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Small Modular Nuclear Reactors: Hope or Hype?

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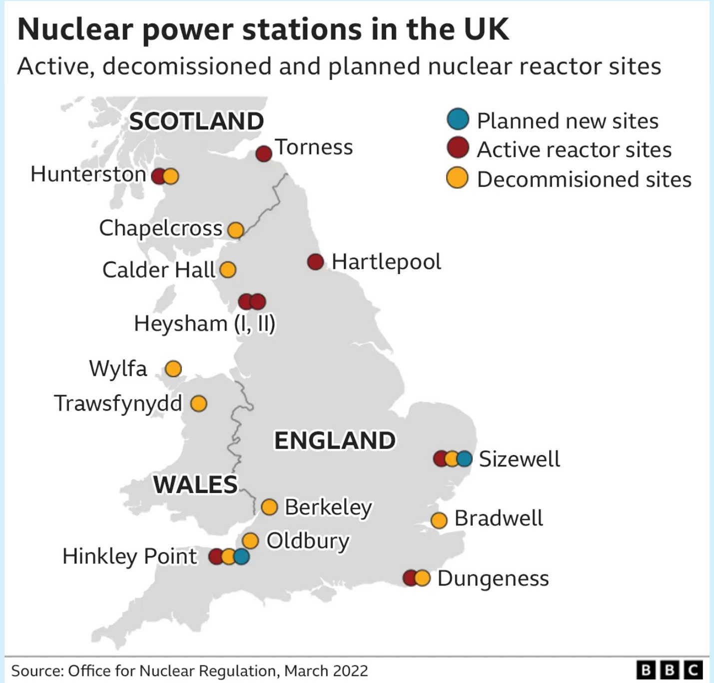
Current UK Status

- ~40 GW demand, 15% Nuclear
- AGR fleet reaches end of life by 2030, latest
  - PWR at Sizewell B – 2035 (+PLEX)
- 2xEPR @Hinkley Point C (completion 2028)
  - Site licence granted in 2012
  - Evolution of Standard 4 loop PWR
  - Large core ~1,630 MWe
  - Secondary containment, molten core catcher
  - EdF funded through CfD; £92.50/MWh strike price*
- EPR @Sizewell C?
  - FID by end of this parliament…?



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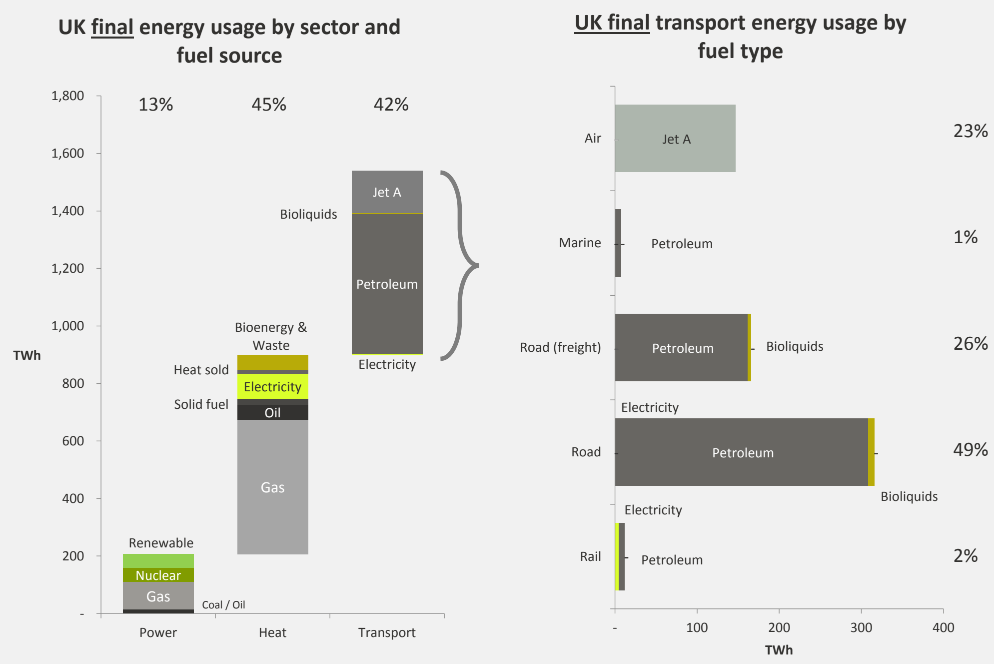
Targets & Drivers

- Climate change & net zero by 2050
  - Electrification
  - +24 GW of nuclear by 2050
- Energy security
- Approaches:
  - Renewables (wind & solar)
  - Hydro-electricity
  - Energy storage (batteries…)
  - Carbon capture & storage (CCS)
  - Nuclear

Only ~12% of energy used in the UK is low carbon by source



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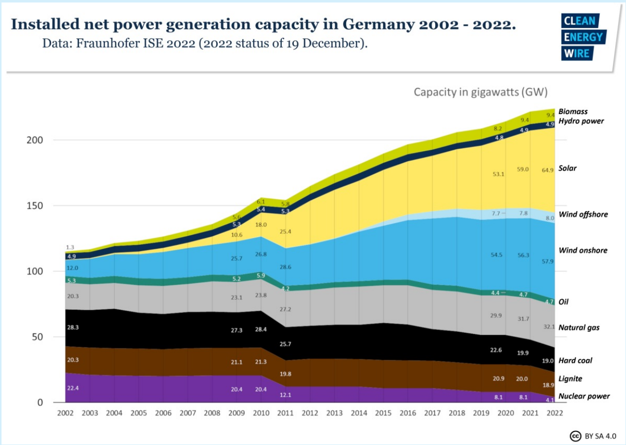
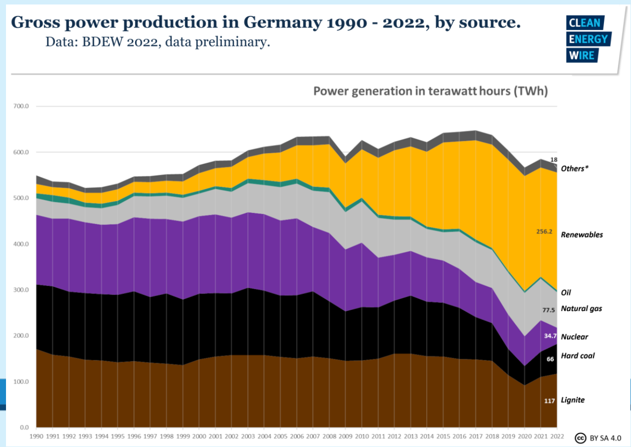
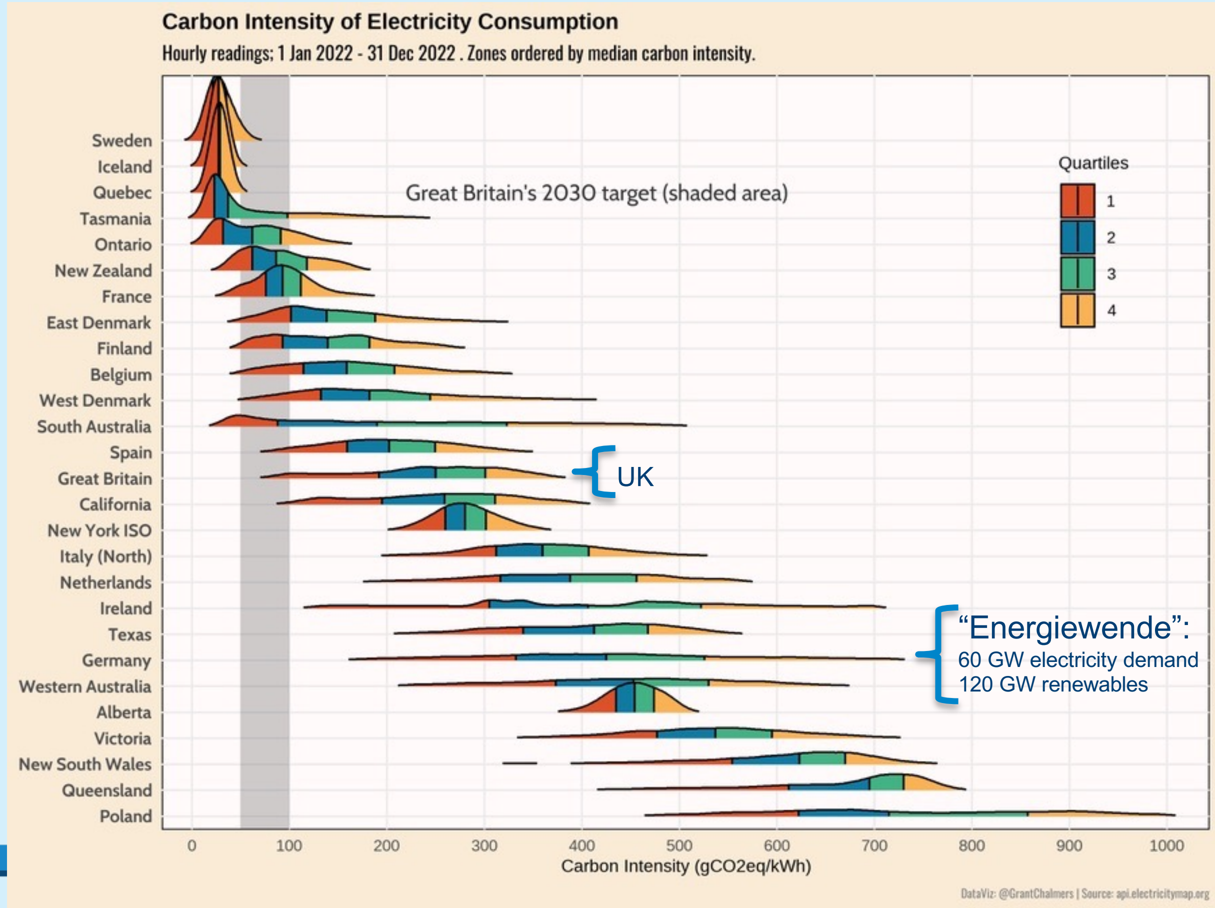
Carbon intensity status: impact of renewables







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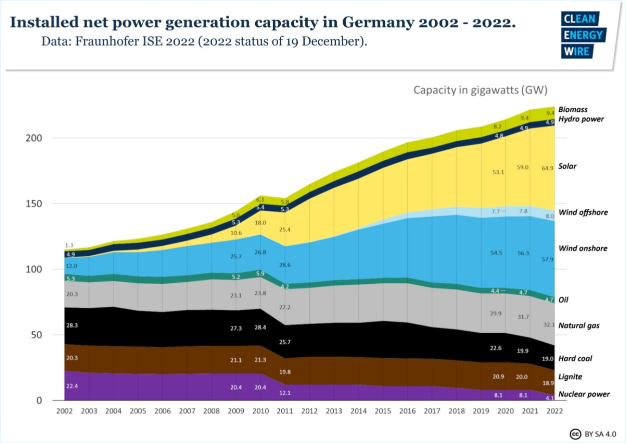
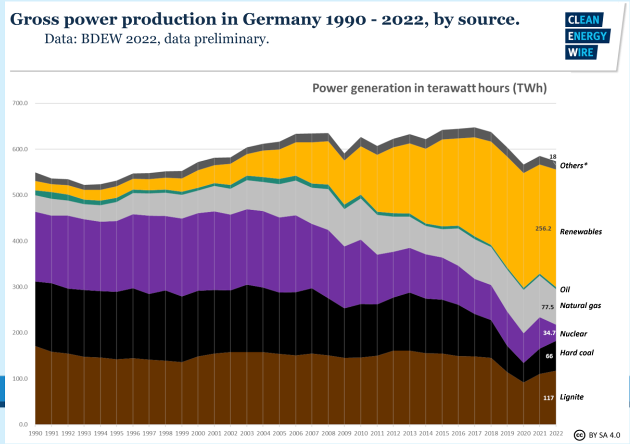
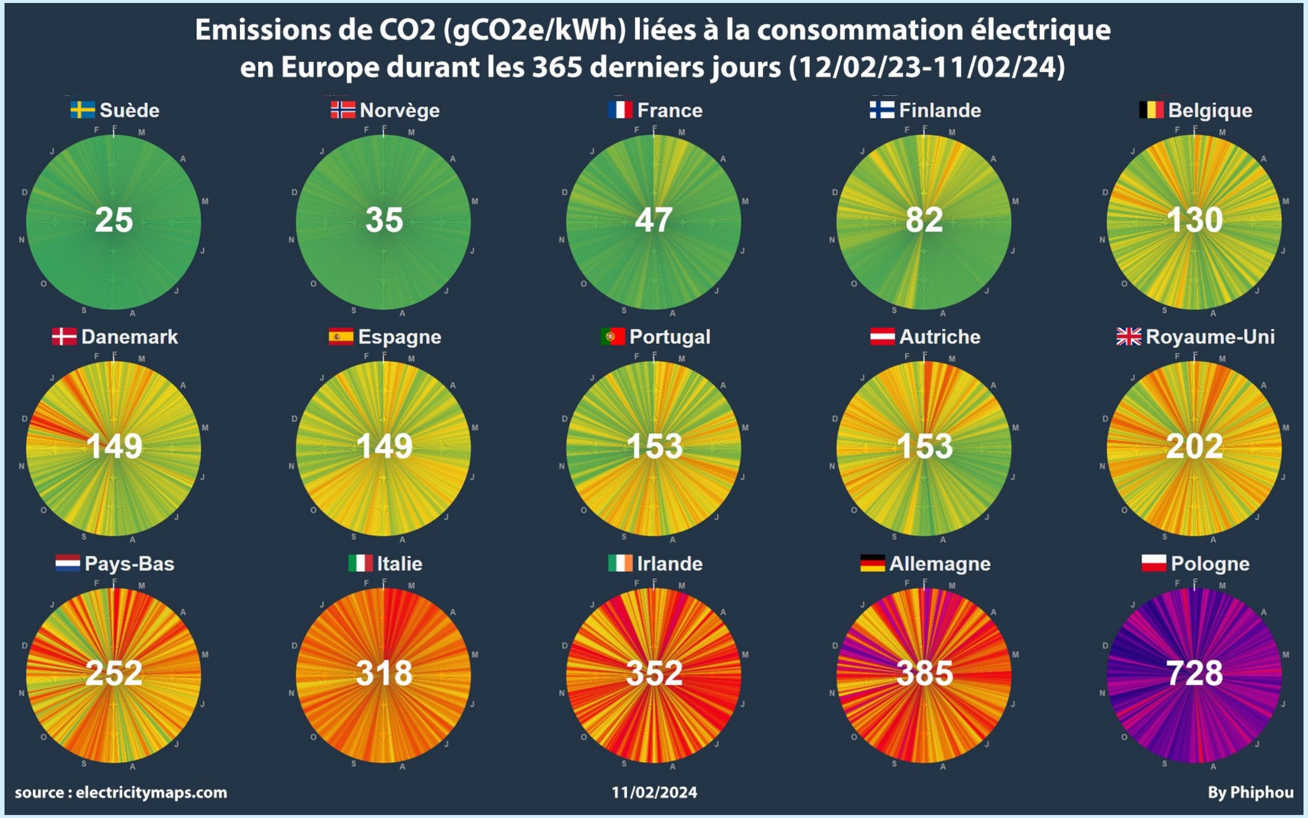
Carbon intensity status: impact of renewables







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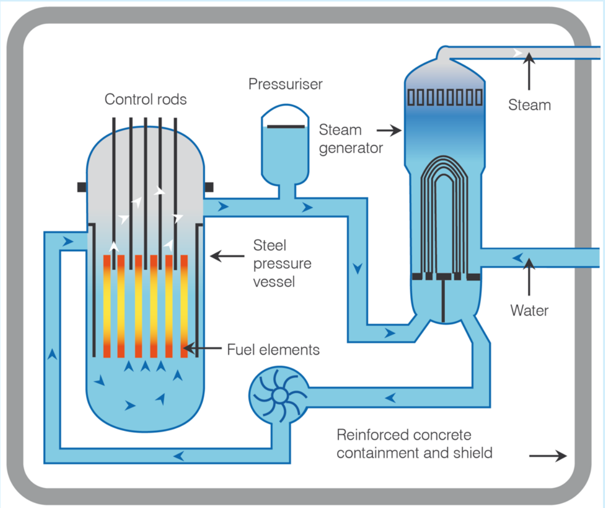
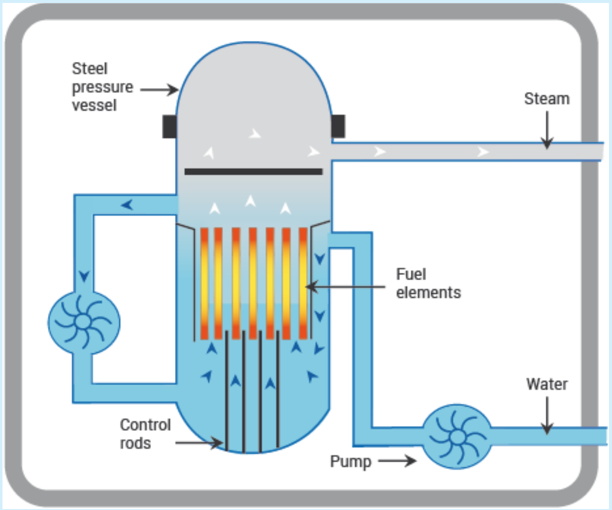
HPC EPR Core size: 4.8 m high; 3.8 m diameter; 241x(17x17 assemblies)
HPC EPR RPV: 13 m high; 4.9 m diameter

Current (large) Reactors

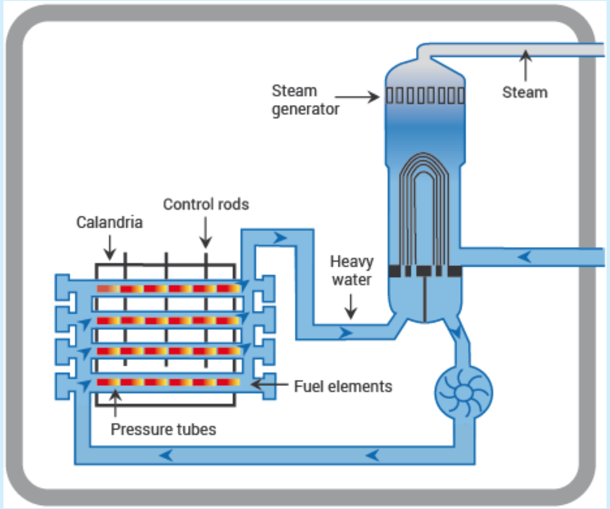
- ~430 Reactors worldwide – almost all are water cooled reactors, ~1 GWe
- ‘Economy of Scale’ drivers led to larger reactors 1950s → 2010s



PWR (301)



BWR (41)



PHWR (46)

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Problems with nuclear: Accidents

- Three-mile island (US)
  - Stuck pilot valve; resulting loss of coolant; meltdown
  - No casualties
- Chernobyl (Ukraine)
  - Imposed coolant flow reduction; positive void coefficient & xenon poisoning
  - 42 direct casualties; ~4000 cases of thyroid cancer over subsequent 40 years
- Fukushima (Japan)
  - Loss of pumping power (inundation of diesel back-up generators), overheating leading to meltdown, hydrogen explosion, radionuclide release
  - 1 casualty*
- Zaphorizia?
  - Potential loss of off offsite power; reliance on diesel back-up in war conditions

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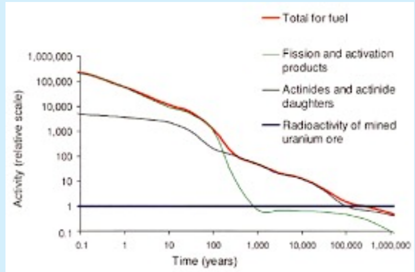
Problems with nuclear: Waste

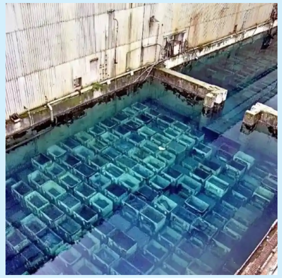
- Categories
  - LLW – discarded equipment, tools, clothing
  - ILW – reactor internals, cladding
  - HLW – fission products
- Disposal
  - Surface repositories
  - Deep geological repositories (Finland)
- Fuel cycles
  - Open cycles, half-open cycles (MOX); thermal reactors
  - Closed cycles; fast reactors (Gen IV)

	Volume (m^3)	% Volume	Activity (TBq)	% Activity
LLW	2,100,000 m^3 **~ $(128m)^3$**	91%	21	0.00003%
ILW	220,000 m^3 **~ $(60m)^3$**	9%	4.5M	6%
HLW	1,300 m^3 **~ $(11m)^3$**	0.1%	75M	94%

UK nuclear waste volumes

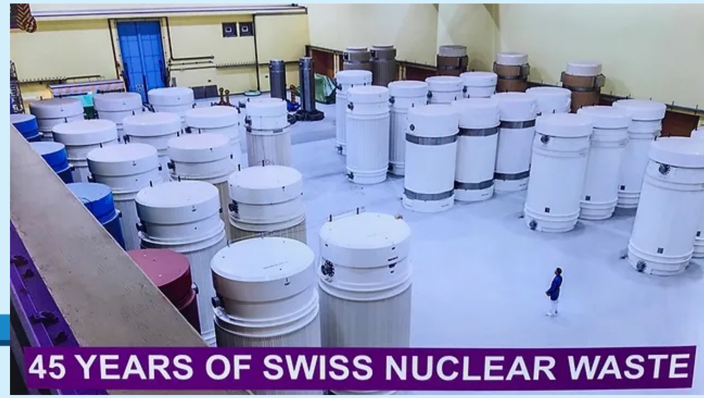


Radioactivity vs time



What not to do…

https://www.theguardian.com/environment/2014/oct/29/sellafield-nuclear-radioactive-risk-storage-ponds-fears



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Problems with nuclear: Costs & Time

- EPR: (Fr-Ge)
  - Flammanville (France) 2008 – 2024 (€3 Bn – €13 Bn)
  - Olkiluoto (Finland) 2009 – 2023 (€4 Bn – €12 Bn)
  - Taishan (China) (2 units) 2010 – 2018* ($10 Bn - $34 Bn)
  - HPC (UK) (2 units) 2017 – 2028 (£18 Bn – £33 Bn)
- AP1000 (US)
  - Vogtle (US) (2 units) 2013 – 2023/4 ($14 Bn - $34 Bn)
  - Sanmen (2 units) (China) 2009 – 2018 ($6 Bn - $8 Bn)
- APR1400 (SK)
  - Barakh (UAE) (4 units) 2011 – 2023 ($30 Bn - $24 Bn)

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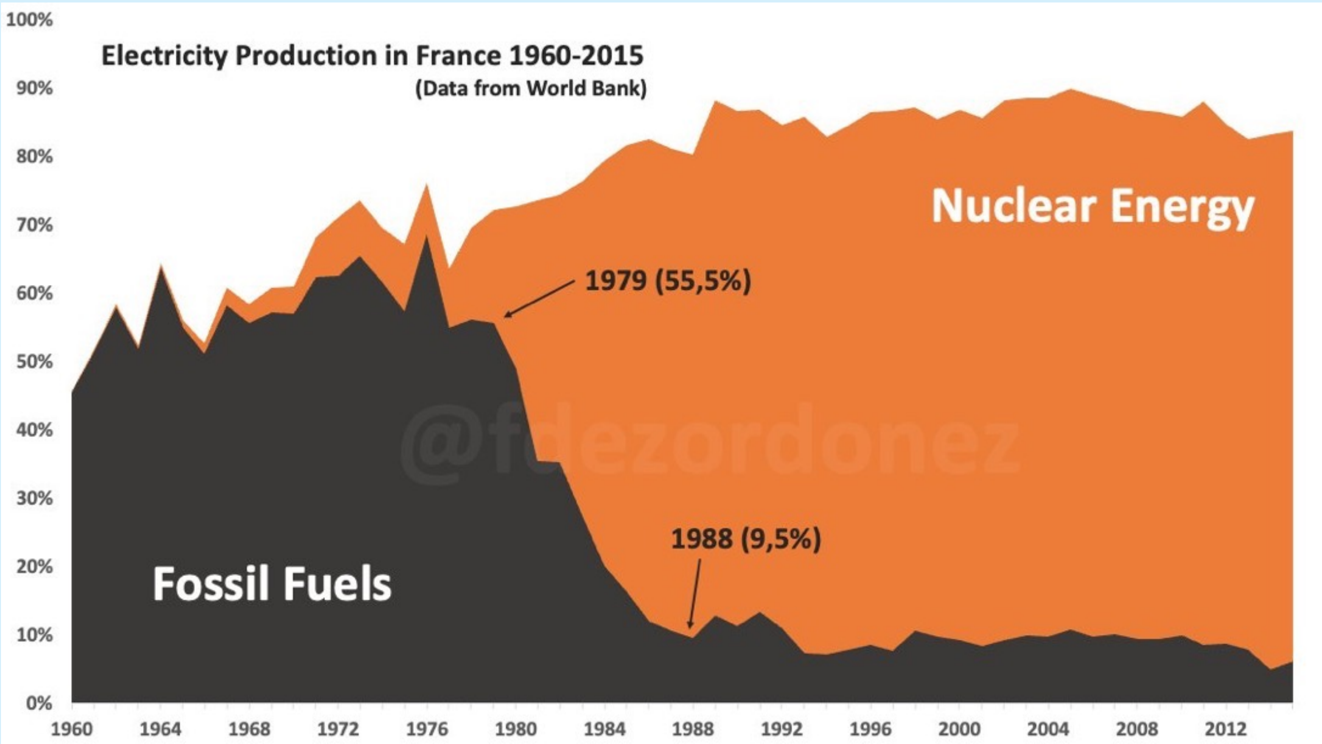
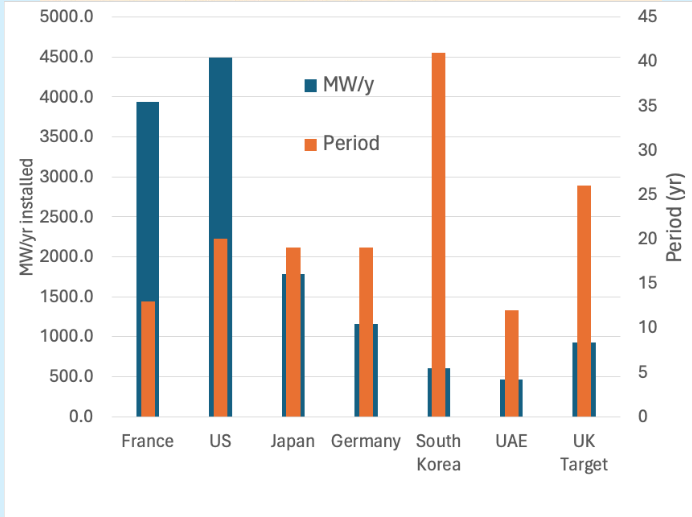
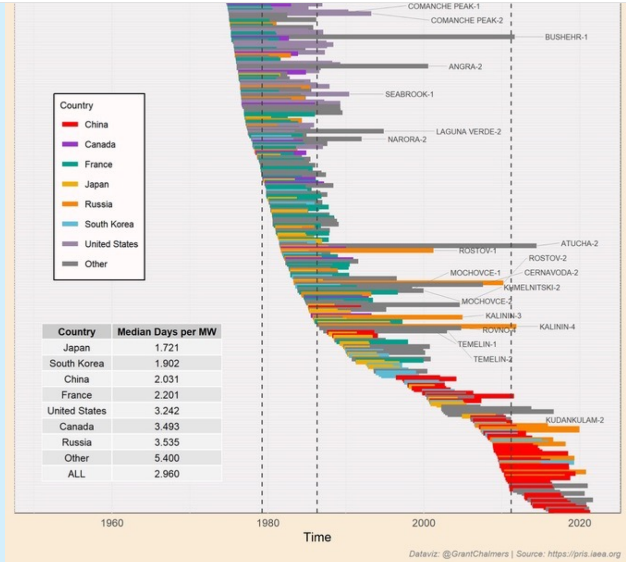
Build Time







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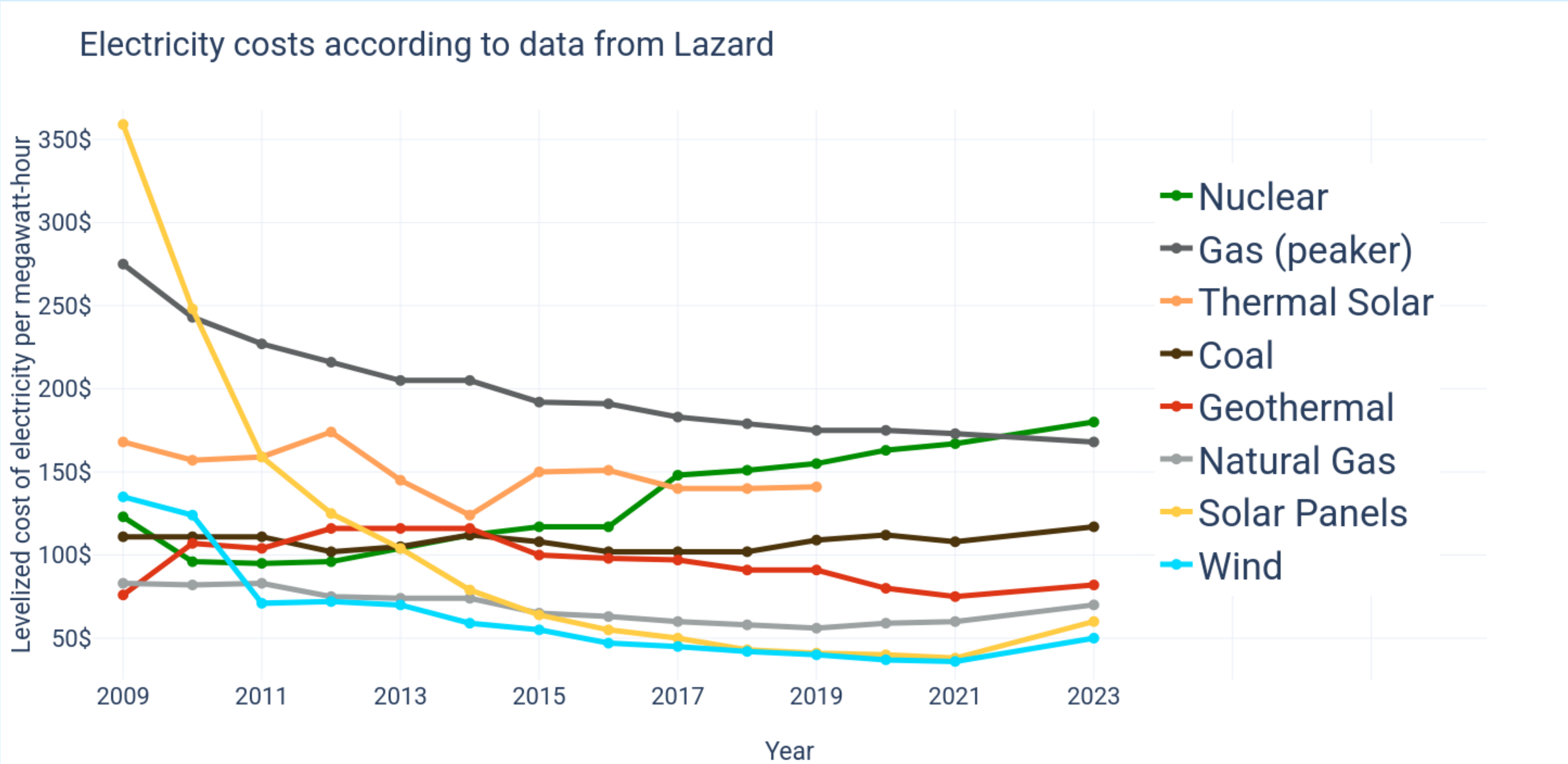
Cost

Levelized cost of electricity (LCOE)



Apples & oranges?

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https://aris.iaea.org

Small Modular Reactors (SMR)

- IAEA definition <300 MWe
- Why?
  - Economy of large production numbers – as opposed to economy of scale
  - Siting (could be sited closer to industry and population sites) (why?)
  - Lower operating inertia – improved load-following (why?)
  - Easier build
    - Few countries have ability to forge large RPVs
    - Smaller scale plant components, better QC, easier transportation, minimization of site preparation
  - Lower capital cost; easier market entry
- In excess of 50 designs (on paper) – see the IAEA ARIS database (https://aris.iaea.org)

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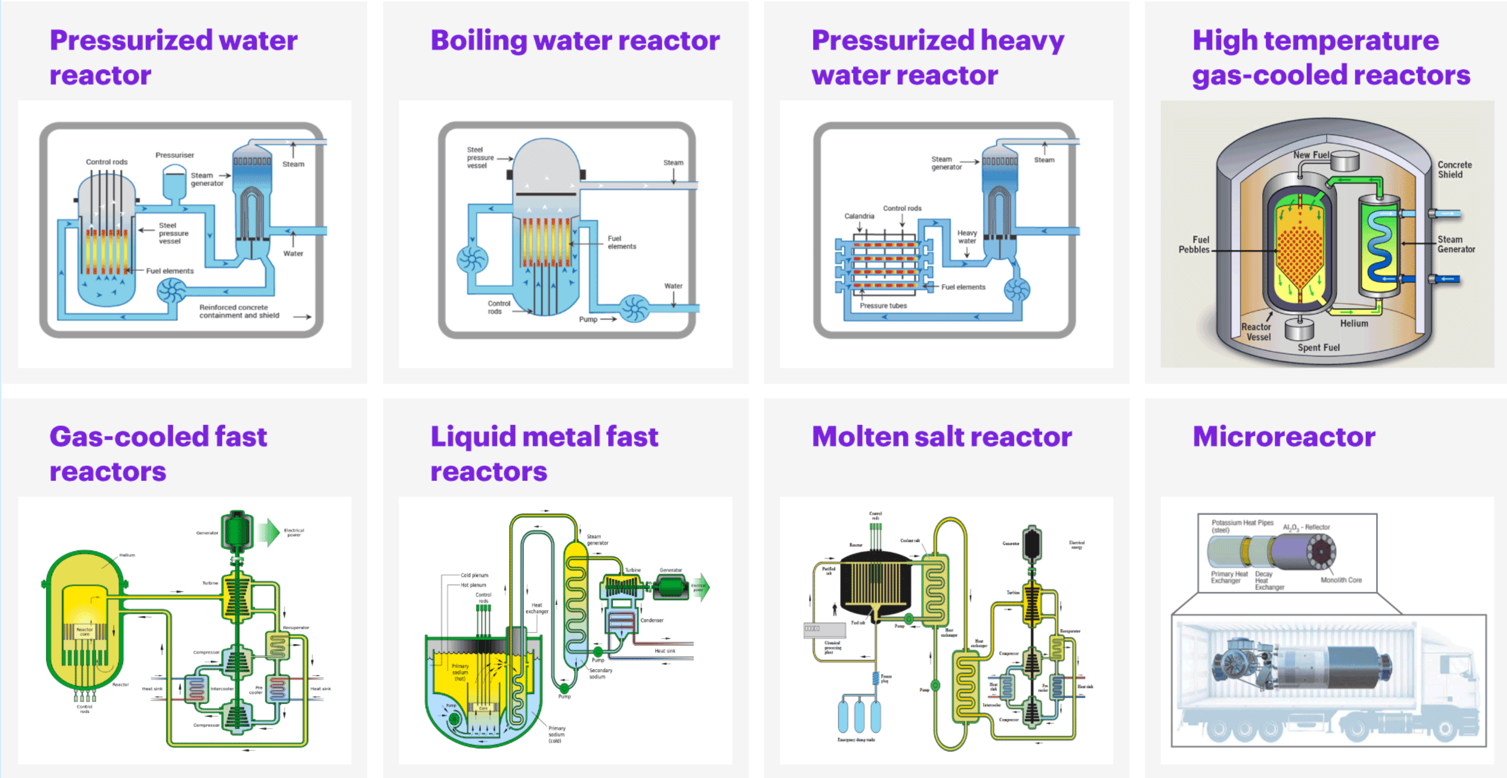
SMRs

- Gen III type
  - 'Thermal'
  - L/HW
- Gen IV type
  - 'Fast'
  - Closed cycle
- Microreactors

Figure 2

Key SMR technologies designs



Source: Kearney Energy Transition Institute analysis

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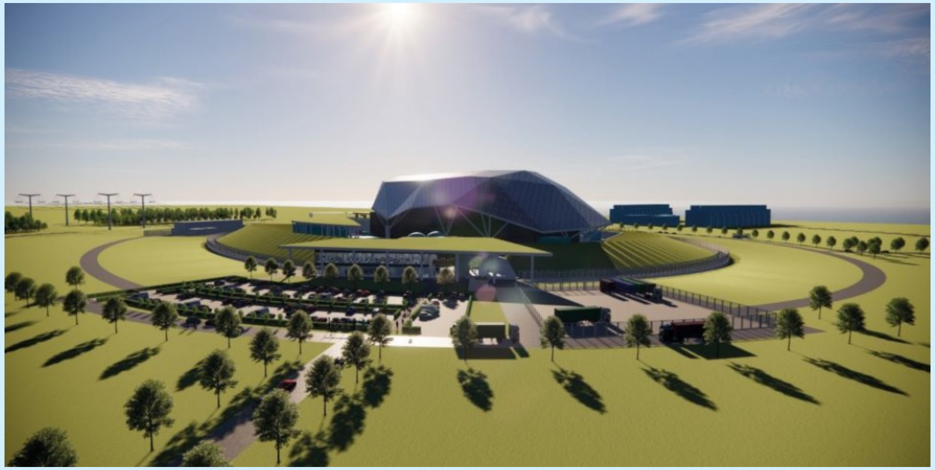
SMRs



- UK SMR Competition
  - RR SMR (440 MWe PWR)
  - NuScale VOYGR SMR (77 MWe iPWR)
  - EdF NUWARD (2x170 MWe iPWR)
  - Westinghouse AP300 (300 MWe PWR)
  - Holtec SMR-160+ (160 MWe)
  - GE-Hitachi BWRX-300 (300 MWe BWR)
- Bids for contracts ended end of 2023, successful bids to be announced Spring 2024*, contracts awarded Summer 2024; FID 2029…

All are LWR thermal spectrum technologies

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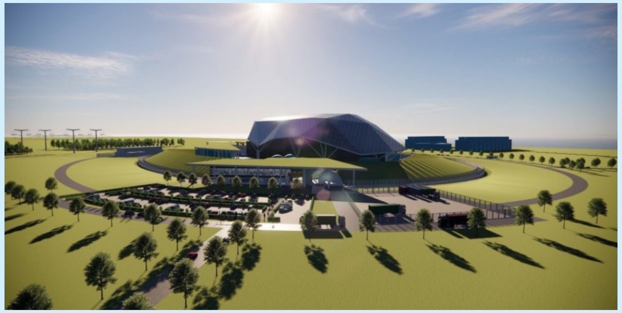
RR SMR (440 MWe)



- UK Design
  - Builds on submarine reactor experience, but is NOT a repackaged sub reactor
  - Essentially a standard 4-loop PWR (think of a smaller Sizewell B) in a smaller package
  - Does not use a dilute boron shim; extensive use of burnable poisons
  - Standard ‘Westinghouse’ fuel – 60 yr lifetime/24 month cycle
- Essentially a minimal technical risk approach
- Status: Entered UK Generic Design Assessment (GDA) 2022, FOAK 2035. 4 UK Sites? Estimated £50/MWh

Core: 2.8 m high; 2.7 m diameter; 121x(17x17 assemblies)
RPV: 7.9 m high; 4.2 m diameter

EPR Core size: 4.8 m high; 3.8 m diameter; 241x(17x17 assemblies). RPV size: 13 m high; 4.9 m diameter

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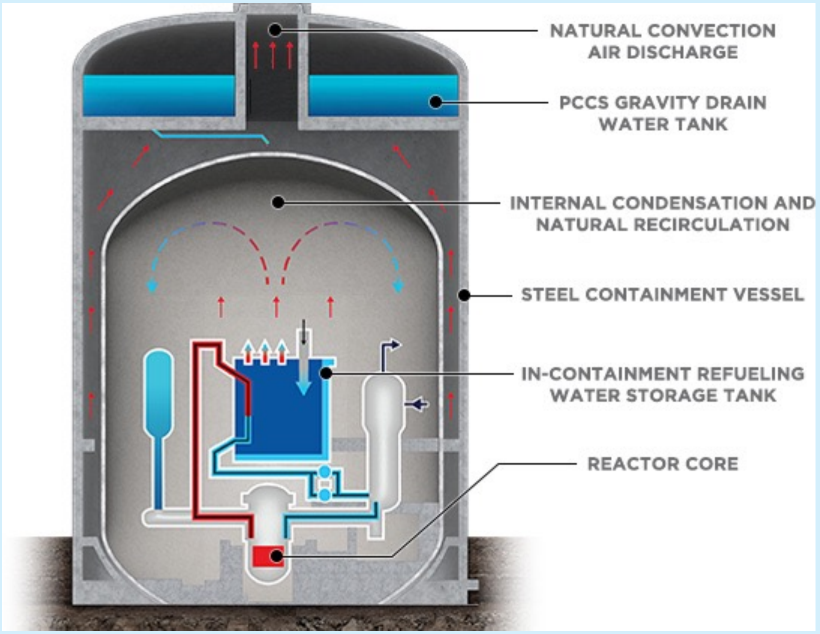
Westinghouse AP300 (300 MWe)

- US Design
  - Compact version of AP600/1000 PWR
  - Designed to achieve and maintain safe shutdown condition without operator action, back-up power or pumps
  - 60 yr lifetime /24 month cycle
- Status: Early phase agreements with Ukraine, Sweden, Finland



Core: ? m high; ? m diameter; 76x(17x17 assemblies)
RPV: 13 m high; 4.0 m diameter

EPR Core size: 4.8 m high; 3.8 m diameter; 241x(17x17 assemblies). RPV size: 13 m high; 4.9 m diameter

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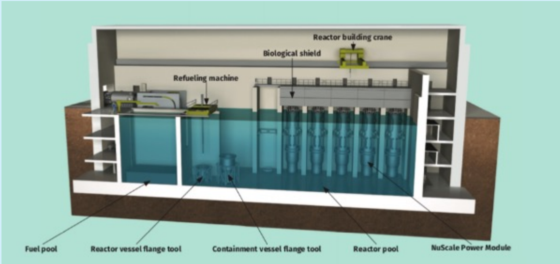
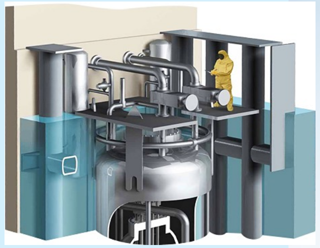
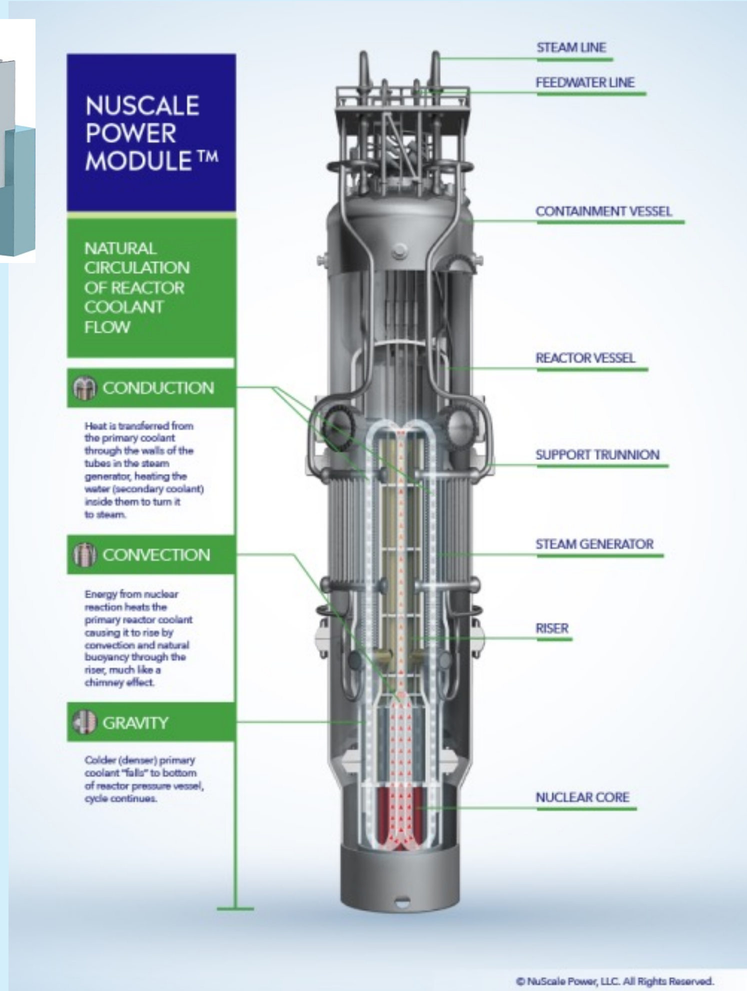




NuScale VOYGR SMR (77 MWe)

- US Design
  - iPWR (steam generator integrated into RPV)
  - No pumps – relies entirely on natural circulation; passive safety
  - Plant consists of multiple VOYGR modules
  - 60 yr lifetime / 24 month cycle
- Status: Received licence from NRC; component manufacturing began 2023. Site agreements in Idaho, and others in the US & EU



Core: 2.0 m high; 2.5 m diameter; 37x(17x17 assemblies)
RPV: 17.8 m high; 3.0 m diameter

EPR Core size: 4.8 m high; 3.8 m diameter; 241x(17x17 assemblies). RPV size: 13 m high; 4.9 m diameter

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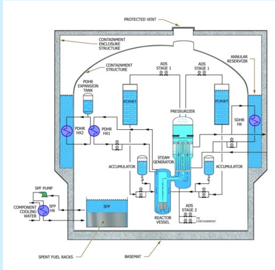
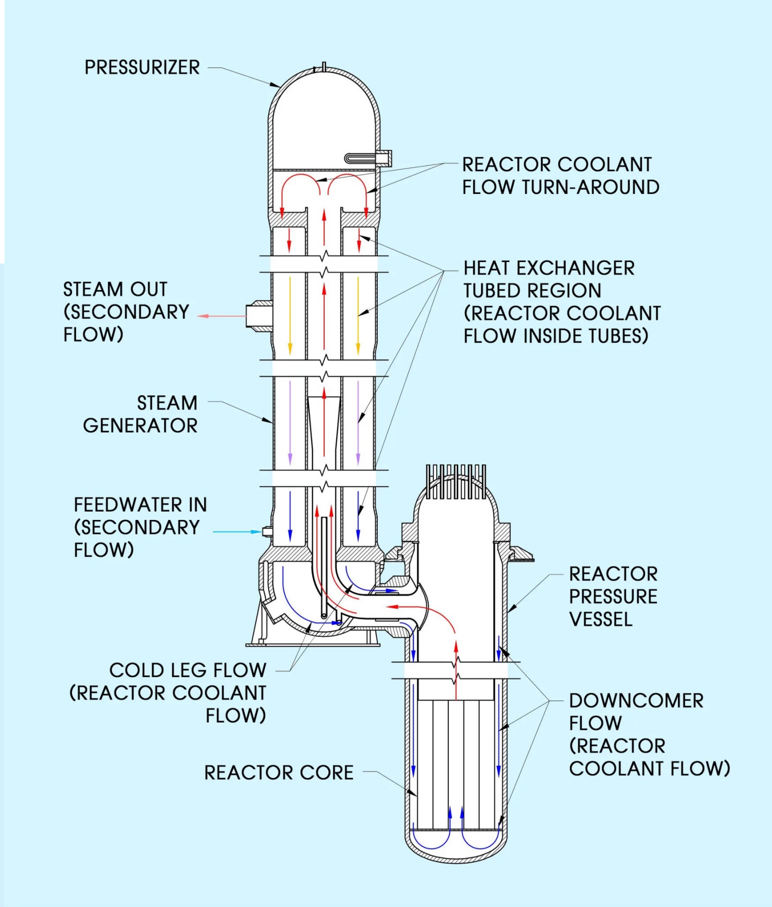
Holtec SMR-160+ (160 MWe)



- US Design
  - Based on a PWR design
  - No pumps or valves – uses natural circulation*
  - Little public detail
  - 60 yr lifetime / 24 month cycle
- Status: Agreements with Oyster Creek (US), Ukraine, Czechia



Core: ? m high; ? m diameter; 57x(?x? assemblies)
RPV: ? m high; ? m diameter

EPR Core size: 4.8 m high; 3.8 m diameter; 241x(17x17 assemblies). RPV size: 13 m high; 4.9 m diameter

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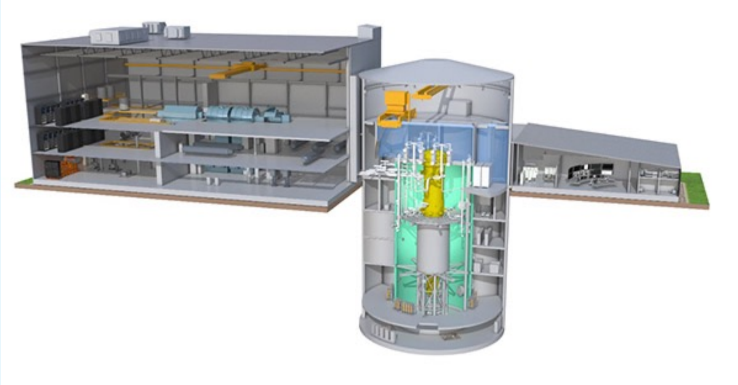
GE-Hitachi BWRX-300 (300 MWe)

- US Design
  - Based on a BWR design
  - No pumps – uses natural circulation
  - Standard fuel ABWR fuel
  - 60 yr lifetime / 24 month cycle
- Status: Sites planned in Ontario, Sweden, Estonia,…



Core: 3.8 m high; 2.5 m diameter; 208x(10x10 assemblies)
RPV: 27.4 m high; 4.0 m diameter

EPR Core size: 4.8 m high; 3.8 m diameter; 241x(17x17 assemblies). RPV size: 13 m high; 4.9 m diameter

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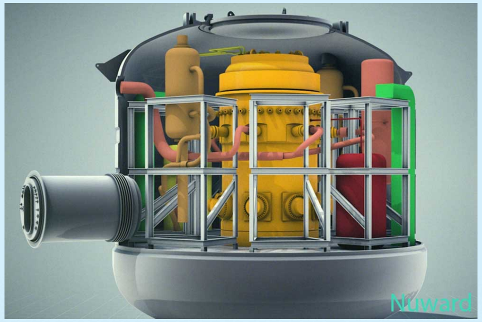
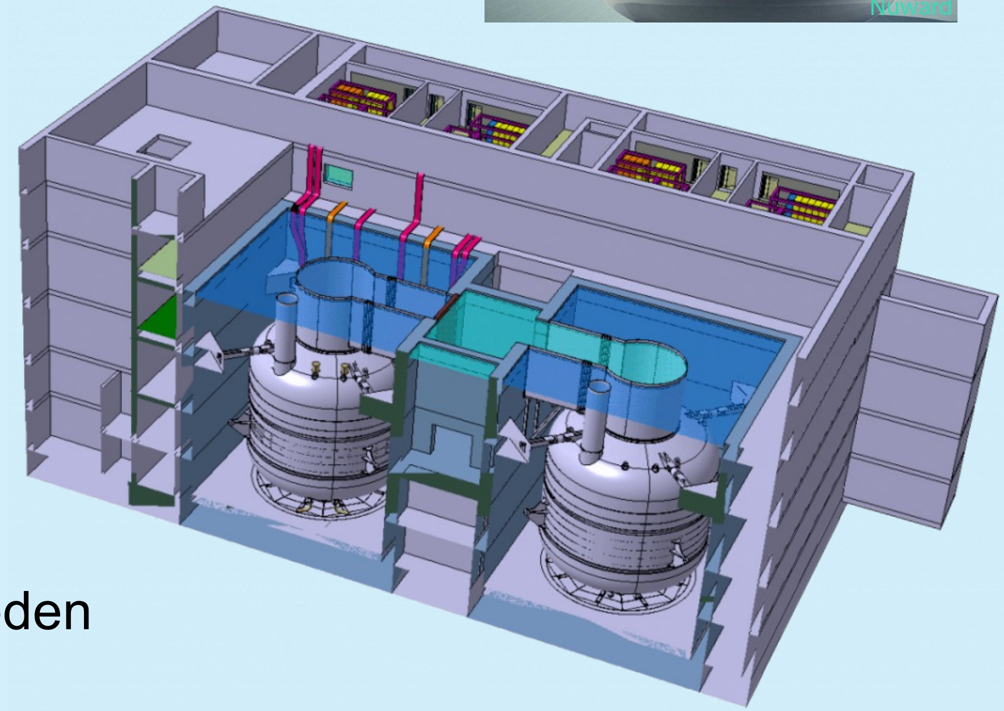
EdF NUWARD (2x170 MWe)



- French Design
  - 2 units based on an iPWR design
  - Forced convection
  - Boron free – burnable poisons
  - 60 yr lifetime / 24 month cycle
  - Little public detail
- Status: MoUs with Poland, Finland, Sweden



Core: ? m high; ? m diameter; 76x(17x17 assemblies)
RPV: 13 m high; 4.0 m diameter

EPR Core size: 4.8 m high; 3.8 m diameter; 241x(17x17 assemblies). RPV size: 13 m high; 4.9 m diameter

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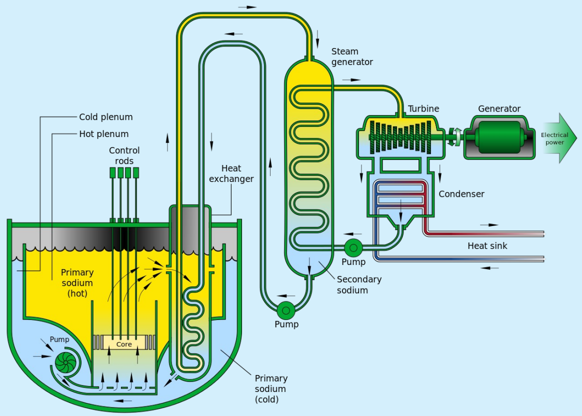
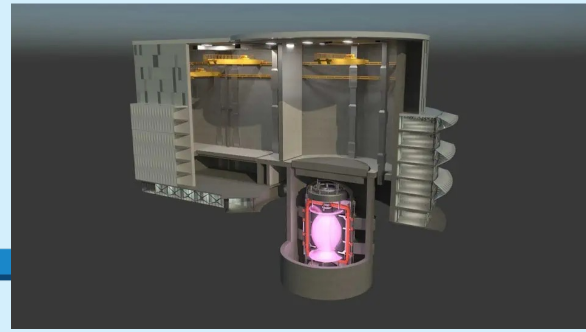
Other

- Microreactors (<25 MWe)
  - Westinghouse eVinci, TerraPower, BWXT,…
  - UK microreactor programme; space applications – RR
- Gen IV/AMR (large or small)
  - Some with fast-spectrum with waste burning capabilities
    - Lead-cooled Fast, Sodium-cooled fast, HT gas cooled
  - UK HTGR programme (+Japan) – thermal, hydrogen
- Fusion
  - Many small fusion proposals, mostly ‘paper’ reactors
  - UK STEP programme (small spherical tokamak)
  - Tokamak Energy, First Light Fusion





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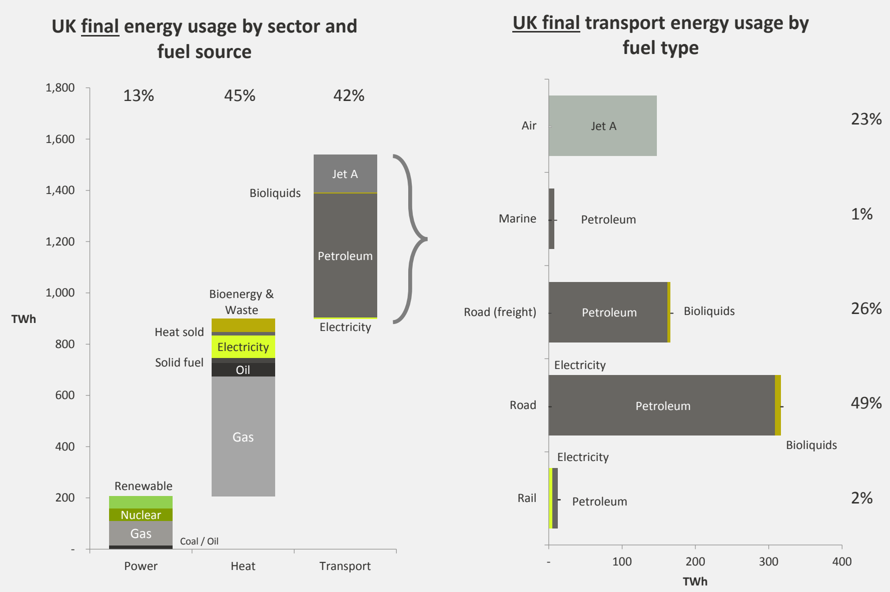
Cogeneration Opportunities

- Climate change - zero-carbon by 2050
  - Electricity, transport, building heating, agriculture, industrial process heating
- High cost of nuclear (compared with renewables*)
  - Intermittency of renewables – load following is an additional cost to nuclear
  - Capital cost, financing
- Cogeneration - 'sweating the asset'
  - Additional revenue streams
  - Note: 2/3 of the energy from an LWR is 'wasted

Only ~12% of energy used in the UK is low carbon by source



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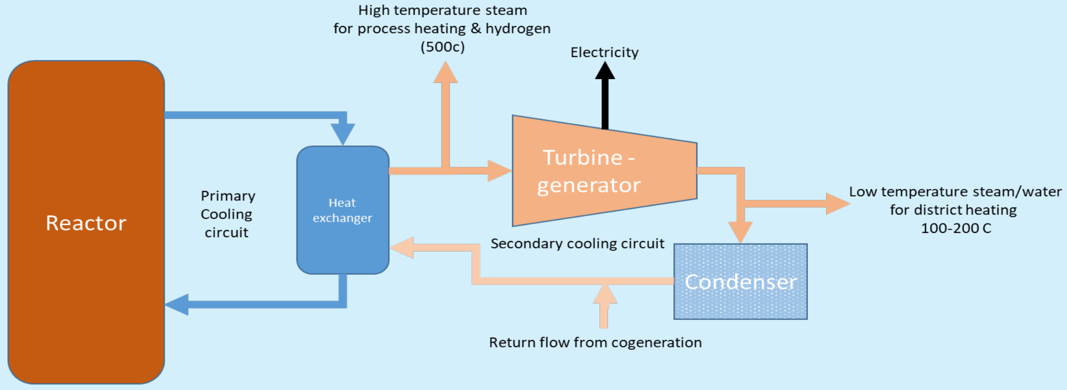
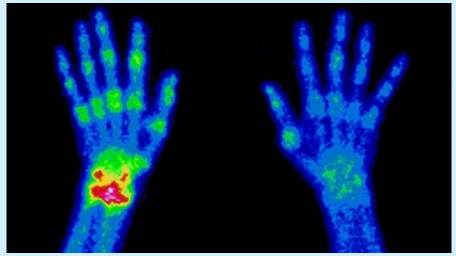
Cogeneration



- District Heating
  - Well developed (although not in the UK)
  - Needs extensive planning and infrastructure
- Desalination
  - Well developed – unimportant in the UK*
- Other Low-temperature process heat requirements
  - Some construction materials (bricks), atomization, humidifica drying
- High temperature process heat
  - Hydrogen economy - vector for load following in a renewables heavy scenario
  - Green steel, cement
  - Many Gen IV/AMR reactor designs produce high temperature steam
- Medical Isotopes, space

https://phys.org/news/2018-06-prototype-nuclear-battery-power.html



https://nationaleconomicseditorial.com/2017/06/29/radioisotopes-nuclear-medicine/

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Hype or hope?

- ‘Small’ reactors are well understood with a long history
  - Early reactors; naval reactors
- ‘Modular’
  - Here meaning production line economics, with benefits in cost, time and quality
  - Applies equally to GW, as history shows: Fr, Ge, US, Japan, UAE
- Planning & financing
  - Most likely to lead to delay (whether SMR or GW)
  - First to market opportunity (ie. RR) may fade for the UK
  - Maybe RR will manufacture outside of the UK

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Thank you