THE ROLE OF NUCLEAR ENERGY IN ACHIEVING NET-ZERO EMISSIONS AND UN-SUSTAINABLE GOALS

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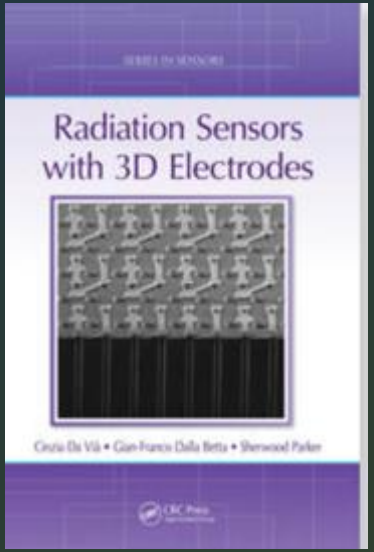
IEEE NPSS Climate Change Initiative, Task Force on SMR, MMR and Advanced Reactors
IEEE ESTEK Leader, IEEE SusTech Inter-Spciety Engagement Collaboration Committee Chair, SSIT ESTEK Chair

Some Information about myself

- Professor at The University of Manchester (UK)
- Visiting Professor at the University of Stony Brook, New York, USA
- Member of the ATLAS Collaboration at CERN – LHC
- Chief editor Frontiers in Physics, Radiation Detectors and Imaging
- Co-Chair of the EU-ATTRACT Independent Committee
- IEEE WIE International Committee Member 2017-2022
- Lead of the NPSS Climate Change Initiative and Task force on Nuclear Energy
- Chair of the IEEE SusTech Inter-Society on Engagement and Collaboration Committee
- Distinguished Lecturer and Organizer of the IEEE NPSS Instrumentation School

Scientific Interests:

- ➢ Radiation Detector development : silicon pixels, 3D silicon detectors, fast timing
- ➢ Radiation effects in silicon, “Lazarus effect”
- ➢ 3D printed detectors, Vertical integrated microsystems
- ➢ Quantum Imaging at X-Ray and Gamma energies
- ➢ Energy generation



“Energy is the golden thread that connects economic growth, social equity, and a healthy planet.”

Ban Ki-Moon

17 goals · 169 targets · Agenda 2030

Nuclear Energy

History: Adopted by all 193 UN member states in 2015, the SDGs are the world's shared blueprint for people, planet and prosperity.

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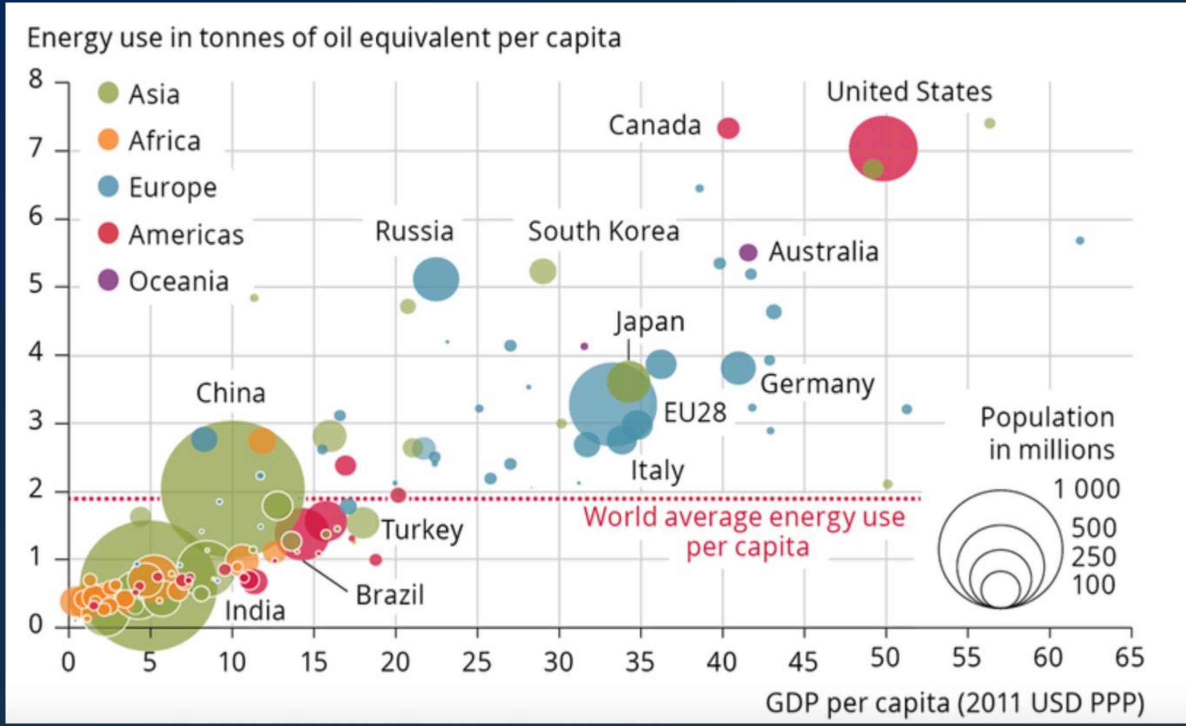
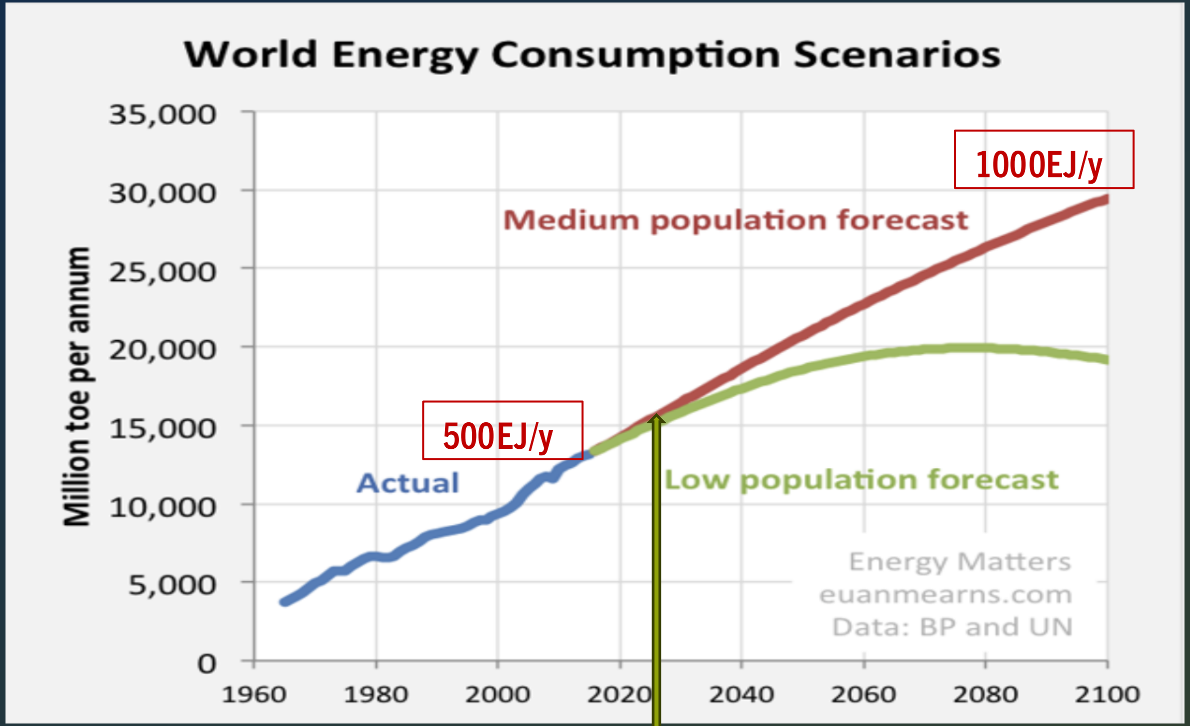
Energy and Economic Growth

Here Energy is expressed in tonnes oil equivalent (toe)



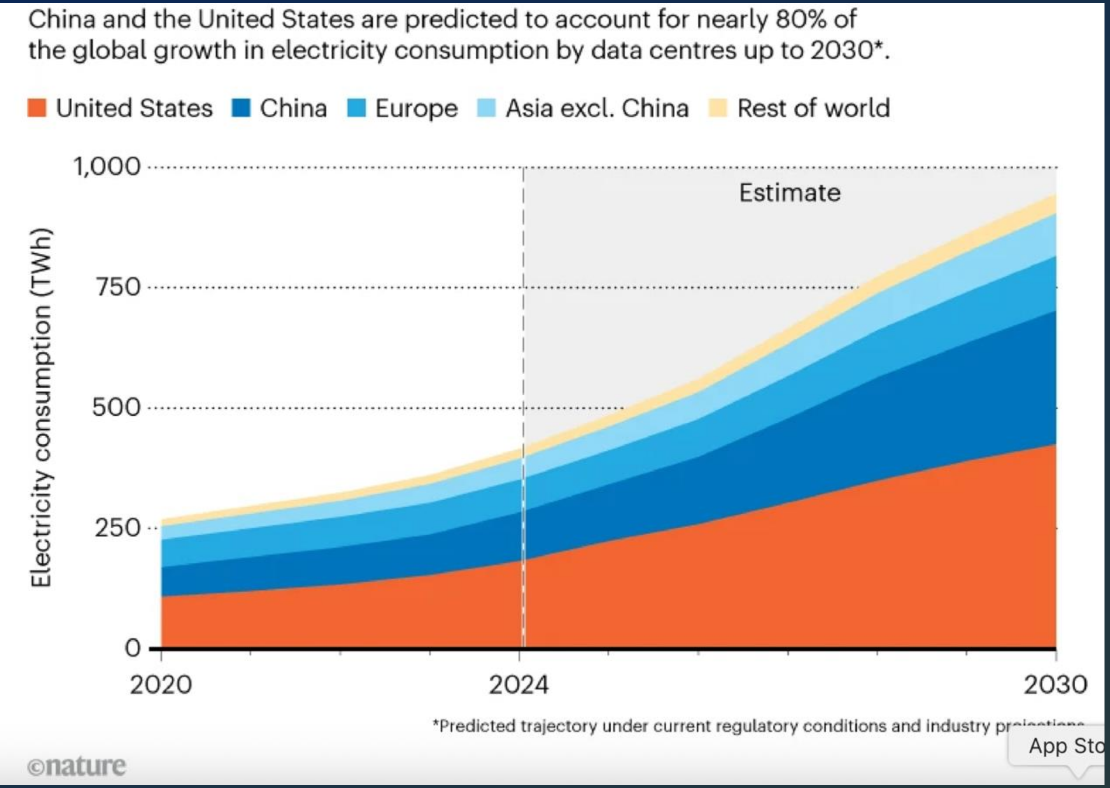


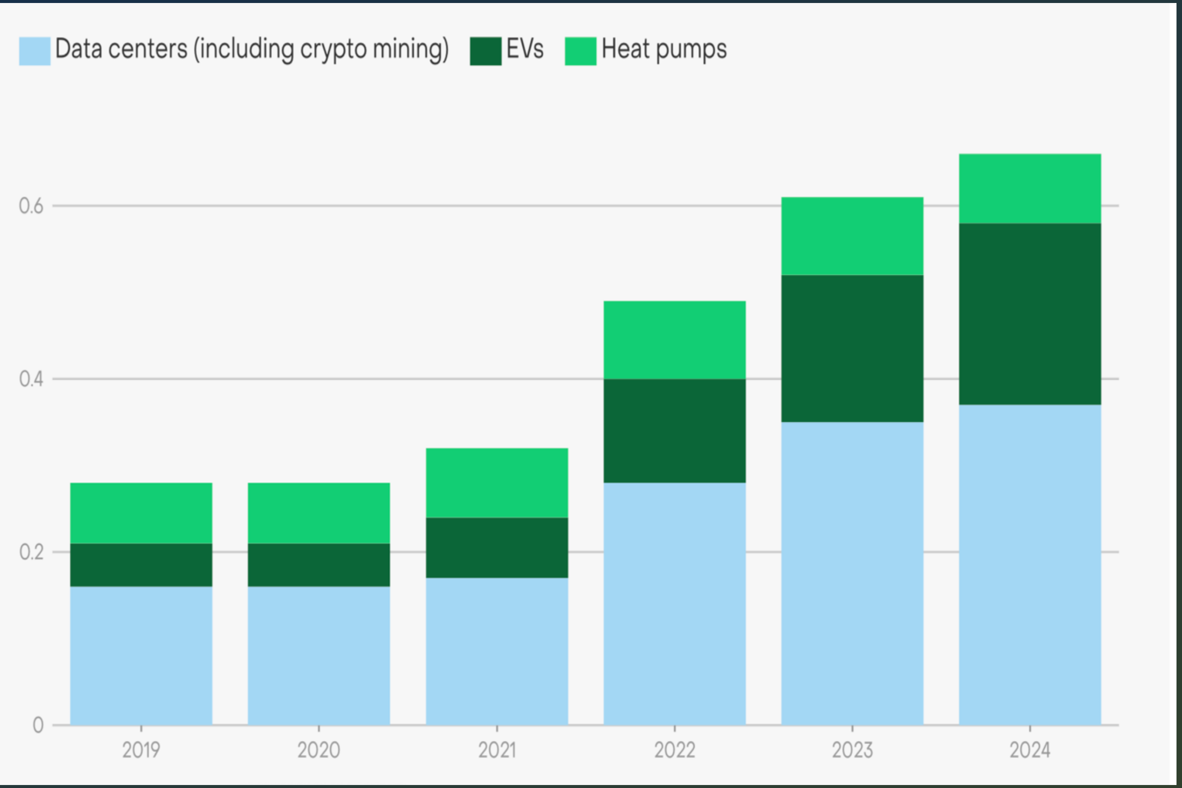
In 2024 the world consumption was 650 exajoules $=1.8 \times 10^{17}$ Wh

Still Millions of people still lack access to clean and reliable energy sources and electricity. Mainly in the Sub-Saharan Africa

Energy Data Centers-EV and Heat Pumps

- Data centres accounted for around 1.5% of the world's electricity consumption in 2024, or 415 (TWh).
- EV electricity demand grew by an impressive 38% in 2024 (+62 TWh)
- Heat pumps are estimated to have added an additional + 22 TWh electricity demand in 2024→heat waves 2026





https://www.iea.org/reports/energy-and-ai

EMBER

The Future: Space Based Energy Generation?

Why Solar Photovoltaics

- Dominant power source for satellites and space stations.
- High-efficiency multi-junction GaAs cells reach >30% efficiency.
- Key issues: radiation damage, thermal cycling, long-term degradation, dust accumulation (Moon/Mars), deployment mechanisms.

Emerging Concepts

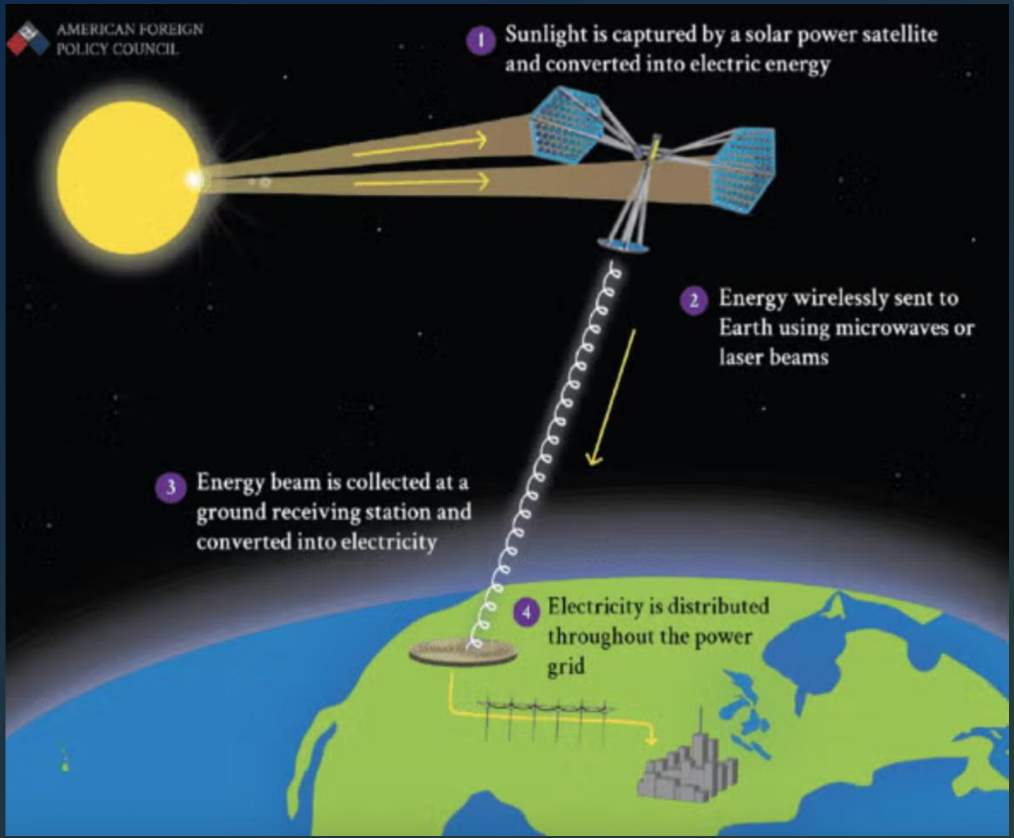
- **Space solar power (SSP)**: large orbital arrays transmitting energy to Earth via **microwaves or lasers.**

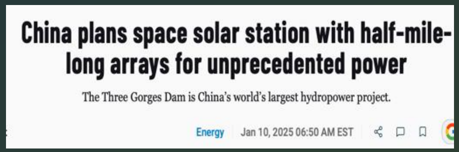
Available space? Regulations?

LEO (Low Earth Orbit) 300-1200km -crowded
In 2025 ~9500 operational satellites (+ 100k fragments and debris)
550km Starlink Shell, 340-360 km OneWeb
Requires distance to avoid collisions-space available

GEO (35,786km) more space available to host 1-10km wide plants but Many slots based on longitude already occupied

ITU (International Communication Union) allocates GEO slots, assigns frequencies but does not control LEO population limits




China plans space solar station with half-mile-long arrays for unprecedented power

The Three Gorges Dam is China's world's largest hydropower project.

Energy Jan 10, 2025 06:50 AM EST

esa

https://www.powermag.com/space-based-solar-power-for-u-s-energy-independence/

"China wants to install the Three Gorged Dam above the Earth" →TGD = 100BKW/h

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Data Centers in Space?

•Power and cooling: Orbital data centers can use nearly limitless solar energy, with power generated much more efficiently than on Earth due to uninterrupted sunlight. The vacuum of space provides natural radiative cooling for heat dissipation, eliminating the need for water-intensive terrestrial cooling systems.

•Scalability and resources: Space offers immense physical space for expansion, freeing data centers from terrestrial constraints. This allows for potential growth to gigawatt scale.

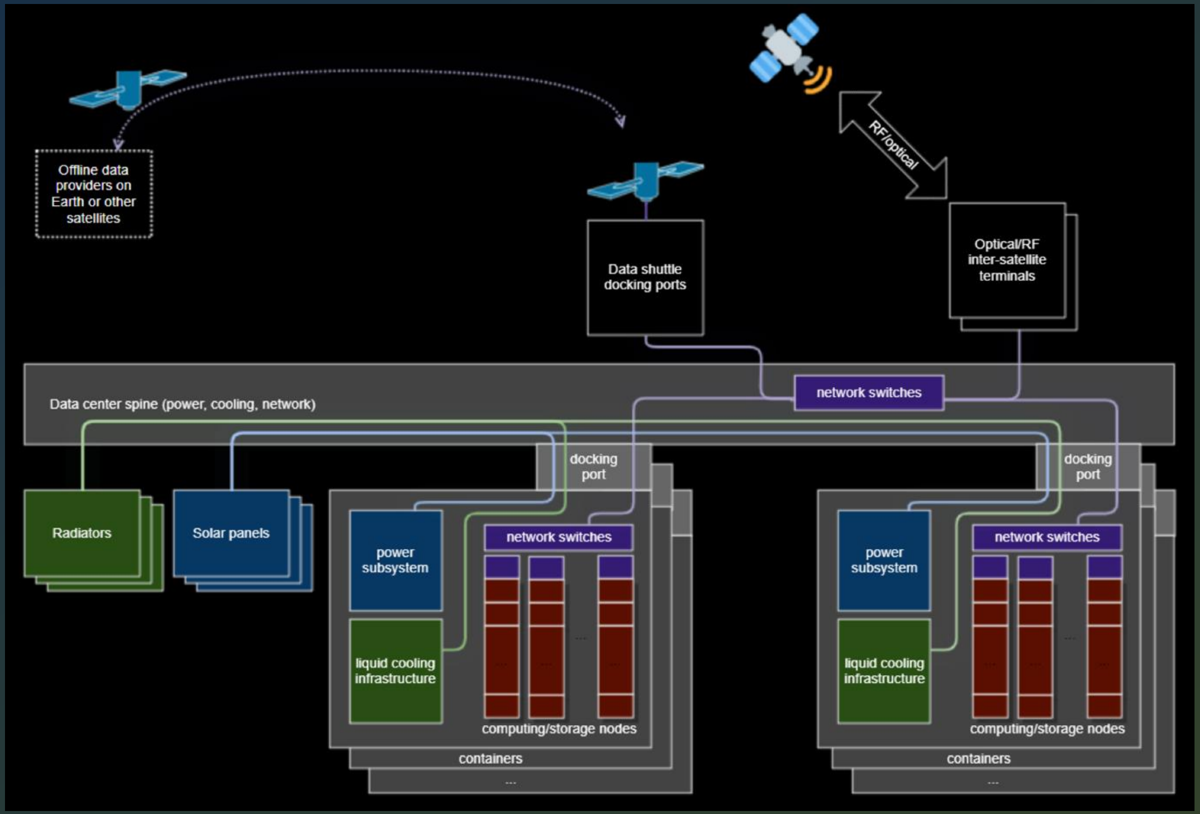
•Data processing and latency: They enable in-orbit edge computing, processing data from satellites closer to its source. This reduces the large amounts of data that need to be transmitted back to Earth, leading to lower latency and faster delivery of information like weather forecasts.

•Connectivity: High-speed laser-based communication systems (optical inter satellite links) allow for faster data transfer rates than many terrestrial fiber networks.

•Security and resilience: Placing data centers in space provides enhanced security through physical isolation—making them nearly impossible to access—and potential protection from terrestrial threats like natural disasters, cyberattacks, and physical conflict.

•Environmental impact: Over time, these facilities could have a lower carbon footprint compared to Earth-based data centers, as they are powered by solar energy and don't require water for cooling.

•Challenges: Key challenges include developing robust, resilient, and self-healing hardware, cybersecurity, thermal management, and overcoming regulatory hurdles.



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Renewable, Non-Renewable and Sustainable Energy

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Renewable Energy Sources

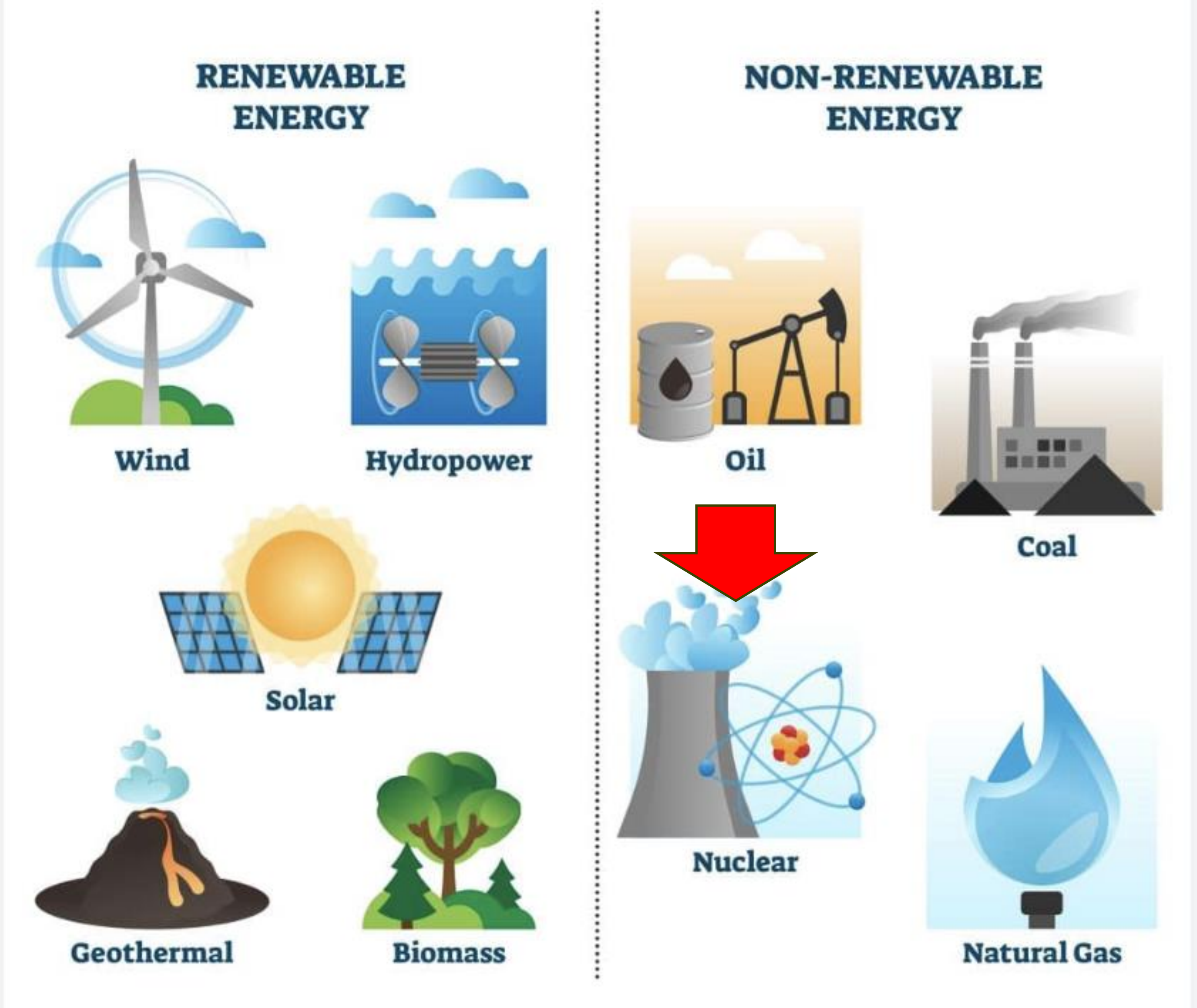
Energy sources that **naturally replenish themselves on a human timescale** and will not run out with continued use.
Examples: Solar, wind, hydropower, geothermal, biomass.

Non-Renewable Energy Sources

Energy sources that **exist in finite amounts** and **cannot be replenished** within a human lifespan once they are depleted.
Examples: Coal, oil, natural gas, nuclear fuels (uranium).

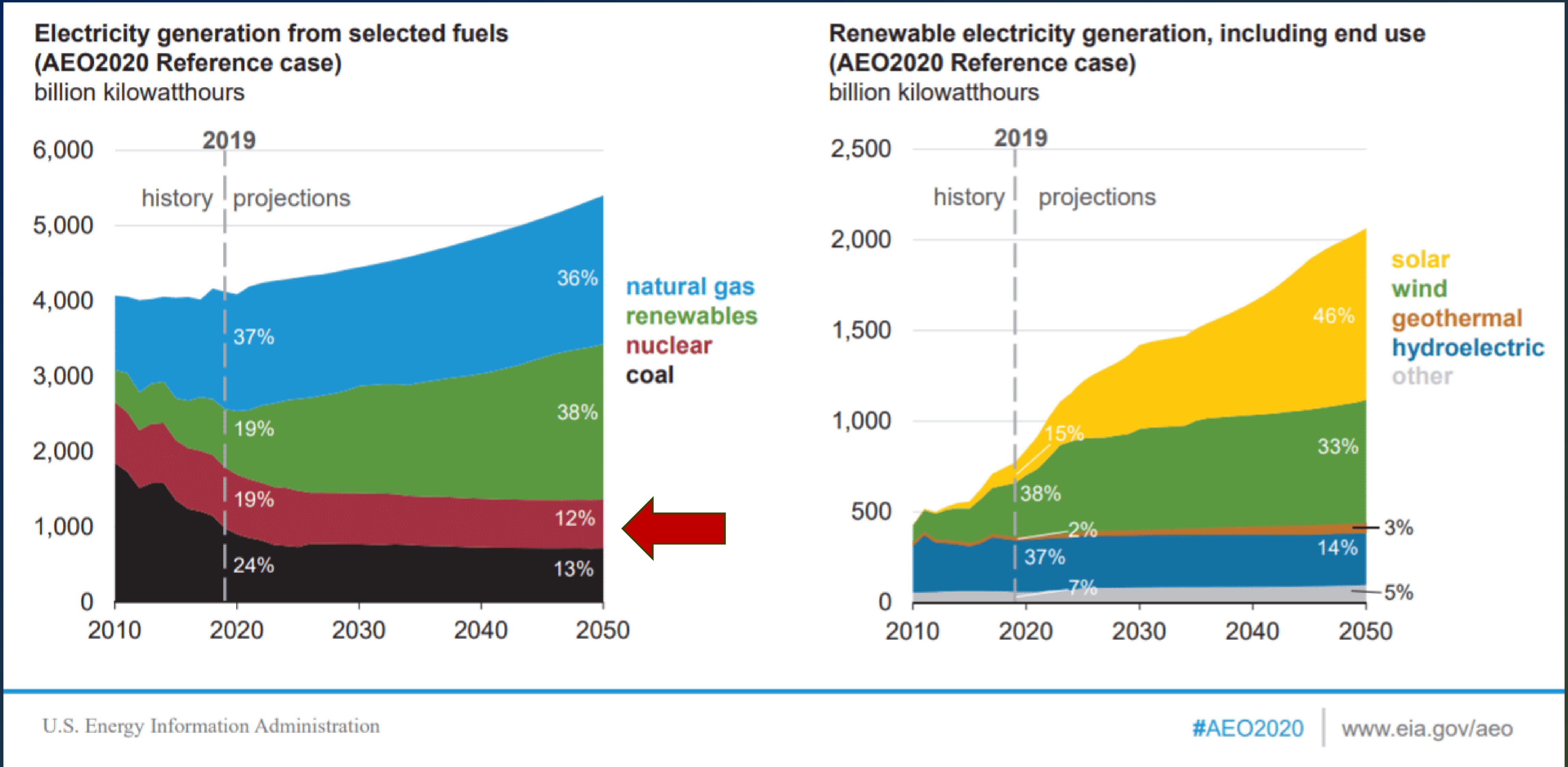
Sustainable Energy Sources

Energy sources that can be used **long-term without causing environmental harm**, while supporting social and economic well-being.
Examples: Solar, wind, geothermal, hydropower, nuclear fusion → CIRCULARITY



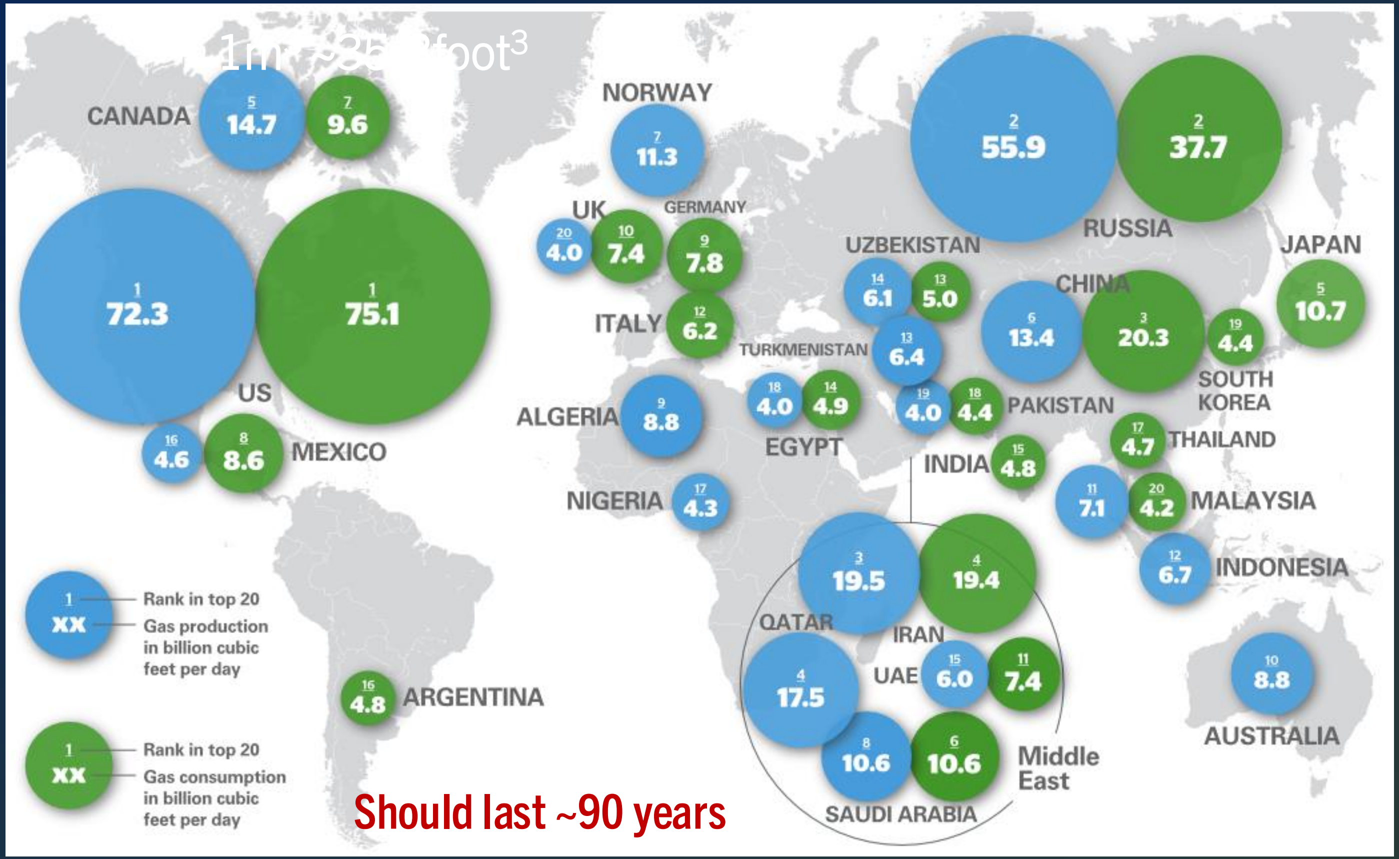
https://www.energyinst.org/statistical-review/about

Historic and Projected Energy Generation by Type



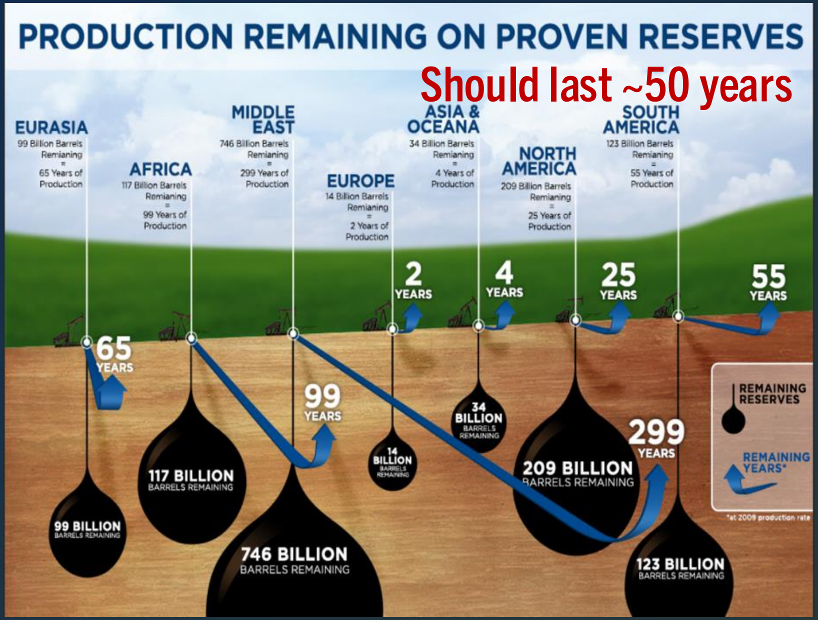
World Reserves in Gas, Oil and Coal

Gas Production, Gas Consumption (in billions of cubic feet)



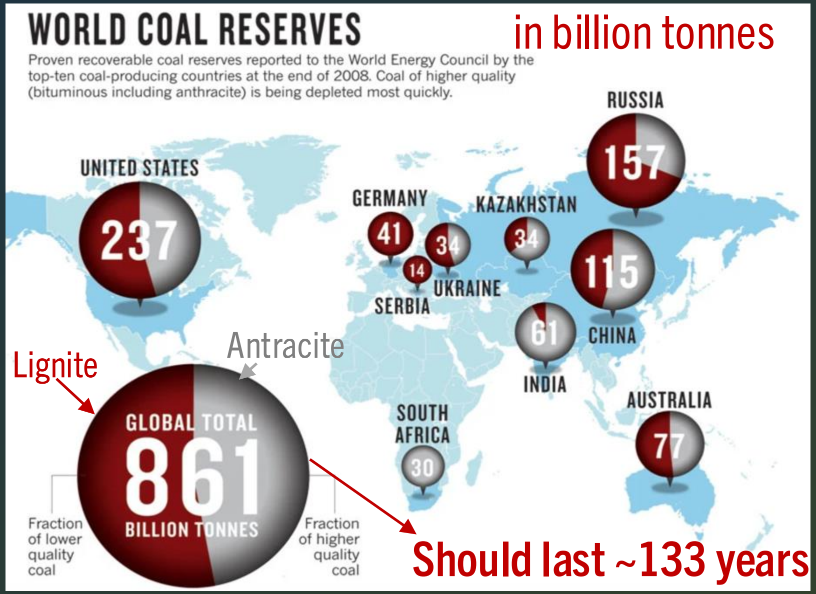
https://www.bp.com/en/global/corporate/news-and-insights/reimagining-energy/global-view-of-gas-infographic.html

Data from 2016



https://350africa.org/why-kenya-should-not-drill-its-oil-reserves/

Data from 2016



https://www.nature.com/articles/468367a

Data from 2012

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Nuclear energy - Present Status

Source IAEA Director General Report 2022

Nuclear energy – generated by large nuclear fission power plants - has been a significant source of electricity generation for decades, contributing to global energy supplies while producing low greenhouse gas emissions.

As of the current state, several countries heavily rely on nuclear power, while others are re-evaluating their nuclear energy strategies due to safety concerns and the rise of alternative energy sources.

Nuclear Fusion has been the source of studies for decades and several countries are investing on fusion projects

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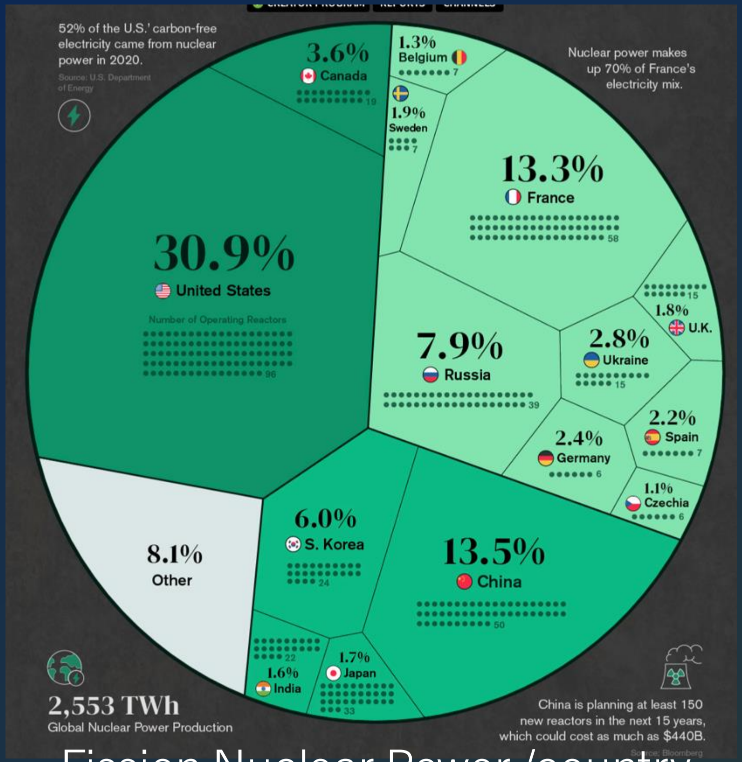
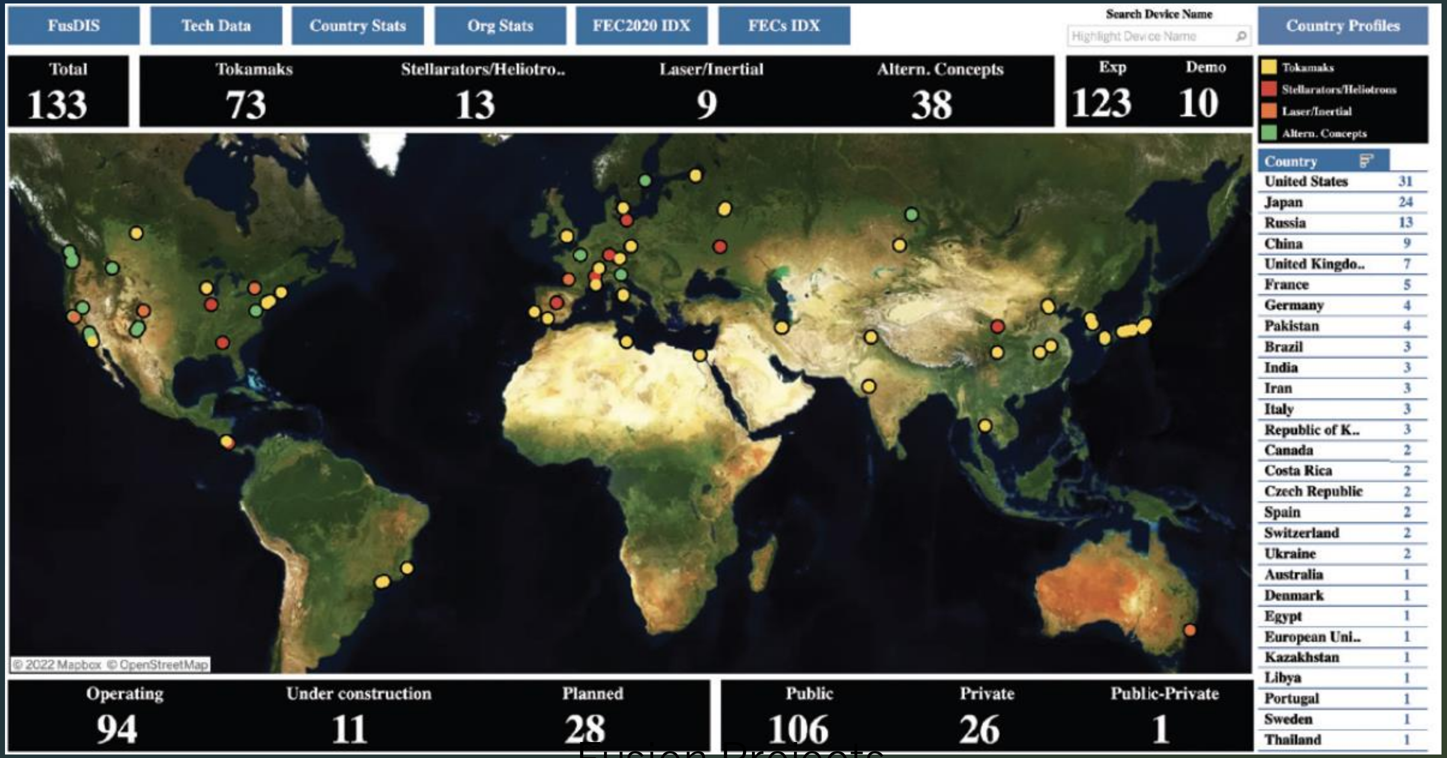


Fission Nuclear Power /country



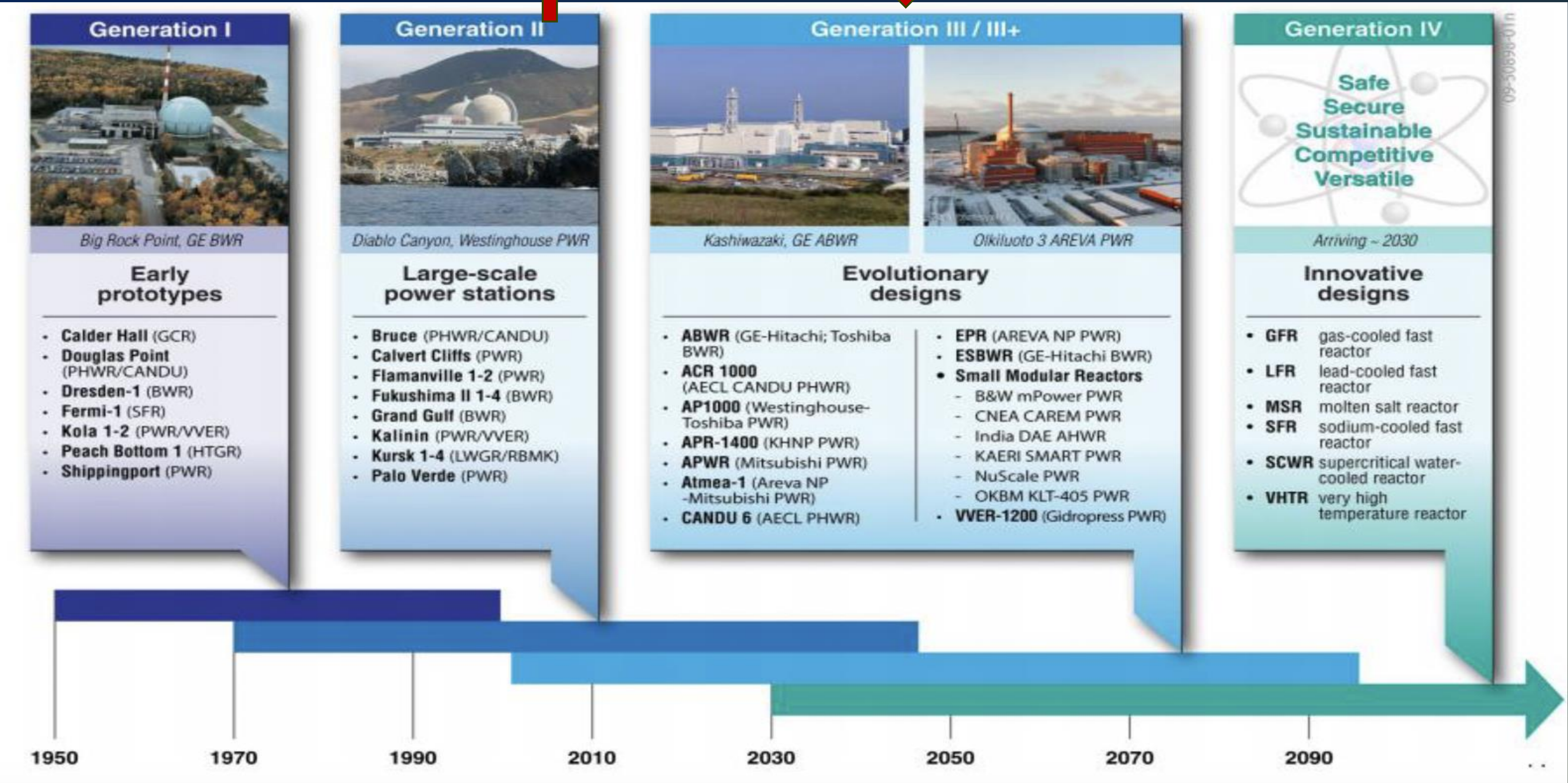
Fusion Projects

Source: Generation IV International Forum, www.gen-4.org
Slide from Varenna2023 -S. Leray

Generations of Nuclear Fission Power Plants

present

preparing



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Nuclear Energy – The Rise of a New Era

Nuclear Energy Offers Low lifecycle carbon, Firm and Reliable, Small Physical Footprint, High Energy Density, Long Life and Safety Record.

Moreover The New Reactor Generations provide:

Advanced Reactor Designs: Next-generation nuclear reactors are being developed with enhanced safety features, improved efficiency, and reduced waste production. Small modular reactors (SMRs) Micro Reactors (MMRs) and advanced fast reactors are among the innovative designs gaining attention.

2.**Use of nuclear energy beyond electricity**: heat generation, H production, water desalinisation, energy storage…

3.**Nuclear Fusion**: nuclear fusion holds the promise of virtually limitless and clean energy. Projects like ITER (International Thermonuclear Experimental Reactor) aim to achieve controlled fusion reactions. Industry is booming with small fusion reactors. New concepts are being proposed.

4.**Innovation in Waste Management**: Research is ongoing to develop more effective and secure methods for managing and disposing of nuclear waste, including advanced reprocessing techniques.

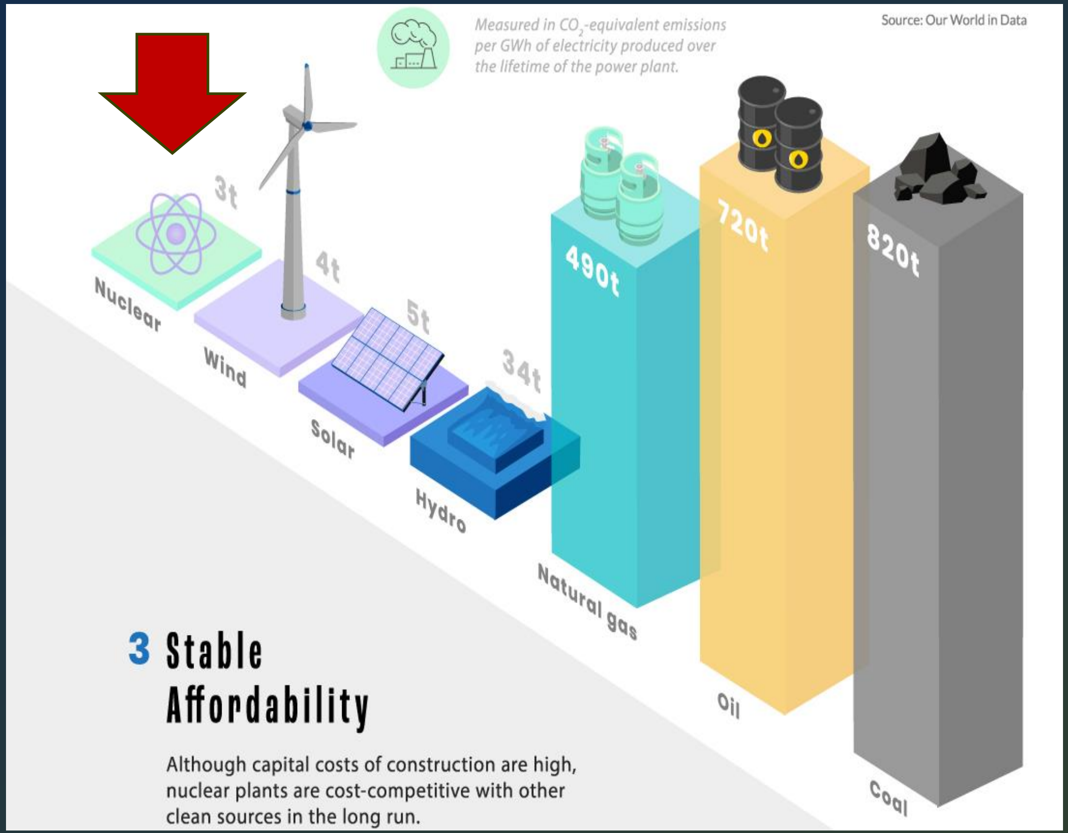
5.**Public Engagement**: Public understanding and acceptance of nuclear energy are being addressed through education, transparency, and open dialogue.

6.**Remaining Challenges**: Capital Cost, Schedule and Delivery Risk, Proliferation and Security, Waste Management

Nuclear lifecycle carbon emission

Emissions come from mining, construction and fuel, not operation

- About 12 g $_{CO_2eq}$/kWh over the full lifecycle , in the same band as wind, well below gas at ~490.
- The existing fleet displaces roughly 1.6 Gt of CO_2 a year.
- 66 Gt avoided since 1971, about two years of global emissions.



Global Warming Potential and Atmospheric Lifetime for Major GHG

The "**Global Warming Potential**" (GWP) of a gas is its **ability to keep heat in the atmosphere** for a defined time.

CO_2 =1 because it serves as a reference

To compare the gases with each other, the warming potential of each gas is converted into CO_2 equivalent over a period of 100 years

(Carbon Dioxide Equivalent)

Gases		Global Warming Potential (GWP) 100-year time horizon	Atmospheric Lifetime (years)
CO_2	Carbon Dioxide	1	100
CH_4	Methane	25	12
N_2O	Nitrous Oxide	265	121
CCl_2F_2 (Freon)	Chloro-Fluoro Carbon	10200	100
CHF_3	Hydro-Fluoro Carbon	12400	222
SF_6	SulfurHexa Fluoride	23500	3200
NF_3	HydrogenTrifluoride	16100	500

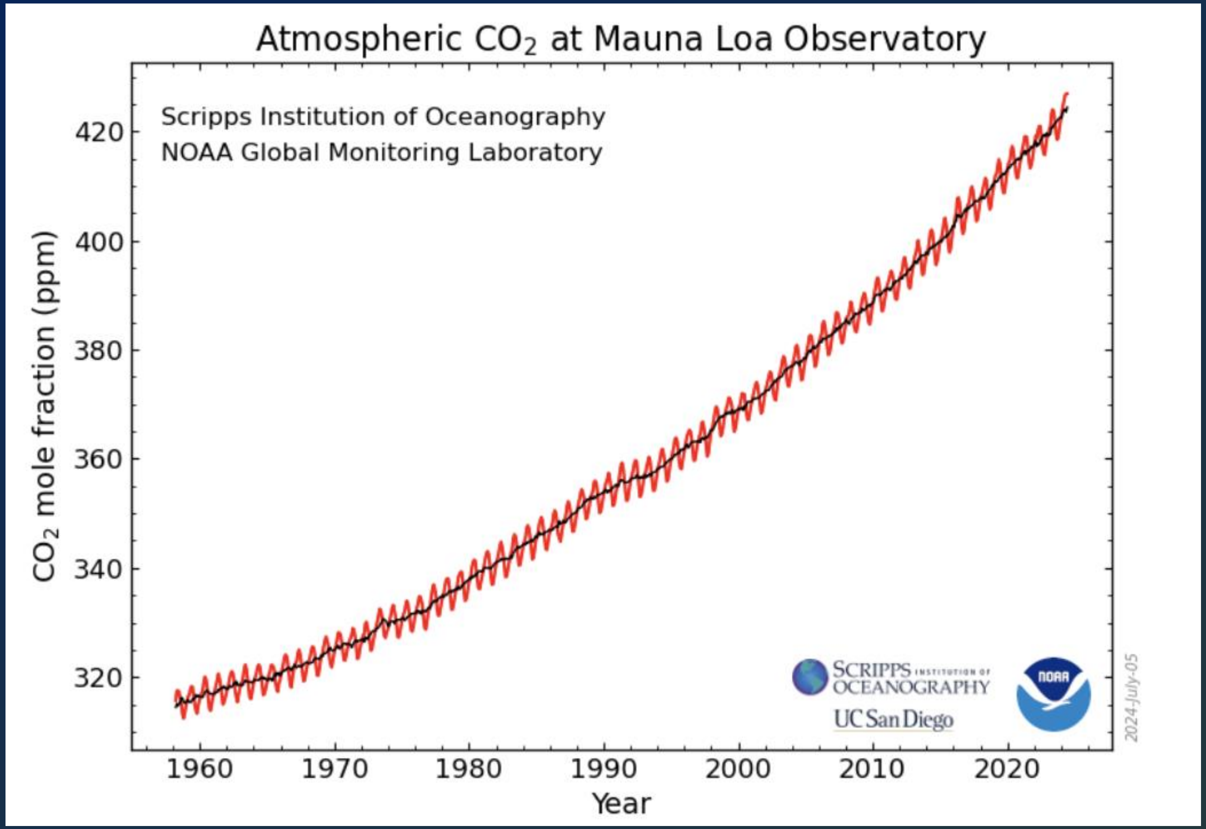
CO_2 contribution of all GHG > 50% , Nord Stream 1&2 leak 2022: 152’500 t

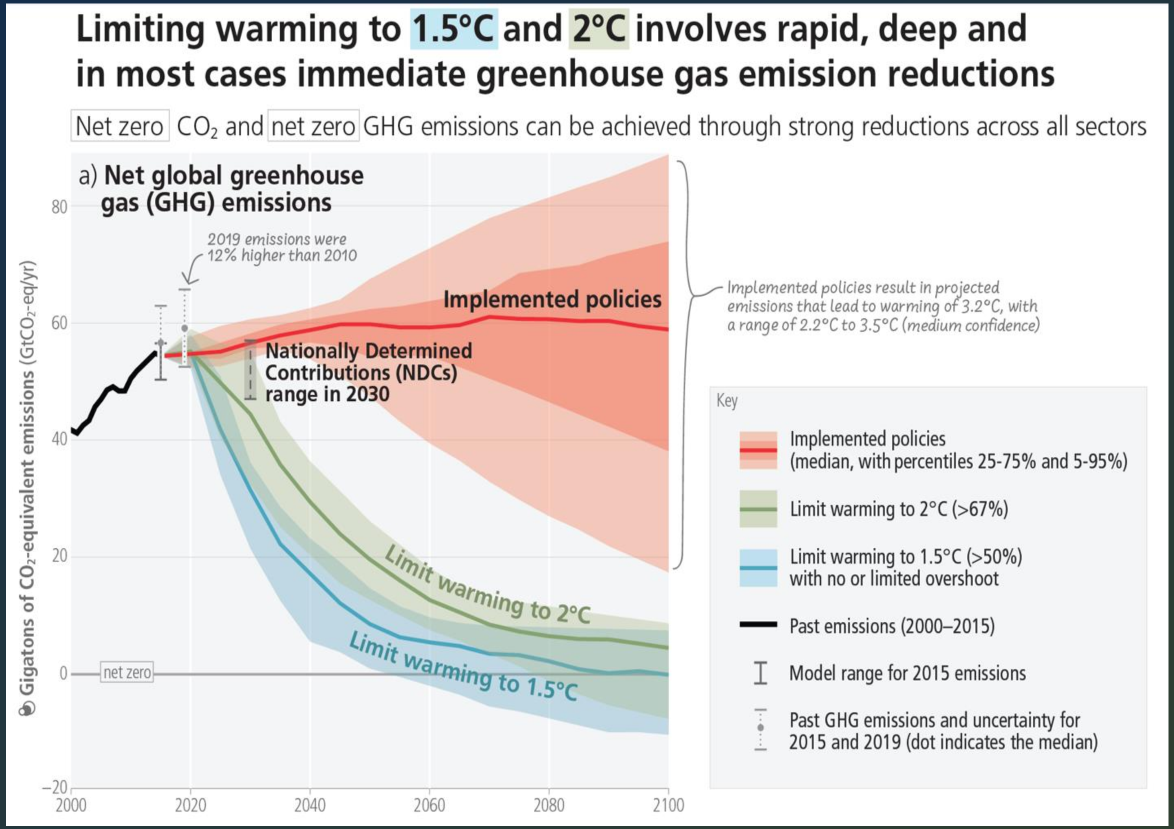
Fifth Assessment Report (IPCC, 2014)
https://www.c2es.org/content/main-greenhouse-gases/.

Net Zero Green House Gases emissions by 2050

AR6 Synthesis Report
Climate Change 2023

Source: Dr. Pieter Tans, NOAA/ESRL
(www.esrl.noaa.gov/gmd/ccgg/trends)





CO_2 increase by >51% since 1750,
from an average 280 to 425 ppm in 2024 !

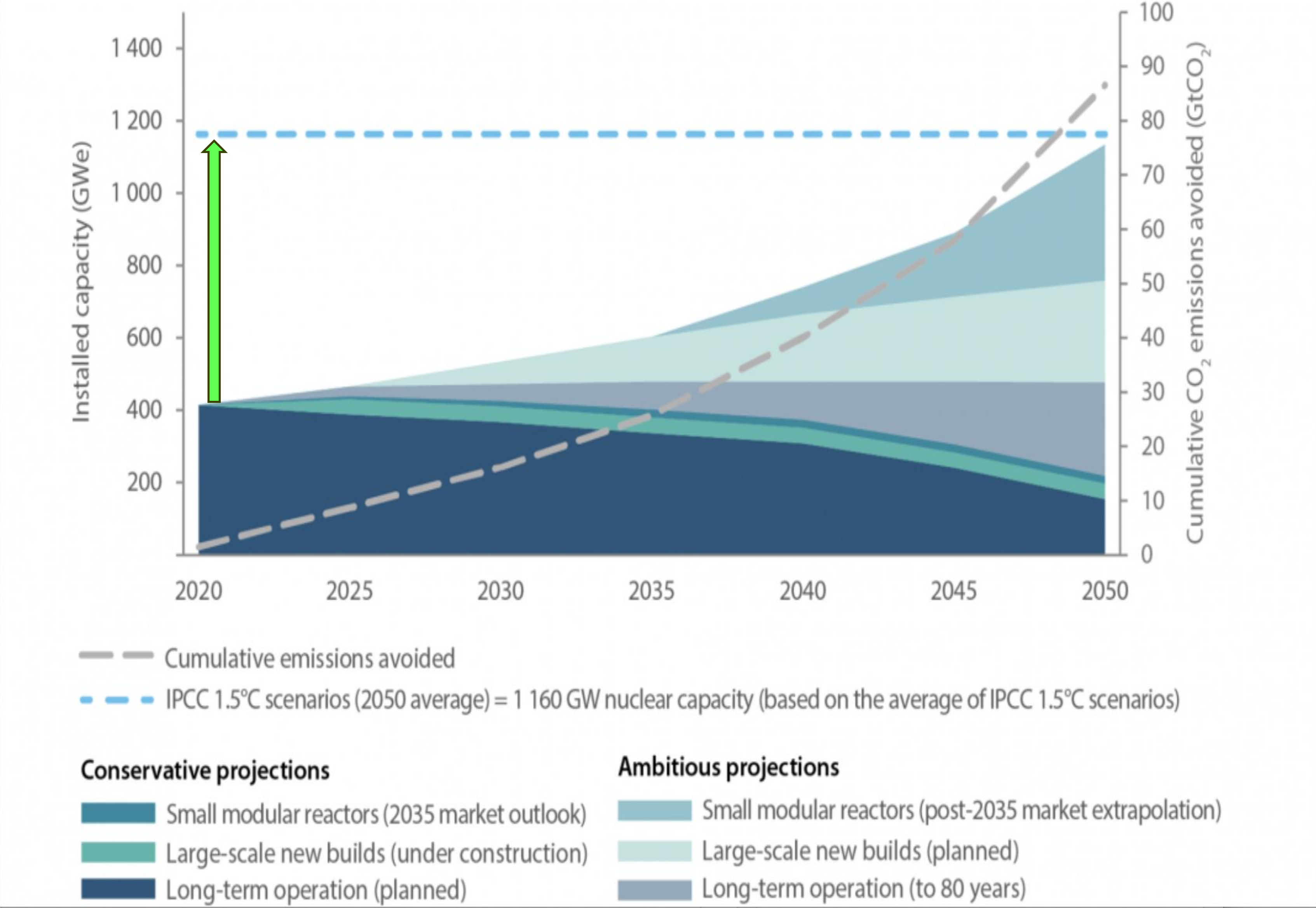
Earth 1.1°C warmer than late 1800s

AR6 Synthesis Report: Climate Change 2023

Projections of Installed Nuclear Capacity by 2050 and reduction of CO_2

In 2018 the IPCC considered 90 pathways consistent with a 1.5°C scenario i.e. pathways with emissions reductions sufficient to limit average global warming to less than 1.5°C.

The IPCC found that, on average, the pathways for the 1.5°C scenario require nuclear to reach 1160 gigawatts of electrical capacity by 2050, up from 394 gigawatts in 2020 (IPCC, 2018).

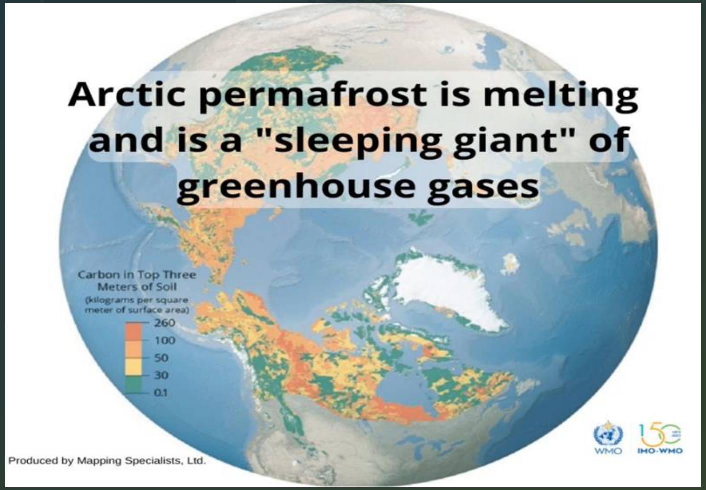


https://www.oecd-nea.org/jcms/pl_69396/meeting-climate-change-targets-the-role-of-nuclear-energy?details=true

Increasing disasters due to extreme weather

World average warmest day on record: 17.15°C on July 22, 2024

Record cryosphere melting, not only at the poles

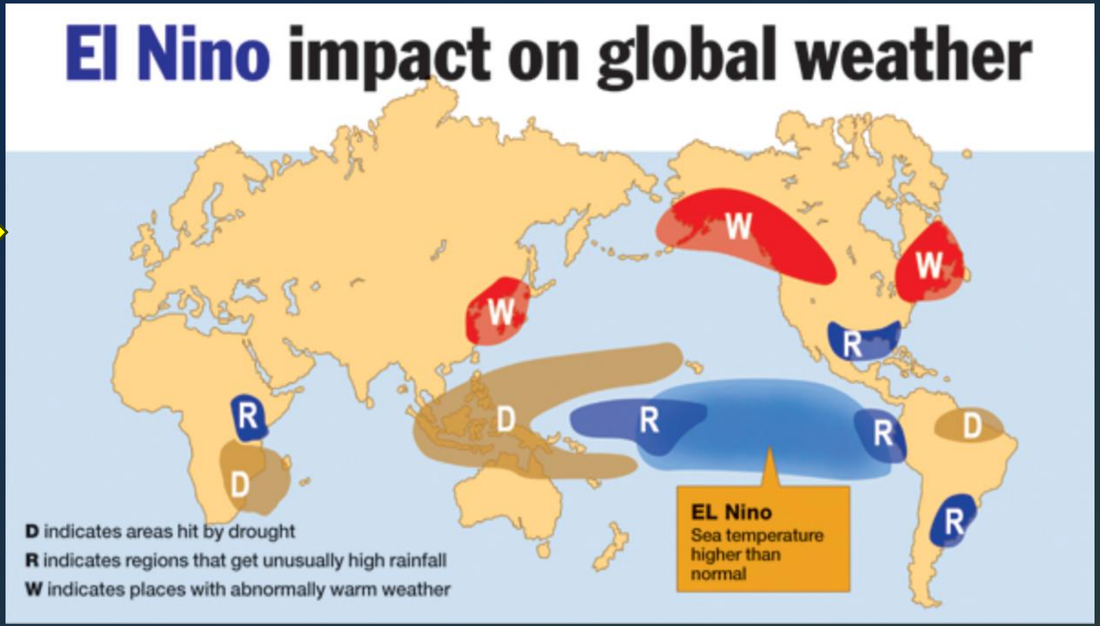


Global temperature rise and El Nino

https://www.telegraphindia.com/science-tech/the-el-nino-row/cid/1376323#goog_rewarded

El Niño is a natural climate pattern in which sea-surface temperatures in the central and eastern equatorial Pacific rise at least 0.5 °C above average, disrupting global weather systems.

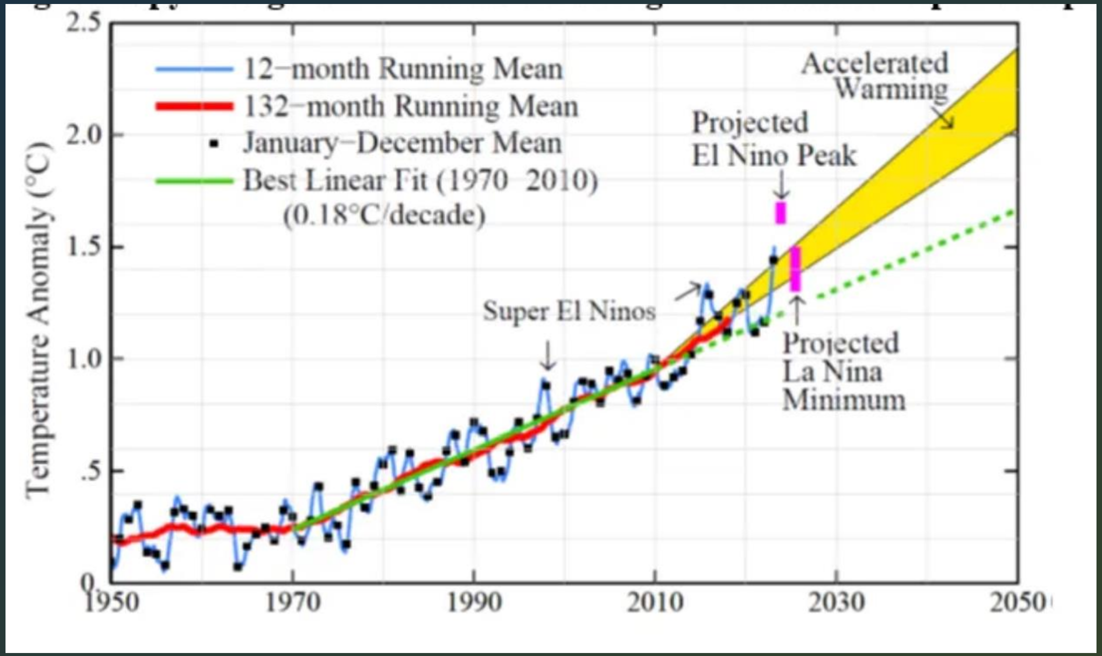
- Historically occurs every 2–7 years and influences rainfall, drought, storms, and global temperatures.



Status in 2026

- NOAA (National Oceanic and Atmospheric Administration) confirmed El Niño conditions in early June 2026, with Pacific waters exceeding the 0.5 °C threshold.

- By late June, Niño 3.4 region anomalies reached about +1.8 °C, already stronger than many past events at midwinter peak.



Forecasts place an 88% chance of a strong event and 63% chance of a very strong "super El Niño" (≥ +2.0 °C).

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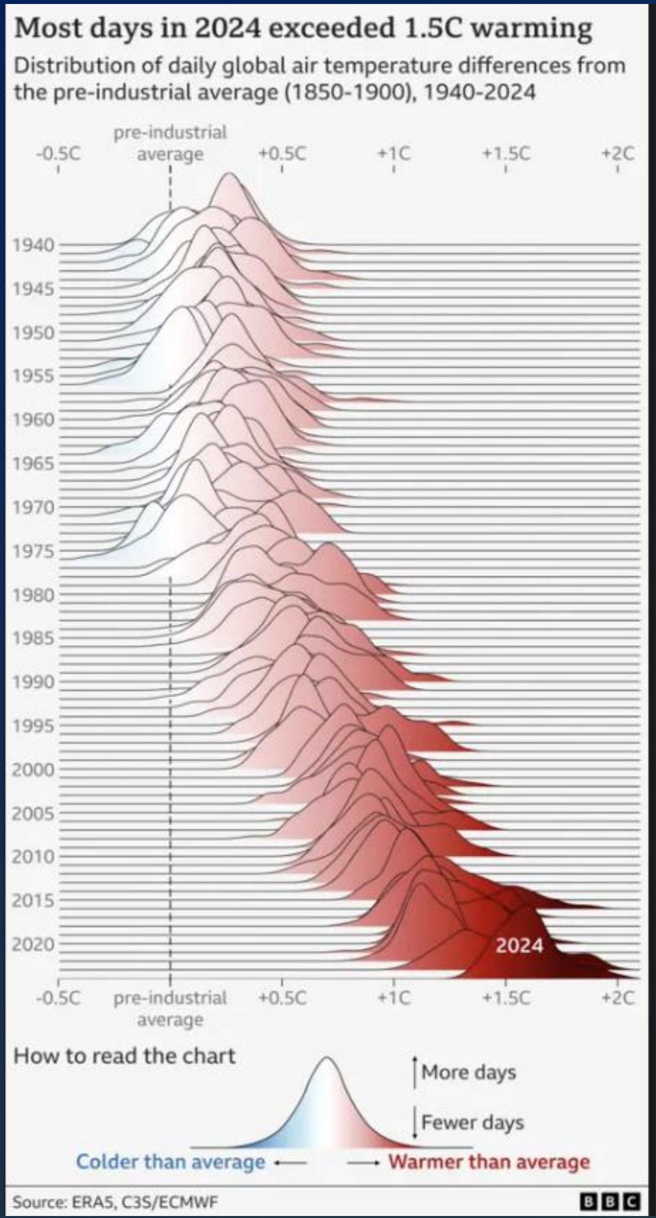
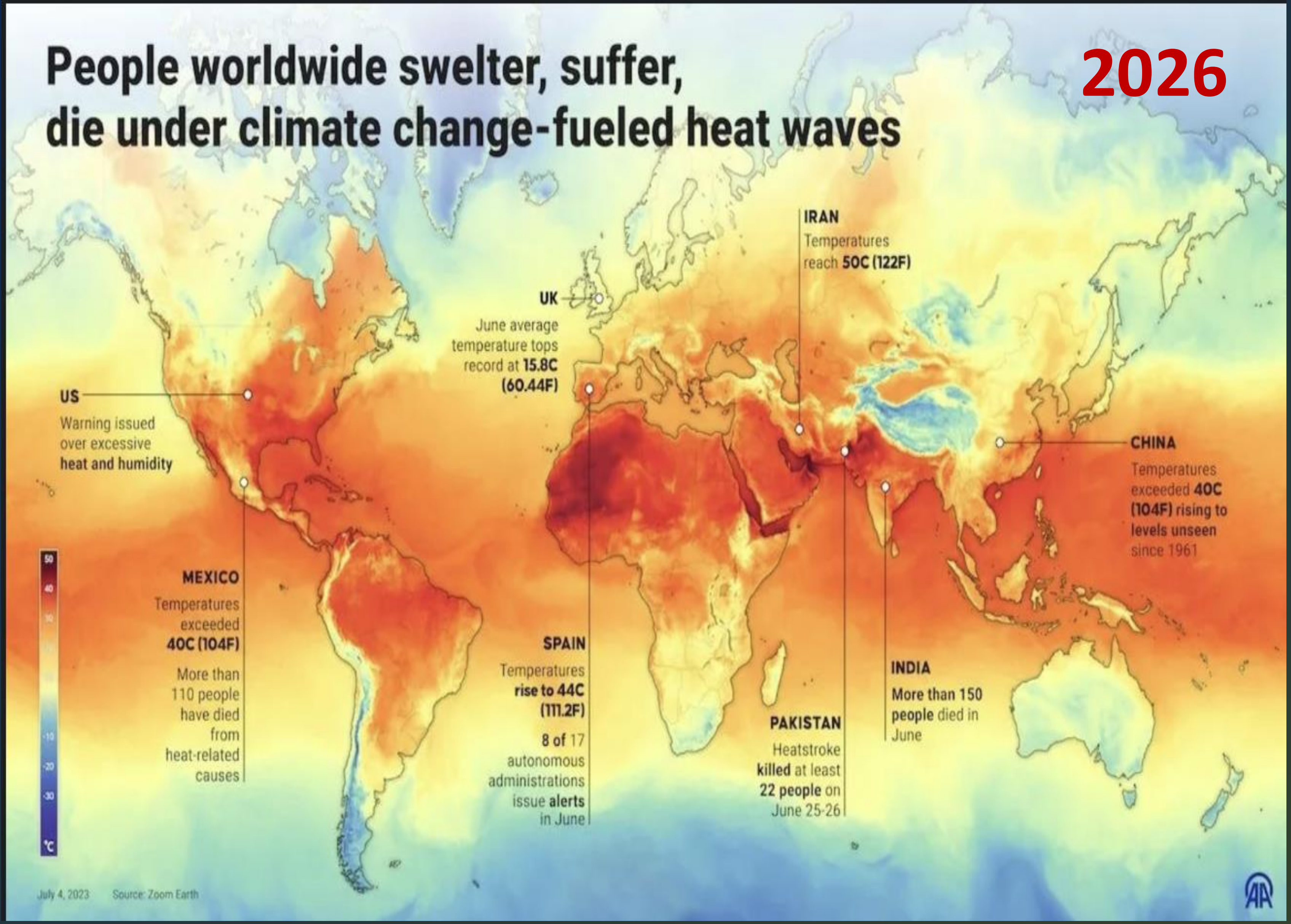
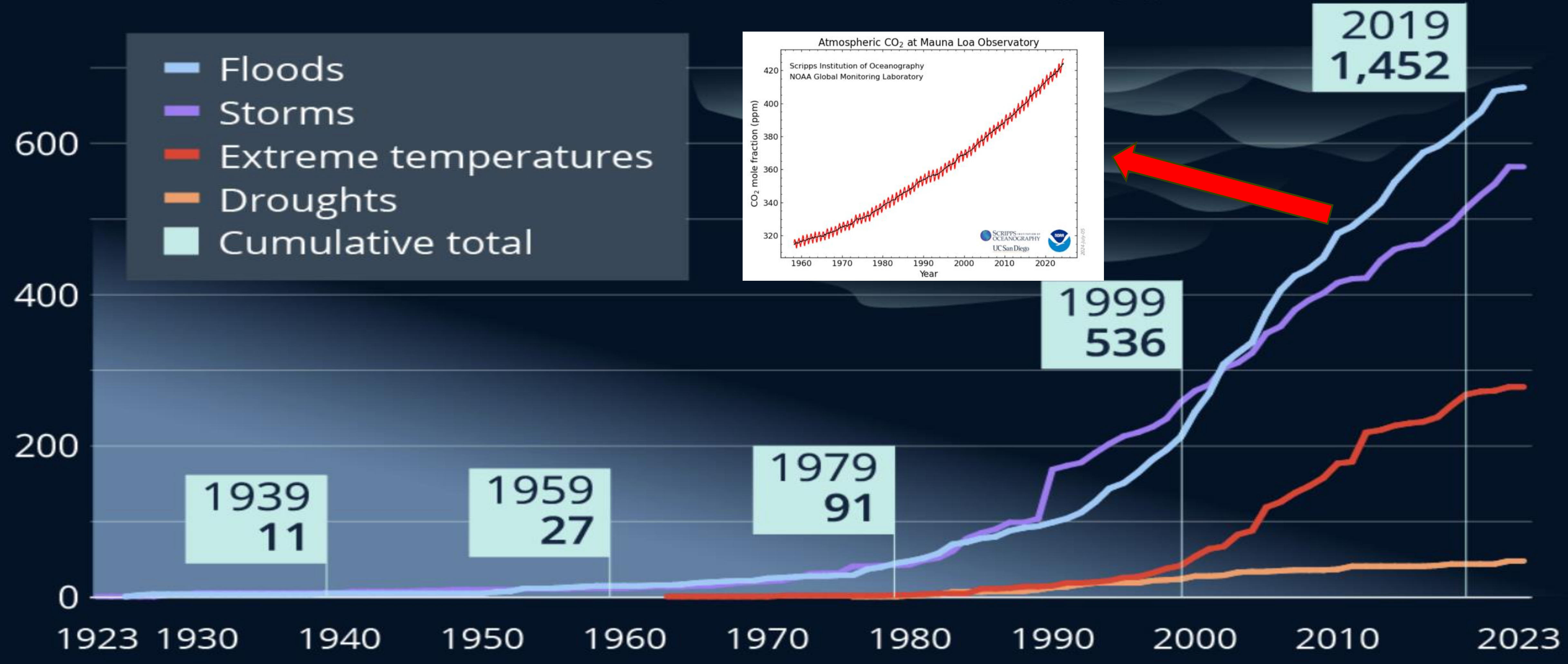




Cumulative number of natural disasters/extreme weather events in Europe since 1923, by type



As of June 14, 2023. A disaster is classified here as at least one of the following: 10+ killed/ 100+ impacted/a state of emergency/a call for international assistance.

Source: The International Disasters Database (EM-DAT)

https://www.statista.com/chart/30288/cumulative-number-of-natural-disasters/

2026 A year of sad records

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26 AUGUST

Nepal

Bhote Koshi glacial flash flood

>1300 dead **~5000** missing

- An avalanche of ice and rock off a glacier blocked the Lhende Khola; the released surge tore down the Bhote Koshi and Trishuli valleys.
- 291 of the missing are foreign nationals; villages, roads and hydropower were washed away.
- About 430 MW of generating capacity damaged the second flood here in 14 months.

A magnitude 4.4 tremor was recorded at 8:37 a.m. Whether it triggered the collapse, or was caused by it, is still being investigated.

Southern Africa
Dec–Feb

Floods and back-to-back cyclones affected 1.5 million people: 300+ deaths, 170,000 displaced, Mozambique worst hit. Rapid analysis linked the rainfall to warming.

Western Europe
June

Hottest June on record, 3.05°C above normal. 45.1°C in southern Spain; Germany set a national record of 41.8°C at Möckern.

Spain & France
July–Aug

The Ávila fire, at roughly 50,000 ha, became the largest in Spain's recorded history. France passed 115,000 ha, also a record. Over 325,000 evacuated.

Iberian Peninsula
January

Nine storms in barely a month. Kristin brought 170 km/h winds and about USD 7.7bn in losses — unusually severe for the region.

Canada & US
Summer

Smoke from more than 100 Canadian wildfires put all of New York State and parts of New Jersey under air-quality advisories.

Asia
July–Aug

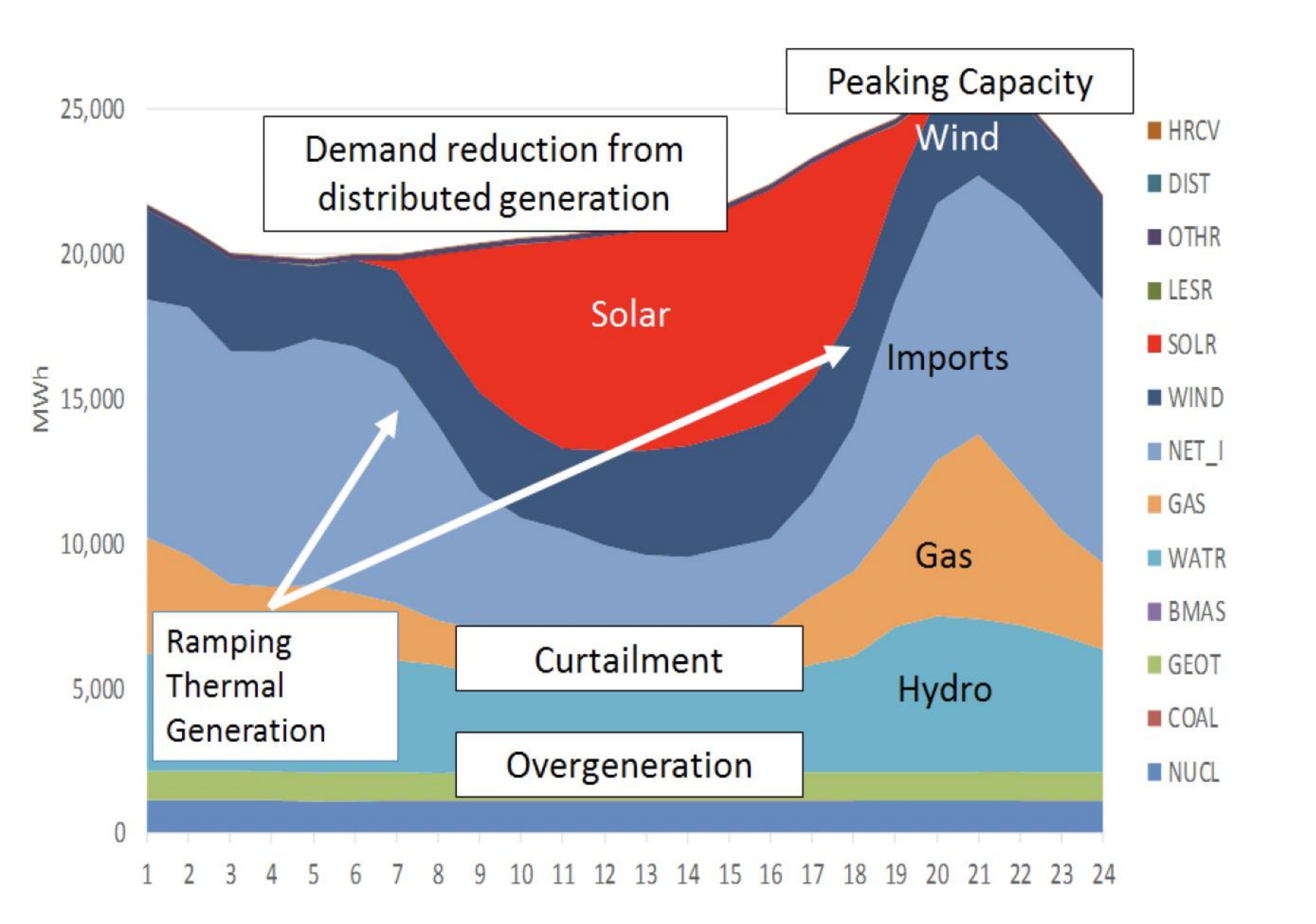
Warmest July on record for the continent. Record heat in Japan and Korea, Indonesia's worst fires since 2015, India's weakest monsoon in two decades.

Nepal figures as of 26 Aug 2026 and still rising. Sources: CNN, Al Jazeera, PBS, WMO, Copernicus/EFFIS, OCHA, Munich Re, World Weather Attribution. Individual events are not caused by climate change alone; attribution studies estimate how much warming raised their likelihood or severity.

Nuclear is Firm and Reliable: Renewable Intermittence and Reliability

The scarce commodity in a high-renewables grid is firmness

- Runs regardless of weather, season or time of day; capacity factors above 90% in the best-run fleets.
- Supplies inertia, short-circuit power and frequency control that grids need for stability.
- Can load-follow: French reactors vary output by up to 80% twice a day.



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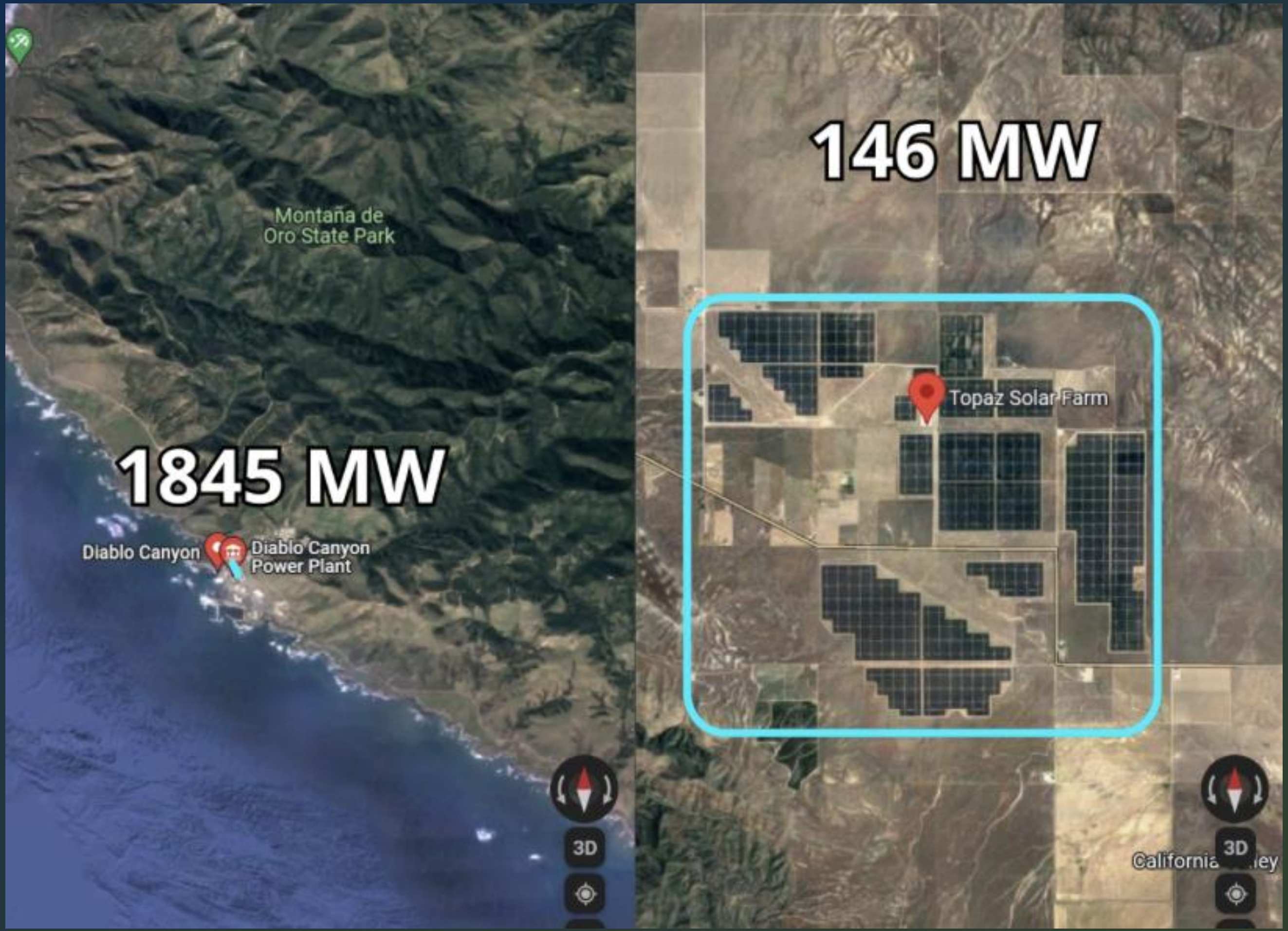
Nuclear physical footprint

Relevant to biodiversity and mineral-security arguments alike

- Lowest land use per MWh of any low-carbon source, far below solar, wind and hydro.
- Lowest critical-mineral intensity: a few kg/MWh against ~186 for onshore wind and ~155 for solar PV.
- Matters increasingly as land and mineral supply become the binding constraints.

Nuclear

Solar



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Nuclear Technology Beyond Electricity

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Health & medicine

- Diagnostic imaging — SPECT and PET scans
- External-beam radiotherapy and brachytherapy
- Targeted radionuclide therapy (Lu-177, Ac-225)
- Sterilising single-use devices, implants and PPE
- Isotope production in research reactors

30m+ procedures a year · 40%+ of single-use devices gamma-sterilised

Food & agriculture

- Mutation breeding for drought- and disease-resistant crops
- Sterile insect technique — fruit fly, tsetse, screwworm, mosquitoes
- Food irradiation and phytosanitary treatment for trade
- Soil, water and fertiliser efficiency studies
- Livestock disease diagnosis; food authenticity testing

Underpins the FAO/IAEA Atoms4Food programme

Industry & materials

- Industrial radiography and non-destructive testing
- Thickness, density and level gauges on production lines
- Radiotracers to diagnose plants, pipelines and reservoirs
- Polymer crosslinking; cable, tyre and coating curing
- Well logging, neutron activation analysis, smoke detectors

Quality control across almost every manufacturing sector

Water, environment & climate

- Isotope hydrology to map, date and manage groundwater
- Ocean acidification and marine pollutant monitoring
- NUTEC Plastics — radiation-based plastic recycling
- Fingerprinting pollution and emission sources
- Palaeoclimate records and radiocarbon dating

Used where no chemical tracer can follow the water

Space, marine & propulsion

- Radioisotope thermoelectric generators for deep-space missions
- Radioisotope heater units keeping instruments alive
- Nuclear thermal and electric propulsion (in development)
- Naval propulsion — submarines, carriers, icebreakers
- Floating and transportable reactors for remote sites

The only practical power source beyond Mars orbit

Heat, hydrogen & fresh water

- District heating — Beznau since 1983, Haiyang, Akademik Lomonosov
- Seawater desalination
- Process heat for cement, glass, metals and refining
- Hydrogen and synthetic fuel production
- Syngas production for the chemicals industry

Where high-temperature SMRs and Gen IV are aimed

Also: neutron scattering for materials and drug design · nuclear forensics and cargo scanning · art authentication and heritage conservation · archaeological dating

Sources: IAEA (nuclear applications, medical sterilization, non-electric applications), FAO/IAEA Joint Centre, NEA No. 7628.

Nuclear energy density (Amount of energy stored in a system per unit volume)

Identified uranium resources cover roughly a century at today's demand

- One gram of U-235 fissioned releases as much energy as three tonnes of coal.
- Years of fuel sit inside the core; no pipeline or daily delivery to interrupt.
- Fuel is a small share of generating cost, so price shocks barely reach the consumer.

Fuel	Energy density	Energy density
	($MJkg^{-1}$)	($MJlitre^{-1}$)
Nuclear fusion of hydrogen	300 000 000	425 000 000
Nuclear fission of uranium 235	77 000 000	1 500 000 000
Liquid hydrogen	143	10
Natural gas (compressed to $200x10^5$ Pa)	54	10
Petrol	46	34
Diesel	45	38
Aviation fuel	43	33
Residential heating oil	43	33
Vegetable oil	42	31
Crude oil	42	37
Liquified natural gas	37	24
Coal (anthracite)	33	72
Charcoal	29	
Coal (bituminous)	24	20
Wood	6-18	2-3
Liquid hydrogen and liquid oxygen	13	6
Household waste	8-10	
TNT	4.2	7

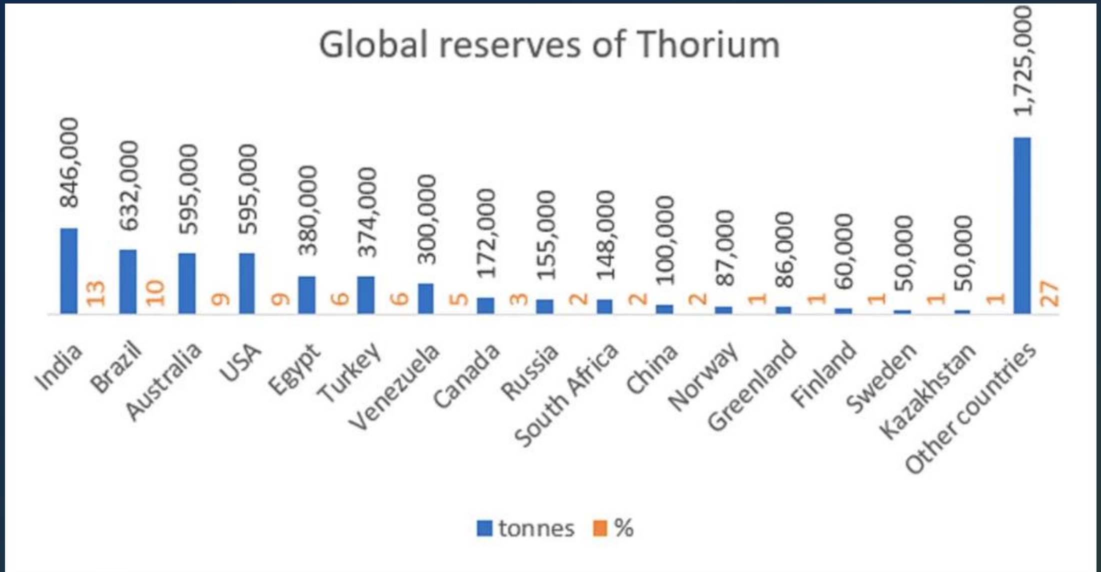
Nuclear fuel-resource availability

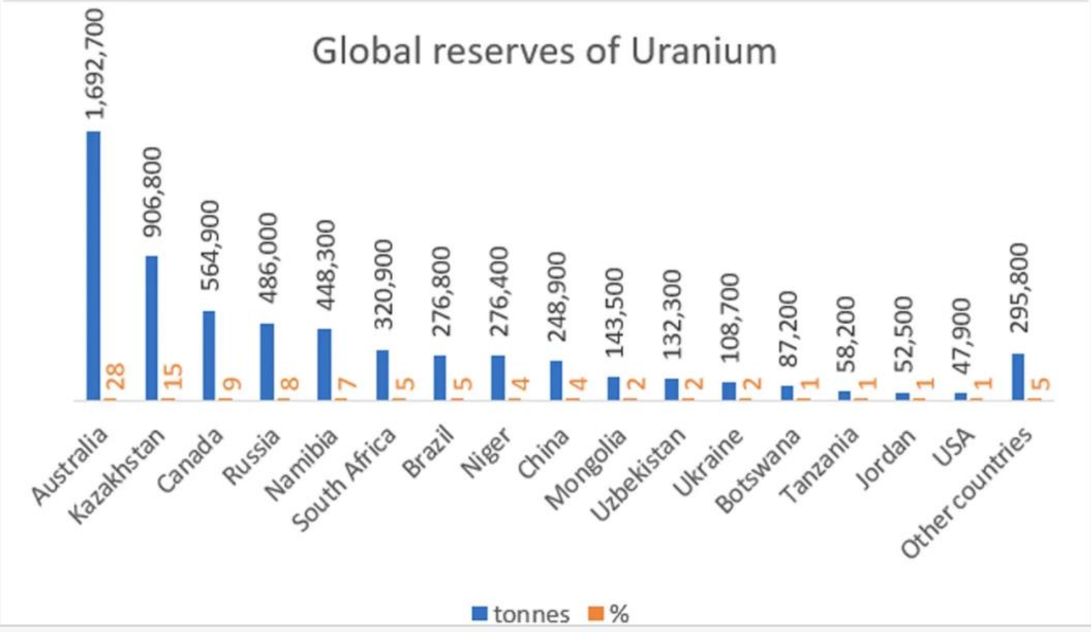
Uranium, once-through LWR: ~100–200 years of identified recoverable resources at today's consumption

- **Broader uranium resources:** several hundred years
- **Uranium + fast breeder/closed fuel cycle: thousands–tens of thousands of years**

Thorium: ~6 million tonnes estimated resources; with an efficient Th–U-233 breeder cycle, **thousands of years**

The lifetime of nuclear resources is determined not only by geological reserves, but by how efficiently the reactor and fuel cycle use the resource.





https://www-pub.iaea.org/MTCD/Publications/PDF/P1700_web.pdf?

https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2023.1132611/full

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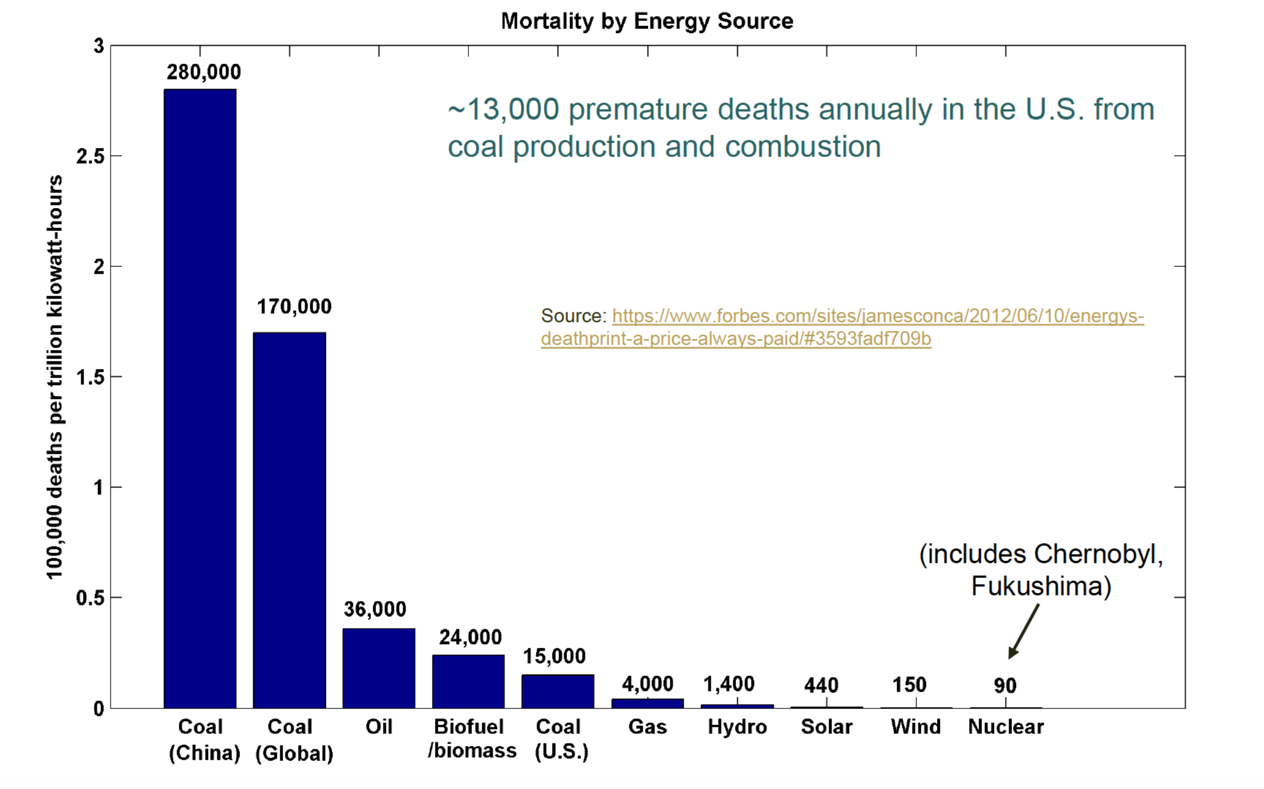
Safety Record

Nuclear Accidents Worldwide

	TMI	Chernobyl	Fukushima
Location and year	US, 1979	USSR, 1986	Japan, 2011
Reactor type	PWR	RBMK	BWR (3 units)
Physical cause	Valve stuck open caused extended coolant leakage	Core instability at low power	Station blackout caused by earthquake and tsunami
Human error	Failed to recognize stuck valve, turned off pumps	Intentionally disabled safety systems to run 'experiment'	None major
Damage	Partial core meltdown	Complete core and superstructure destruction + cladding material fire	Analysis suggests 3 core meltdowns
Mitigation	Containment worked as designed	This reactor design does not have a robust containment	Containments partially failed
Release	Minimal	Massive and unmitigated, fueled by fire	Substantial, mostly into atmosphere and ocean
Public health impact	None from radiation exposure, but lots of anxiety	Radiation-induced casualties among first responders, increased incidence of thyroid cancer in locals	Minimal from radiation exposure, but much distress and several casualties from forced evacuation
Current status	Fuel removed	Debris contained within 'sarcophagus'	Safe shutdown

Each accident has been a learning experience ⇒ NPPs worldwide have gotten safer and safer

Mortality by Energy Source



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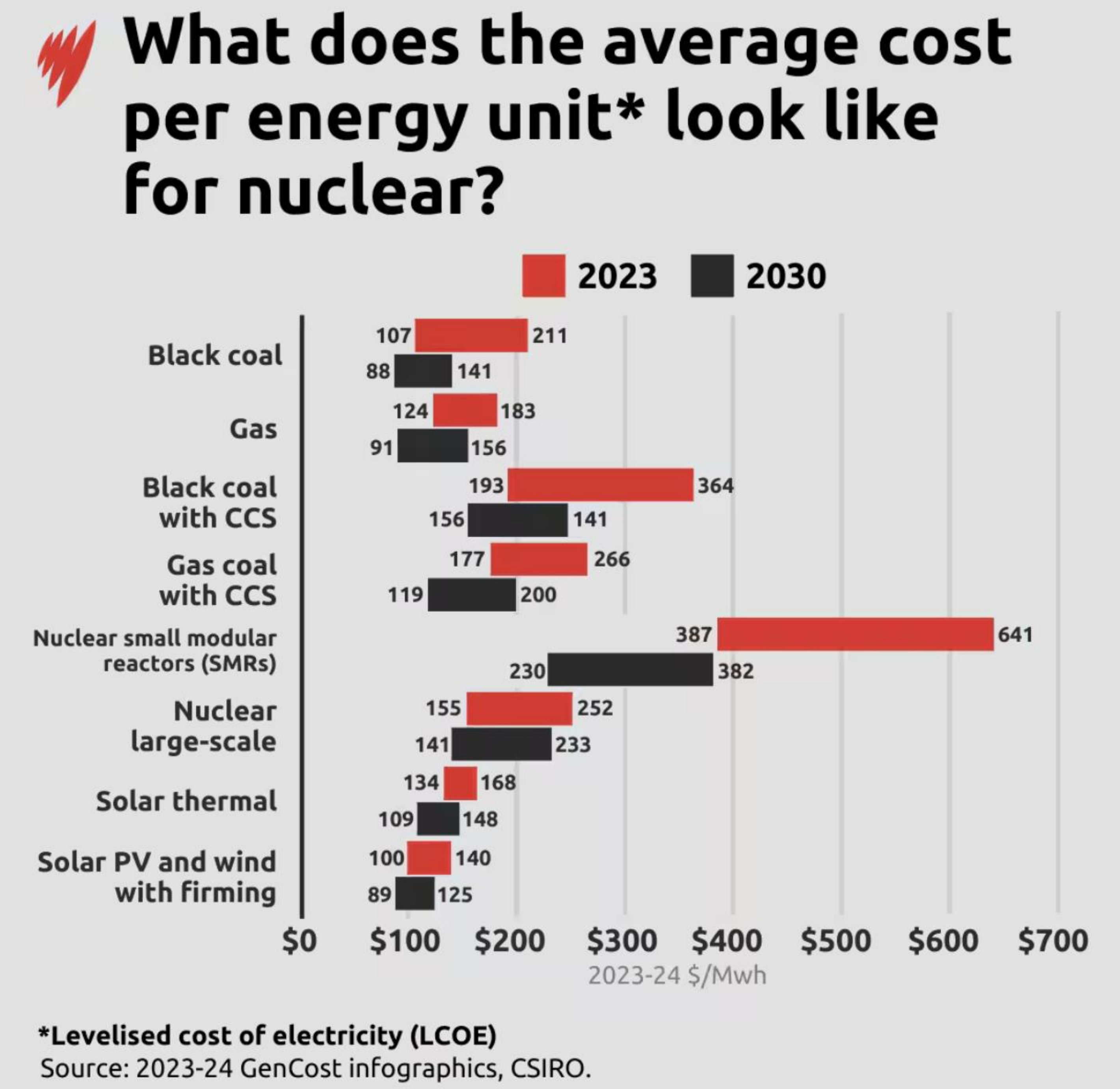
Challenge: Capital cost

Financing structure matters more than engineering to the final price

- Capital is up to 75% of the cost of nuclear electricity the plant is paid for long before it earns.
- Raising the cost of capital from 6% to 9% lifts the levelized cost by roughly 50%.
- Recent Western builds ran far over: Flamanville 3 and Hinkley Point C both multiples of budget.



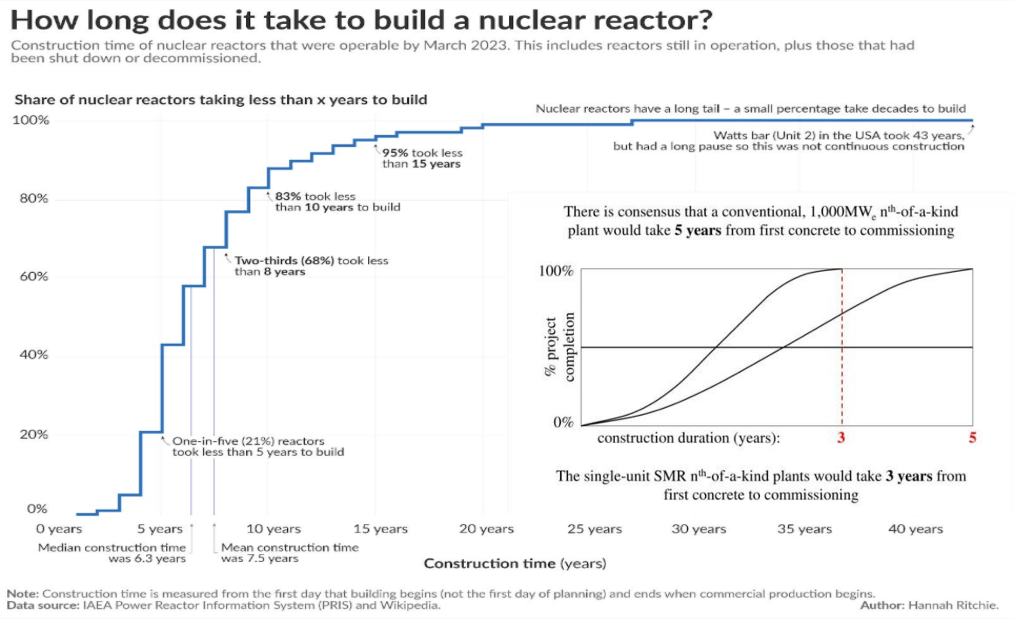
Schedule and delivery risk

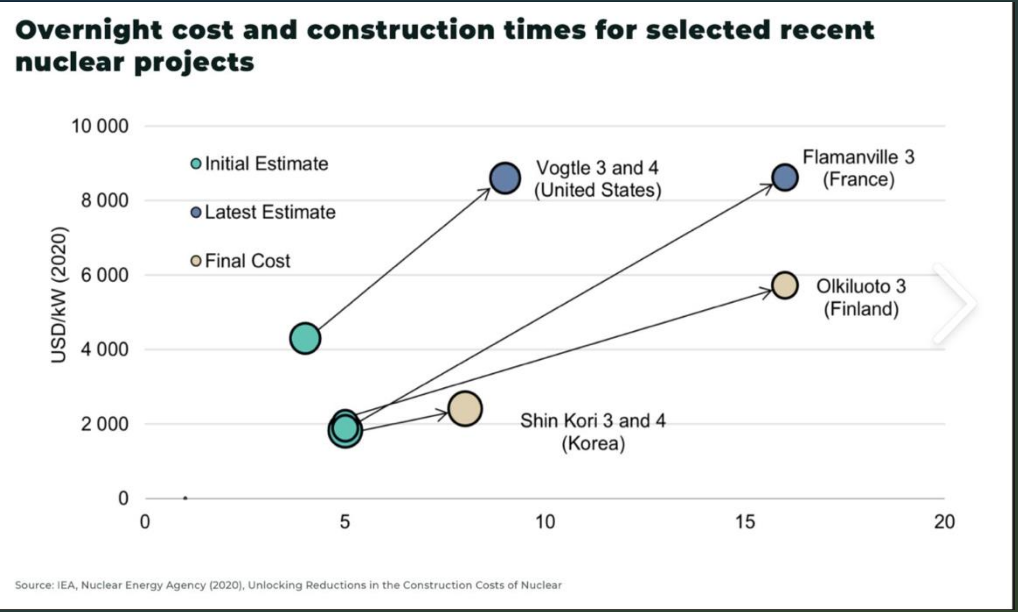
Late delivery is what destroys the economics, not the technology

- Western new builds have taken a decade or more once licensing and planning are counted; renewables take one to two years.

- First-of-a-kind projects absorb the learning costs; delay compounds because interest accrues throughout.

- China and Korea average 5–6 years evidence the problem is programmatic, not physical.





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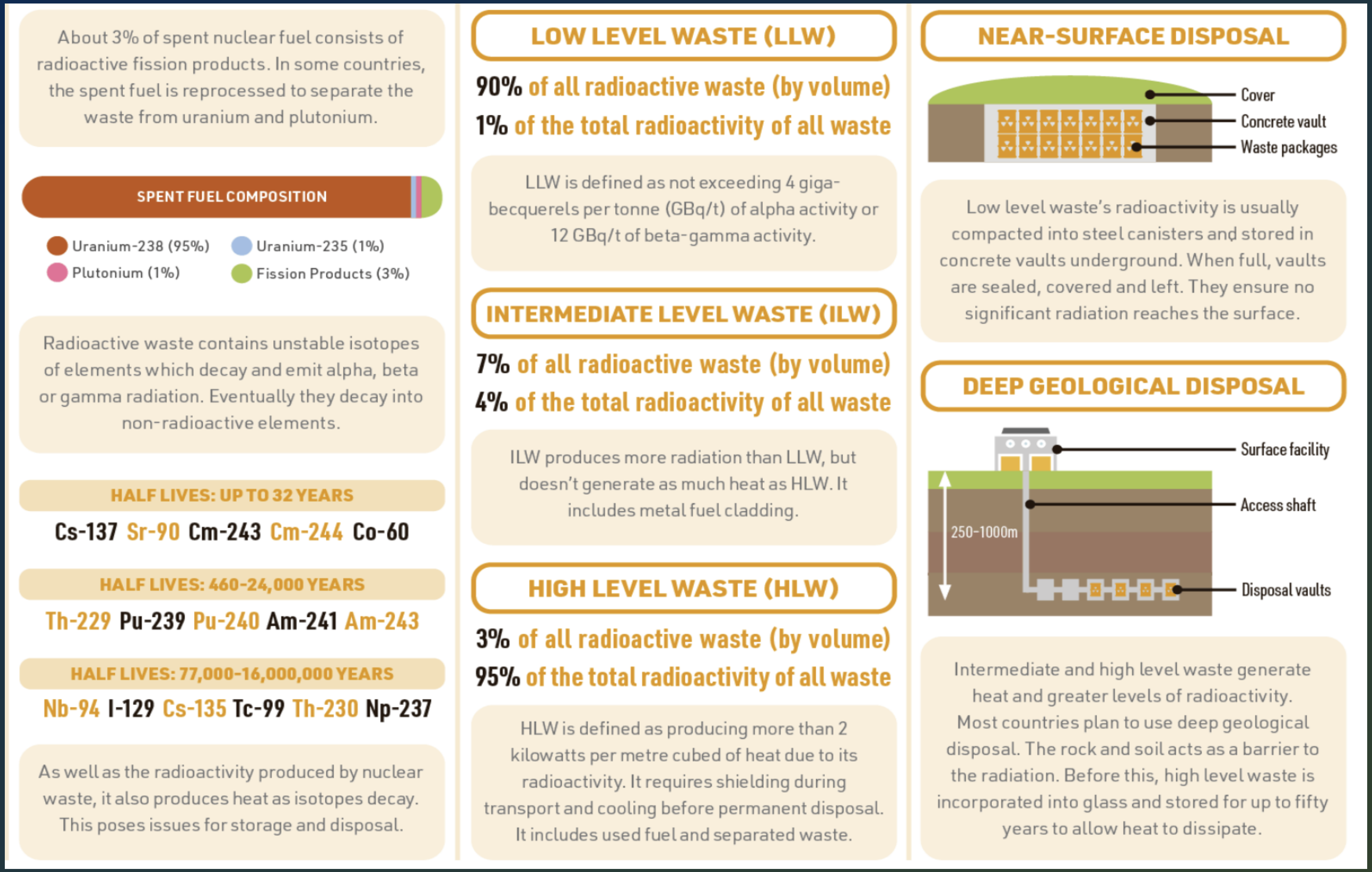
Waste and decommissioning

- *Technically solved, institutionally unresolved in most countries*
- No deep geological repository is yet disposing of commercial spent fuel anywhere in the world.
- Finland's Onkalo is closest: favourable safety assessment from STUK, first disposal hole drilled 26 August 2026, operating licence still pending.
- Everywhere else, spent fuel sits in interim storage awaiting a political decision.

Types of Waste

Waste Disposal



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symmetry | volume 9 | issue 1 |
february 2012

Transmutation of Nuclear Waste

- Use of Accelerator Driven Systems (ADS) to generate a beam of particles to help transform spent nuclear fuel into a re-useable form
- It could reduce the time required for long-term geological storage from 300,000 years to 500 years.
- Uses the abundant thorium, as a safer, cleaner, more proliferation-resistant fuel for energy production in nuclear reactors.
- EUROTRANS Project→ MYRRHA, the Multipurpose hYbrid Research Reactor for High-end Applications , Belgium
- Prototype projects GUINEVERE and Venus, (TRANSNMUTEX (CERN startup)
- Project X at Fermilab could be used as a demonstrator
- Thorium fuel cycle is pursued in : China, India, France Denmark, Turkey and USA

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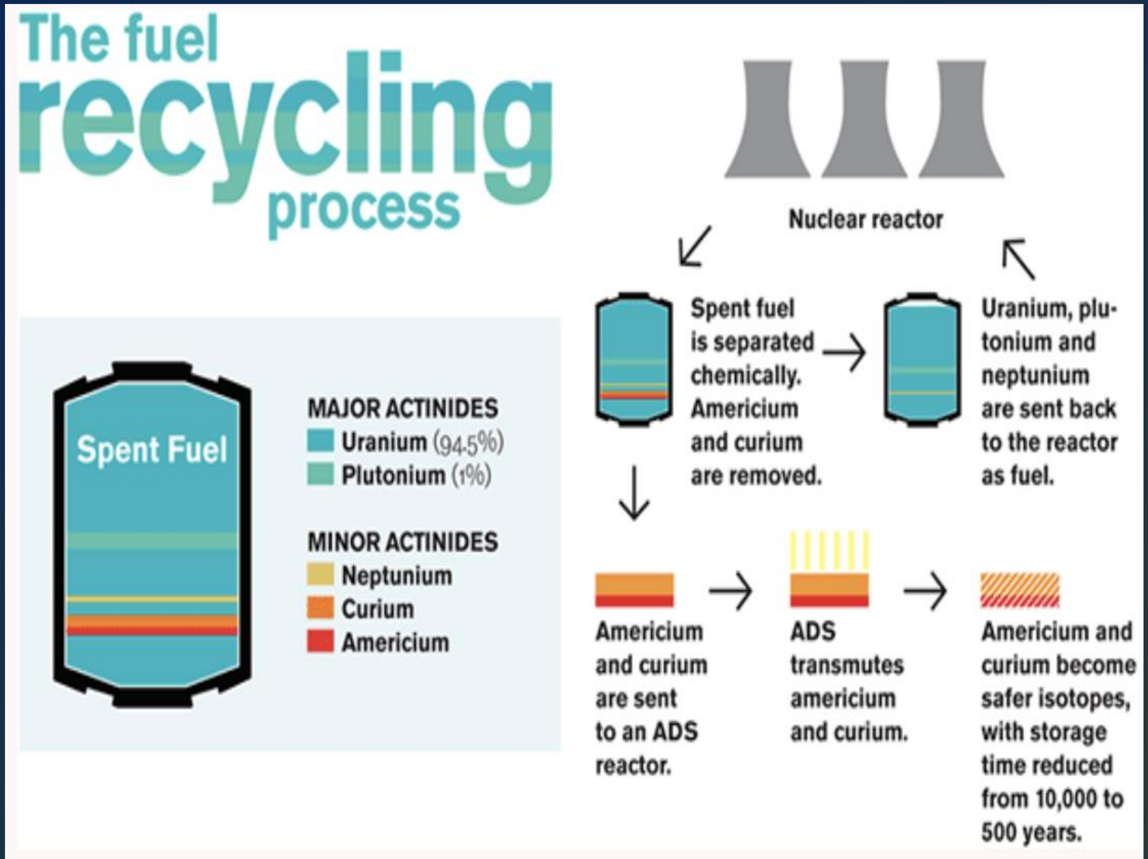
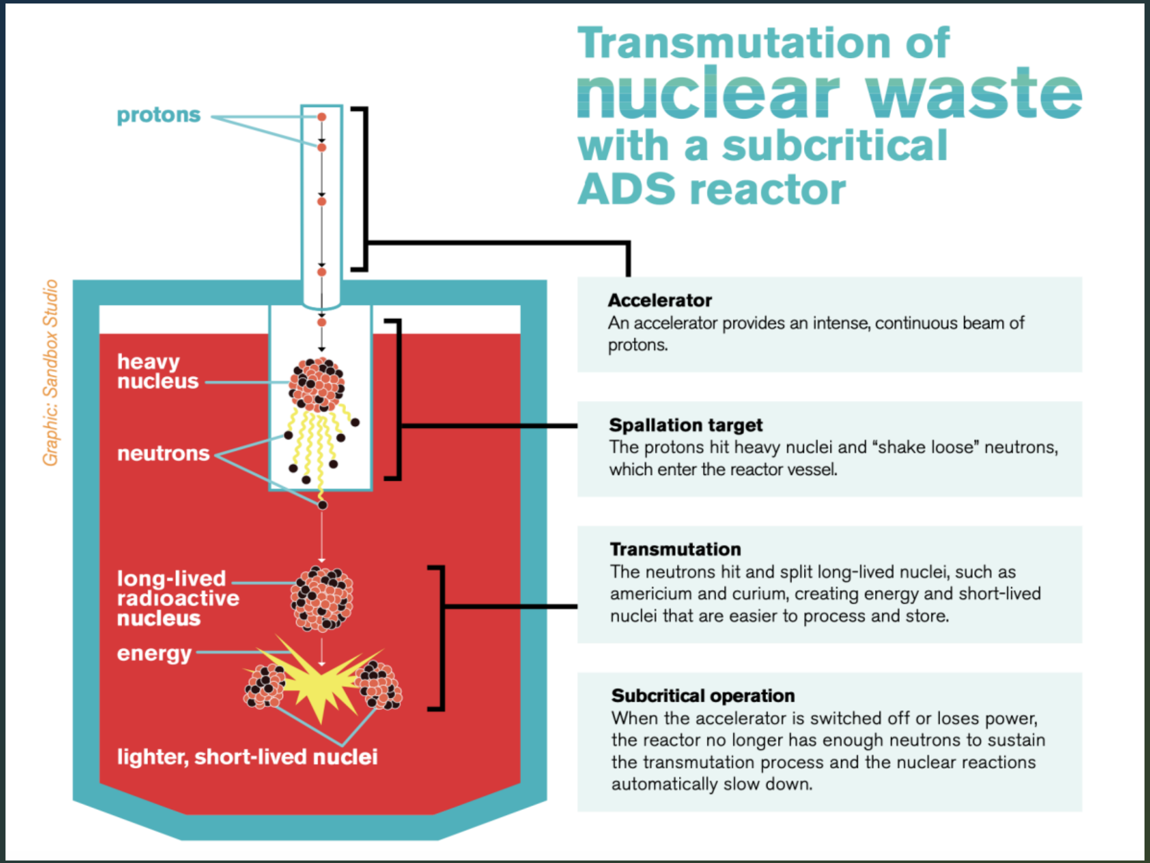
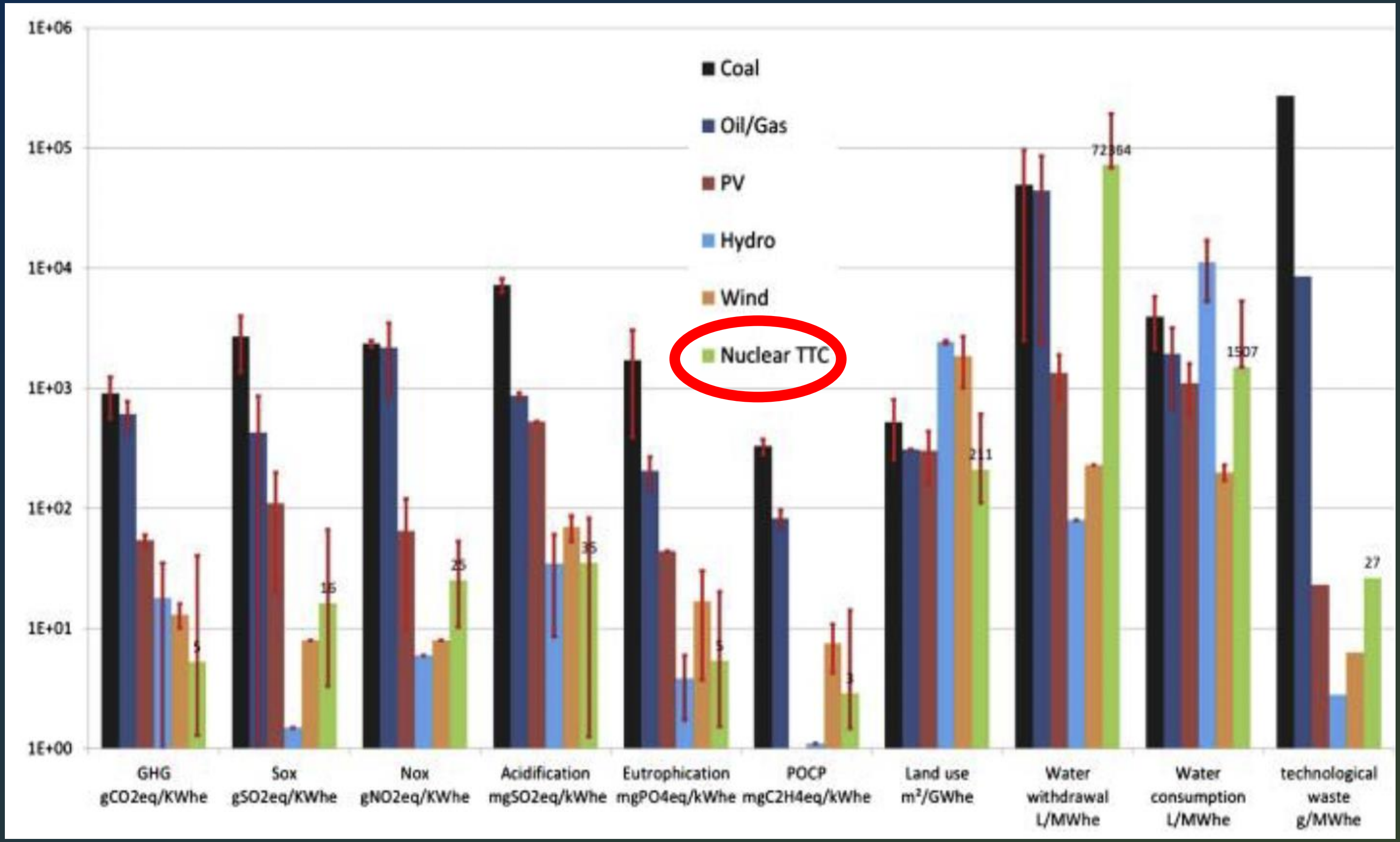




Nuclear Waste Disposal: Environmental Impact

Ch. Poinssotet al. / Energy 69 (2014)

- Green-House-Gases emissions (GHG, gCO2eq/kWhe)
- Atmospheric Pollution (mg/kWhe)
  - SOx
  - Nox
- Water Pollution (mg/kWhe),
  - Acidification
  - Eutrophisation
  - POCP (photochemical ozone creation potential)
- Land-Use (m2/GWhe)
- Water Consumption (l/MWhe)
- Water Withdrawal (l/MWhe)
- Production of Technological Waste (g/MWhe)



Public confidence and politics

Kuhika Gupta
Associate Director
Institute for Public Policy Research and Analysis
University of Oklahoma

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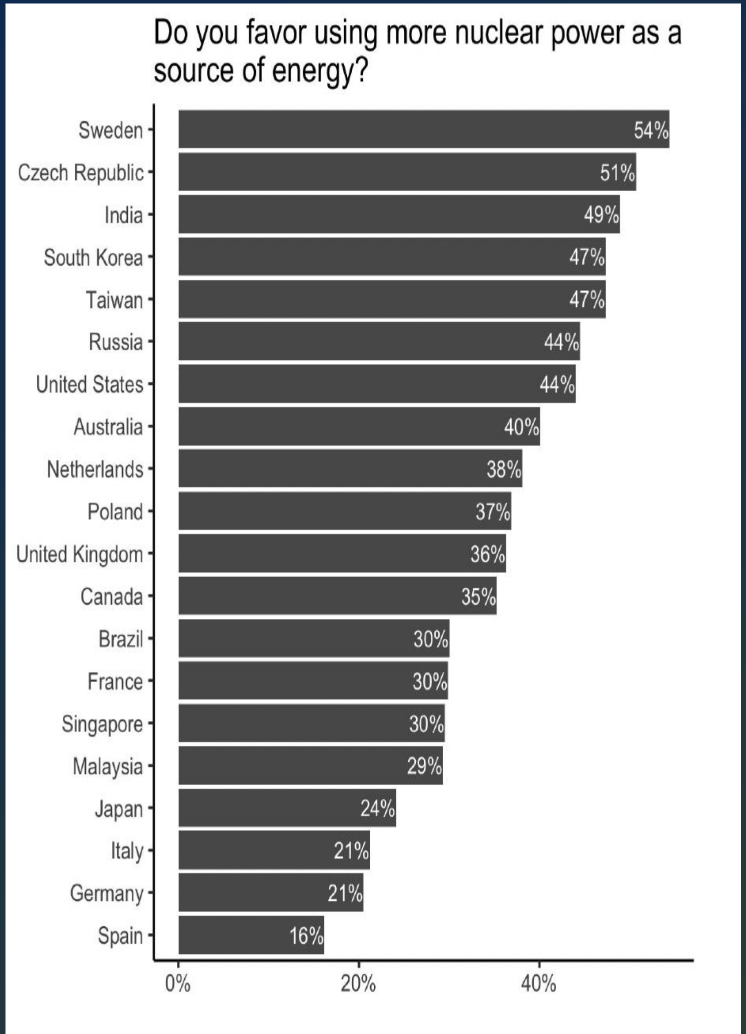
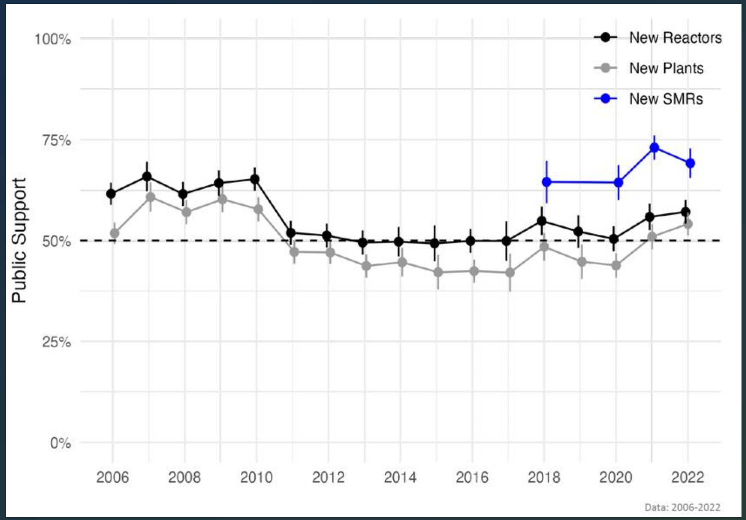
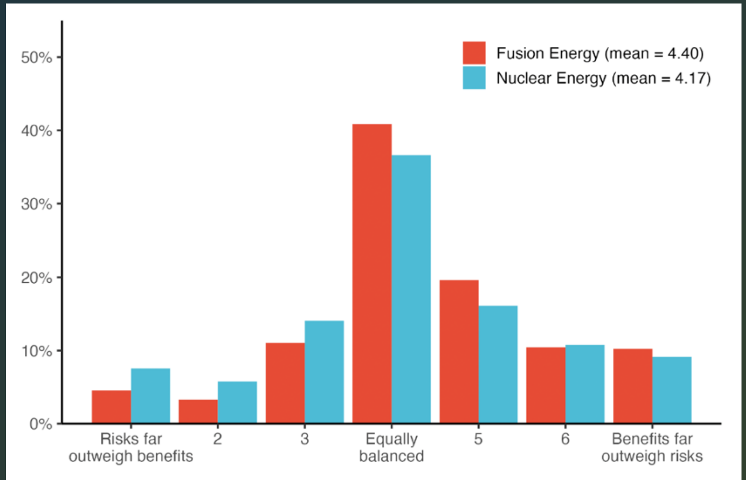
Trust, values and benefit-sharing, not just communication

- Support is mixed and varies sharply by country and demographic, shaped by Three Mile Island, Chernobyl and Fukushima.
- Phase-out decisions have closed reactors that were technically fit to continue. →Germany
- Policy can reverse between governments fatal for an asset with a 60-year horizon.



PEW Research Center, International Science Survey 2019-2020





The distribution of respondent perceptions about the risks and benefits of fusion energy and nuclear energy.

Proliferation and security

- Enrichment and reprocessing are inherently dual-use and require intrusive safeguards.
- Russia holds roughly 44% of world enrichment capacity and about 20% of conversion; HALEU (uranium enriched to between 5% and 20% U-235) for advanced reactors is commercially available only from Russia and China.
- War has put an operating plant at Zaporizhzhia in the middle of a front line.

SMRs Proliferation Risks and Challenges

- **High-Assay Low-Enriched Uranium (HALEU):** Many advanced SMR designs rely on HALEU, enriched between 5% and 20% uranium-235, which shortens the enrichment pathway toward weapons-grade material if diverted.
- **Transport and Factory Modules:** Transportable or factory-sealed modules make fuel and reactor components harder to track and protect during transit compared to fixed, centralized facilities. **Newcomer Countries:** Deploying SMRs to nations with limited regulatory capacity or weak governance structures increases the risk of undetected material diversion or insufficient physical protection.
- **Inspection Frequency:** Long refueling intervals (or lifetime cores) reduce the frequency of physical on-site inspections, forcing heavy reliance on remote monitoring systems that may struggle to detect undeclared activities.

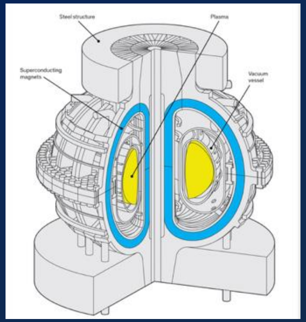
SMRs Security Advantages and Mitigations

- **Passive Safety:** Most SMR architectures utilize physics and gravity for cooling and shutdown, mitigating core damage risks during a terrorist takeover or loss-of-power scenario.
- **Reduced Footprint:** A smaller physical plant area and lower total inventory of fissile material per module simplify on-site physical protection and localized monitoring.
- **Sealed Cores:** Certain designs feature factory-sealed units that eliminate on-site refueling and restrict direct access to fresh or spent fuel throughout their operational lifespan.

https://vcdnp.org/smr-deployment/

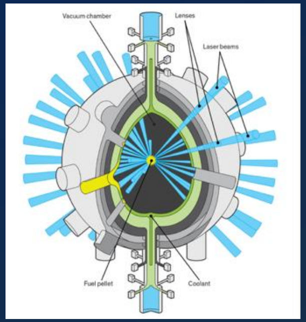
Nuclear Fusion?? Current Fusion Technologies

Magnetic Confinement Fusion



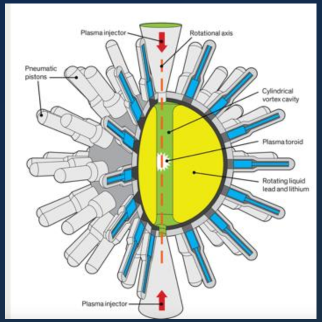
Tokamak JET, ITER
Powerful toroidal magnets and hot plasma

Inertial Confinement Fusion



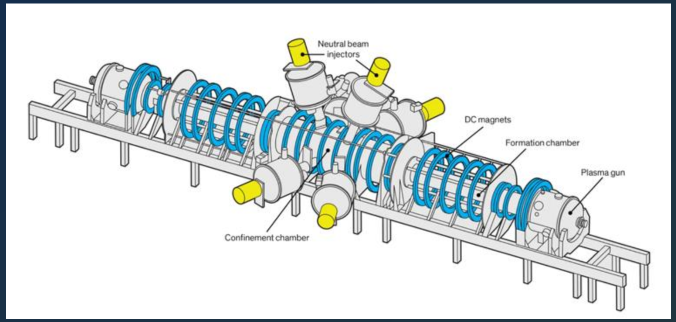
Powerful pulsed laser or ion beams on pellets

Magnetized Target Fusion



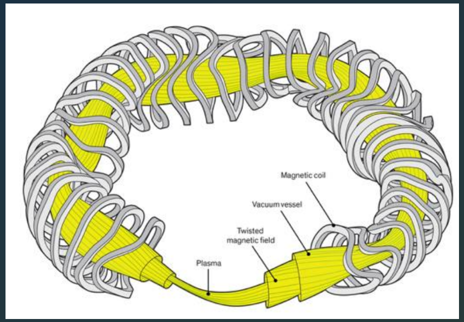
Hybrid approach
Combining magnetic and inertial confinement

Field Reversed Configuration



Uses plasma guns to accelerate two plasmas into each other and then heats them with particle beams.

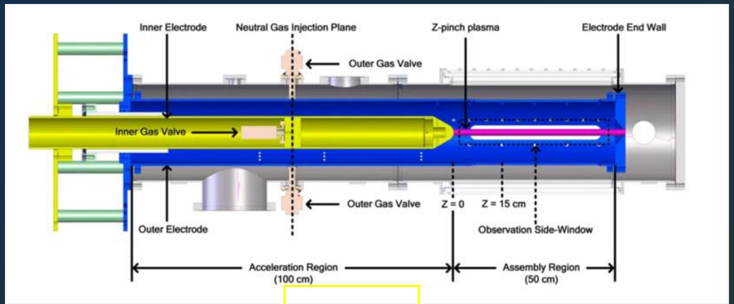
Stellarator



Spiralling ribbon shape produces high-density plasma that's symmetrical and more stable than a tokamak's, allowing the reactor to run for long periods of time.

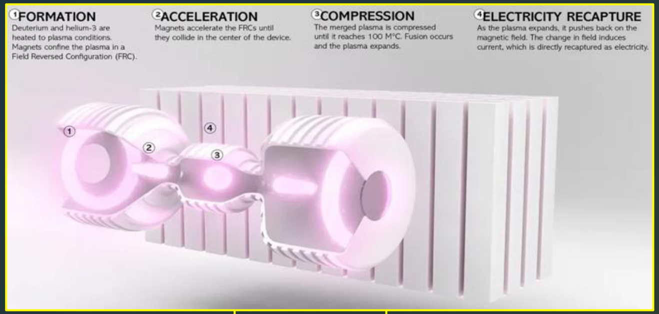
Novel "Compact" Ideas

ZAP FUzeQ Reactor = Z-pinched D plasma



~2m

Helion: D+He plasma collision



~12m

MIT SPARC-CFS Demonstrator =2-T coil

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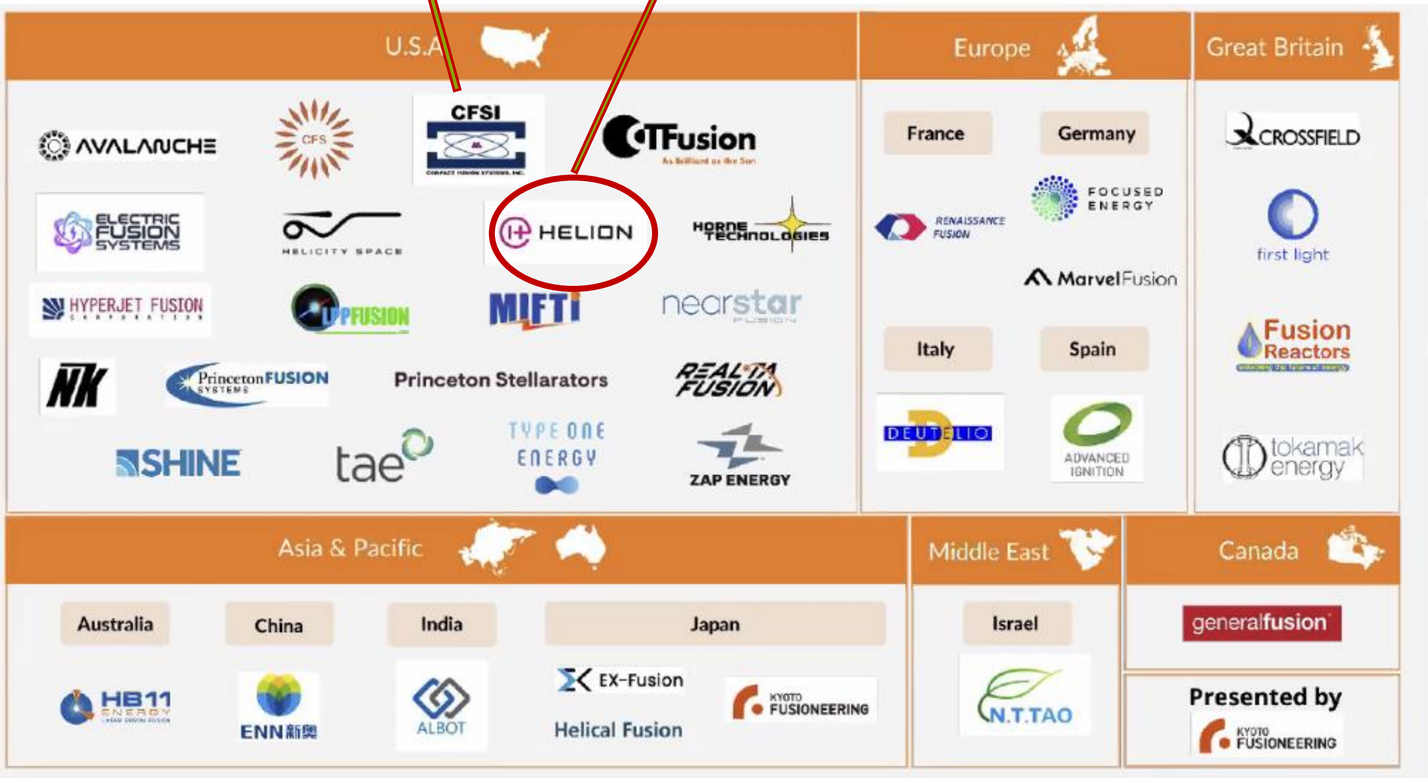
Nuclear Fusion and Private Industry

Private Fusion Industry has experience staggering growth

Commonwealth **Fusion** Systems
SPARC-MIT

Spinoff from Boeing



- 5.5 B$ raised
- Over 30 companies
- Industry association
- Wider geographic spread
- Wide array of technical approaches
- Is this competition for CFS..yes.
  Is that good. Yes!

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Conclusion. Future Energy Mix: Solar-Led, Wind-Supported, Storage-Enabled...

- Fossil Fuel Phase Out
- Solar becomes the backbone of global electricity
  - highest global potential, lowest cost, fastest growing, works in several environments

2024

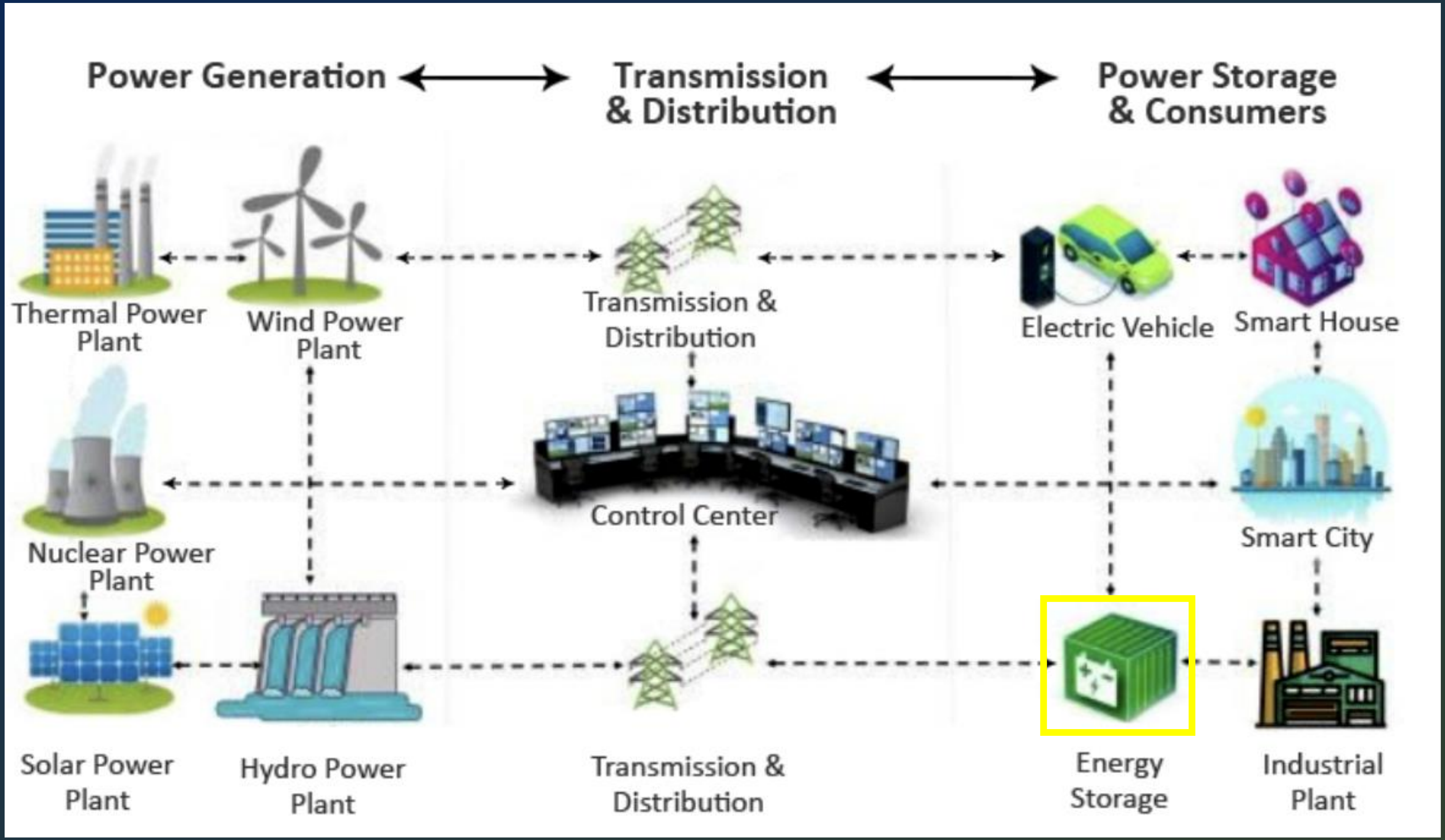
- Wind provides complementary power (night + winter)
  - Day/Night cycle split slide (Solar = day; Wind = night), offshore
- Storage unlocks >80–100% renewables penetration
  - Lithium batteries for short-duration, Flow batteries for 6–12 hours, Pumped hydro for long-duration, Hydrogen for seasonal and industrial energy
- Geothermal adds 24/7 stability
  - Works day and night, all year
- Nuclear Comes Back with 24/7 cheaper and safer technologies
- Hydrogen decarbonizes heavy industry
  - Powers shipping and aviation, Provides seasonal energy storage
- Fusion emerges post-2040 as ultra-dense clean power
  - Huge power from tiny land areas, Many private companies now hitting record breakthrough, Still experimental

....Local "Smart" Grids"..

Advanced Materials
Infrastructure

DIGITAL

SWITCHES



STORAGE

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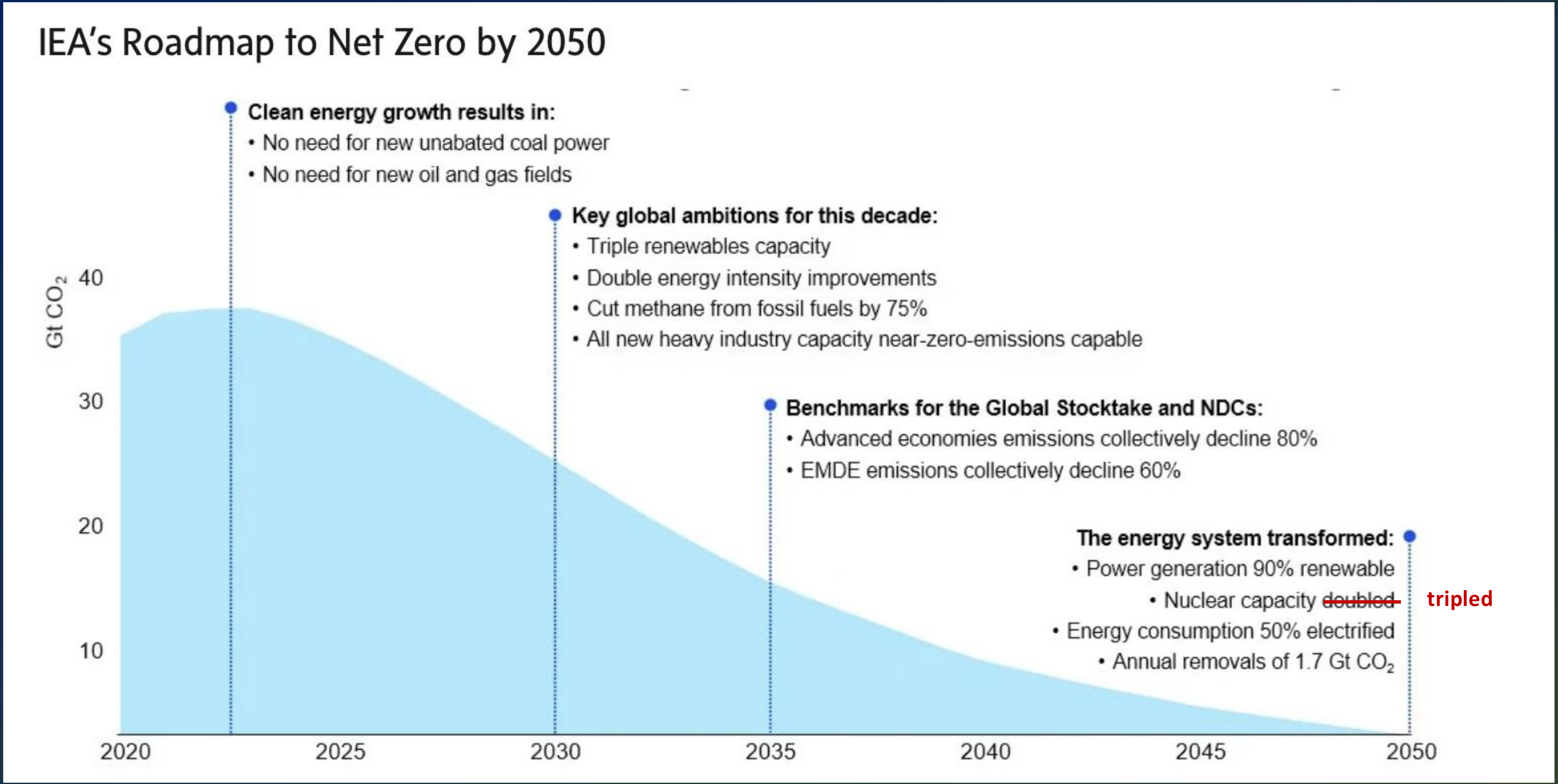
.... To Meet the SDG Targets

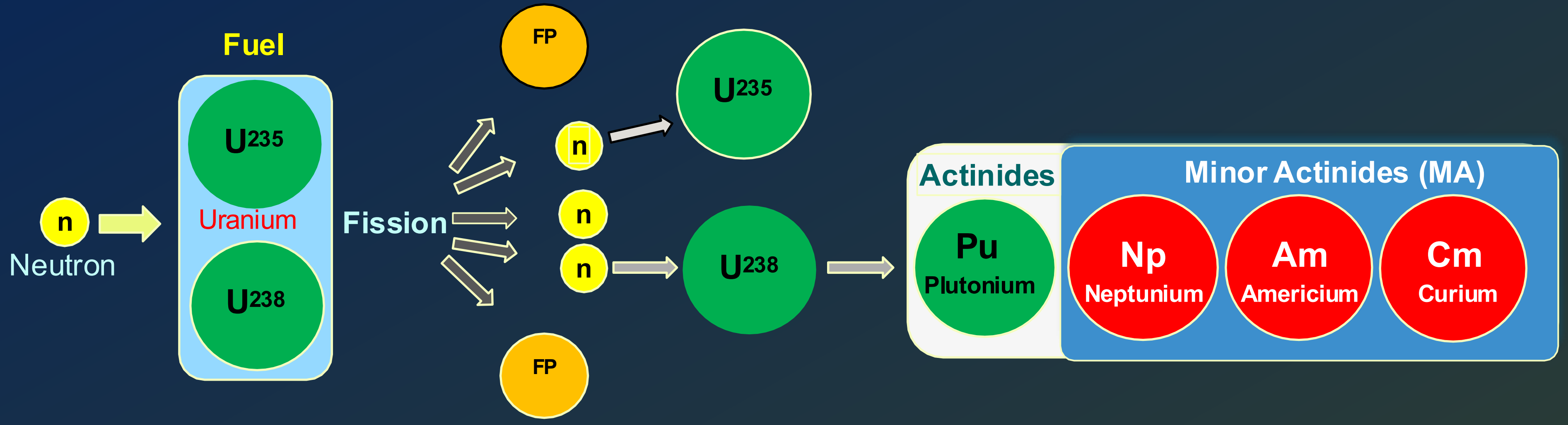



SPRINGFIELD
NUCLEAR
SAFEST PLANT
IN AMERICA

High-Level Waste (HLW)

- HLW concern is not only radioactivity but also radiotoxicity management
- Each fission reaction delivers 200 MeV of energy

FP= Fission Product



1 ton of nuclear fuel used 4,5 year in commercial PWR reactor **produces electricity for 100,000 Belgian families per year** (3500 kWh/y per family)

After 4,5 years the spent nuclear fuel contains:

- **94,7% of resources we can recycle (U+Pu)**
- **5,1% of nuclear waste with low radiotoxicity (FP's)**
- **0,2% of high radiotoxicity nuclear waste**

Source: SCK•CEN MYRRHA Project Team