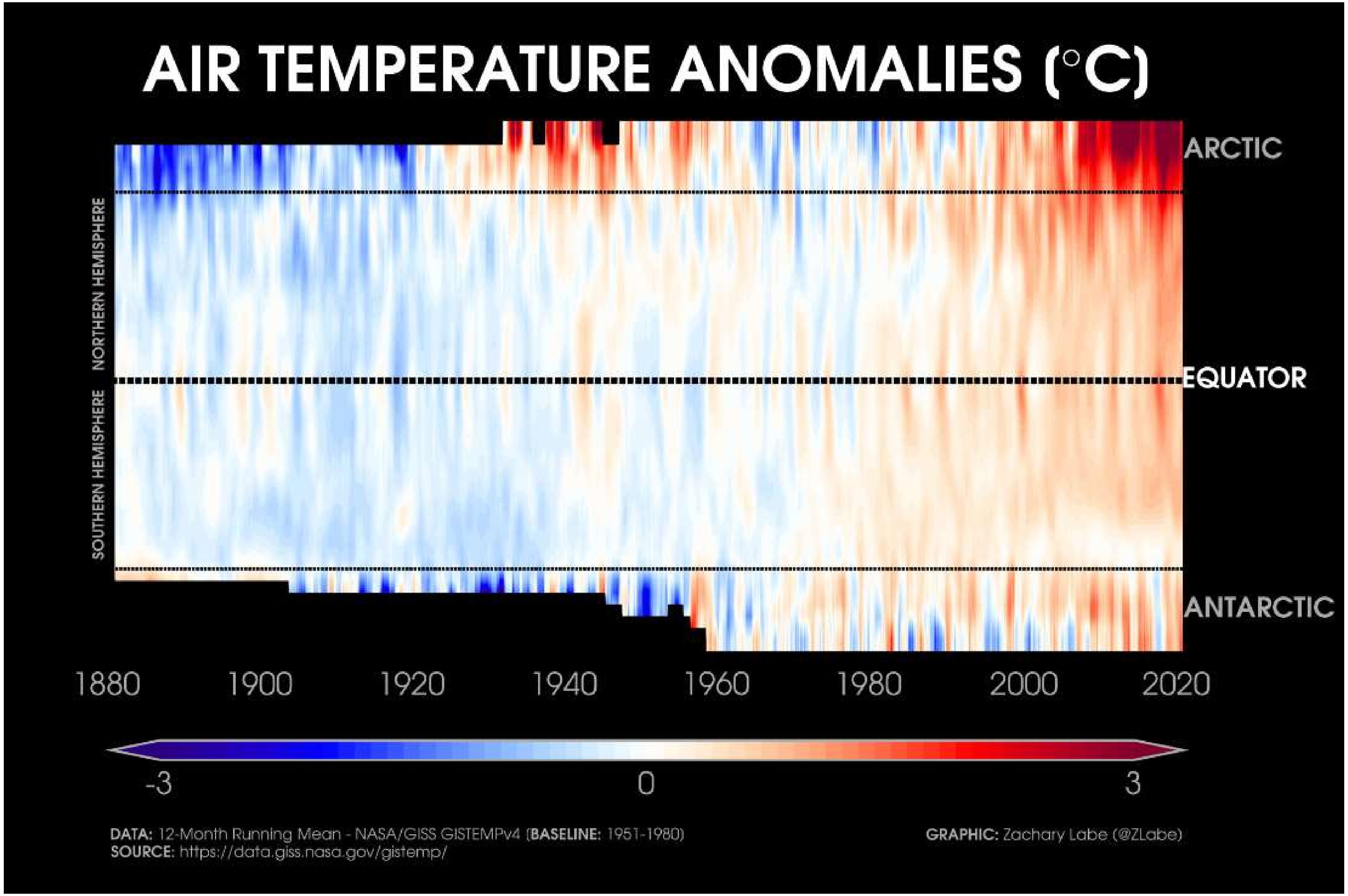
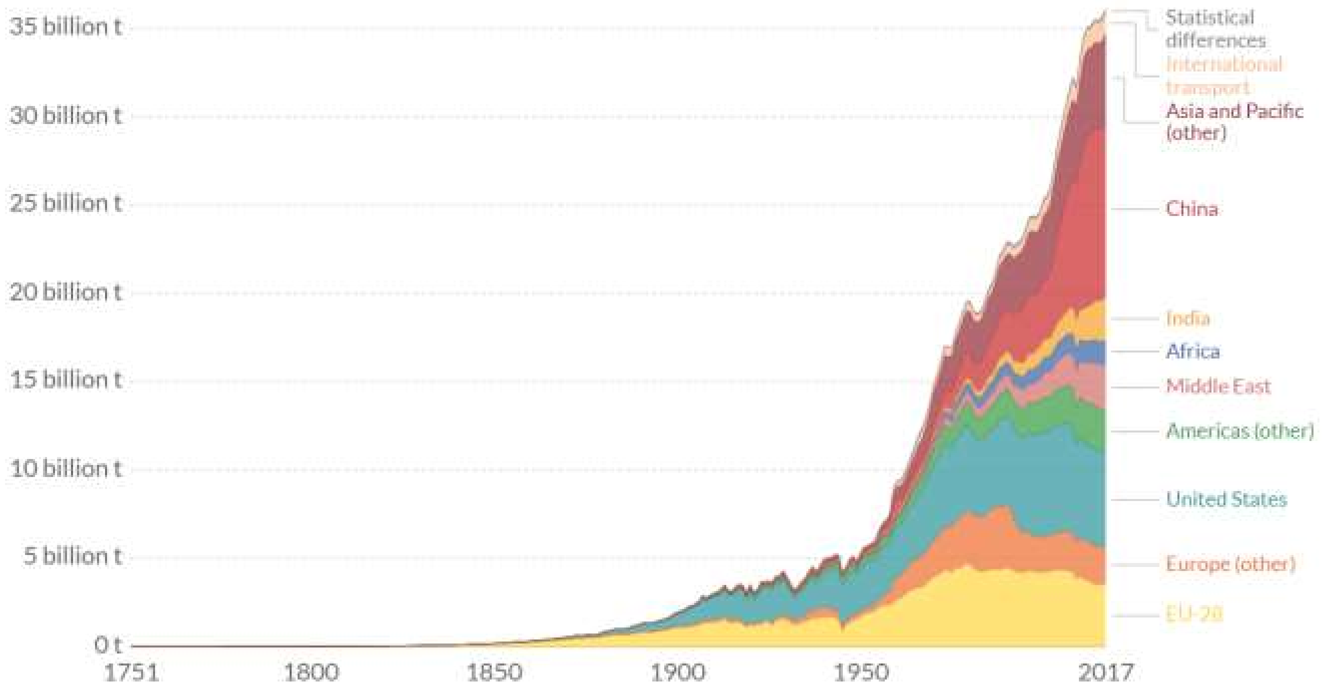
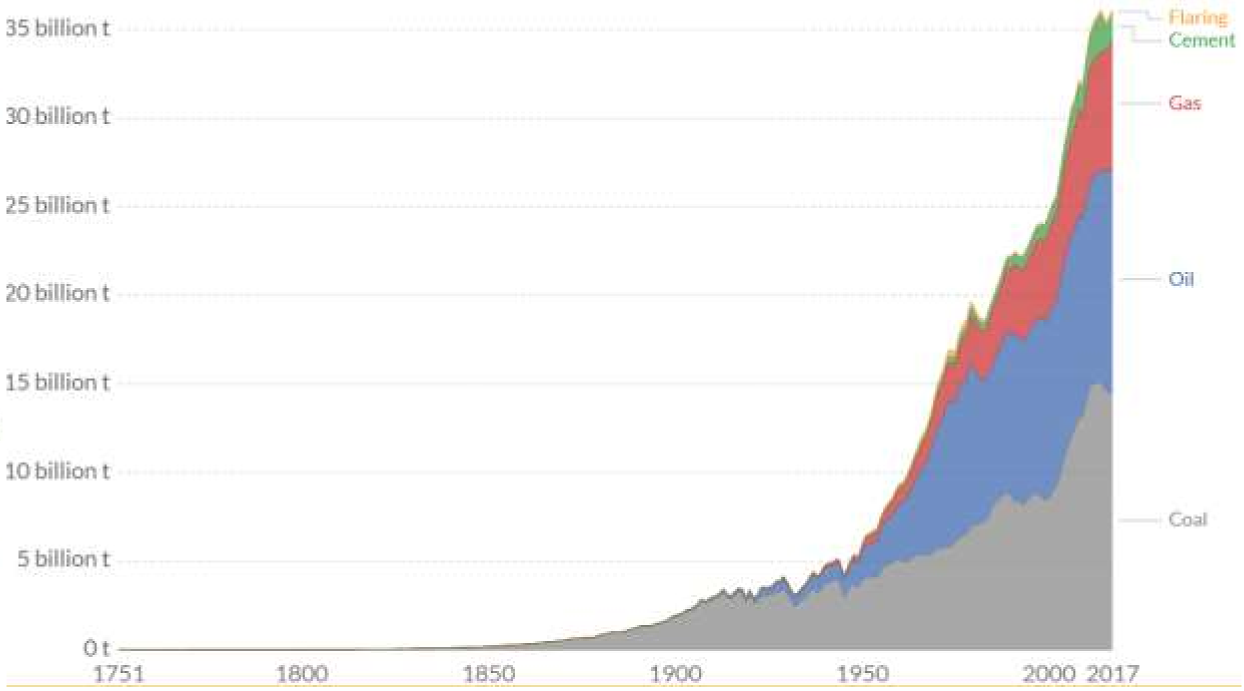

NUCLEAR : THE DREAMING REALITY
Prof. Damien ERNST
- Pierre Demet -

Climate change



The culprit: Greenhouse gas (GHG) emissions





CO2 emissions from the combustion of fossil fuels and cement production: 36 Gt (65% of GHG emissions).

Total man-made GHG emissions: 55 Gt-CO2-equivalent (Other sources: F-gases 2%, Nitrous Oxide 6%, Methane 16%, CO_2 emitted from direct human-induced impacts on forestry and other land use 11%)

Sources: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions and https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

Nuclear: One of the three credible ways to eliminate fossil fuels

Nuclear, solar and wind energy are the only types of energy that are sufficiently cheap and abundant enough to meet our energy needs in a CO2-free way.

Here are some energy-related numbers:

- Total global final energy consumption in 2016: **111,000 TWh**.
- 2.3% growth in energy use in 2018.
- Average final energy consumption per person, per day: **40 kWh**
- Average power produced by a top professionnel cyclist during a half-hour hill climb: 400 W. 100 hours of climbing needed to produce 40 kWh!
- Average energy consumption per person, per day in the **EU-28**: **100 kWh**

Why are we not including biomass?

A typical forest can absorb energy from the sun at an average rate of 0.2 W/m^2 (photovoltaic panels can harvest 50 W/m^2 in the best locations).

For producing 111000 TWh of energy, 63 million km^2 of forest is needed.

Earth's surface: 510,1 million km^2
Ocean surface: 360 million km^2
Land surface: 134 million km^2
Forest surface: 40 million km^2

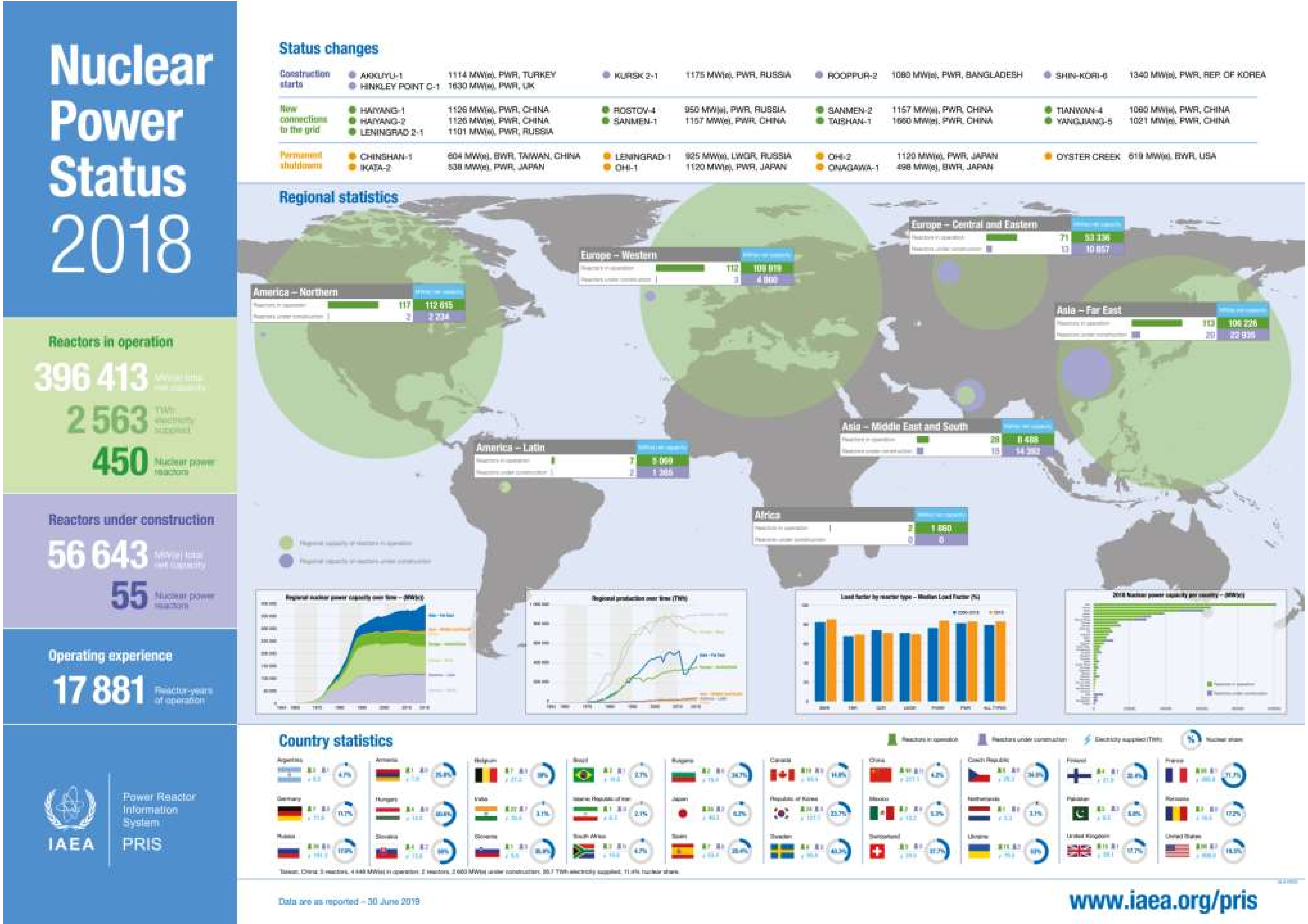
Source: https://metro.co.uk/2019/04/19/heartbreaking-moment-orangutan-takes-digger-david-attenboroughs-new-documentary-9258461/

Producing 111,000 TWh of electricity using nuclear power

<u>European pressurized reactor (EPR)</u>

- Power: 1650 MWe, 4500 MWth.
- Load factor: 90%
- Fuel: 25 tons of enriched uranium per year (5%). 150 tons of natural uranium per year (when using MOX fuel that allows to use 25% less uranium through recycling).
- Two are in operation in Taishan (China). Connection to the grid of the Olkiluoto EPR (Finland) in July 2020. Flamanville in 2022.

To produce 111,000 TWh of electricity, we would need, annually, **8532** EPRs.



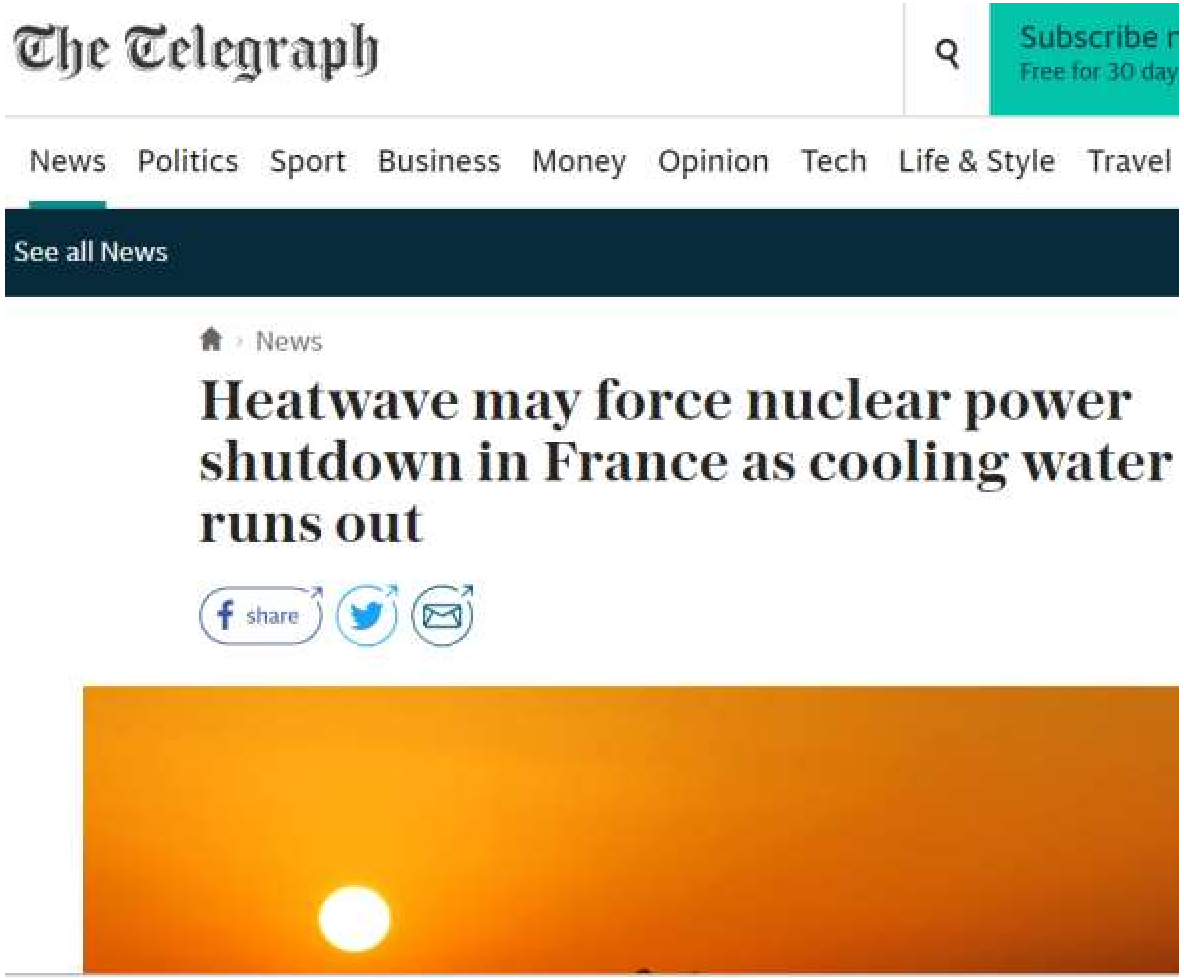
Nuclear Power Status 2018
Reactors in operation
396 413
2 563
450 Nuclear power reactors
Reactors under construction
56 643
55 Nuclear power reactors
Operating experience
17 881 Reactor-years of operation
IAEA
Power Reactor Information System
PRIS
Status changes
Construction starts
AKKUYU-1 1114 MW(e), PWR, TURKEY
HINKLEY POINT C-1 1630 MW(e), PWR, UK
KURSK 2-1 1175 MW(e), PWR, RUSSIA
ROOPPUR-2 1080 MW(e), PWR, BANGLADESH
SHIN-KORI-6 1340 MW(e), PWR, REP. OF KOREA
New connections to the grid
HAIYANG-1 1126 MW(e), PWR, CHINA
HAIYANG-2 1126 MW(e), PWR, CHINA
LENINGRAD 2-1 1101 MW(e), PWR, RUSSIA
ROSTOV-4 950 MW(e), PWR, RUSSIA
SANMEN-1 1157 MW(e), PWR, CHINA
SANMEN-2 1157 MW(e), PWR, CHINA
TAISHAN-1 1660 MW(e), PWR, CHINA
TIANWAN-4 1060 MW(e), PWR, CHINA
YANGJIANG-5 1021 MW(e), PWR, CHINA
Permanent shutdowns
CHINSHAN-1 604 MW(e), BWR, TAIWAN, CHINA
IKATA-2 538 MW(e), PWR, JAPAN
LENINGRAD-1 925 MW(e), LWGR, RUSSIA
OHI-1 1120 MW(e), PWR, JAPAN
OHI-2 1120 MW(e), PWR, JAPAN
ONAGAWA-1 498 MW(e), BWR, JAPAN
OYSTER CREEK 619 MW(e), BWR, USA
Regional statistics
America – Northern 117 112 615 2 2 234
Europe – Western 112 3
Europe – Central and Eastern 71 53 336 13 10 857
Asia – Far East 113 106 226 20 22 935
Asia – Middle East and South 28 15
America – Latin 7 2
Africa 2 1 860 0 0
Country statistics
Data are as reported – 30 June 2019
www.iaea.org/pris

Not enough water for cooling down these reactors?

When an EPR is running, 2850 MW of heat power needs to be dissipated.

Correspond to the heat power needed for the vaporisation of 1.162 m^3/s of water!

For the whole EPR fleet (with a 90% load factor), the amound of power needed would be 8922.7 m^3/s



Vaporization of water at 20 °C requires 0.685 kWh/kg.

Congo river:
41000 m³/s

Mississipi:
16790 m³/s

Danube:
6500 m³/s

Power plant can cool down with a fully closed-circuit for water!

The 375 MW Twinerg power plant (2002-2016). The excess heat for district heating was dissipated in the atmosphere through a heat exchanger (on the left in the image).

But is there enough uranium?

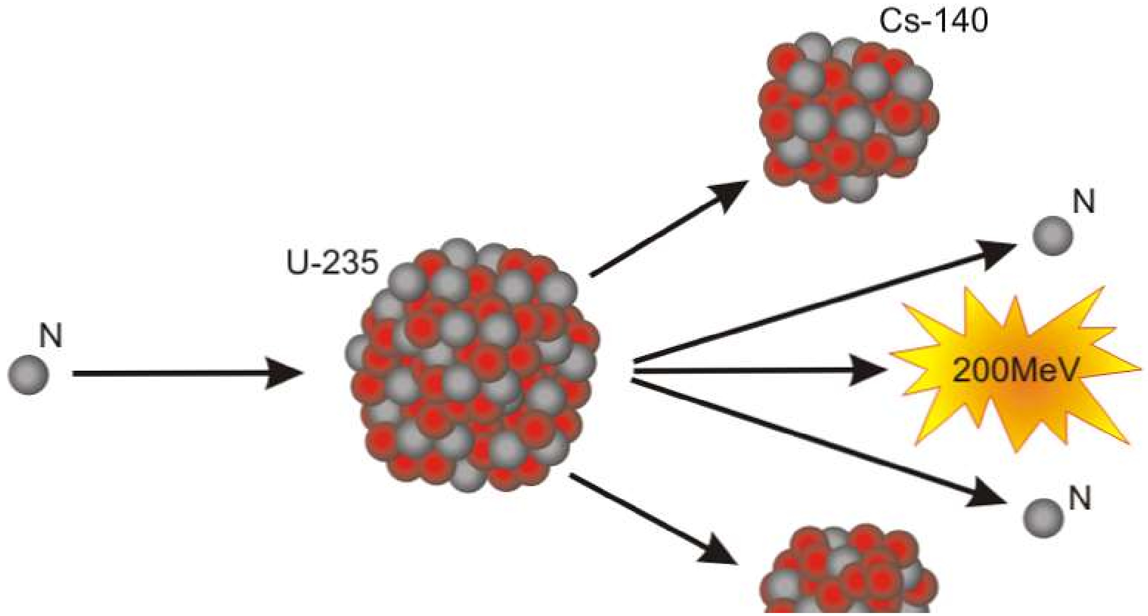
Identified resources in Uranium : 8Mt (at a price < 260$/kgU).

Evaluated terresterial ultimate resources: 72Mt (<260$/kgU).

These resources provide to our fleet of 8532 EPR:

$\frac{72*10^6}{8532*150}$ = 56 years of autonomy.

Not that much because there is only 0.7% of ^{235}U in uranium ore and 99.3% of ^{238}U which is not fissile.



Fission of an atom generates in average around 200 MeV of energy.
186 MeV directly.
14 MeV afterwards due to a degradation of fission products.
Many different types of fission products can be produced.

Source: AIEA : Uranium 2018, Resources, Production and Demand

But wait - there is plenty of uranium in the ocean

Uranium in the ocean: 4,5 Gt (0.003 g per ton of sea water).

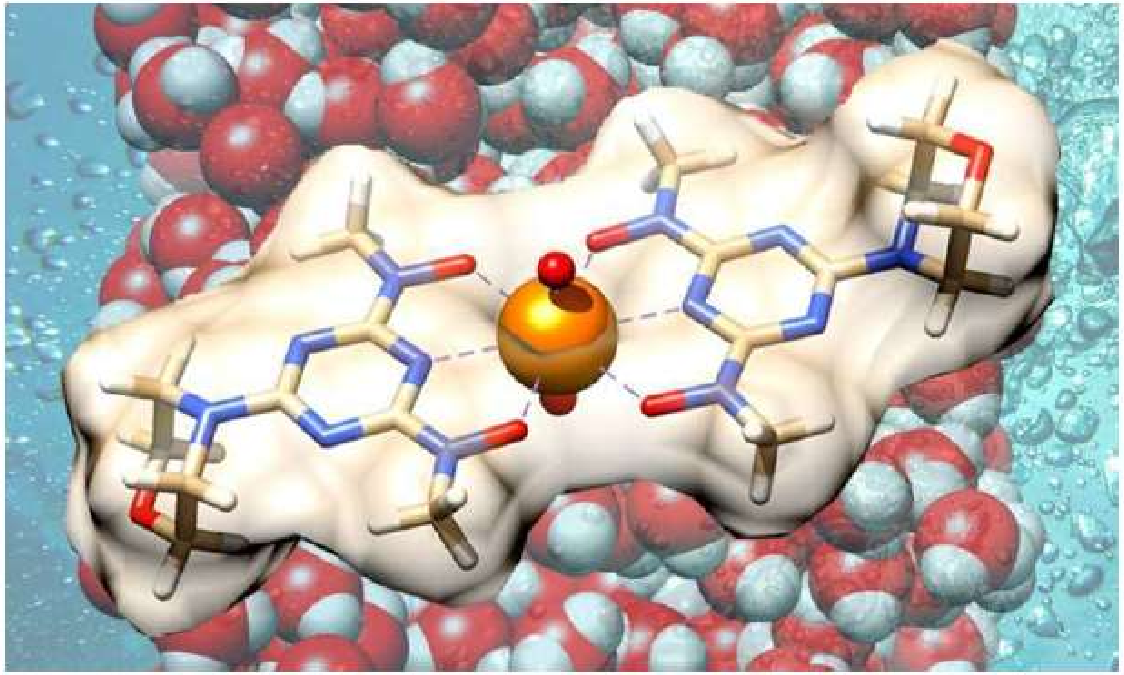
Let us assume we can extract 10% of this resources - 450 million tons of uranium.

This equates to 350 years of fuel for our fleet of 8532 EPR.

MAY 16, 2019

Bio-inspired material targets oceans' uranium stores for sustainable nuclear energy

by Ashley C Huff, Oak Ridge National Laboratory



Combining fundamental chemistry with high-performance computing resources at ORNL, researchers demonstrate a more efficient method for recovering uranium from seawater, unveiling a prototype material that outperforms best-in-class uranium adsorbents. Credit: Alexander Ivanov/Oak Ridge National Laboratory, U.S. Dept. of Energy.

Scientists have demonstrated a new bio-inspired material for an eco-friendly and cost-effective approach to recovering uranium from seawater.

A research team from the Department of Energy's Oak Ridge and Lawrence Berkeley National Laboratories, the University of California - Berkeley, and the University of South Florida developed a material that selectively binds dissolved uranium with a low-cost polymer adsorbent. The results, published in *Nature Communications*, could help push past bottlenecks in the cost and efficiency of extracting uranium resources from oceans for sustainable energy production.

Source: The Pacific Northwest National Laboratory, Global energy policy research

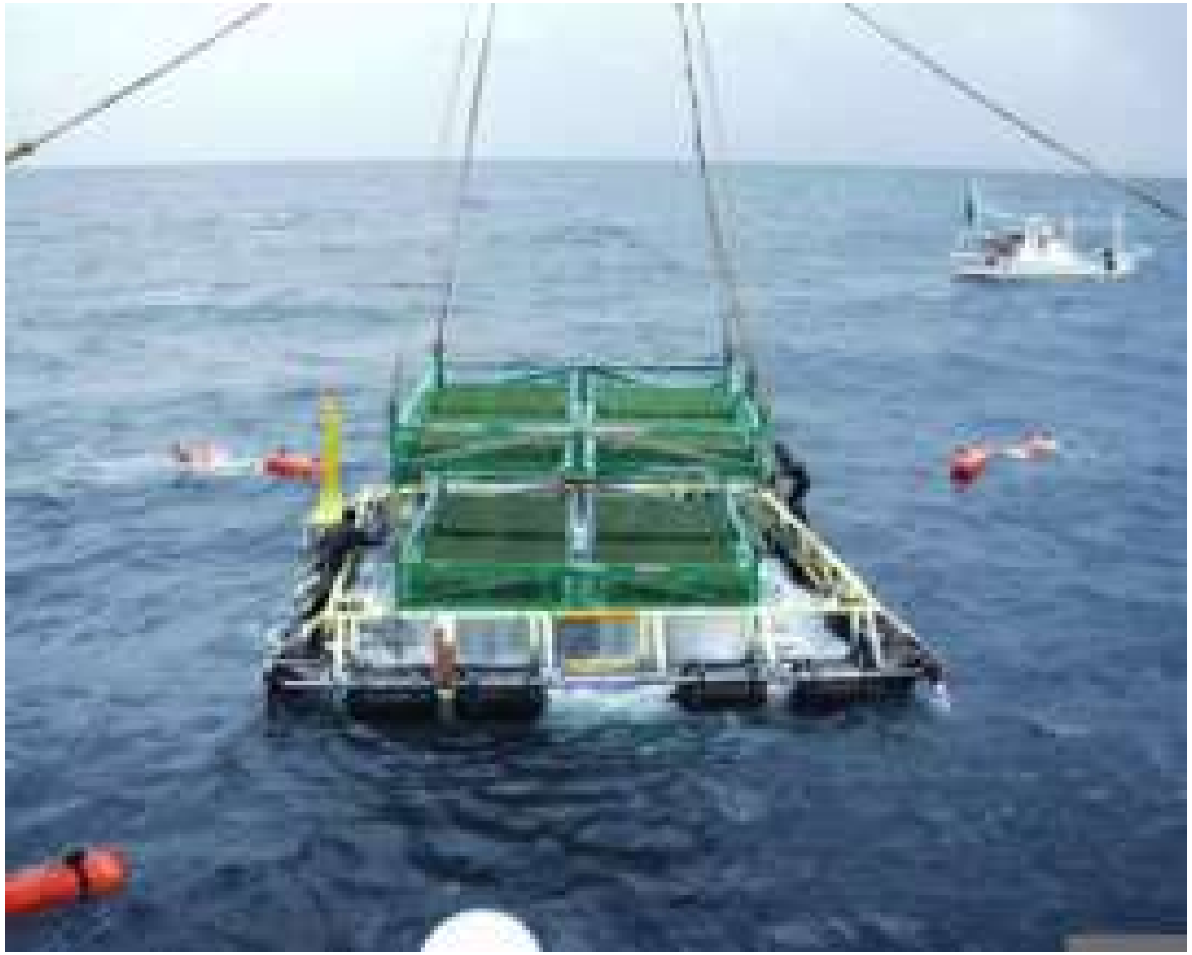
For this **Japanese experiment** (in the late 1990s),
1 kg of uranium was collected over 240 days or around 1.5 kg per annum.

Dimension of the device: 8 m x 8 m = 64 m^2.

8532 EPRs needs 150 x 8532 = 1,279,800 t of uranium per year.

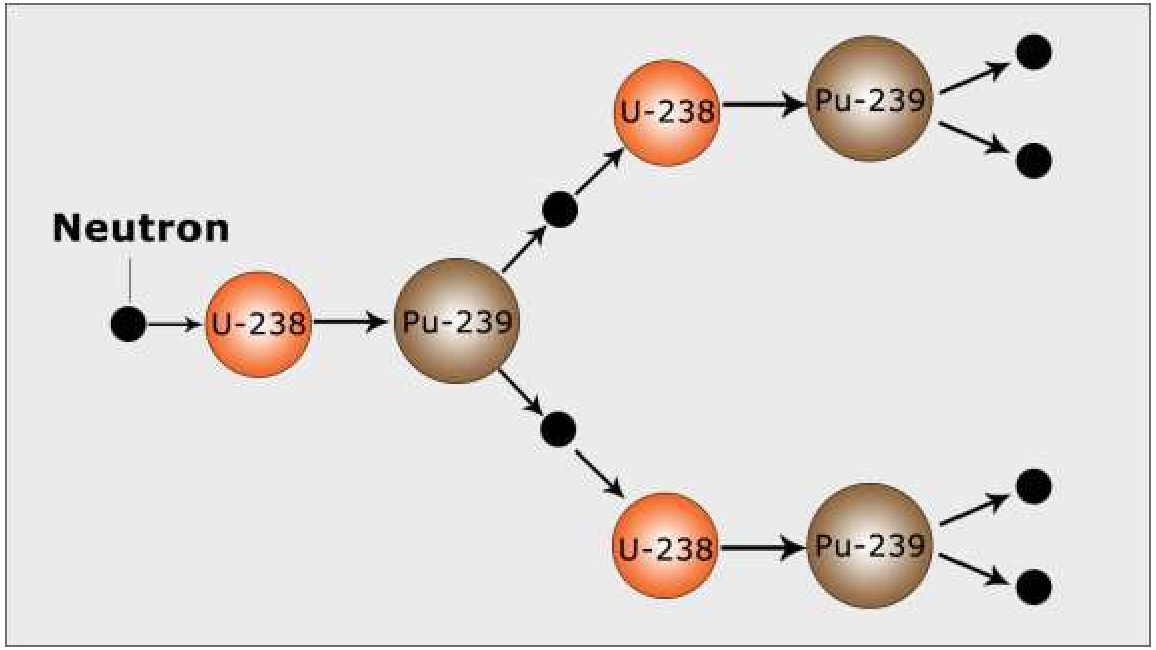
Size of the collecting device:

$$\frac{1,279,800,000}{1,5 * 1,000,000} = 853\ km^2$$



And there are fast-neutron (breeder) reactors

Fast-breeder reactors could, in principle, extract almost all of the energy contained in uranium, decreasing fuel requirements by at least a factor of 50 compared to widely used Pressured Water Reactors.

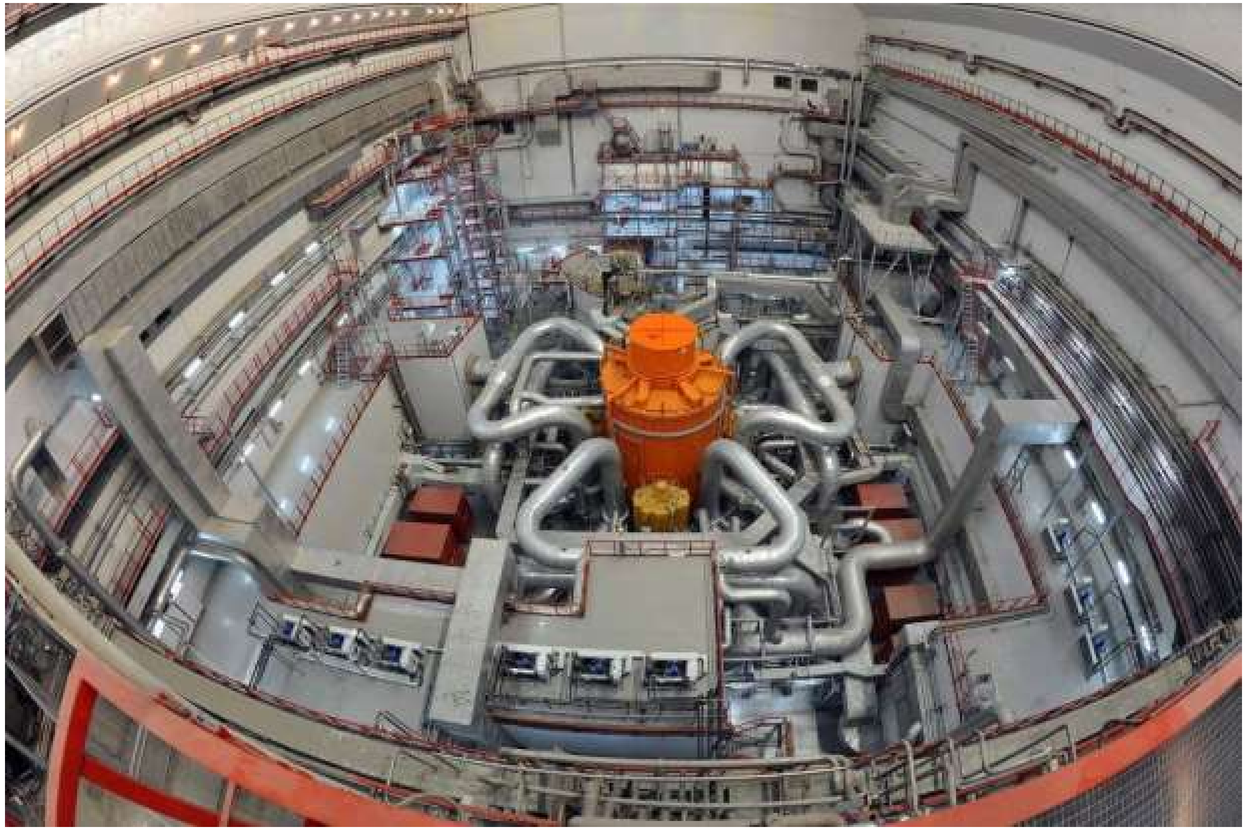


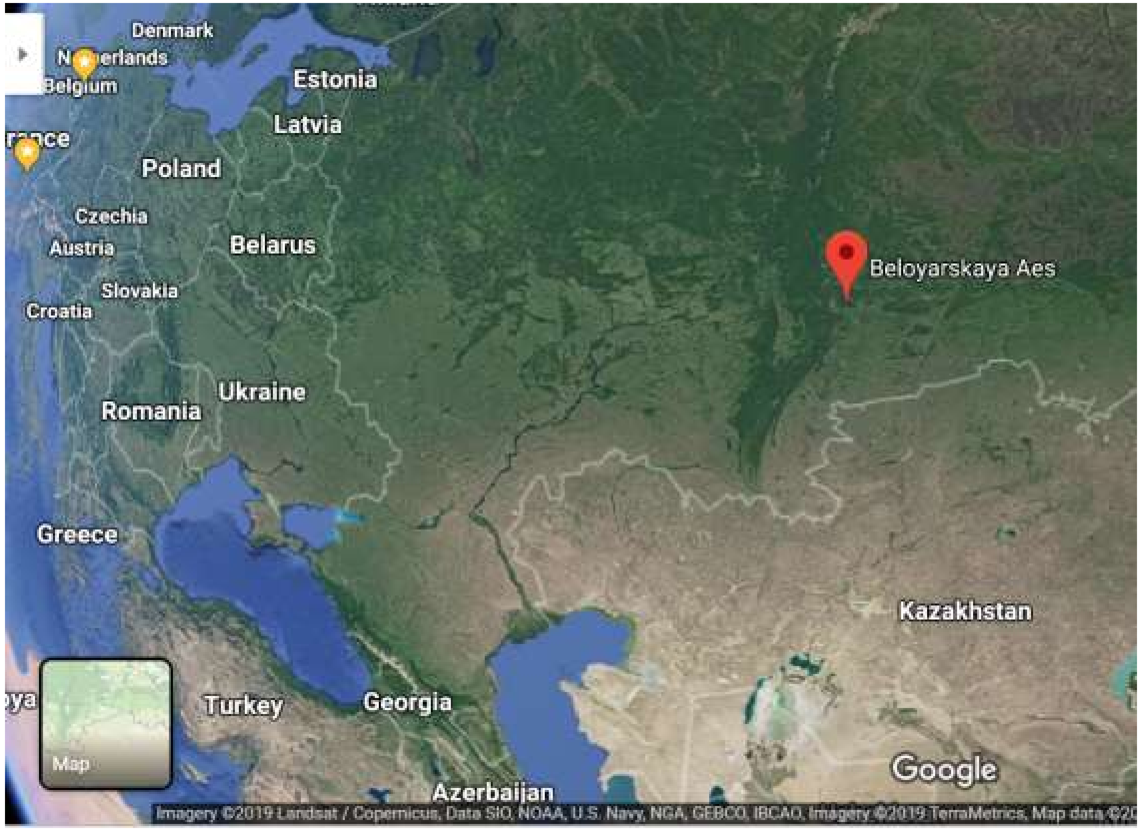
Land reserves: 56*50 = **2800 years**

Land reserves + 10% sea water reserves:
(56 + 350)*50 = **20,300 years**

Two commercially operating fast-neutron reactors: the BN-600 reactor (560 MWe) and the BN-800 reactor (880 MWe). Sodium-cooled reactors.

BN-800 Beloïarsk reactor





NUCLEAR ENGINEERING INTERNATIONAL

France cancels ASTRID fast reactor project

2 September 2019

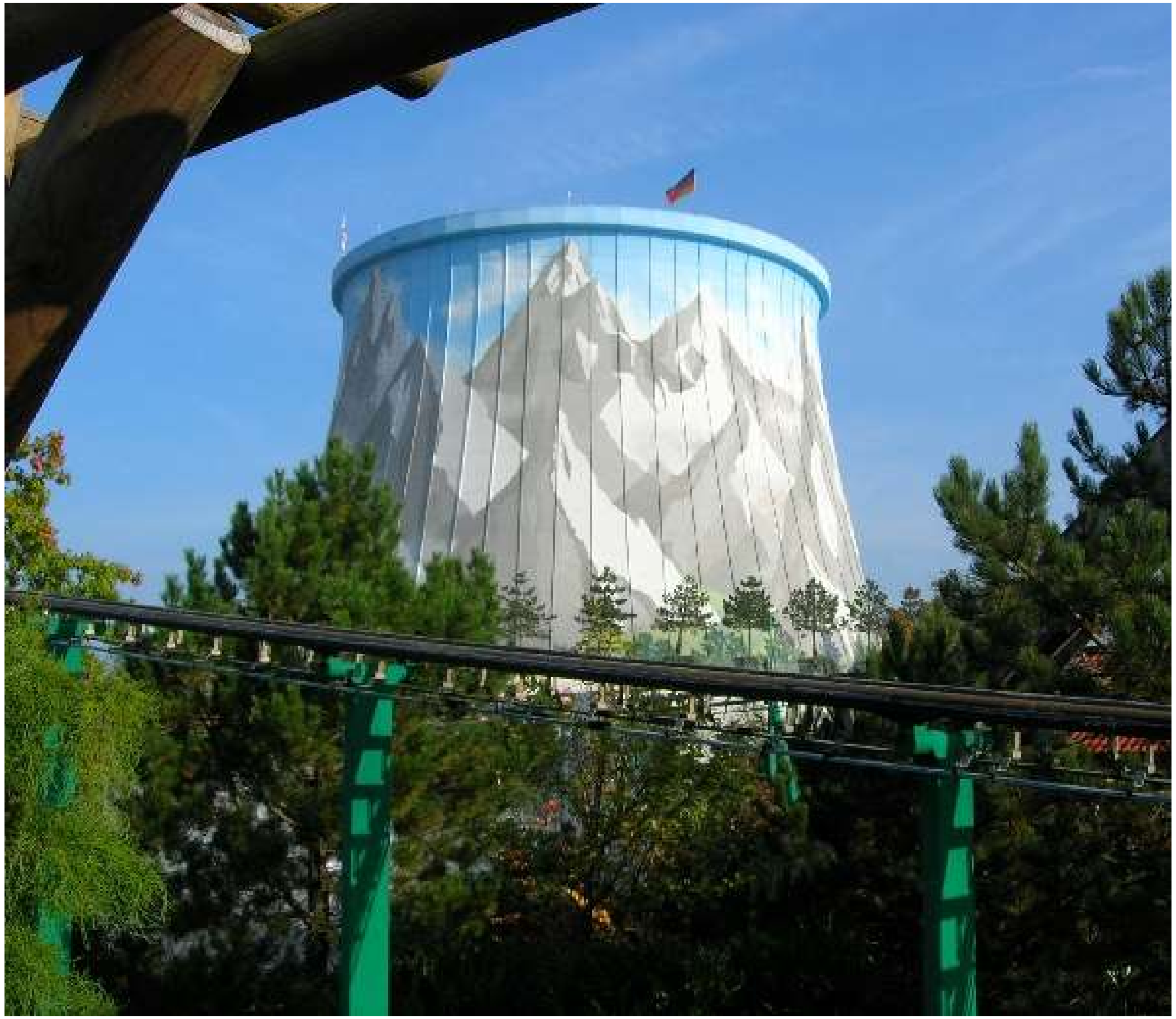
Print   Email

France's Commissariat a l'energie atomique et aux energies alternatives (CEA - Atomic & Alternative Energies Commission) is abandoning plans to build its prototype fast-breeder for the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project, Le Monde reported on 30 August.

Some design studies still in progress will continue this year but will be shelved after the 25-person unit coordinating the programme was closed in the spring. CEA told Le Monde that "the project to build a prototype reactor is not planned in the short or medium term" but will be deferred until " the second half of the century". According to the Court of Auditors, nearly €738 million ($811m) had been invested in this plan by the end of 2017, including nearly €500 million as a large loan from the Investments for the Future programme. "We saw preparatory projects stop, and we saw that financing for the prototype no longer appeared in the budgets," said Didier Guillaume, CFDT central union delegate at CEA.

In November 2018, CEA had already said it was considering reducing Astrid's capacity from the originally planned 600MW commercial size to a 100-200MW research model. CEA's recent decision confirms reports in

Wunderland Kalkar



The SNR-300 was a fast breeder sodium cooled nuclear reactor built near the town of Kalkar (Germany).

The reactor was completed in 1985 but never taken online. SNR-300 was to output 327 megawatts. The project cost about 3.5 billion €. 250 million € financed by Belgium.

The site is now the location of a theme park, Wunderland Kalkar.

Safety issues of nuclear power

Chernobyl (April 1986)

Fukushima (March 2011)

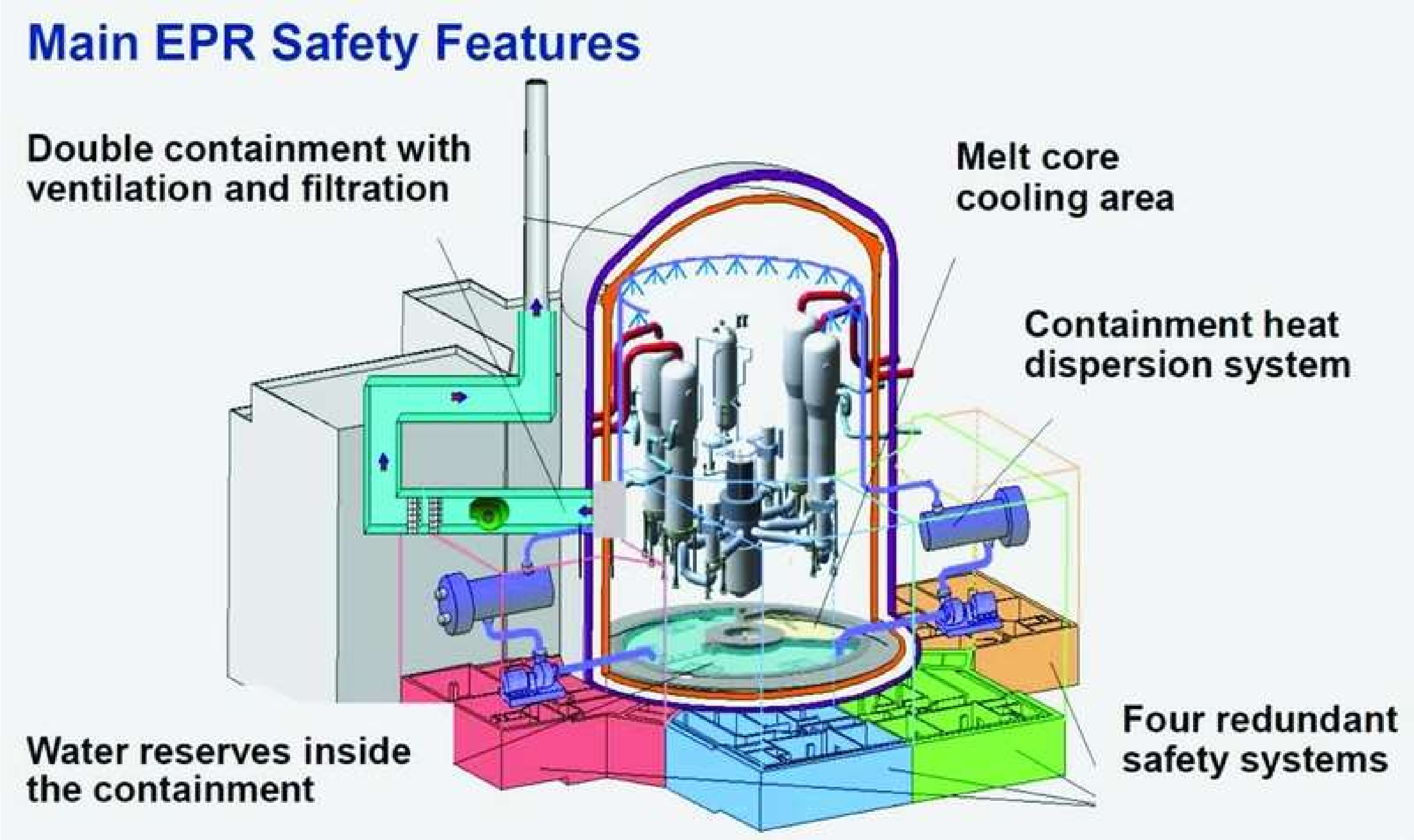
30 years after Chernobyl disaster, wildlife is flourishing in radioactive wasteland

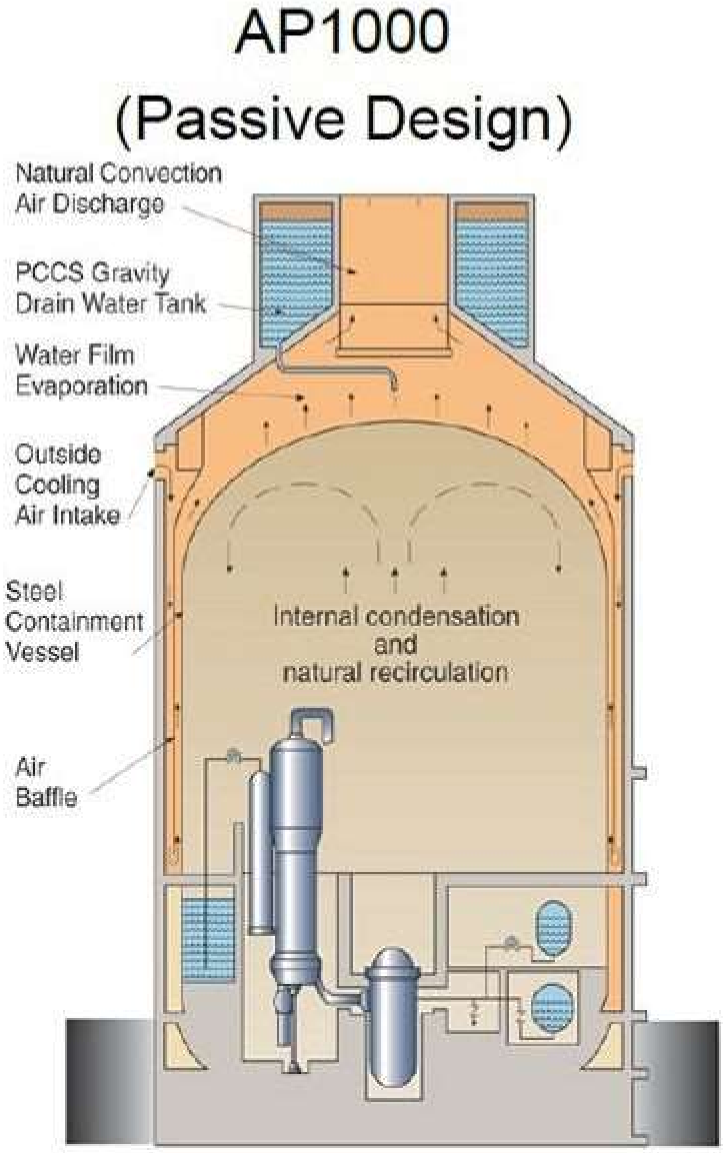
Los Angeles, today

Chernobyl, today

Source: https://www.telegraph.co.uk/news/2016/04/23/wildlife-returns-to-radioactive-wasteland-of-chernobyl/

Gen III reactors safer

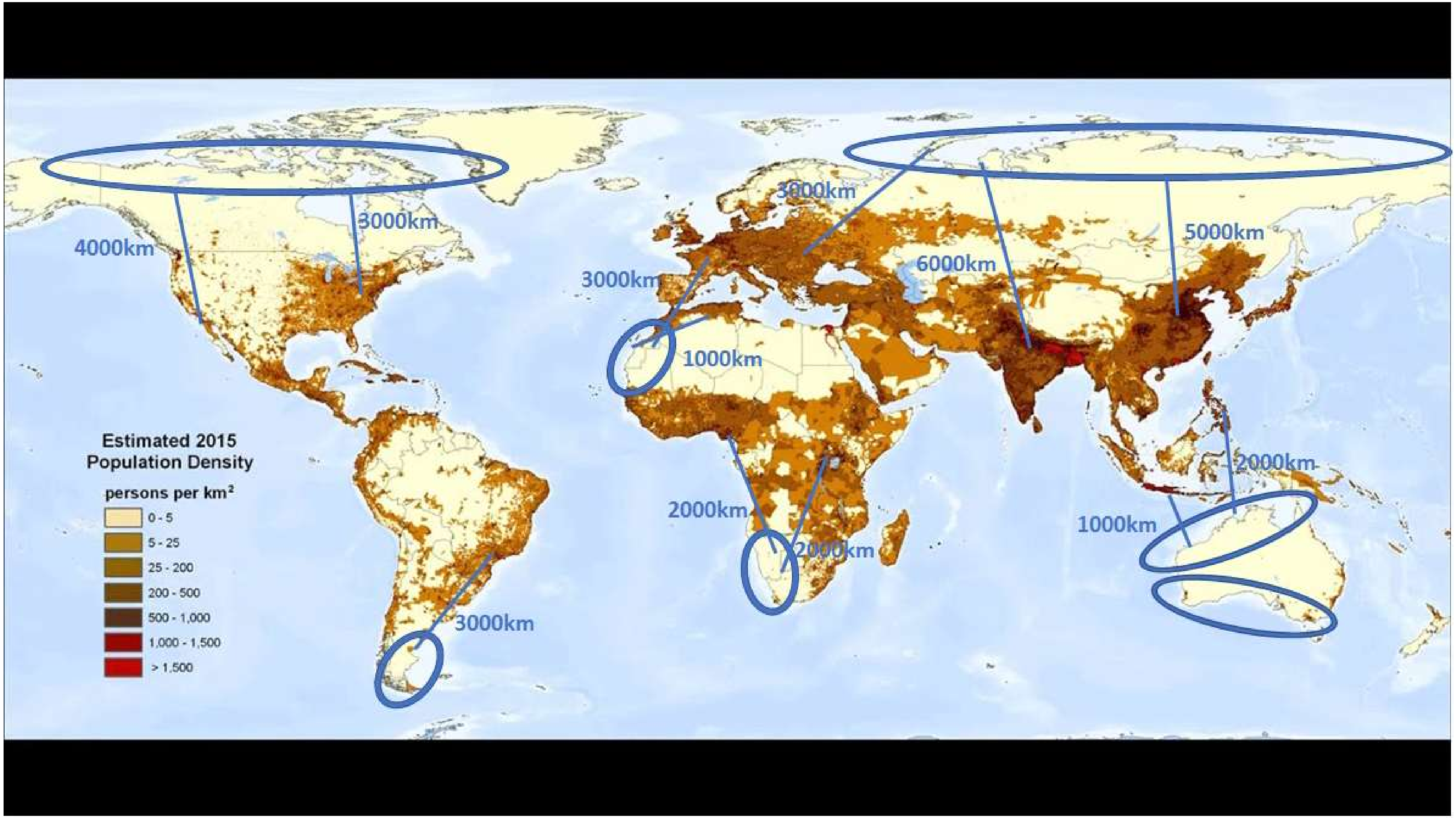




Gen IV reactors even safer

Two interesting features for Myrrha: (a) when the proton accelerator stops, the reaction stops immediately (b) this ADS-type of reactor makes it easier to burn safely large quantities of minor actinides whose fission produces little delayed neutrons (c) the lead-bismuth coolant is opaque to gamma radiation, but transparent to neutron flux; it melts easily at a low temperature, but does not boil until an extremely high temperature is reached (1740 °C); it does not greatly expand or contract when exposed to heat or cold; it has a high heat capacity; it will naturally circulate through the reactor core without pumps being required - whether during normal operation or as a means of residual decay heat removal; and it will solidify once decay heat from a used reactor has dropped to a low level.

Put these reactors where noboby lives!



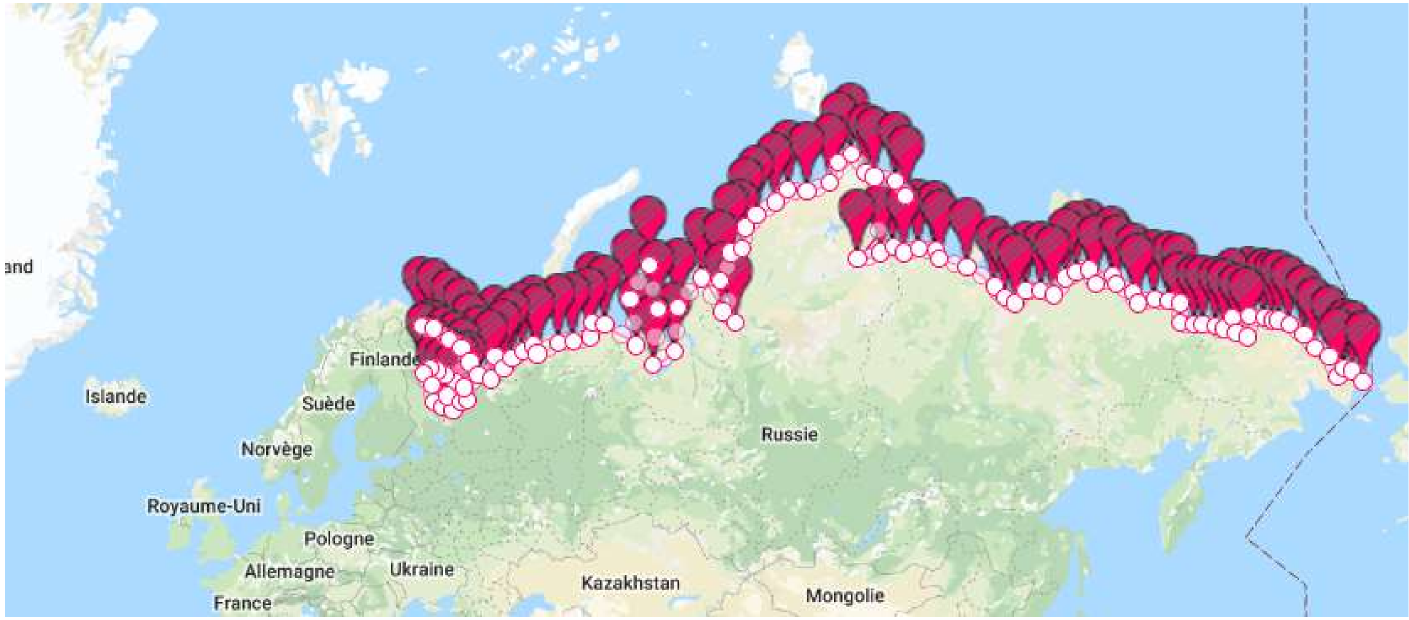
Good bye pipelines, hello power lines

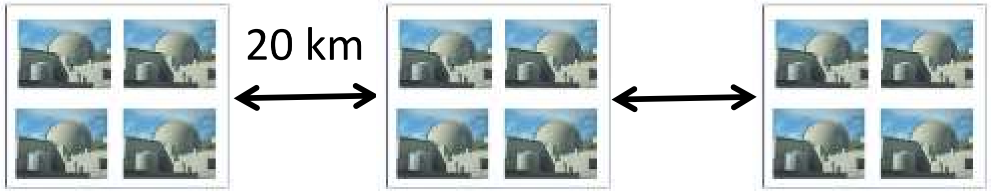
Northern Russia: about 12,000km of coastline.

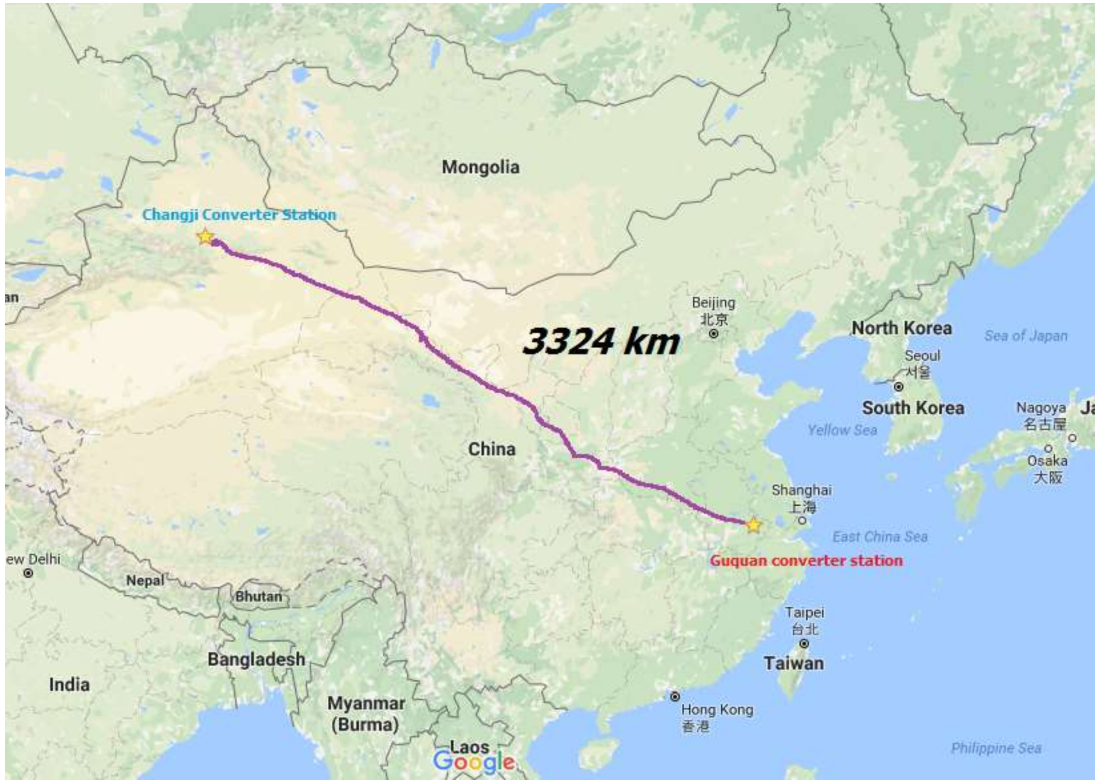
Around 2400 EPRs (600*4) could be built in groups of 4 EPRs spaced 20 km apart.

In case of an INES 7 type incident, only four generators would be in an exclusion zone.

Chernobyl accident in 1986 with reactor 4. Reactor 2 closed in 1991, reactor 1 in 1996 and reactor 3 in 2000 => Even if the reactors were all grouped together, it is very unlikely that a major incident on one would endanger the integrity of the others.







Construction of an ultra-high voltage line (UHVDC, 1100kV, 12GW, 3000km) between Changji and Guquan, China

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INTERVIEW ENERGY ENVIRONMENT

Governments at COP24 should focus on building a global electricity grid – Prof. Damien Ernst

11 December 2018

by *Steve Gillman*

Republish

Prof. Damien Ernst says current emissions-cutting activities are not working and it's time to consider new strategies. Image credit - University of Liège

More info on the Global Grid: [Global electricity network - Feasibility study]

Hit parade of the less expensive new nuclear power plants

#9 Flamanville

Reactor(s): 1 EPR
Power: 1650 MWe
Price: 12,6G€
Construction: 2007-?
Price per MWe: **7,6 million €/MWe**

#8 Hinkley Point

Reactor(s): 2 EPR
Power: 2x1650 MWe
Price: 22,5G€
Construction: 2018-?
Price per MWe: **6,8 million €/MWe**

#7 Olkiluoto

Reactor(s): 1 EPR
Power: 1650MWe
Price: 8,5G€
Construction: 2005-?
Price per MWe: **5,2 million €/MWe**

#6 Barakah

Reactor(s): 4 APR-1400 (KEPCO)
Power: 4x1400 MWe
Price: 24,4G€
Construction: 2010-?
Price per MWe: **4,3 million €/MWe**

#5 Fuqing

Reactor(s): 2 Hualong 1 (CNNC and CGNPG)
Power: 2x1090 MWe
Price: 5,7G€
Construction: 2015-?
Price per MWe: **3,2 million €/MWe**

#4 Leningrad

Reactor(s): 2 VVER-1200 (Rosatom)
Power: 2x1085 MWe
Price: 4,9G€
Construction: 2008-?
Price per MWe: **2,8 million €/MWe**

#3 Sanmen

Reactor(s): 2 AP1000 (Westinghouse)
Power: 2x1000 MWe
Price: 5,5G€
Construction: 2009-2019
Price per MWe: **2,75 million €/MWe**

#2 Taishan

Reactor(s): 2 EPR
Power: 2x1650 MWe
Price: 8G€
Construction: 2009-2018
Price per MWe: **2,4 million €/MWe**

#1 Beloyarsk

Reactor(s): 1 BN-800
Power: 800 MWe
Price: 1,8G€
Construction: 2006-2016
Price per MWe: **2,2 million €/MWe**

Nuclear energy in €/MWh

Cost of fuel (production, recyling and disposal): 9€/MWh

Variable O&M costs: 6.9€/MWh

Fixed O&M costs equal to 63000 € /(MWe*year) or to $\frac{63000€/\text{MWe}}{\text{load factor}*8760\text{h}} = 8.0€/\text{MWh}$

Price of CAPEX per MWh (with a WACC equal to 0) for **Flamanville**: $\frac{7.6\text{M}€/\text{MWe}}{60\text{years}*\text{load factor}*8760\text{h}}$= 16€/MWh

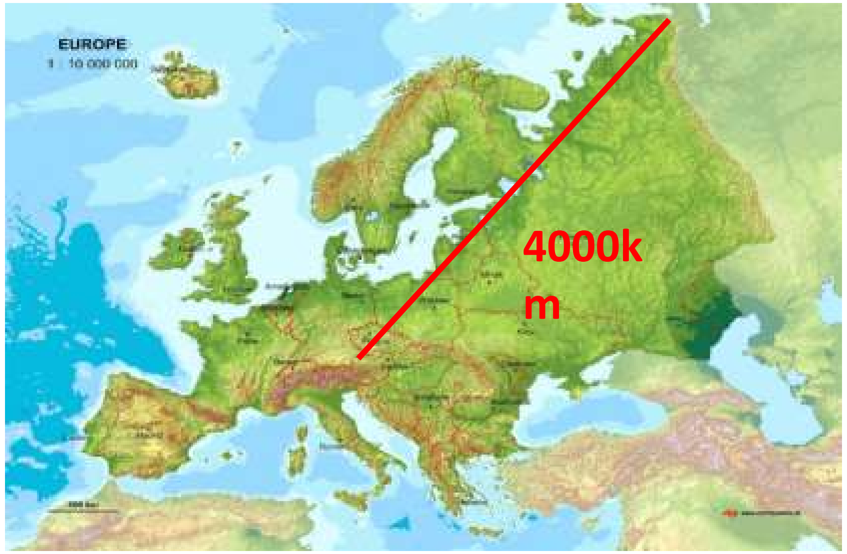
Price of CAPEX per MWh (with a WACC equal to 0) for **Beloyarsk**: $\frac{2.2\text{M}€/\text{MWe}}{60\text{years}*\text{load factor}*8760\text{h}}$= 4.6€/MWh

Cost for nuclear energy without a Global Grid	
The cheapest 28.5€/MWh	The most expensive 39.9€/MWh

Source: Projected costs of generating electricity, 2015 Edition, IEA-NEA

Estimation of the price with additional investment in a Global Grid setting

Direct current overhead line (UHVDC 1000kV)	AC/DC converter
Cost: 0,22M€/km/GW Losses: 3%/1000 km Lifetime: 50 years	Cost: 90M€/GW Losses: 1% Lifetime: 25 years



Cost of transmission infrastructure = $\frac{\frac{0{,}22\text{M€}/km * 4000km}{50\ years} + \frac{2*90\ \text{M€}}{25\ years}}{1000\ \text{MW} * 8760\text{h}} = 2.83\text{€}/\text{MWh}$

Cost for nuclear with GG $= \frac{\textbf{Cost of nuclear without GG}}{\textbf{1}-\textbf{losses}} +$ **Cost of transmission infrastructure**

Cost for nuclear energy with a Global Grid	
The cheapest 35.9€/MWh	The most expensive 49.2€/MWh

Source: Global electricity network - Feasibility study

I want Sun!

INDEPENDENT Friday 20 September 2019 15:45

A new wave of offshore wind farms around the UK will generate power more cheaply than burning coal and for the first time will not require any subsidy.

The cost of power from offshore wind has plummeted 30 per cent in two years with a raft of 12 new energy projects coming in at a record low price of between £39.65 and £41.61 per megawatt hour, the government revealed on Friday.

46 €/MWh for offshore wind power

Forbes Oct 17, 2019, 12:21pm

Saudi Arabia's Acwa Power submitted a tariff of just 1.6953 U.S. cents per kilowatt hour (kWh) for the 900MW fifth phase of Dubai's Mohammed bin Rashid Al Maktoum (MBR) Solar Park, according to a report by the *Middle East Economic Digest*. That sets a new record for unsubsidized solar PV production, in the region at least. However, it is still a little way short of the 1.654 cents/kWh achieved in Portugal earlier this year.

15 €/MWh for solar PV

Cost of nuclear vs cost renewables: a few thoughts

In €/MWh, solar PV is much cheaper than nuclear power.

Li-Ion batteries: cost of 100 k€/MWh, efficiency 92%, last for ten years at once cycle per day. Storing 1MWh of solar energy for 24 hours in Saudi Arabia would increase its cost from 15 €/MWh to 15/0.92+100,000/(365*10)= 43.7 €/MWh

In an optimized Global Grid setting, renewable energy is likely to be much cheaper than nuclear power.

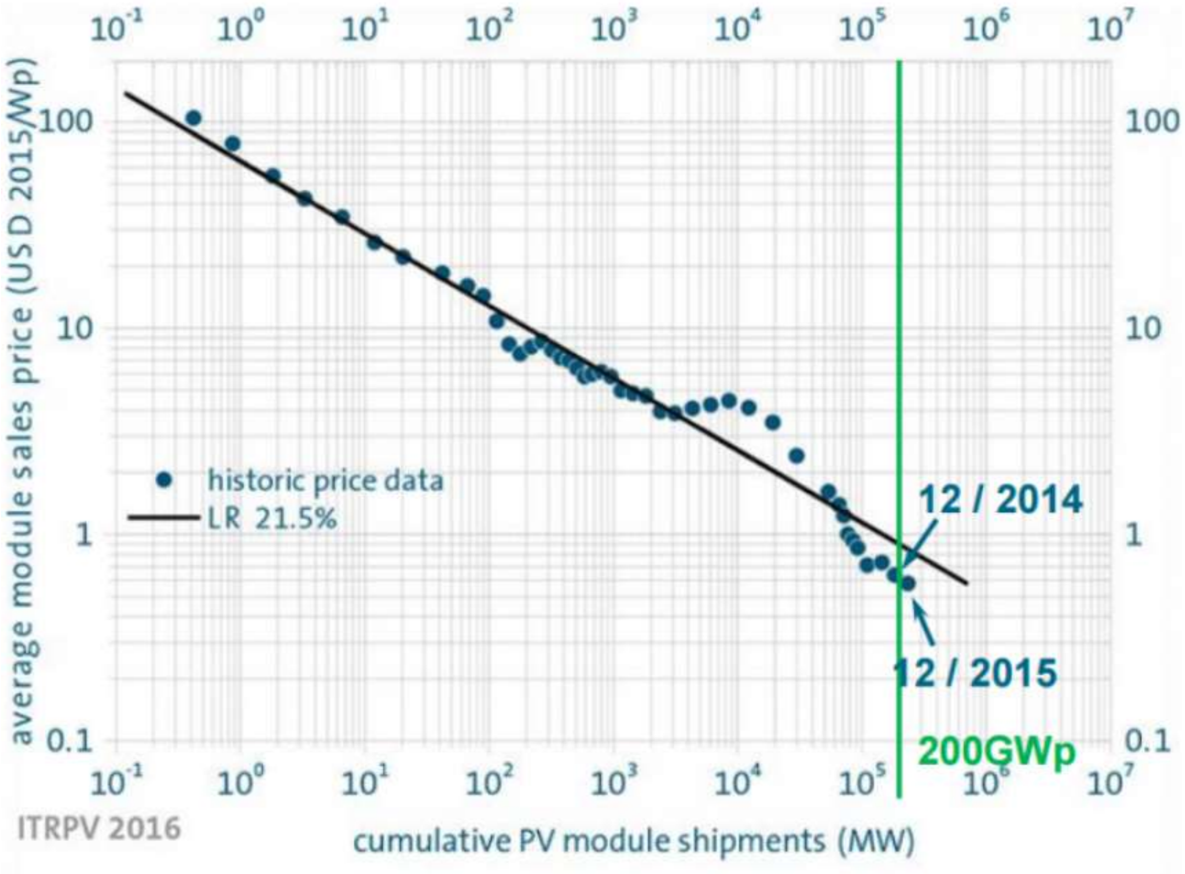
In a non Global Grid setting, and in many countries, nuclear can put out of business electrical mixes with gas, storage and renewables.

A non-zero Weighted Average Cost of Capital (WACC) for nuclear will significantly increase its costs.

Power-to-gas technologies may further endanger the competitiveness of nuclear power in the future, even without a Global Grid.

Three strategies for reducing the cost of nuclear energy

#1 Build more nuclear power plants to move down the learning curve



Learning rate for PV around 25% (for each doubling of capacity, price of PV modules has decreased by 25%).

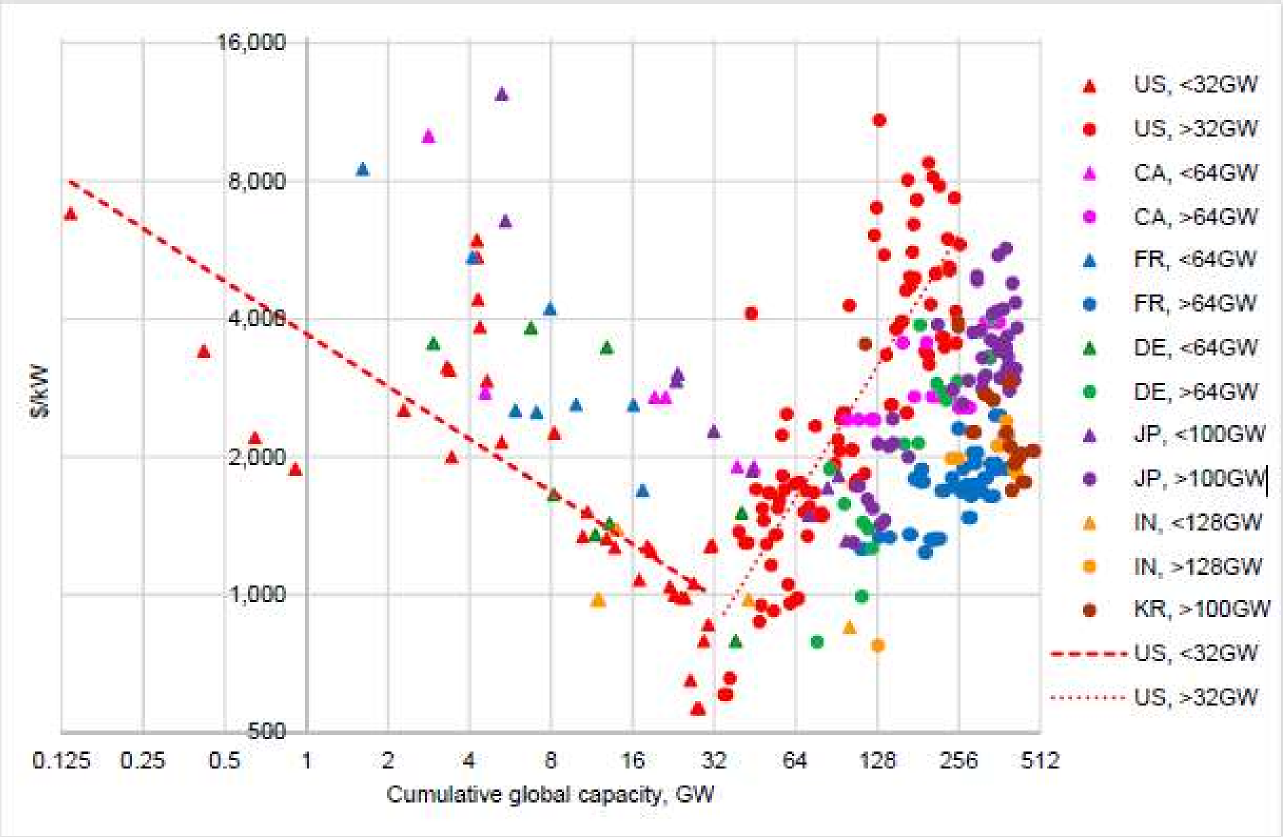


Figure 1. Overnight construction cost (in 2010 US $/kW) plotted against cumulative global capacity (GW), based on construction start dates, of nuclear power reactors for seven countries, including regression lines for US before and after 32 GW cumulative global capacity.

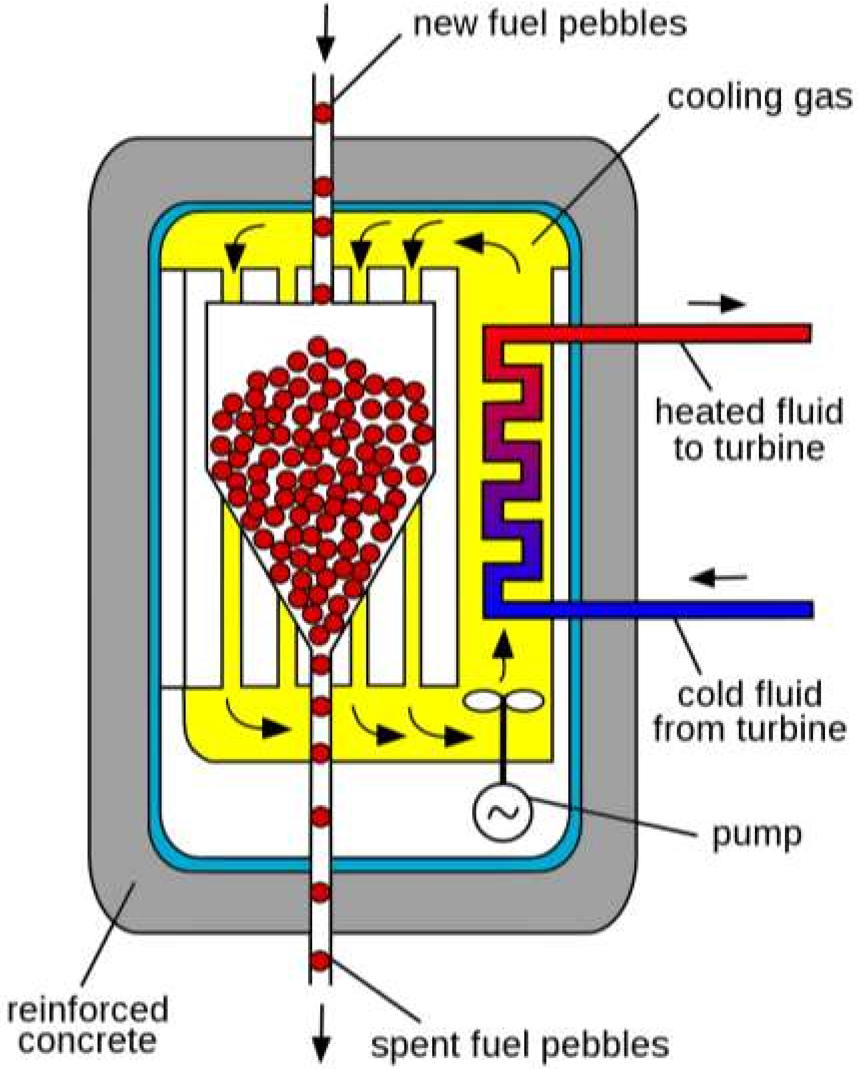
May not be that simple to achieve the same success for nuclear power as with PV since.

Due to **add-on environmental requirements and labour cost increases**, learning rates have become negative after first being positive.

<u>Example:</u> In the US, pre-reversal learning rates were around 24%. After 32 GW of cumulative global capacity (1967), they went down to minus 102%.

Source: Nuclear Power Learning and Deployment Rates; Disruption and Global Benefits Forgone

#2 Innovate[3]

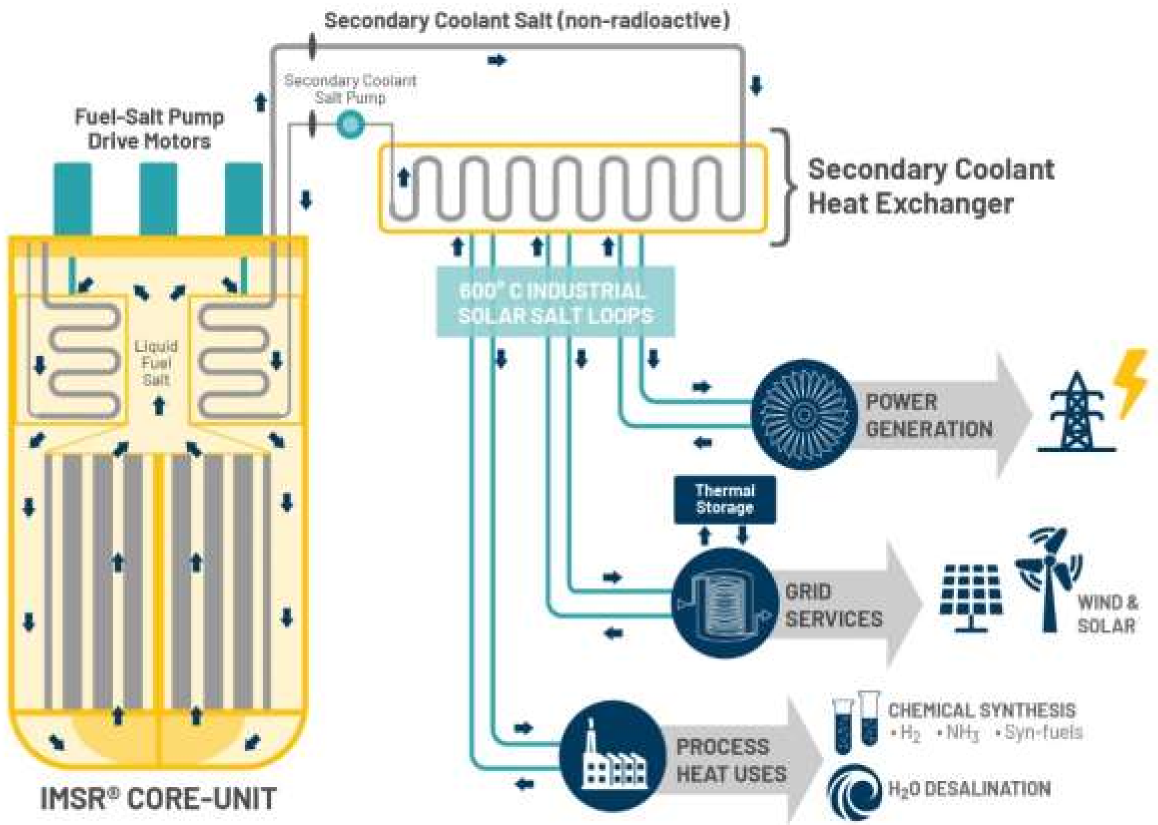


The **pebble bed** generator: a good example of innovation.

1. Can work at higher temperature, as cooled by gas. Better efficiency.
2. Intrinsically safe (*doppler broadening* effect to decrease reactor power as fuel temperature increases; reactor cooled by an inert and fireproof gas; convection of the gas driven by the heat ensures passive cooling; pebbles are composed of TRISO particles that can withstand extreme temperatures which are well beyond the threshold of current nuclear fuels).
3. Fuel replacement is continuous.

Source: https://en.wikipedia.org/wiki/Pebble-bed_reactor

#2 Innovate[4]



Molten Salt reactors offer even greater perspectives:

1. Intrinsically safe (near **atmospheric pressure**, *doppler broadening* effect, high boiling point, fission products chemically bound to coolant, unlimited air cooling…).
2. **Waste burner** capabilities: Reduction of spent fuel inventory through fast-spectrum neutrons.

Source: https://www.terrestrialenergy.com/

world nuclear news

Energy & Environment | New Nuclear | Regulation & Safety | Nuclear Policies | Corporate | Uranium & Fuel | Wa

Moltex Energy raises USD7.5 million through crowdfunding

16 September 2019

Share

UK-based Moltex Energy, creator of the Stable Salt Reactor (SSR), has raised GBP6 million (USD7.5 million) in funding through online investment platform Shadow Foundr. The funding will support the company through the pre-licensing process in Canada and will allow the further development of the business in the UK.

Moltex's vision of an SSR plant (Image: Moltex)

And people believe in the potential of molten salt reactors: Moltex the first nuclear company to raise funds thanks to public crowdfunding!

Source: http://world-nuclear-news.org/Articles/Moltex-Energy-raises-USD7-5-million-through-crowdf

#3 Valorise lost heat

world nuclear news

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Finnish cities might consider SMRs for district heating

15 December 2017

Share

A number of Finnish cities have received political initiatives to evaluate the feasibility of using small modular reactors (SMRs) instead of fossil fuels to provide district heating, according to Energy for Humanity. A recent study looked at completely decarbonising electricity, transport and heating in Helsinki through the use of small, advanced reactors.

Most of the district heating in Finland is produced by burning coal, natural gas, wood fuels and peat, said the non-profit organisation, which is funded by philanthropic donations and advocates for climate action and energy access. It noted that while many Finnish cities have progressive climate policies and goals, they have struggled to decarbonise heating and liquid fuels.

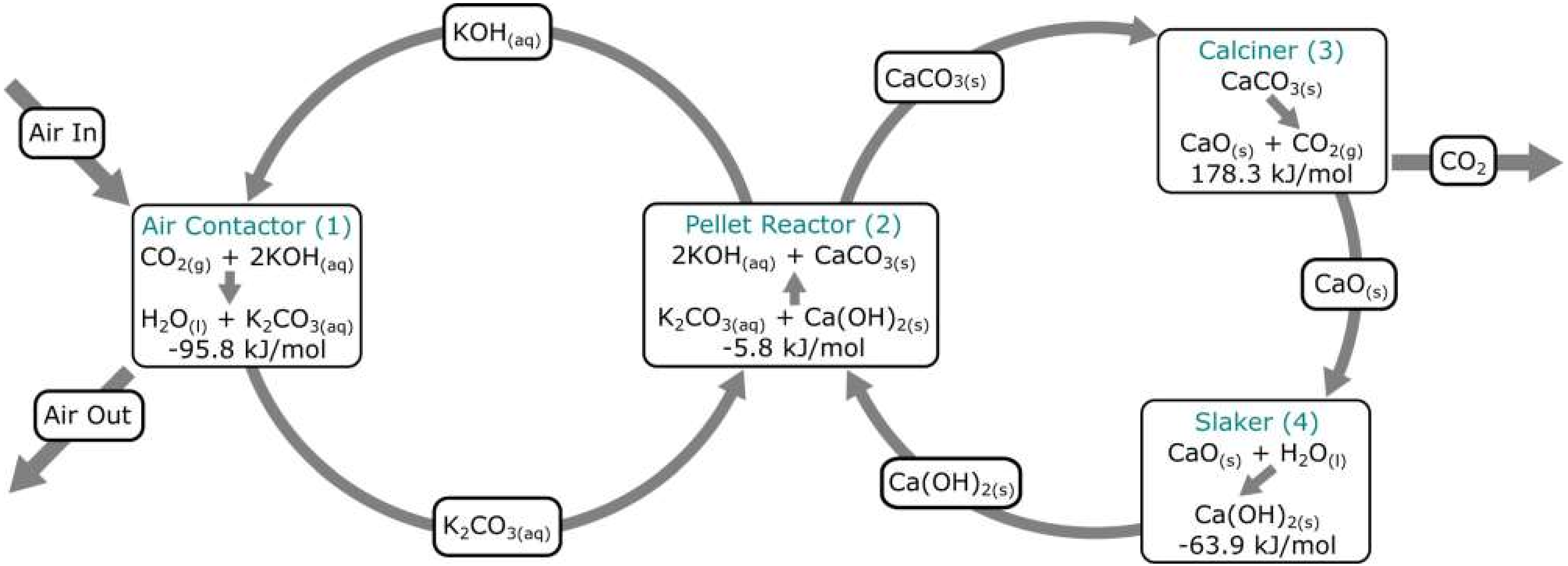
"More than half of the greenhouse emissions of all of Helsinki come from district heating, mainly run by fossil fuels," said Petrus Pennanen, Helsinki city council member and vice chair of the Finnish Pirate Party. "If we are serious about decarbonising Helsinki, we need to at least take an honest look at these upcoming reactors."

Easier to valorise heat from Small Modular Reactors (SMRs) than than large ones since it is difficult to transport heat over long distances.

SMRs may offer a great solution to decarbonize heating.

Small Modular Reactors can also help reduce the costs of nuclear power.

Using this heat for CO_2 capture



Process commercialized by **Carbon Engineering** for capturing CO_2. Air leaves with a CO_2 concentration of around 110 ppm. Energy required per ton of CO_2 captured and compressed at 150 bars: around 1.4 MWh of heat (at a temperature of more than 600 °C for the calciner – provided now by burning natural gas) and 0.4 MWh of electricity.

Source: https://carbonengineering.com/

What can be done with this CO_2?

1. Storing CO_2 underground.

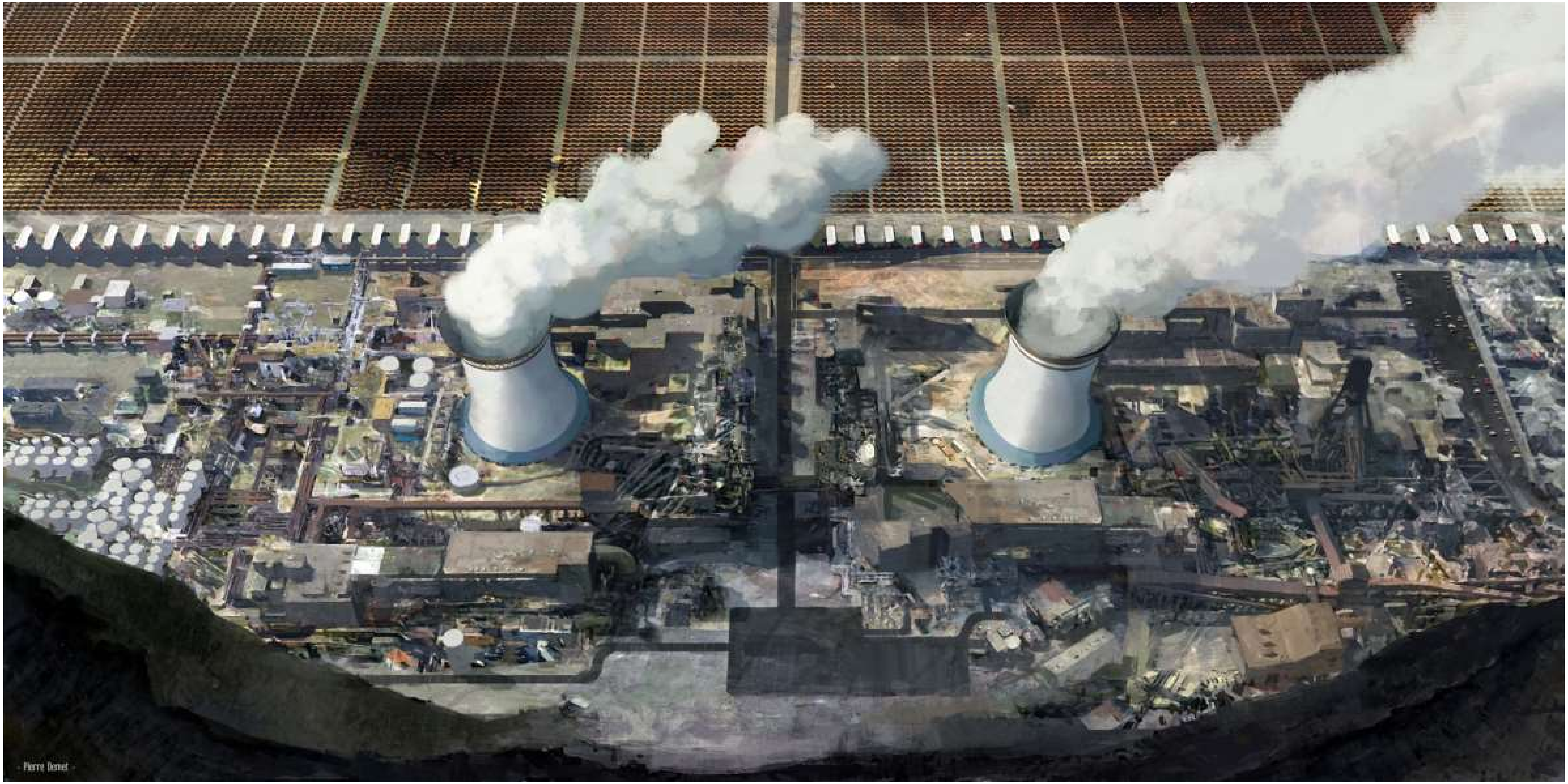
2. Synthesize green fossil fuels using green hydrogen produced from water electrolysis with green energy. Example: the Sabatier reaction for producing CH_4

$$CO_2 + 4\,H_2 \xrightarrow[\text{pressure}]{400\ ^\circ\text{C}} CH_4 + 2\,H_2O \qquad \Delta H = -165.0 \text{ kJ/mol}$$

3. Transform CO_2 into graphite (pure coal) using, for example, the Bosch reaction, and building a mountain of coal.

High-temperature heat input can help optimise Solutions 2. and 3.


- Pierre Demet -



Energy needed to return to 280 ppm of CO_2

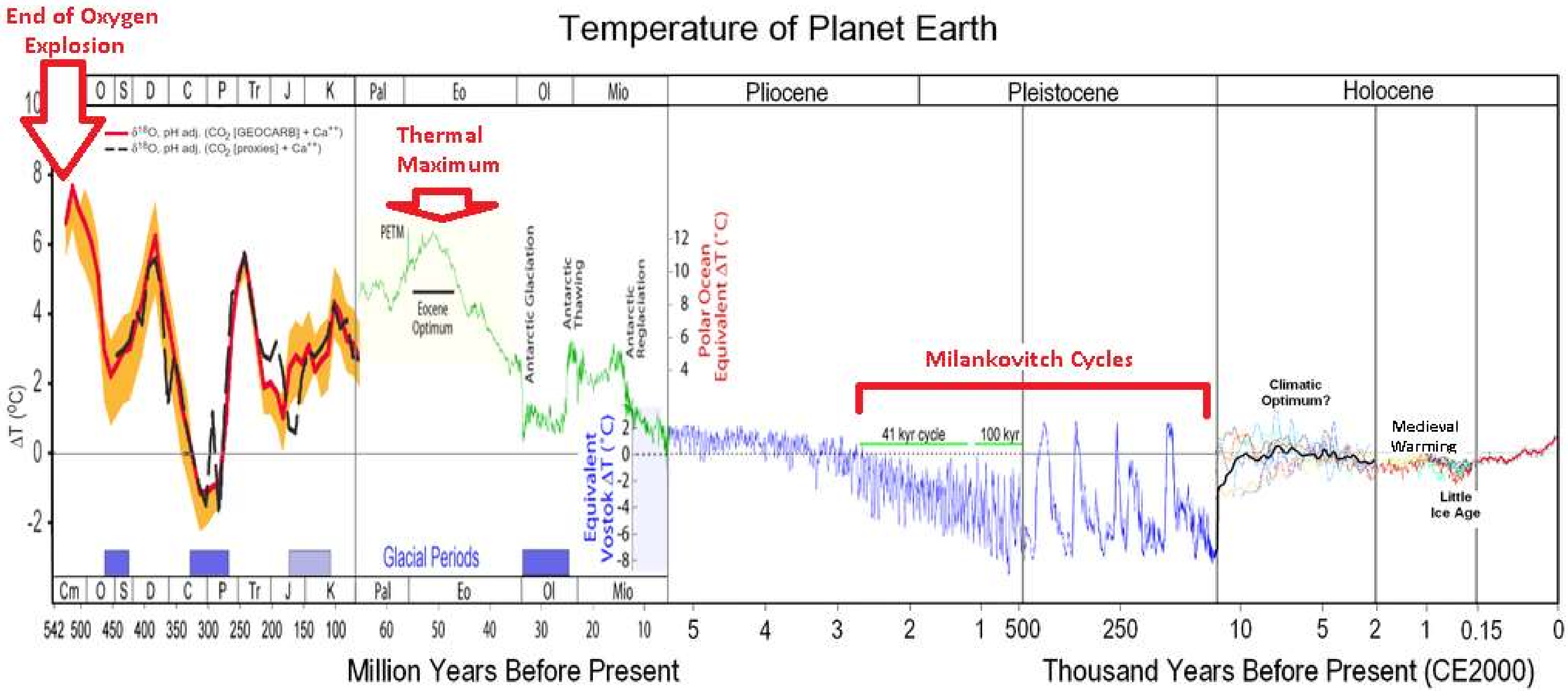
There are around 3.25 x 10^{12} tons of CO_2 in the atmosphere. To return to preindustrial levels (280 ppm), $\frac{412-280}{412}$ * 3.25 x 10^{12}=1.04 x 10^{12} tons of CO_2 have to be removed from the atmosphere.

Removing 1 ton of CO_2 from the atmosphere requires (1.4+0.4)=1.8 MWh.

One ton of graphite generates 8.9 MWh when combusted. Due to the energy conservation principle, transforming one ton of CO_2 into graphite and O_2 would at least require $\frac{12}{(2*16+12)}$ * 8.9 = 2.42 MWh of energy.

Transforming 1.05 x 10^{12} of CO2 into graphite would require a minimum of 4,431,000 TWh of energy. This is 40 times our annual final energy consumption.

Burning this coal if one day the Earth is cooling down again



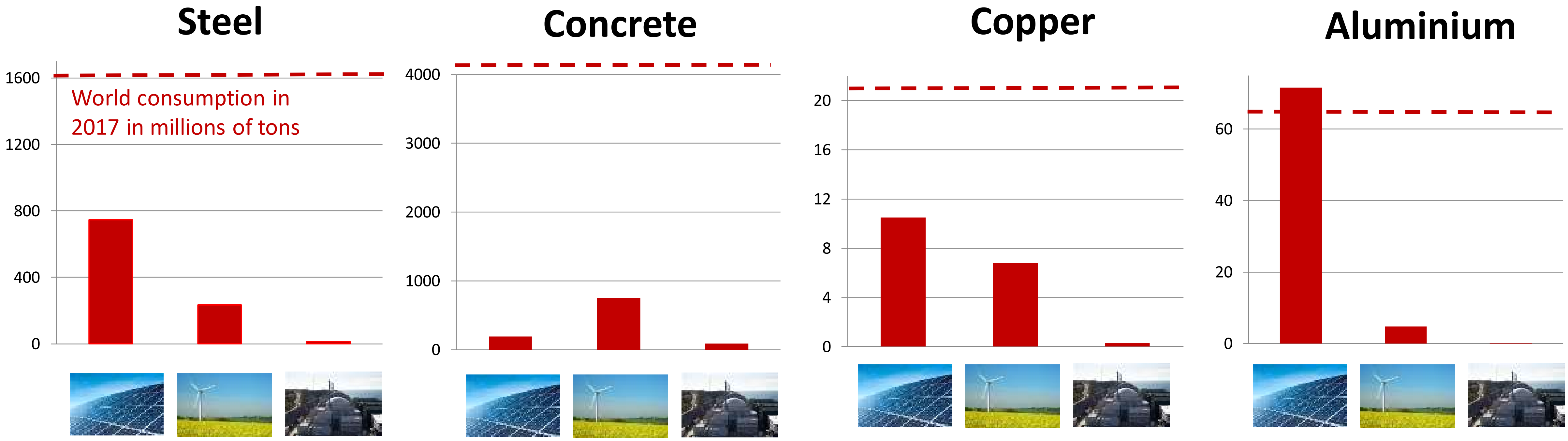
Source: [4.5 Billion Years of the Earth's Temperature]

Raw materials for generating CO_2-free energy

Consumption of materials in ton/MW	Nuclear	Photovoltaic panels	Wind turbines
Steel	44	355	138
Concrete	307	92	440
Copper	1	5	4
Aluminium	0,1	34,1	2,8

Source: Matières premières et énergie: les enjeux de demain, Olivier Vidal

How much raw material do we need every year to go 100% solar-, wind- or nuclear-powered? The answer:



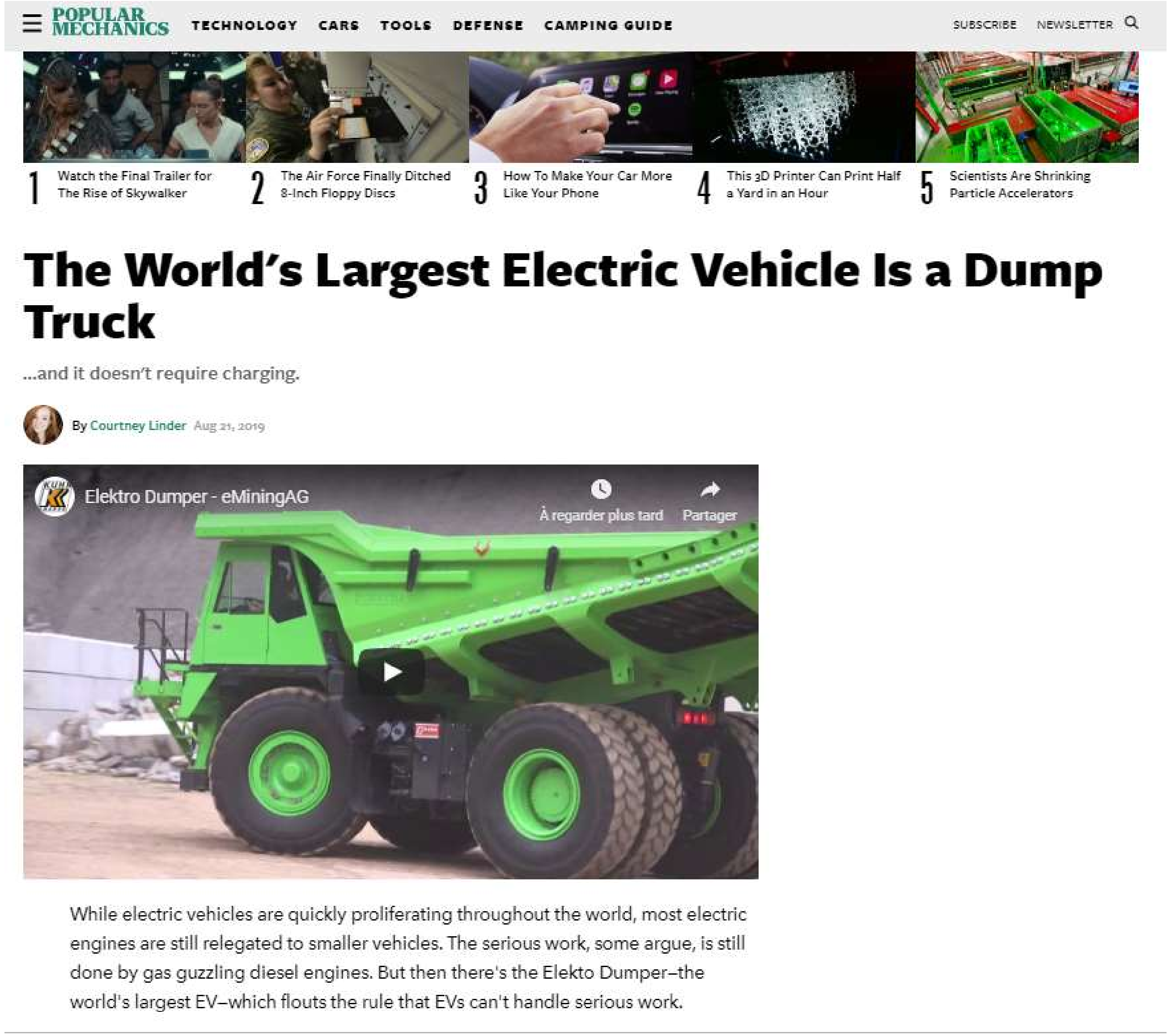
Data: Load factor for PV = 0.2, Wind=0.3, Nuclear = 0.9. Lifetime (in years) PV= 30, Wind = 25, Nuclear = 60.

Chuquicamata copper mine (Chile).
Production in 2018: 321 kt.

 : 32 Chuquicamata mines

 : 21 Chuquicamata mines

 : <1 Chuquicamata mine



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The World's Largest Electric Vehicle Is a Dump Truck

...and it doesn't require charging.

By Courtney Linder Aug 21, 2019

While electric vehicles are quickly proliferating throughout the world, most electric engines are still relegated to smaller vehicles. The serious work, some argue, is still done by gas guzzling diesel engines. But then there's the Elekto Dumper–the world's largest EV–which flouts the rule that EVs can't handle serious work.

Is extracting raw materials an environmental problem if the mining industry goes green?

Handling nuclear waste: The standard approach

Option	Suitable waste types	Examples
Near-surface disposal at ground level, or in caverns below ground level (at depths of tens of metres)	LLW and short-lived ILW	• Implemented for LLW in many countries, including Czech Republic, Finland, France, Japan, Netherlands, Spain, Sweden, UK, and USA. • Implemented in Finland and Sweden for LLW and short-lived ILW.
Deep geological disposal (at depths between 250m and 1000m for mined repositories, or 2000m to 5000m for boreholes)	Long-lived ILW and HLW (including used fuel)	• Most countries have investigated deep geological disposal and it is official policy in several countries. • Implemented in the USA for defence-related truansuranic waste at WIPP. • Preferred sites selected in France, Sweden, Finland, and the USA[a]. • Geological repository site selection process commenced in the UK and Canada.

LLW: Low-level radioactive waste
ILW: Intermediate-level radioactive waste
HLW: High-level radioactive waste

This is highly controversial.

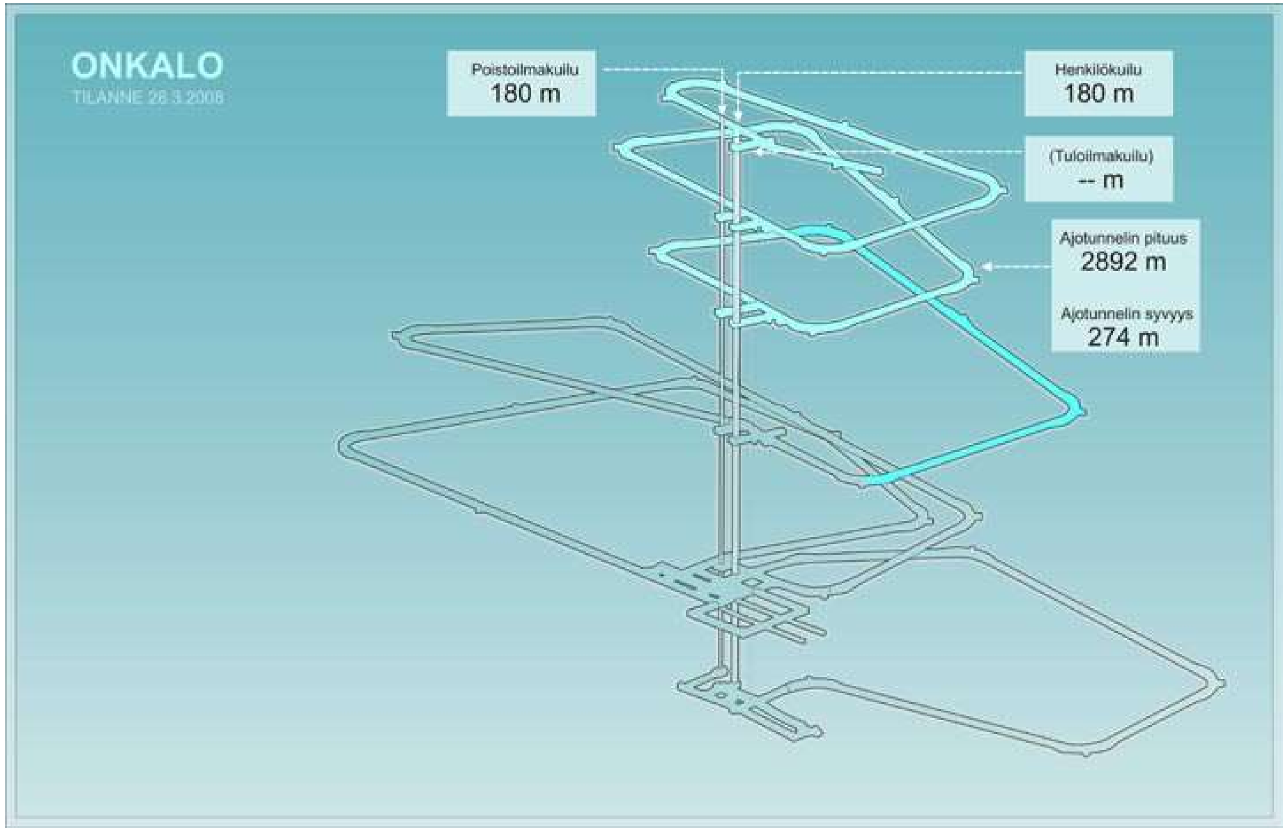
The amount of HLW could be greatly reduced by reprocessing spent fuel and burning minor actinides in fast-neutron reactors (full nuclear cycle).

Reprocessing may, however, increase the volume of radioactive material due to contamination.

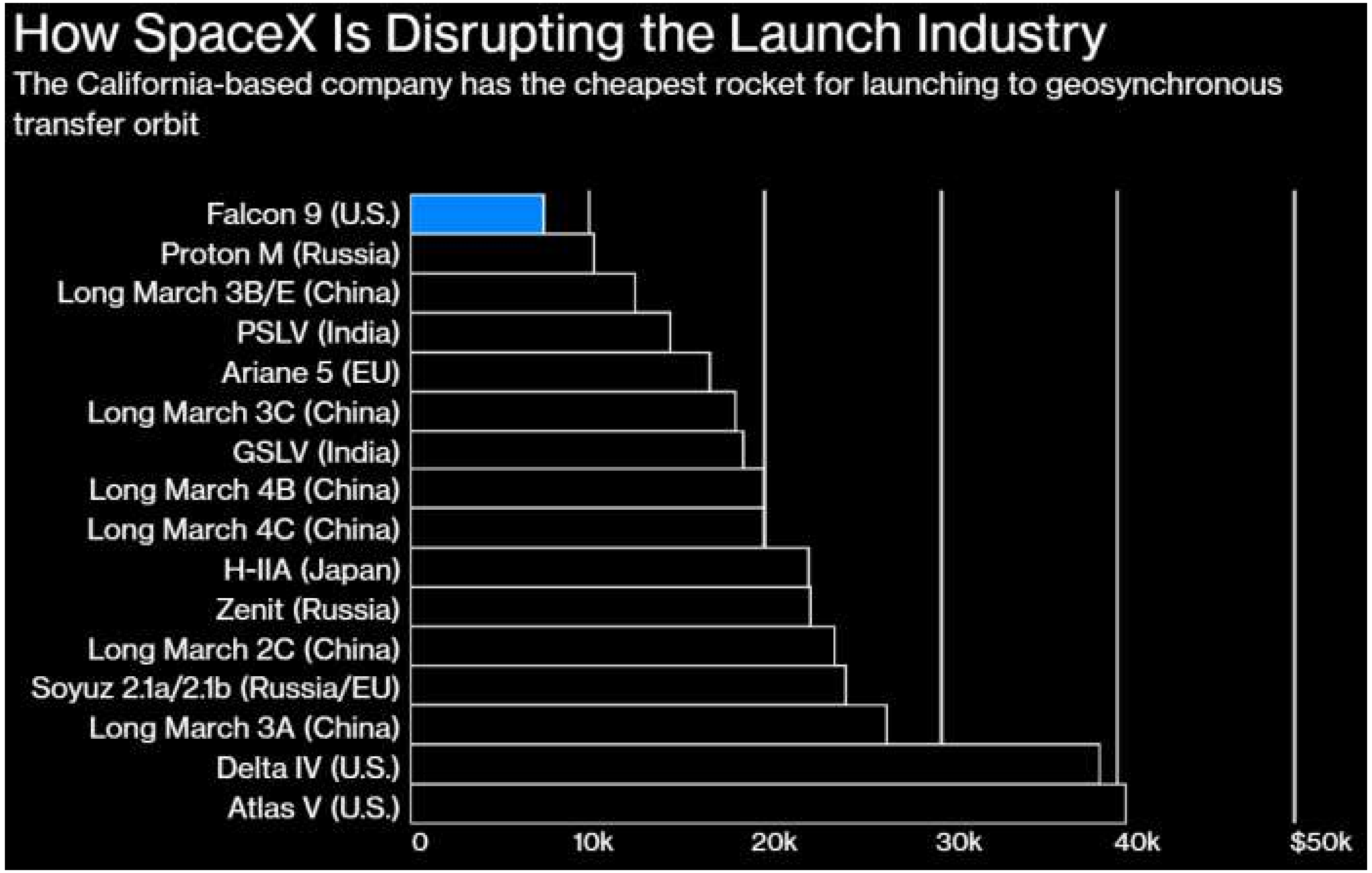
Low-level surface disposal in Dessel (Belgium)

Concrete monolith for storing low-level radioactive waste.
Artist representation.

Deep geological disposal in Onkalo (Finland)



Sending long-lived radioactive waste to the Moon



Cost per kg sent into a geosynchronous transfer orbit.

The space industry is changing. We are entering the era of cheap space travel thanks to private entrepreneurs.

Reliability of rockets will improve and will drop dramatically.

Going to the Moon may soon become as common as crossing the Atlantic was a century ago.

Source: The New Rockets Racing to Make Space Affordable

EXPANDING THE POSSIBILITIES FOR HUMAN EXPERIENCE

SEEING THE FUTURE HAPPEN FASTER

Relativity is the first and only company to automate aerospace manufacturing by integrating intelligent robotics, software, and proprietary metal 3D printing technology. Leading an unrivaled team to solve problems never solved before, our leadership includes seasoned veterans and experts from the world's most renowned aerospace, 3D printing, and technology companies. Together, we are revolutionizing how rockets are built and flown.

See the video on Youtube: https://www.youtube.com/watch?v=Ff1kTF9Zv3Y

Energy spent sending nuclear waste to the moon versus energy generated by the uranium

We assume that the nuclear fuel cycle is limited to the production of MOX. From the 150 tons of uranium ore needed yearly for an EPR, only around 25 tons of enriched uranium enters the nuclear fuel cycle. We assume we want to send this amount to the moon. The EPR produces 13,008,600 MWh with this uranium.

Saturn V could send 40 tons to the Moon, consuming around 4000 MWh of fuel per launch.

Energy for sending 25 tons of waste to the Moon is **5203 less** than the energy generated yearly by the EPR => From a standalone energy point of view, sending waste to the Moon is feasible.

Source: How do the Saturn V and other rockets compare with various nuclear bombs in terms of power, force, and energy?


- Pierre Demet -

Running out of renewable energy

Over the last 30 years, global energy consumption has grown at an average 2% per year.

The potential of renewable energy is limited. Limitations are induced also by land-use competition, and acceptance, together with resource quality and perhaps also remoteness.

For wind energy resources, the theoretical maximum is somewhere between 157,000 TWh and 594,000 TWh. Some authors predict that it could be as little as 9000 TWh in pratice.

Potential for solar energy is orders of magnitude higher, especially if solar PV can be harvested on oceans.

Source: Quantifying a realistic, worldwide wind and solar electricity supply ; Global Available Wind Energy with Physical and Energy Return on Investment Constraints


- Pierre Demet

Covering the equivalent of Africa with PV panels

Let us suppose that the total feasible renewable energy potential is equal to the energy obtained by covering a quarter of Africa with 20%-efficient PV panels. With 60,000,000 TWh of solar energy reaching Africa every year, the total renewable energy potential would be of 12,000,000 TWh.

With a 2% energy consumption growth, $\frac{\ln\left(\frac{12,000,000}{111,000}\right)}{\ln(1.02)} =$ 236 years are needed to achieve this consumption level.

Fast-neutrons reactors would exhaust land reserves of uranium + 10% of sea water reserves in around 186 years if generating this amount of energy yearly.

Fusion to the rescue?

The deuterium-deuterium reaction:

$$ {}_{\cdot 1}H^2 + {}_{\cdot 1}H^2 \rightarrow {}_{\cdot 2}He^3 + {}_{\cdot 0}n^1 + 3.27MeV $$

Energy released by the fusion of 1 kg of deuterium is equal to 0.022 TWh. Sea reserve of deuterium: are 45 Tt (around 31 g per ton of sea water against 0.003 g for uranium).

Energy generated through fusion of 10% of deuterium reserve in a 30% efficient generator: 3×10^{13} TWh, which would last for around 2,5 million years at a yearly global energy consumption level of 12,000,000 TWh.

Construction site of ITER (International Thermonuclear Experimental Reactor)

Final word: *By the time human civilization reaches a level of energy consumption equivalent to the renewable energy potential of the Earth, it may have also reached a level of technological development that allows technical solutions other than fusion to generate additional energy.*


Pierre Demet