A JOURNEY THROUGH THE FUTURE OF ENERGY

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University of Bern & The University of Chicago

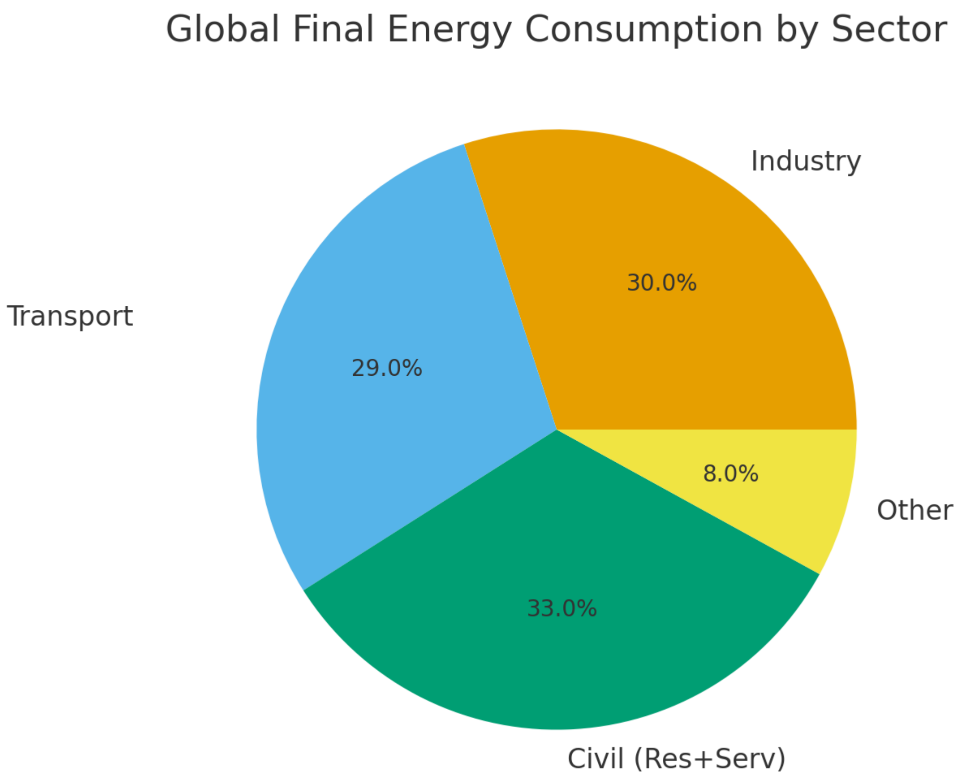
ACADEMIA SINICA – DECEMBER 15TH, 2025

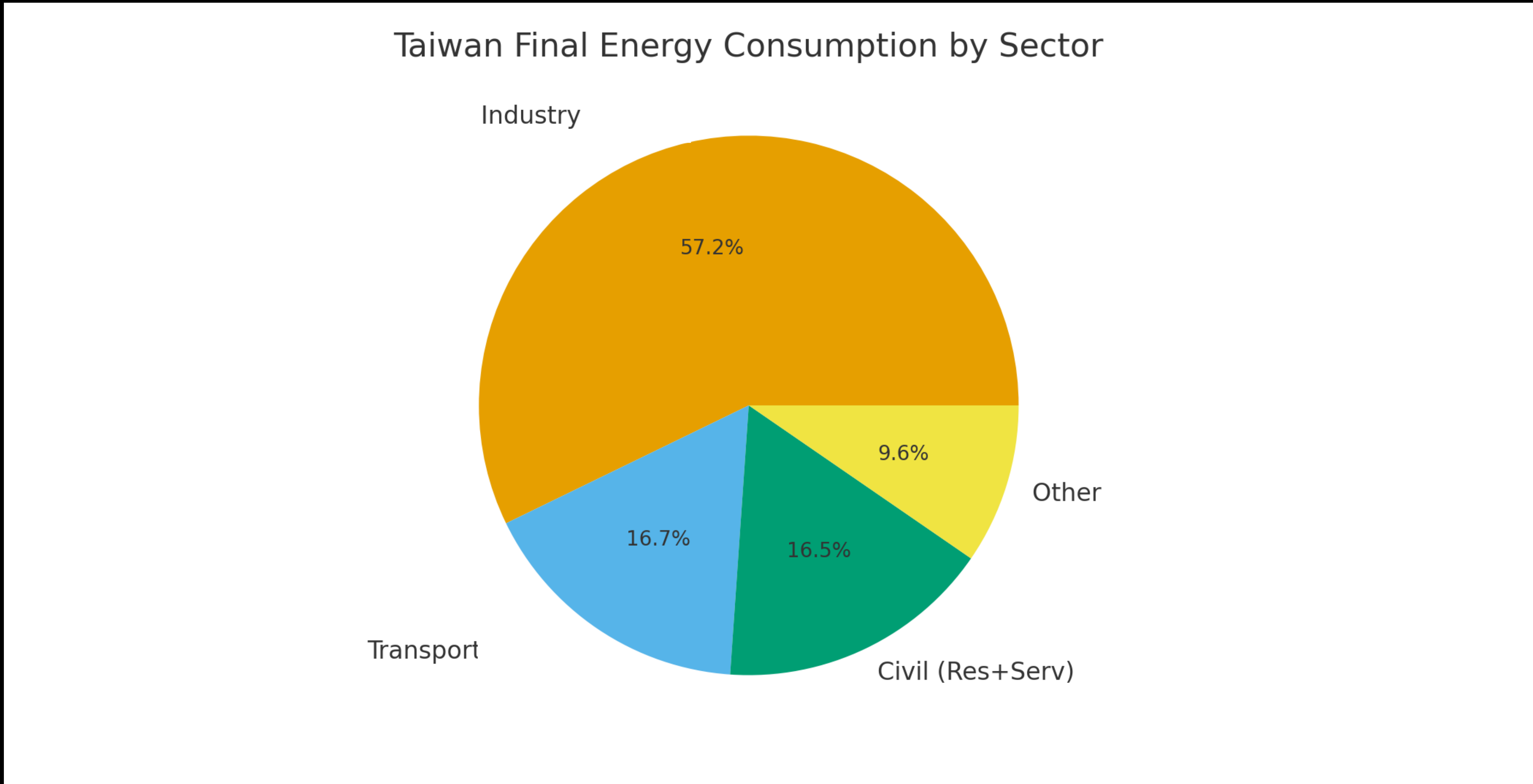
THE WORLD IS ENERGY HUNGRY

Energy consumption in one year:

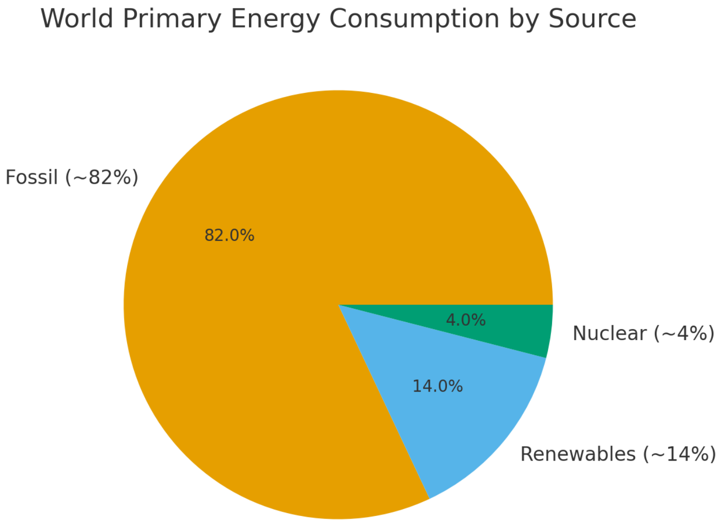
6×10^{20} joule

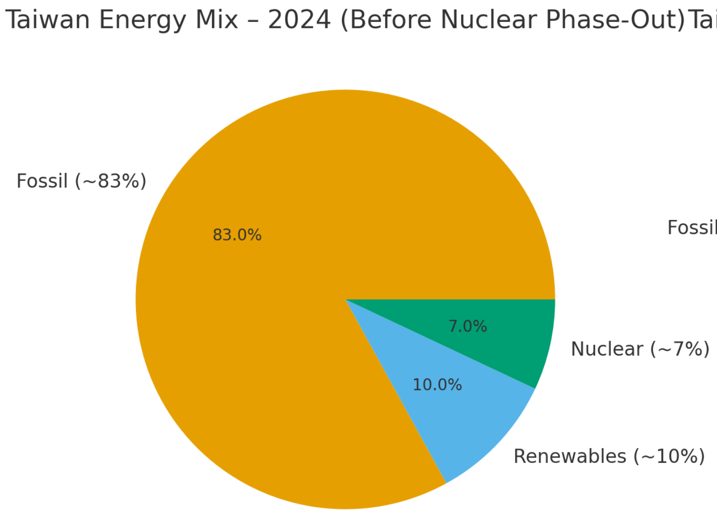
(170 million GWh)

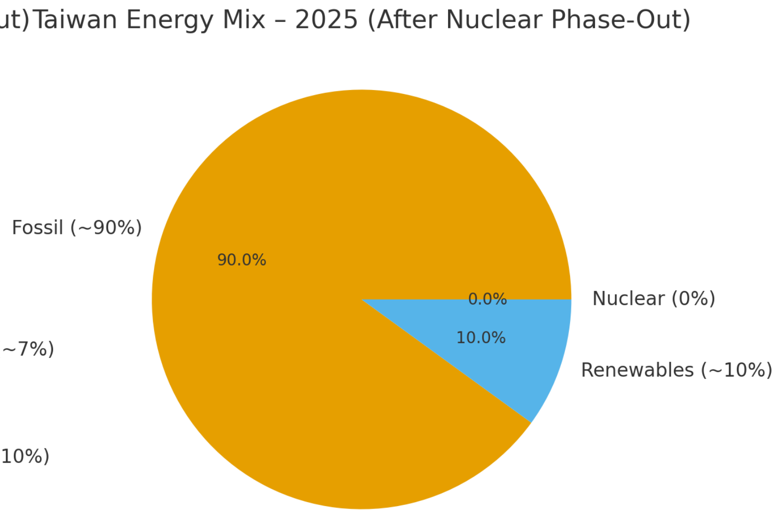


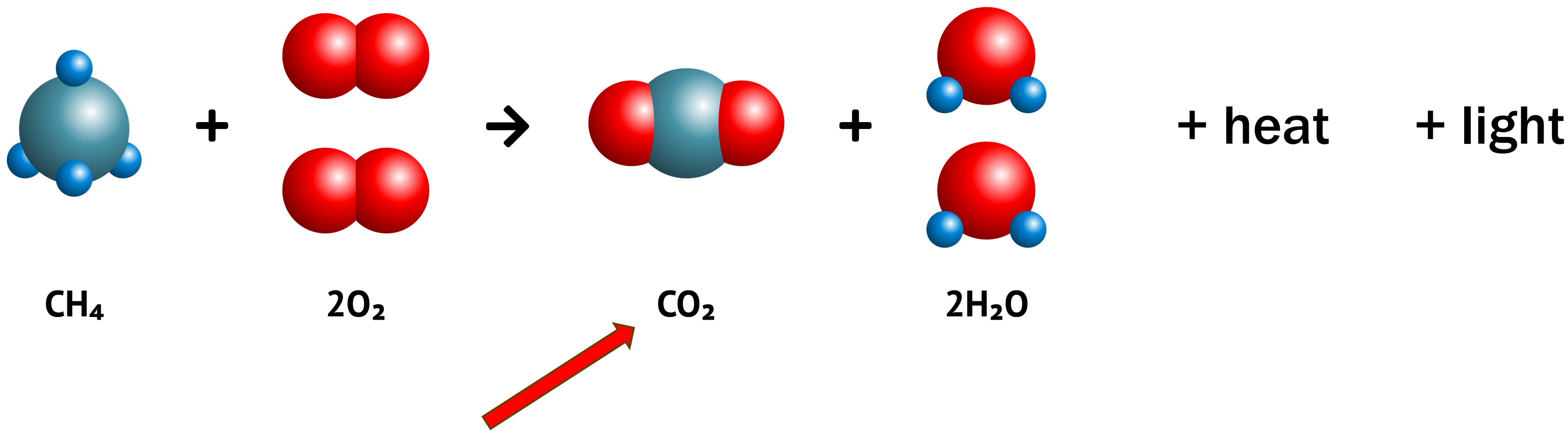

Taiwan Final Energy Consumption by Sector
Industry
57.2%
Transport
16.7%
Civil (Res+Serv)
16.5%
Other
9.6%

ENERGY SOURCES

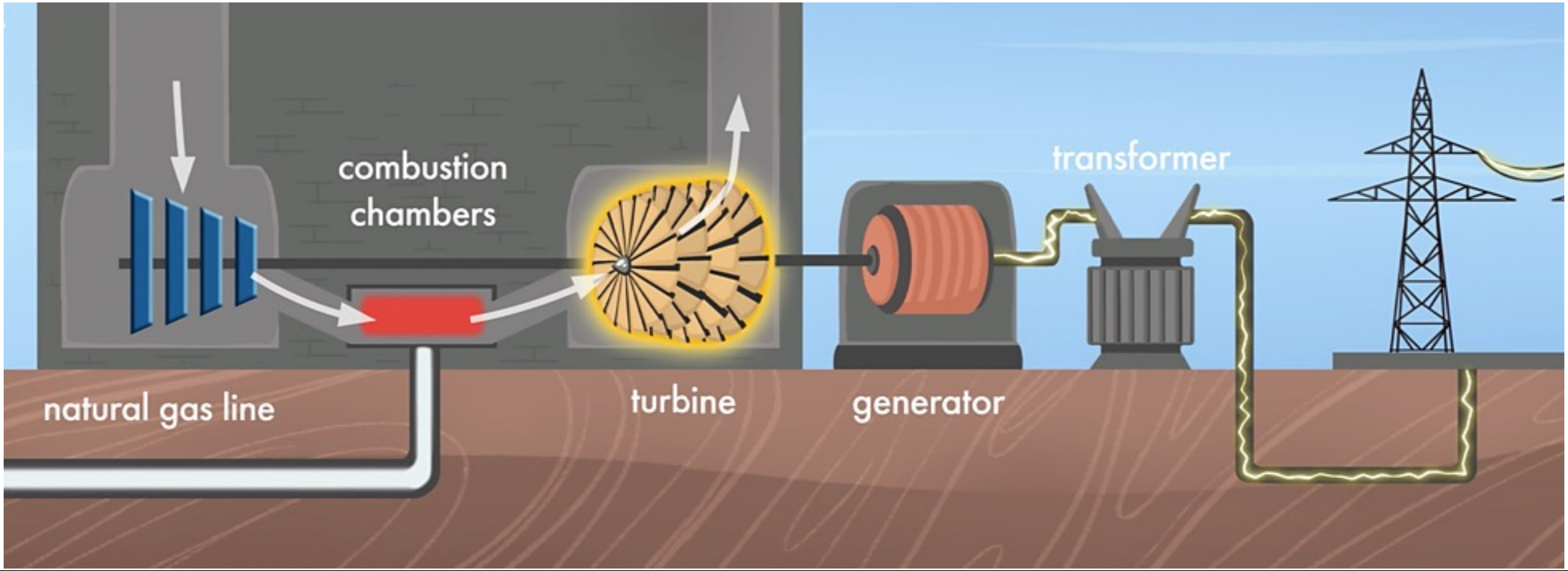








BURNING FOSSILS: CO_2 PRODUCTION



SOURCE → USABLE ENERGY

SHALL WE KEEP GOING «BUSINESS AS USUAL»?

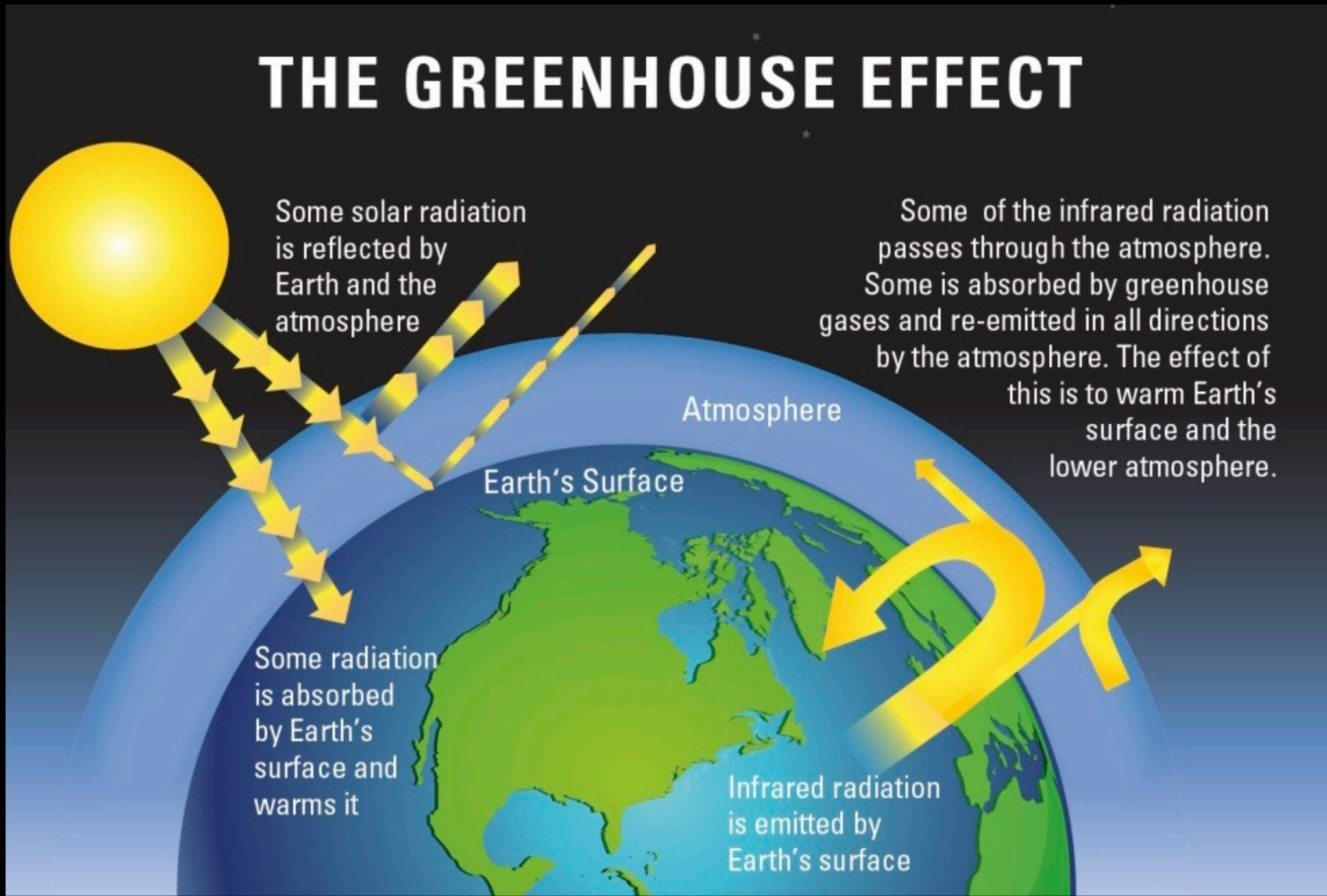
The answer is NO

- Prizes change
- International scenario
- National independence
- Progress of technology

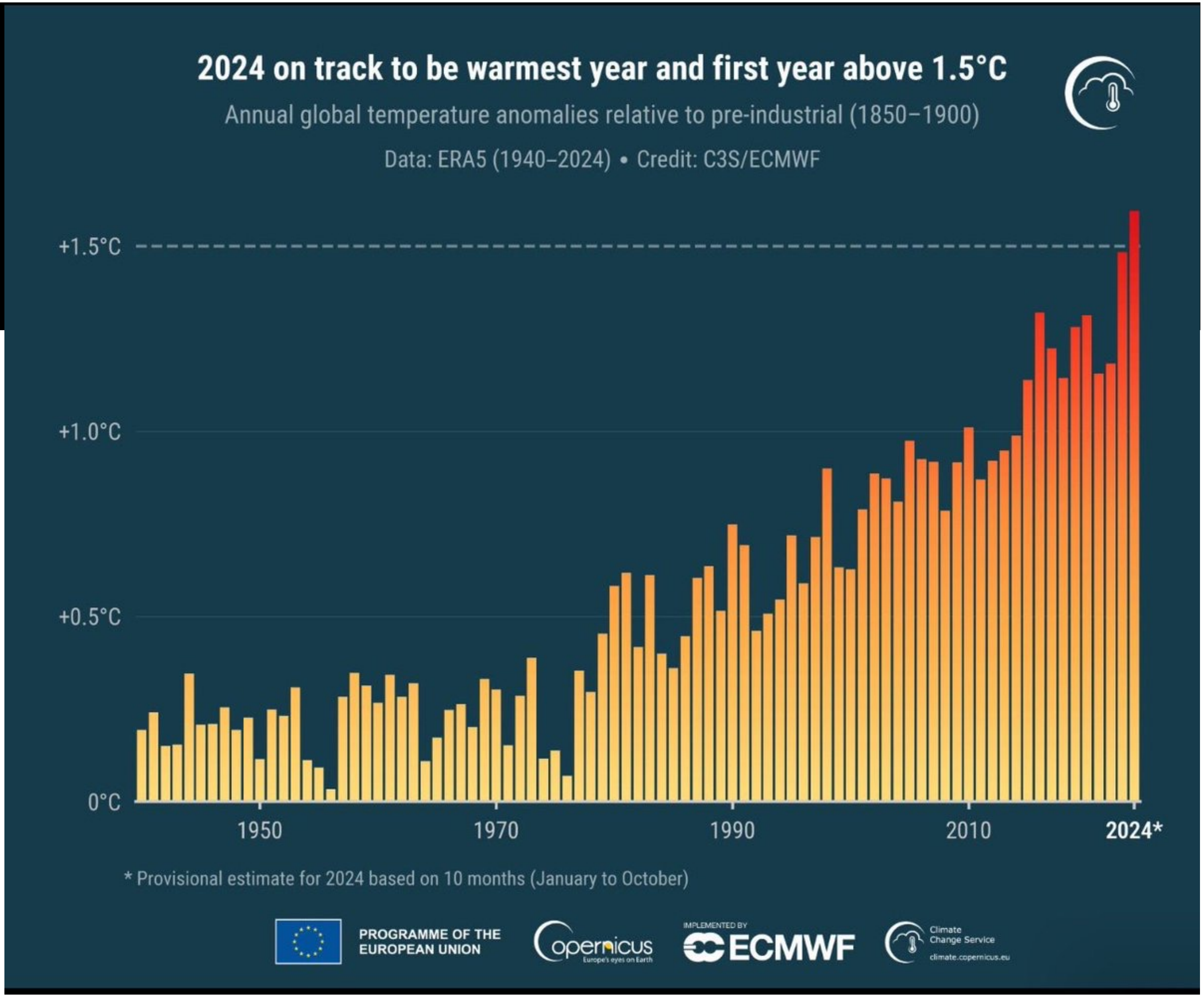
and, more important:

THE CLIMATE CRYSIS!

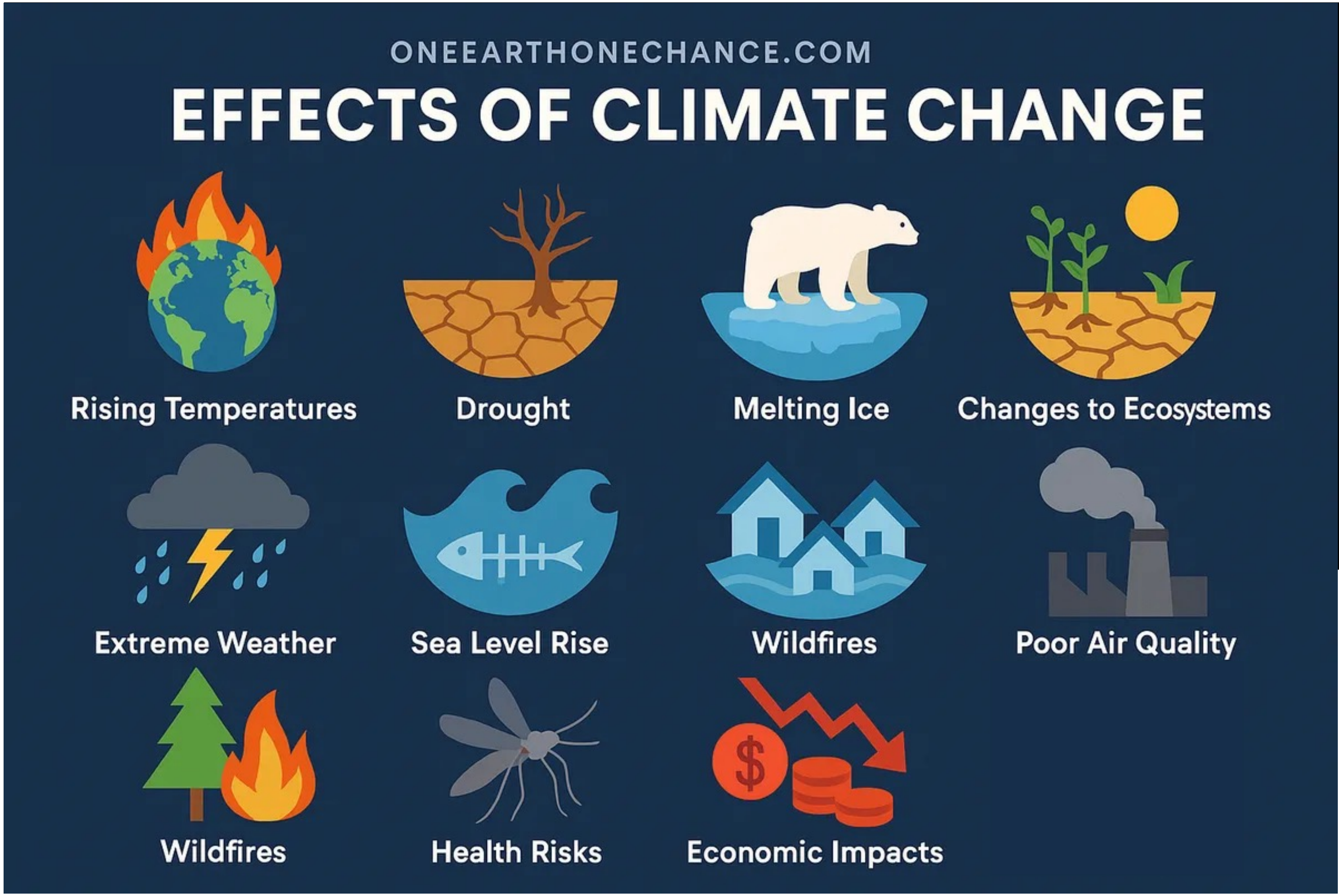
WHAT IS WRONG WITH CO_2?



HEATING UP!



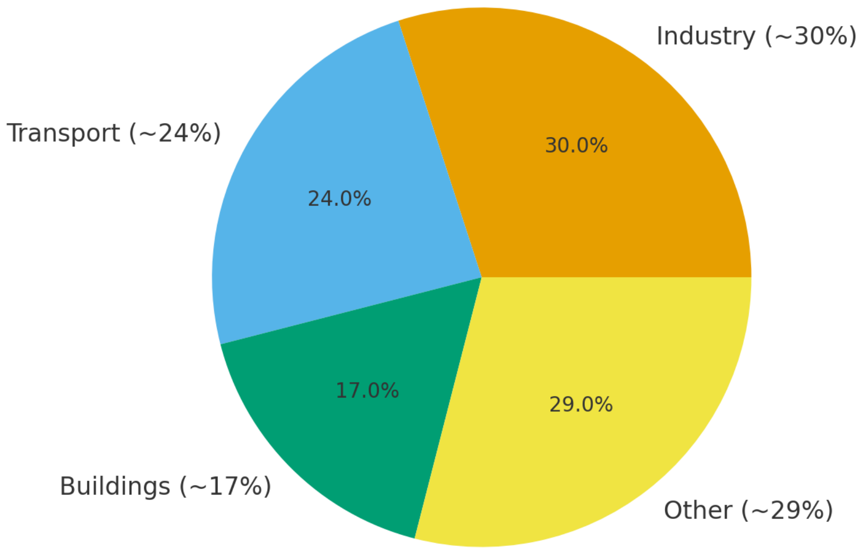
2024 on track to be warmest year and first year above 1.5°C
Annual global temperature anomalies relative to pre-industrial (1850–1900)
Data: ERA5 (1940–2024) • Credit: C3S/ECMWF
+1.5°C
+1.0°C
+0.5°C
0°C
1950
1970
1990
2010
2024*
* Provisional estimate for 2024 based on 10 months (January to October)
PROGRAMME OF THE EUROPEAN UNION
Copernicus
IMPLEMENTED BY
ECMWF
Climate Change Service
climate.copernicus.eu



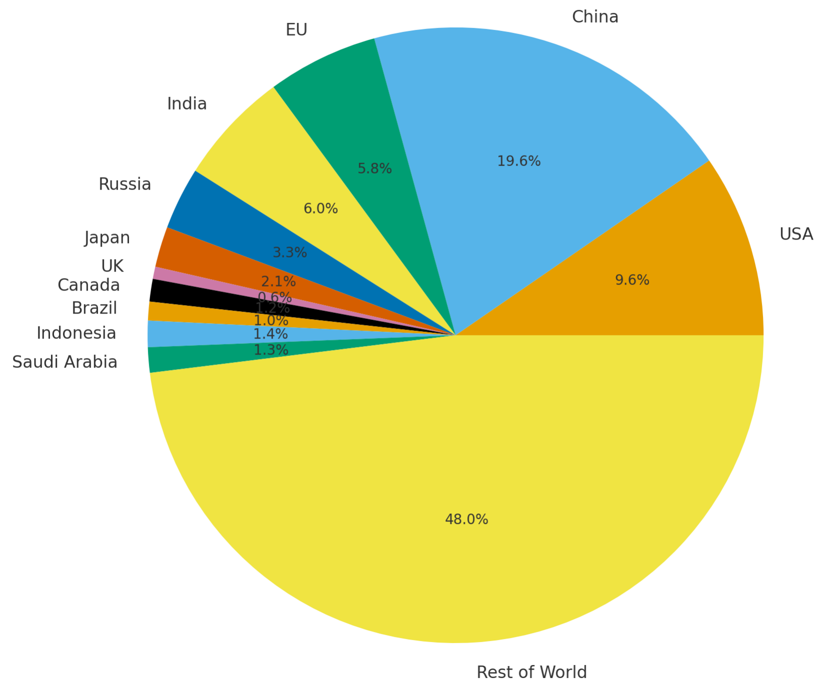
DRAMATIC CONDITIONS

WHO IS CONTRIBUTING?

Global CO_2 Emissions by Sector



Global CO_2 Emissions Share (Population-Weighted)



WE NEED TO DE-CARBONIZE!

- Get rid of energy sources producing CO_2 and other green house gases
- Renewable sources: wind, solar, geothermal, hydroelectric,…
- Develop green or quasi-green hydrogen (not an energy source, but a carrier)
- Exploit green nuclear power (III and IV generation fission, and, eventually, fusion)
- Most important: tailored energy portfolios!

COMPARISON OF DIFFERENT GREEN ENERGY SOURCES

Comparative Table of Green and Low-Carbon Energy Sources

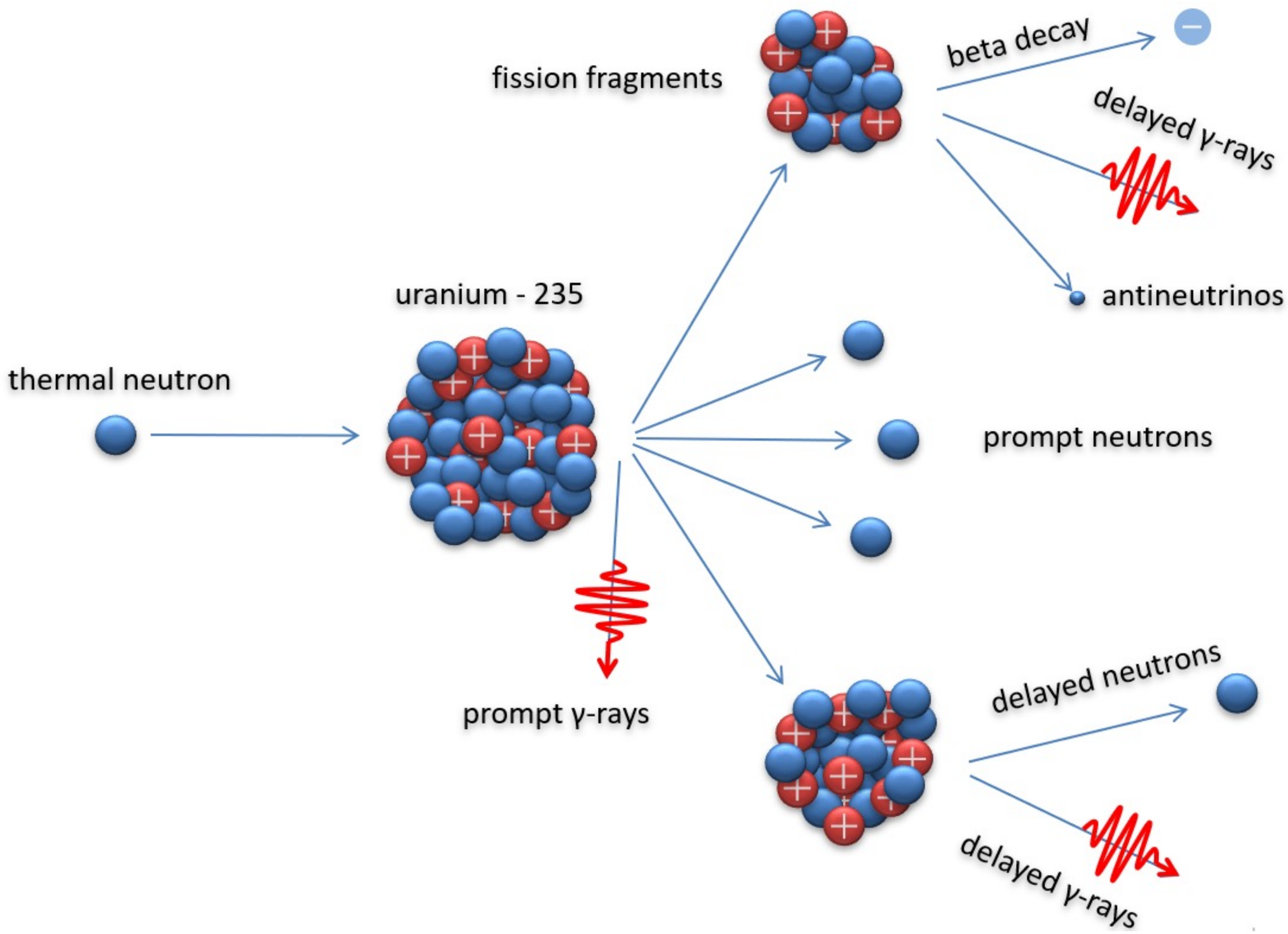
Energy Source	Capacity Factor	Cost per kWh (typical)	Infrastructure Cost	Pros	Cons
Wind	~30–40%	Low (very competitive)	Medium	Cheap electricity, scalable, fast deployment	Intermittent, visual/land impact, grid integration
Solar PV	~15–25%	Very low	Low	Fastest cost decline, modular, scalable	Low CF, depends on sunlight, large land use
Solar Thermal (CSP)	~35–45%	Medium–High	High	Dispatchable with thermal storage, high-temp heat	Expensive, limited to high-insolation regions
Geothermal	~70–90%	Low–Medium	High (drilling)	Baseload renewable, very stable output	Geographically limited, exploration risk
Hydro	~40–60%	Low	Very High	Dispatchable, long lifetime, mature tech	Ecological impact, requires suitable geography, drought-sensitive
Gen III Nuclear	~85–92%	Low–Medium	Very High	Highest reliability, baseload, low CO_2	Long build times, regulatory burden, waste management
SMR (Small Modular Reactors)	~90–95%	Medium (uncertain)	High (but lower than Gen III)	Modular, scalable, enhanced safety	Not yet widely deployed, cost still uncertain

COST ESTIMATE

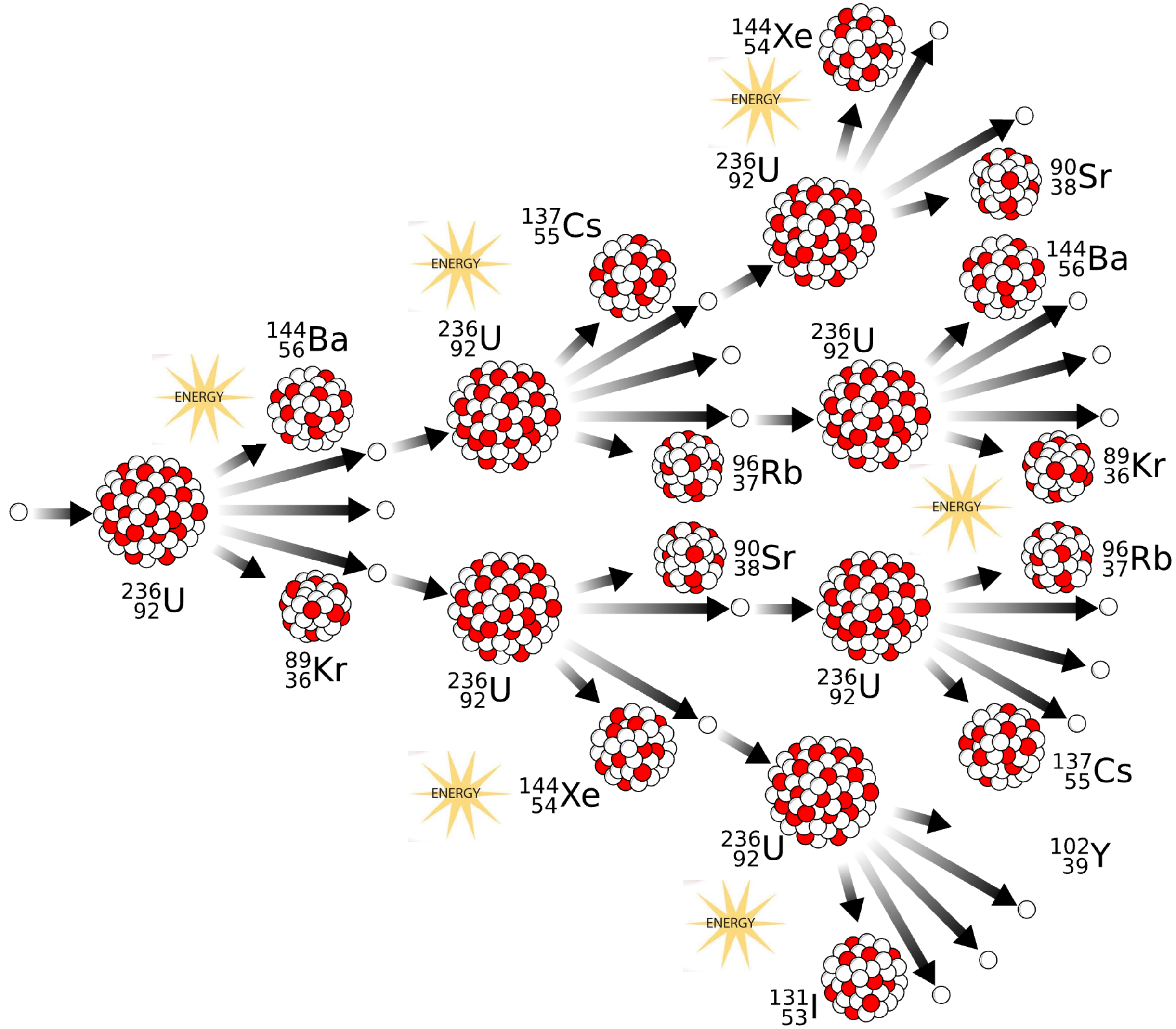
Technology	LCOE (USD/kWh)	Notes
Solar PV (utility-scale)	0.02 – 0.06	One of the lowest; depends on sun resource & financing
Onshore Wind	0.03 – 0.07	Very cost-effective in windy regions
Offshore Wind	0.08 – 0.15	Higher than onshore; installation/maintenance
Hydropower	0.03 – 0.08	Low operating cost; depends on dam/site
Geothermal	0.04 – 0.10	Highly location-dependent (resource quality)
Solar CSP (with storage)	0.08 – 0.18	Thermal storage adds value & cost
Natural Gas (CCGT)	0.05 – 0.10	Fuel cost sensitive; low capital cost
Gen III Nuclear	0.10 – 0.18+	Higher capital cost; stable output
SMRs (projected)	0.08 – 0.15+	Early projects; cost uncertain & financing important

FOCUS ON NUCLEAR ENERGY

NUCLEAR FISSION



NUCLEAR REACTION CHAIN



FROM FISSION CHAIN TO NUCLEAR REACTORS (1)

A machine that keeps a controlled nuclear chain reaction and converts the released energy into heat.

Fuel rods of enriched U-235 uranium undergo fission.

As neutrons are normally too fast to sustain an efficient reaction, the reactor includes a moderator (water, heavy water or graphite) to slow neutrons and keep the chain reaction self-sustaining.

→

The reaction rate is regulated by **control rods** made of neutron-absorbing materials.

By inserting or withdrawing these rods, operators can slow or accelerate the reactor's power.

In an emergency, they can be fully inserted to stop the reaction instantaneously.

→

The heat produced in the core is removed by a **coolant**, typically high-pressure water, which carries thermal energy to a steam generator.

The resulting steam drives a turbine connected to an electrical generator.

After turning the turbine, the steam is cooled, condensed, and recirculated, closing the cycle.

→

All this his takes place inside multiple layers of engineered protection:

fuel pellets and their metal cladding, steel reactor vessel, primary coolant circuit, and thick reinforced concrete containment structure.

Modern reactors add passive safety features that allow the system to remain stable or shut down even without external power or operator action.

→

Reactor operation can last several decades with just a few technical stops for replacing the exhausted fuel. This makes the «capacity factor» of this form of energy the highest

FROM FISSION CHAIN TO NUCLEAR REACTORS (2)

A nuclear reactor is all about controlling how many neutrons from one fission event go on to cause the next one.

Everything depends on a single idea: the multiplication of neutrons inside the core.

We describe this using a number called *k*, the «multiplication factor».

Subcritical (k< 1): the chain reaction dies out.

When the reactor is subcritical, each generation of neutrons produces less neutrons than the one before.

Fission can still happen, but the reaction fades away.

No power is produced in a sustained way. This is the natural state of the reactor when it is shut down.

Critical (k=1): the chain reaction is steady. Each generation of neutrons produces **exactly one new generation.**

The reaction is **self-sustaining**, the power level stays **stable**, and this is the condition in which the reactor operates.

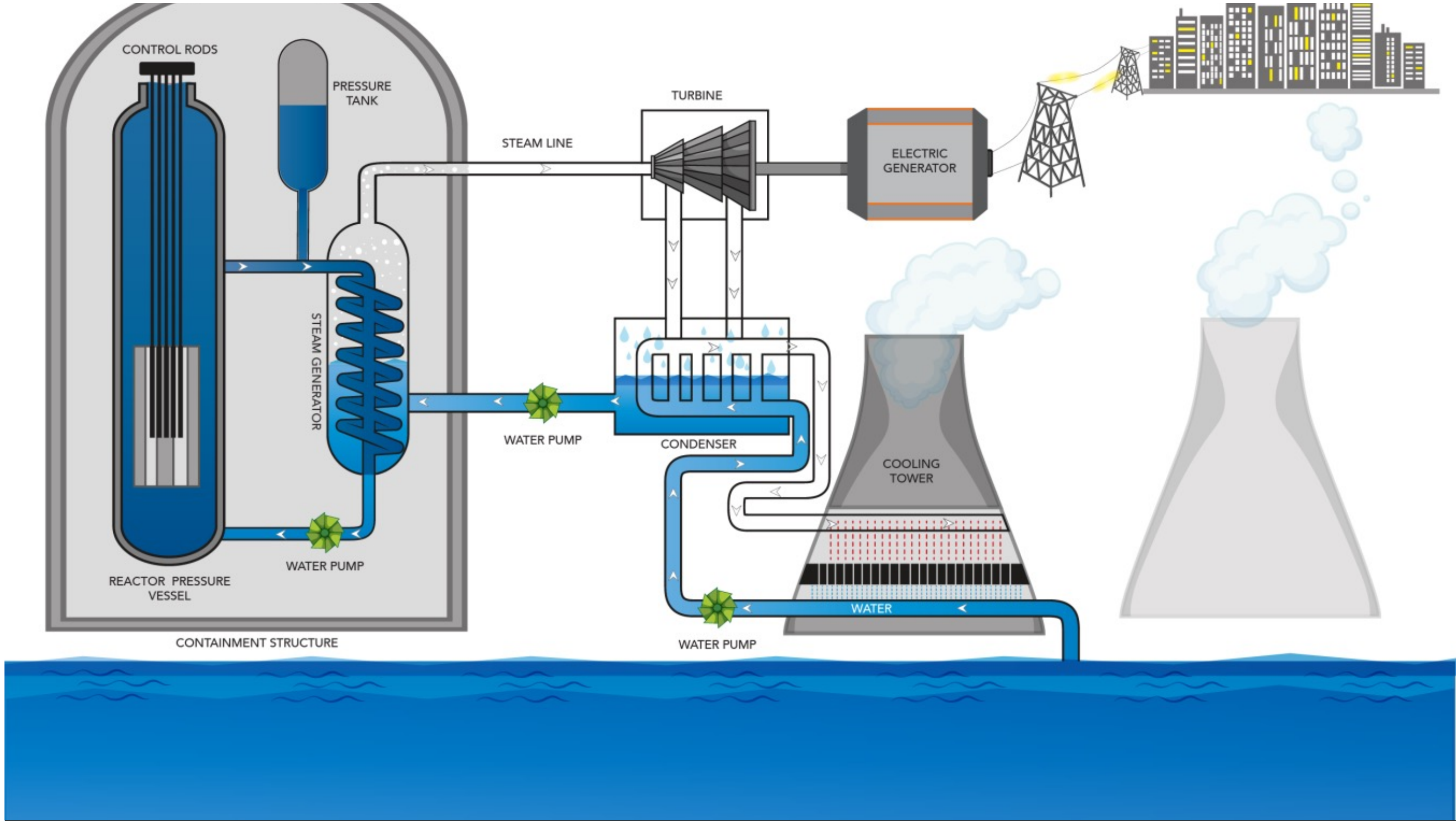
Control rods and other systems adjust the neutron balance to **keep k=1** safely and precisely.

Supercritical (k>1): the chain reaction grows. Each generation of neutrons produces **more** neutrons than the one before.

The operation is called delayed supercritical: power increases slowly by k slightly above 1, relying on delayed neutrons to keep the growth slow, safe and controllable.

In essence, subcritical means the reaction dies out, critical means it is steady, and supercritical means it grows, to produce the design energy.

Power reactors are engineered so that any growth is slow, gentle, safe and controlled by design.



Heat from fission reactions → electricity

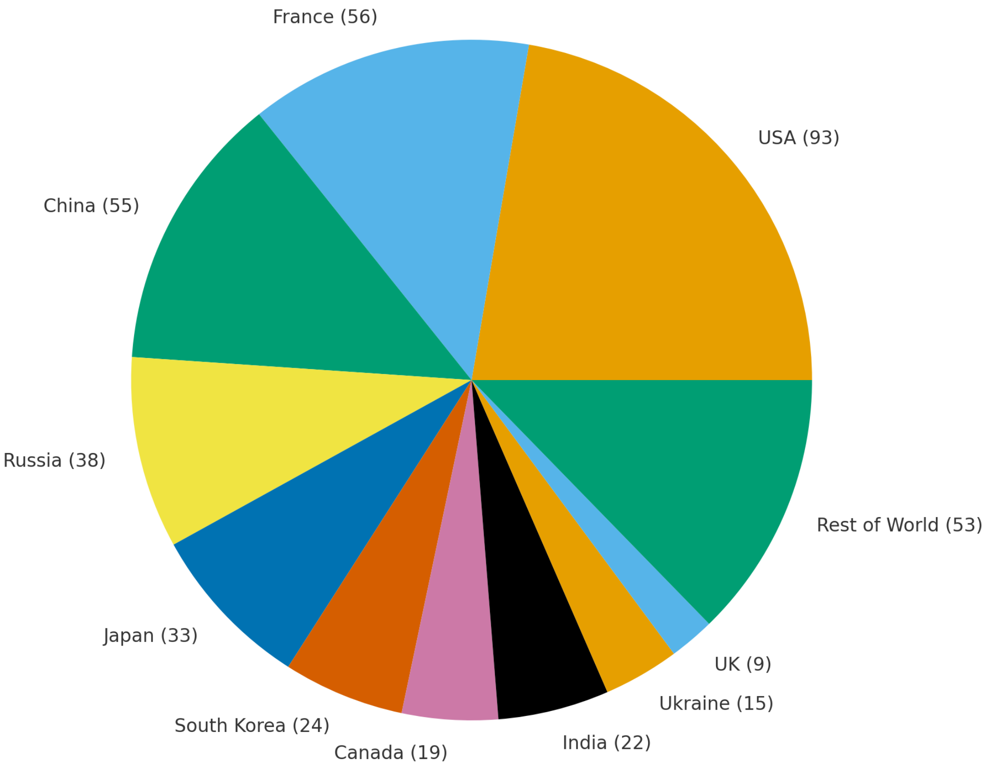
HOW DOES A NUCLEAR POWER LOOK LIKE

FUEL

- U-238 (~99% of total, not subject to chain fission but fissionable)
- U-235 (ok for fission, but less than 1% in nature): need enrichment
- Uranium purity: 3-5%. HALEU (High Assay Low Enriched Uranium): 5-20%
- Pu-239 used as well
- MOX (Mixed Oxide Fuel): ~ 20% Pu, 80% depleted U (see later)

NUCLEAR REACTORS IN THE WORLD

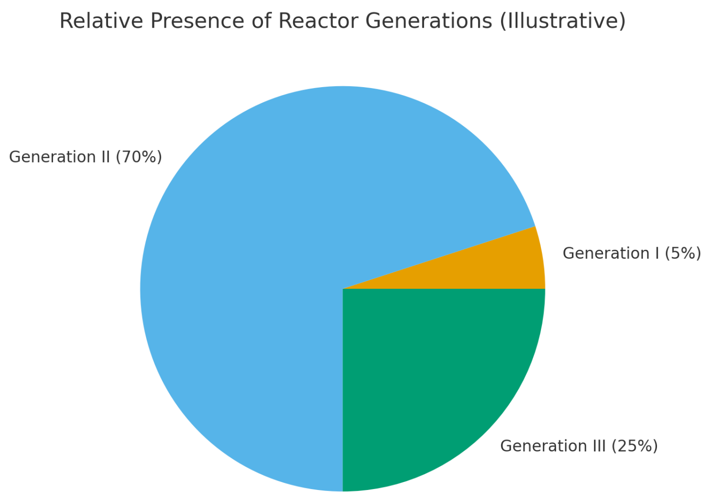
Operating Nuclear Reactors Worldwide by Country (≈417 Total)



Country / Region	Operating Reactors	Capacity (GW_e)
USA	93	96 GW_e
France	56	63 GW_e
China	55	53 GW_e
Russia	38	30 GW_e
Japan	33	32 GW_e
South Korea	24	23 GW_e
Canada	19	14 GW_e
Ukraine	15	13 GW_e
UK	9	6 GW_e
India	22	7 GW_e
Rest of World	53	40–45 GW_e
World Total	417	377-382 GW_e

>400 reactors worldwide (more to come)

GENERATIONS



Reactor Generation	Period / Deployment	Key Features	Power Output	Lifetime / Safety
Generation I	Late 1940s–1960s (post–WWII prototypes)	Prototype and demonstration reactors; used mainly for research; low automation	Very low output (kWe–tens of MWe)	Short lifetime; primitive safety concepts
Generation II	Commercial deployment from 1960s onward	Large commercial reactors; various coolants (PWR, BWR, gas, sodium); more reliable and cheaper than Gen I	Up to and exceeding **1000 MWe**	Designed for 40+ years; produces spent fuel; safety systems partially automated
Generation III / III+	Built today (1990s–present)	Major improvements: higher efficiency, advanced fuels, passive safety, digital controls	Typically **1000–1700 MWe**	Designed for 60–80 years; IAEA projects up to **100 years**; resilient to human error and extreme events (post-Chernobyl & Fukushima features)

Zhangzhou III generation power plant: $15 billion, 10 years, 1 GW$_e$ x 6 units

BREAKTHROUGH:
THE IV GENERATION

IV GENERATION NUCLEAR REACTORS

- Circa 2000: international commission to propose the development of a new generation of facilities
- Four technologies were retained: molten-salt cooled reactors, liquid-sodium-cooled fast reactors, supercritical water-cooled reactors, liquid-lead cooled fast reactors
- Today: nearly 80 private and public companies are developing IV generation reactors

Some keywords need to be better understood:

COOLING WITHOUT WATER? FAST REACTORS?

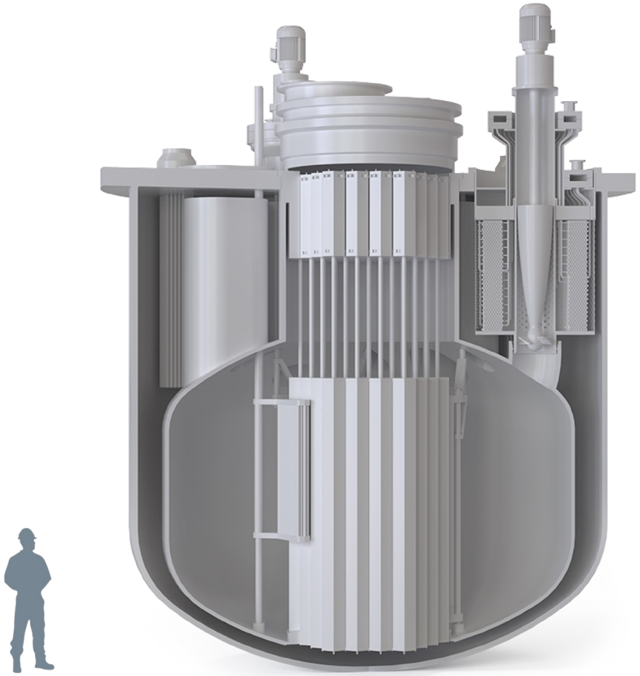
FAST NUCLEAR REACTORS

- 1-2 MeV, up to 20’000 km/s, no moderation
- Induce fissions not only in U-235 or Pu-239 but also U-238, Pu-238, Pu-240 and some heavy actinides
- Produce by «breeding» more fissile material than the reactor consumes: U-238 captures a neutron and becomes Pu-239, a fissile isotope (~x100 better use of fuel)
- Burn and reduce the long-lived actinides in nuclear waste (lifetime hundreds of years instead of tens of thousands). About 10% of this waste is rare earths
- No moderator: non water coolants as sodium or lead (liquid from ~330^{o} to 1750^{o} Celsius). Higher temperatures: more safety and higher thermodynamical efficiency
- Can use low-enriched fuel and processed nuclear waste (*e.g.* MOX)

DEVELOPMENT OF SMR (SMALL MODULAR REACTOR)

- Generation IV large reactors with much improved performance, reliability and safety features are being developed worldwide. However, a revolution in the field is happening in parallel
- A similar «revolution» occurred in the ‘80s when we went from large computer mainframes to small and performing personal computers
- SMR exploit both options of thermal and fast neutrons, and exhibit many interesting features

SMR DESIGN



Rendering of a 30 MW_e fast SMR, lead-cooled, using MOX as fuel

by ***newcleo*** (www.newcleo.com)

To be operated in France by early 2030's

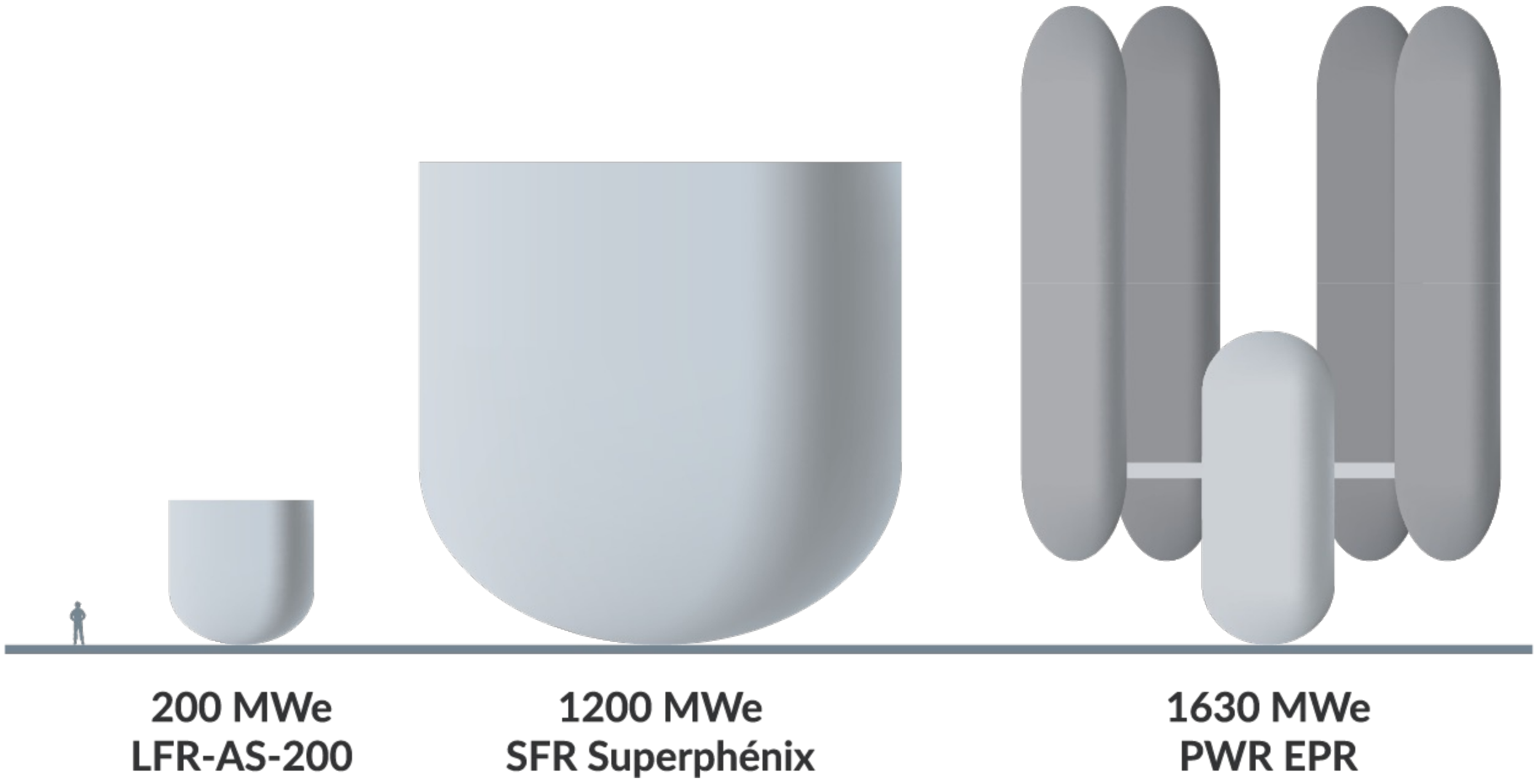
WHY SMR?

- **Small power output:** (50-300 MW_e), allowing flexible deployment
- **Modular construction**: factory-built and shipped to the site, reduced construction time
- **Scalable architecture**: multiple modules added over time to match demand growth
- **Enhanced safety**: rely on passive safety systems (gravity, natural circulation, convection)
- **Lower cooling and site requirements**: remote sites, industries, retired fossil plants
- **Reduced staffing needs:** simplified operations compared with large reactors
- **Potential for underground installation**: improving protection, safety and security
- **Flexible applications beyond grid electricity**: district heating, desalination, hydrogen production, industrial heat
- **Fuel flexibility**: LEU, HALEU, MOX
- **Lower financial risk**: incremental investment and shorter construction schedules
- **Costs**: in perspective, same cost of a large infrastructure of similar integrated power
- **Standardization of design**: repeatable builds and improved licensing efficiency

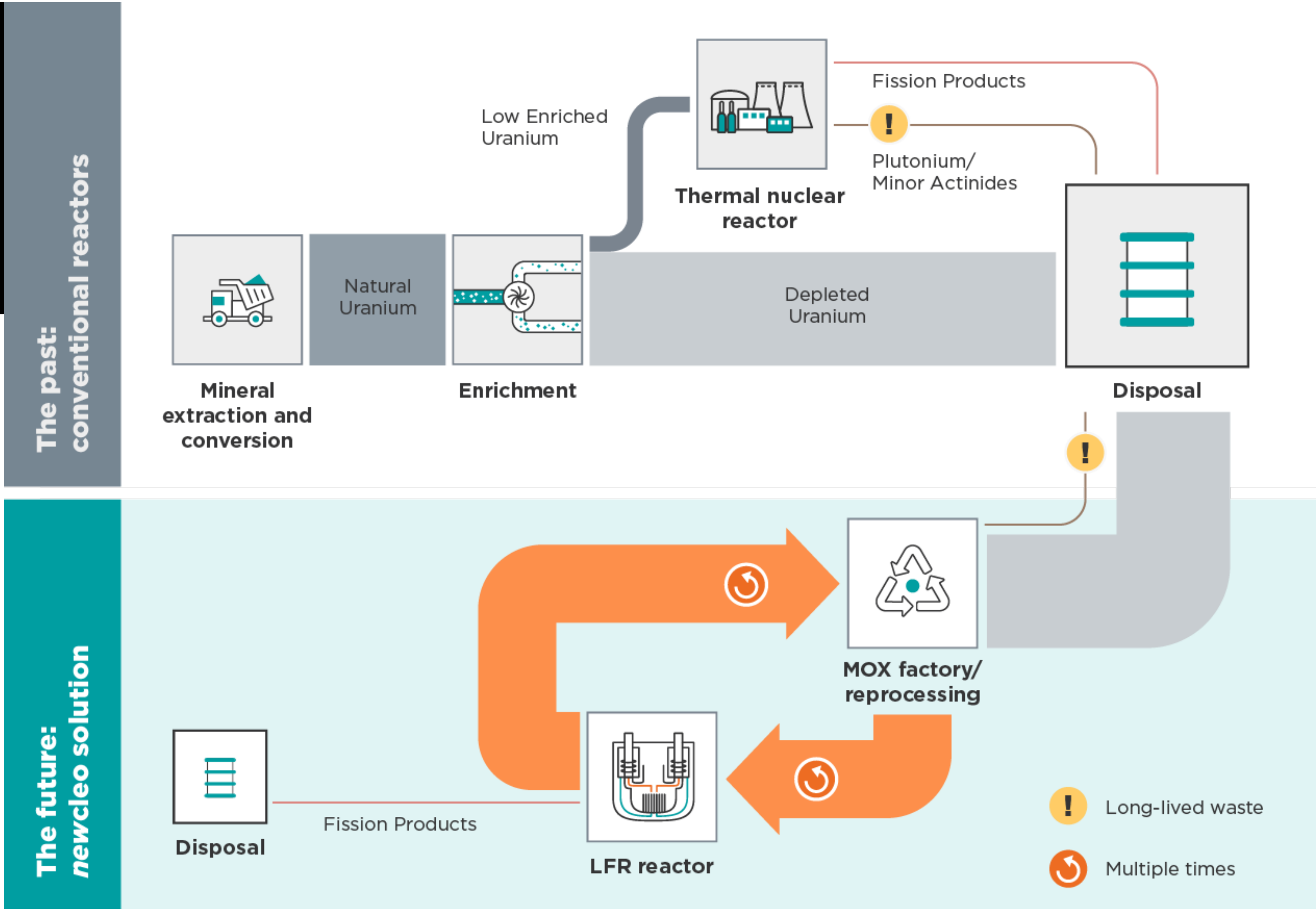
SMR AND MOX

- MOX fuel is a blend of plutonium oxide and uranium oxide
- Used in many countries (mainly where there are plutonium stockpiles)
- MOX is particularly suited for fast SMR:
  - Fast reactors operate well on plutonium and higher actinides
  - Many fast-spectrum fuels are MOX or MOX-like mixtures (*e.g.*, high-Pu content)
  - MOX supports breeding and burning of plutonium and actinides
  - Improves fuel utilization, burns long-lived waste, supports closed fuel cycles

EXAMPLES OF INNER VESSELS



FUEL CYCLE

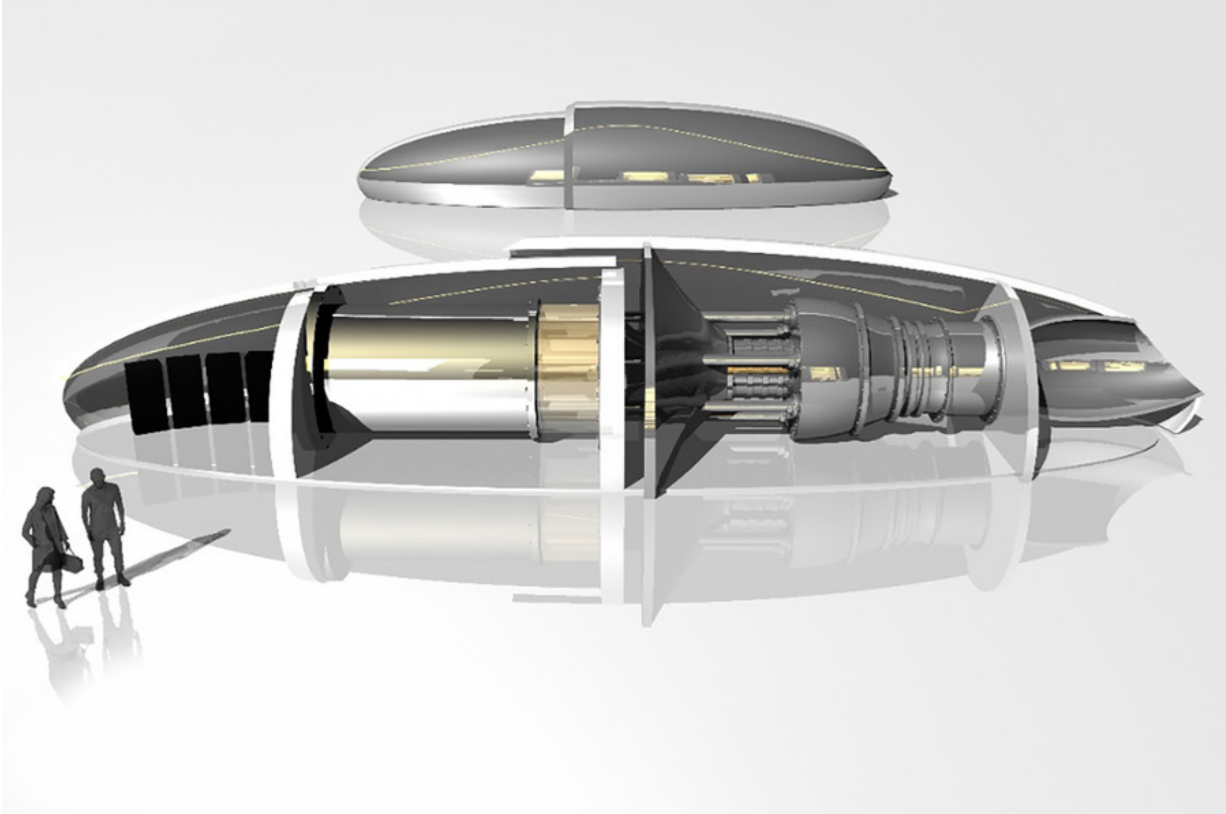


newcleo.com

EVER SMALLER: NUCLEAR «BATTERIES»

Nuclear batteries are microreactors, often for fast neutrons, HALEU-fueled, factory-built units capable of delivering 1–20 MW_e of carbon-free power for years

Now moving from prototype to early commercialization and poised to serve industry, defense, transport and resilient civil infrastructure



MAIN BATTERY FEATURES

General: sealed units, transportable by truck, rail, or aircraft, to run 5–20 years without maintenance, relying entirely on passive safety, retrieved by the vendor after end of life (energy-as-a-service)

Use: remote communities, military bases, AI data centers, industrial microgrids, disaster-response power, sea transport, lunar and Martian missions

Technical: 0.5–20 MW_e,1–60 MW_t, sodium or lead cooled

Development: more than 20 companies involved in USA, Canada, Russia, China, NASA/DoE. Commercialization early 2030s

Advantages: deployment flexibility (remote areas), high reliability for years, no onsite fuel handling, small footprint, mass production, small cost, possibly installed underground

Challenges: Licensing a reactor that can be shipped by truck, public acceptance, mass manufacturing, HALEU supply

NUCLEAR POWER AND SOCIETY

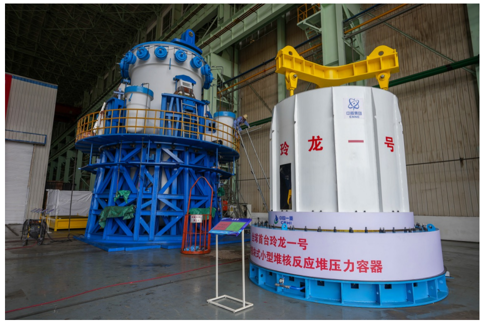
- Fear of nuclear energy: atomic bomb, radiation, Chernobyl
- The right question is not «*should we be afraid*?» but «*what does the evidence tell us today*?»
- Chernobyl (1986): a unique accident caused by a flawed reactor design and an unauthorized experiment. Direct deaths: 65 emergency workers from acute radiation syndrome. Long-term effects: estimate a few thousand excess cancer cases over decades (mostly thyroid), but not a catastrophic population-scale disaster. Key scientific point: that accident cannot occur in any modern reactor design
- Fukushima (2011): Triggered by a magnitude-9 earthquake and tsunami, not by a failure of nuclear physics. Direct radiation deaths: 0. Independent analyses conclude that health impacts from radiation exposure are expected to be very low to none for the general public. The real human tragedy came from the evacuation itself, not radiation
- Deaths per TWh of electricity by *Our World in Data*, *EU ExternE*, *IPCC*.
  Coal: 24.6 (air pollution + accidents), oil: 18.4, biomass: 4.6, gas: 2.8, wind: 0.04, solar: 0.02, nuclear: 0.03 (including Chernobyl and Fukushima)
- Today's Gen. III and IV reactors include passive safety systems that work without electricity or human intervention, inherent physics barriers that shut the reaction down automatically, strong containment structures, probability-of-failure analyses orders of magnitude more conservative than in aerospace. An accident like Chernobyl is physically impossible in any reactor designed after the 1990s
- Last but not least: a nuclear reactor would never create a nuclear explosion: impossible by design and fuel enrichment

AN EXERCISE:
A TAILORED DE-CARBONIZED ENERGY PORTFOLIO FOR TAIWAN (2035-2045)?

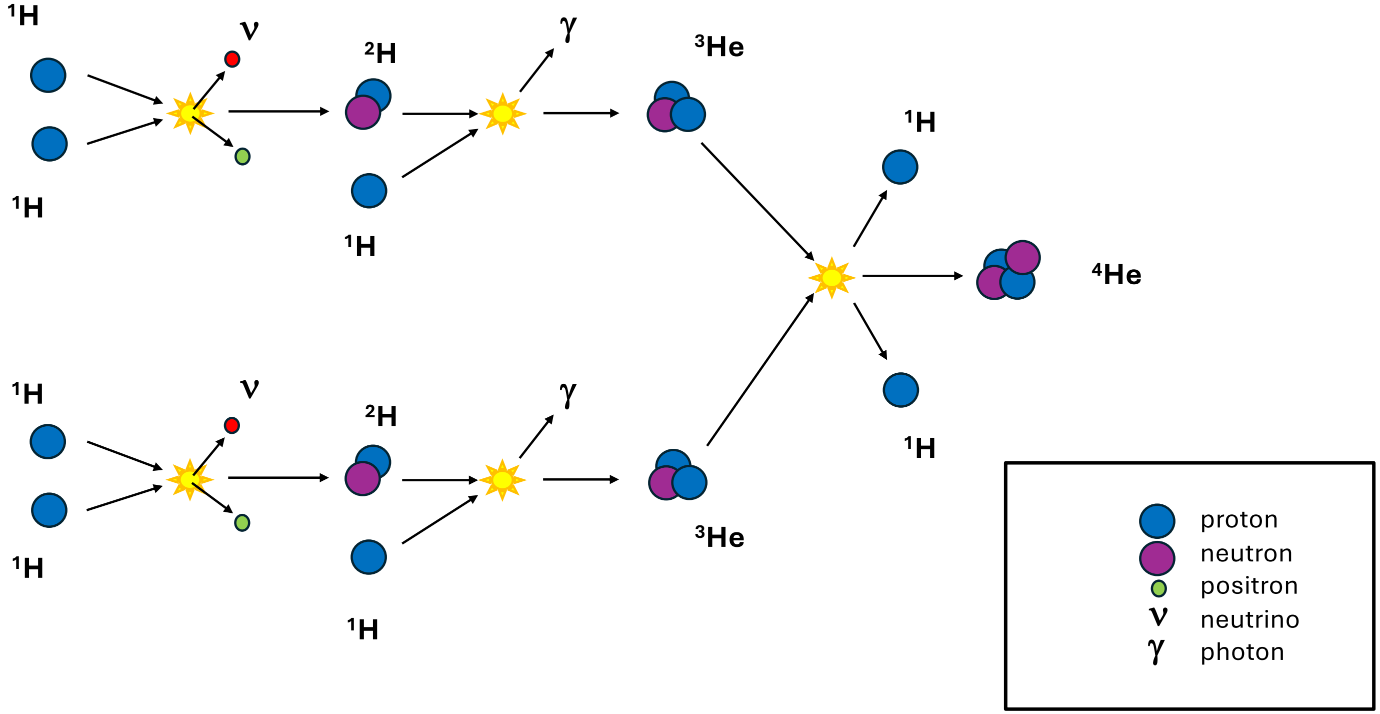
Energy Source	Scenario A – With Gen-IV / SMR	Scenario B – Without Nuclear
Offshore Wind	20–25%	25–30%
Solar PV (mainly rooftop)	20–25%	25–30%
Other renewables (hydro, biomass, geo)	5%	5%
Nuclear (Gen-IV / SMR)	**15–20%**	0%
Gas (LNG + hydrogen + C-capture)	25–30%	**35–45%**
Coal	0–5%	0–5%
System characteristics	Strong firm low-carbon capacity; stable grid; reduced LNG dependence	Heavy reliance on «flexible» gas; large storage required; higher import vulnerability

Looking 10 to 20 years ahead, a credible decarbonized energy portfolio for Taiwan must combine large-scale offshore wind and rooftop solar with a firm, low-carbon backbone.

With advanced Generation IV nuclear systems and SMR this backbone becomes robust and secure; without them, Taiwan must rely heavily on decarbonized gas, large storage systems, and a much more complex and vulnerable grid.



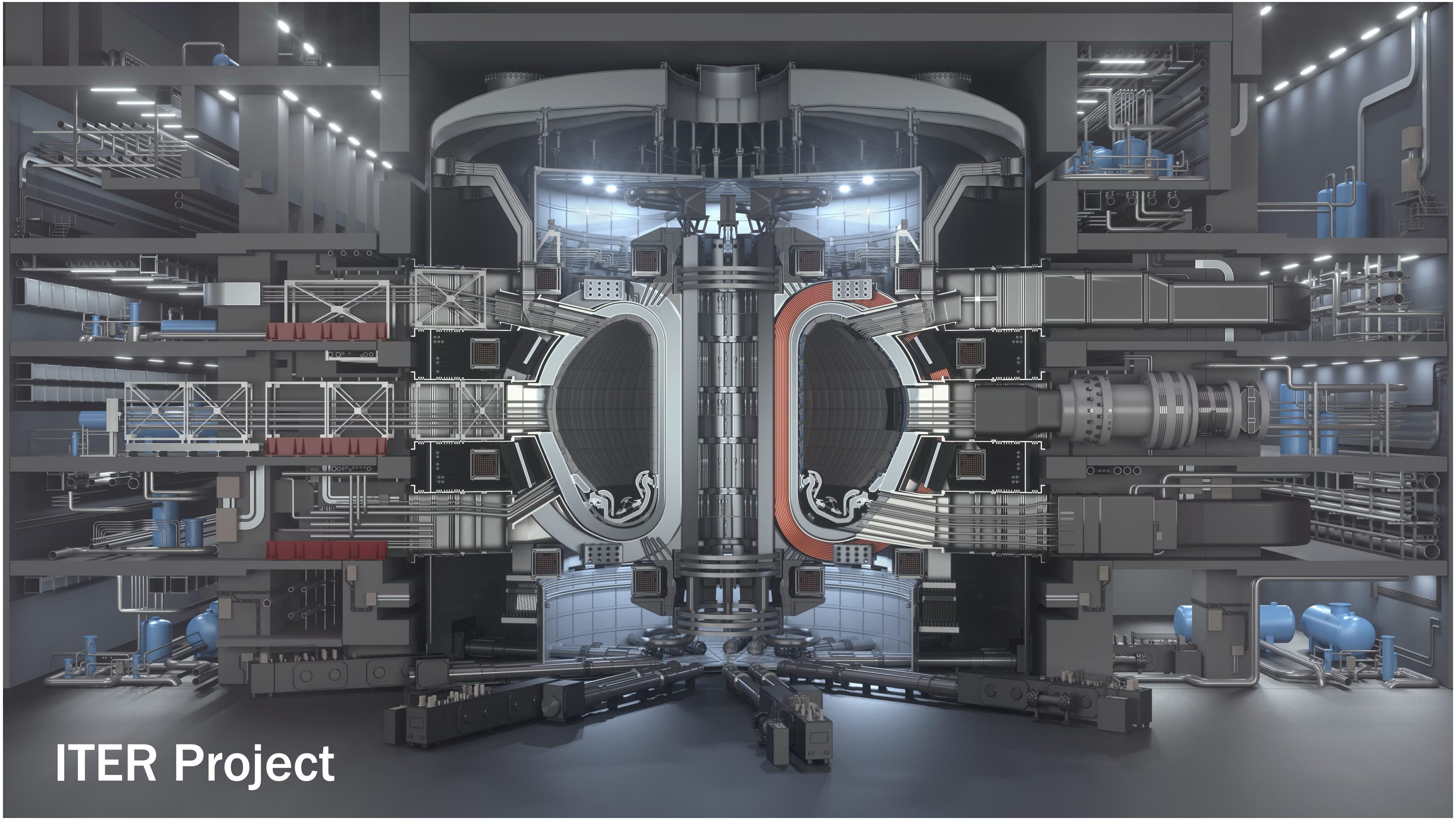
A FEW WORDS ON ENERGY PRODUCTION FROM NUCLEAR FUSION: THE WAY STARS BURN



STATUS OF CONTROLLED NUCLEAR FUSION

- After decades of research, controlled fusion has reached critical technical milestones but remains pre-commercial
- Magnetic confinement (tokamak design): the ITER project in France, under construction by an international consortium, aims to produce ten times more fusion power than input heating (Q>10) in the 2030s
- Inertial confinement (laser-driven): the US National Ignition Facility has achieved short pulses of net energy gain (Q>1) in 2021–2022, but these are still single-shot experiments
- Private sector innovation: >10 startups are pursuing compact magnetic or alternative approaches. Some claim grid-connected demonstrators by the early 2030s, though this remains scientifically and economically unproven
- Realistic timeline:

2025-2030	ITER first plasma, several private devices proofs-of-principle
2030-2045	ITER deuterium-tritium operation; demo power plants worldwide for heat and electricity
2050	Deployment of commercial fusion stations; integration into grids


ITER Project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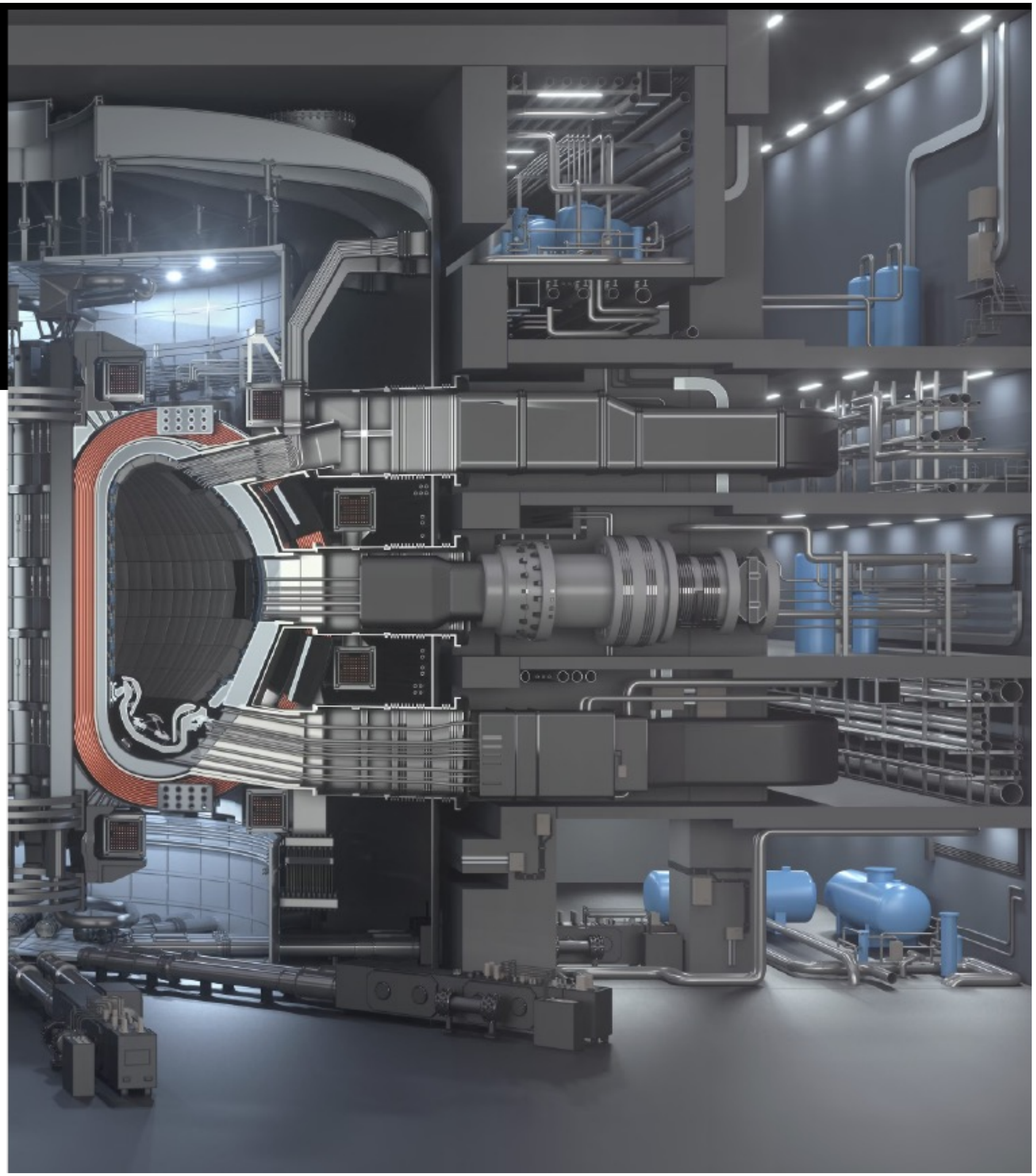

PROS AND CONS

Advantages	Drawbacks/Challenges
Virtually limitless fuel (lithium-derived tritium). At least in the beginning, tritium provided by fission reactors	Technological immaturity – no power-producing reactor yet demonstrated
No long-lived high-level waste compared with fission	Intense neutron flux damages materials; need for advanced structural alloys
Inherent safety – no chain reaction, self-limiting plasma	Extremely high CAPEX (tens of billions € for large reactors)
No CO_2 emissions during operation	Tritium handling and breeding pose radiological and supply challenges
High energy density and baseload potential	Complex maintenance in highly activated environments
Global scientific collaboration and innovation driver	Slow timelines – commercialization unlikely before the 2050s

Stefano Buono
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THE NEW NUCLEAR POWER

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