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MacroVoices 2024 Holiday Special

Advanced Nuclear Technologies for Energy Transition

Joint presentation by Thomas-Jam Pedersen and Erik Townsend

Episode 1 of 2:

Advanced Nuclear Reactor Designs for Energy Transition

FOURTH TURNING
CAPITAL MANAGEMENT, LLC

Topics for this episode…

Most analysts focus on "Triple-Nuclear" initiative announced at COP28 in Dubai in late 2023

But 3x Nuclear isn't enough!

To fully replace energy we now derive from Fossil Fuels would require 24x Nuclear, not 3x!

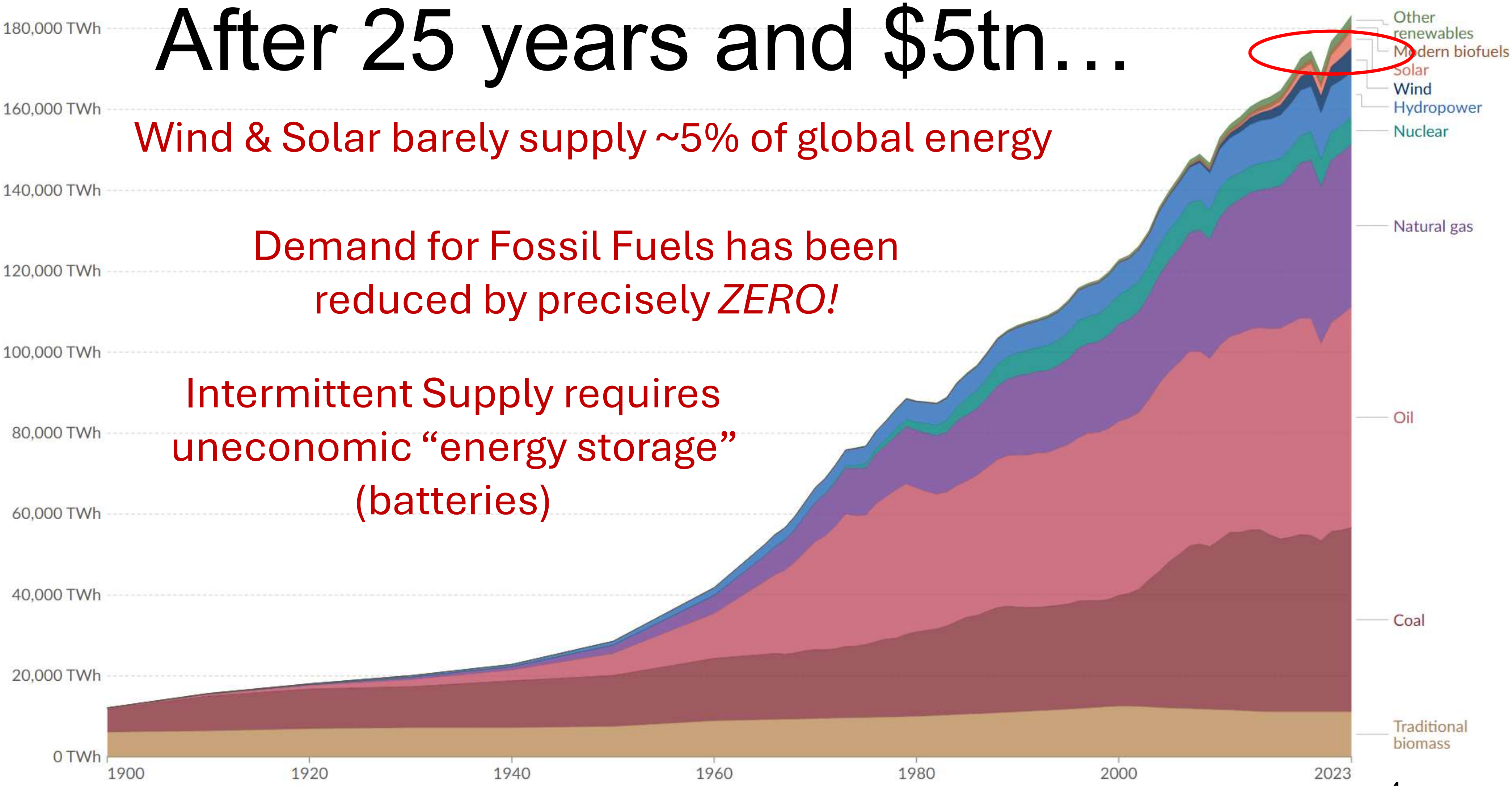
Is it even *possible* to build 24x current nuclear energy capacity?

- Ever?
- By 2050?
- Which Advanced Nuclear Energy technologies could enable this, if any?

Part 2 (next week) Will address:

- Nuclear Fuels for Energy Transition-scale Nuclear Buildout
  - Uranium isn't enough!
- Why the fuel supply chain challenges are even more daunting than the engineering challenges when you consider 24x scale nuclear build-out
- Deep dive on Uranium-based Nuclear Fuels
  - LEU, HALEU, TRISO, MOX, etc.
- Uranium-233 and Thorium

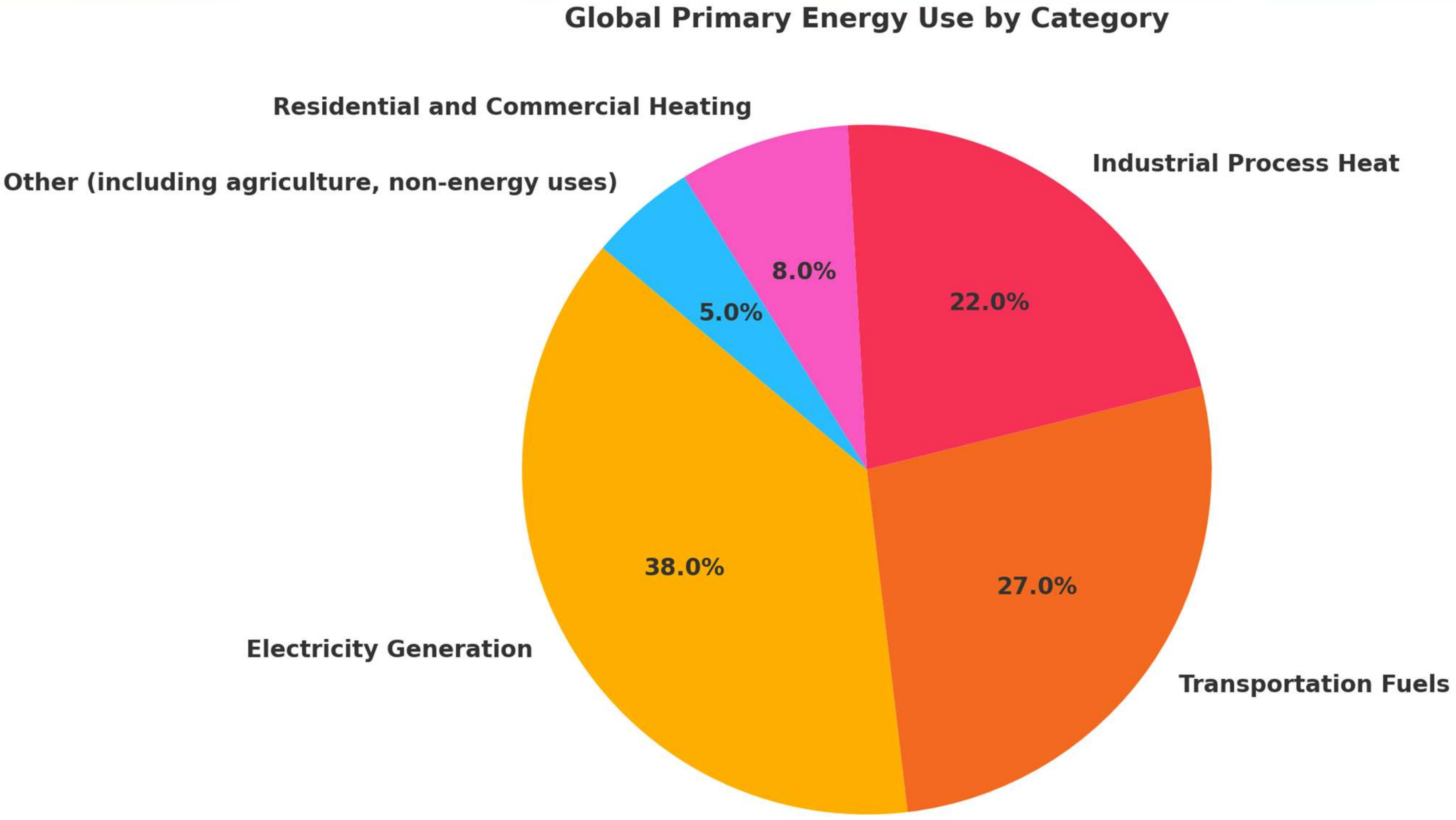
After 25 years and $5tn…



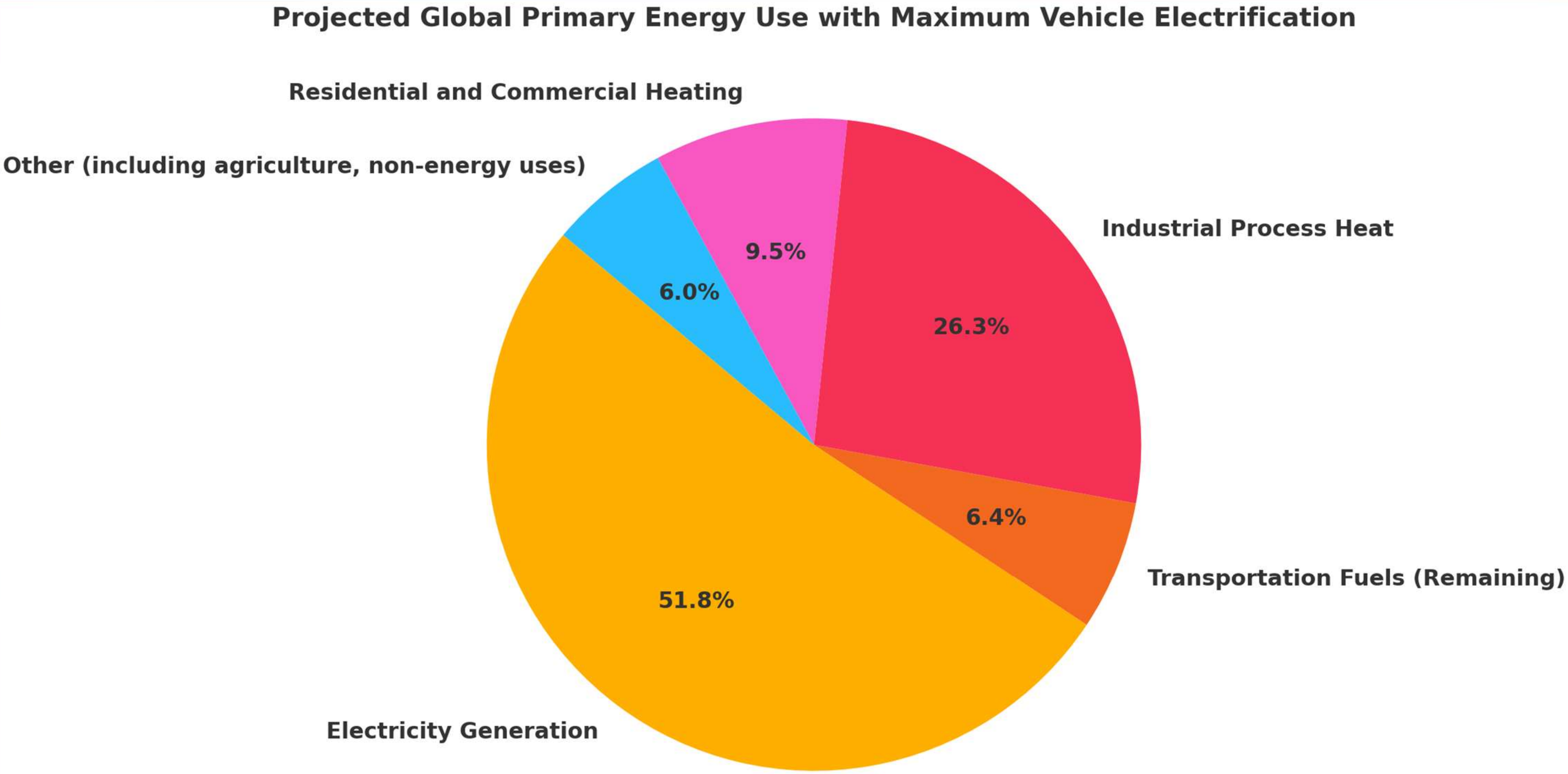
Wind & Solar barely supply ~5% of global energy

Demand for Fossil Fuels has been reduced by precisely *ZERO!*

Intermittent Supply requires uneconomic "energy storage" (batteries)



Source: ChatGPT 4o



Projected Global Primary Energy Use with Maximum Vehicle Electrification

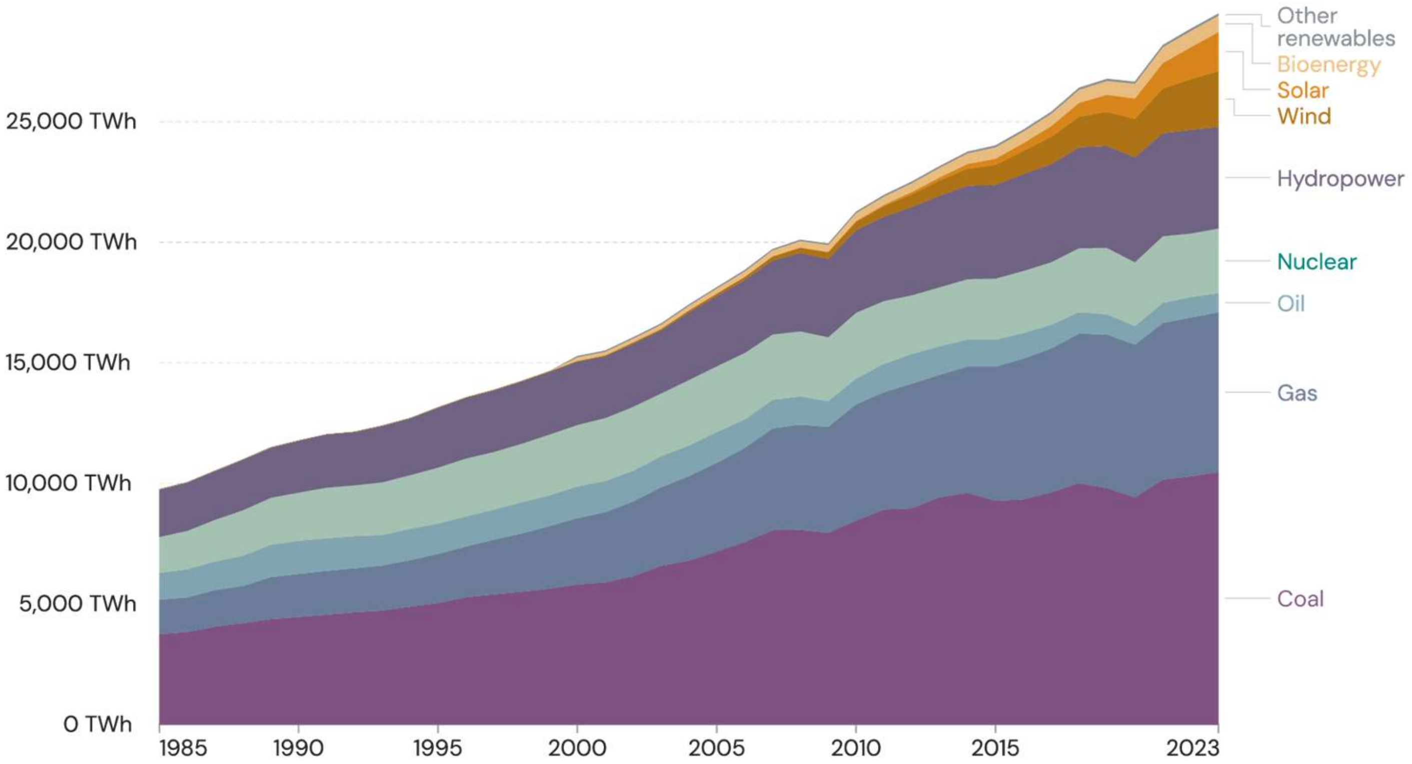
Source: ChatGPT 4o

Electricity production by source, World

Measured in terawatt-hours

Today global electricity market:

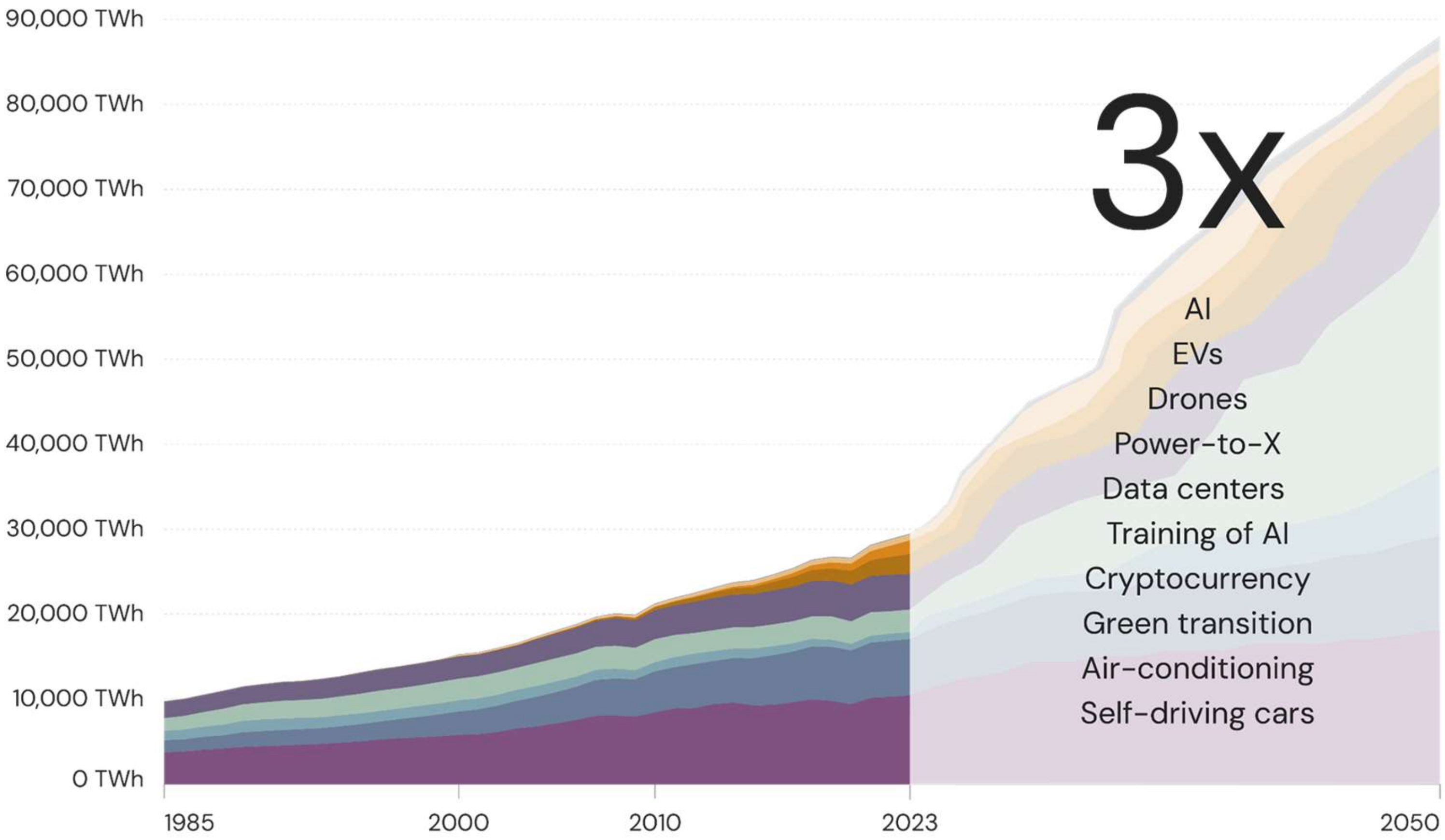
4.5 trillion USD



Source: Vaclav Smil (2017) and BP Statistical Review of World Energy

Electricity production by source, World

Measured in terawatt-hours



3x

AI
EVs
Drones
Power-to-X
Data centers
Training of AI
Cryptocurrency
Green transition
Air-conditioning
Self-driving cars

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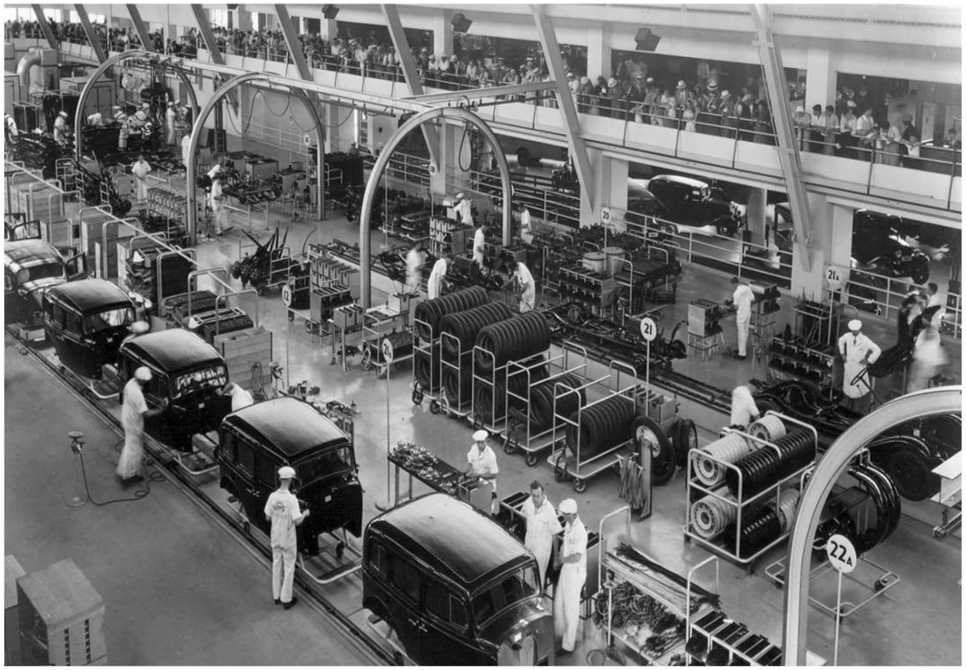
We need the iPhone of Nuclear Reactors

- One economic design that can be **mass-produced** in very large qty.
  - i.e. 24x Nuclear, not 3x Nuclear
- The "**work horse** of Energy Transition"
- Should be suitable for both **electricity generation** and **process heat**.

The Nuclear Henry Ford Moment

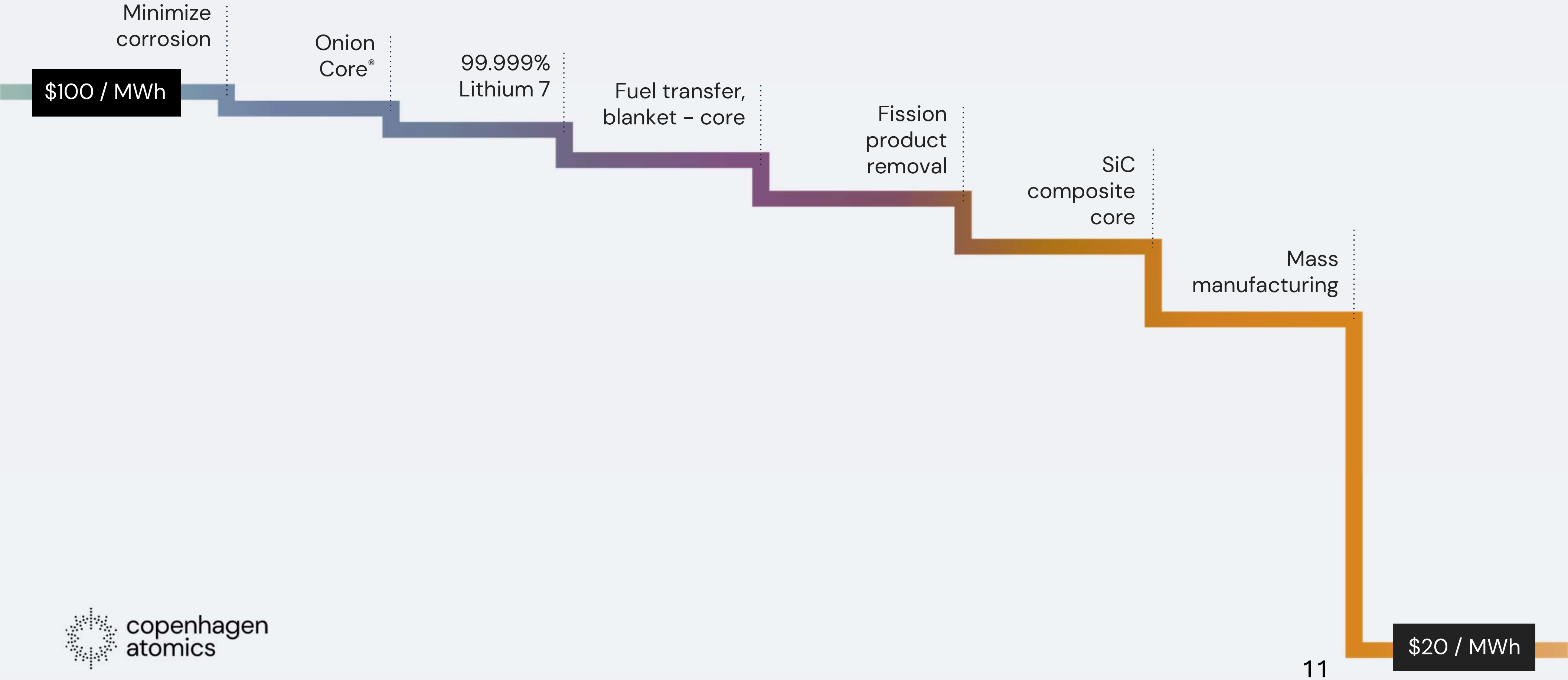
(Why right now is an unprecedented moment of opportunity in Nuclear History)



Ford Assembly line in the 1920s

- The key to the whole plan is to **embrace economies of scale inherent to assembly line mass-production** of reactor modules, CO_2 turbines, and other powerplant components.
- There are **<500** power reactors operating today worldwide
- The proposition is to build **~126,840** more over 20 years (!)
  - Begs the obvious question… Is there really demand?
- Unprecedented “Henry Ford Moment” of opportunity!
  - Even the “Green” Climate Community has warmed up to Nuclear
  - Energy Transition movement creates unprecedented demand for **economically viable clean energy**
  - **Beating *everyone* including fossil fuel energy on cost enables massive demand creation!**

Essential steps towards $20 / MWh



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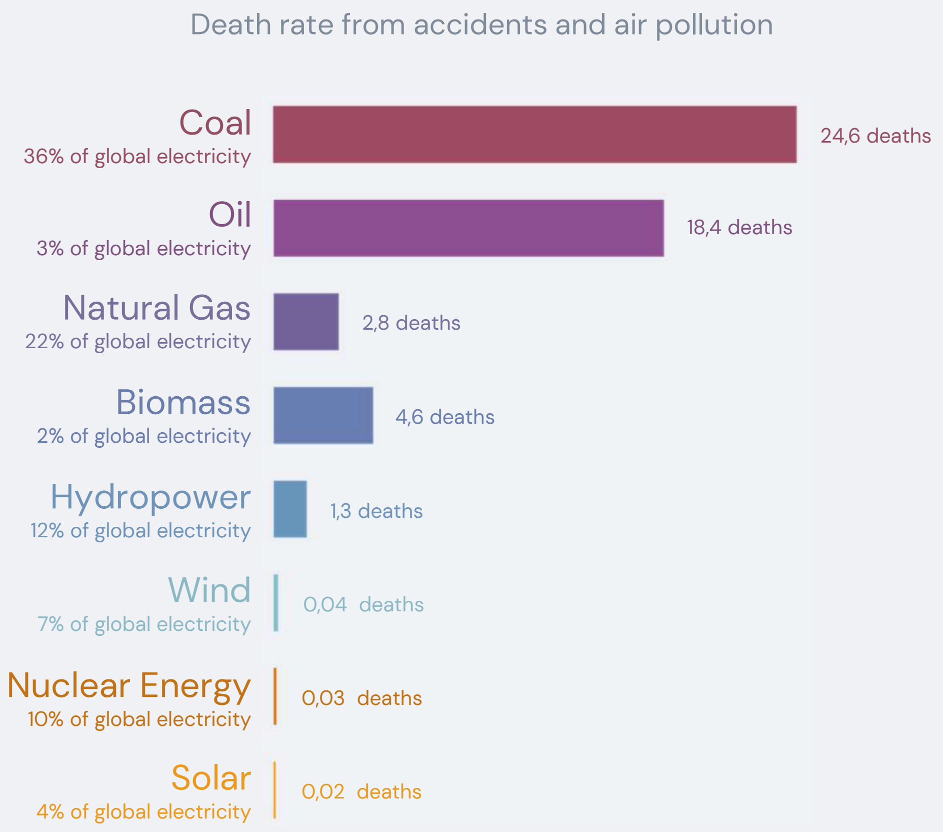
What are the safest energy sources?

Measured as deaths per terawatt-hour of electricity production.

1 terawatt-hour is the annual electricity consumption of 150.000 people in the EU.


Death rate from accidents and air pollution

● 1230 times higher than solar.

● Incl. Deaths from Chernobyl & Fukushima.

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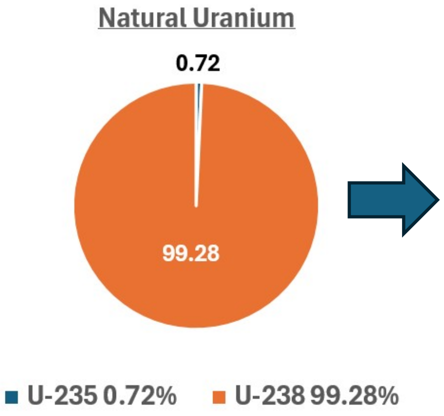
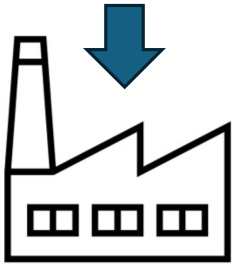
Conventional (i.e. AP1000 LWR) Fuel Cycle

~13.8kg U_3O_8



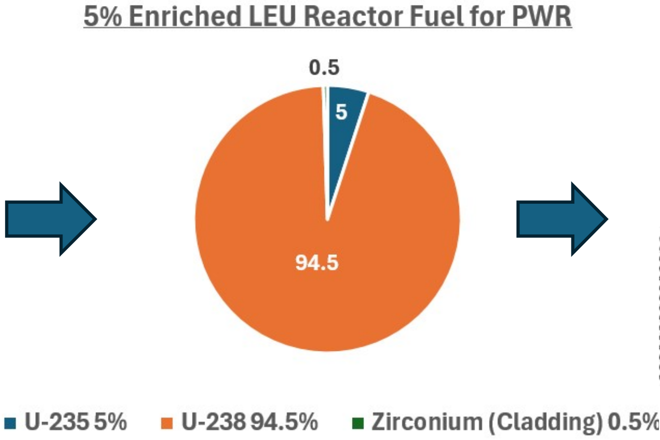
~\$175/kg

~310 – 370 kWh/kg Energy Required



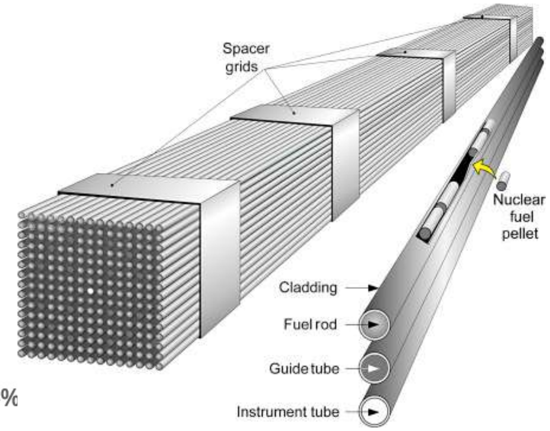
Conversion & Enrichment

1 kg 5% Low-Enriched Uranium

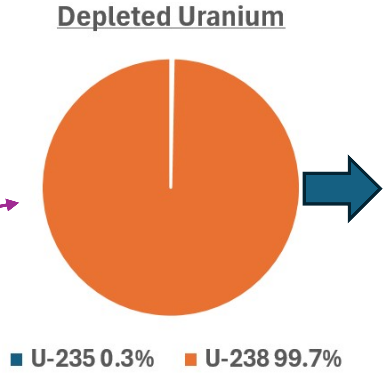


~\$3,500/kg

AP1000 Fuel Bundle (requires many kg LEU)



~\$4,000/kg



~12.8kg "D.U."

The "waste" from the enrichment process is called *depleted uranium* (DU).

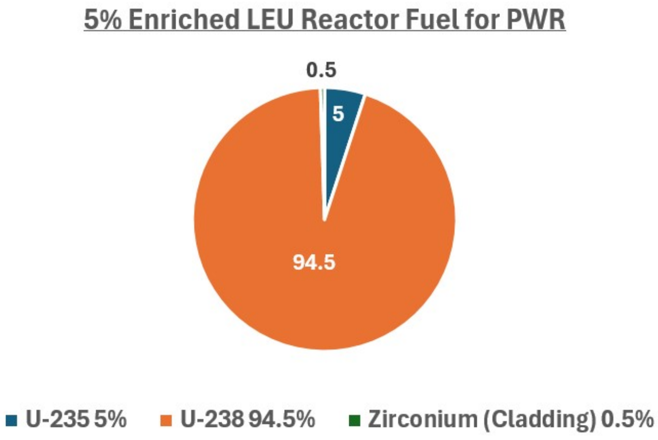
Currently, the most common use for DU is making armor-piercing bullets

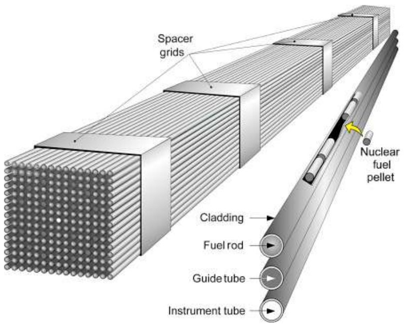
Conventional Nuclear Fuel Cycle (Cont'd)

Westinghouse AP1000 Nuclear Power Station

1,117 MW(e) Generation Capacity
Requires cooling water source (river/ocean)

CAPEX Data from Vogtle, GA:
Original Cost Est. ~$7.5bn per reactor
Actual cost ~$15bn per reactor
(= $13,428/kw)

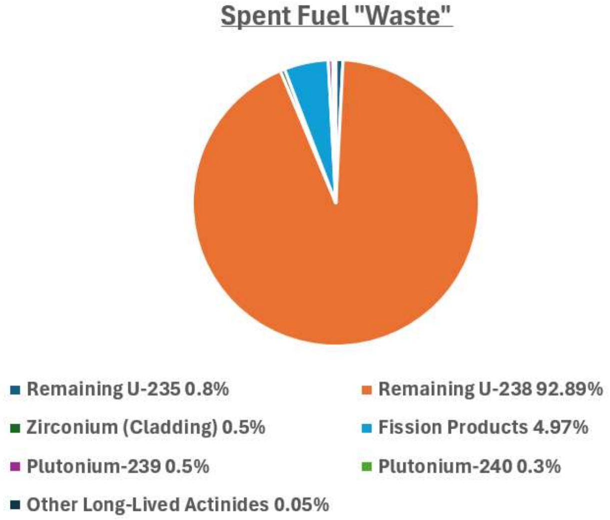

5% Enriched LEU Reactor Fuel for PWR



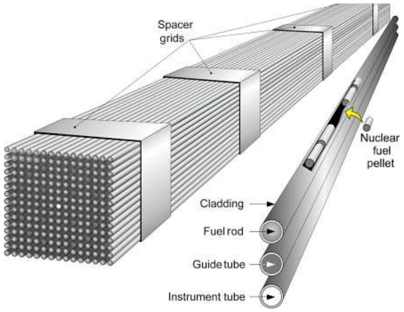
AP1000 5% LEU Fuel Bundle
(~$4,000 USD/kg)

80,000 kg Fuel Load (~$320mm)

Yields ~396-420MWh Electricity per kg (5% LEU)


Spent Fuel "Waste"

80,000 kg "Waste"



AP1000 Spent Fuel "Waste" Bundle

<5% Of the Energy it contains has been consumed!

Small
Misunderstood Nuclear
Reactors

SMR = A marketing phrase that "caught on", but has no agreed meaning

There are at least FOUR different *meanings* of MODULAR in common use that are relevant to understand…

SMR Meaning 1: Smaller conventional reactors

Westinghouse AP1000 Nuclear Power Station

1,117 MW(e) Generation Capacity
Requires cooling water source (river/ocean)

Yields ~396-420 MWh Electricity per kg (5% LEU)

Westinghouse AP300 SMR

300 MW(e) Generation Capacity
Requires cooling water source (river/ocean)

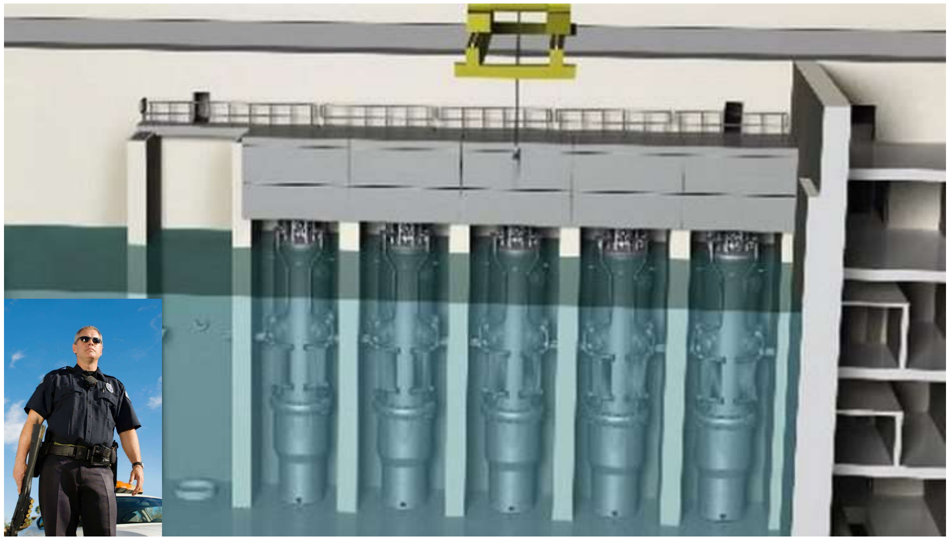
Yields ~396 MWh Electricity per kg (5% LEU)

More of the parts are factory-built to reduce build time from ~7 yrs to “only” 3 - 4 yrs.
Advertised target build cost is ~$2,500/kw vs ~$6,700/kw for AP1000.
Otherwise, it’s the same 1950s PWR Nuclear technology with modern automation & safety systems

SMR Meaning 2: Micro-reactors

- Very SMALL reactors designed to compete with DIESEL GENERATOR SETS
  - Remote mining sites
  - Small applications
- May be portable, i.e. on a truck
- Sometimes called “Nuclear Batteries”
- Best applications are military bases
- May also be viable for remote villages, mines, etc.
- Most are based on LWR Technology
  - Same once-thru fuel cycle, makes waste that contains plutonium
- A few (e.g. Oklo) are Gen IV advanced reactors
- People promoting them NEVER mention:
  - How will they comply with rules requiring armed guards at nuclear power stations?
  - How will they comply with “Site License” requirements in current regulations?
- How does “Modular” fit in???

SMR Meaning 3: Each Reactor is a Module



- **MODULARITY in this case means that each nuclear reactor is a MODULE**
- **Assembly of the reactor modules from factory-made parts is more efficient than custom-build**
- **To make different sized power plants, different numbers of reactor modules could be used**
- **The Nuscale reactors depicted here are old-school PWR technology, same fuel cycle and approximate efficiency and fuel-energy yield as conventional nuclear plants**
- **You still need armed guards**

~~SMR~~ Meaning 4: Each Reactor is a Module - CA

“Please don’t call Copenhagen Atomics an SMR Company!!! We don’t want to be part of that…”

- **MODULARITY in this case means that each nuclear reactor is a MODULE**
- **In the Copenhagen Atomics model, each reactor module is mass produced in the form factor of a standard 40’ shipping container**
- **This is a Gen IV THORIUM fueled reactor.**
- **Only the “kickstarter” fuel produces a small amount of Plutonium waste. Thorium fuel produces no Plutonium.**
- **Designed to be ganged together to make large power stations or process heat plants**

Generation IV or “Advanced” Nuclear Reactors

The common theme is to **replace water with a better coolant**.

There are several noteworthy designs we’ll overview in this section.

What's wrong with Water as a Coolant?

- Capacity limited by boiling temp-> lower thermal efficiency
- Need to pressurize the reactor core increases safety risks
- Hydrogen explosions a la Fukushima
- Even when pressurized, temperature is limited to ~350C
  - Not suitable for some process heat applications
  - Including some like Hydrogen Production that are essential to Energy Transition

Features of Gen IV (Advanced) Reactors

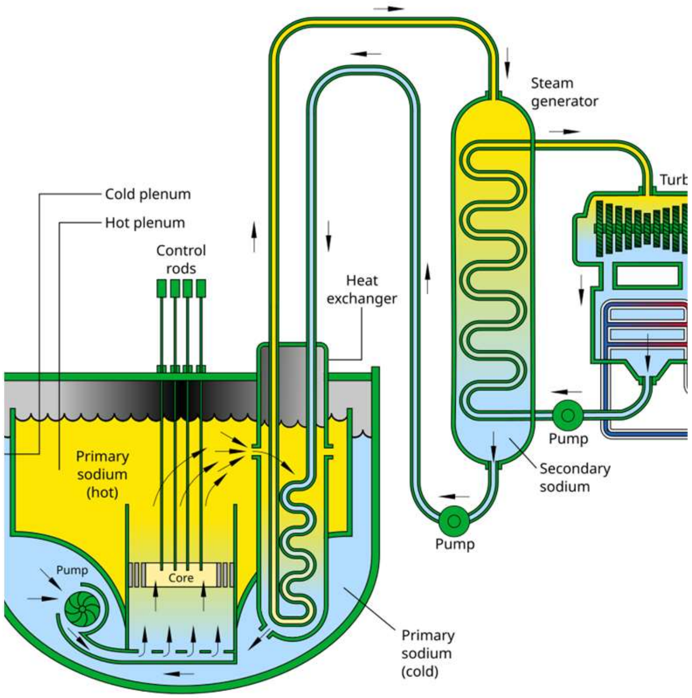
- Replace water with a better coolant -> No need to pressurize = Safer
  - Widespread propaganda that PWR was chosen for its safety is total BS, but widely believed in nuclear industry
    - "…to claim that light water reactors were chosen because of their superior safety belied an ignorance of how the technology had actually evolved"

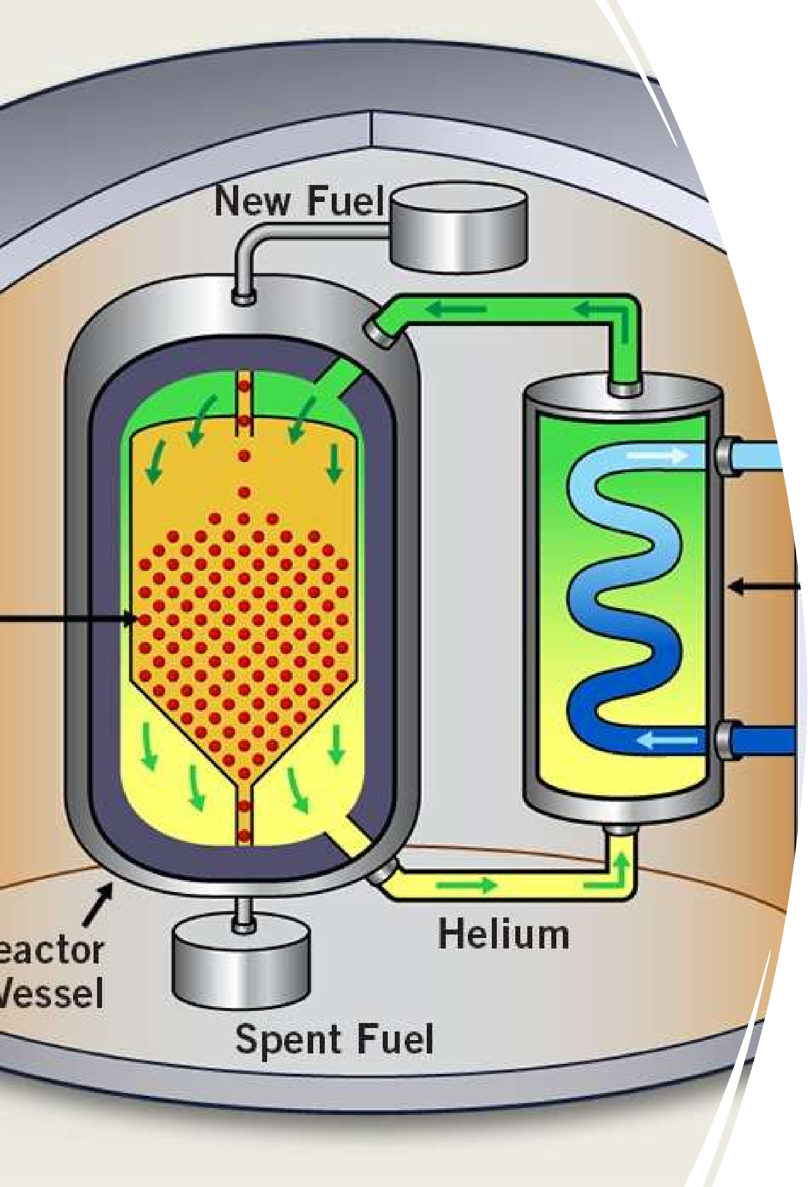
      –Alvin Weinberg, **inventor** of the Pressurized Water Reactor
  - Common Gen IV coolants:
    - Liquid metal (usually Sodium), gas (usually helium), and molten salt are
- Use Fuel more efficiently, produce less waste
- Higher Temps -> Higher Thermal Efficiency
  - And suitable for more process heat applications

Sodium-Cooled Fast Reactors

- **Why Sodium Coolant?**
  - 884C vs. 100C boiling temperature
  - No hydrogen explosions
  - Higher temps mean it can produce more energy than a Light Water Reactor (LWR)
  - Generally only suitable in fast-neutron reactor designs. These coolants don't work well in Thermal Spectrum (slow-neutron) reactors
- **Why fast neutrons?**
  - Use more of the fuel by transforming more U-238 into Pu-239
  - Produce less waste because more fuel was burned
- **Fast reactors often require 19.75% enriched HALEU fuel** **-** Supply chain challenges coming next week

Examples include Terra's Natrium, Oklo, GE Hitachi PRISM, Newcleo, Dual Fluid Energy





High-Temperature Gas Cooled (Incl. Pebble Bed)

- Why is higher-temperature so important?
  - Hydrogen production
  - Other high-temp process heat applications, e.g. concrete, smelting steel
  - Popular "Pebble Bed" design is seen as safer
  - Easier to use air cooling – build anywhere without adjacent ocean or river
- While super-high temps are possible in these designs, they are extremely costly to achieve.
- Most current pebble bed reactors being proposed will run at temps lower than max possible because too much expense would be involved going higher
- Why cool it with gas, and what gasses are used?
  - No boiling point – it's already a gas

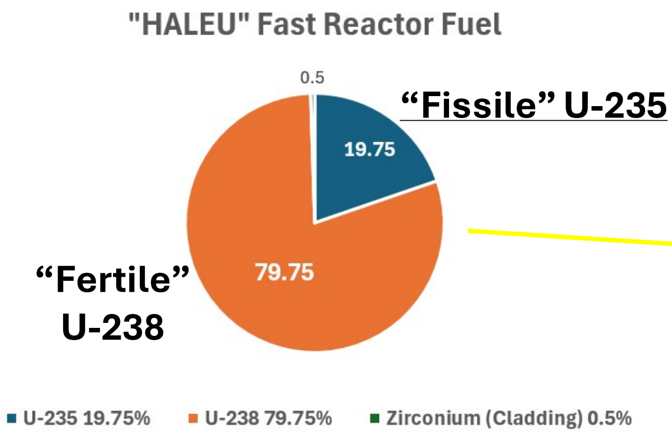
- Requires "TRISO" fuel pebbles – safer but expensive to produce

Examples are X-Energy and Ultra Safe Nuclear Corp

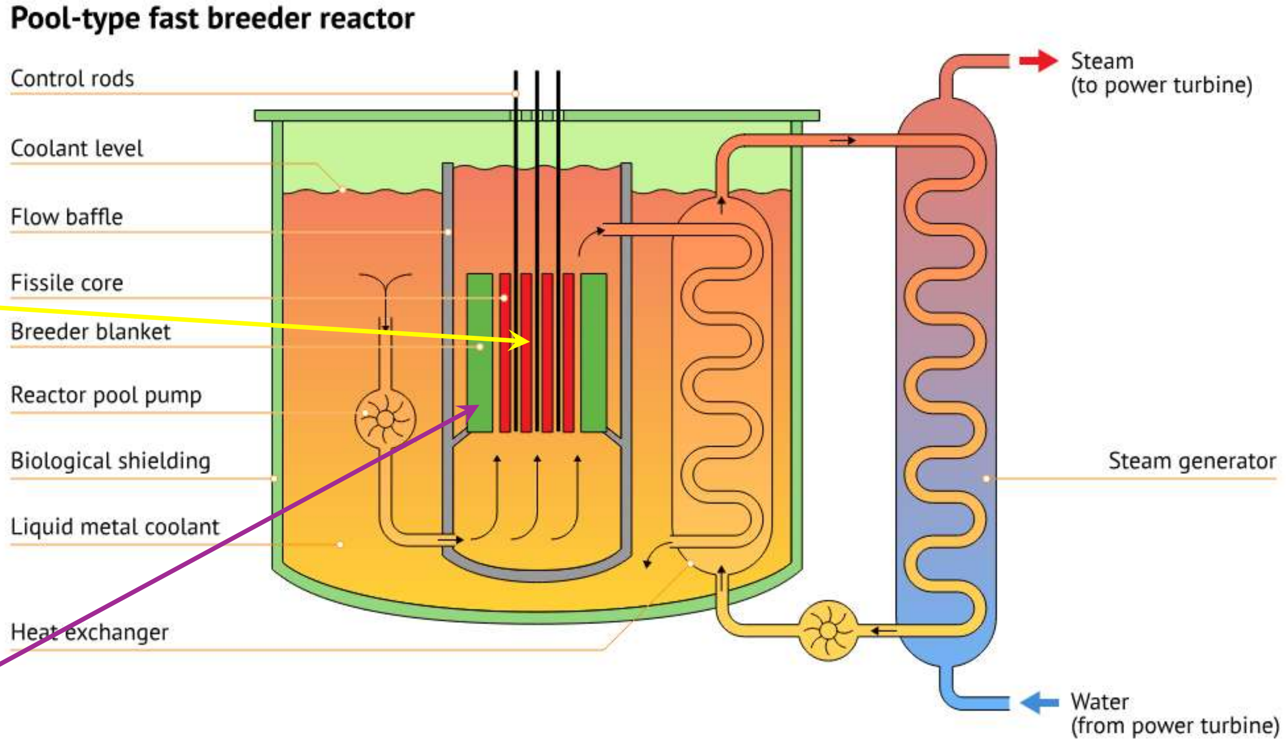
More on “Fast” Reactors

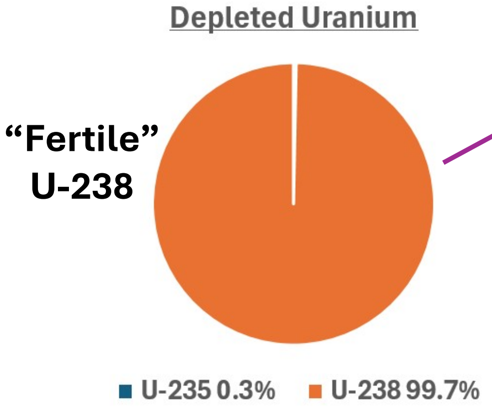
The quest for Breeder Reactors

The main reason Fast-neutron reactor designs were a big trend in the 1960s was the perception that they were the only way to build the sought-after “Breeder”.



~$25,000/kg (!)





"Super Cheap" - $10-20/kg?

In the 1960s, it was widely believed that the only way to make a *breeder* reactor work was to use fast neutrons, requiring a more complex and expensive design.

Alvin Weinberg, inventor of the PWR, was a lone voice, proposing that a slow neutron breeder was possible, but only with a different fuel and coolant. He wasn't *proven* right until 2022, when advanced modeling software became available.

To this day, few nuclear scientists/engineers understand the economic and engineering arguments favoring slow rather than fast-neutron breeder reactors.

Design Limitations on Small Size Fast Neutron Reactors

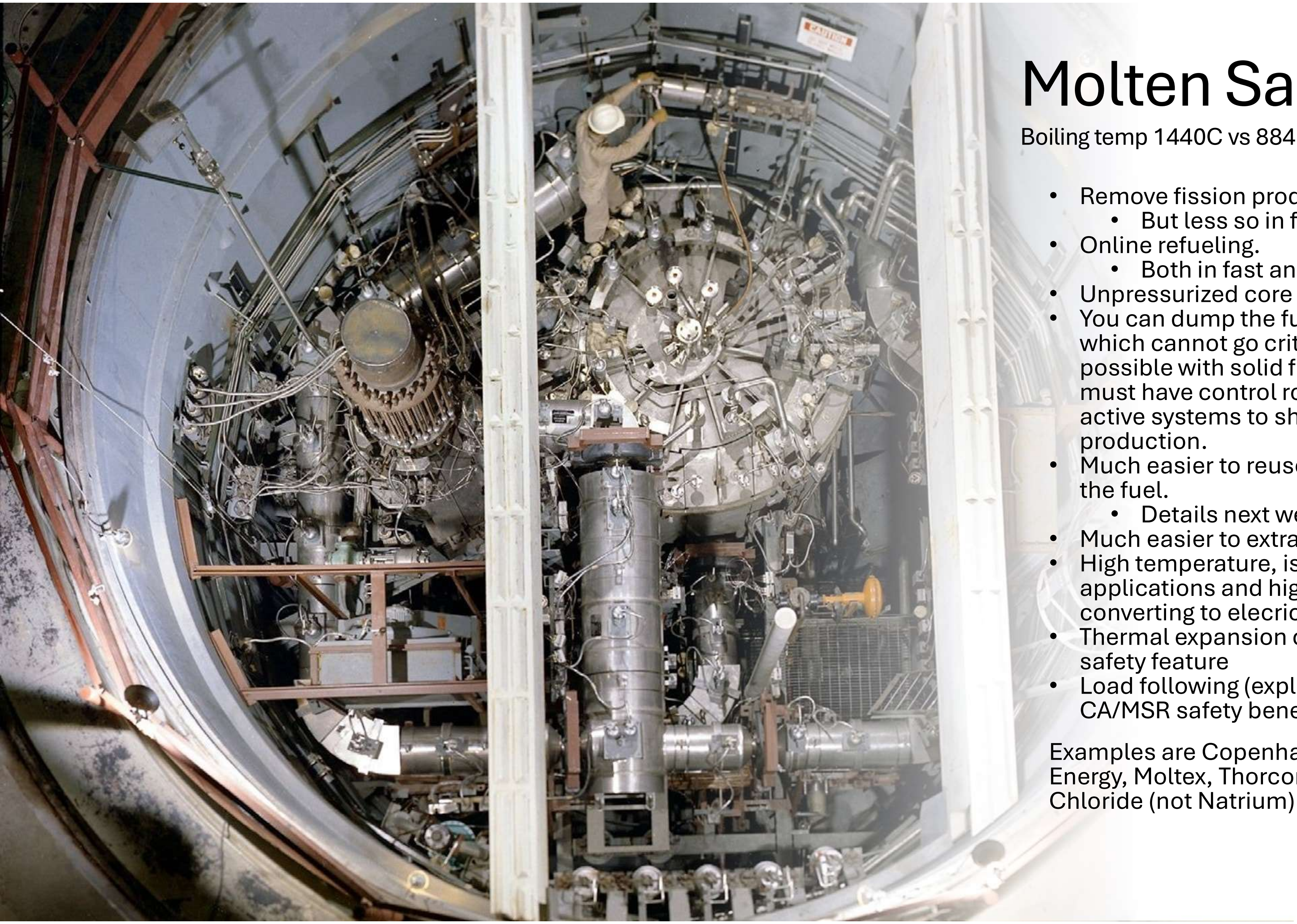
- Fast neutrons fly farther and therefore require a physically larger reactor core with a very large fuel load

- But the market has already told us smaller reactors are the way of the future.

- The several companies that are promoting fast sodium reactors aren't even talking about breeder reactors—which used to be the goal that drove nuclear engineers to want to use fast neutrons in the first place.

    - They know that's not realistic. They are focused on using fast neutrons to burn ***more*** of the U238 and reduce the amount of fuel waste left over after a given amount of energy is produced.

- So what we can expect from SMALL fast sodium reactors going forward is that they will use more of the U238 as fuel (higher burn-up), but it's not realistic to expect fast **breeder** reactors unless they go back to very large reactor sizes, i.e. 5GW(t)+

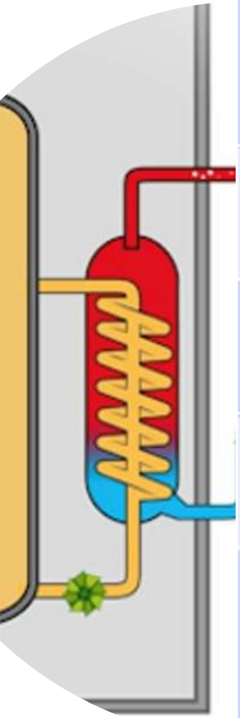


Molten Salt Reactors

Boiling temp 1440C vs 884C for Sodium or 100C Water

- Remove fission products.
  - But less so in fast molten salt reactors.
- Online refueling.
  - Both in fast and slow neutrons reactors.
- Unpressurized core = safety and cost benefits
- You can dump the fuel into a configuration which cannot go critical. (safety) ---- this is not possible with solid fuel reactors, therefore you must have control rods (which could fail) and active systems to shut down. Lower cost fuel production.
- Much easier to reuse or reprocess or recycle the fuel.
  - Details next week
- Much easier to extract medical isotopes etc.
- High temperature, is better for some applications and higher efficiency when converting to elecricity.
- Thermal expansion coefficient of salt creates safety feature
- Load following (explain what it means, and the CA/MSR safety benefit)

Examples are Copenhagen Atomics, Flibe Energy, Moltex, Thorcon, Thorizon, Terra Fast Chloride (not Natrium) reactor



Feature	Benefit
Unpressurized molten salt coolant	Completely eliminates **core depressurization** and **hydrogen explosion** risks. Can **operate in the desert,** without requiring cooling water.
Liquid Fueled	Eliminates **melt-down** risk & enables **load-following.** Can **refuel** while operating.
Much higher temperatures than pressurized LWRs	Use for **seawater desalination** & **hydrogen** based **synthetic liquid fuel** production.
Thorium Fueled	Reduces waste storage to 300 years from 100k years and **reduces weapons proliferation** risks.
Waste Burning	Can burn spent nuclear fuel waste from reactors of yesteryear, disposing of that waste and eliminating need to store it for 1,000’s of years.
Fully automated, remotely managed	No control room or human operator needed. Human operator error risk eliminated.

Thorium Molten Salt Reactor =

?

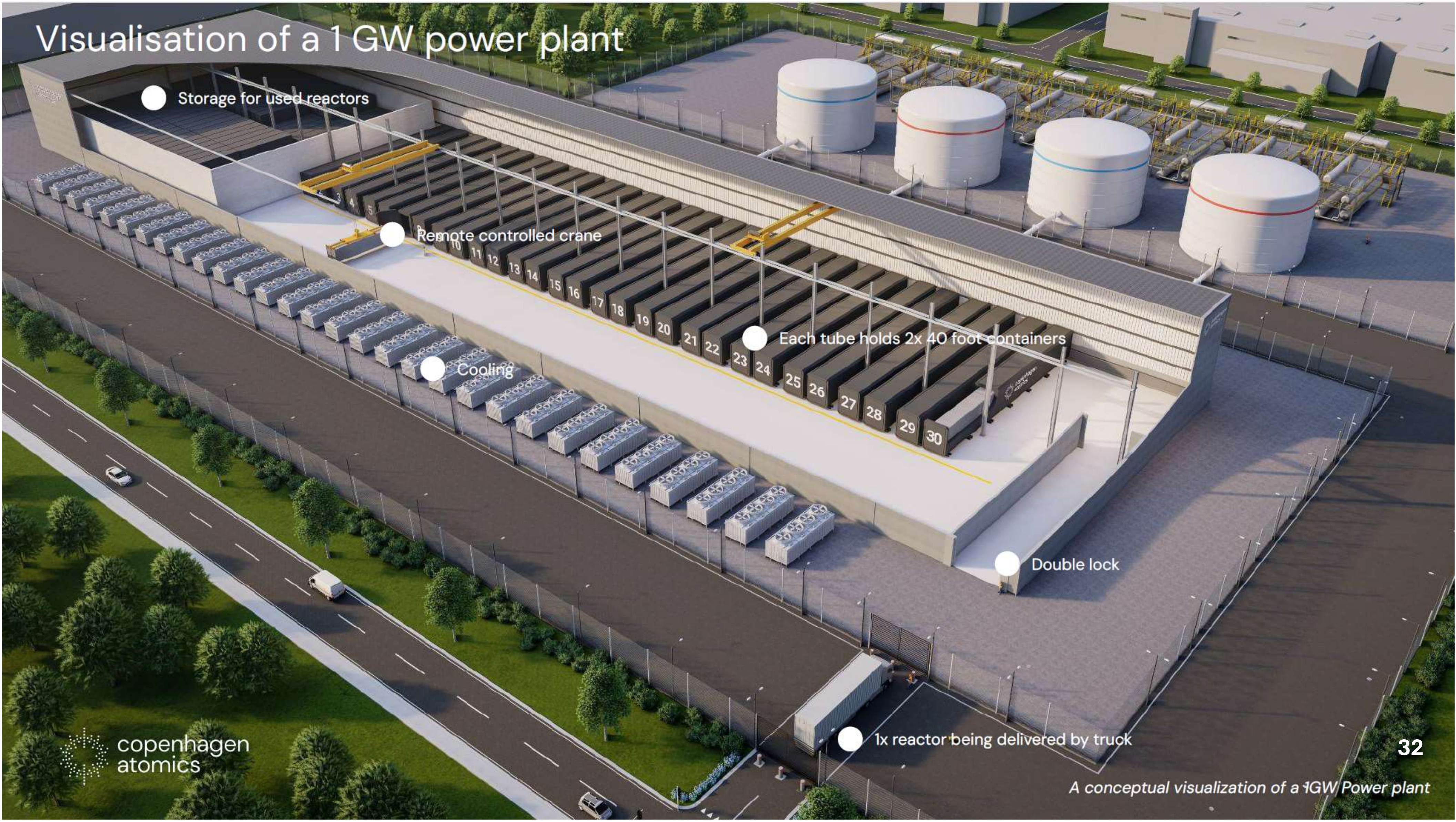
Why Erik & Thomas-Jam agree the best “workhorse reactor to do the bulk of the work for energy transition” should be a Thorium liquid-fueled molten salt reactor:

- One economic design that can be **mass-produced** in very large qty. on a factory assembly line
- The “**iPhone of nuclear reactors**”
- Suitable for both **electricity generation** and **process heat**.

Why MSR is better than Sodium Fast Reactors or HTGRs for Energy Transition

- Short answers:
  - Breeder reactors will ultimately be of immense importance to Energy Transition, so the technology best suited to achieving breeder reactor commercialization is what matters most.
  - The reasons MSRs will ultimately win out over Fast Sodium reactors and HTGRs derive primarily from the benefits of Thorium over HALEU or TRISO fuels.
- Long answers:
  - Are coming in ***full detail*** in next week's podcast.
- For now:
  - It's much easier and less expensive to build a thermal spectrum (slow-neutron) Thorium breeder reactor than to build a fast neutron Uranium->Plutonium breeder reactor.
  - The **fuel cost** for a HALEU-fueled fast breeder is at least 10x higher than for a Thorium MSR breeder. The LWR fuel cost is at least 100x higher.

Visualisation of a 1 GW power plant



A conceptual visualization of a 1GW Power plant

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Factory facility

9.000 m²

Office & lab space

2.000 m²

Customers

11

Team size

+75

Employees from

15 countries

Sub suppliers

+200

Accumulated component testing

+100 years

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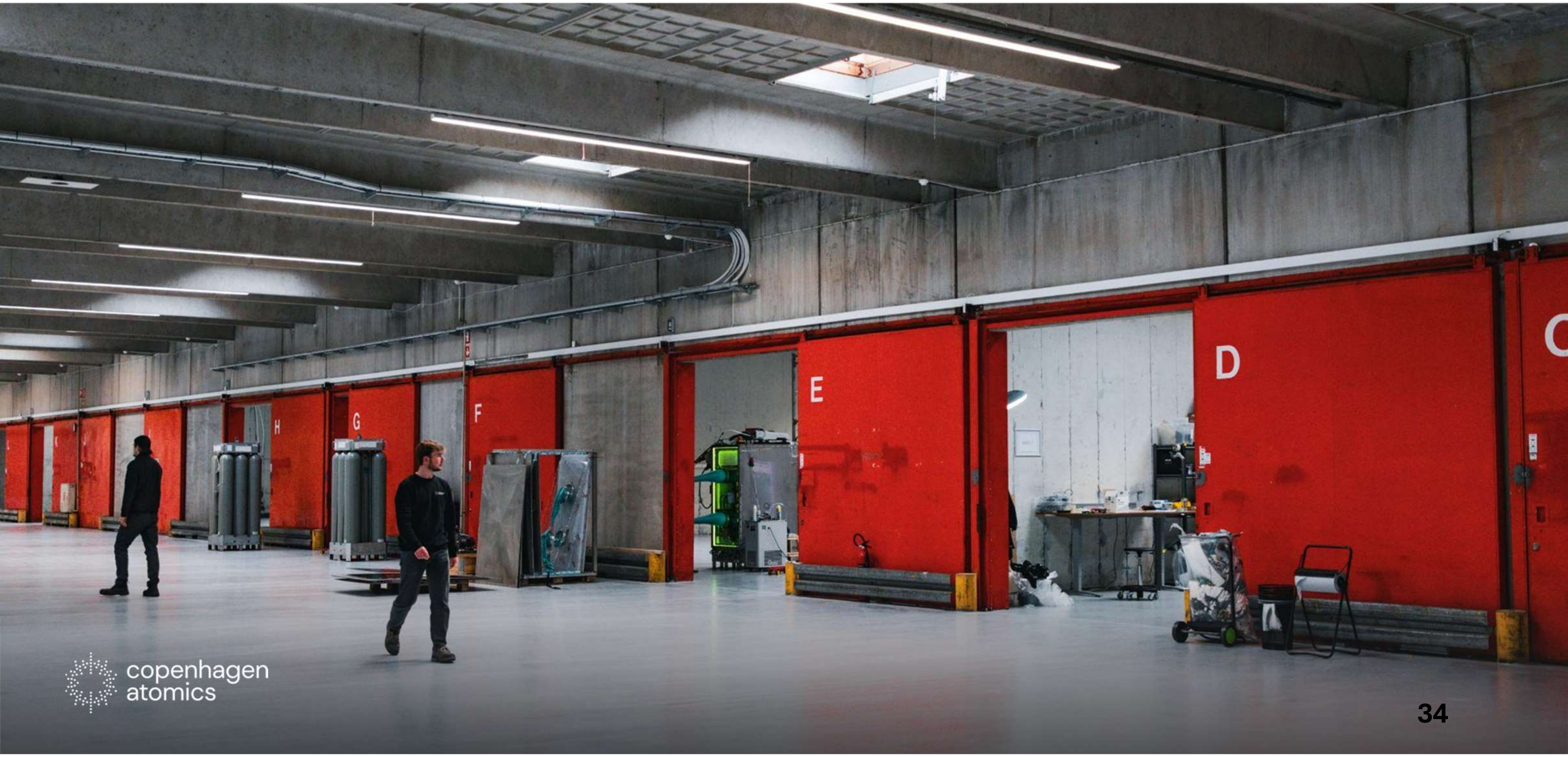
Inside Copenhagen Atomics' new facility



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Salt tanks

Pumps

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Loops

Specs

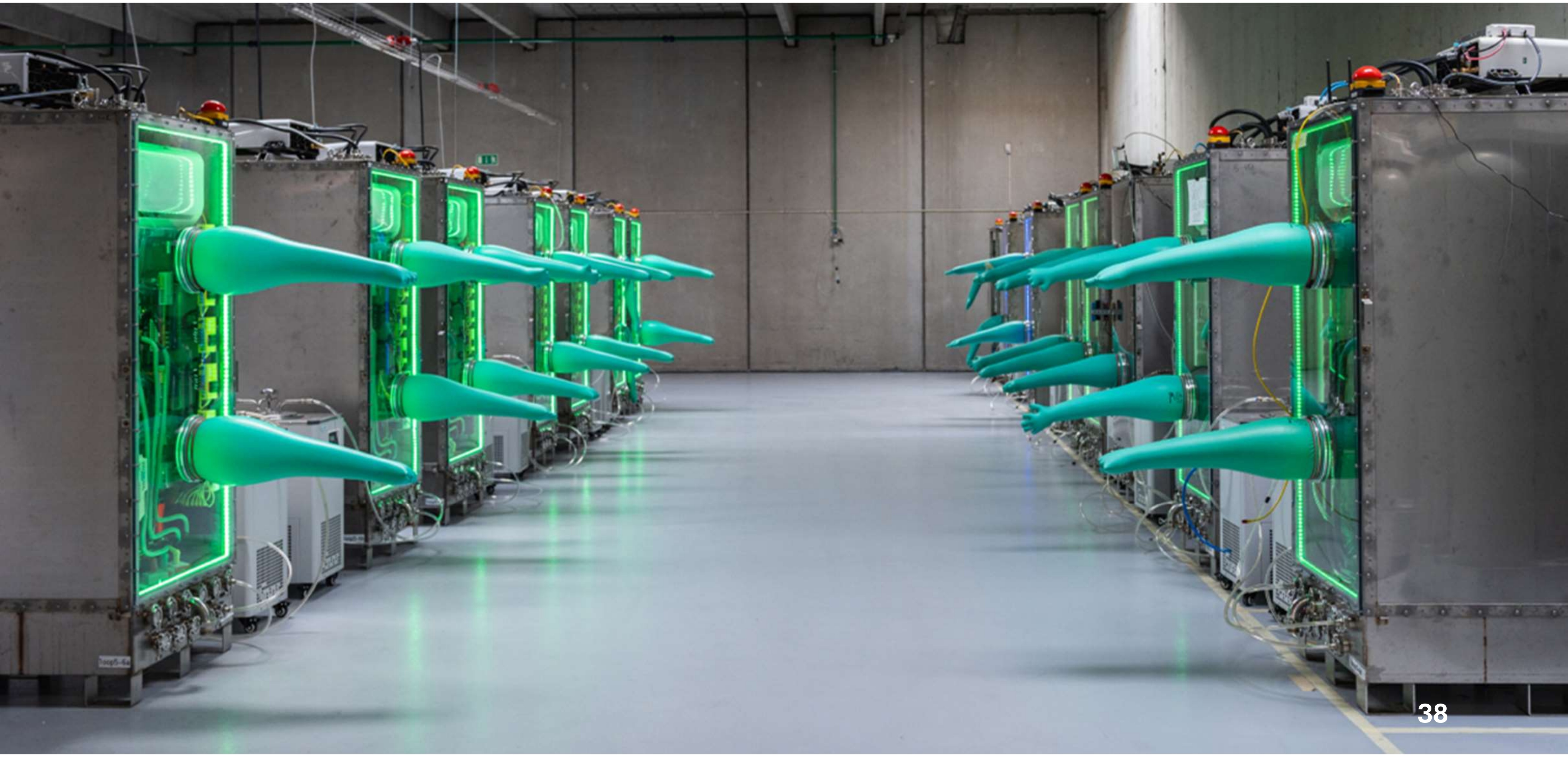
Pump
Valve
Flow meter
Pressure sensor
Salt leak sensor

1000h warranty

Upcoming

Online salt chemistry monitoring

Worlds largest molten salt test facility



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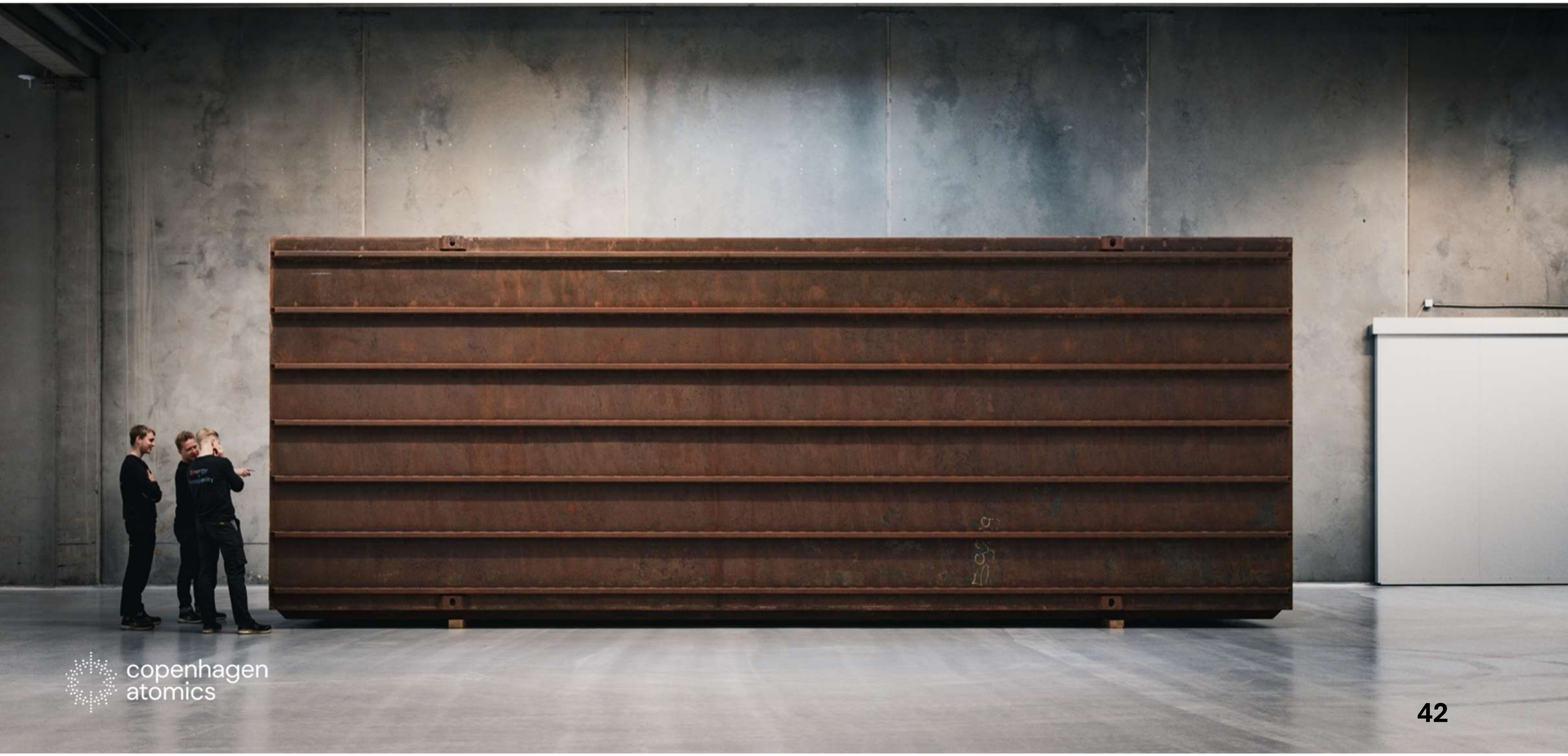
The Onion Core®

Non-fission prototype

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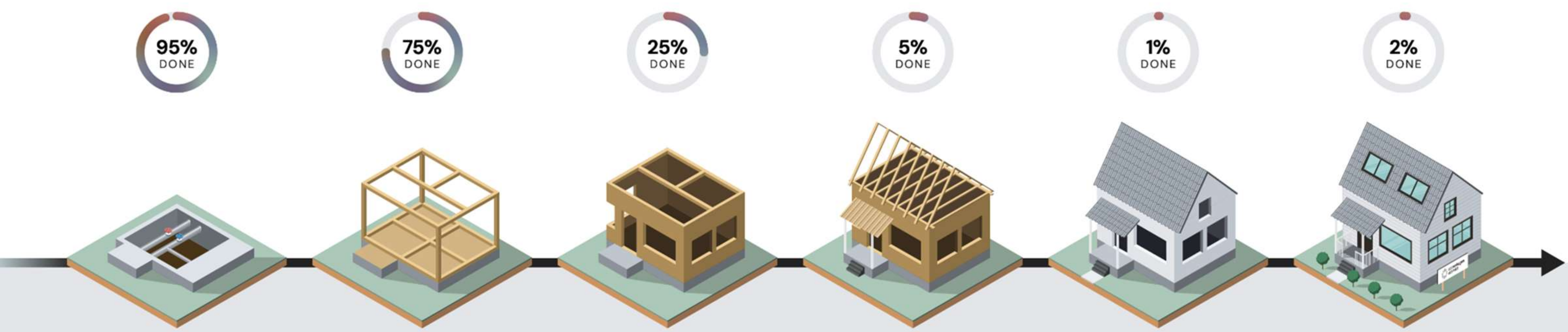
CURRENT STATUS
DECEMBER 2023



95% DONE	**75%** DONE	**25%** DONE	**5%** DONE	**1%** DONE	**2%** DONE
2015-2026	2020-2024	2023-2026	2025-2029	2029-2035	2032-2035
Technology foundation	Non-radioactive prototype reactor	1 MW Nuclear Test Reactor	First commercial reactor	Assembly line reactor production	Waster Burner Breeder Reactor

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Copenhagen Atomics' superpowers

Most pumped loops, sold to MIT and national labs

Own Lithium-7 production

Onion Core®, best in class neutron economy.

Sales to cover 25% of the running cost

Pathway to soft funding

(CO2 removal / (€200 million by 2029)

10x ROI by 2028, when we get big industrial investor

Our team is actively engaging in dialogue with international key players in the industry

DTU
Berkeley UNIVERSITY OF CALIFORNIA
MIT Massachusetts Institute of Technology
KAERI
INL Idaho National Laboratory
Argonne NATIONAL LABORATORY
TOPSOE
M UNIVERSITY OF MICHIGAN
PSI
Thorium ENERGY ALLIANCE
NATIONAL NUCLEAR LABORATORY

From left to right

Thomas Steenberg
Founder and Director
M.sc. Chemical Engineering
& Ph.D. material science

Thomas Jam Pedersen
Founder and CEO
M.sc. Electrical Engineering
& software & mathematical modelling

Peter Szabo
Founder and CAO
Ph.D. Chemical Engineering

Aslak Stubsgaard
Founder and CTO
M.sc. Theoretical Physics

Current Capital Raise:

- Copenhagen Atomics is currently in an active capital raise
  - Participation is limited to Institutional and Accredited Investors
  - Minimum investment is 100,000 EUR
- We'll give Thomas-Jam the stage at the end of *next* week's podcast covering nuclear fuels for energy transition for a proper pitch on the company and its capital needs
- If you can't wait till next week, the CFO is Mike Christiansen

  Invest@copenhagenatomics.com