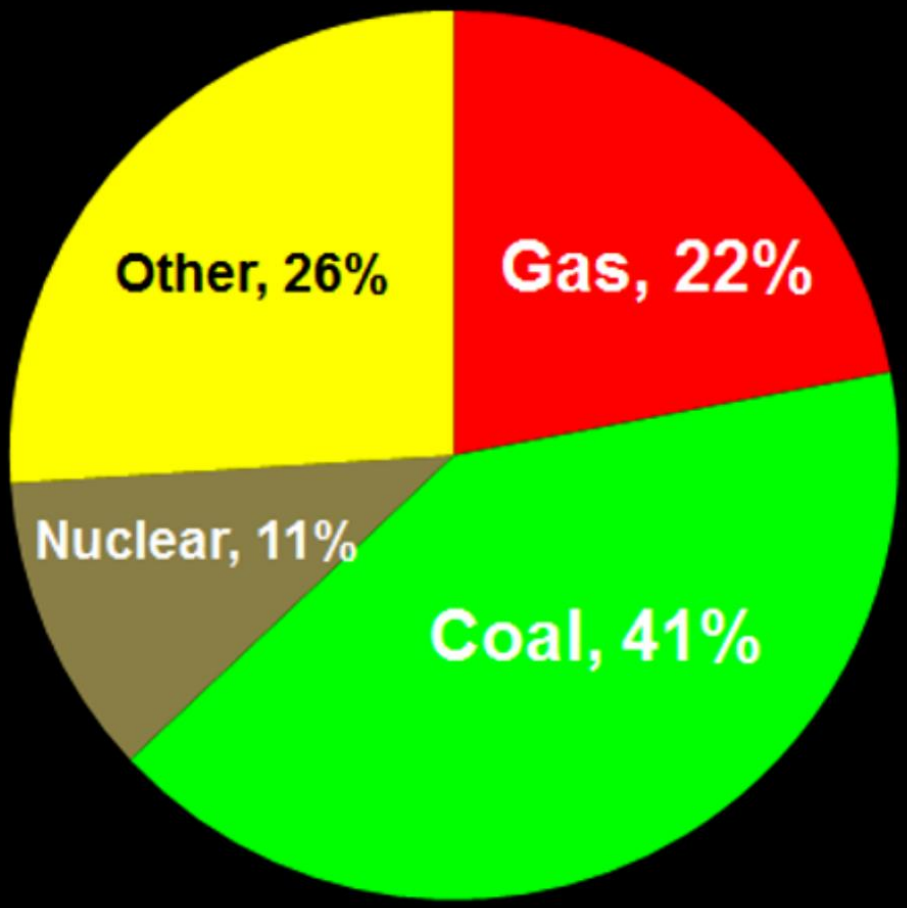
Source: BP Statistical Review of World Energy, June 2018

Electricity Generation, 2017

by source

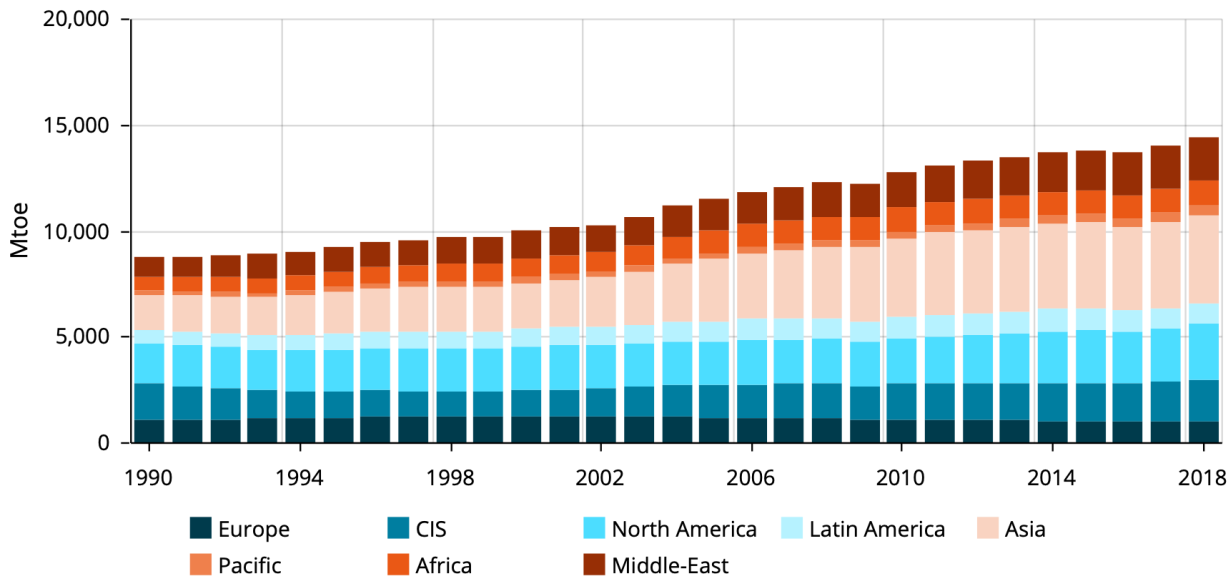


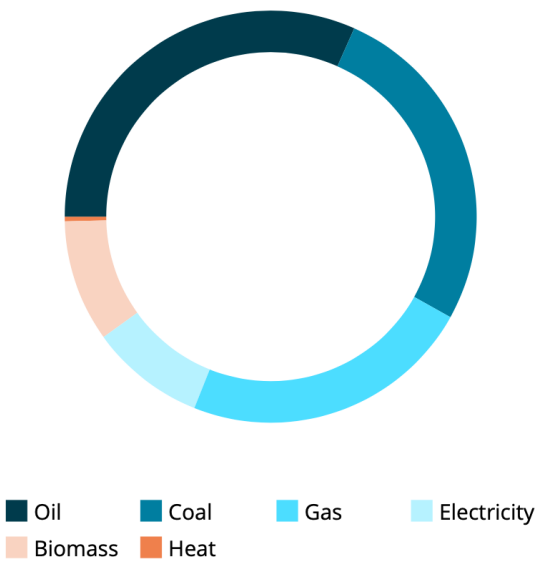
U.S.: 4,050 TWh



World: 24,200 TWh

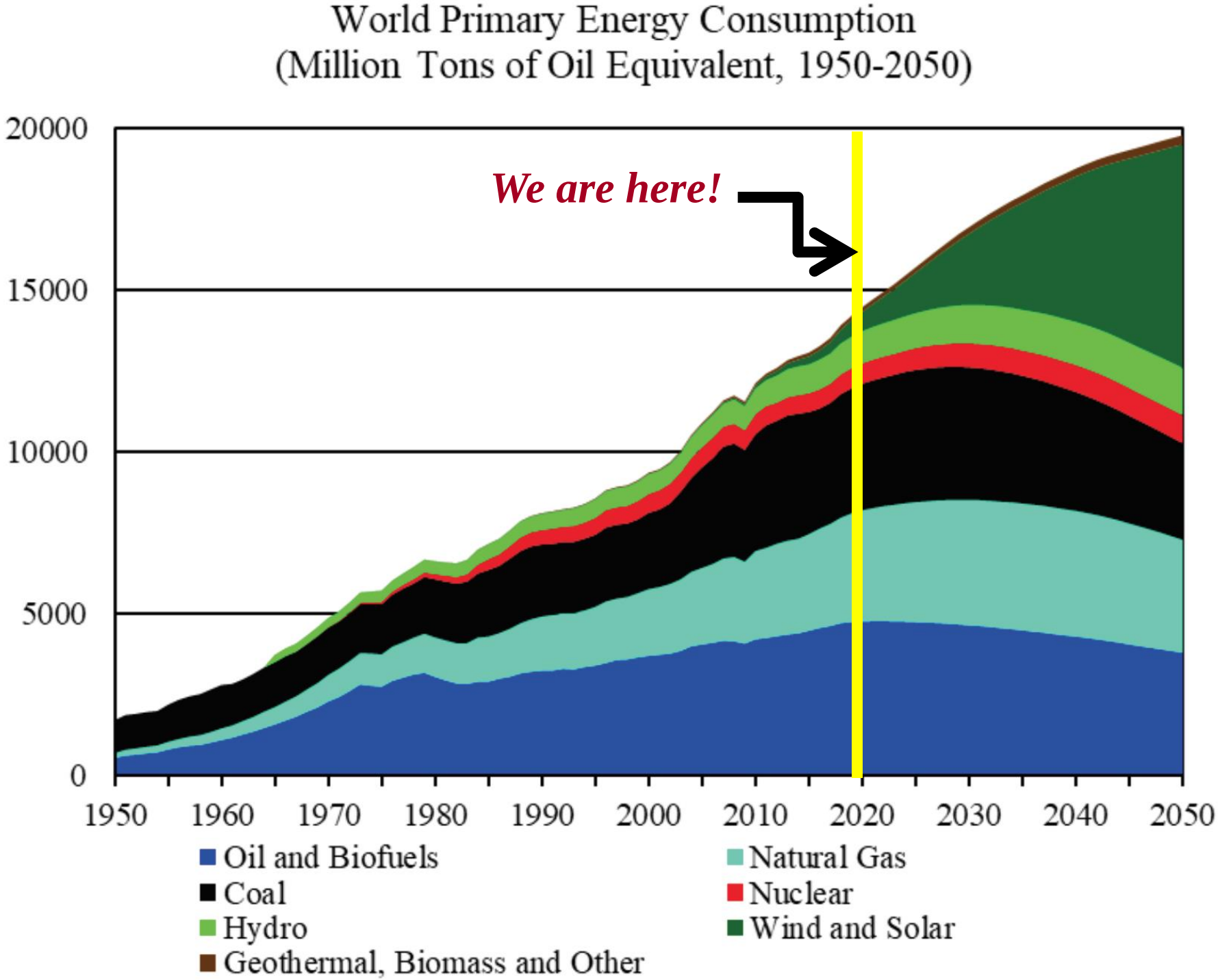
Energy consumption in time



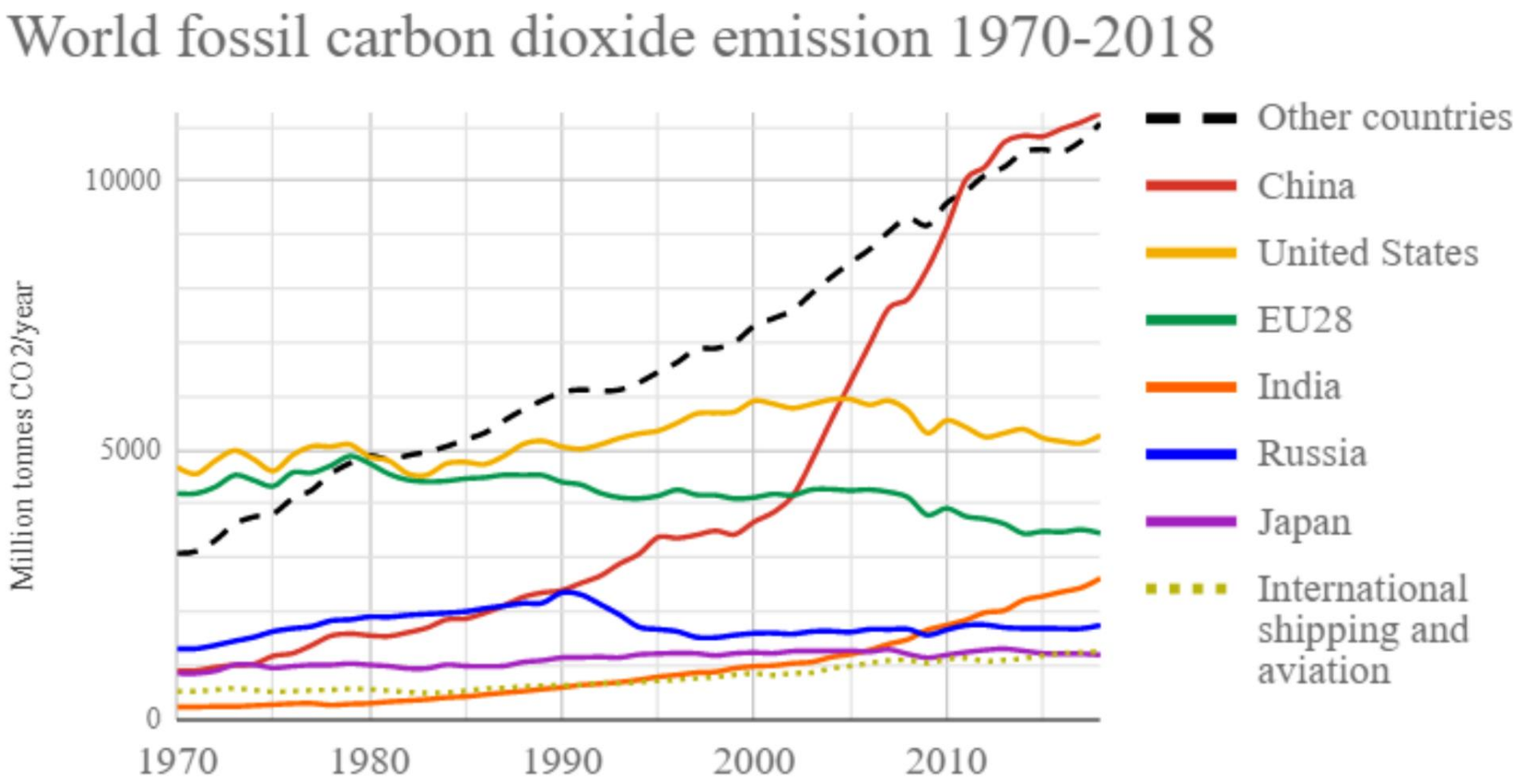


The unit is Mtoe = 10^6 ton oil equivalent!

New York – Sydney flight (in October) took 100 ton!

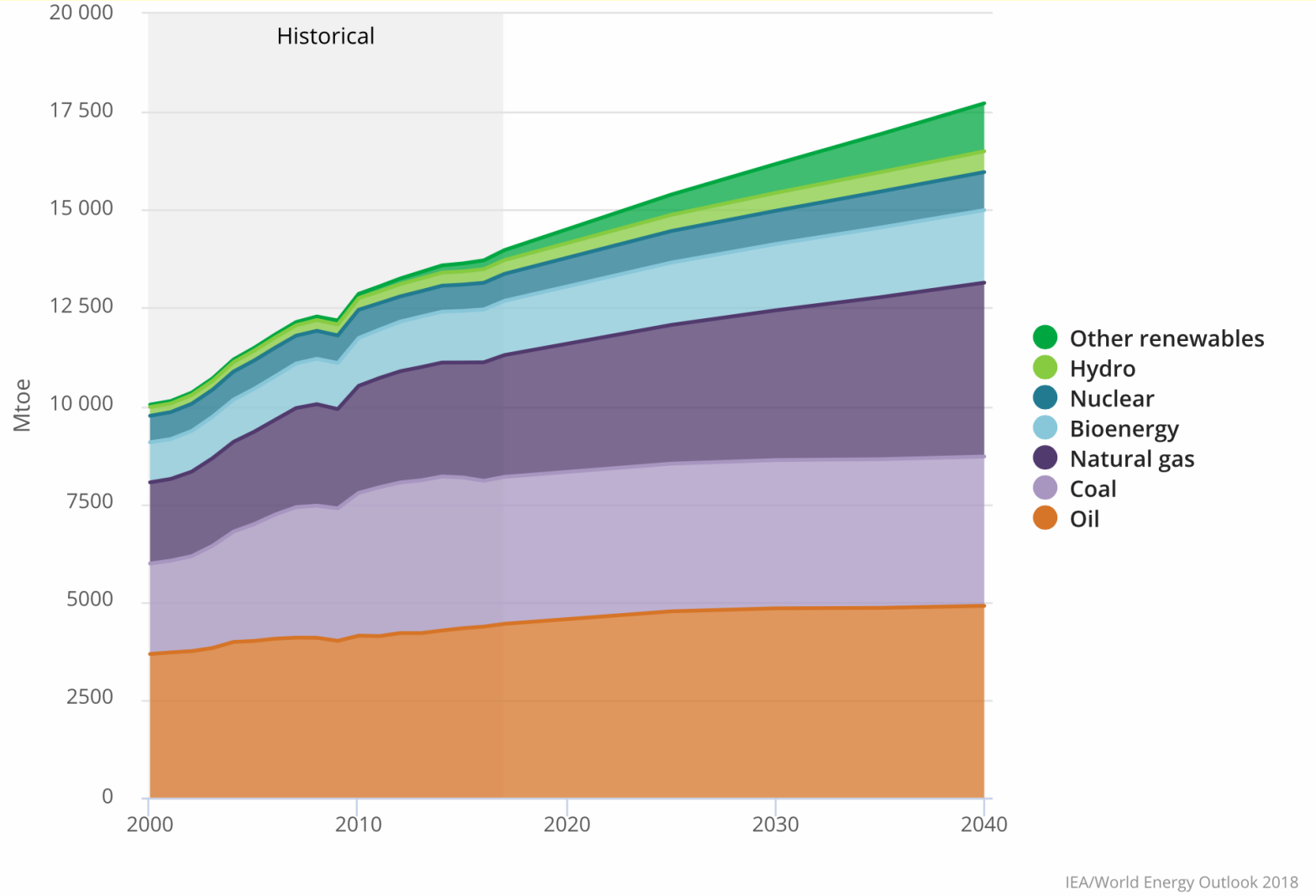

World Primary Energy Consumption
(Million Tons of Oil Equivalent, 1950-2050)
We are here!
20000
15000
10000
5000
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Oil and Biofuels
Natural Gas
Coal
Nuclear
Hydro
Wind and Solar
Geothermal, Biomass and Other

World's CO_2 emission



Energy consumption “new policies”

- 2017: nuclear 5%, renewables 14%; CO_2 32.6 Gton
- 2040: nuclear 5%, renewables 20%; CO_2 35.9 Gton



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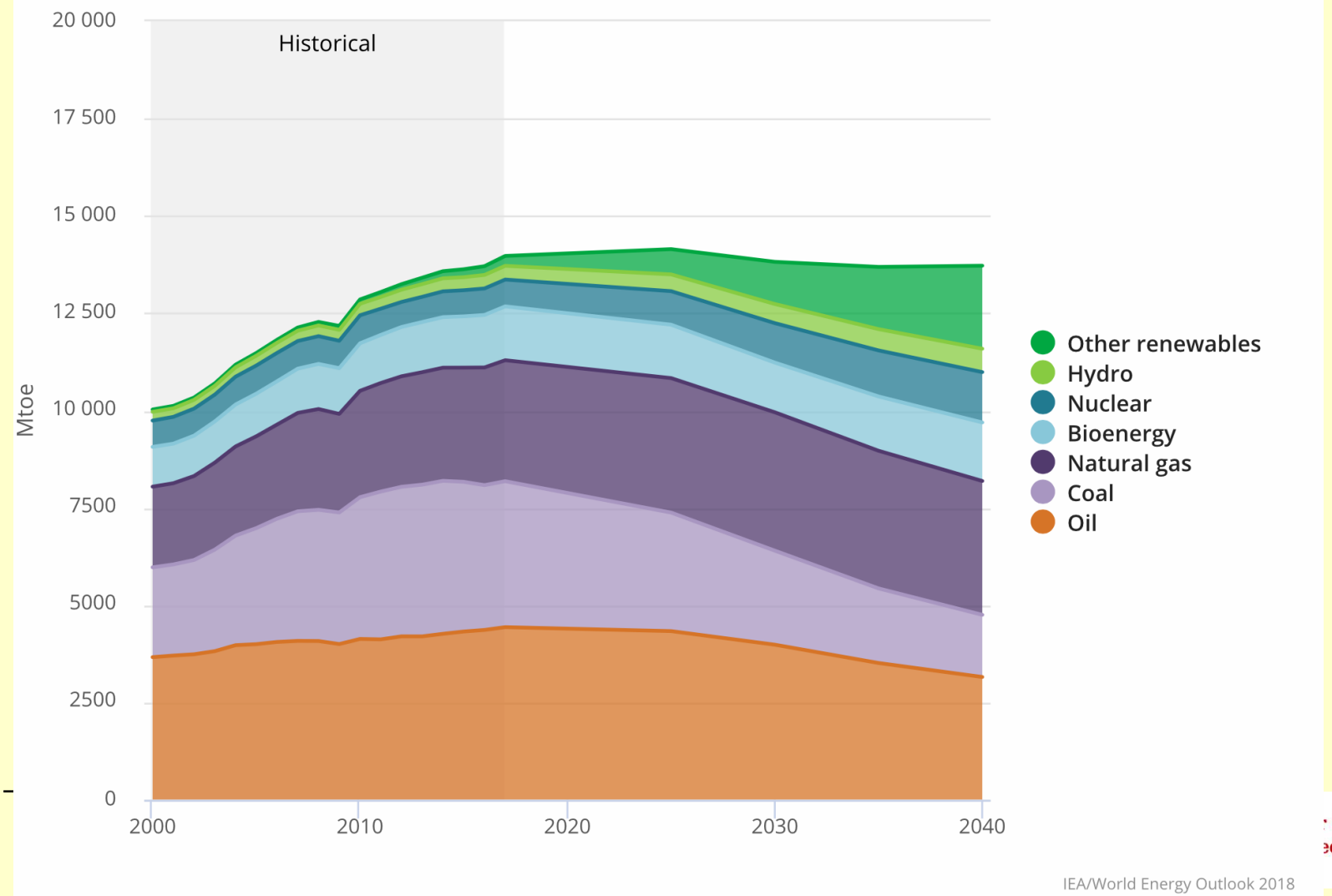
Forget about the Paris Agreement!

We only have a 5 percent chance of sticking to Paris COP21 climate goals.

Energy consumption “sustainable”

- 2017: nuclear 5%, renewables 14%; CO_2 32.6 Gton
- 2040: nuclear 9%, renewables 31%; CO_2 17.6 Gton



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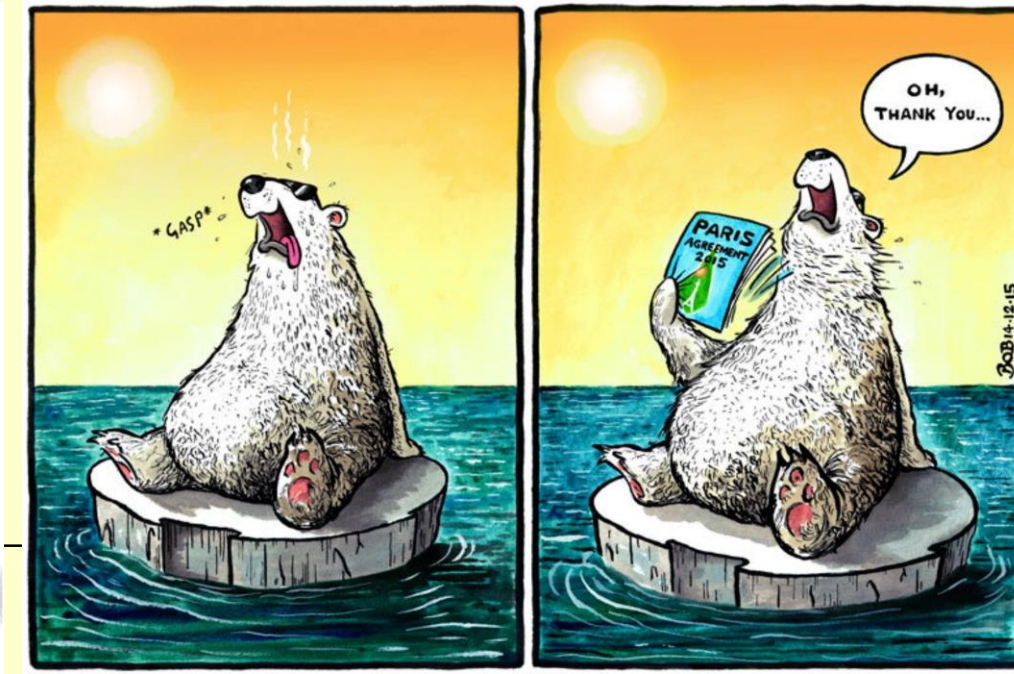
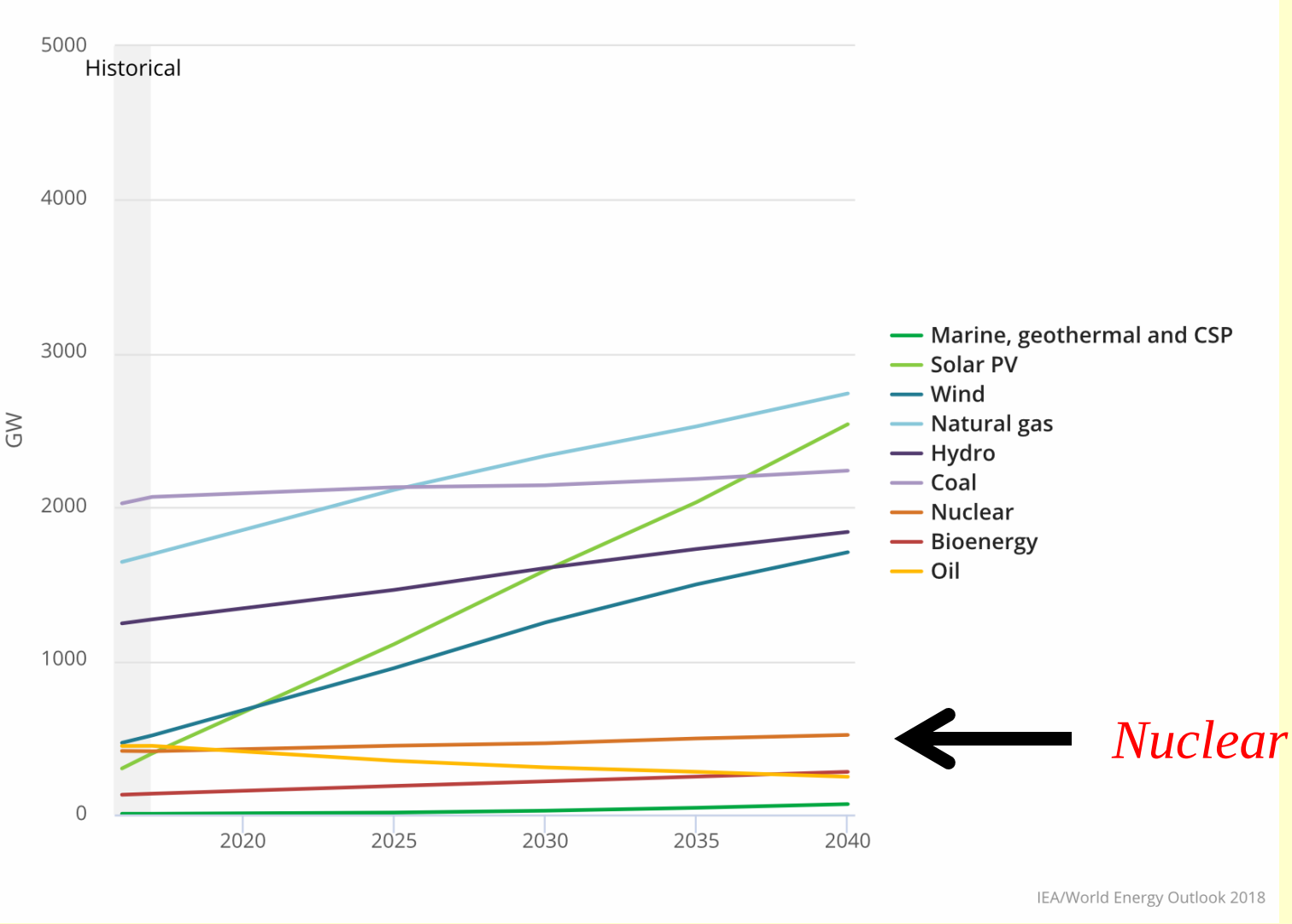
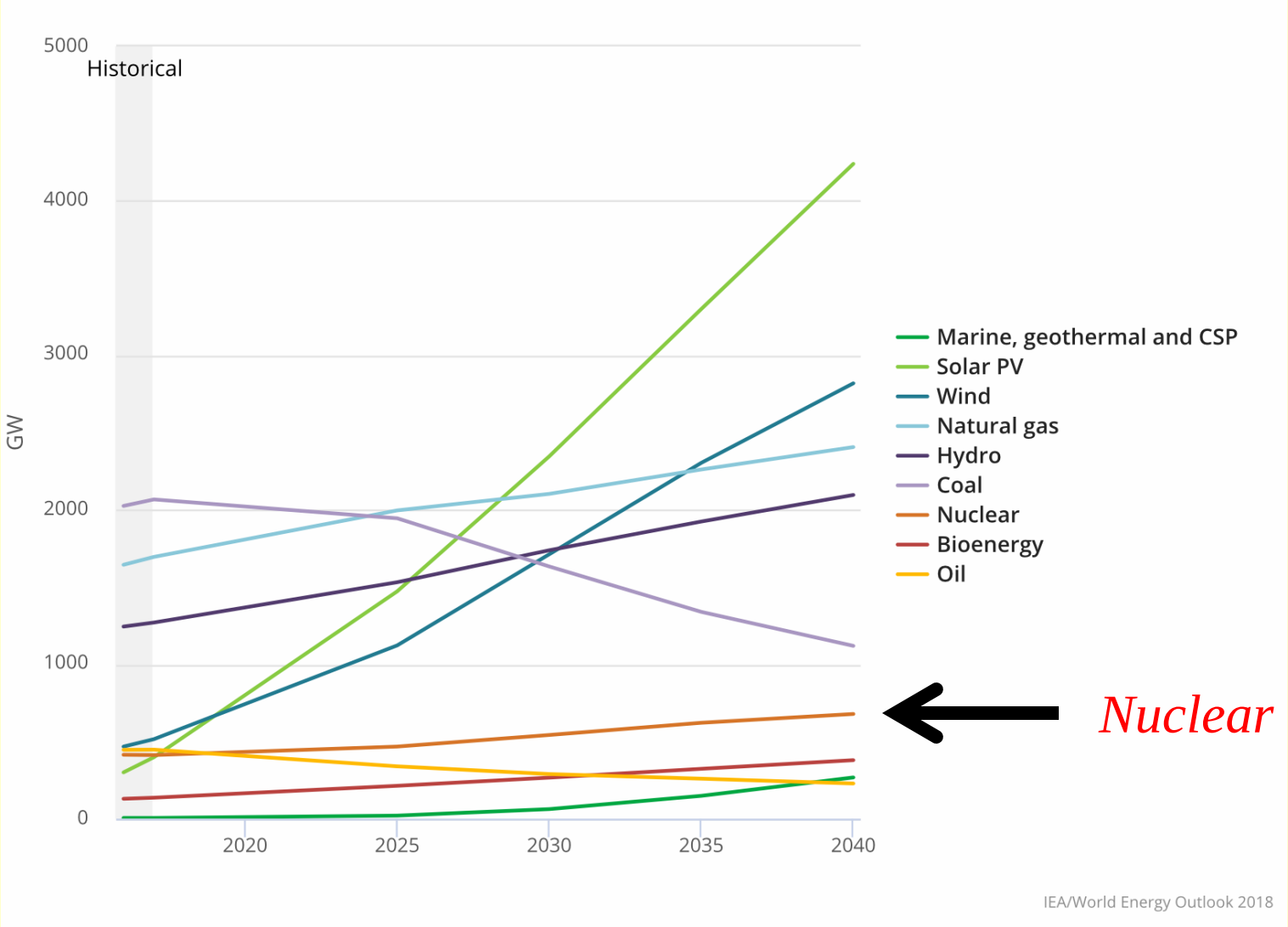
There is hope for Paris Agreement!



Installed power generation capacity, new policies



Installed power generation capacity, sustainable



Nuclear electricity production in Europe

- In 2018, nuclear power plants generated 25.5% of the electricity produced in the EU:
  - 14 member states have nuclear power plants;
  - 128 nuclear reactors produced 119 GWe;
  - Under construction: 4 in the EU and 10 in Russia and Belorussia.

Climate change and nuclear energy

2016	CO2	CO2-free	Nuclear	Bio+waste
world	81%	19%	5%	10%
EU 28	72%	**28%**	14%	10%
Belgium	71%	29%	20%	7%
France	47%	**53%**	42%	7%
Germany	79%	21%	7%	10%
Sweden	29%	**71%**	33%	25%

Countries with a high percentage CO_2-free energy use (nuclear) electricity for heating.

Still a lot to do for CO_2-free transport.

Data International Energy Agency, Total primary energy supply

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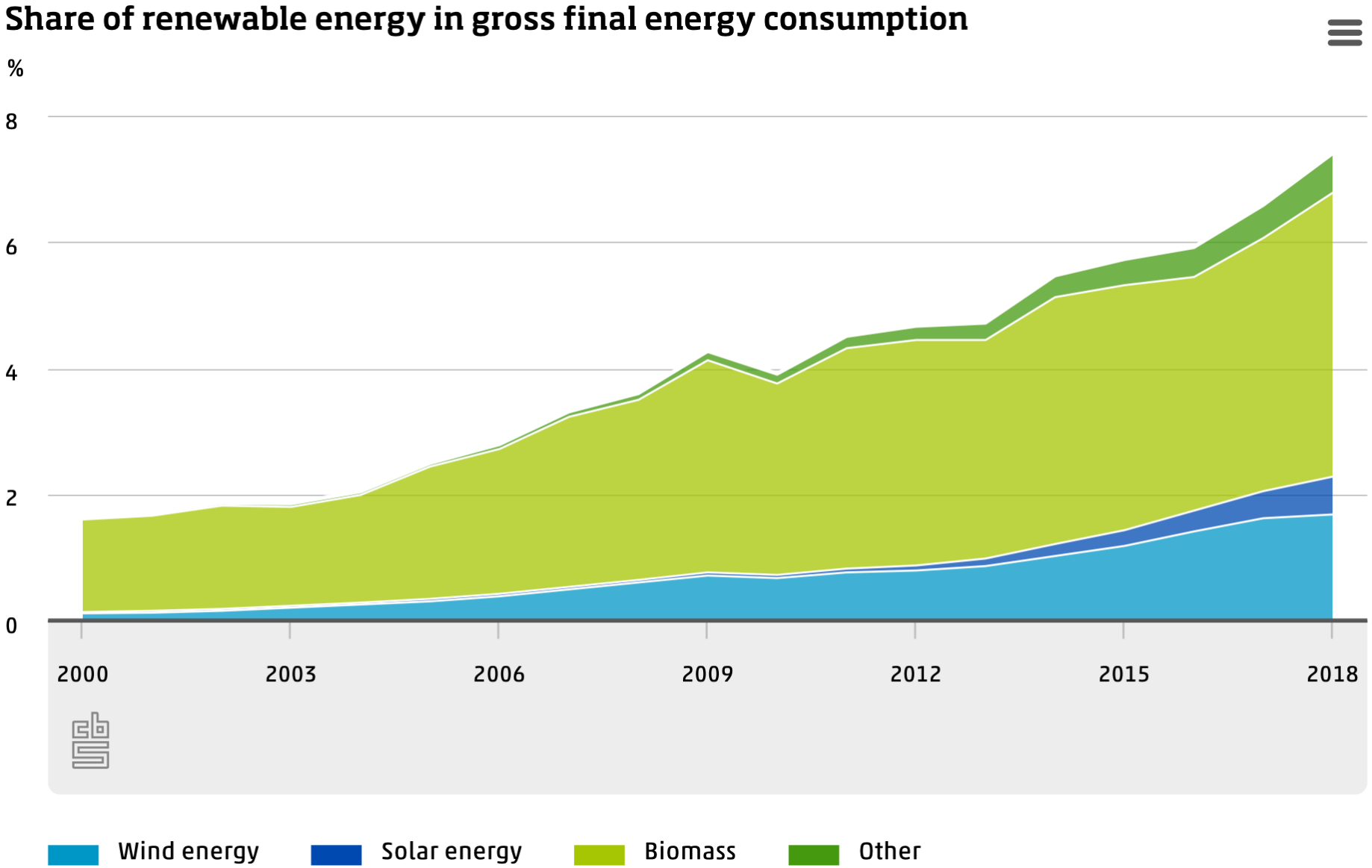
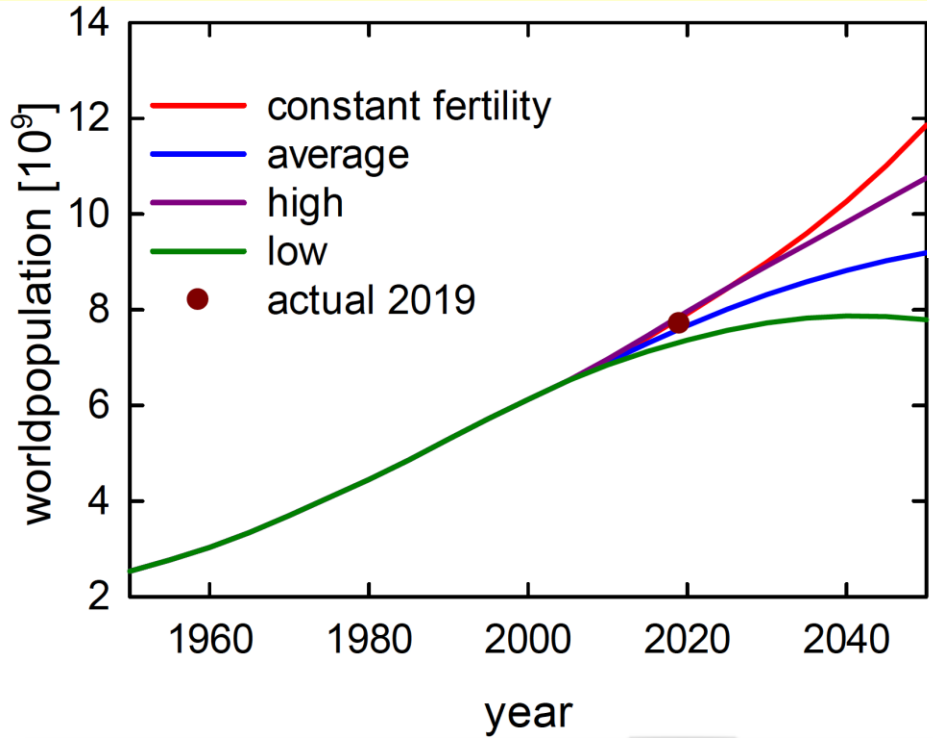
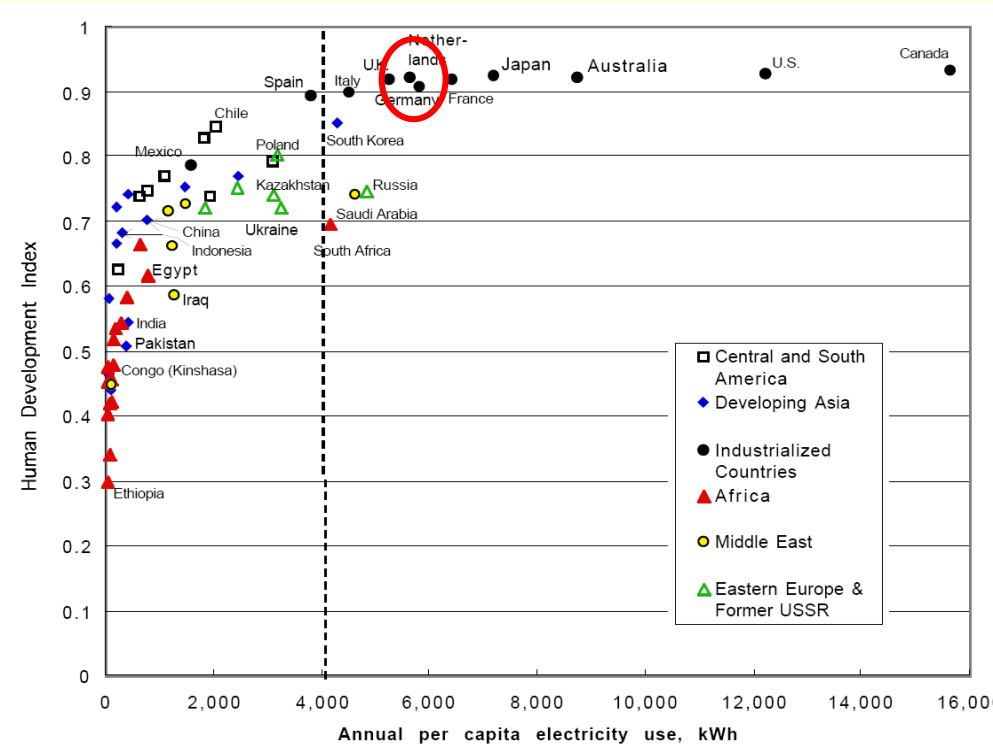
Renewables in the Netherlands



Energy consumption and the population growth





Source: the walt.com

Reserves

Reserves

With the consumption level of 2016

- **Gas** **14 years**
- **Oil** **16 years**
- **Coal** **40 years**
- **^{235}U** **30 years (current fuel cycle)**

New Nuclear Technologies

- **^{238}U** **2000 years (Breeder reactors)**
- **^{232}Th** **8000 years (Thorium reactors)**

More reserves are sought for but the world consumption is also increasing by more than a quarter in the next 20 years.

How to proceed?

- Energy saving
- Accelerate the renewables
- Transition
  - Carbon sequestration
  - Nuclear fission
- Nuclear fusion ???

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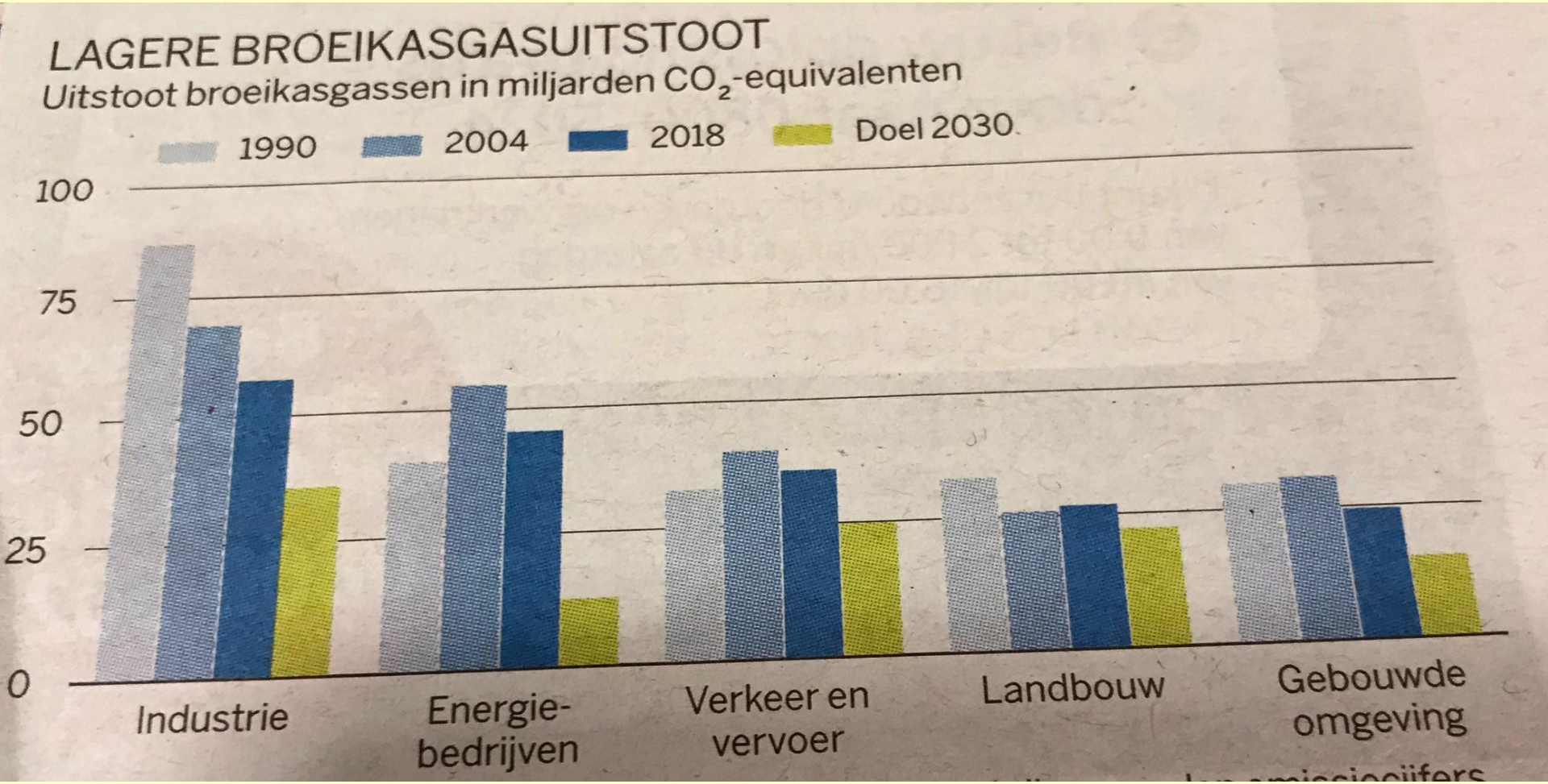

Volkskrant 23/09/2019

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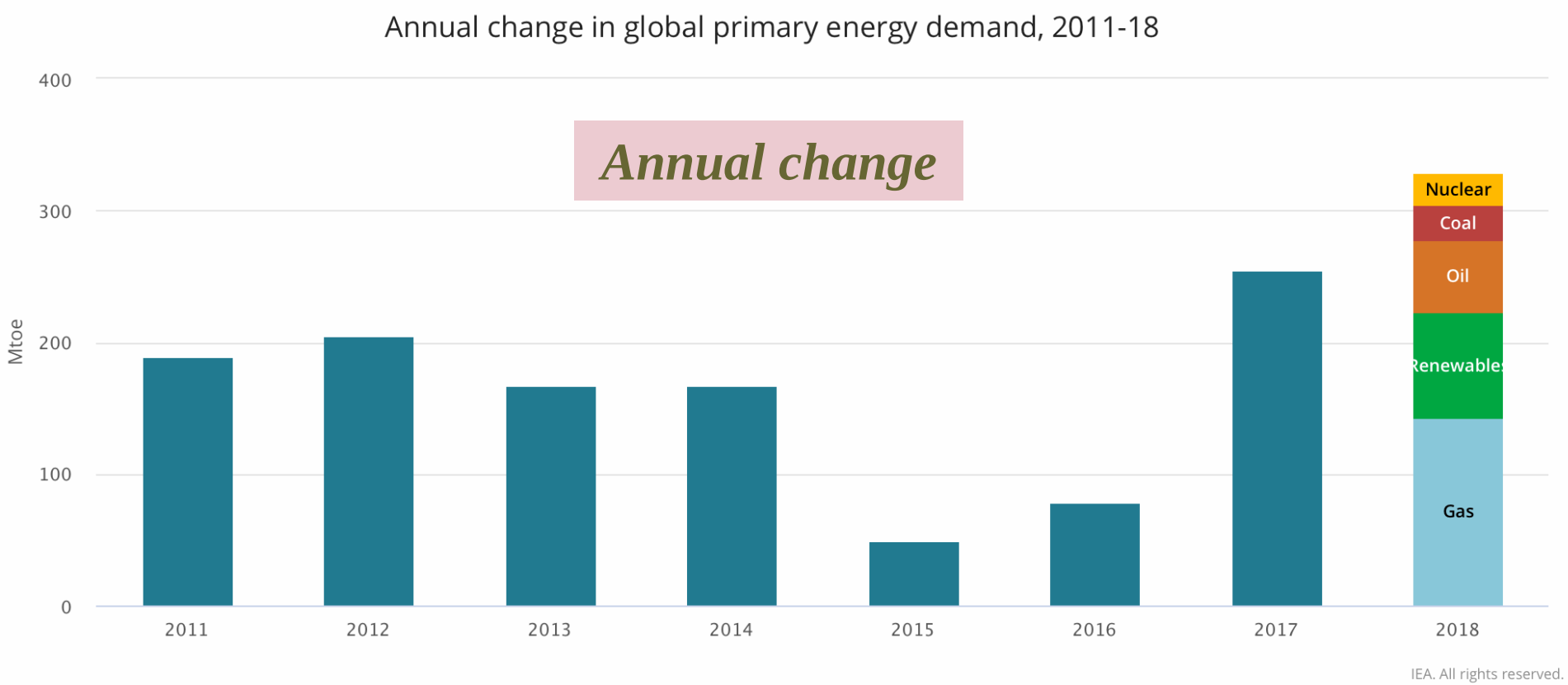
Present situation



2011

2018

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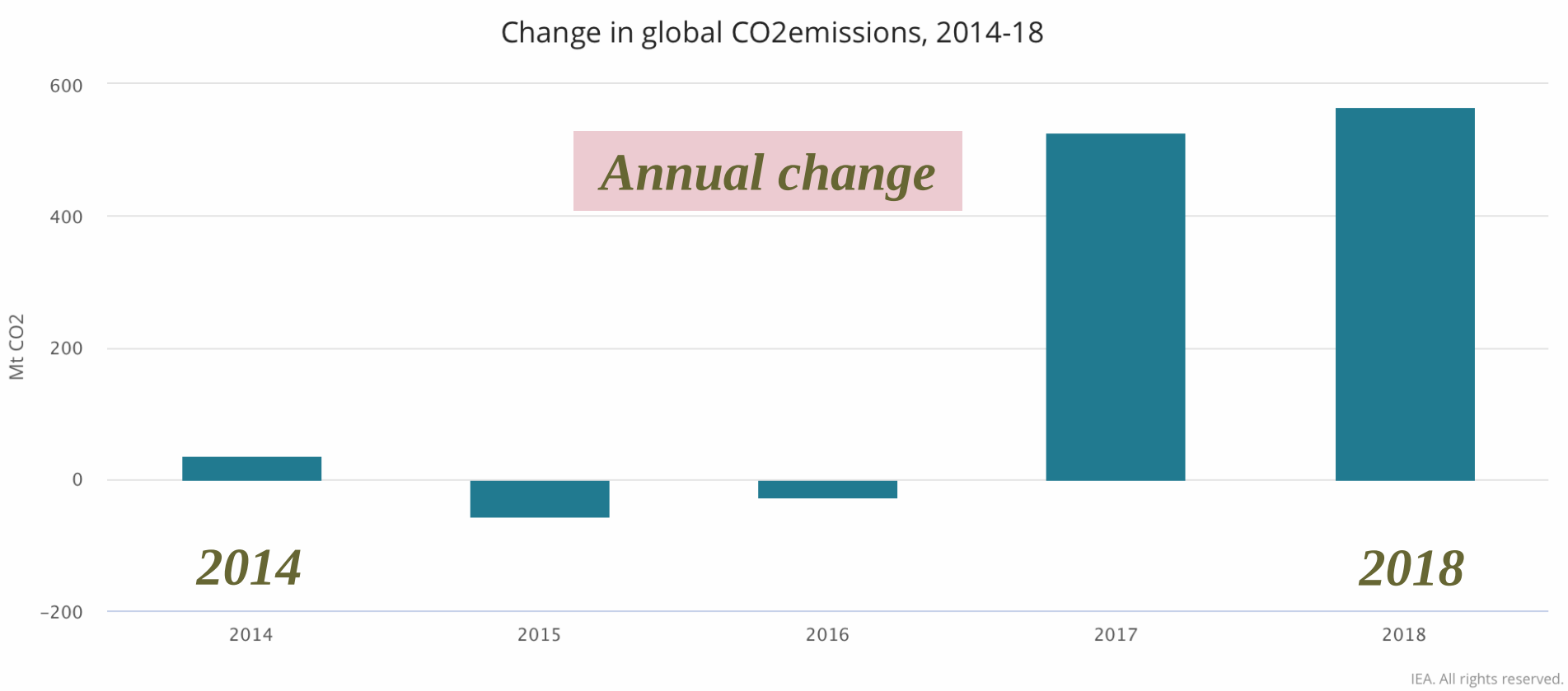
Present situation

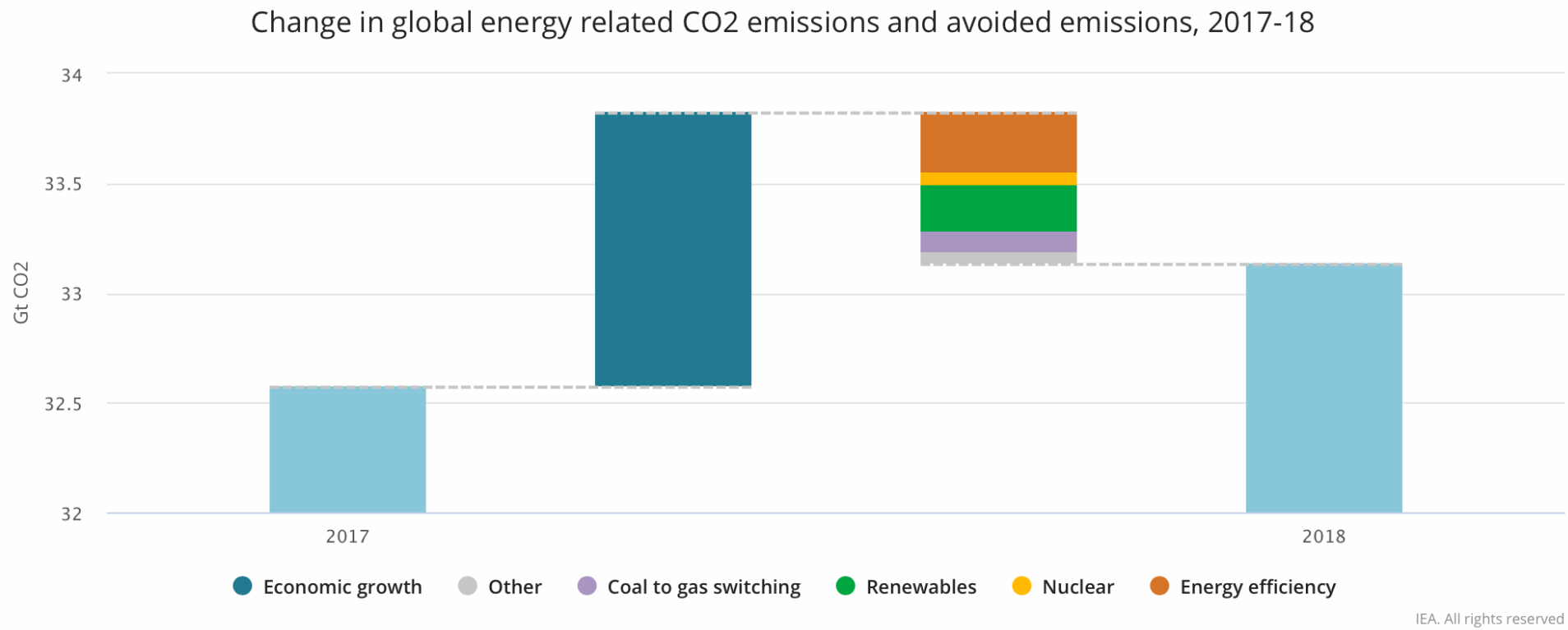


Present situation

Renewables

Growth in renewable electricity generation by region and technology, 2017-18

Present situation



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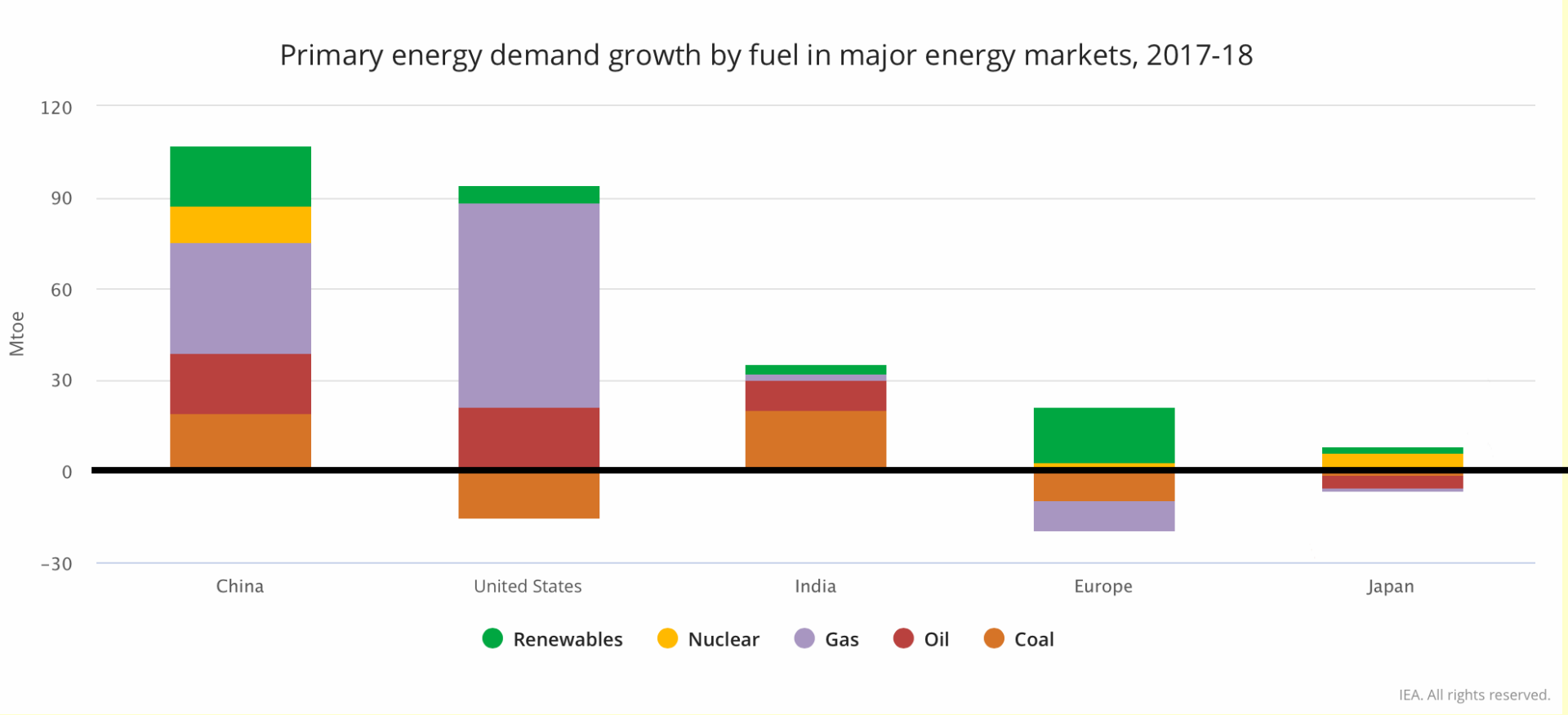

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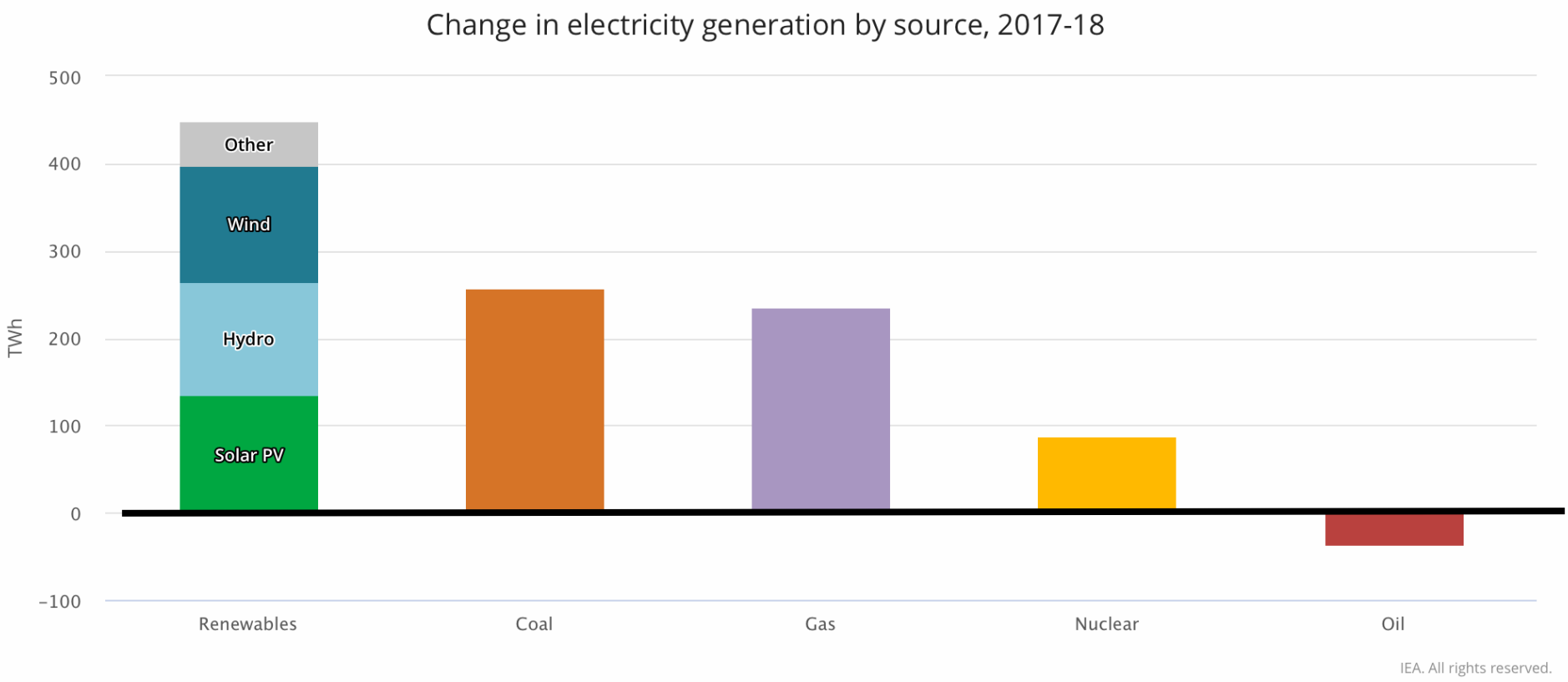

Electricity production & CO_2 emission!

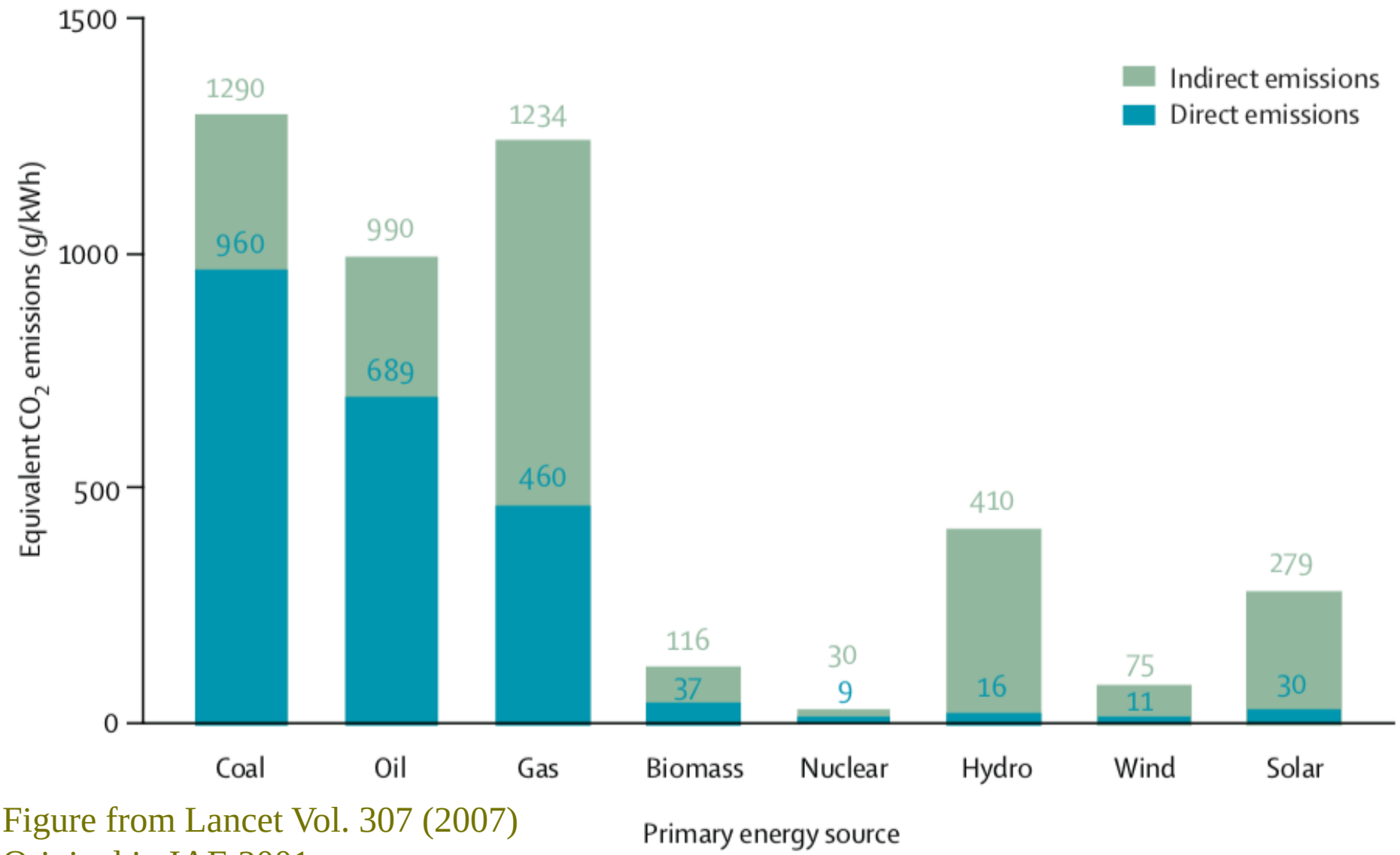

Figure from Lancet Vol. 307 (2007)
Original in IAE 2001

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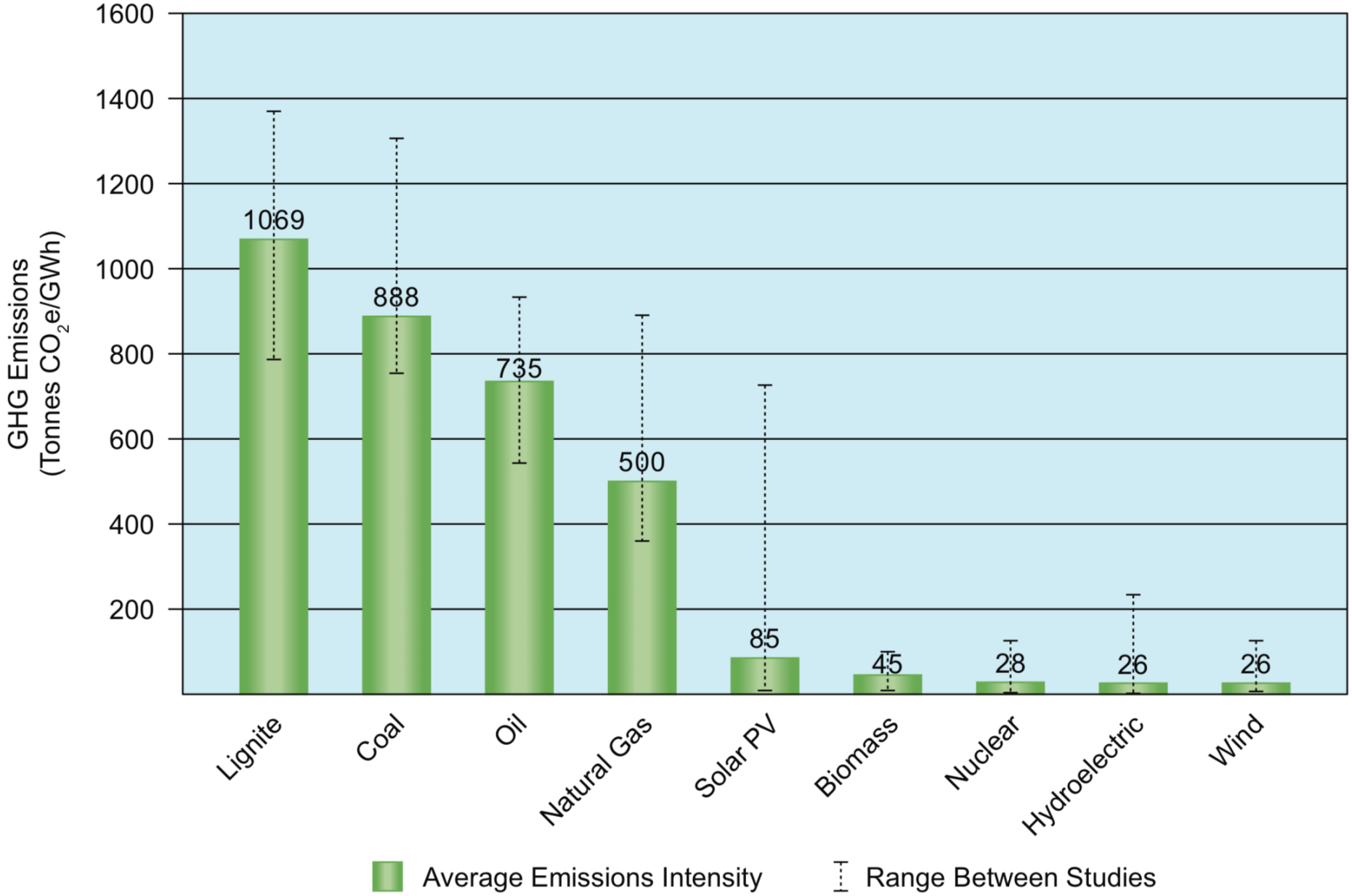

Electricity production & CO_2 emission!

Deaths and accidents

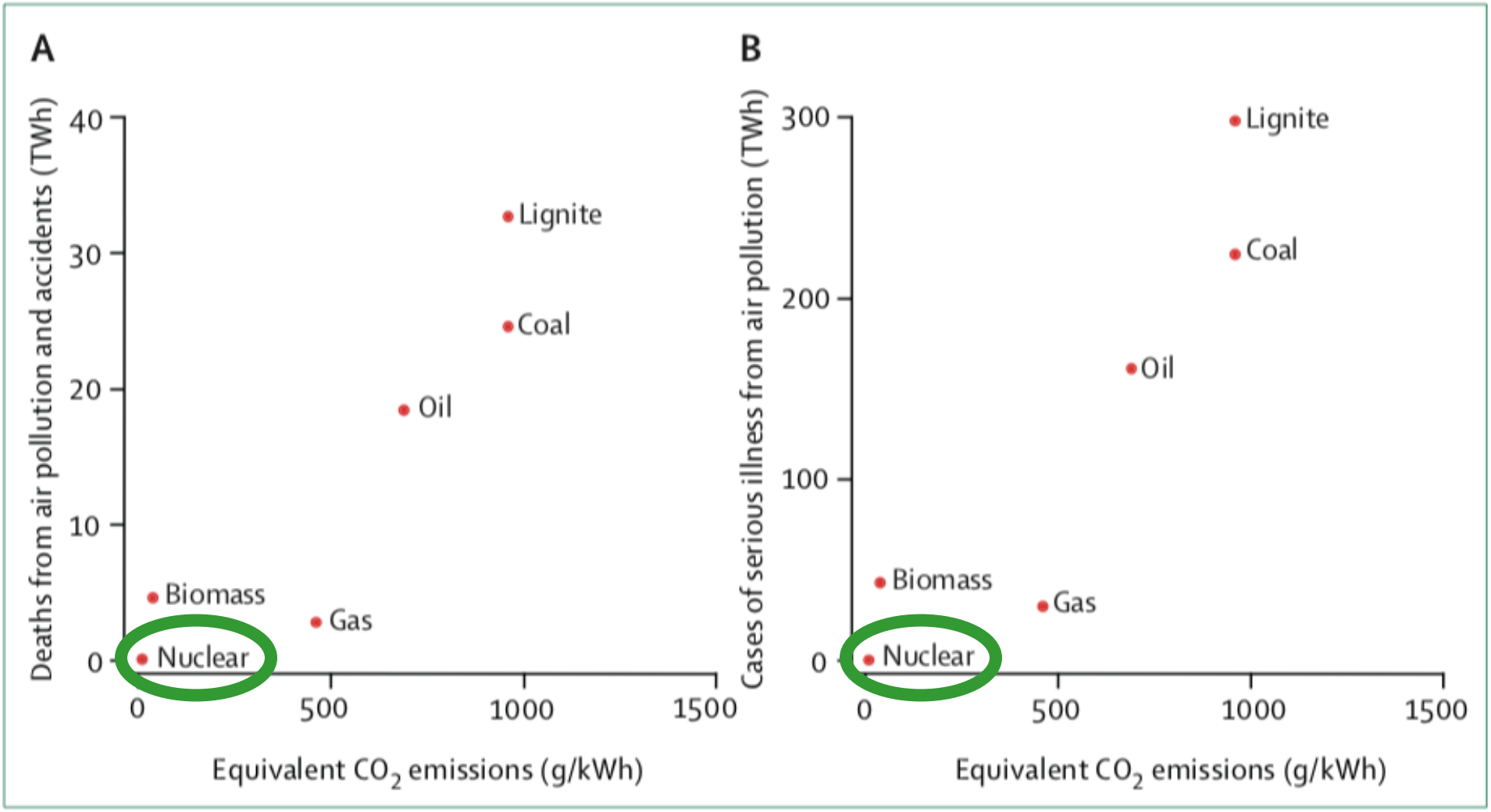

Figure from Lancet Vol. 307 (2007)
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Sustainable Sources

- Sun
- Wind
- Geothermal
- Tidal energy
- Wood (?)
- Nuclear

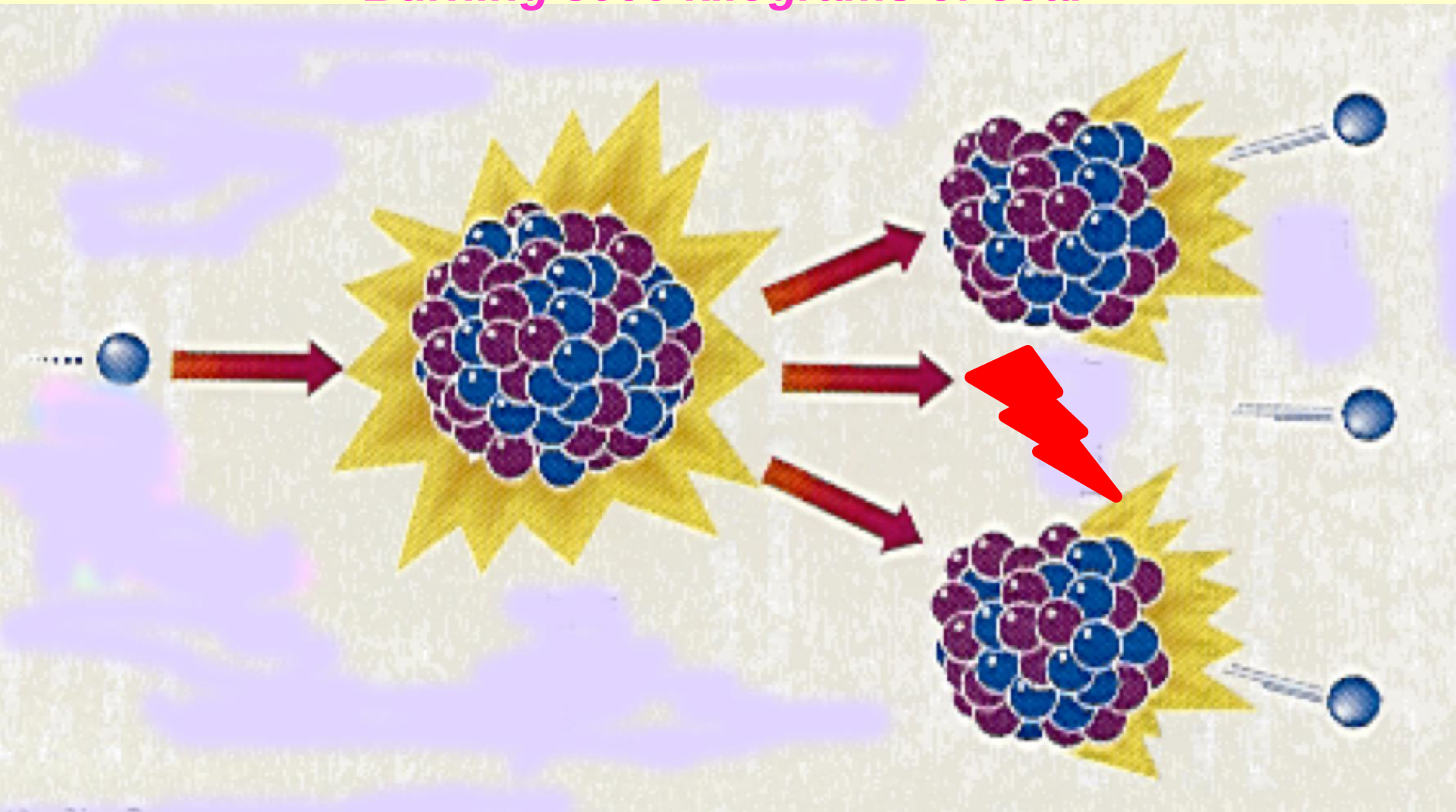
The challenges for energy

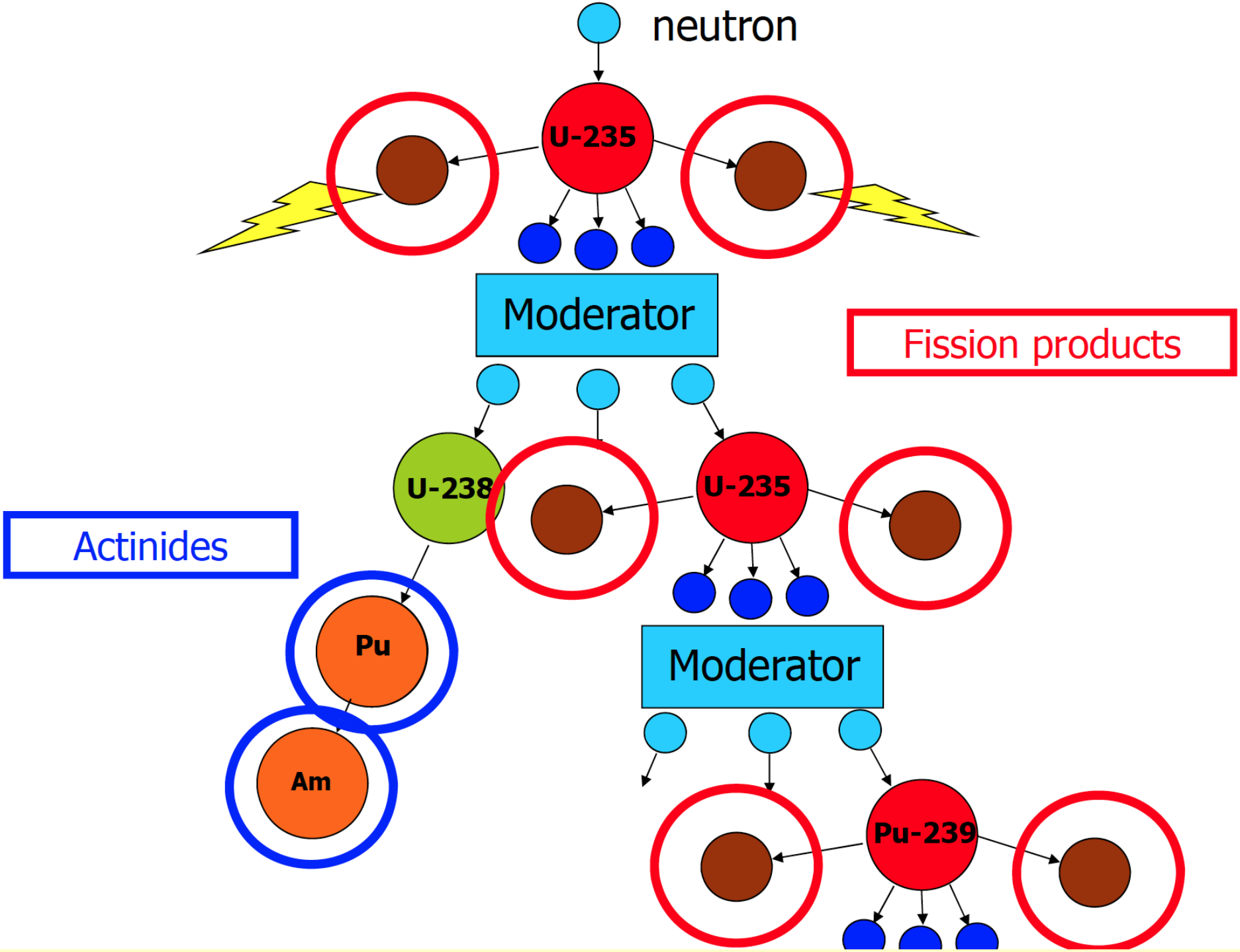
- **Societal**
  - **Safety**
  - **Waste management**
  - **Proliferation**
- **Technical**
  - **Efficient fuel use**
  - **Minimum CO_2 emission**
- **Economical**
  - **Costs**

Technical issues

Nuclear fission $E = mc^2$

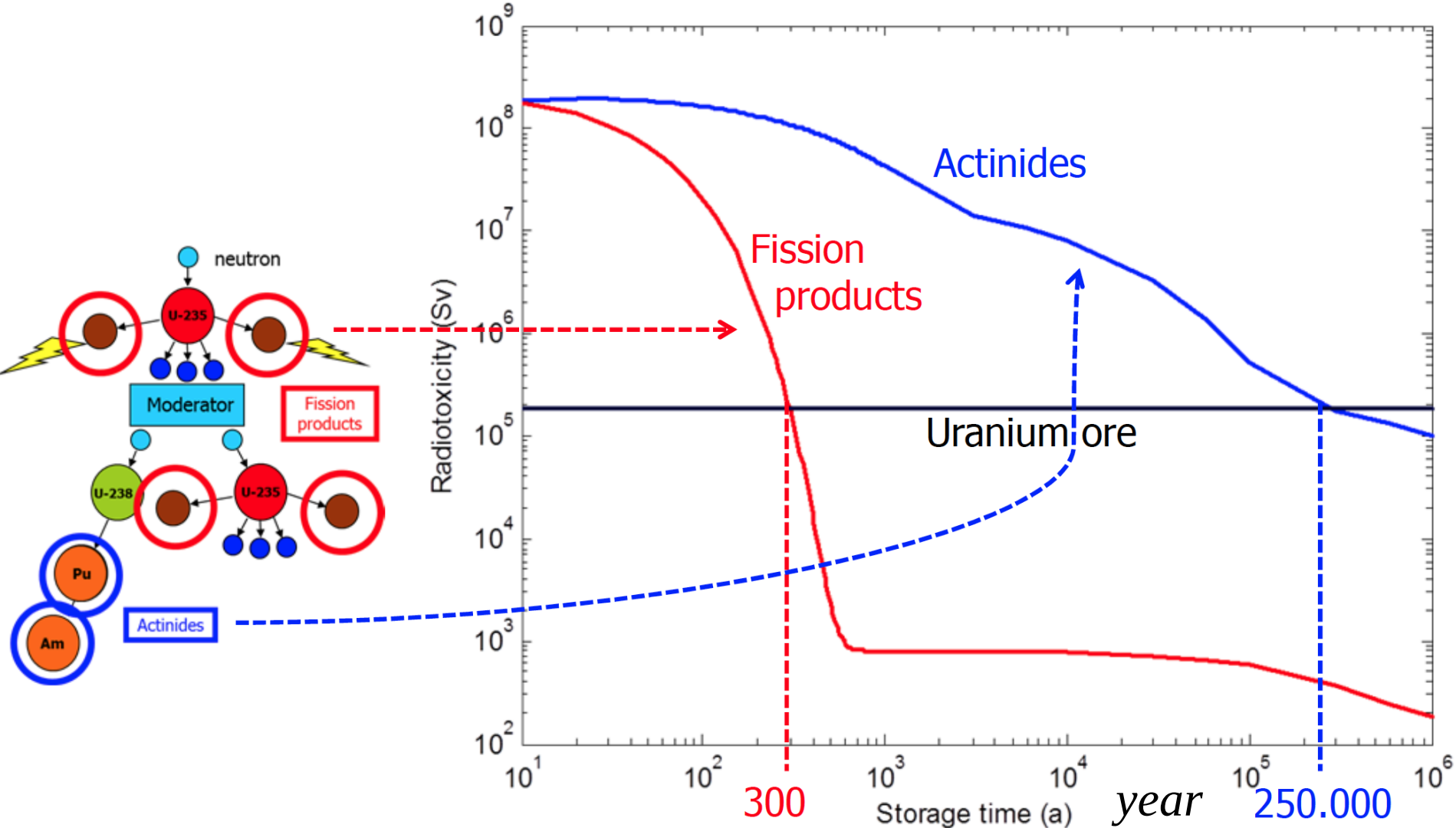
Fissioning of 1 gram of uranium releases as much energy as
Burning 2500 liters of Petrol or
Burning 3000 kilograms of coal



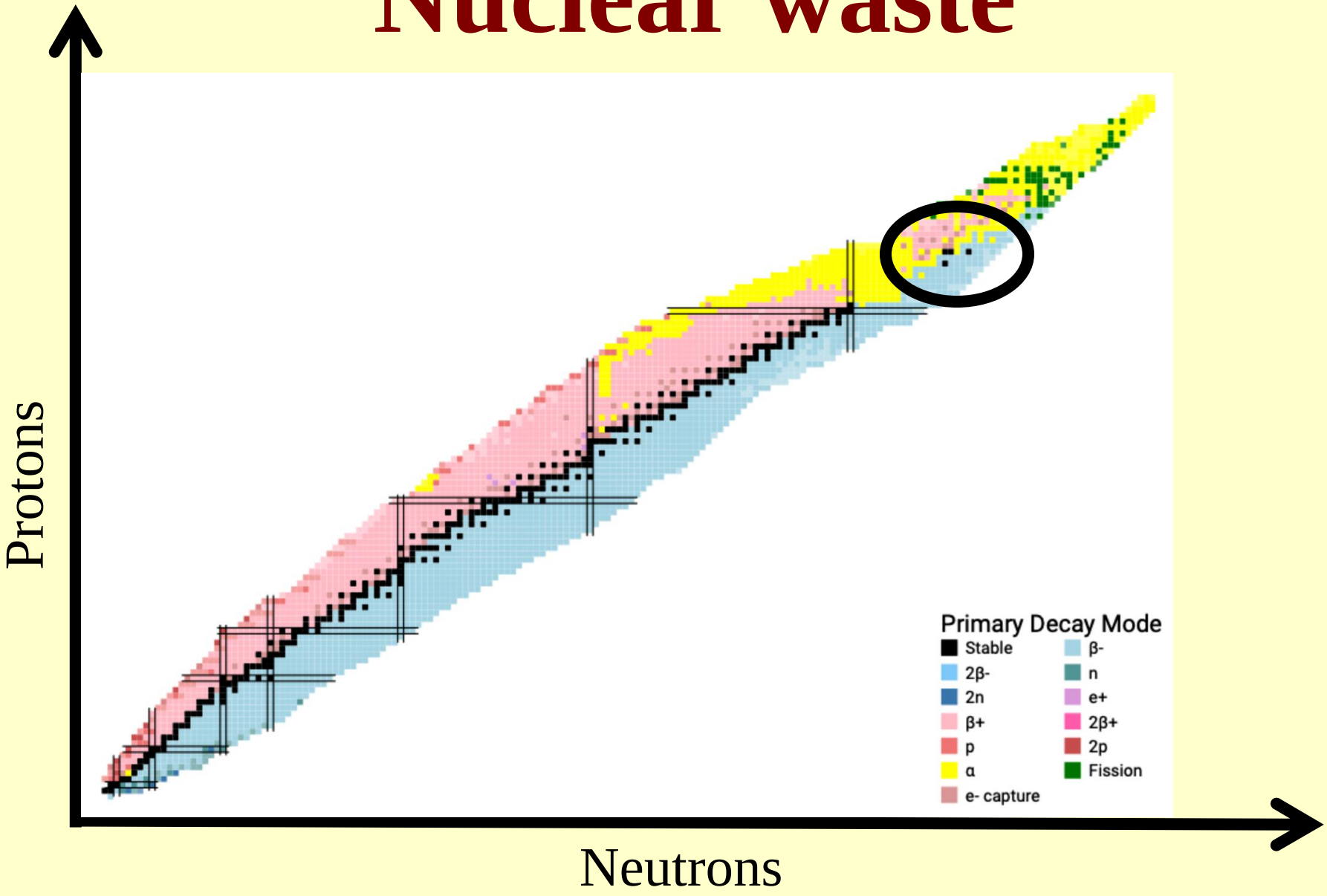

neutron
U-235
Moderator
Fission products
U-238
U-235
Actinides
Pu
Am
Moderator
Pu-239

Nuclear waste

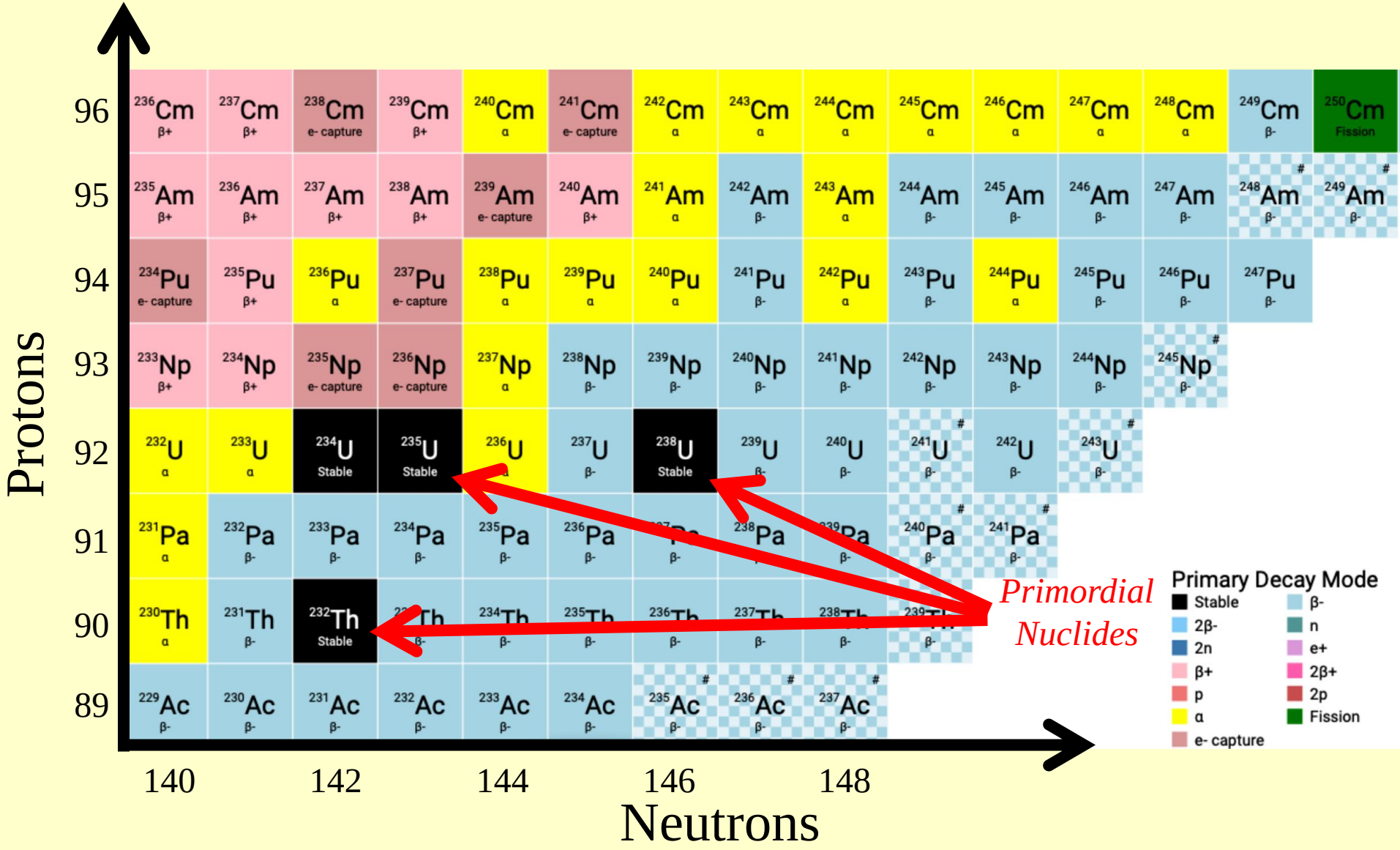
Radiotoxicity LWR



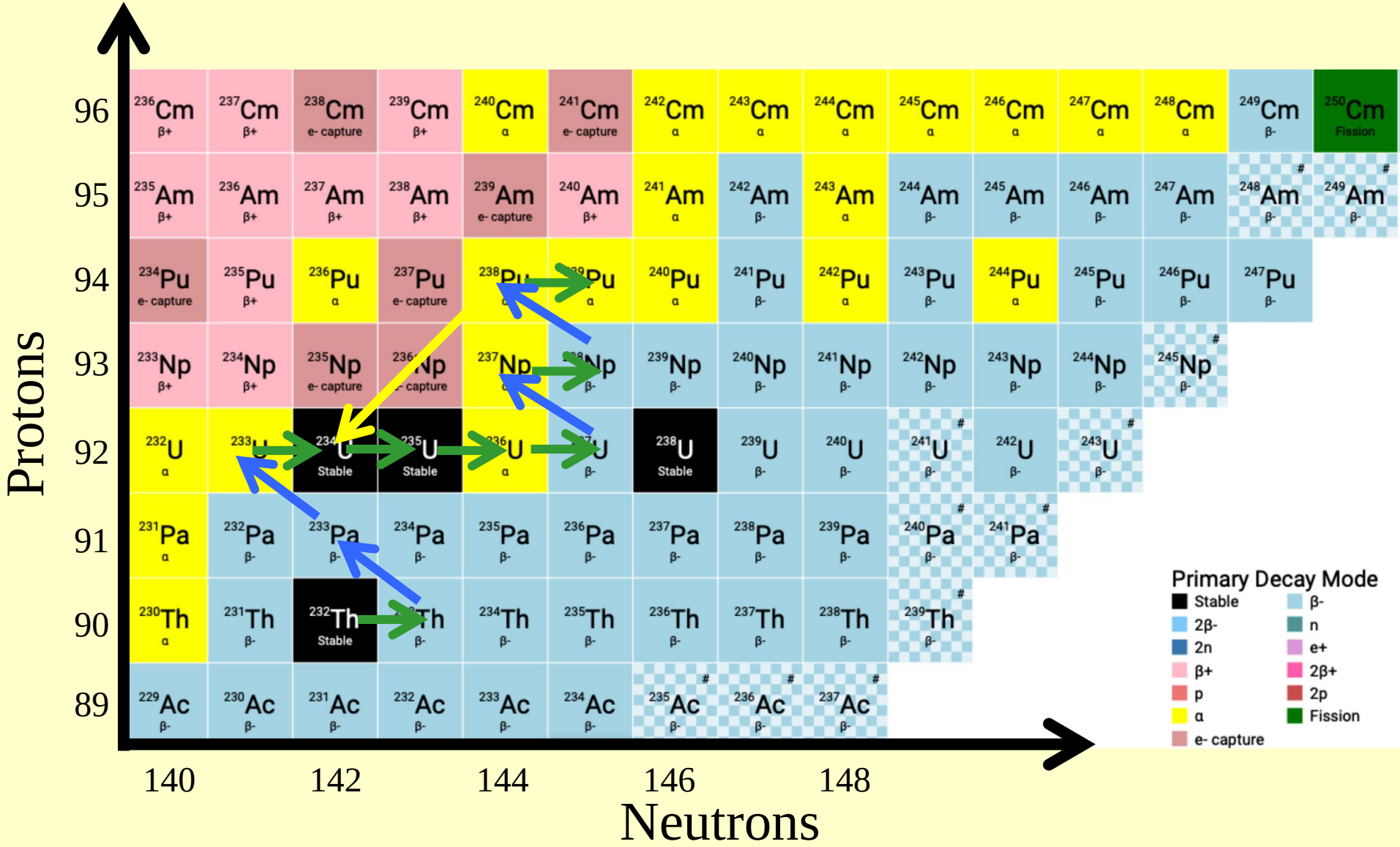
Nuclear waste



Nuclear waste



Nuclear waste



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Nuclear waste

Small numbers

- **Waste per household in NL for nuclear electricity: ~0.5 g/year uranium fission**

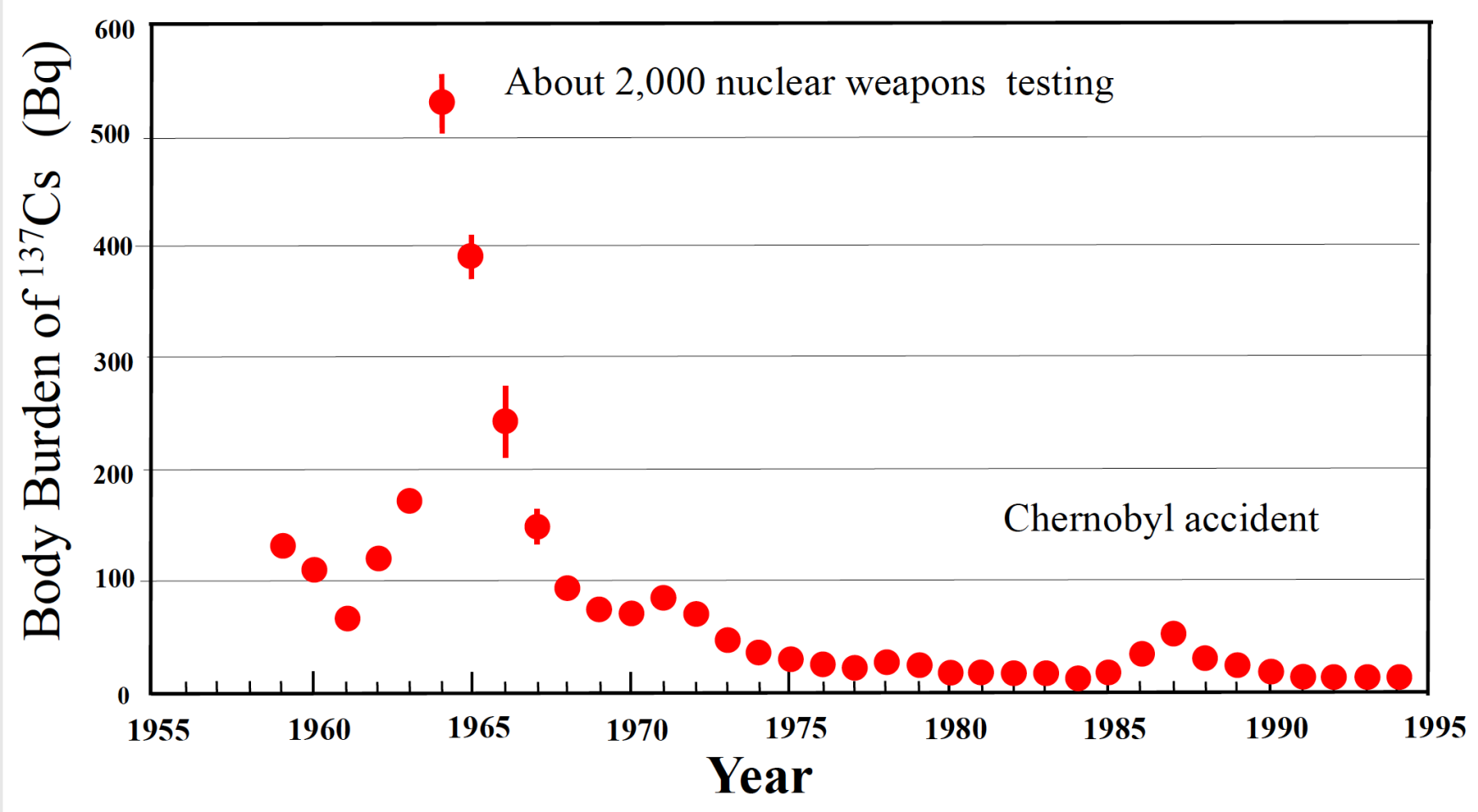
- **In a lifetime of a household: about 5 ml**

- **Borssele reactor produces 1.3 m^3 waste/year**

- **Borssele reactor prevents emission of 2 billion kg CO_2/year (if coal is used)**

Safety

History



Annual average of ^{137}Cs body burden of 20 Japanese male adults as a Function of elapsed year around the atomic bomb test around the world

M. Uchiayama et al., Health Phys. 71, 320 (1996)

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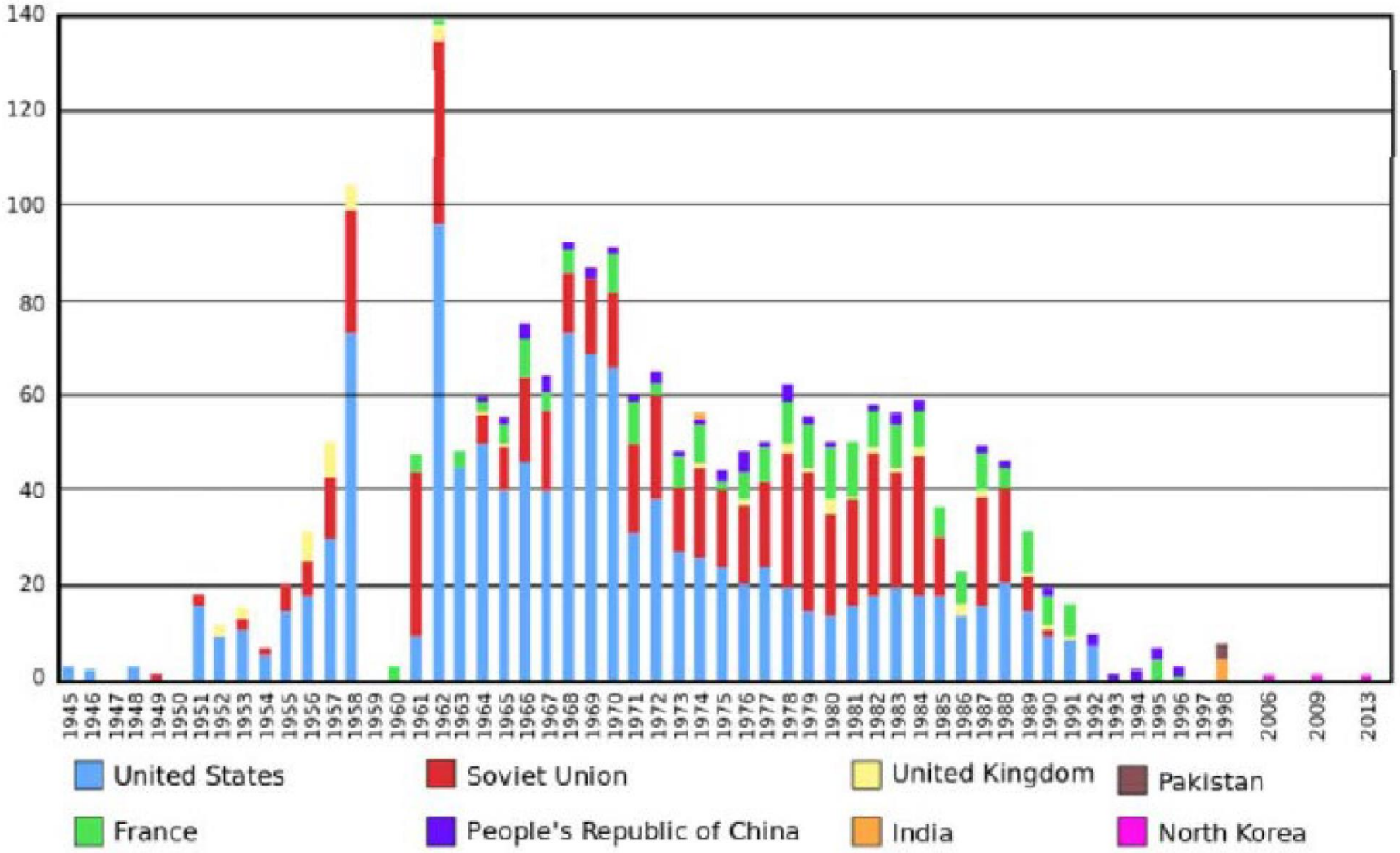
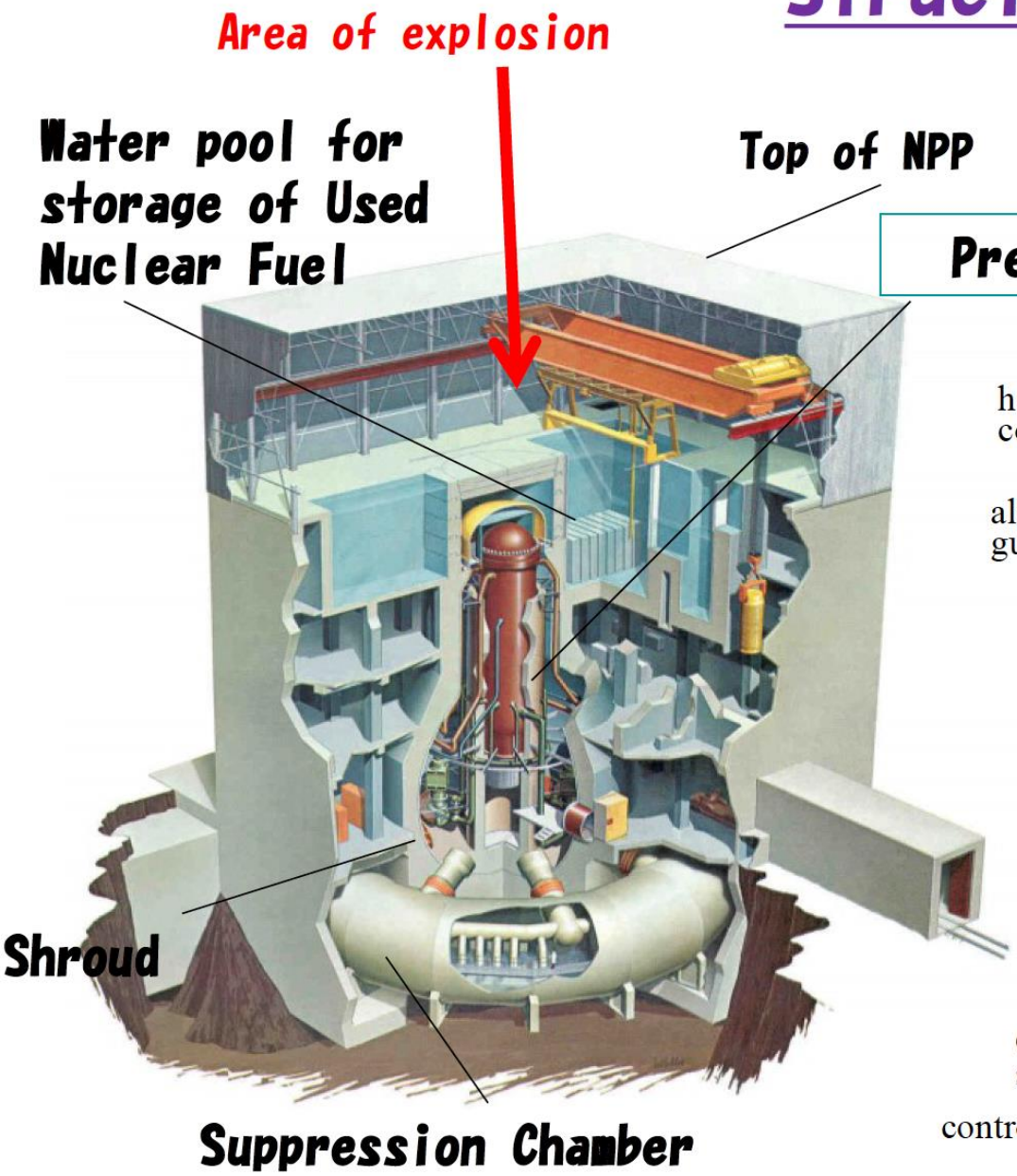
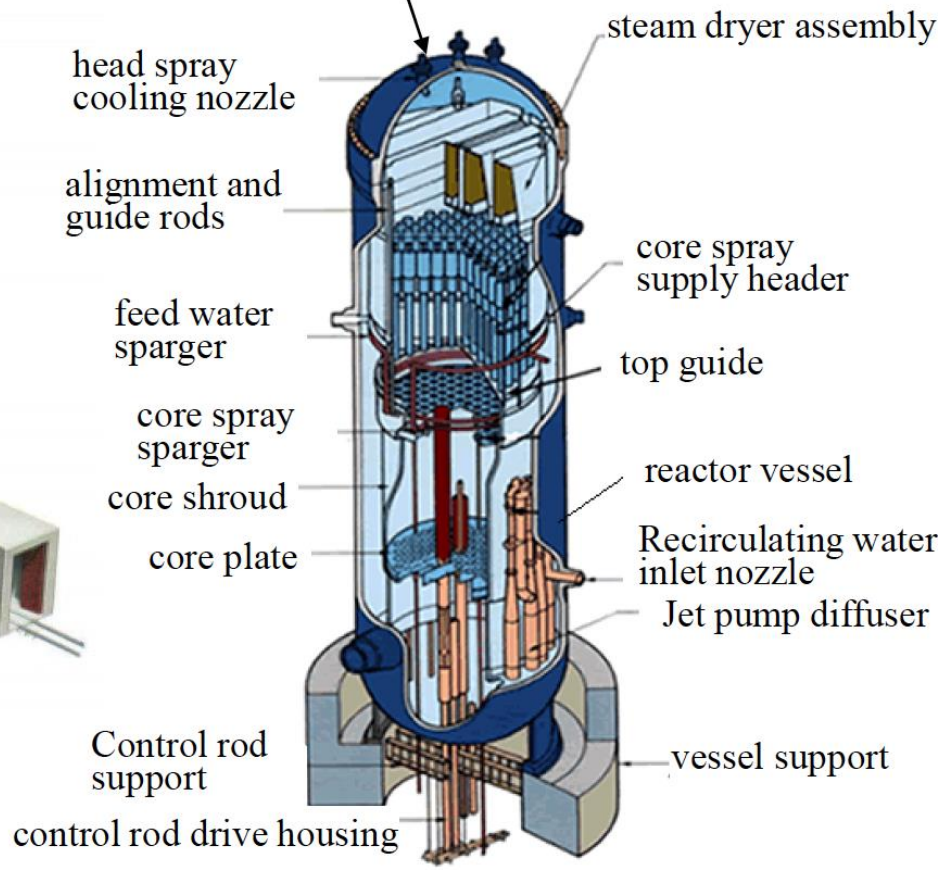
World nuclear tests 1945-2013

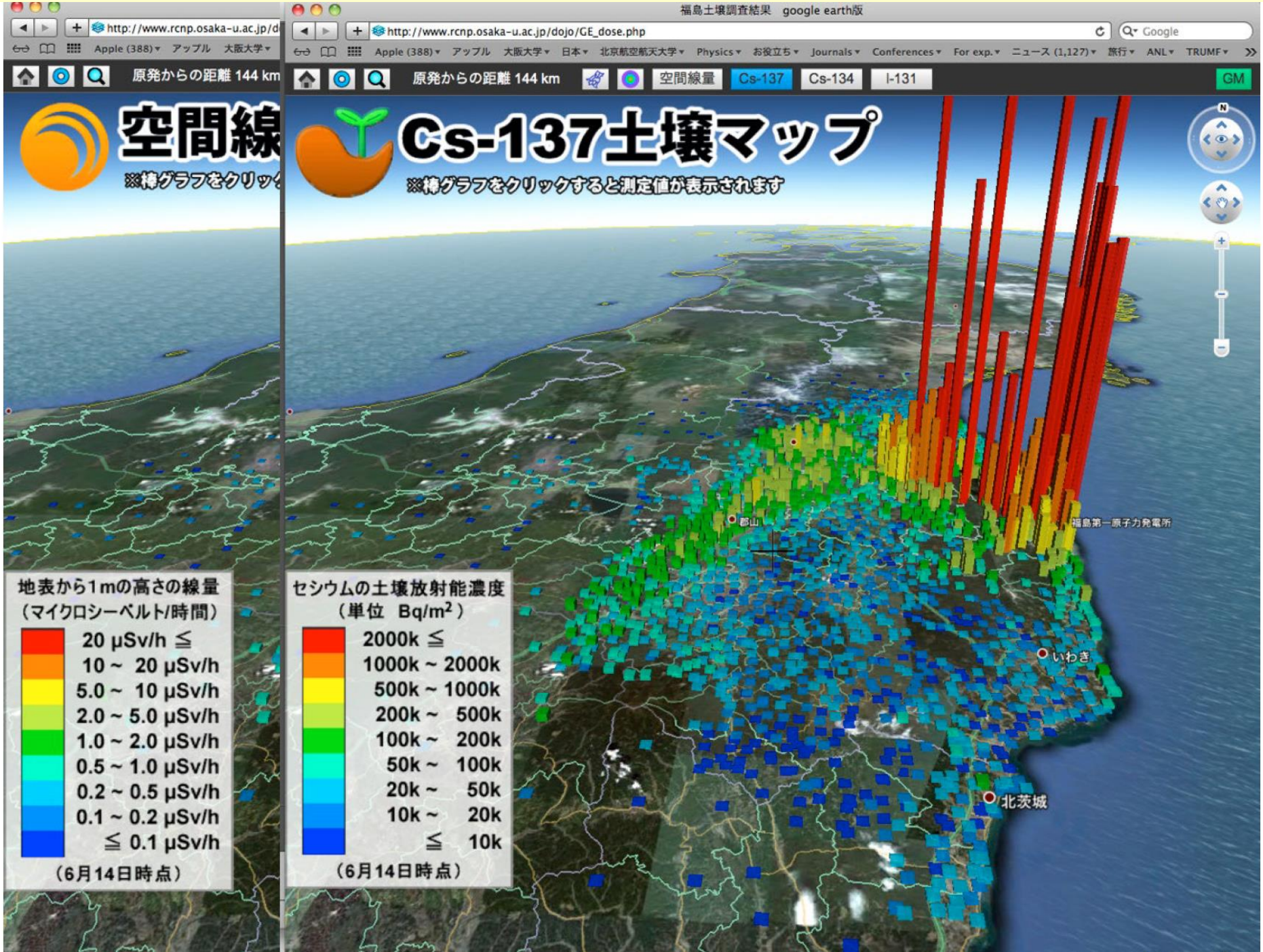


Structure of Fukushima-NPP (BWR)





Structure of Mark I Reactor Vessel

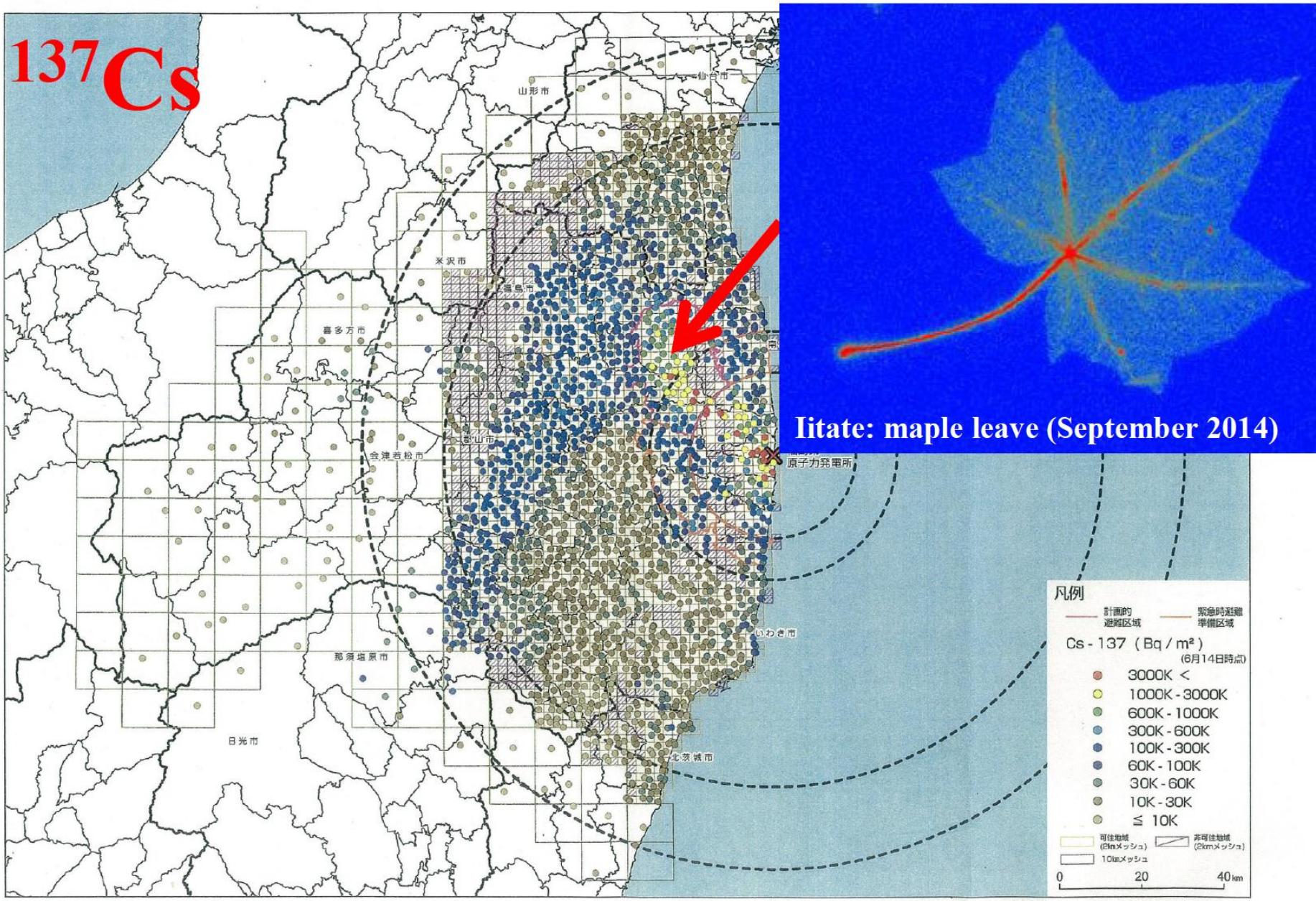

福島土壌調査結果　google earth版
http://www.rcnp.osaka-u.ac.jp/dojo/GE_dose.php
原発からの距離 144 km
空間線量
Cs-137
Cs-134
I-131
GM
Cs-137土壌マップ
※棒グラフをクリックすると測定値が表示されます
地表から1mの高さの線量
（マイクロシーベルト/時間）
20 μSv/h ≦
10 ~ 20 μSv/h
5.0 ~ 10 μSv/h
2.0 ~ 5.0 μSv/h
1.0 ~ 2.0 μSv/h
0.5 ~ 1.0 μSv/h
0.2 ~ 0.5 μSv/h
0.1 ~ 0.2 μSv/h
≦ 0.1 μSv/h
（6月14日時点）
セシウムの土壌放射能濃度
（単位 Bq/m²）
2000k ≦
1000k ~ 2000k
500k ~ 1000k
200k ~ 500k
100k ~ 200k
50k ~ 100k
20k ~ 50k
10k ~ 20k
≦ 10k
（6月14日時点）
福島第一原子力発電所
いわき
北茨城

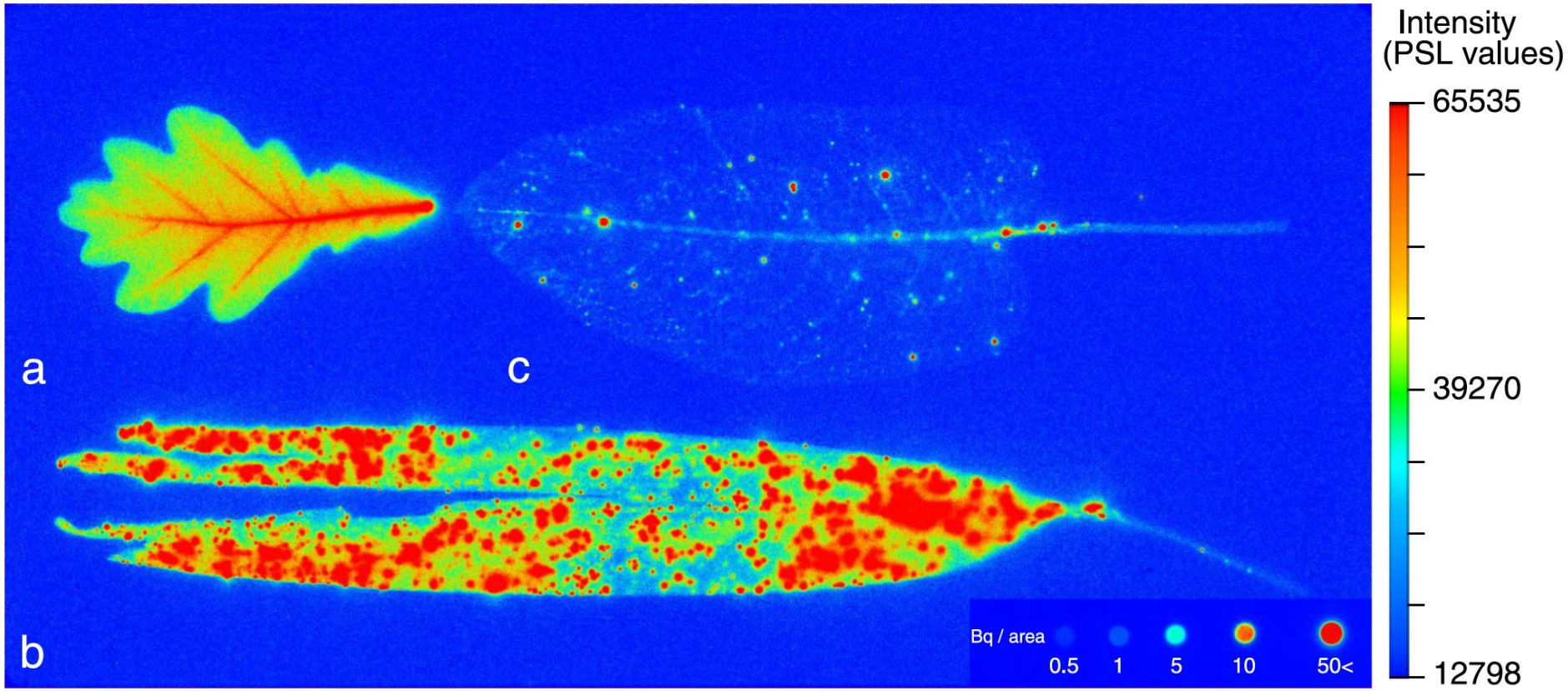
Comparison between Chernobyl and Fukushima

	Chernobyl	Fukushima Daiichi
Acute radiation injury	134 persons died by renal failure	No person
Emergency response	6 days later, evacuation from 30 km zone.	27 hours later, evacuation from 20 km zone.
Responses for individual persons (Dose)	1 year : 100 mSv 2 year : 30 mSv 3 year, 4 year : 25 mSv 5 year : 20 mSv 6 year 6 mSv	1 year : 20 mSv
Radiation dose of Individual person	More than 50 mSv for 270,000	Less than 20 mSv in average. evacuated people: about 120,000
Food regulation (^{131}I)	Milk : 3700 Bq/kg (introduced after 10 days)	Milk : 300 Bq/kg (introduced after 6 days)
Food regulation (^{134}, ^{137}Cs)	Milk : 100 Bq/kg Special regulation for children : 40 Bq/kg (after 11-15 years)	Milk : 50 Bq/kg For children : 50 Bq/kg (after 1 year)

M. Fujiwara, I. Tanitaha, H. Nakajima, M. Takahashi, T. Saito, A. Tohsaki, J. Yamamoto,

"Radioactivity absorption into tree leaves" (2015-2017) three year project



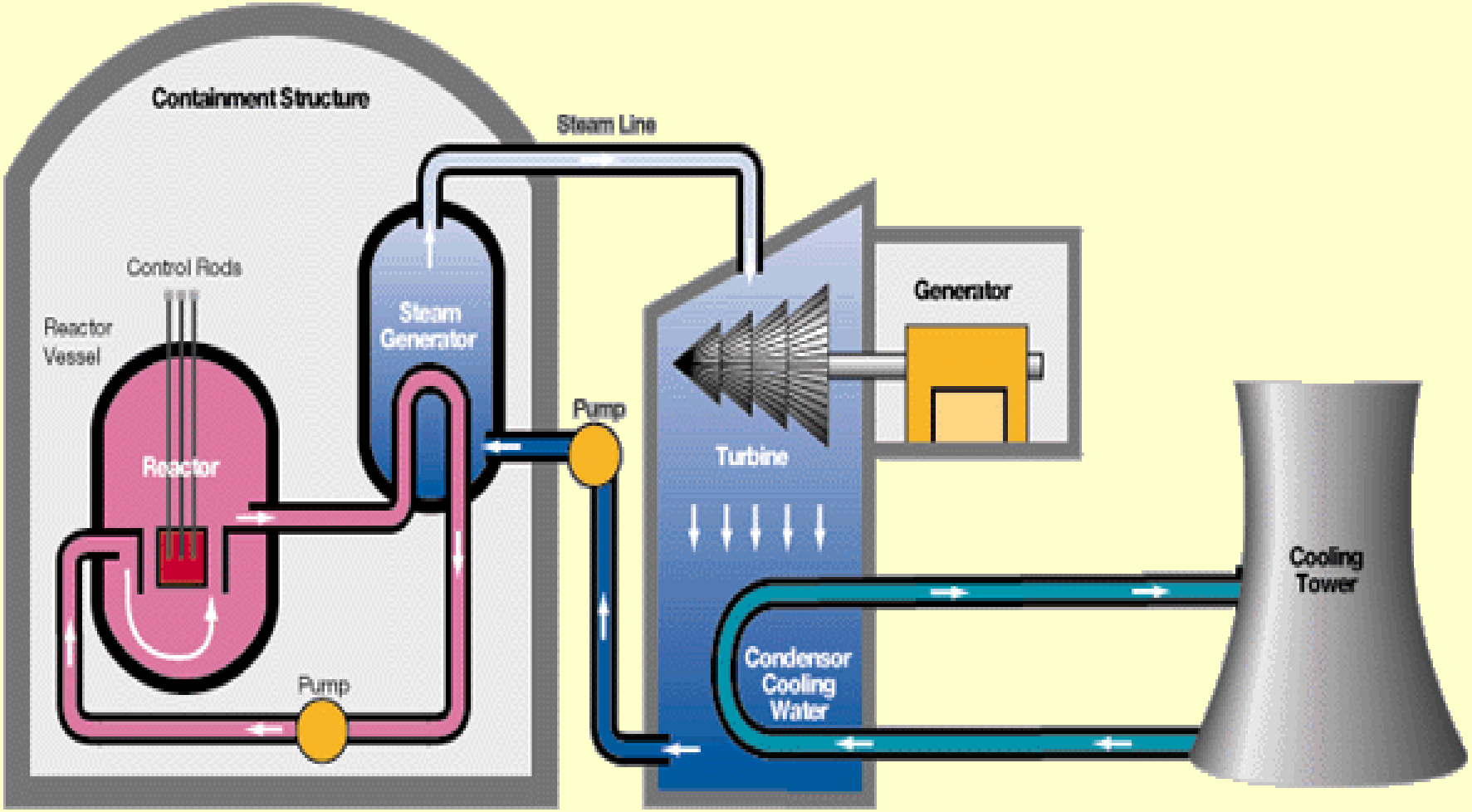

a
c
b
Bq / area
0.5
1
5
10
50<
Intensity
(PSL values)
65535
39270
12798

Energy-related deaths

- ✓ one disaster in which Typhoon Nina in 1975 washed out the Banqiao (Shimantan) Dam (Henan Province, China) and 171,000 people perished.
- ✓ greater than 1000 immediate deaths followed the rupture of the NNPC petroleum pipeline in 1998 and the resulting explosion
- ✓ predicted latent death toll of greater than 1000, as a result of the 1986 steam explosion at the Chernobyl nuclear reactor in the Ukraine.
- ✓ Coal mining accidents resulted in 5,938 immediate deaths in 2005, and 4746 immediate deaths in 2006 in China alone according to the WWF.
- ✓ In the US alone, more than 100,000 coal miners were killed in accidents over the past century.
- ✓ Coal mining fatalities in the US between 1990 and 2012 have continued to decline, with fewer than 100 each year.
- ✓ According to China's National Coal Mine Safety Administration, the country saw 375 coal-mining-related deaths in 2017.
- ✓ According to the World Health Organization in 2012, urban outdoor air pollution, from the burning of fossil fuels and biomass is estimated to cause 3 million deaths worldwide per year and indoor air pollution from biomass and fossil fuel burning is estimated to cause approximately 4.3 million premature deaths. In 2013 a team of researchers estimated the number of premature deaths caused by particulate matter in outdoor air pollution as 2.1 million, occurring annually.

Partial Solution

Reactors


Containment Structure
Steam Line
Control Rods
Reactor Vessel
Steam Generator
Reactor
Pump
Pump
Turbine
Generator
Cooling Tower
Condensor Cooling Water

Reactors

- Advantages
  - ✓ Almost no CO_2
  - ✓ Can be made on any scale
  - ✓ New designs inherently safe

- Disadvantages
  - ★ Long-lived radioactive waste
  - ★ Capital intensive and large
  - ★ Proliferation

Reactors

- **Imagine a reactor with:**

  - ✓ **No surplus fuel in the core;**
  - ✓ **No issues with the decay-heat removal;**
  - ✓ **No high-pressure coolant;**
  - ✓ **No volatile fission products;**
  - ✓ **No long-lived nuclear waste;**
  - ✓ **No “end” to the fuel material.**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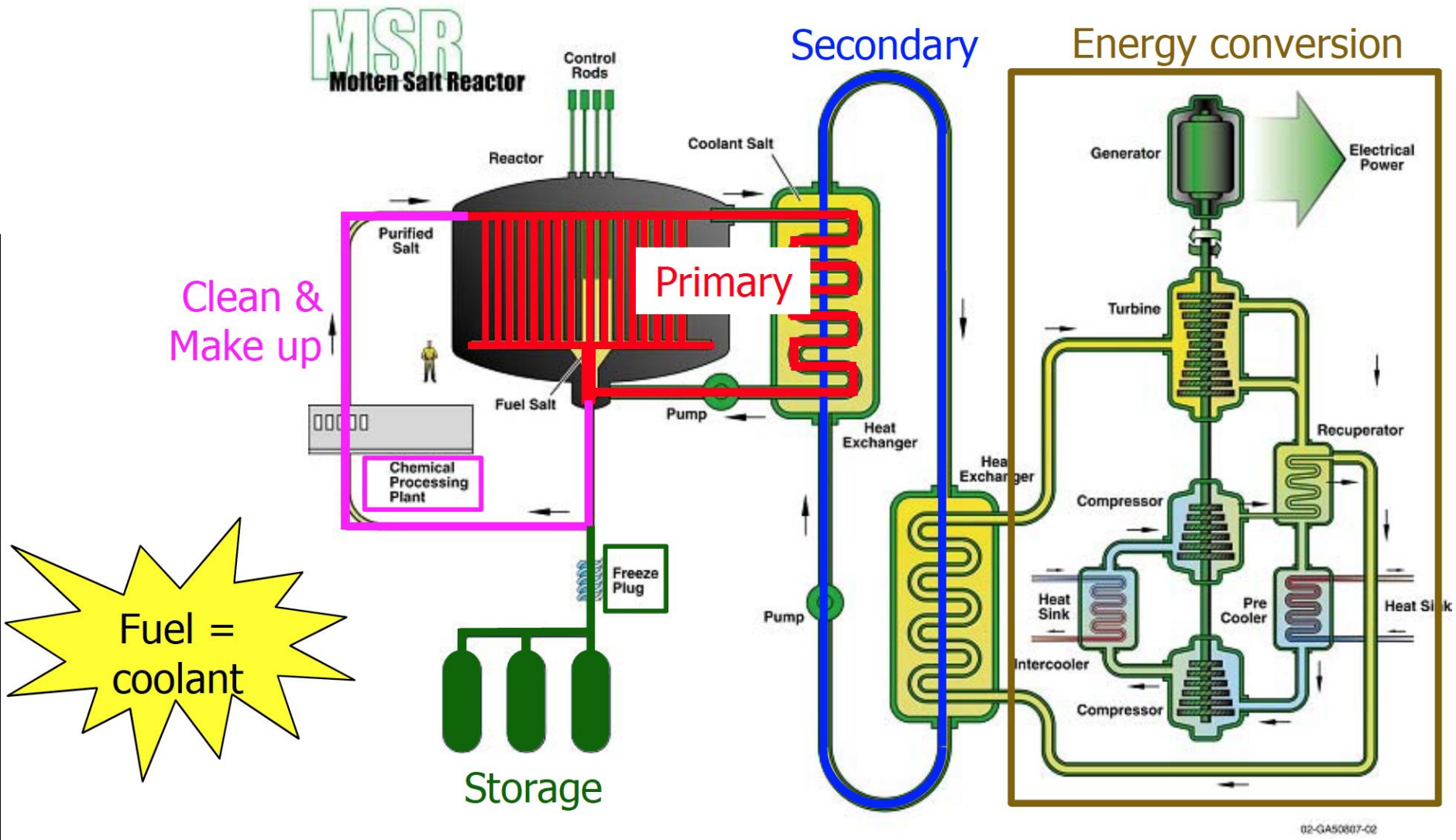
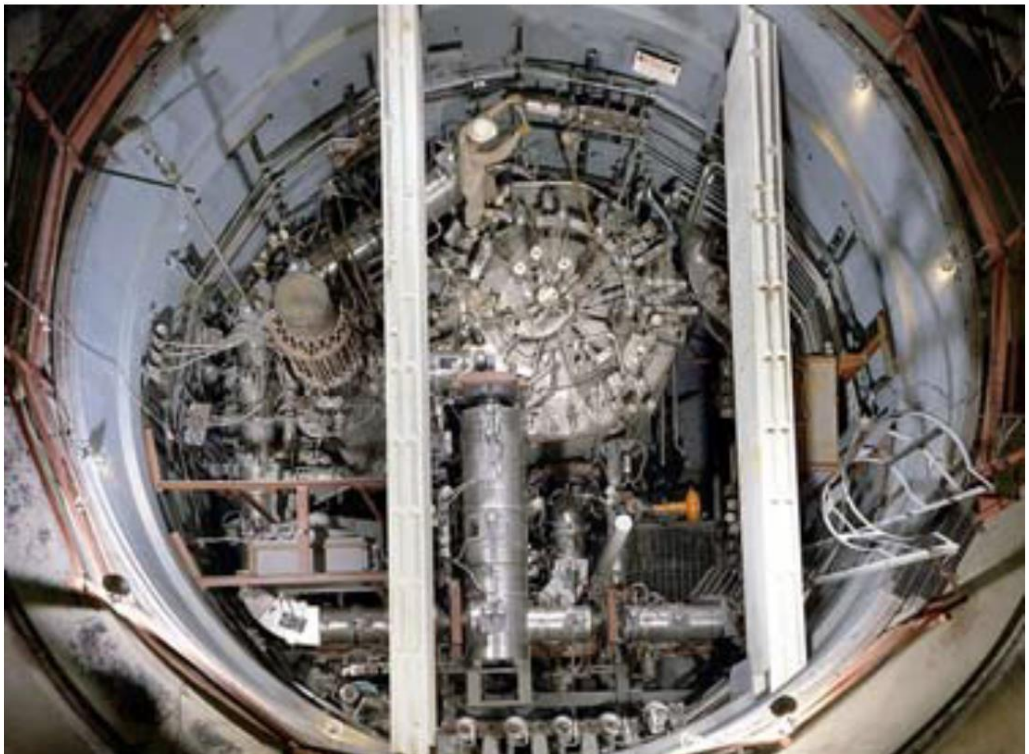
NedandLarry.com
Is this your dream or mine?
Pretty sure it's mine
Robin Crossman

Molten Salt Reactor (MSR)



Molten-Salt Reactor Experiments

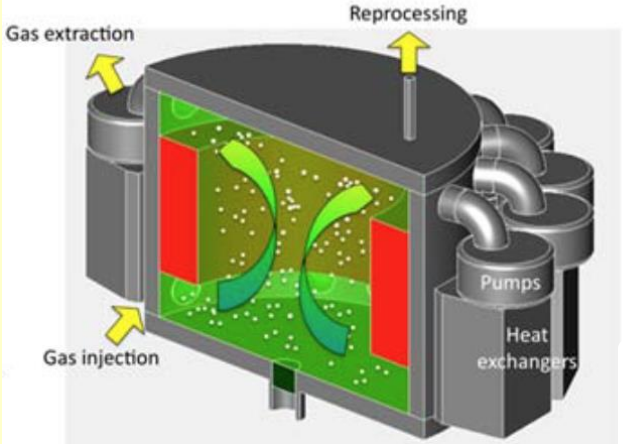
MSRE 1965-1969

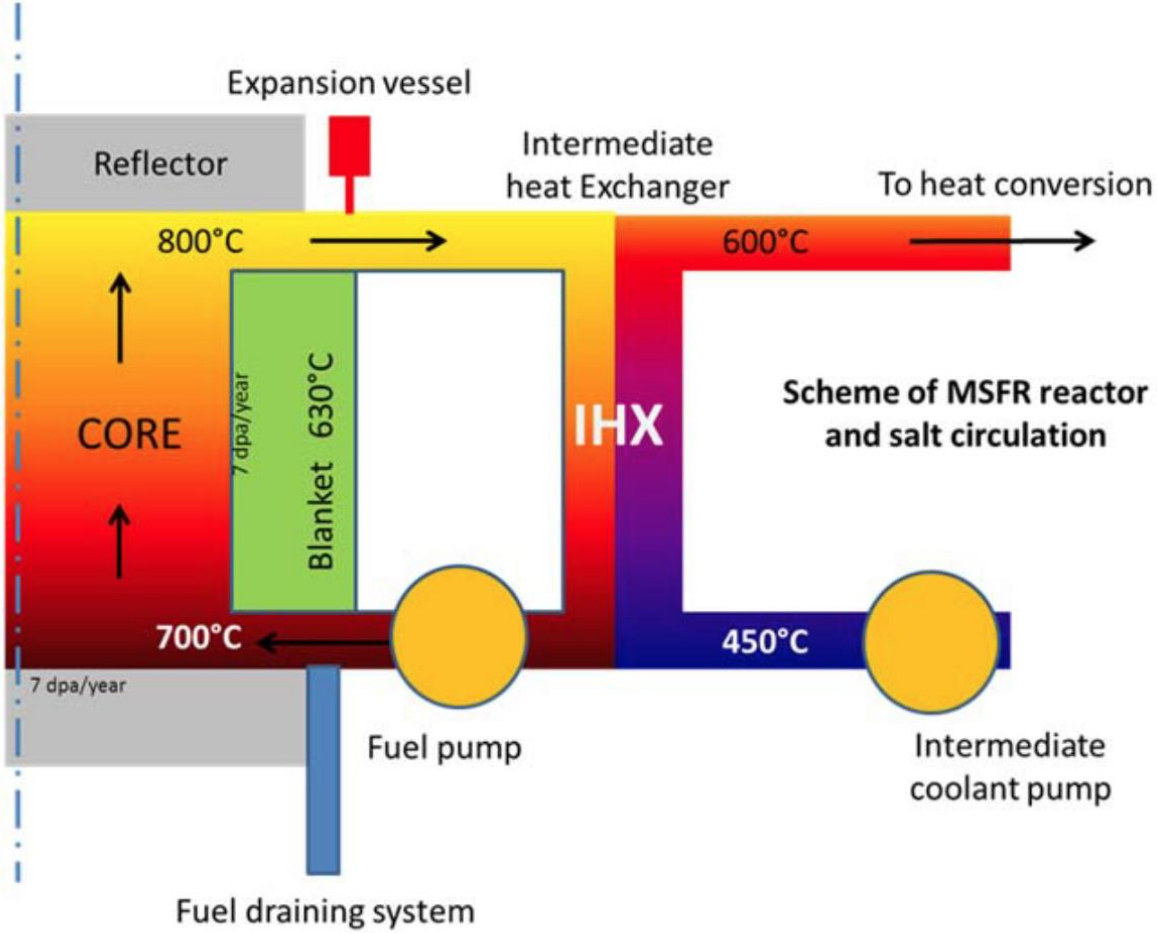


Molten Salt Reactor (MSR)

Working parameters MSFR

High temperature (750 ^{0}C)
Low pressure (1 bar)
Circulation time (4 sec)
LiF-ThF4-UF4-(TRU)F3
(77.5-6.6-12.3-3.6 mol%).
Online processing / fueling
Three (fuel) salt loops





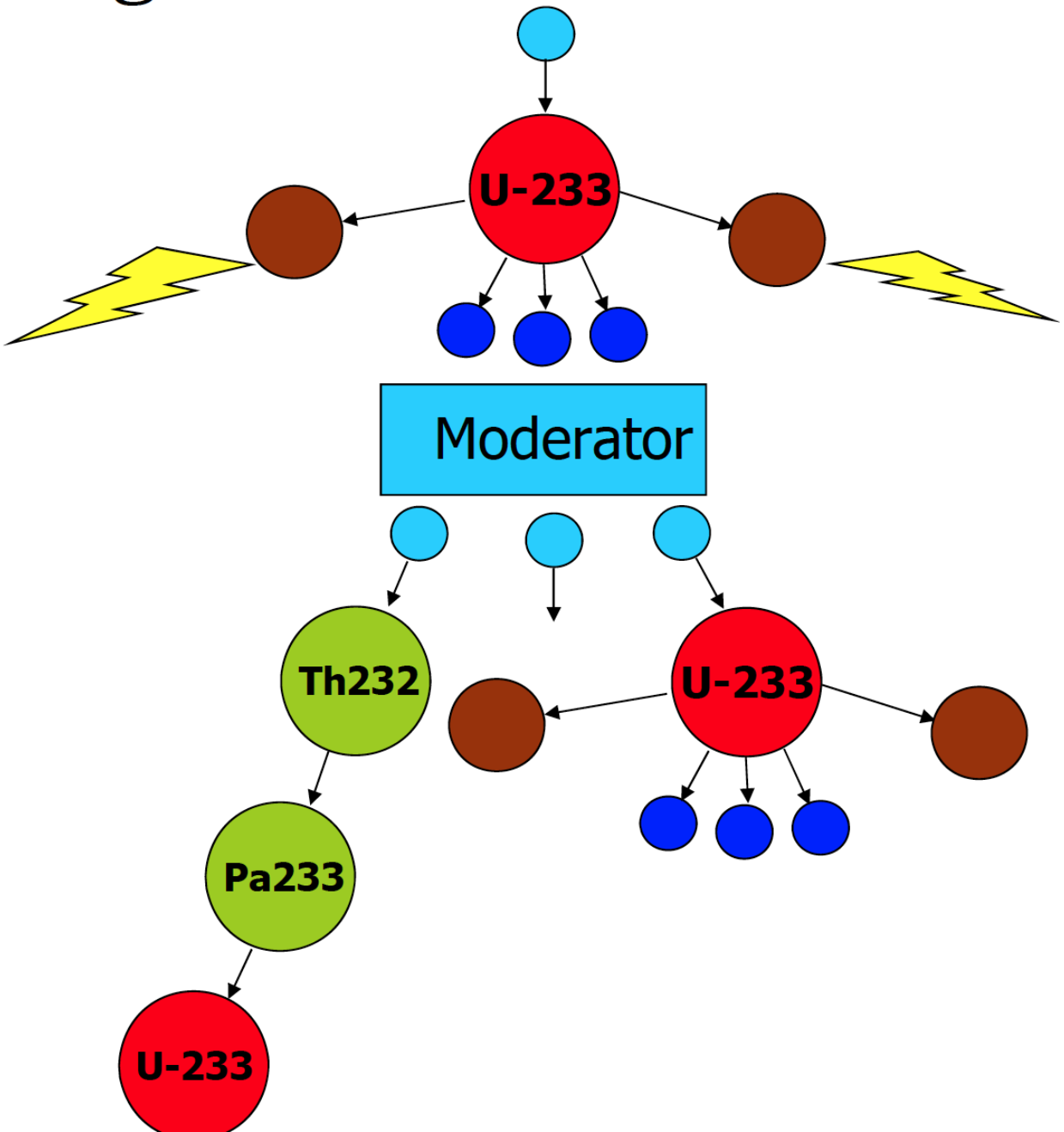
Advantages of Molten Salt Reactor

- ✓ **Fuel Salt is at ambient pressure**
  - **No driving force for dispersion**
- ✓ **Fuel salt is fluid**
  - **No compaction, free expansion**
  - **Freeze plugs and draining**
  - **Load-following**
- ✓ **Fuel salt cleaning**
  - **Removal of fission products**
- ✓ **Flexible fuel cycle**
  - **From breeding to burning**
  - **No external fuel processing**

Challenges for Molten Salt Reactor

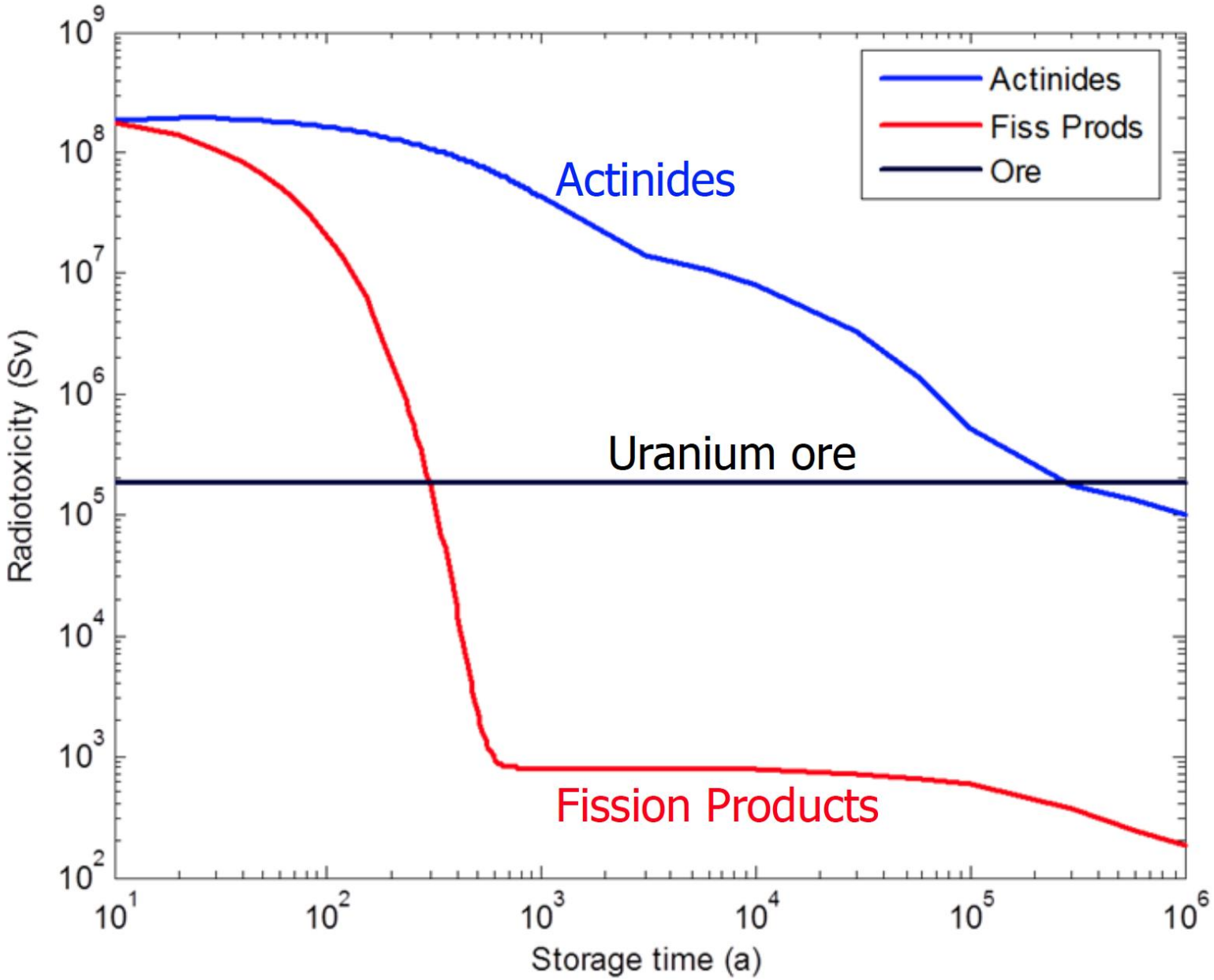
- ✓ Corrosion of material
- ✓ Distribution of delay neutrons

Breeding with thorium



er for advanced
technology

Nuclear waste



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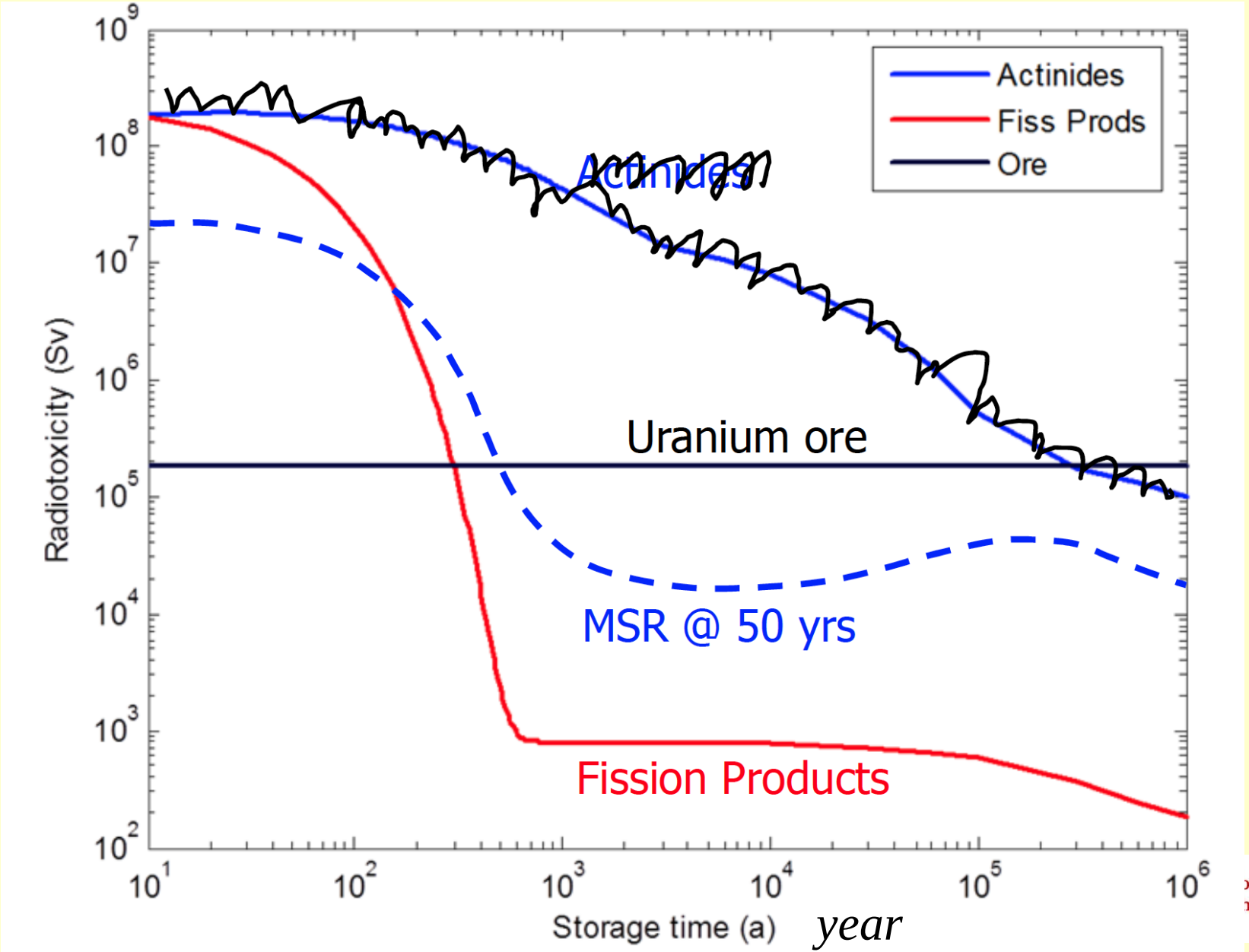
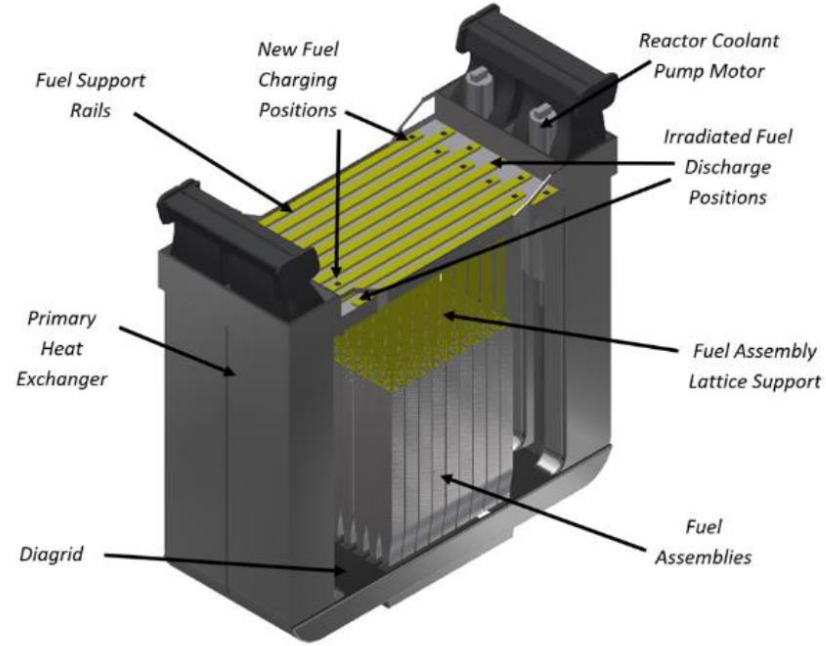
Nuclear waste

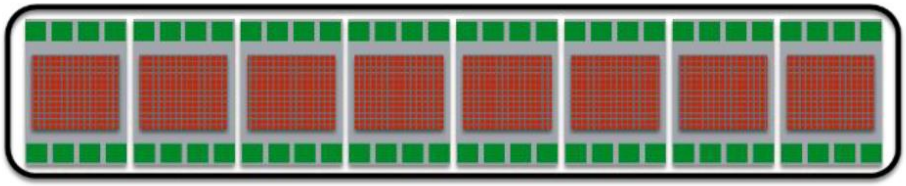


Modular reactors

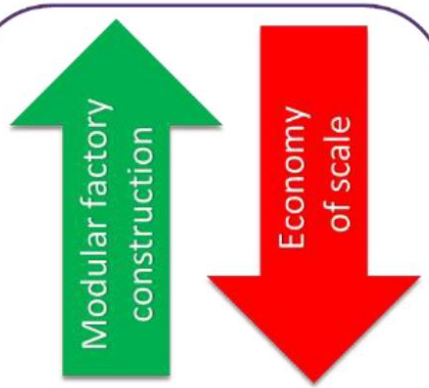
Modular reactors



Factory produced 150MWe module contains supports, pumps, primary heat exchanger, shutdown blades, instrumentation, flow ducts, fuel assembly handling etc



Up to 8 identical modules placed in single reactor tank creating single reactor up to 1200MWe



Conventional Small Modular Reactor

Stable Salt Reactor

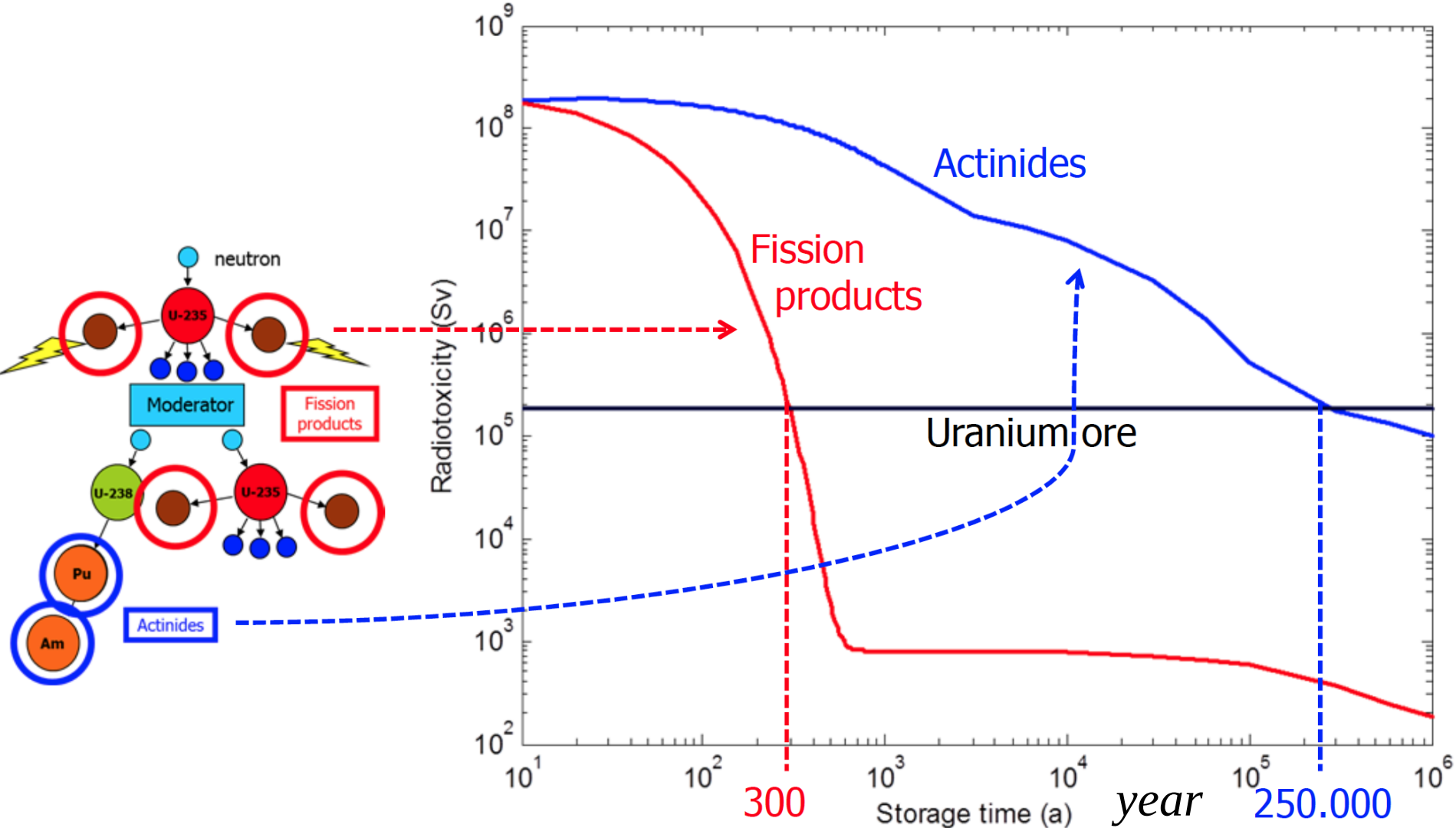
Modular reactors

- ✓ Compnay: NuScale Power
- ✓ Power output: 50-200 MW
- ✓ Expected lifespan: 60 years
- ✓ Costs:
  - ➢ 100 M$ for prototype
  - ➢ 2000 M$ to develop
- ✓ Available: 2026

And the existing waste??

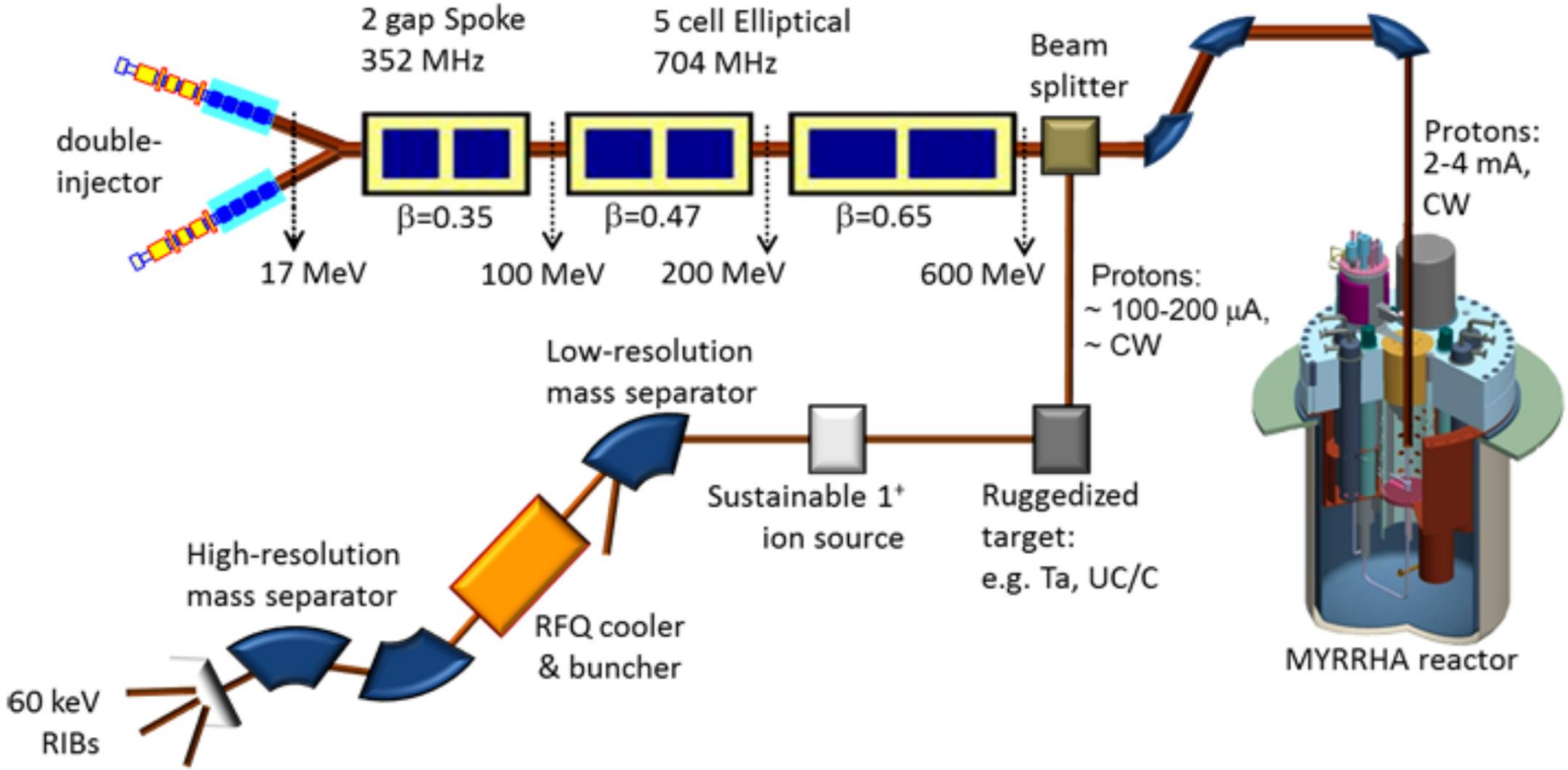
Nuclear waste

Radiotoxicity LWR



Accelerator Driven System

MYRRHA project, Belgium



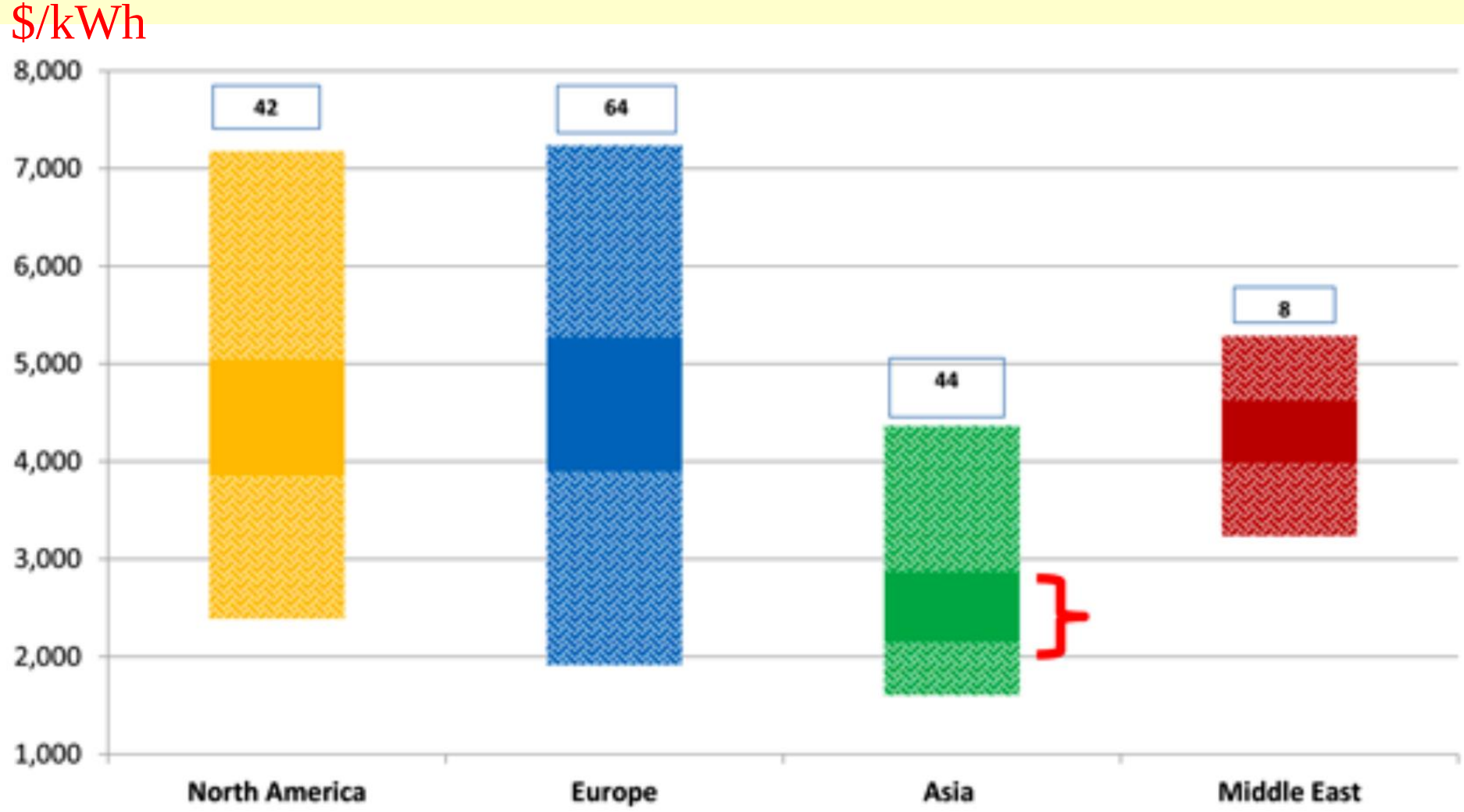
Accelerator Driven System

- ✓ develop technologies allowing to process radioactive waste through transmutation;
- ✓ produce new radioisotopes for the diagnosis and treatment of disease such as cancer;
- ✓ conduct fundamental scientific research in nuclear physics, atomic physics, fundamental interactions, solid-state physics, nuclear medicine, …;
- ✓ help develop advanced nuclear reactors, essentially reactors cooled by lead-bismuth;
- ✓ test materials and components for new nuclear fission and nuclear fusion reactors;
- ✓ conduct pioneering research in all aspects of nuclear energy.

Costs

Costs

Overnight costs – initial investments



Note: Data collected from various publications and studies to keep track of nuclear power plants investment costs, since 2008 (updated August 2014), *all data in 2013 USD*

Overnight costs and LCOE according to Nuclear Energy Agency

- ✓ From $1900/kWe in *1990s* to $3850/kWe in *2009*!
- ✓ In 2015: $2021/kWh in South Korea to $6215/kWe in Hungary!
- ✓ China: two estimates: $1807/kWe and $2615/kWe

- ✓ LCOE: @3% discount rate: $29/MWh in Korea to $64/MWh in the UK
- ✓ LCOE: @7% discount rate: $40/MWh in Korea to $101/MWh in the UK
- ✓ LCOE: @10% discount rate: $51/MWh in Korea to $136/MWh in the UK

Numbers from World Nuclear Association

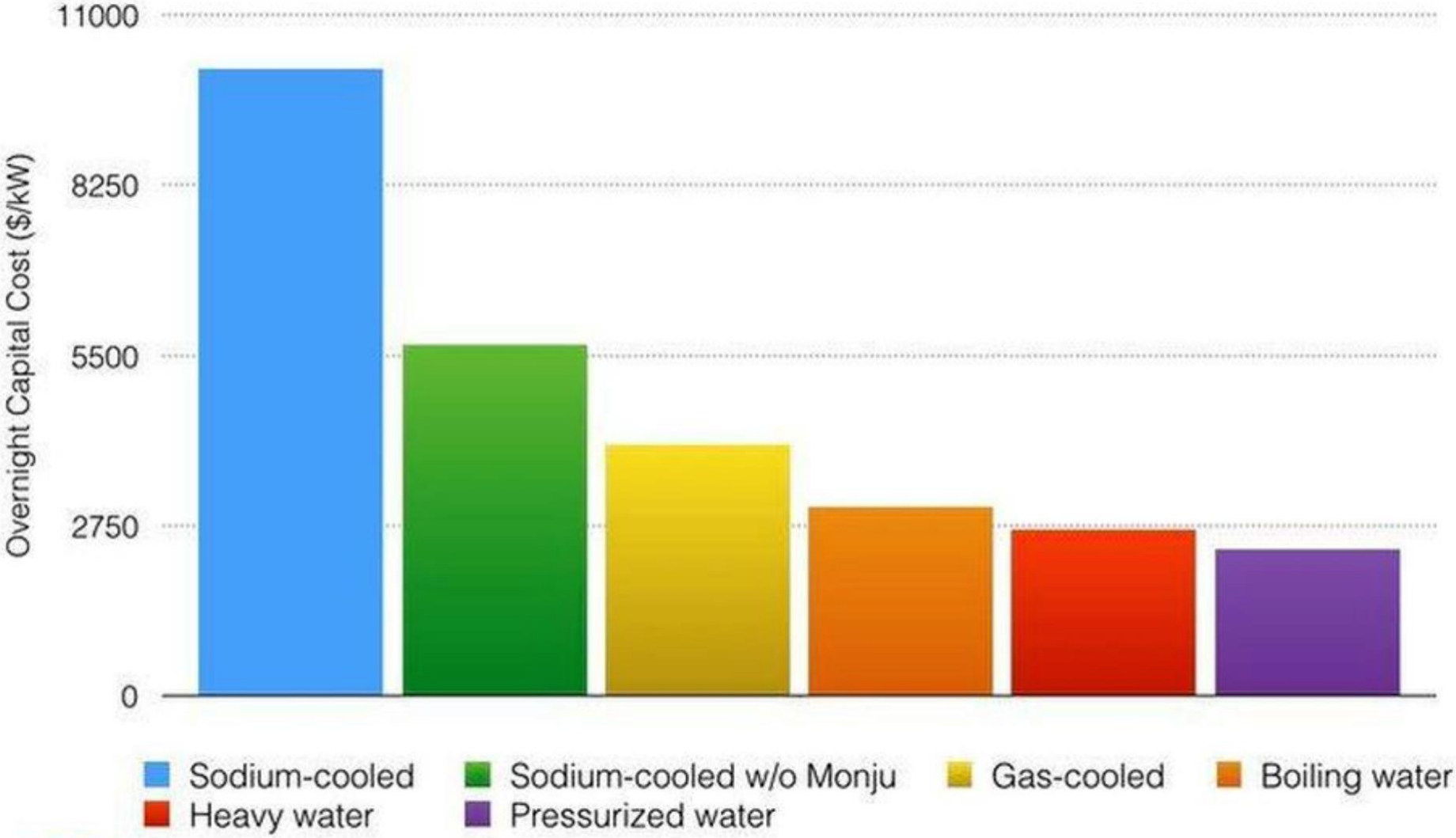
Costs

USA, 2017

- ✓ **Advanced nuclear: 9.9 c/kWh**
- ✓ **Natural gas: 5.7-10.9 c/kWh (depending on the technology**
- ✓ **Coal with 90% carbon sequestration: 12.3 c/kWh**
- ✓ **Wind on shore: 5.2 c/kWh**
- ✓ **Wind off shore: 14.6 c/kWh**
- ✓ **Solar PV: 6.7 c/kWh**
- ✓ **Solar thermal: 18.4 c/kWh**

Numbers from World Nuclear Association

Construction cost of reactors by type



Source: Lovering, J. R., Yip, A., & Nordhaus, T. 2016. Historical construction costs of global nuclear power reactors. *Energy Policy*, *91*, 371-382. Accessed March 7, 2017. http://www.sciencedirect.com/science/article/pii/S0301421516300106

ENVIRONMENTAL PROGRESS

Historical opportunity

Number of reactors by age

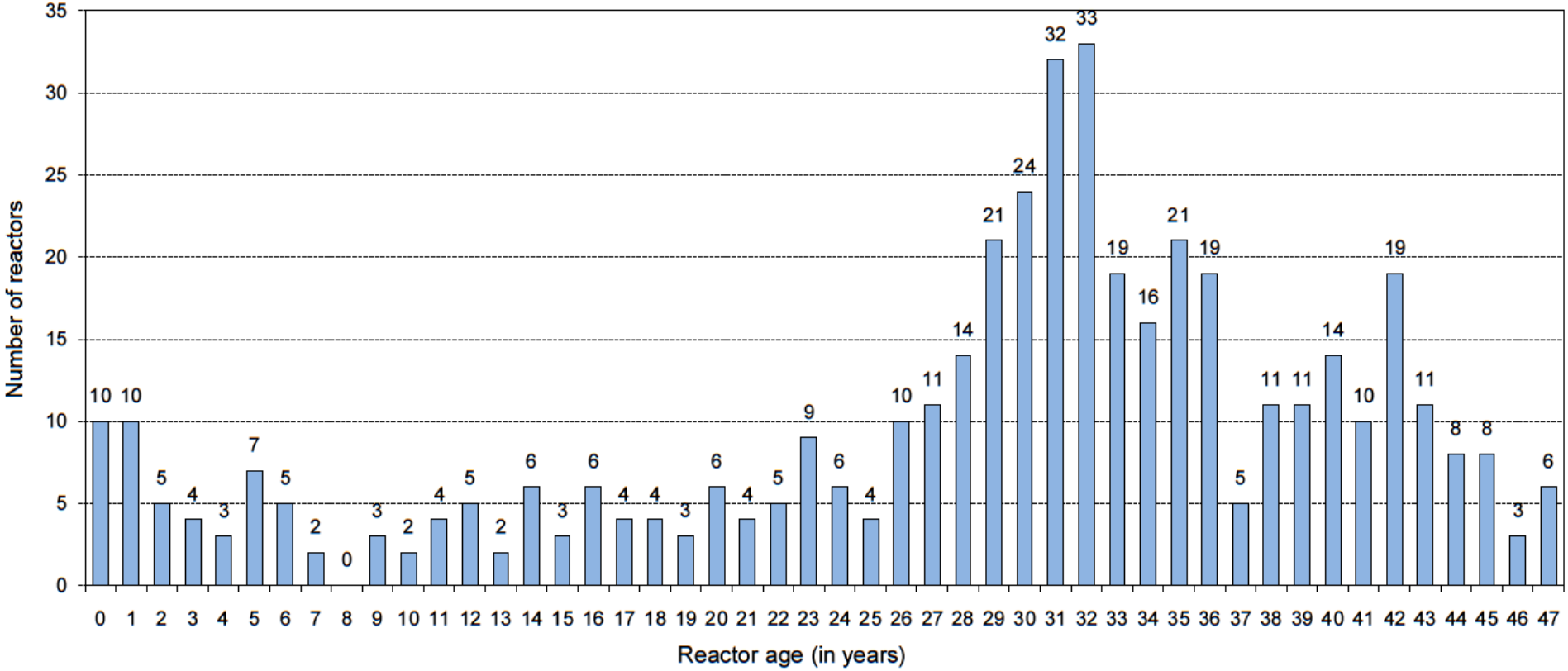


Figure 5. Number of operational reactors by age (as of 31 Dec. 2016).

Table from IAEA report

REFERENCE DATA SERIES No. 2, 2017 Edition

university of groningen

kvi - center for advanced radiation technology

Thank you!