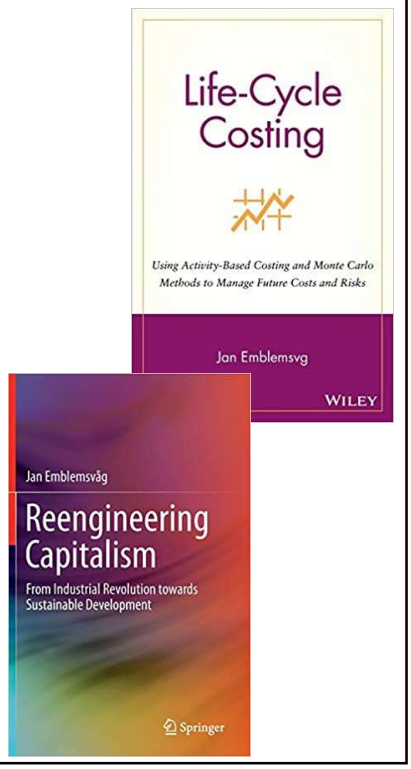
Nuclear power for a sustainable world

JAN EMBLEMSVÅG

2022-03-07

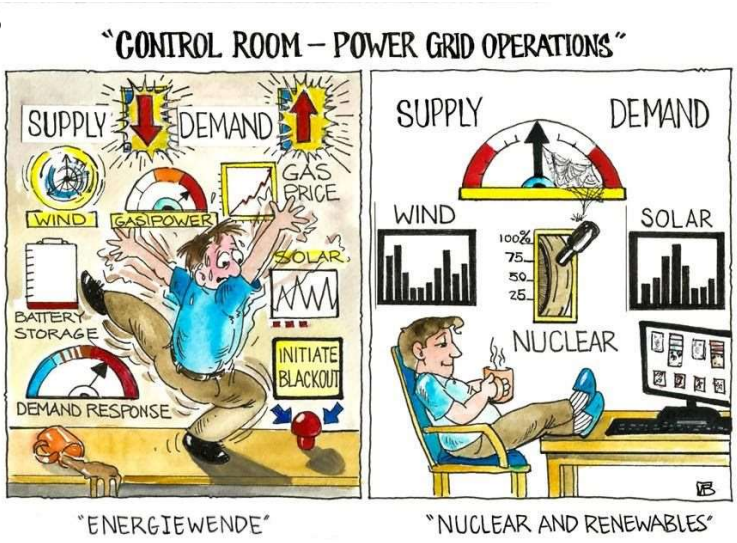
A few words about myself

- 20 years in top management positions primarily in maritime industry
- Professor at NTNU
- Written several books and about 40 journal papers
- Hold a PhD (99) and M.Sc. (95) at Georgia Institute of Technology and a 'Sivilingeniør' from Norwegian Institute of Technology (NTH) (94)



Content

- Some myths and facts
- Nuclear innovations
- The Molten Salt Reactor (MSR)
- Fuel cycles
- Economics
- The way forward

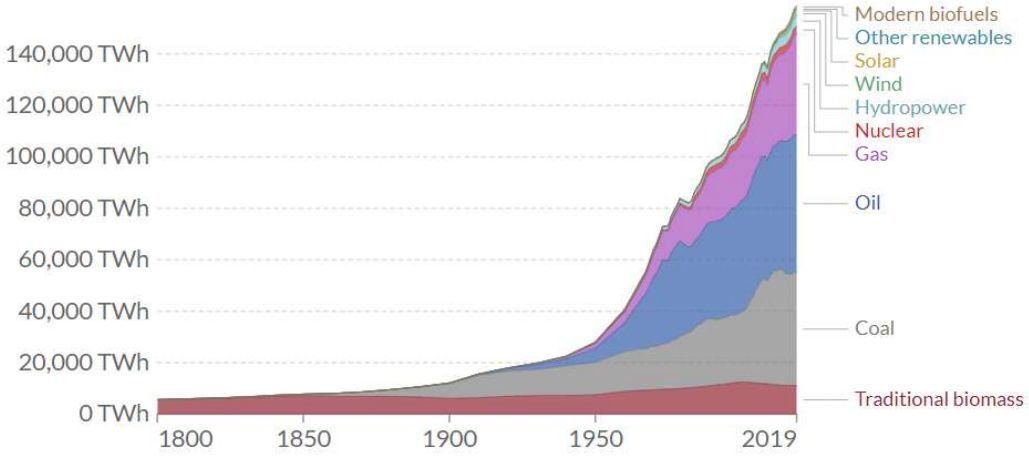


Myth: A green transition

Direct primary energy consumption does not take account of inefficiencies in fossil fuel production.

☐ Relative

Very little improvement (1.5%)



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

OurWorldInData.org/energy • CC BY

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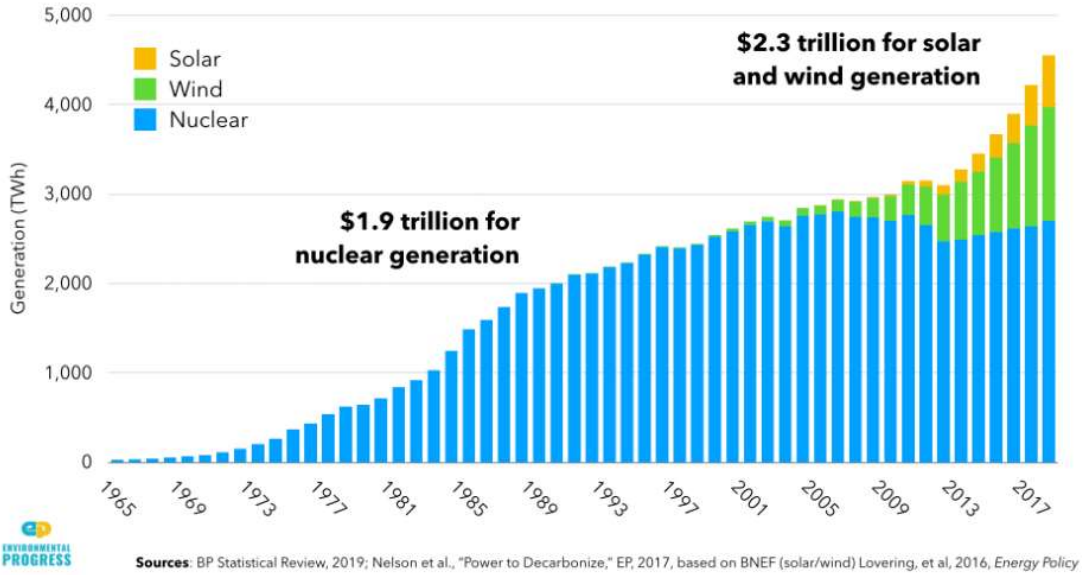
Myth; Nuclear is expensive



ENVIRONMENTAL PROGRESS

Sources: BP Statistical Review, 2019; Nelson et al., "Power to Decarbonize," EP, 2017, based on BNEF (solar/wind) Lovering, et al, 2016, *Energy Policy*

5

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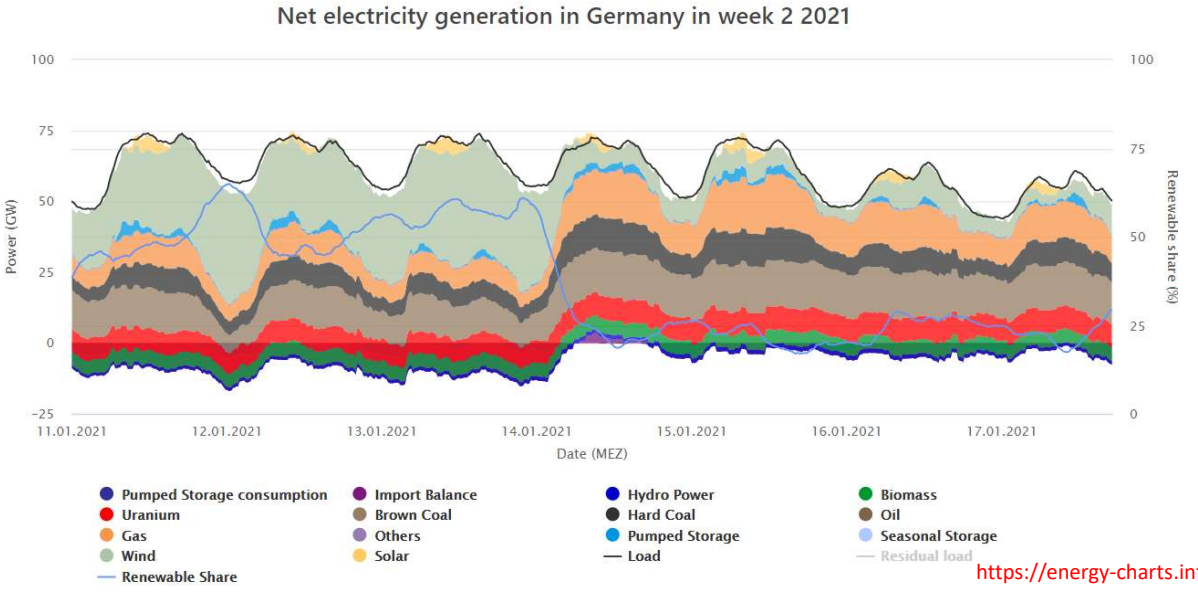
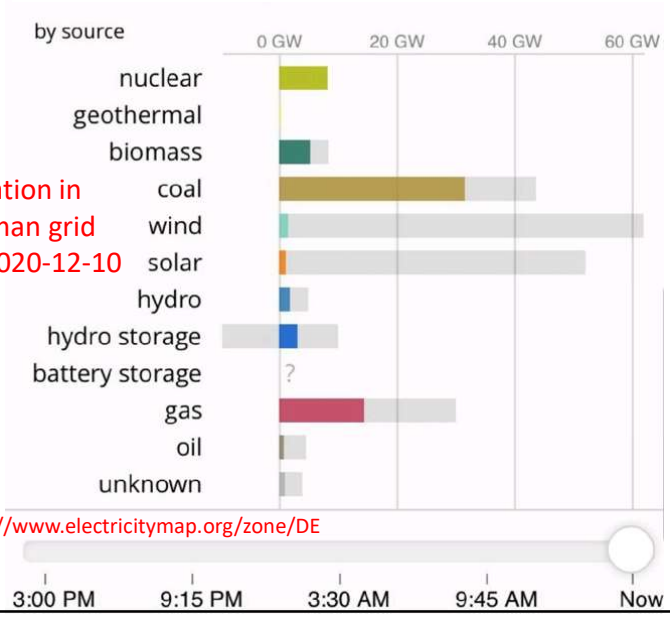
But isn't wind cheaper than nuclear?



https://energy-charts.info/

Large capacity but low production



Situation in German grid on 2020-12-10

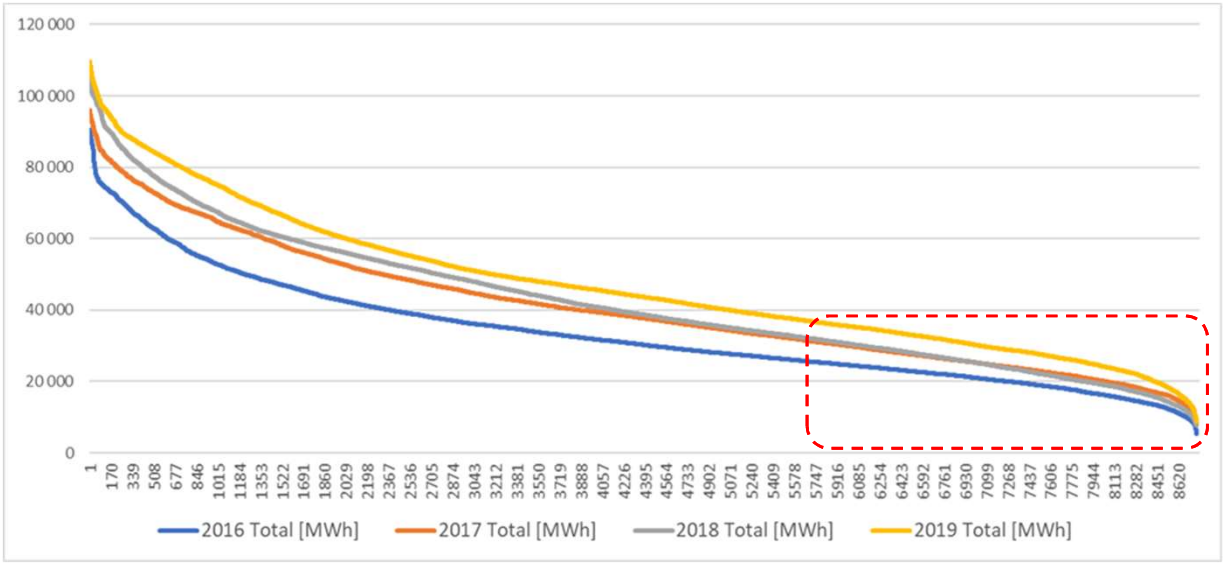
https://www.electricitymap.org/zone/DE

- In 2000, Germany had 121 GW capacity, generating 577 TWh
- In 2019, it produced just 5% more (607 TWh) with an 80% higher installed capacity (218.1 GW)
- It had two generating systems at huge costs
- Expected to cost 6,000 bn Euros

Source: Smil, V. (2020). "Energiewende, 20 Years Later." IEEE Spectrum 57(12):pp.22-23.

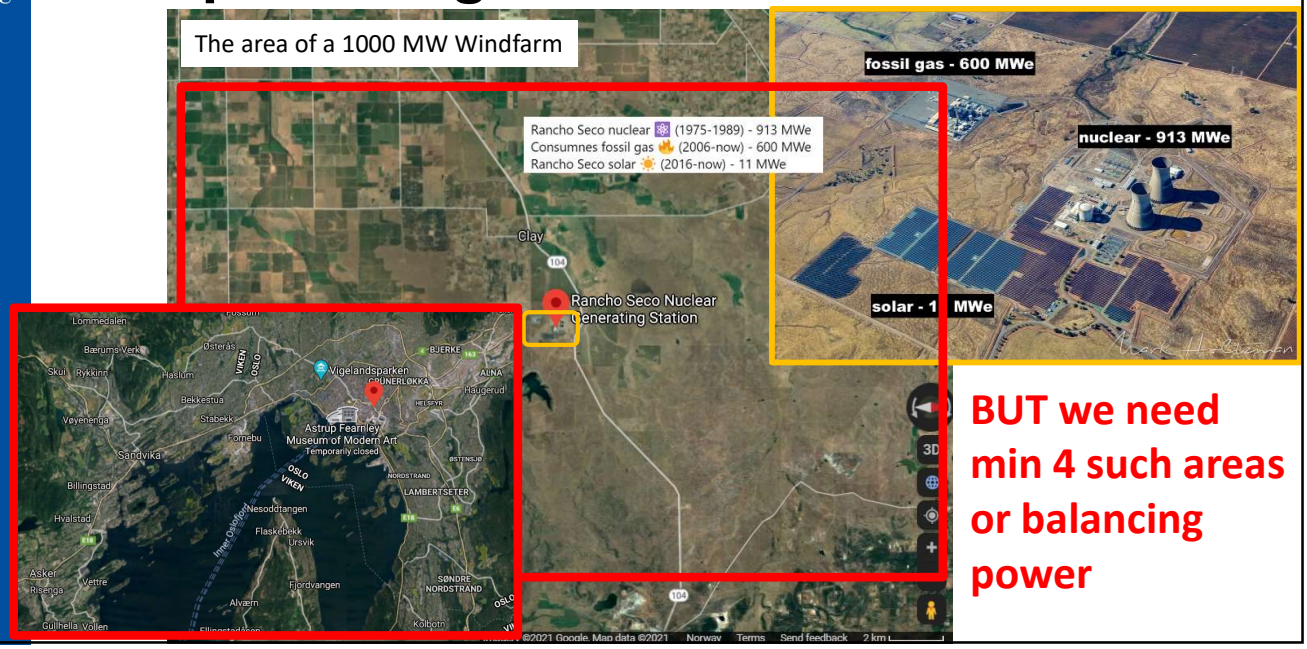
7

Expansion (ENTSOE) does not help



8

Expansion gives area conflict



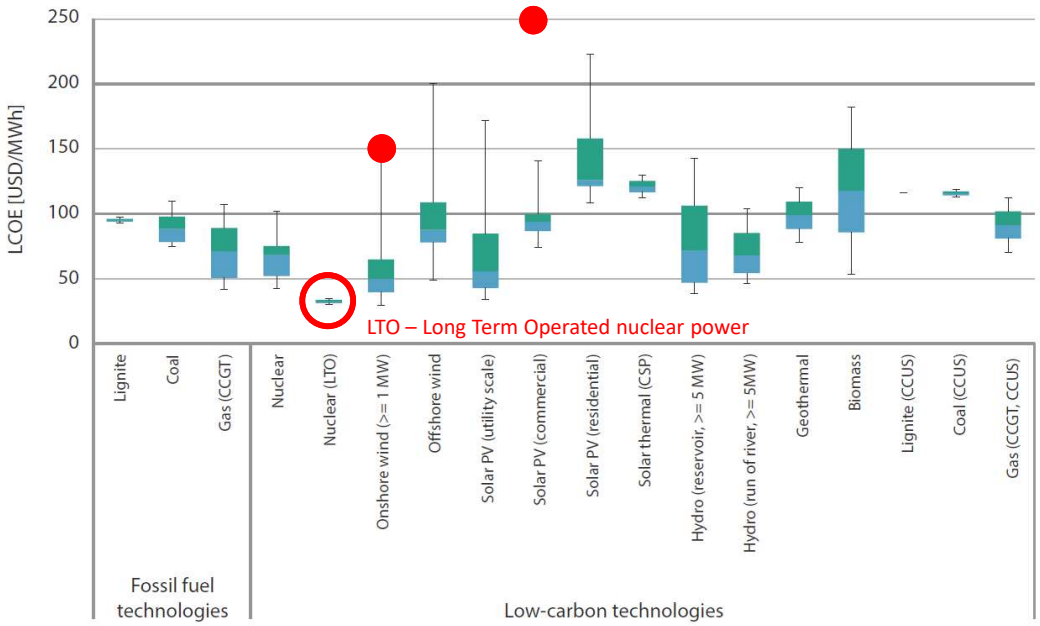
BUT we need min 4 such areas or balancing power

Correct LCOE

- Electricity comes with a certain quality – RAM;
  - **R**eliability
  - **A**vailability
  - **M**aintainability
- Comparison between technologies requires comparable RAM otherwise opportunity costs are transferred to others in the system
- Renewable energy requires balancing power – in 26 OECD countries this is gas

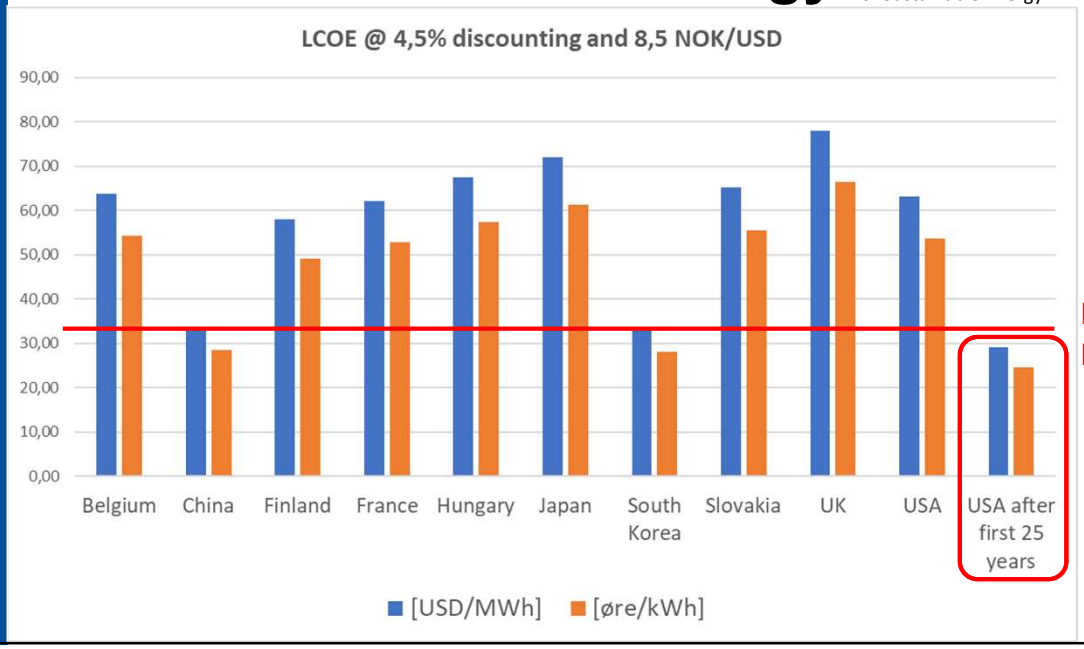
10

LCOE [USD/MWh], IEA (2020)



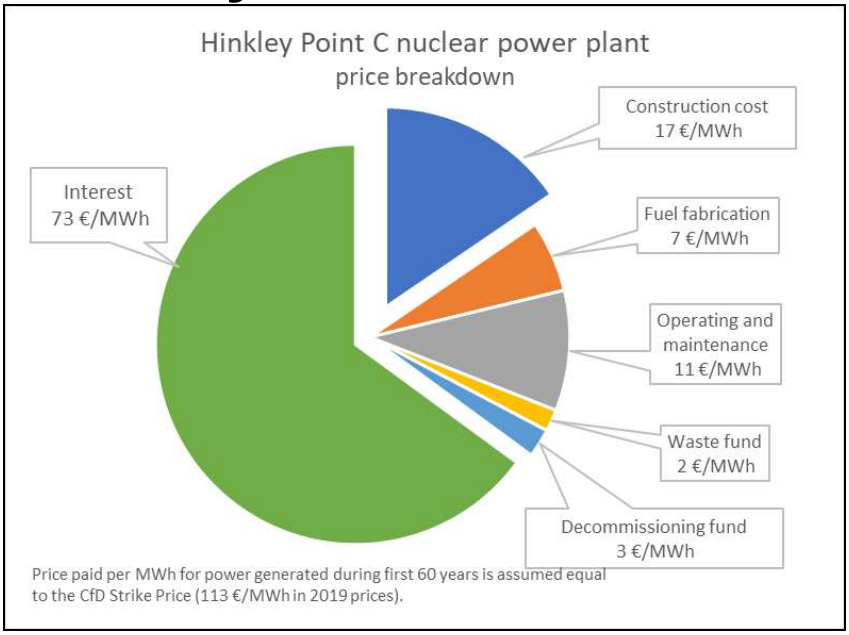
Levelized Cost Of Energy

Source: Emblemsvåg, Jan. (2021) Safe, Clean, Proliferation Resistant and Cost-Effective Thorium-based Molten Salt Reactors for Sustainable Development. International Journal of Sustainable Energy.



Norwegian Hydro power

Hinkley Point C is instructive



- Expensive financing
- 100 bn Euros in profit!
- New reactor design (EPR)

Source:
- National Audit Office (2017). Hinkley Point C
- Joris van Dorp; https://medium.com/generation-atomic/the-hinkley-point-c-case-is-nuclear-energy-expensive-f89b1aa05c27

13

Offshore wind vs Nuclear

Offshore wind;

- 8 years construction time
- CAPEX is 30 MNOK/MW
- Ca 50 bn NOK per offshore wind power plant
- 7.0 TWh/year for 25 years

Nuclear (AP1000);

- 5 years construction time
- CAPEX is 19 MNOK/MW
- Ca 30 bn NOK per nuclear powerplant
- 8.5 TWh/year for 60 years

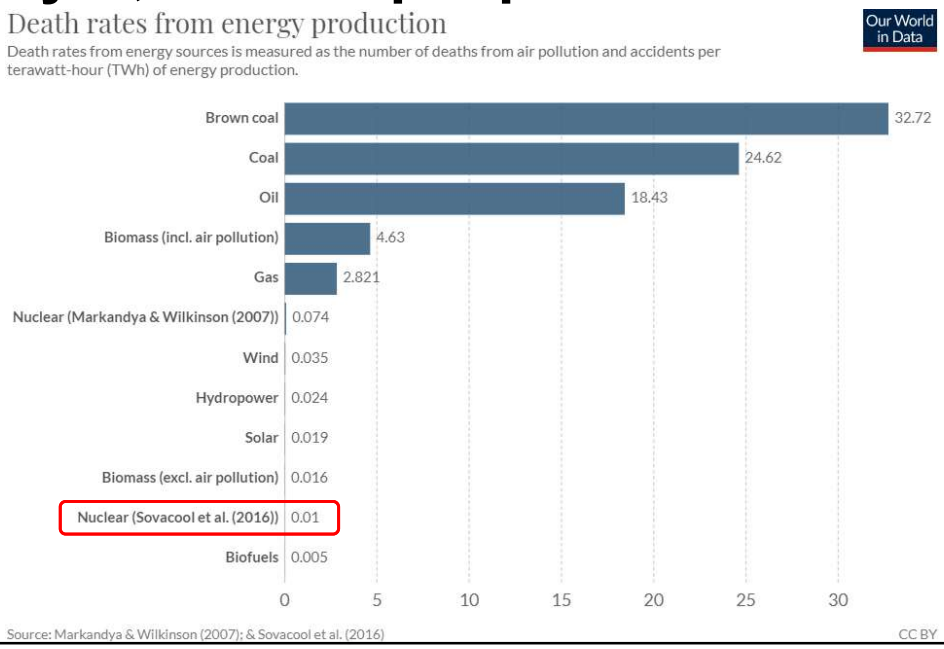
Floating offshore wind (2020)

the japan times

BUSINESS

¥60 billion wind power project off Fukushima to be dismantled

Myth; A lot of people has died



16

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Myth; Nuclear generates a lot of waste

- All nuclear waste ever produced in the US fits on a football field, 50 feet high
- Over 90% of the energy is left
- Ca 250,000 TWh
- Ca 300 years of production with the current mix of the US grid

17

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Waste storage

Zwilag in Switzerland

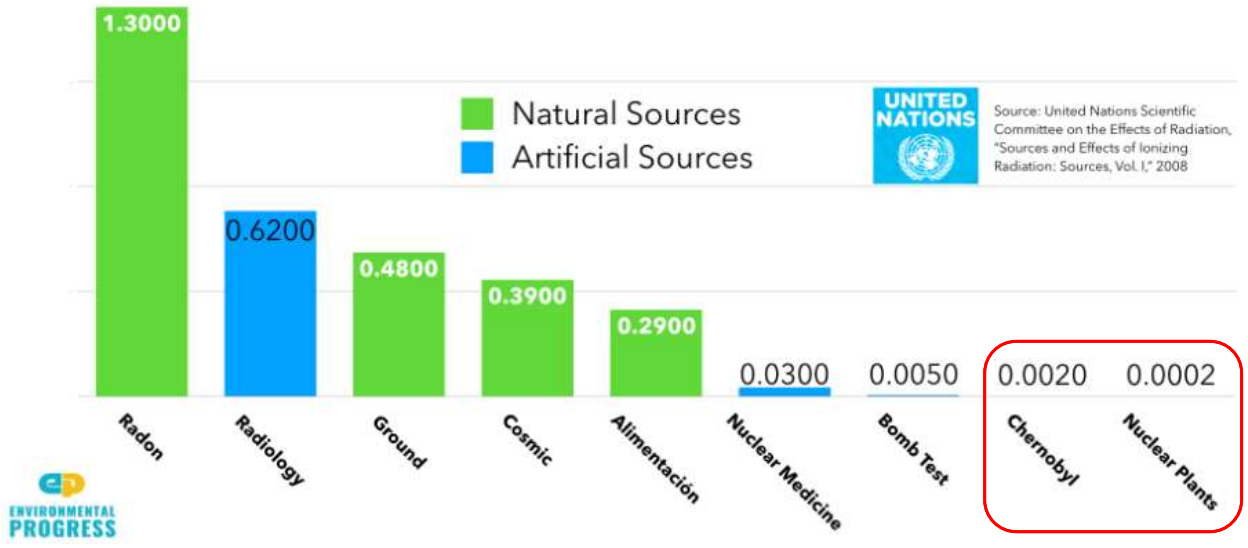
- Swiss central storage
- 99.5% of the radiation is found in 10.2% of the material
- In 2018, there was 2,355 m^3 material from which Switzerland had produced 2,667 TWh by the end of 2018
- In 2075, there will be 9,200 m3 (21^3)
- Gen IV would have given 100,000 TWh

Waste storage (2)

- After 40 years, only 1 permille of radioactivity is left
- Yet, rules mandate storage for thousands of years
- The cost is included in the production costs of nuclear power plants
- Nuclear waste is extremely valuable, which is why intermediate storage is used
- Gen IV reactors can use this 'waste'

19

Myth; Nuclear radiation is a problem



20

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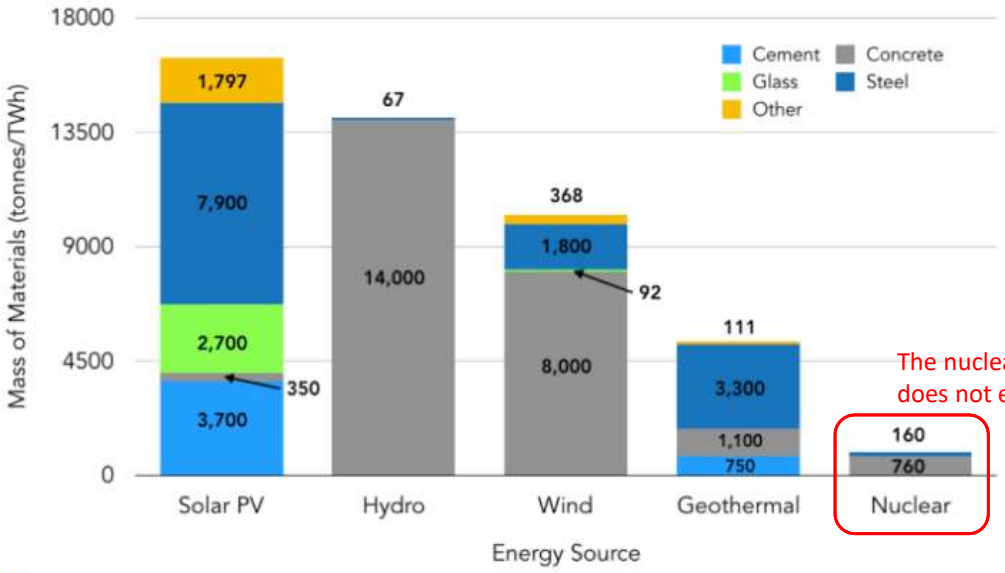
Fact; Low footprint and no emissions



The nuclear materials does not even show up!

"Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities." Table 10. September 2015. United States Department of Energy. Nuclear and hydro require 10 tonnes/TWh and 1 tonne/TWh of other materials, respectively, but are unable to be labeled on the graph.

21

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Fact; Nuclear is renewable!

- There is ca 4.6 bn tonnes (3.3 ppb) uranium in seawater
- The earth rocks contain ca 100,000 bn tons uranium which replenish the oceans at 16,000 tonnes per year

Extraction using old yarn

Source: https://www.forbes.com/sites/jamesconca/2016/07/01/uranium-seawater-extraction-makes-nuclear-power-completely-renewable

Source: https://www.pnnl.gov/news/release.aspx?id=4514

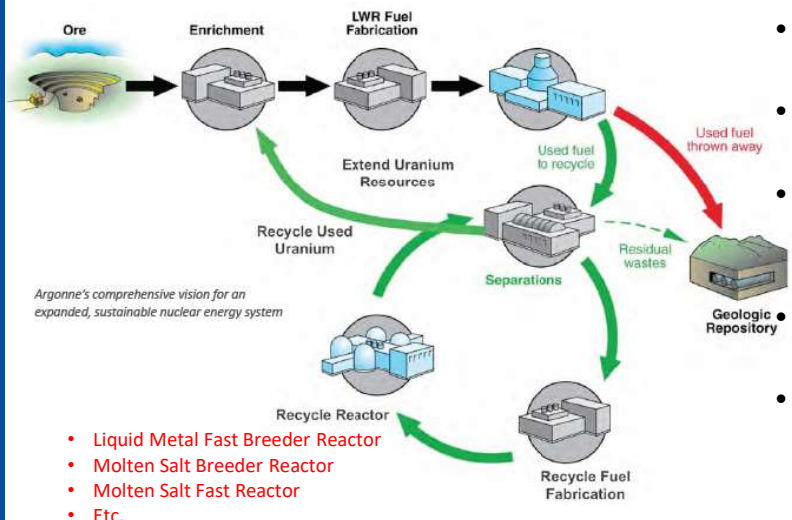
22

China plans to build 9 GW/year

NUCNET.ORG

China / Beijing 'To Start Construction' Of Facility For Extracting Uranium From Sea :: NucNet | The Independen...

Fuel recycling is also possible

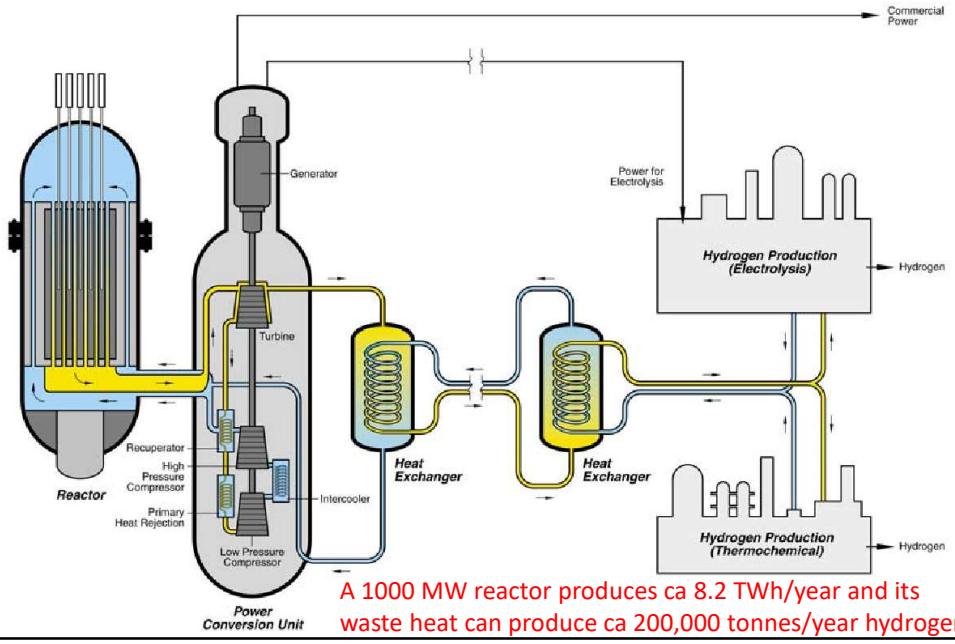


- Liquid Metal Fast Breeder Reactor
- Molten Salt Breeder Reactor
- Molten Salt Fast Reactor
- Etc.

- 100 times more energy extracted
- Ensure inexhaustible supplies of low-cost uranium resources
- Minimize the risk that used fuel would be used for weapons production
- Markedly reduce the amount of waste and the time to store it
- Reduce storage time to about 300 years

Source: ANL (2018). Pyroprocessing Technologies: Recycling used Nuclear Fuel for a Sustainable Energy Future. Lemont, IL, US Department of Energy, Argonne National Laboratory (ANL) https://www.anl.gov/sites/www/files/2018-2010/Pyroprocessing_brochure_2018.pdf.

Spin-offs are interesting



A 1000 MW reactor produces ca 8.2 TWh/year and its waste heat can produce ca 200,000 tonnes/year hydrogen

Electricity production for grid

AND/OR

hydrogen production

AND

thermo-chemical hydrogen production

25

Key-points from history

1. Massive disinformation about realities
2. Some traditional reactors have issues, BUT they are far less than what is commonly believed
3. Traditional nuclear reactors are **safer** and **cheaper** than almost all other power sources
4. Nuclear power is **renewable**
5. Nuclear power offers realistic options for an array of largescale, zero emission applications such as hydrogen

26

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BUT MODERN NUCLEAR POWER (4TH GENERATION) HAS ELIMINATED THESE RISKS AND IT BURNS NUCLEAR WASTE AND GENERATES UP TO 100 TIMES MORE ENERGY!

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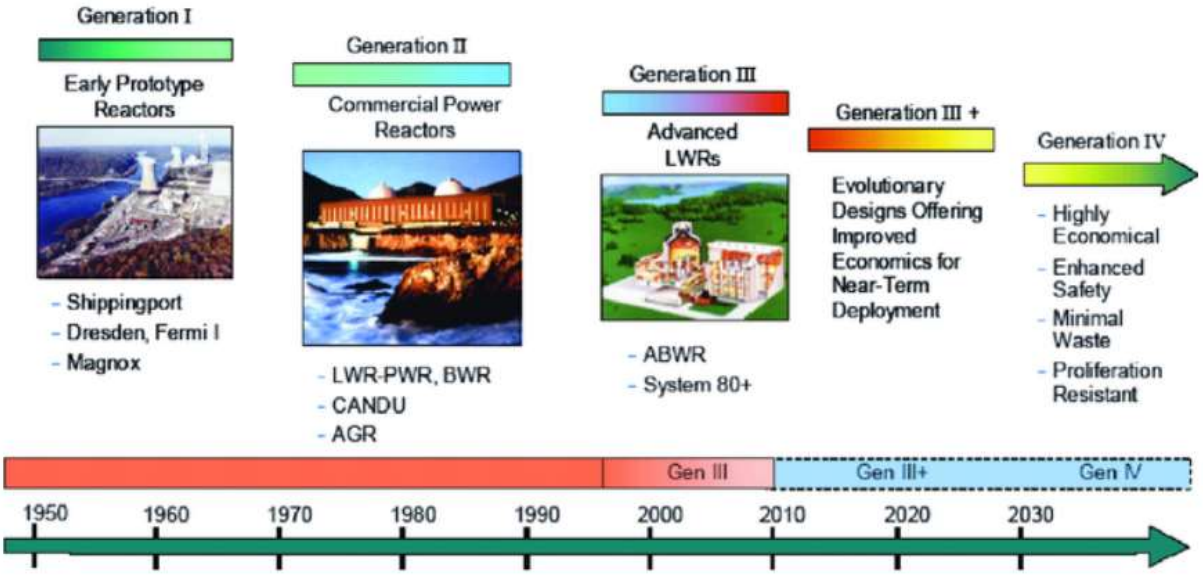
From Generation I to IV



Source: IPCC - https://archive.ipcc.ch/publications_and_data/ar4/wg3/en/figure-4-9.html

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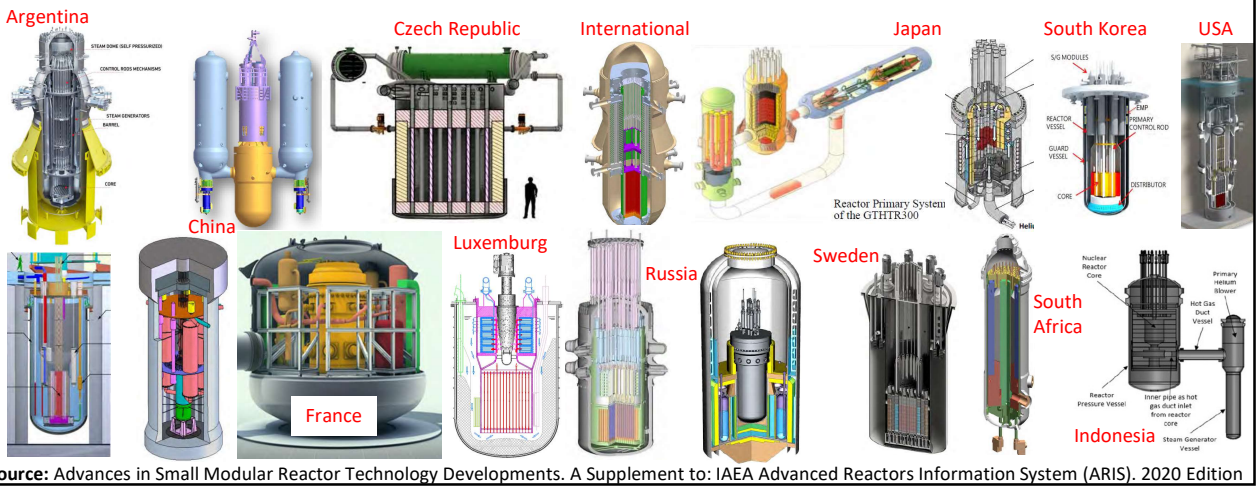
Nuclear innovations are many

Not in scale

67 different Small Modular Reactors (SMR) under development in 2020… here are 17;



Source: Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS). 2020 Edition

29

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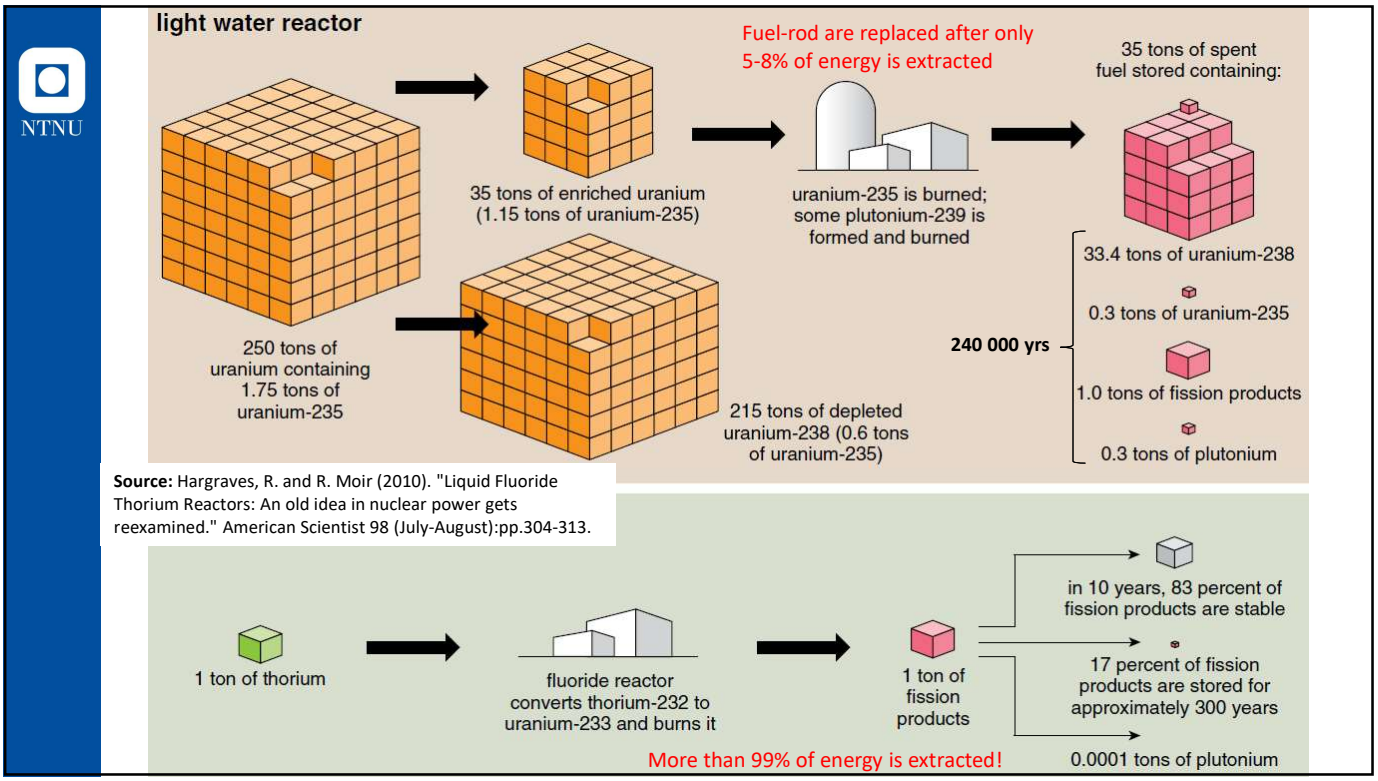
Introducing the Molten Salt Reactor (MSR)

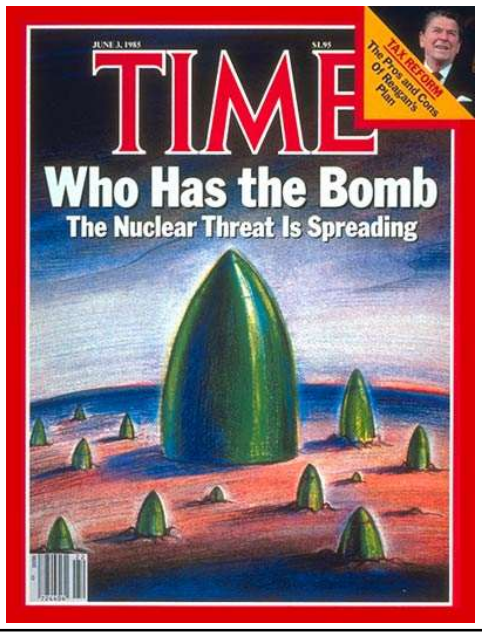
- The MSR is a liquid, chemical device and not a mechanical device based on fuel rods as in traditional nuclear reactors
- An MSR operated perfectly between 1965 and 1969 at 7 MWth
- 80% uptime!
- MSR is ideal due to scalability, safety, simplicity and costs
- The breeder versions can become over 100 times more effective than current nuclear plants

30



Why was development stopped?

- It as Cold War
- The LWR was more developed
- Needed for submarines
- The USA needed plutonium and uranium for bombs
- ORNL / Weinberg did not work politically



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Then came 9/11…

- We need a safe, non-proliferation technology
- "The most promising path forward is to return to the road not taken 50 years ago" – Newsweek

33

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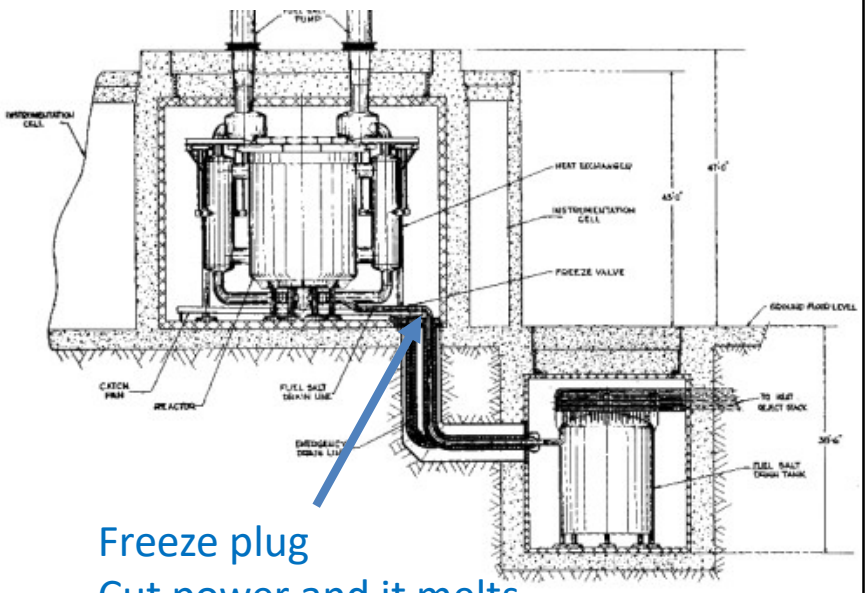
All MSRs are walk-away safe!

1. Inherently stable (negative reactivity)
2. Fuel is already melted – cannot boil
3. Atmospheric pressure prevents explosions



Freeze plug
Cut power and it melts

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The reactor design is more important than the fuel type

- Nuclear power is 95% nuclear engineering and 5% nuclear physics (H. Rickover)
- Fuel;
  - MSR works with uranium
  - MSR works with thorium
  - MSR works with TRU (trans-uranium elements, i.e. > 92) – nuclear rest material
- Major reactor design types;
  - Once through fuel cycle – chemical (re)processing offline
  - Closed loop fuel cycle – chemical (re)processing online

35

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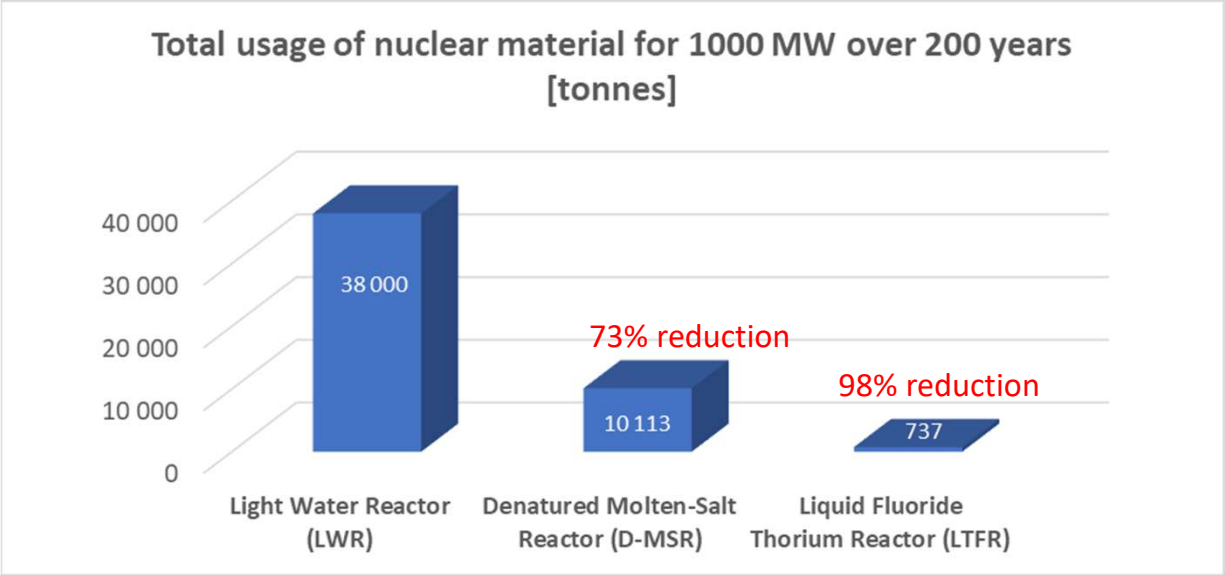
Dramatic reduction of waste



36

Source: Moir, R. W. and E. Teller (2005). "Thorium-Fueled Underground Power Plant based on Molten Salt Technology." Nuclear Technology 151(9):pp.334-340.

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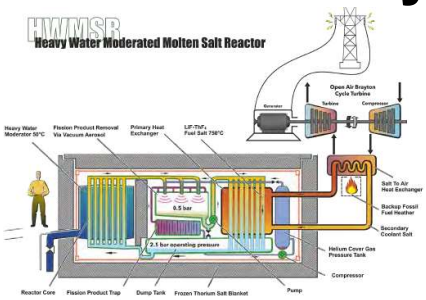
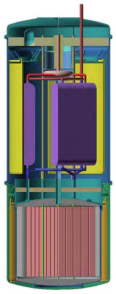
Development of MSR today

Not in scale

- Integrated MSR
- 195 MWe
- 56 years life-span
- 7 years service-life
- Th + LEU
- Basic design
- Canada



- Heavy Water MSR
- 100 MW(th)
- 3-5 years life-span
- Continuous service-life
- TRU (Waste burner)
- Conceptual design
- Denmark



- Smal Modular MSR
- 168 MWe
- 60 years life-span
- 10 years service-life
- Th + LEU
- Pre-conceptual design
- China

- ThorCon (Denatured MSR)
- 200 MW(e)
- 80 years life-span
- Continuous service-life
- Th, Pu and LEU
- Basic design completed
- USA / Indonesia

37

Source: Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS). 2020 Edition

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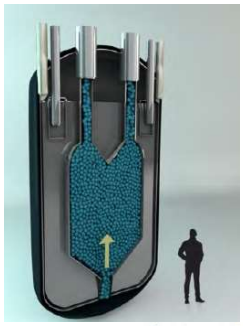
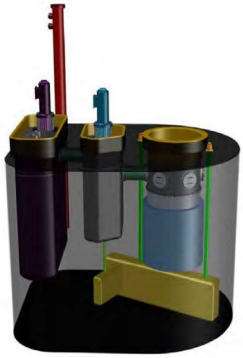
Development of MSR today (2)

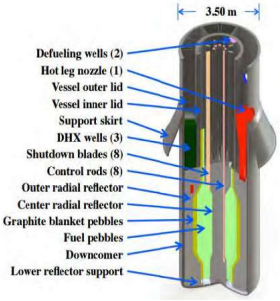
Not in scale



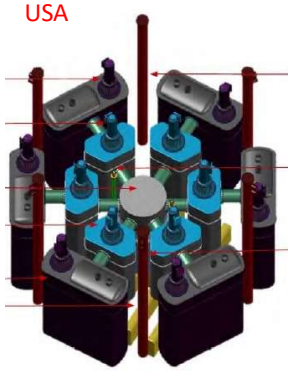
- Modular, pebble bed, high temperature, salt-cooled reactor
- 140 MWe
- 20 years life-span
- Continuous
- U (TRISO)
- Conceptual design
- USA



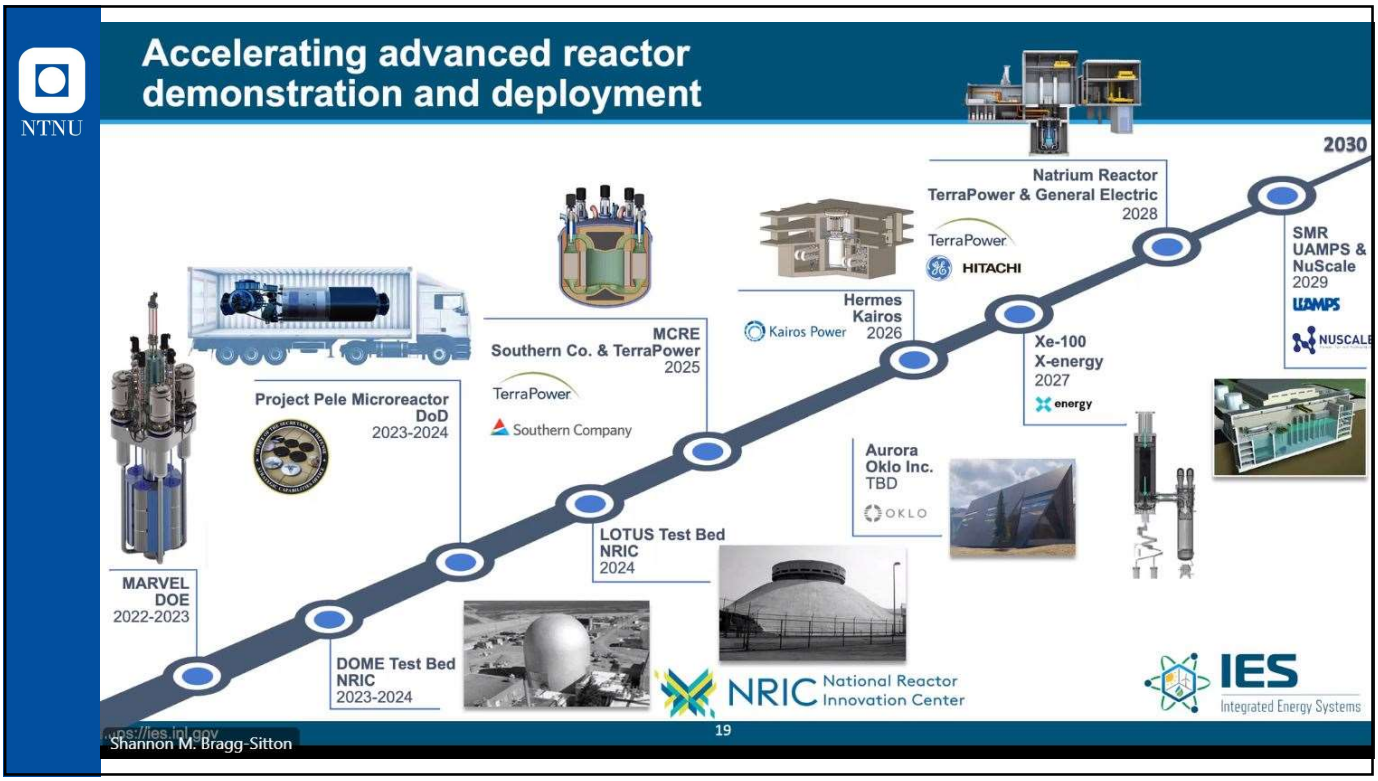
- Molten Chloride Salt Fast Reactor
- 50/200/400/1200 MWe
- 40 years life-span
- Continuous
- U /Pu
- Conceptual design
- USA

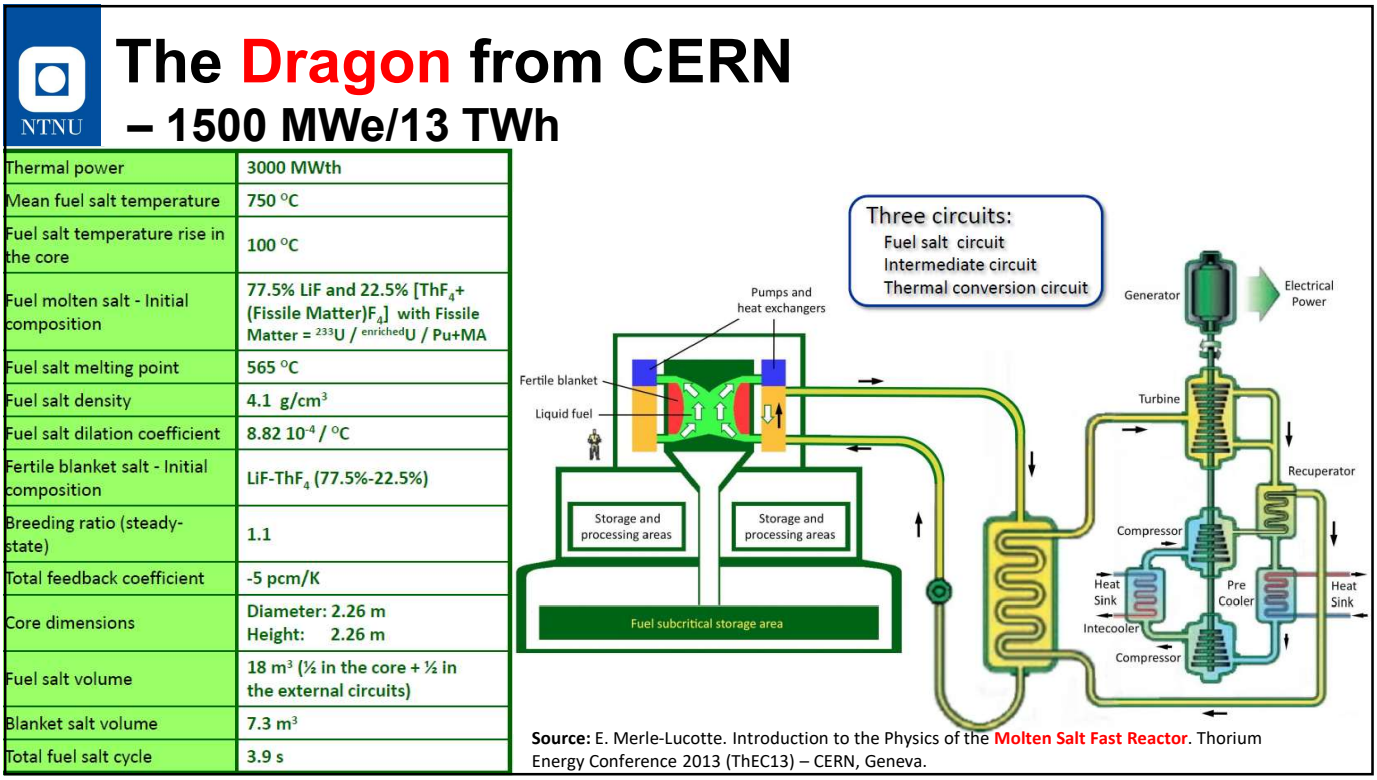


- Fluoride-salt-cooled high temperature reactor (FHR)
- 100 MWe
- 60 years life-span
- Continuous
- U (TRISO)
- Pre-Conceptual
- USA



38





Thermal power	3000 MWth
Mean fuel salt temperature	750 °C
Fuel salt temperature rise in the core	100 °C
Fuel molten salt - Initial composition	77.5% LiF and 22.5% [ThF_4+ (Fissile Matter)F_4] with Fissile Matter = ^{233}U / $^{enriched}U$ / Pu+MA
Fuel salt melting point	565 °C
Fuel salt density	4.1 g/cm^3
Fuel salt dilation coefficient	8.82 10^{-4} / °C
Fertile blanket salt - Initial composition	LiF-ThF_4 (77.5%-22.5%)
Breeding ratio (steady-state)	1.1
Total feedback coefficient	-5 pcm/K
Core dimensions	Diameter: 2.26 m Height: 2.26 m
Fuel salt volume	18 m^3 (½ in the core + ½ in the external circuits)
Blanket salt volume	7.3 m^3
Total fuel salt cycle	3.9 s

Source: E. Merle-Lucotte. Introduction to the Physics of the **Molten Salt Fast Reactor**. Thorium Energy Conference 2013 (ThEC13) – CERN, Geneva.

MSR is cheaper than coal

(before CO_2 taxes)

Item	1978$			2000$		
Direct costs, M$	MSR	PWR	Coal	MSR	PWR	Coal
	Cost/kWh, ¢/kWh					
Capital	0.83b	0.85b	0.65b	2.01b	2.07b	1.58b
O&M	0.24c	0.47d	0.33d	0.58c	1.13d	0.80d
Fuel	0.46c	0.31e	0.71f	1.11c	0.74e	1.72f
Waste disposal	0.04g	0.04g	0.04d	0.10g	0.10g	0.09d
Decom	0.02c	0.03d	--	0.04c	0.07d	--
Total	1.58	1.69	1.73	3.84	4.11	4.19

Ca 30 øre/kWh

Source: Moir, R.W. (2002). "The cost of electricity from Molten Salt Reactors (MSR)." Nuclear Technology 138(1):93-95.

The way forward

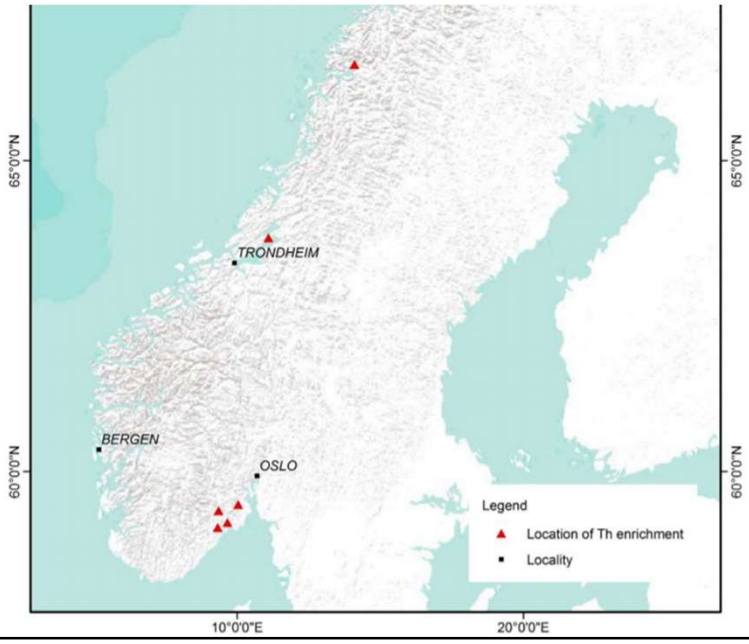
- The technology readiness-level for the thorium-based MSR is in the early demonstration stage
- China is testing a small reactor now
- Work is required on;
  - The materials for piping and pressure vessels
  - The chemical cleaning process of the salt
  - Political front

42

Norway's 'contribution'…

- We are going to spend 21 bn NOK on 16,500 kg radioactive 'waste'
- BUT; Why not use it as start-fuel in a new, modern reactor AND fund the research for more than a decade?
- Work with the other Nordic countries?

We have thorium



- Estimates range from 87,000 tonnes to 320,000 tonnes
- 2,000+ years!
- Initial estimates are often wrong
- Extract Thorium + REE + phosphate
- Uranium from the sea

BUT; we need to act

Takk for meg ☺

Question and Answer