Does net zero need nuclear?

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HISTORY OF NUCLEAR POWER IN THE UK

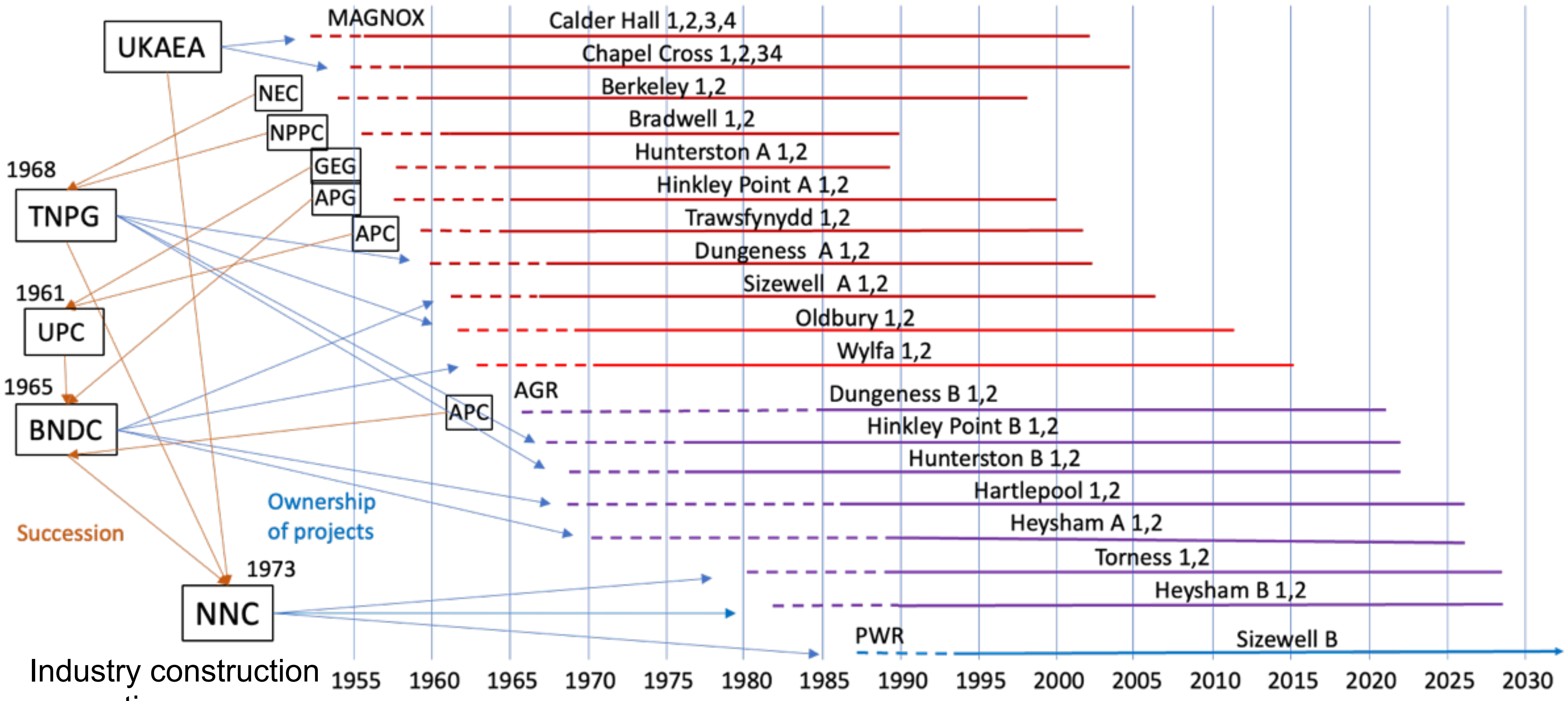
History in brief - 1

- The UK was the first country to commit to nuclear power with the construction of the Calder Hall station, adjacent to the Sellafield (Widescale) fuel cycle plant.
- The technology was based on the Windscale plutonium production, graphite moderated piles but with fuel clad in Magnox (a Mg alloy) and cooled with pressurised CO_2.
- The design and construction of the reactors barely took 3 years and a total of 26 “Magnox” reactors were built. All are shutdown and are being decommissioned.
- The were followed by the AGRs (Advanced Gas cooled Reactors) also graphite moderated and CO_2 cooled, but with a slightly enriched ceramic UO_2 fuel.
- The first Magnox reactors were a success but the later reactors took longer to build. A Magnox reactor was exported each to Japan and Italy. France had a similar design.
- AGR construction was problematic, with some stations taking over 10 years to build and some no reaching design output. What went wrong?

History in brief -2

- In short, the industry structure was a mess with too many small consortia vying for contracts. The design details of each reactor were different. Learning from construction was not passed on.
- Eventually they all merged into one company NNC (National Nuclear Corporation) which is now absorbed into Jacobs via AMEC Foster Wheeler.
- Around 1980 it was decided to switch technology to PWRs (Pressurised Water Reactors) developed from the nuclear submarine development.
- A Westinghouse design was chosen, but it would be modified to meet UK needs and regulation, NNC.
- Only one was built as Sizewell B and went online on 1994 and plans for more reactors at Sizewell and other sites abandoned. Why?
- It probably wasn’t Chernobyl, but that didn't help. It certainly was because nuclear power was too expensive and that was the time of the dash for gas, closure of public research centres and privatisation of our infrastructure.

The nuclear power stations built in the UK to date



Industry construction consortia

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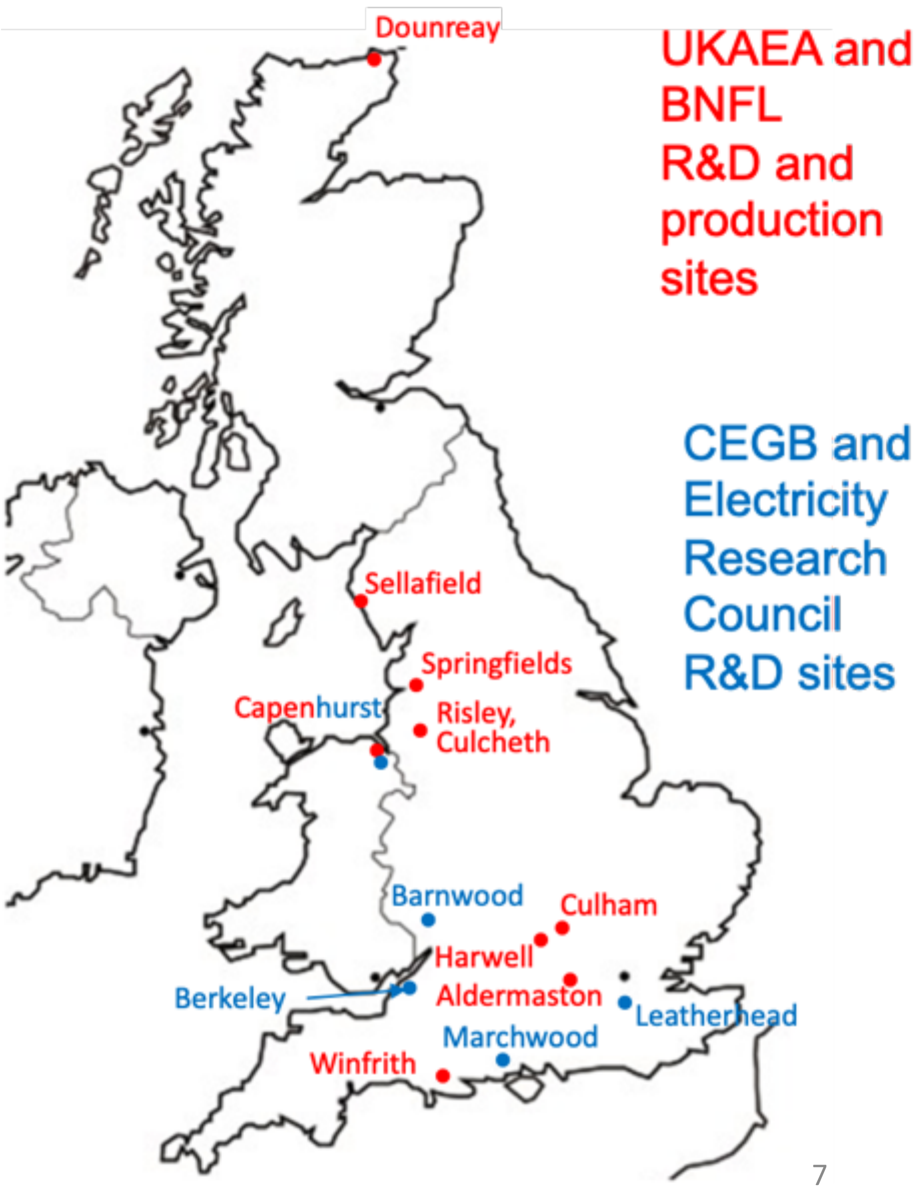
THE DESTRUCTION OF THE UK'S NUCLEAR RESEARCH BASE

The UK's nuclear research base

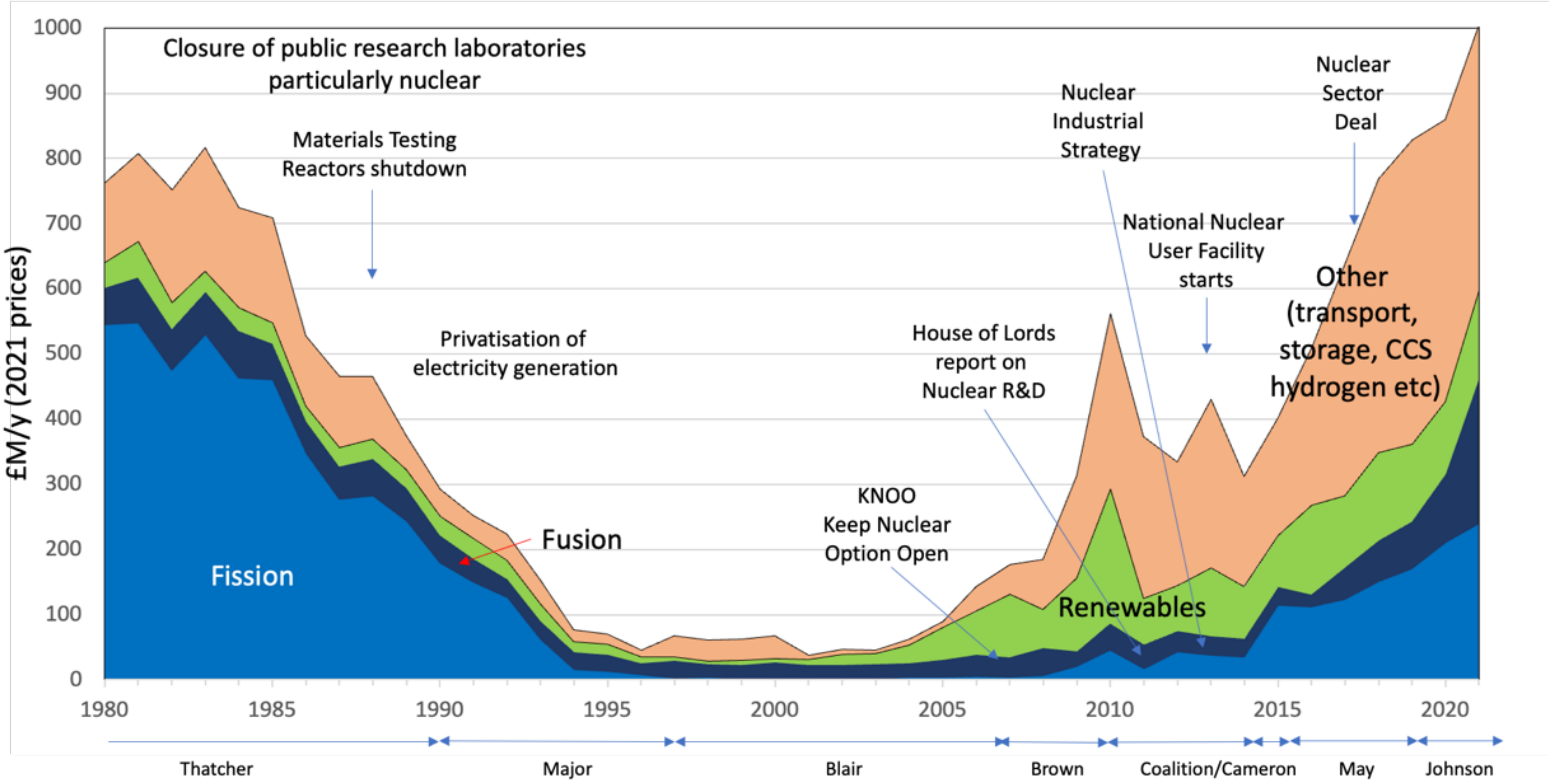
The UKAEA was founded in 1954 from the Ministry of Supply initially for the weapons programme.

- Aldermaston (Atomic Weapons Research Establishment) was transferred from the UKAEA to MOD in 1975
- Engineering design and development work was done at Risley, and safety directorate setup at Culcheth.
- The production activities at Windscale were expanded onto the adjacent Sellafield site and this name was adopted of the whole facility.
- Reprocessing at Sellafield, nuclear fuel production at Springfield and fuel enrichment at Capenhurst were incorporated into the BNFL in 1971.
- In 1955 a centre for fast reactor research was established at Dounreay in the North of Scotland
- Harwell, set up in 1946, was the main R&D centre. In 1958 it set up a reactor development centre at Winfrith in Dorset and in 1960 a thermonuclear fusion research centre at Culham.
- The network of research and engineering development centres of the CEGB also carried out independent nuclear related research.



UKAEA = UK Atomic Energy Authority
BNFL = British Nuclear Fuels Ltd
CEGB= Central Electricity Generating Board

UK Public funding of low carbon energy RD&D



International Energy Agency data

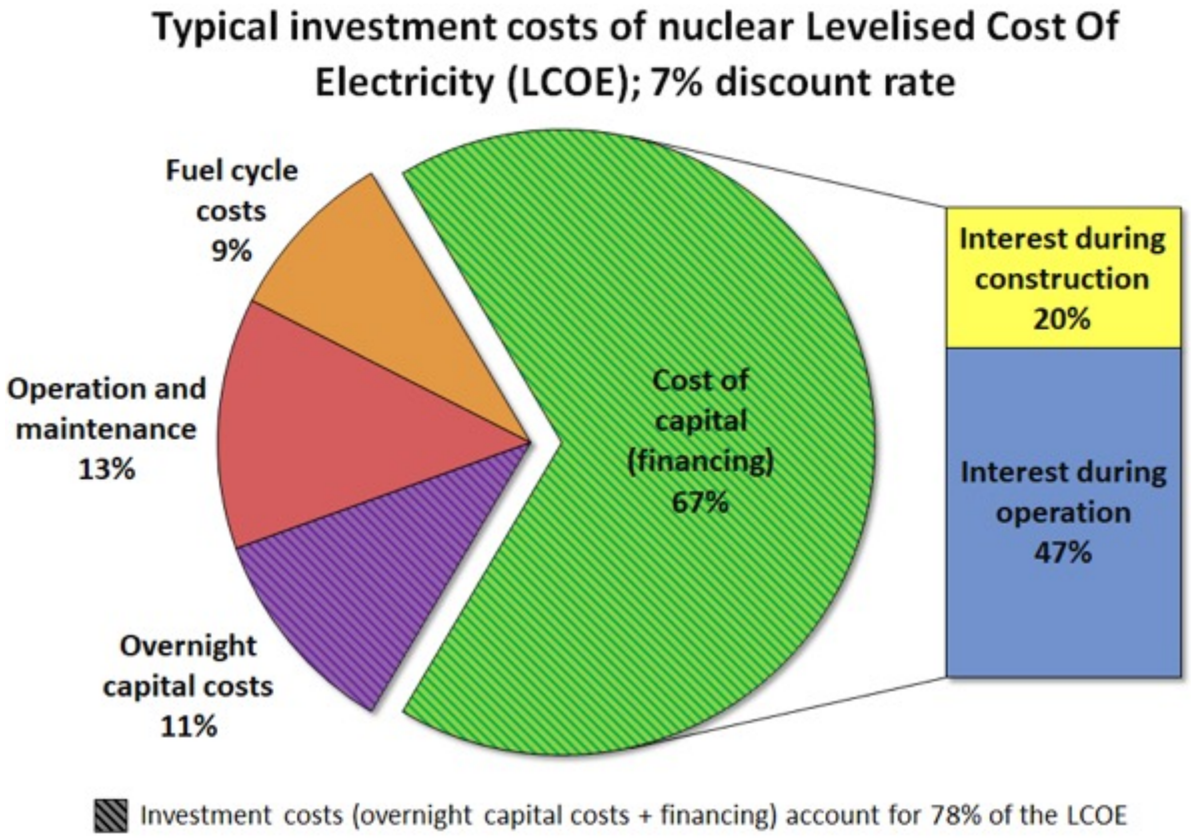
Nuclear R&D in the UK now

- The UKAEA survives as the nuclear fusion organisation at Culham – now expanding with new facilities in Rotherham and soon at Fiddlers Ferry.
- The fission part of UKAEA was privatised as AEA Technology plc in 1996 but it eventually failed and its remaining facilities and staff are in a range of organisations.
- BNFL transferred its nuclear sites to the NDA (Nuclear Decommissioning Authority) which is also managing the decommissioning of the Magnox reactors and the UKAEA research sites.
- The National Nuclear Laboratory is a Government owned RTO containing most of the R&D capability of BNFL plus some of the remaining capability from AEA Technology. It has operations on former BNFL sites but also Culham and a site in Somerset. It is particularly strong on nuclear fuel cycle research but also some capability on reactor systems.
- Capabilities in UK universities have strengthened since 2006 with increased Government funding:
  - Universities of Manchester, Imperial College, Bangor, Birmingham, Bristol, Sheffield. Leeds, Oxford, Cambridge, Lancaster, Liverpool and others have established specialised research groups and facilities.
  - The Royce National advanced Materials Institute with its hub at Manchester.
  - The Nuclear Advanced Manufacturing Research Centre, at Rotherham is hosted but the University of Sheffield.
  - Industry has also benefitted from over £500M funding for the Nuclear Innovation Programme, 2016-2021 and further funding since then on advanced systems.

CURRENT PROBLEMS WITH ENERGY SOURCES

Four issues with nuclear power at the moment

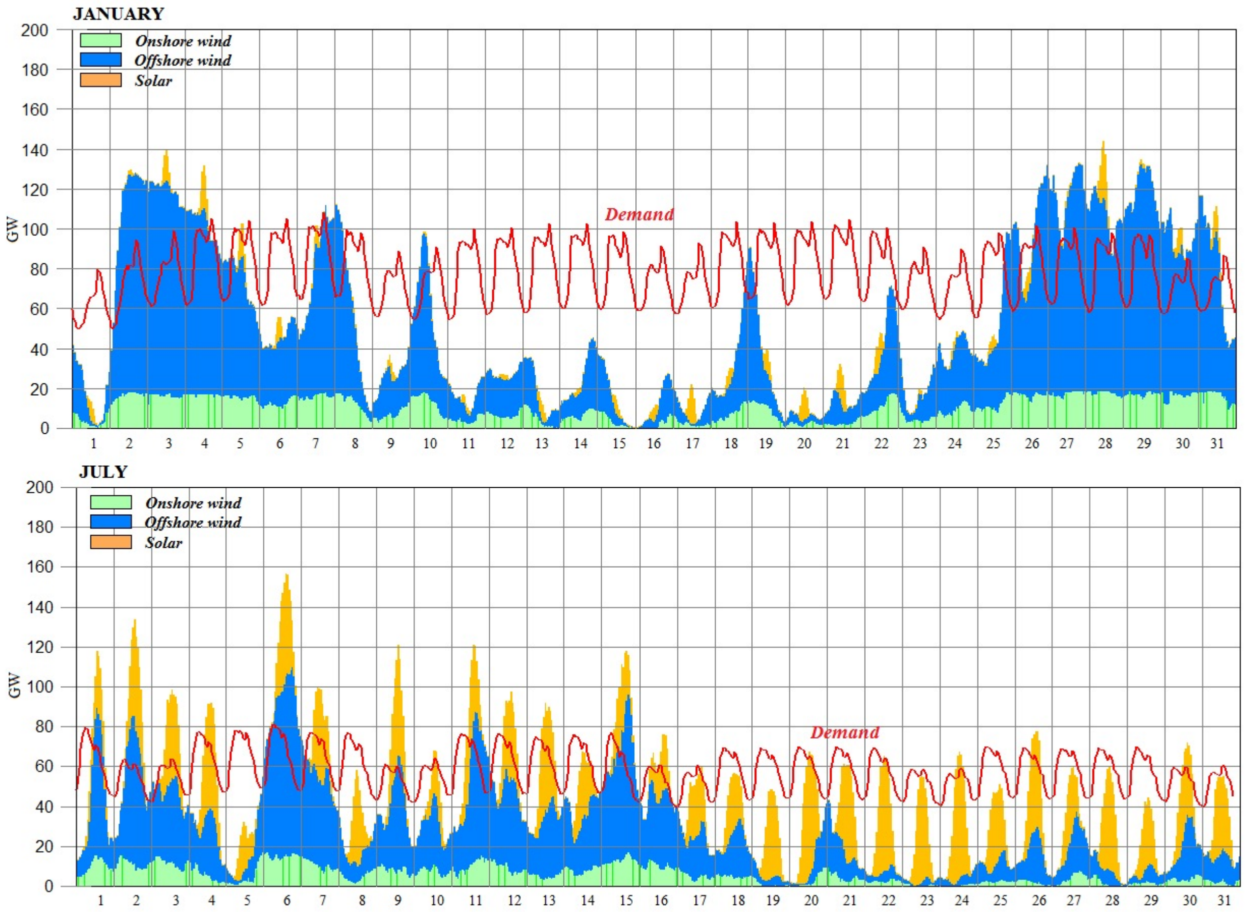
1. Too expensive – high capital cost and high unit cost leading to high rates of return on investment
2. Takes too long to construct – adds to costs through interest rates
3. Too inflexible - high capital costs mean that plant has to be run continuously to be cost effective
4. Currently focussed on supplying electricity



Bodel et al, Generic Feasibility Assessment: Helping to Choose the Nuclear Piece of the Net Zero Jigsaw. Energies 2021, 14, 1229.

Six issues with renewables

1. Low availability in UK, solar around 10%, land based wind 25%, off-shore wind 40-50%.
2. Unpredictability – requires support from “firm” power and/or energy storage.
3. Dominance of capital costs mean that dumping excess power at times of low demand is expensive, but storage is also expensive.
4. Solar PV and wind are limited to supplying electricity.
5. Require large areas of land or sea, limiting supply potential.
6. Large fractions of intermittent renewables on the grid, without energy storage, increases the price of their own and other power sources



Demand and intermittent renewables supply scenario for the UK in 2050 using typical seasonal variations

From Euan Mearn’s Energy Matters

7 Issues with natural gas + CCUS*

1. As the last year has shown natural gas supplies are not secure and the price can fluctuate alarmingly.
2. The Cameron Government cancelled the CCS demonstration programme in 2015 and a renewed programme was only announced in the budget last week!
3. If captured CO_2 is used to produce synfuels for transport then it is eventually released to the atmosphere, only CO_2 captured from the atmosphere or from biofuels can be carbon neutral.
4. CCS is typically ~90% efficient in capturing CO2, that means 10% of the CO_2 is released to the atmosphere.
5. There will be further releases of CO_2 into the atmosphere during transport to the disposal site and during injection into the storage borehole. There is also uncertainty on how much CO_2 can eventually escape from the store.
6. With new monitoring technology, the true extent to methane releases into the atmosphere from natural gas extraction operations is becoming apparent, particularly from fracking.
7. We only have limited ability to use carbon negative sources to offset residual emissions from continued use of natural gas with CCS.

*CCUS = carbon capture use and storage

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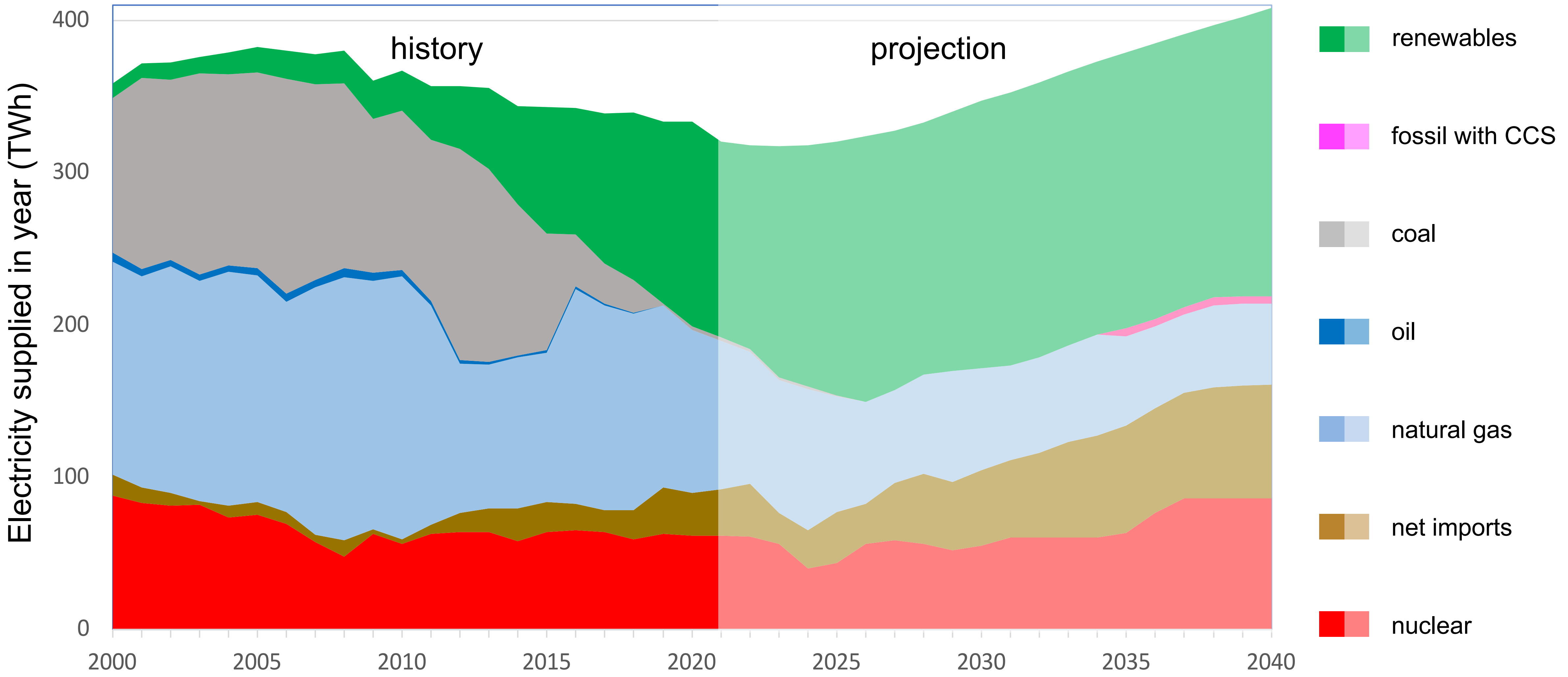
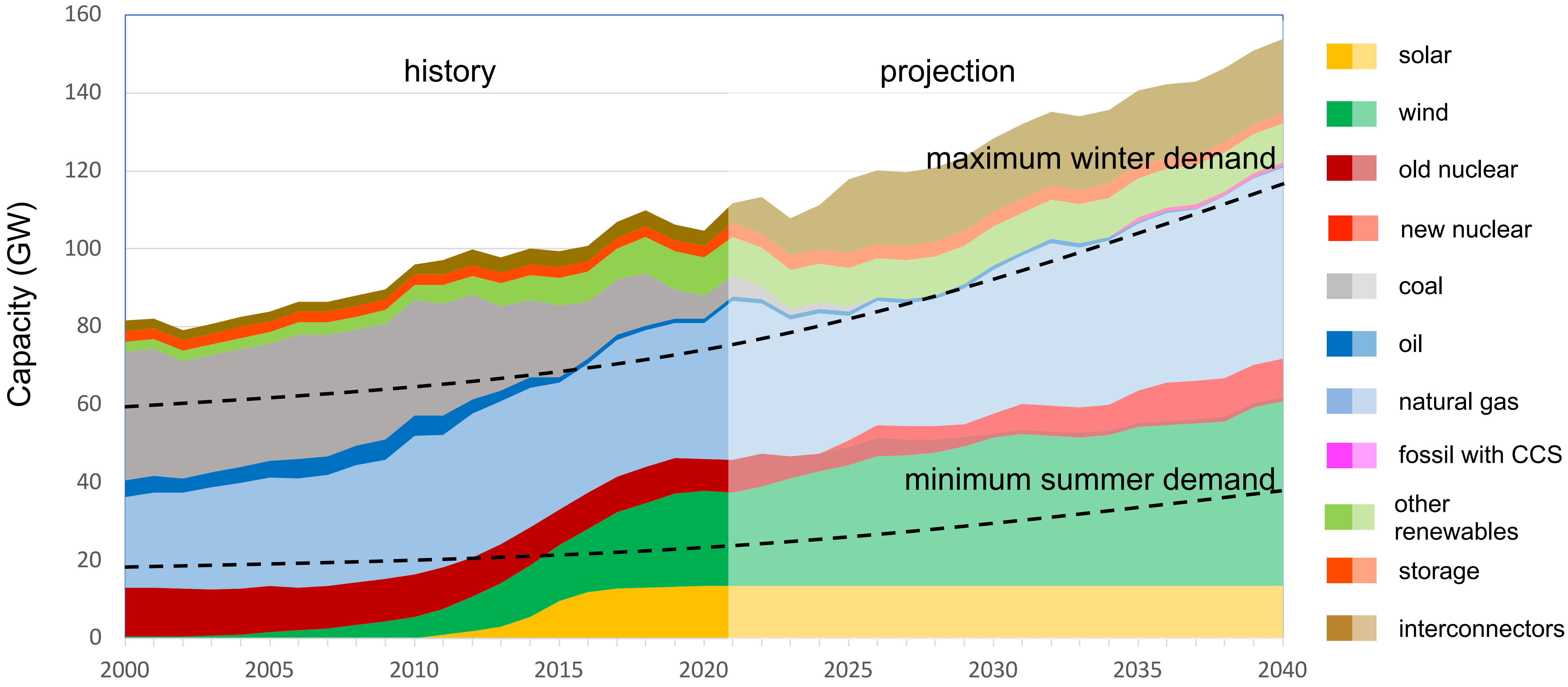
HOW ARE WE DOING WITH NET ZERO?

GB electricity supply



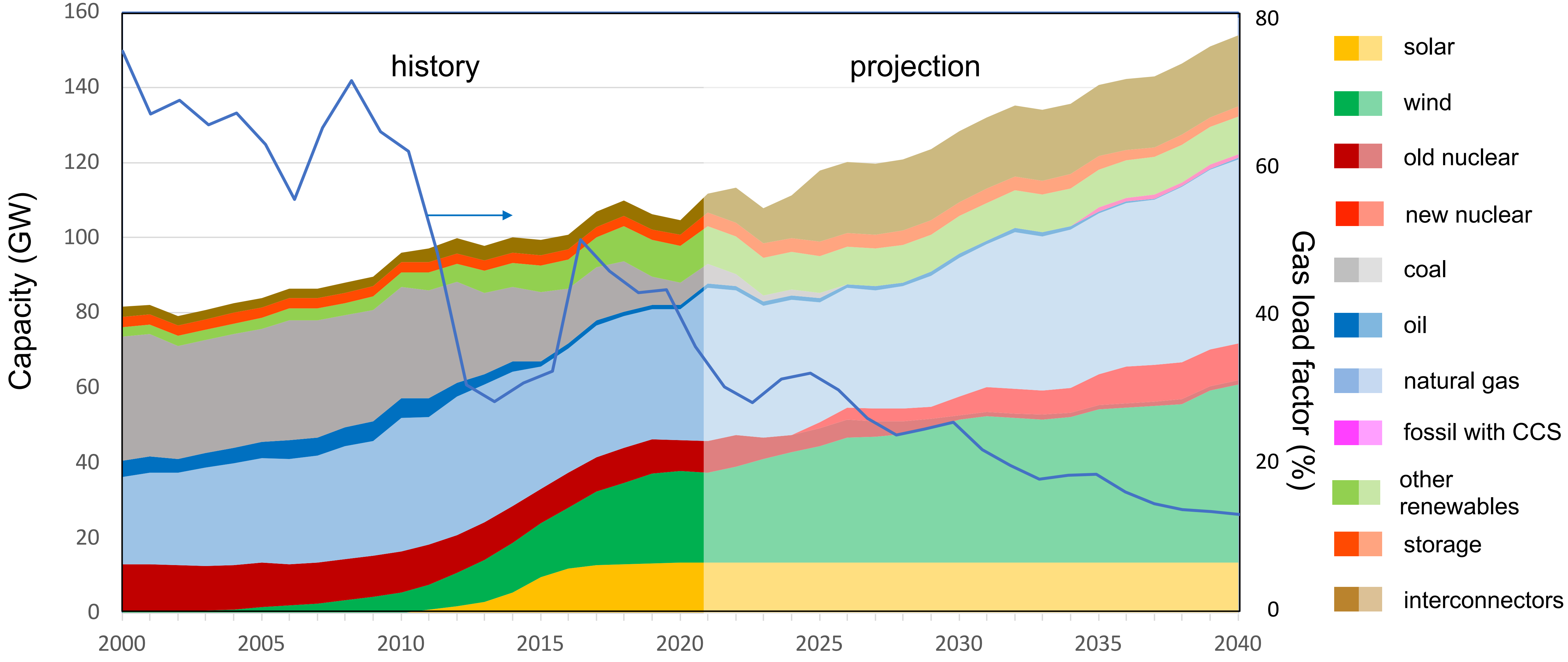
Data from;
Digest of United Kingdom Energy Statistics (DUKES) 2021
BEIS, Updated energy and emissions projections 2019

GB electricity capacity



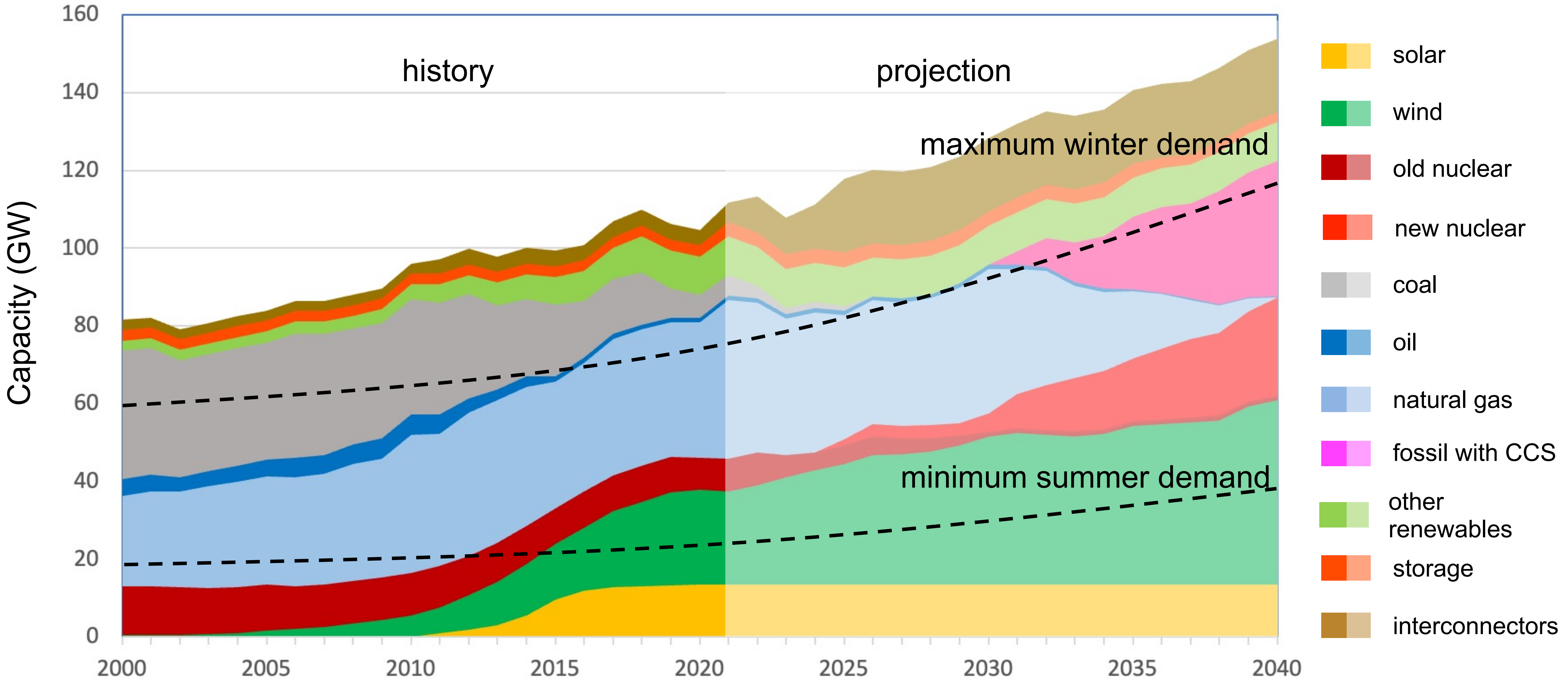
Data from;
Digest of United Kingdom Energy Statistics (DUKES) 2021
BEIS, Updated energy and emissions projections 2019

GB electricity capacity – impact on gas load factor and cost



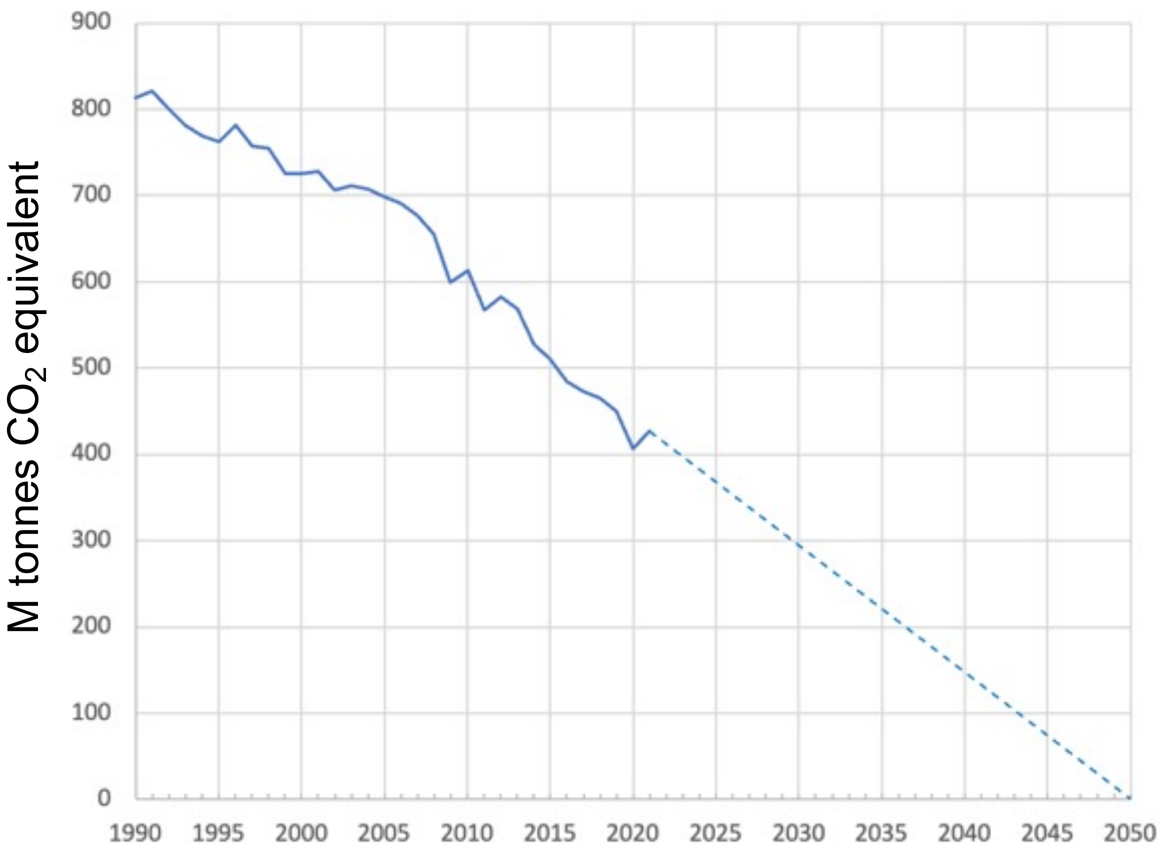
Data from;
Digest of United Kingdom Energy Statistics (DUKES) 2021
BEIS, Updated energy and emissions projections 2019

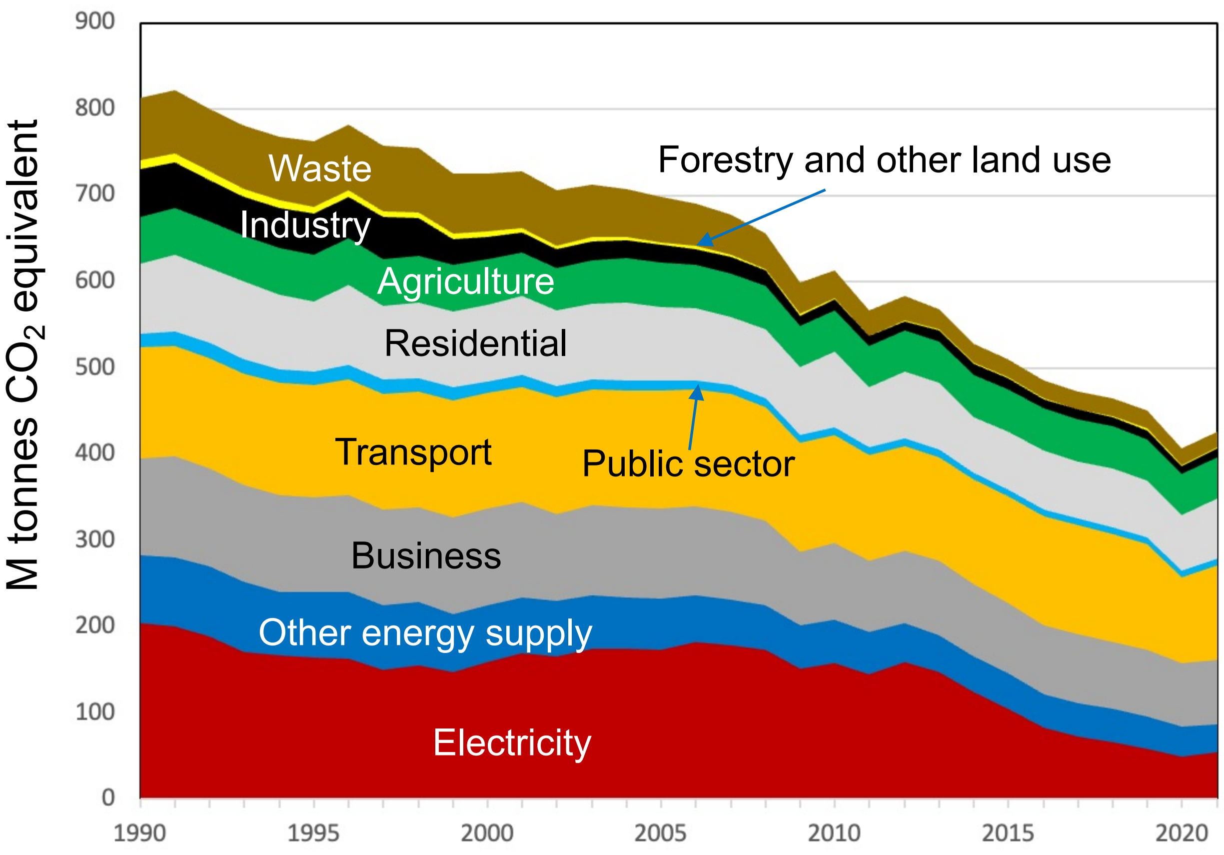
GB electricity capacity needed = fully abated by 2040



Data from;
Digest of United Kingdom Energy Statistics (DUKES) 2021
BEIS, Updated energy and emissions projections 2019

The road to Net Zero – emissions statistics





We look like we are doing pretty well – on track, until you remember the death of British industry in the 1990s and the effects of austerity after the 2008 crash. Even Brexit and COVID did their bit in reducing our emissions through impact on the economy. Looking at the sector breakdown we can see the effect of de-industrialisation. On the positive side the removal of coal as a fuel and the growth in use of renewables have had a major effect over the last 10 years. We are recycling more and taking energy from waste. The business, transport, residential and agricultural sectors have not shown significant recent reductions.

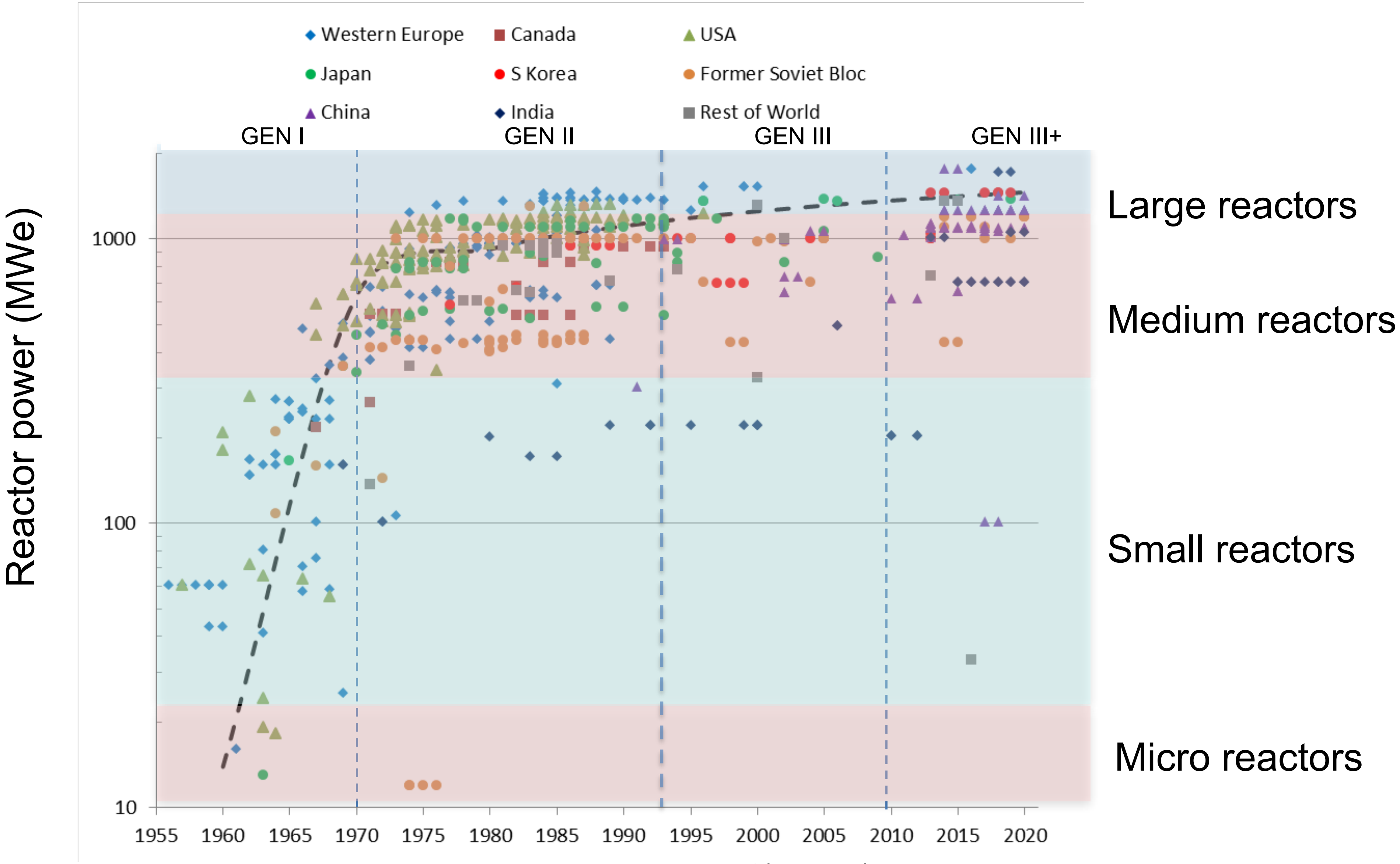
Data from Final UK greenhouse gas emissions national statistics: 1990 to 2021

HOW DO WE SOLVE THE NUCLEAR ISSUES?

UK approach to getting nuclear relevant to Net Zero

- Reducing the cost of nuclear
  - Reducing the costs of investment RAB (Regulated Asset Base)
  - Move to modular construction
  - Series construction of same design
- Reducing the time for construction
- Increasing the flexibility of nuclear power supply
  - Load following possible with new GENIII+ reactors, but expensive
  - Adding thermal energy storage to higher temperature advanced reactor designs
- Increasing non–grid applications of nuclear energy
  - Hydrogen and synthetics fuel production
  - Domestic and city heat networks using waste heat from power plant, business and industry
  - Industrial heat supply from higher temperature advanced reactors

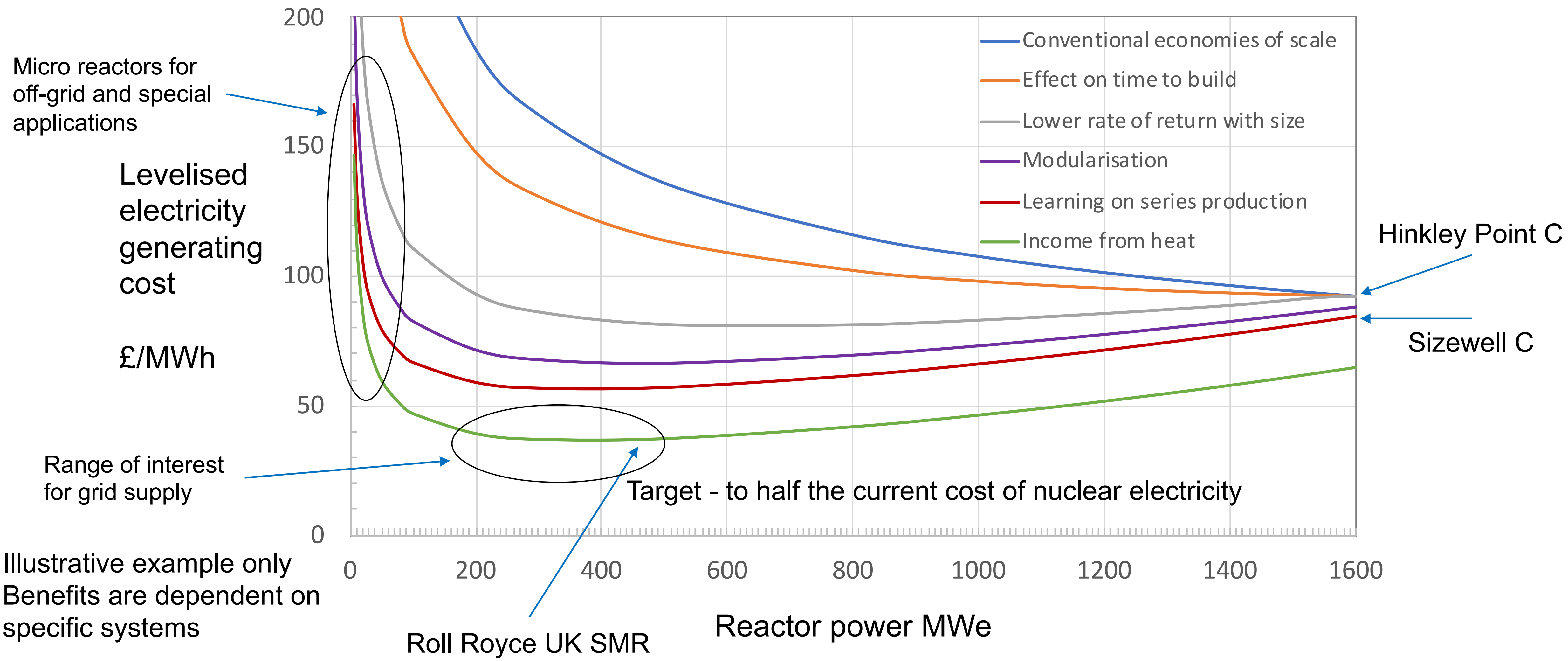
In the beginning there were just small reactors



Going Smaller - SMRs

- Getting the costs and reactor construction time down is most easily achieved by reducing the size. Getting smaller also means there are more reactors needed to produce the required power, so more experience can be gained with series production. Smaller reactor modules are also easier to transport from factory to the reactor site.
- The term SMR (Small Modular Reactor) came originally from “Small and Medium Sized Reactor” and interest grew rapidly after the Fukushima accident in 2011. However, the origin goes back to post Chernobyl with the SIR (Safe Integral Reactor) concept developed in 1989 by ABB, UKAEA and Rolls Royce, with an integral PWR design with the objective of both higher safety and lower costs. The steam generators, pressuriser and pumps are built into the RPV (Reactor Pressure Vessel) in Integral PWRs .
- The term SMR went on to be defined by the IAEA to any reactor with a of power <300MWe. BEIS uses the term SMR to be any smaller light water cooled reactor with no specified upper or lower limit.

Benefits of reduced size and use of heat



Illustrative example only
Benefits are dependent on
specific systems

Based on work by the Energy Technologies Institute

SMRs that could be built in the UK

In the Budget last week the Chancellor announced a competition to build SMRs via Great British Nuclear, but no details yet. There are many SMR concepts available but the ones most likely to be built in the UK are:

- Rolls Royce UK Small Modular Reactor
  - Unit power 470MWe. Conventional design but low risk and can be built with UK supply chain in less than 5 years. The main innovations are on modular construction and advanced manufacturing. Designed to be built as single units on UK brownfield sites, eg former coal fired power stations
- NuScale VOYGR
  - Designed to be built in blocks of 12 units at 77MWe per unit, located in a large water pool. Integral PWR design with several advanced safety features with including a tight containment vessel. The Wylfa site has been under discussion for a first site.
- Hitachi-GE BWRX-300
  - Small BWR design with 290 MWe unit size. Entered the GDA (ONR Generic Design Assessment) 2023.
- HOLTEC SMR 160
  - Close coupled (almost integral PWR with steam generators and pressuriser located close to RPV) with 160 MWe unit size. Entered the GDA (ONR Generic Design Assessment) 2023.

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ADVANCED MODULAR REACTORS (AMR)

Advanced reactor systems

- Generation IV reactors were seen at the start of the Millennium as some thing new that would open up new opportunities for nuclear and a new International collaboration was formed in 2000 to encourage collaboration – GIF (Gen IV International Forum. The UK was one of the founding members of GIF but only participated through EU initiatives as nuclear research was at a low ebb. The UK has restarted participation in 2019 with the new initiatives.
- GIF focusses on 6 lines of development (described in the next slide) but in fact these were not all new. Work on the sodium cooled fast reactors had been a major international activity, with the UK as a leading member from the mid 1950s until around 1990. Also the UK had hosted the first demonstration of the HTGR (High Temperature Gas cooled Reactor).
- The resurgence of interest in the UK is with AMRs (Advanced Modular Reactors) where the benefits from advanced reactors are combined with those of smaller designs.

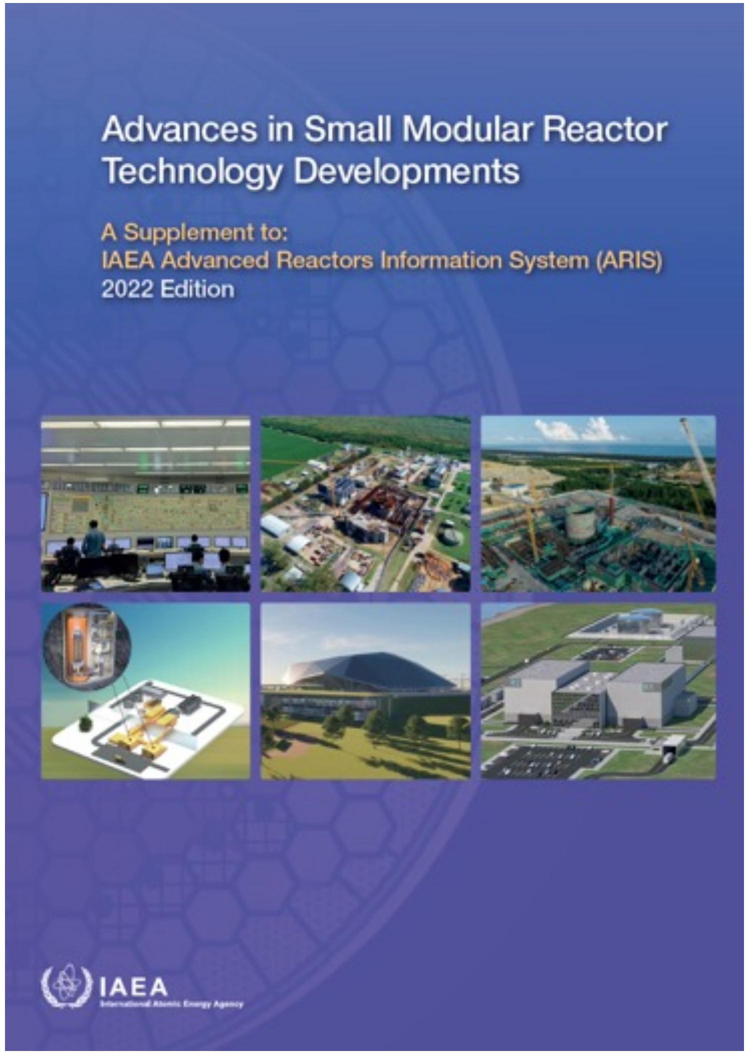
Overview of Gen IV Systems

System	Neutron Spectrum	Coolant	Primary outlet T ˚C	Fuel Cycle
Sodium Cooled Fast Reactor, SFR	Fast	Sodium	485 - 600	Closed/ Open?
Lead Cooled Fast Reactor, LFR	Fast	Lead or Pb-Bi	480 - 540	Closed/ Open?
Gas Cooled Fast Reactor, GFR	Fast	Helium	600 - 900	Closed
High (or Very High) Temperature Gas Cooled Reactor, HTGR or VHTR	Thermal	Helium	750 - 1000	Open?
Molten Salt Reactor, MSR	Fast/ Thermal	Fluoride or Chloride Salts	700 - 800	Closed
Supercritical Water Reactor , SCWR	Thermal/ Fast	Water	510 - 625	Open/ Closed
Gen III Water Reactors, PWR, BWR, Candu, etc	Thermal	Water/ Heavy Water	310	Open/ Closed
Advanced Gas Cooled Reactor, AGR	Thermal	CO_2	635	Open/ Closed

IAEA ARIS Database

- The IAEA maintains databases on research reactors (RRD), power reactors (PRIS) and advanced reactors (ARIS). These are comprehensive on reactors that have been built, but for reactors concepts they rely on submissions to the database from developers. Despite this the the biennial ARIS SMR book gives a good idea of the level of activity, though most of the concepts described will never be built.
- The number of reactor concepts has grown substantially over the last 10 years.

	SMR BOOK 2012	SMR BOOK 2022
– Light Water Reactors	18	35
– Heavy Water Reactors	3	0
– High Temp. Gas Cooled Reactors	3	19
– Sodium Cooled Fast reactors	5	3
– Lead Cooled Fast Reactors	3	6
– Gas cooled Fast Reactors	1	2
– Molten Salt Cooled reactors	0	14
– Supercritical Water Reactors	0	0 (1 in database)
– Heat-pipe micro reactors	0	4



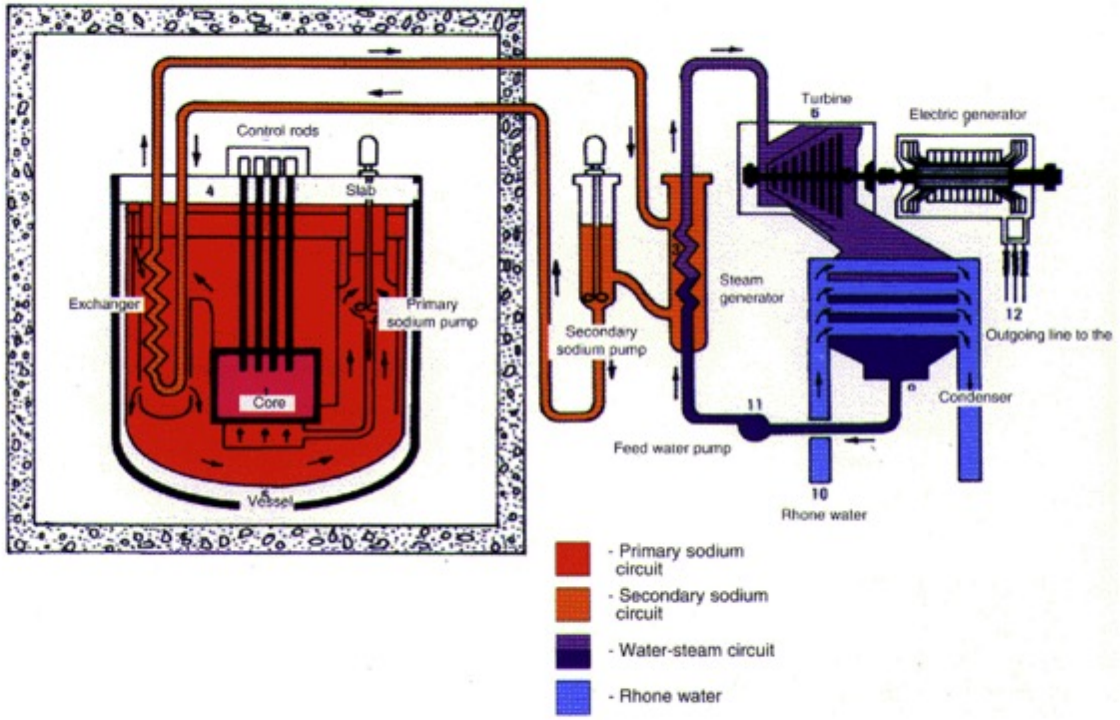
https://aris.iaea.org/Publications/SMR_booklet_2022.pdf

International Viewpoint

- Argentina is currently constructing the first SMR based on an integral PWR
  – CAREM 25, a 30MWe demonstration reactor.
- China is currently commission a twin 105MWe reactor station – HTR-PM a pebble-bed HTGR built with support of a HTR-10 a small pebble-bed experimental reactor.
  China also started construction in 2021 of a 120 MWe integral PWR – ACP-100.
- USA has a large programme of SMR and AMR development at Idaho and other National Laboratories supporting many industry projects, but no construction of a first plant yet.
- Canada has programme for SMR demonstration with 12 different concepts but with a particular focus on micro-reactor designs that could be applied in remote area. The programme involves pre-licensing studies with Canadian regulator and offers of demonstration sites by Canadian Nuclear Laboratories and utilities.
- Russia is currently constructing the first prototype LFR - BREST-OD300. Russia also has a large SFR programme with several operating reactors and the construction of a new experimental reactor for development.
- Japan has been operating the only VHTR so far – HTTR a 30MWth experimental prismatic reactor that has demonstrated high temperature gas turbine generation and hydrogen production.

Sodium Fast Reactor (SFR)

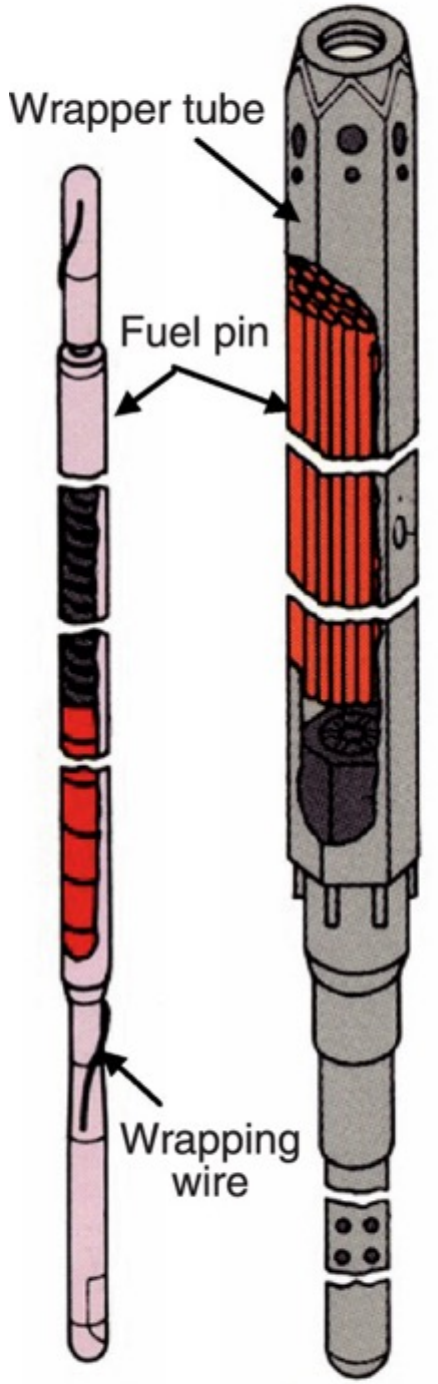
- There has been nearly 70 years of development of sodium and Na-K cooled reactors – almost all have been fast reactors but Na has also been used as coolant in thermal reactors. In terms of relevant experience, there have been over 200 reactor operating years experience of SFRs.
- The most common configuration, the pool reactor with an secondary sodium circuit, is shown in the diagram. Typically the primary circuit temperature are 450ºC inlet and 560ºC outlet. The main restriction being the margin to Na boiling, the creep resistance of the fuel cladding and for metal fuel, melting at clad interface.
- The main operating issues have been the dimensional stability and embrittlement of cladding and fuel assembly wrappers (flow tubes) and leaks in steam generator welds from SCC.



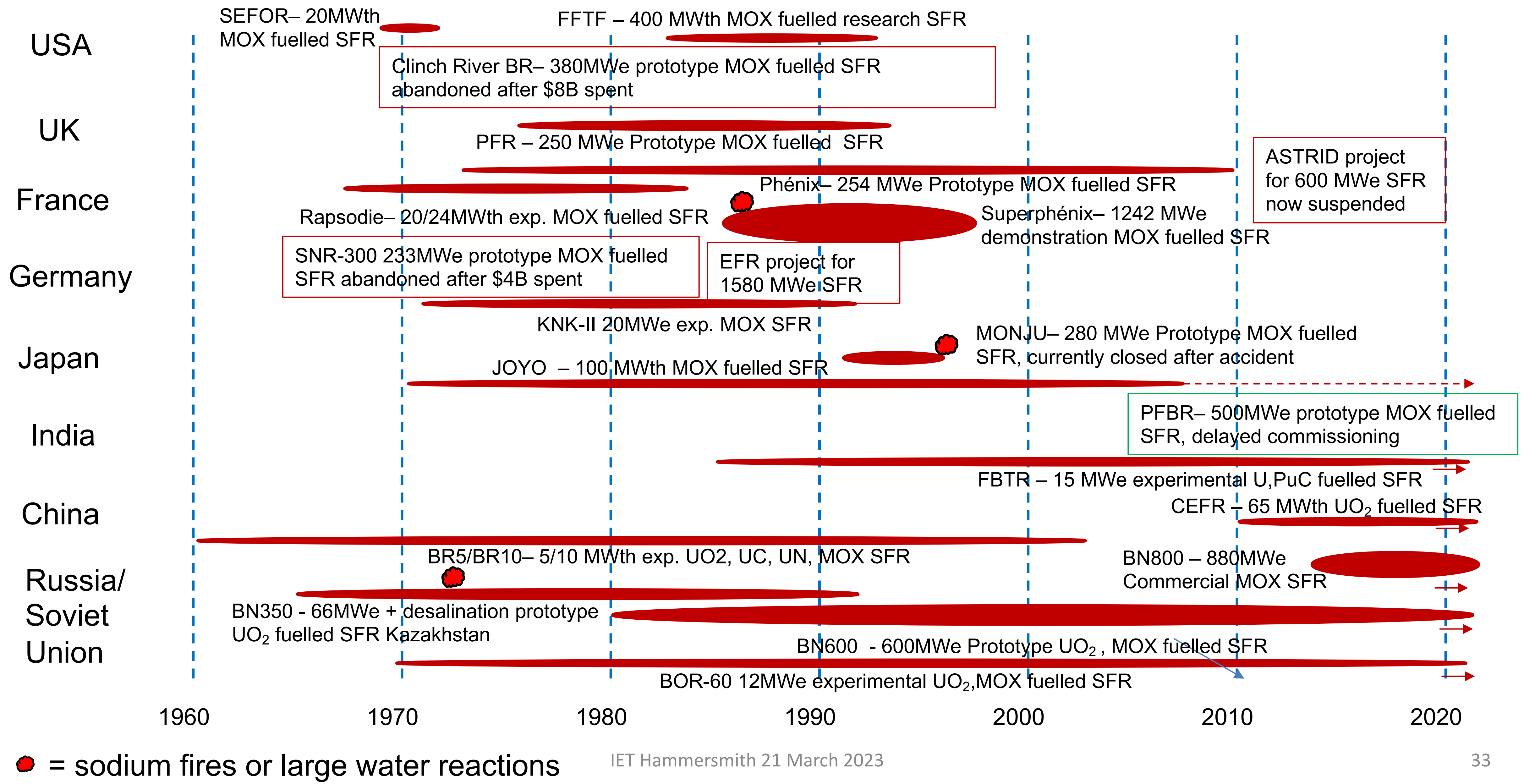
The Phénix reactor, which operated from 1974 to 2010, was one of the most successful ”prototype” reactors, at 250 MWe and successfully closed the fuel cycle with net breeding.
From: K. Aoto, Progress in Nuclear Energy 77 (2014) 247e265.

SFR fuel

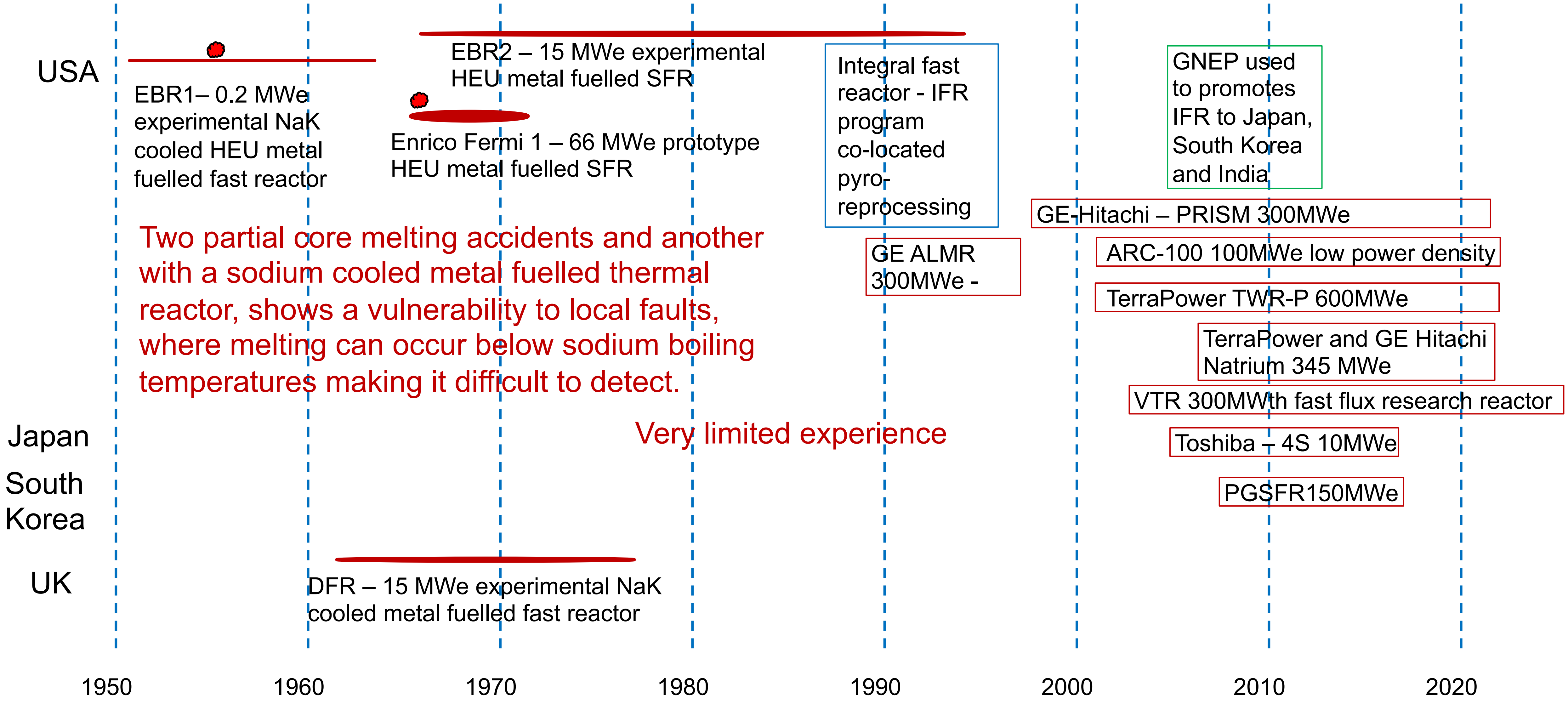
- Most experience on fast reactor fuel is with MOX (U,PuO_2), where either oxide pellets or oxide granules (vibro fuel) are put into stainless steels fuel pins (rods) typically 6 mm dia. Pellets can be solid or are annular, ie have a central hole to accommodate swelling.
- Future fuels may use carbides or nitrides which have higher thermal conductivity.
- In the USA U,Pu,10% Zr metal alloy fuels are used currently. There is much less experience on these fuels but a lot of hype. Both MOX and metal fuels have to potential to go to very high burn-ups, but here is a history of core melting in metal fuelled reactors, as the fuel has a low melting point.
- The fuel pins are packed into hexagonal stainless steel or nickel alloy wrappers to make subassemblies. A key issue is radiation damage from fast neutrons that makes the clad and wrappers brittle and also to swell. The main impact is on core distortions from void swelling; variations in temperature and flux in the core cause variations in swelling and hence bowing of long structures.



Timeline ceramic fuelled SFR



Timeline metal fuelled SFR

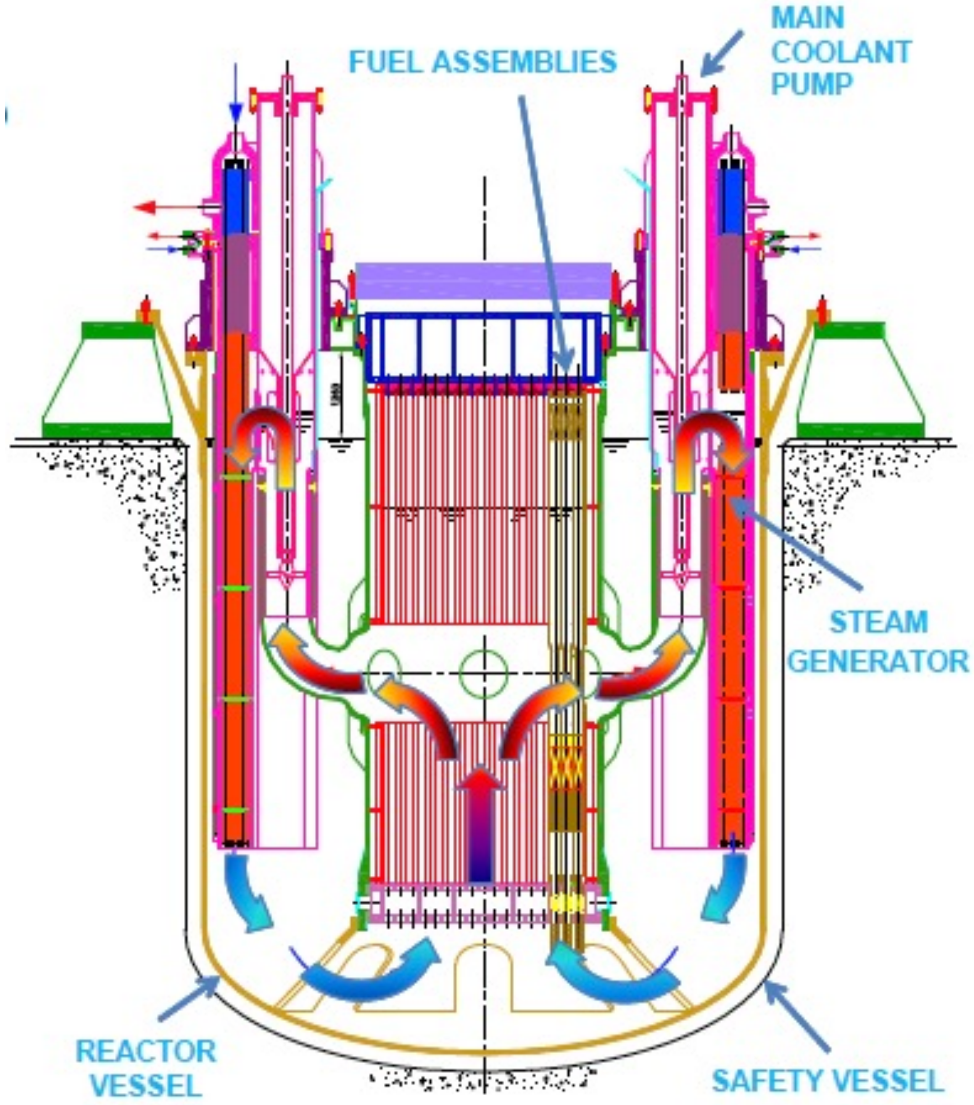


= significant accident

GNEP = Global Nuclear Energy Partnership

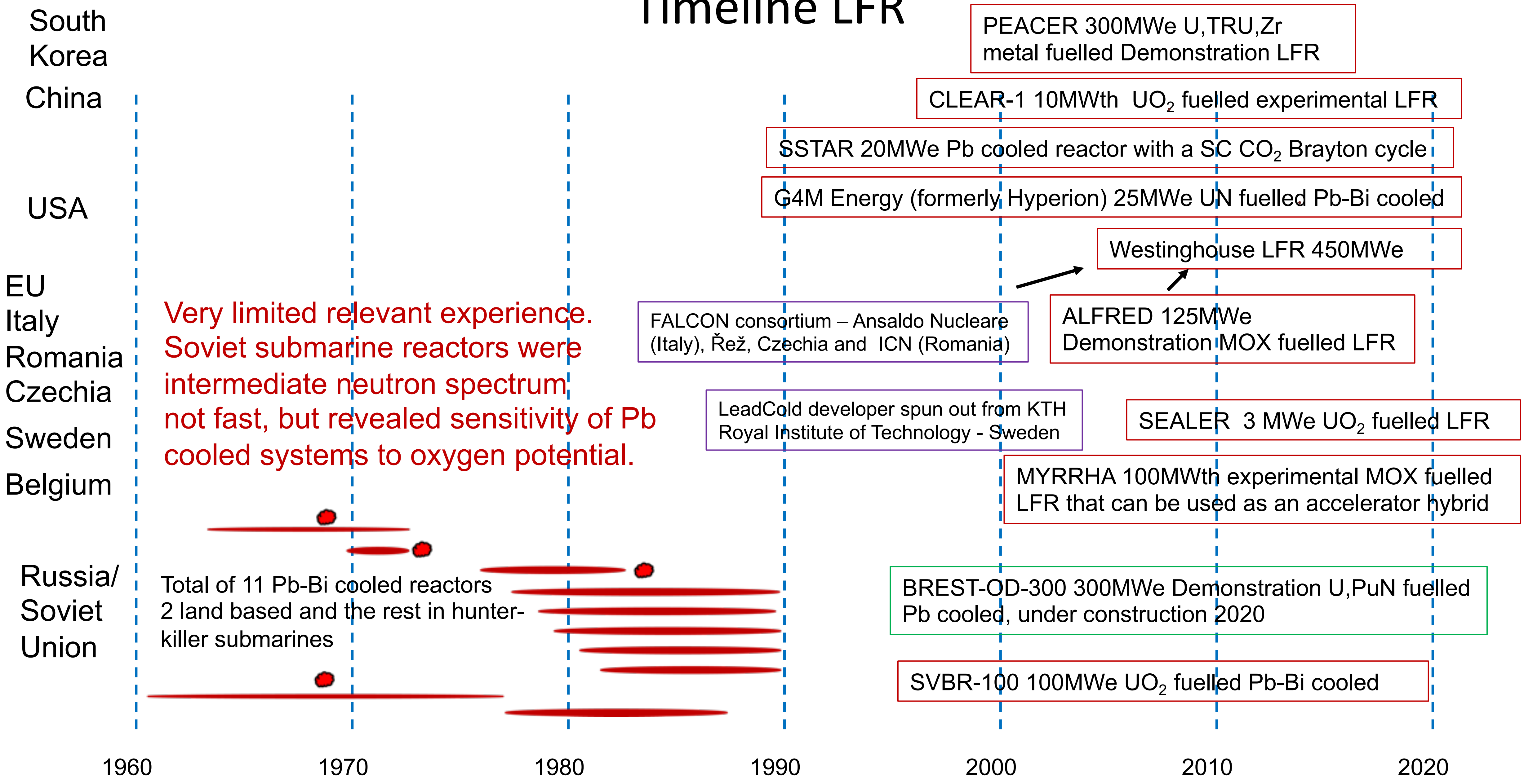
Lead and Pb-Bi Cooled Reactors (LFR)

- Pb-Bi eutectic alloy was used as a coolant in Soviet Alfa-class submarines. Interest in molten Pb as a fast reactor coolant grew from Russian work in the late 1990s. Since then there have been over 12 conceptual designs of Pb and Pb-Bi cooled reactors.
- The diagram here shows the most common configuration which at first looks similar to a pool type SFR. The main difference is the absence of a secondary circuit. The steam generators are integral in the reactor vessel. This is possible as lead does not react exothermically with water. However, a leak of high pressure steam into the primary circuit is not a good idea.
- LFR would use similar fuel to SFRs.
- The main issue with LFR materials choice is corrosion, which limits the core outlet temperature to ~550^{o}C .



Schematic of EU ALFRED concept

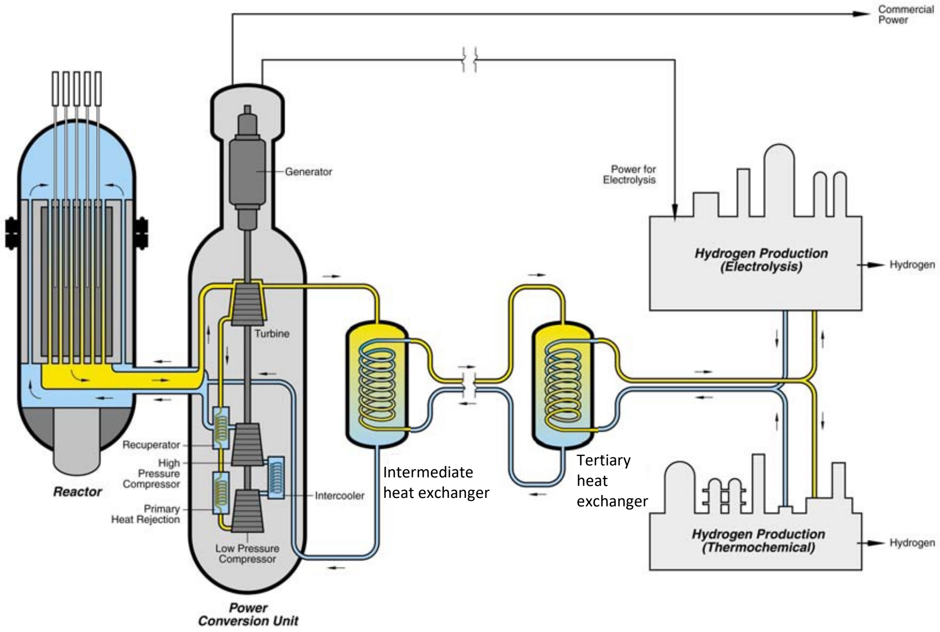
Timeline LFR



= significant accident

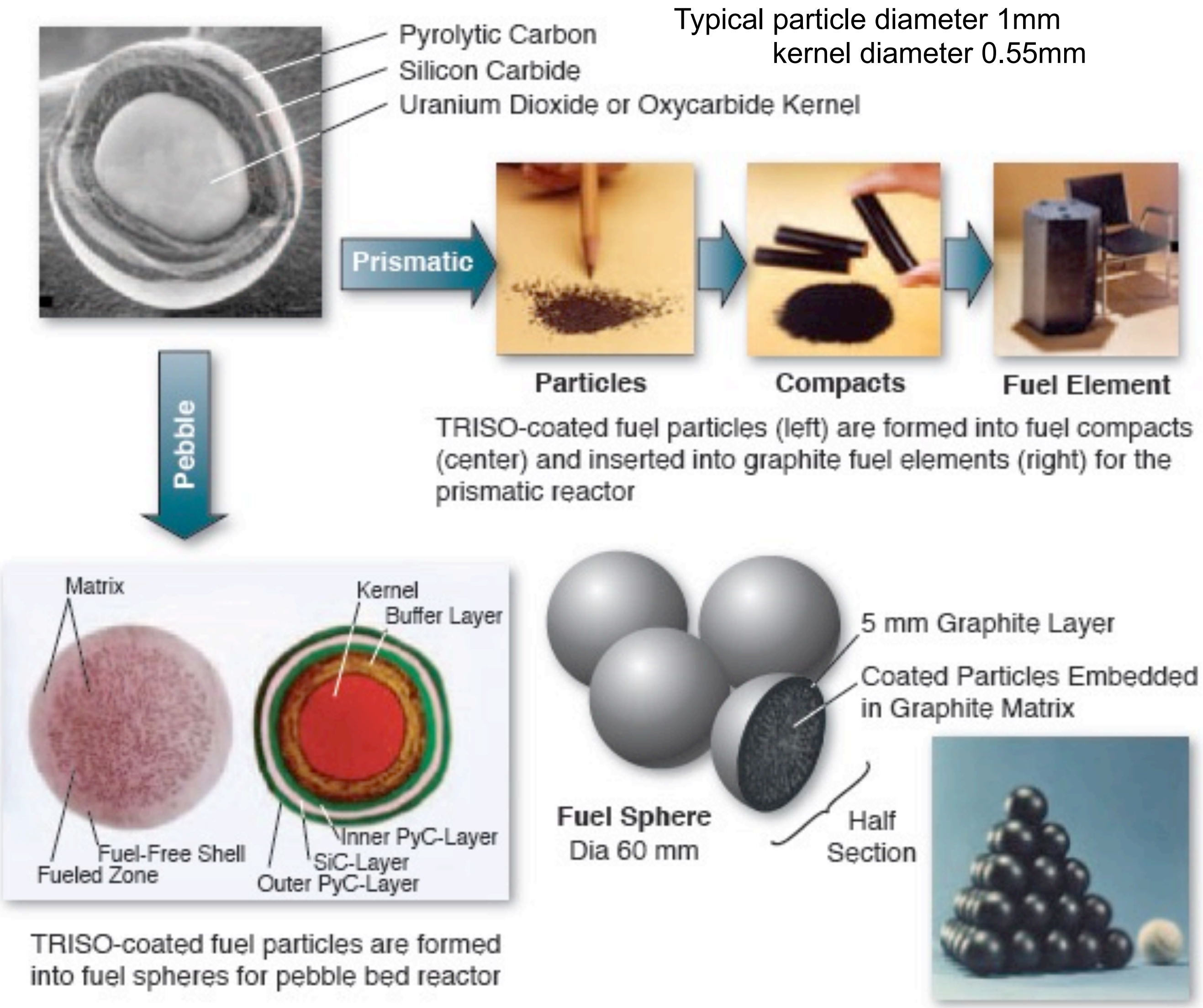
VHTRs (Very High Temperature Gas Cooled Reactors)

- Goal to reach outlet temperatures close to 1000°C. HTGRS currently uses steam cycles with outlet temperatures <750°C.
- Probably the safest reactor designs, with very high fuel integrity with TRISO particles, strong negative reactivity coefficient with temperature and long reactions times.



- Two types: prismatic cores with long fuel assembles; and pebble-bed where the fuel is in the form of spheres containing the fuel particles, that flow though the core.
- Currently China is leading development of the pebble-bed reactors, with a steam cycle that are currently being commissioned. Japan is leading on development of true VHTRS with a prismatic core, efficient gas turbine generation and high quality heat supply for industrial applications.

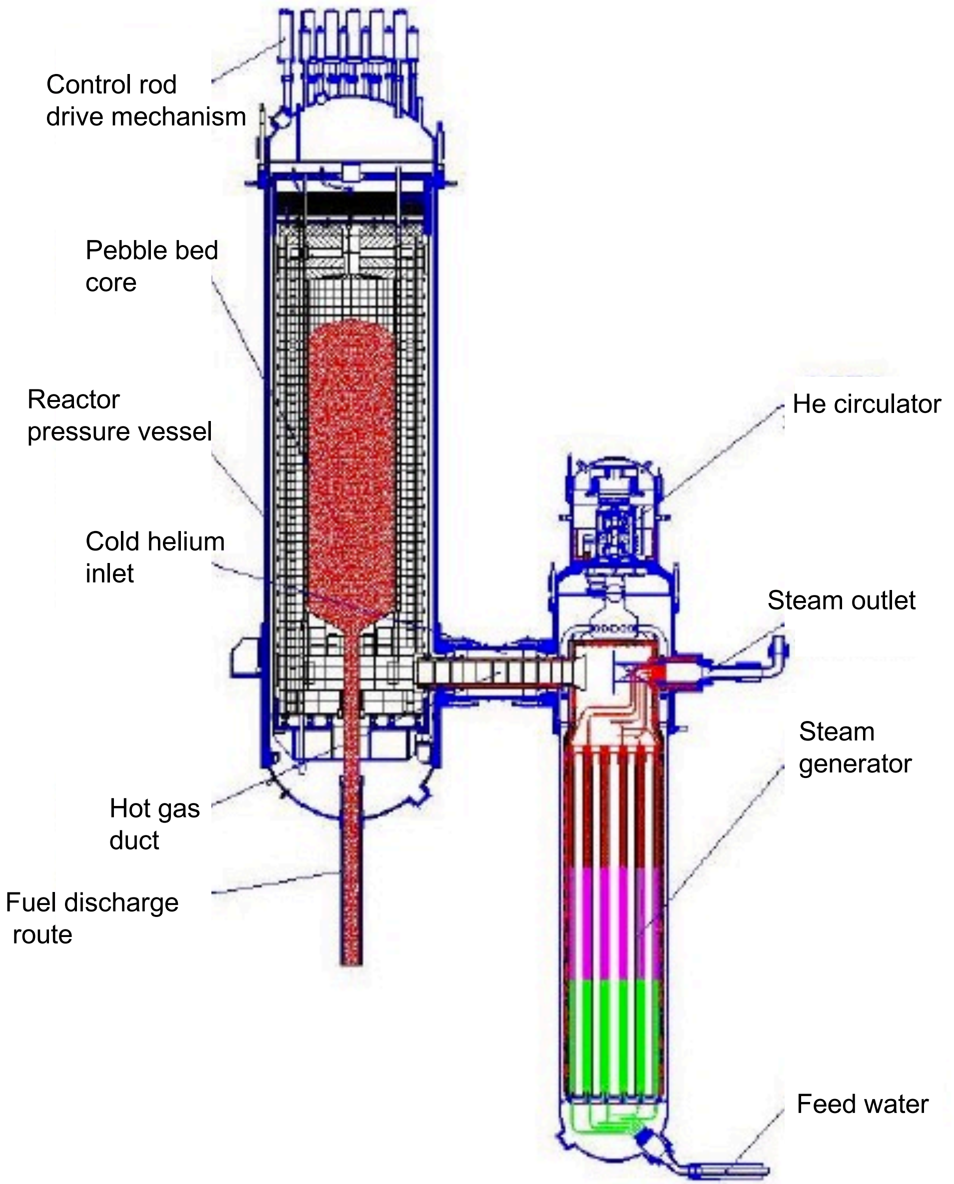
HTGR particle fuel (TRISO) prismatic and pebble



- TRISO fuel particles are the common factor in high temperature gas cooled reactors. The were first developed in the UK as part of the DRAGON project.
- The two main reactor types using TRISO fuel are referred to as prismatic and pebble bed reactors.
- In prismatic reactors the TRISO fuel is incorporated into a graphite matrix, which is made into prismatic fuel elements to make the core.
- In pebble bed reactors the TRISO particles are incorporated into graphite spheres which flow through the reactor.

HTR-PM Design

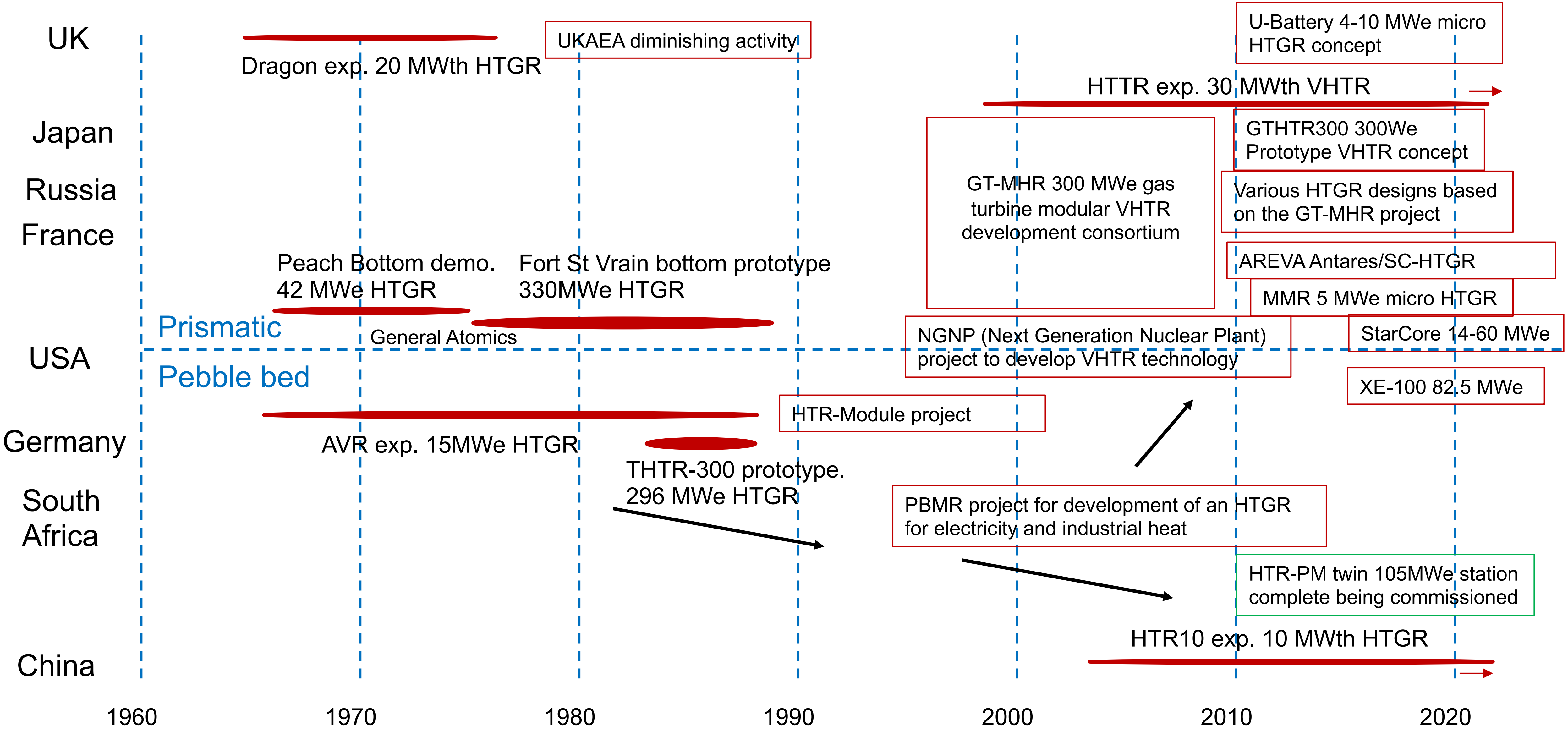
- The HTR-PM power station, with a pair of 105 MWe reactors, is currently being commissioned in Shandong in China. Strongly influence by earlier work in Germany.
- Twin units each 105 MWe or 250 MWth
- Helium coolant at 7MPa, inlet 250°C, outlet 750°C.
- Fuel 60 mm dia. pebbles with 8.5% enriched UO_2 TRISO fuel
- Core 11m H/3m D, very low power density
- Developed by INET, Tsinghua University and current being built at Huaneng with the China Nuclear Industry and Construction Group.
- No HTGR projects have discussed spent fuel management, but it is assumed to be direct disposal of TRISO particles with or without removal of graphite matrix.
- The US Xe-100 reactor is similar to HTR-PM, but with a power of 200 MWth and 82.5MWe.



Cross section of HTR-PM reactor and steam generator

Picture from Tsinghua University

Timeline HTGR



Molten Salt Reactors (MSR)

MSRs are a collection of different reactor designs that are cooled by fluoride of chloride molten salts. I will use the following classification:

1. Molten Salt reactor (MSR) no qualification

- A thermal reactor consisting of blocks of solid moderator (eg graphite) with channels for fluoride salt with the fuel dissolved in the salt.

2. Fluoride High Temperature Reactor (FHR)

- A thermal reactor consisting of a HTGR core but cooled by a molten fluoride salt instead of He.

3. Molten Salt Fast Reactor (MSFR)

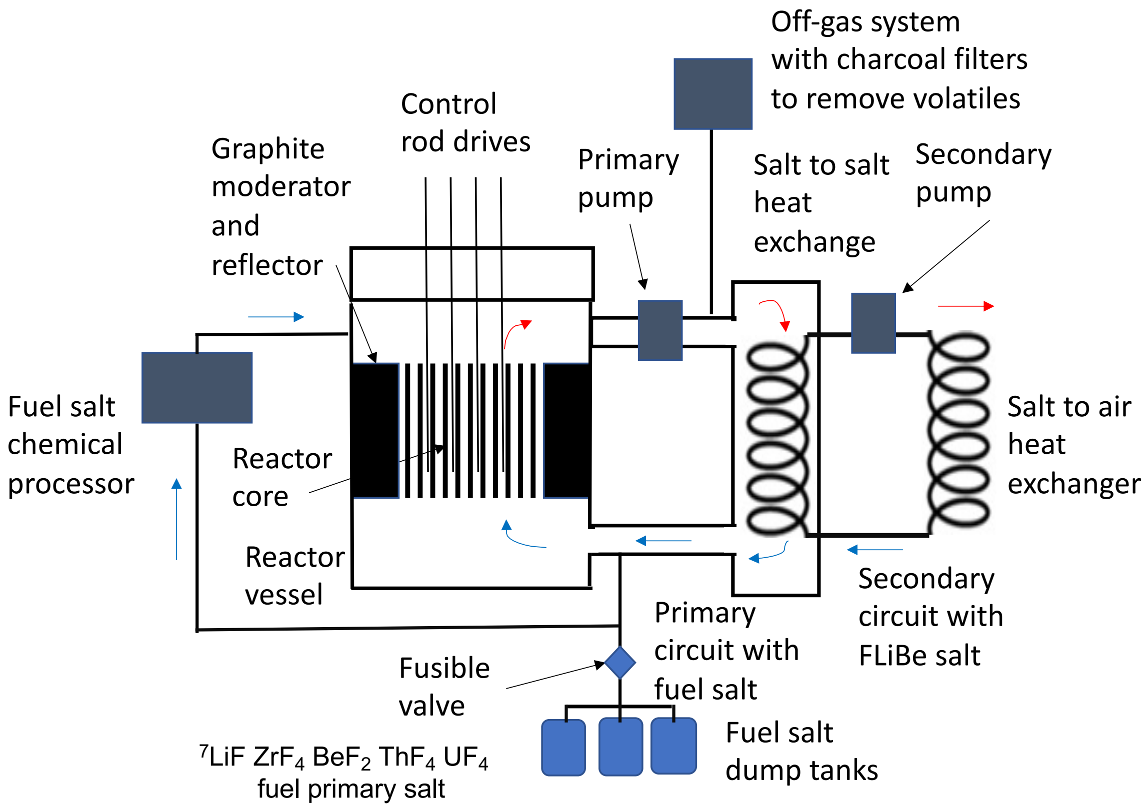
- A fast reactor with the fuel dissolved in a fluoride or chloride salt.

4. Stable Salt Fast Reactor (SSR) trade marked name for reactor designed by Moltex,

- The fuel is a molten salt in fuel pins cooled with a separate salt with our fuel. This can be either a fast reactor (SSR-W) with a chloride fuel salt and no moderator or a thermal reactor with a graphite moderator and the fuel as a fluoride salt in fuel pins.

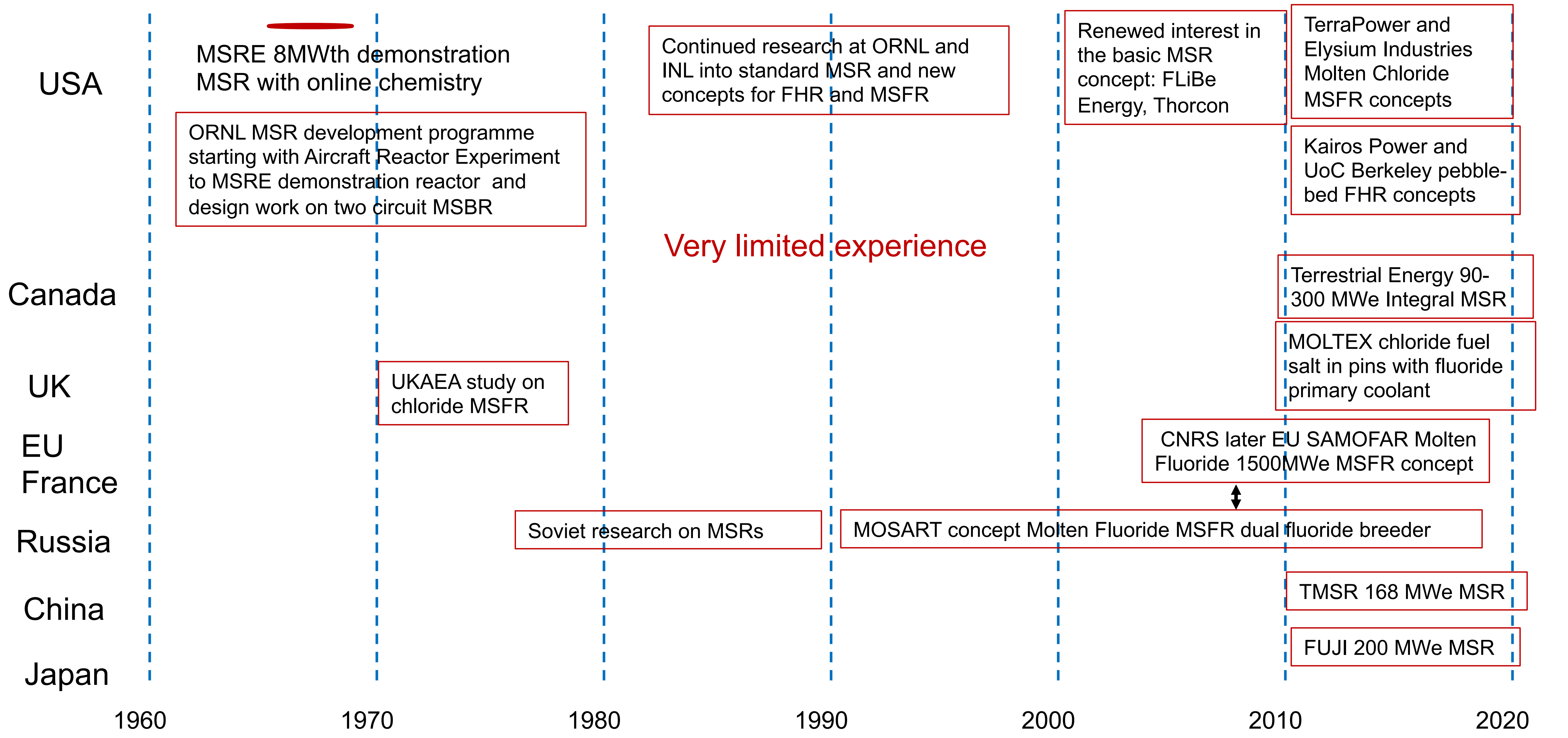
Molten Salt Reactor Experiment (MSRE) at ORNL

- In the mid-1950s the USA started to explore molten salt reactors for aircraft propulsion and two test reactors were briefly operated
- The remarkable MSRE reactor ran at ORNL from 1965 to 1969, for 2 reactor operating years equivalent.
- This MSRE concept demonstrated:
  - The use of thorium breeder and ^{235}U, ^{239}Pu and ^{233}U fuel in an 8 MWth reactor;
  - Adjacent salt chemical processing to remove oxides using HF, to filter solids, remove uranium using fluorine to convert to UF_6 and distil, and to adjust U^{4+}/U^{3+} ratio to control F potential;
  - Removal of inert gases Xe and Kr at the primary pump to give greater flexibility on power changes;
  - The introduction of Hastelloy N, a low Cr high Ni Mo alloy, that gives good resistance to corrosion from fluoride salts.



Sketch of the MSRE system components

Timeline MSR



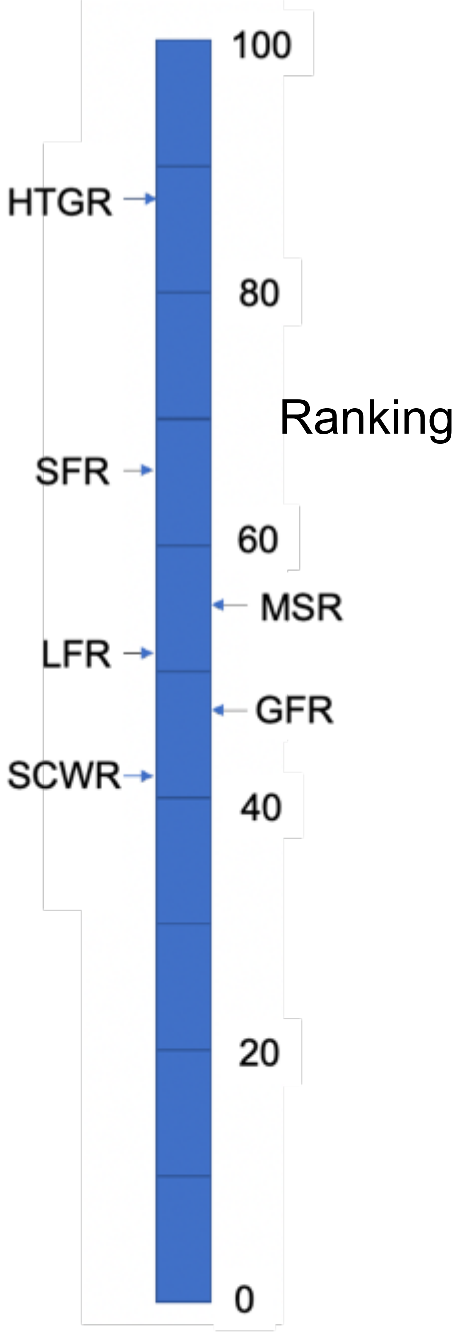
Operating experience of advanced reactor systems

System	Operating experience including experimental reactors not producing electricity (reactor operational years)	Operating experience from electricity production registered on IAEA PRIS (reactor full power years equivalent)
High Temperature Gas Cooled Reactor (HTR/HTGR/VHTR)	~150	20.1
Sodium Cooled Fast Reactor (SFR)	Oxide fuel ~250 Metal fuel ~25	Oxide fuel 61.4 Metal fuel 5.6
Lead Cooled Fast Reactor (LFR)	~70 in Soviet submarines Not fast flux, Pb-Bi coolant	0
Molten Salt Reactor (MSR)	Thermal ~2, Fast 0	0 No electricity generation
Advanced Gas-cooled Reactors (AGR)	~530	~365

Operating experience of Gas-cooled Fast Reactors (GFR), molten salt cooled fast reactors, and supercritical water cooled reactors is ZERO.

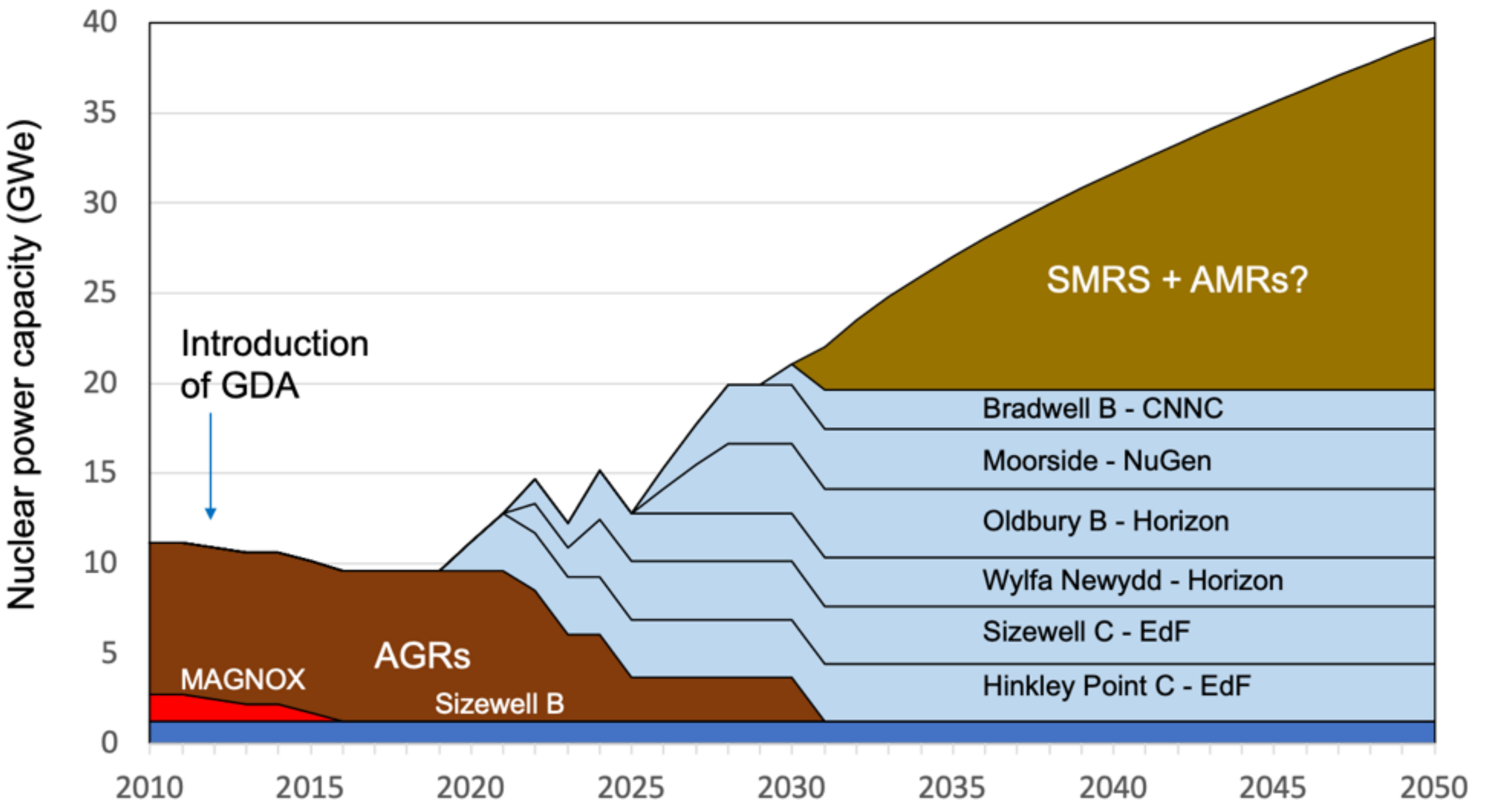
NIRO Technical Assessment of AMRs

	HTGR	SFR	LFR	MSR	SCWR	GFR
Timescales for delivery	Very High	Very High	Medium	Medium	Low	Low
Heat	Very High	Medium	Medium	High	Medium	High
Safety	Very High	Medium	Medium	Medium	Low	Low
Security	Very High	Medium	Medium	Medium	Medium	Medium
UK Value	High	High	Medium	Low	Low	Low
Economic Cost	High	Medium	Medium	Medium	Medium	Medium
Deployability	High	High	High	High	Medium	High
Adaptability	High	High	High	Very High	Medium	High
Waste & Environment	Medium	High	High	High	High	Very High
International	Very High	High	Medium	Medium	Low	Low

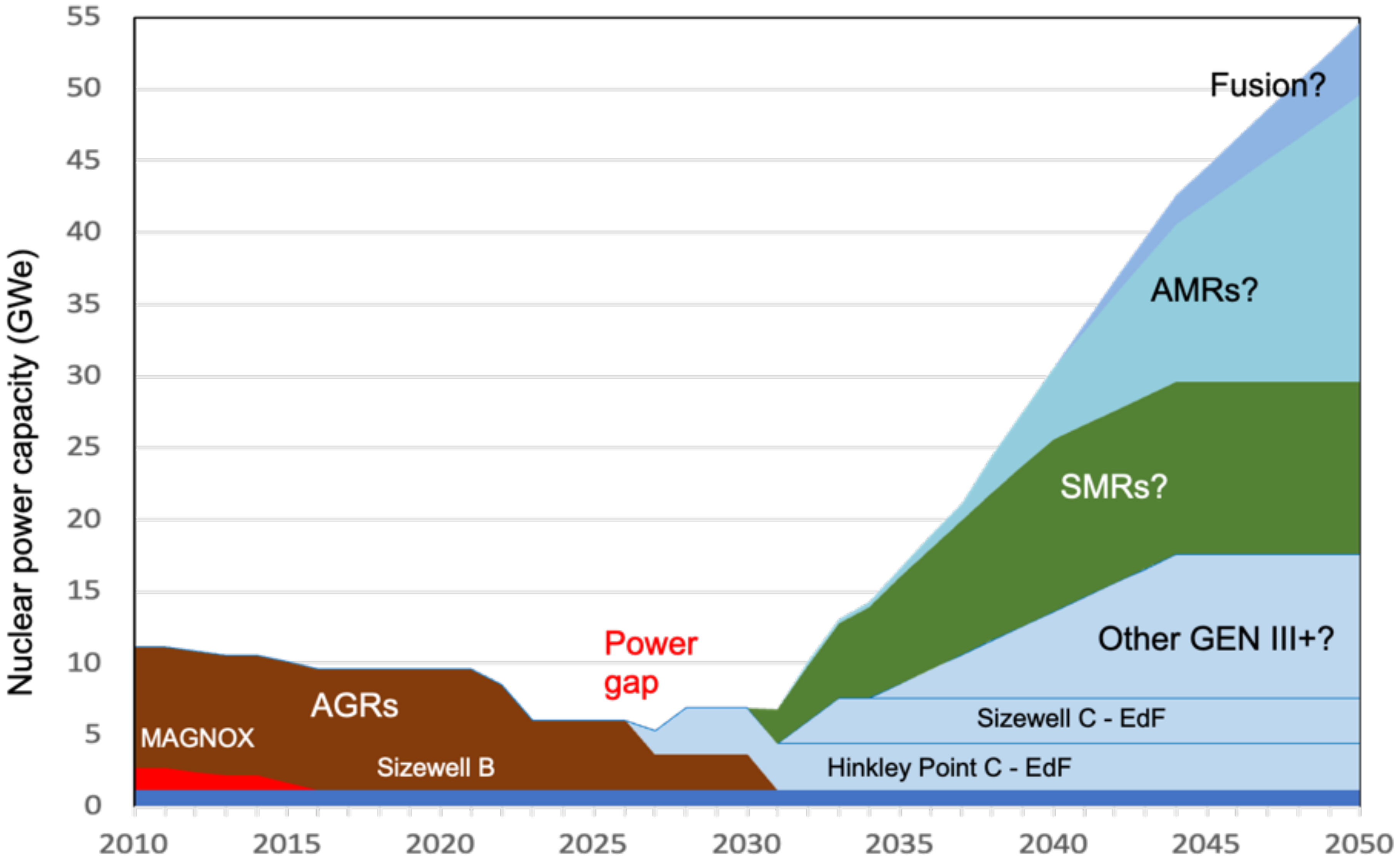


Advanced modular reactors technical assessment, NIRO report July 2021

Nuclear New Build as viewed in 2014



Nuclear New Build as viewed in 2023?



Proposed new strategy for nuclear power

The emergent current policy for nuclear power has been led by NIRAB an independent body set up in 2014 and supported by NIRO. Work by others includes, Lucid Catalyst, National Nuclear laboratory and Dalton Nuclear Institute:

- Smaller modular reactors to reduce overall and unit costs.
- Heat storage to increase flexibility.
- Use of waste heat to contribute to Net Zero.
- Dedicated reactors for hydrogen and synthetic fuels production in large low-carbon nuclear “refineries”.
- Move to high temperature systems to widen range of industrial applications – high temperature gas cooled reactors (HTGR) with heat potentially available up to 950^{o}C.

NIRAB = Nuclear Innovation and Research Advisory Board
NIRO = Nuclear Innovation and Research Office

The University of Manchester
Dalton Nuclear Institute

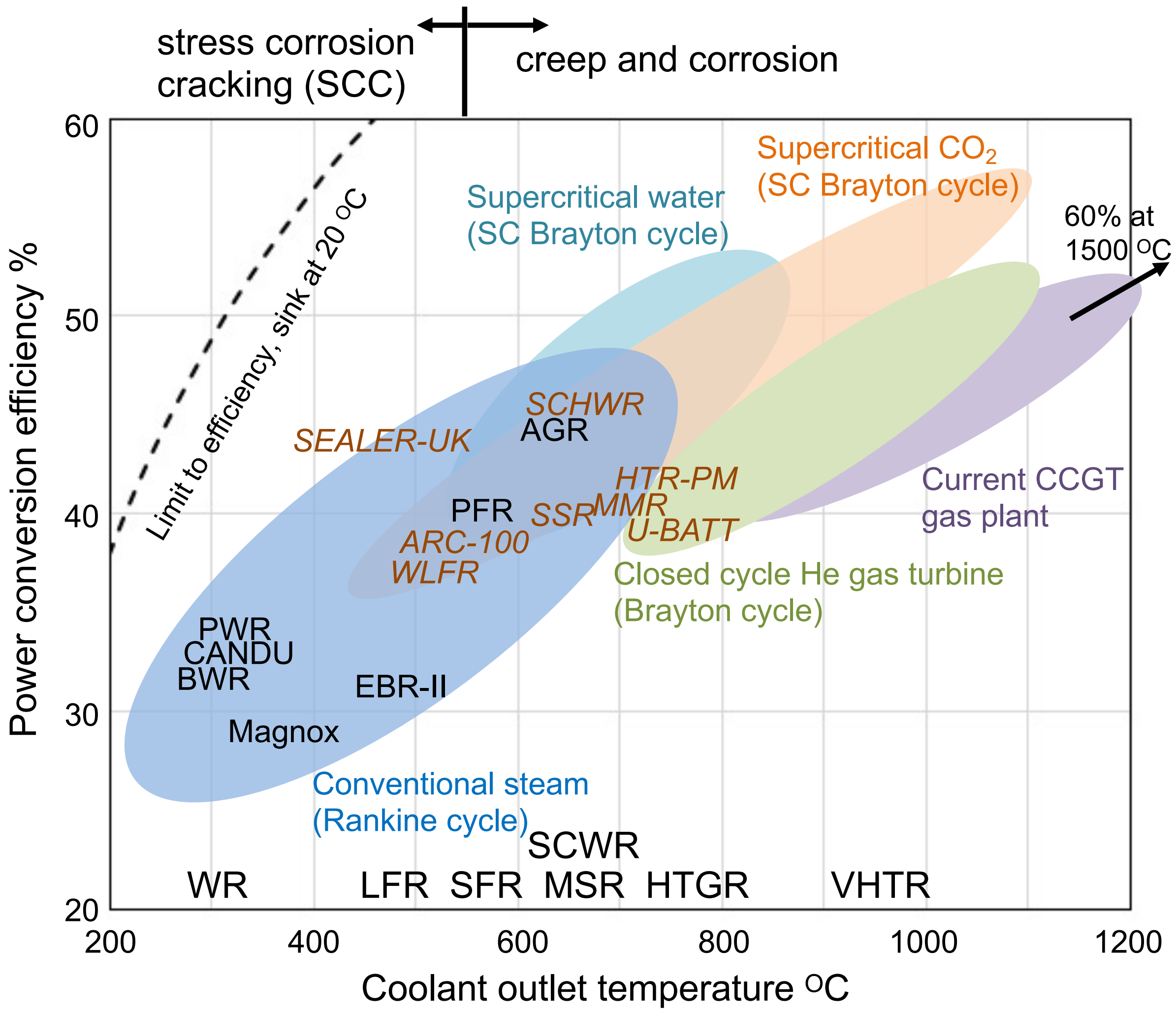
USE OF NUCLEAR HEAT

UK AMR RD&D programme

- In February 2022 BEIS announced the AMR research, development and demonstration project and for the first time fixed a target reactor type – the HTGR in order to look at the wider application of nuclear energy to include high quality heat as well as electricity.
- The programme is aimed at having a demonstration HTGR operating by early 2030s.
- Phase A, funded at £2.5M, has started to allow organisations involved to prepare for Phase B, funded at £27.5M, which is aimed at having two FEEDs (Front End Engineering Designs) ready for selection by April 2024. A total of £355M is available for development work in Phase C of the project.
- Phase A of the programme is in two lots:
    1. Reactor demonstration: EDF Energy on user requirements; NNL teamed with JAEA on the Japanese VHTR design, U-Battery on their design work; and Ultra Safe Nuclear Corp. on their MMR design. Note also that the Xe-100 pebble-bed design has entered the GDA process in 2023, so it may bid to enter Phase B.
    2. Fuel demonstration: NNL with Urenco and JAEA on HTGR fuel development and enrichment requirements, Westinghouse Springfields Fuels Ltd on HTGR fuel manufacture.
- Phase A is due to complete by end of March 2023 and its outputs will influence Phase B.

Energy conversion systems

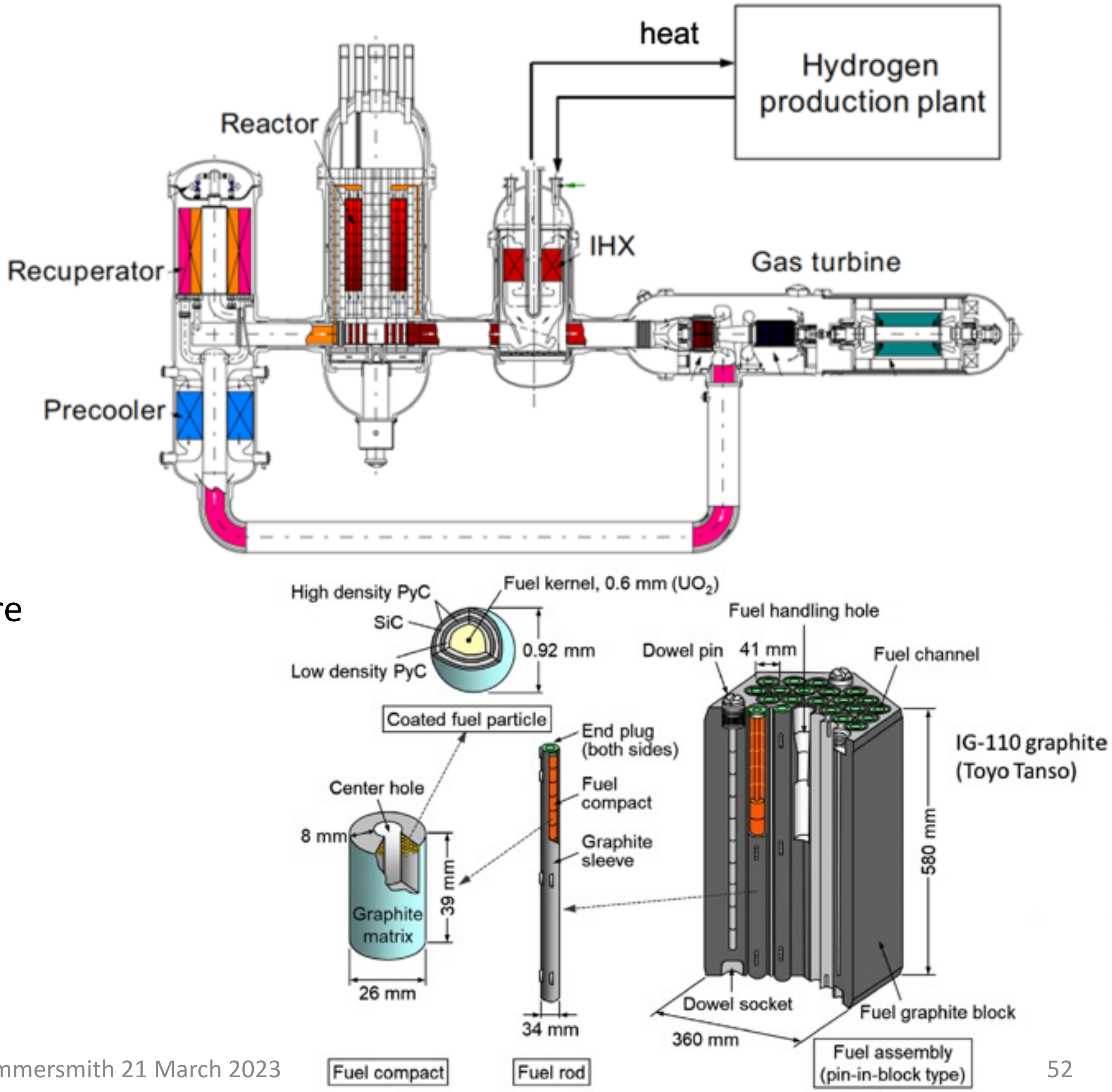
- Current LWR are limited to efficiencies of up to ~35%, but AGRs and GEN IV reactors with super-heated steam cycles are able to achieve 40-45% as will future fusion plant .
- Closed cycle gas turbines, supercritical water or CO_2 Brayton cycles are more likely to achieve efficiencies >50%.
- Use of waste heat reduces efficiencies, but the high temperatures of GEN IV plant allow some higher-grade heat to be bled off to improve usefulness.



GT-HTR300 VHTR

The GT-HTR300C is a collaboration between JAEA and Japanese industry based on the GT-HTR international collaboration. There is renewed interest in the design for use of high quality nuclear heat.

- Designed to be used for power production, 600 MWth, 300 MWe.
- Helium coolant at 7MPa, inlet 587 °C, outlet - 950°C.
- RPV 23m H - 8m D
- Annular core 8m H/3.6m ID/5.5m OD, annular core to facilitate radial conductive decay heat removal
- Fuel pin-in-block design (similar to HTTR), TRISO fuel particles, dispersed in annular cylindrical fuel compacts, packed into graphite sleeves and fitted into hexagonal blocks to form a fuel element.
- Av. fuel enrichment 14%, burnup 120 MWd/kg.



K. Kumitomi et al, Nuclear Engineering and Design 233 (2004) 309–327
High Temperature Gas-cooled Reactors. Chapter 2, 2021

GTHTR300C hydrogen production with SOEC (solid oxide electrolysis cells)

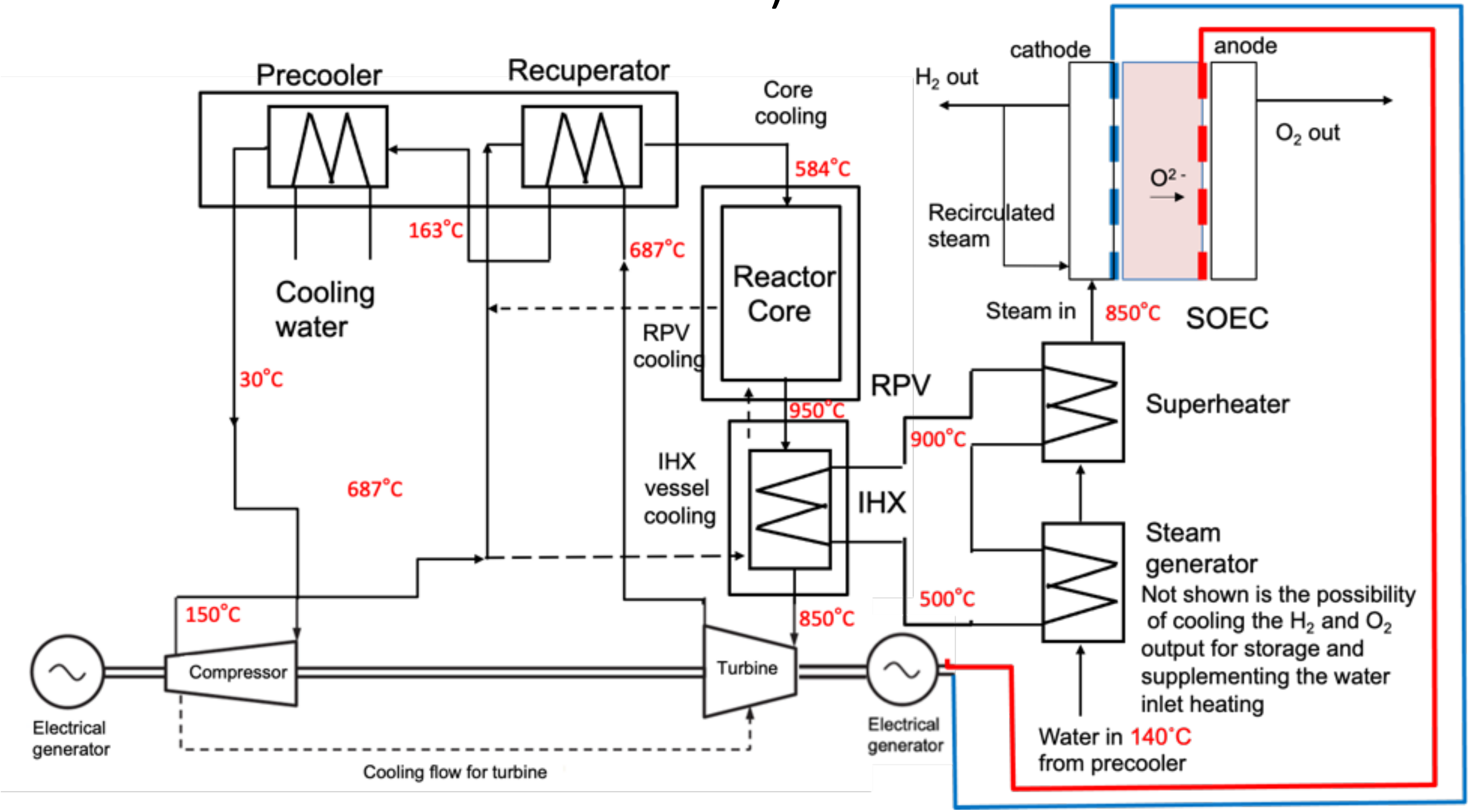
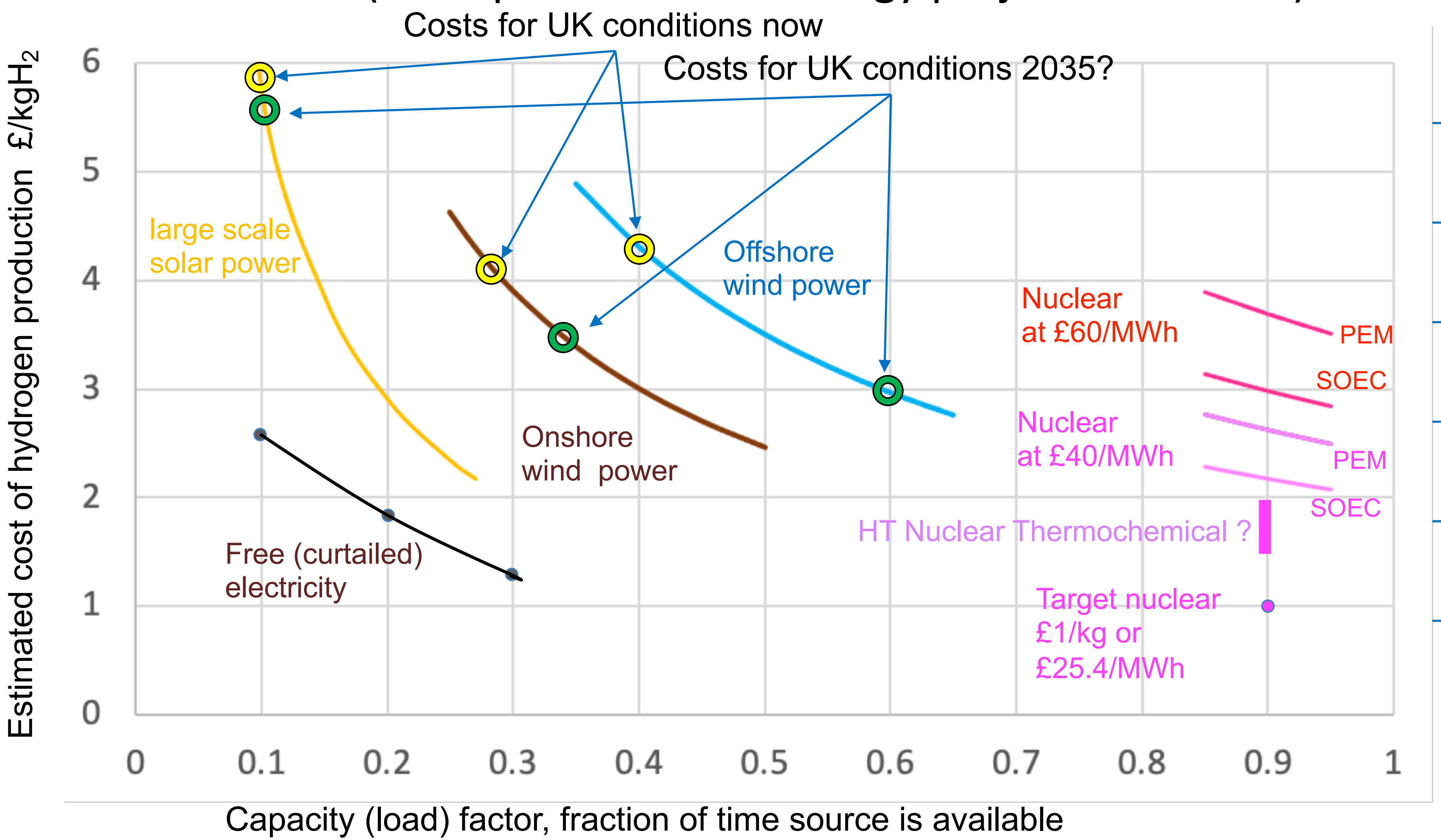


Figure modified from High Temperature Gas-cooled Reactors. Chapter 5, 2021

Comparing the cost of hydrogen from different energy sources

(2020 prices for technology projected to 2035)



The wholesale natural gas price peaked at £222/MWh in 2022 and was ~ £120/MWh in December 2022, in March 2023 it was ~ £34/MWh. The price was ~£10-20/MWh for most of the 2010s.

Data for plots from BEIS report "Hydrogen Production Costs 2021, Ceres Power SOEC Teach-in 2021 and the Bloom Electrolyzer White Paper 2022

Figure inspired by E Ingersoll and K Gogan *Energy Environ. Sci.*,. 12-1 (2019) pp. 19–40

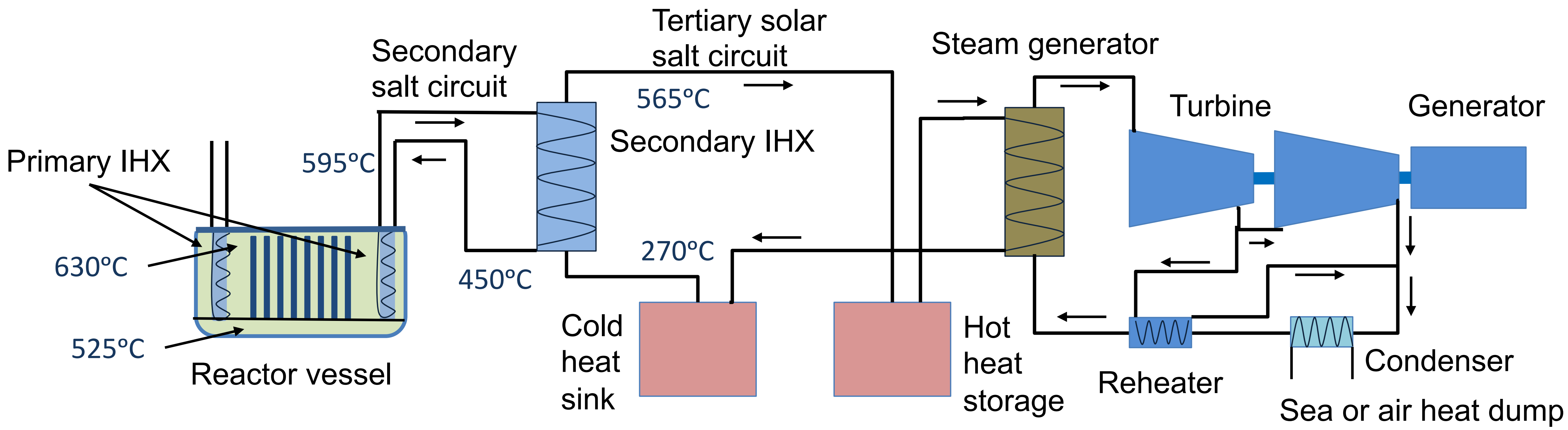
Comparison of electricity sources and hydrogen production

	Solar PV	Onshore wind	Offshore wind	Nuclear new build	Natural gas + CCS
Current levelised cost £/MWhe	44	46	57	93→60 Relies on baseload	85 will be higher with renewables
Load factor % (DUKES actual)	11 (~10)	35 (~25)	55 (~40)	85-95 renewables require more flexibility	87-95 much lower with renewables
Energy density MWe/km^2	~50	~3	~6	~1000	~220
Area (km^2) to generate 1400TWhe/year, equivalent to replacing all fossil fuels	~29,000 12% UK land area	~152,000 63% UK land area	~48,500 12% of UK EEZ	~177 0.075% UK land area	~800 0.34% UK land area
Carbon emissions kg CO_2 equiv./MWhe	43-94	20-45	9-15	7.5-17	140-200 (420-600)‡
Cost of hydrogen production £/kg	~5.8*	~4.1*	~4.3*	~3.7*	~2+ dependent on gas price
Carbon emissions kg CO_2 equiv./kg H_2	1.32-2.5	0.52-1.14		0.47-0.96	3-9 (10.1-17.2)‡

*Conventional PE Electrolysis +Steam reforming of natural gas ‡Unabated values

Data from;
Digest of United Kingdom Energy Statistics (DUKES) 2021
BEIS, Updated energy and emissions projections 2019
and B. Parkinson et al, *Energy Environ. Sci., 2019, 12, 19*

Secondary/tertiary salt circuits for energy storage

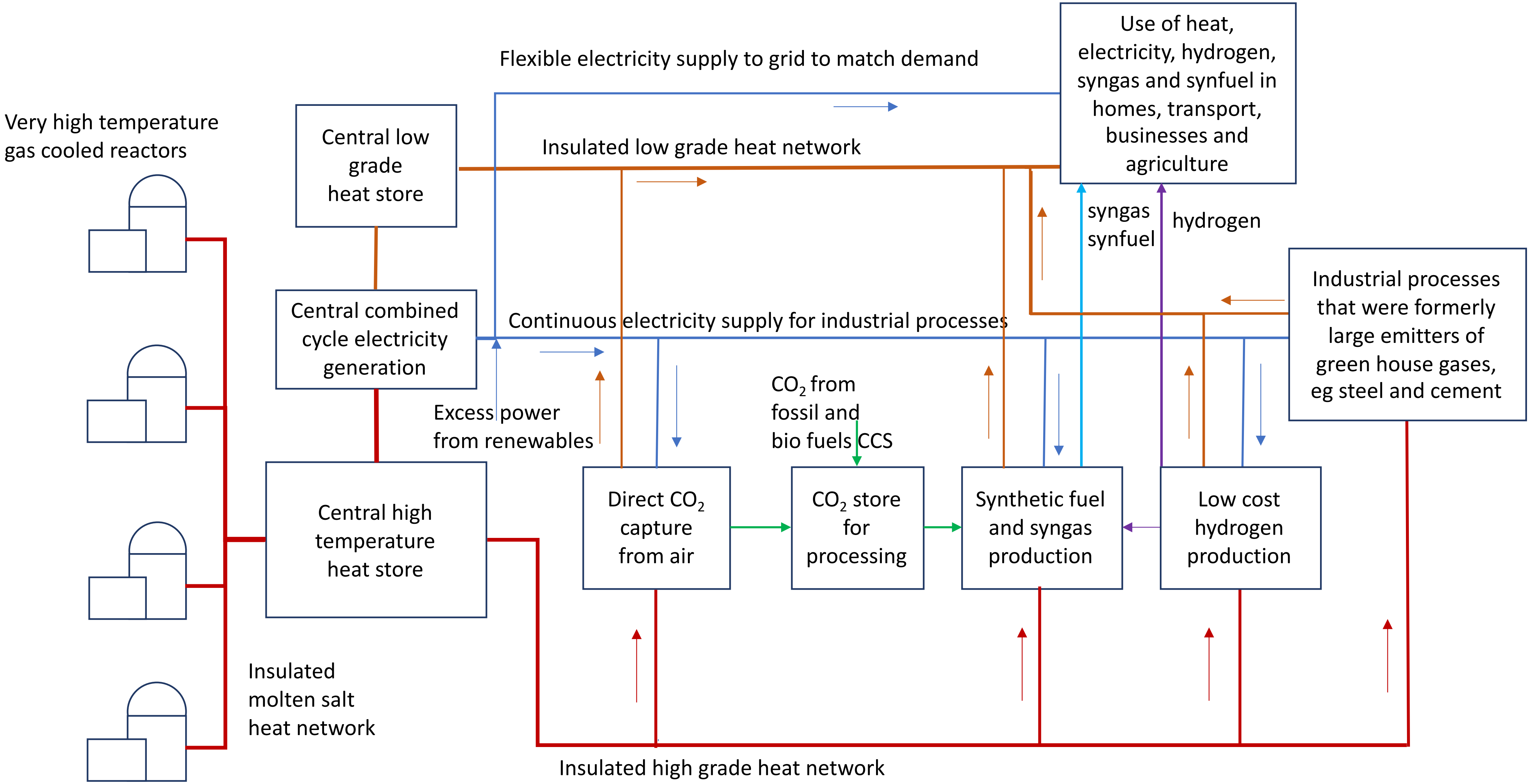


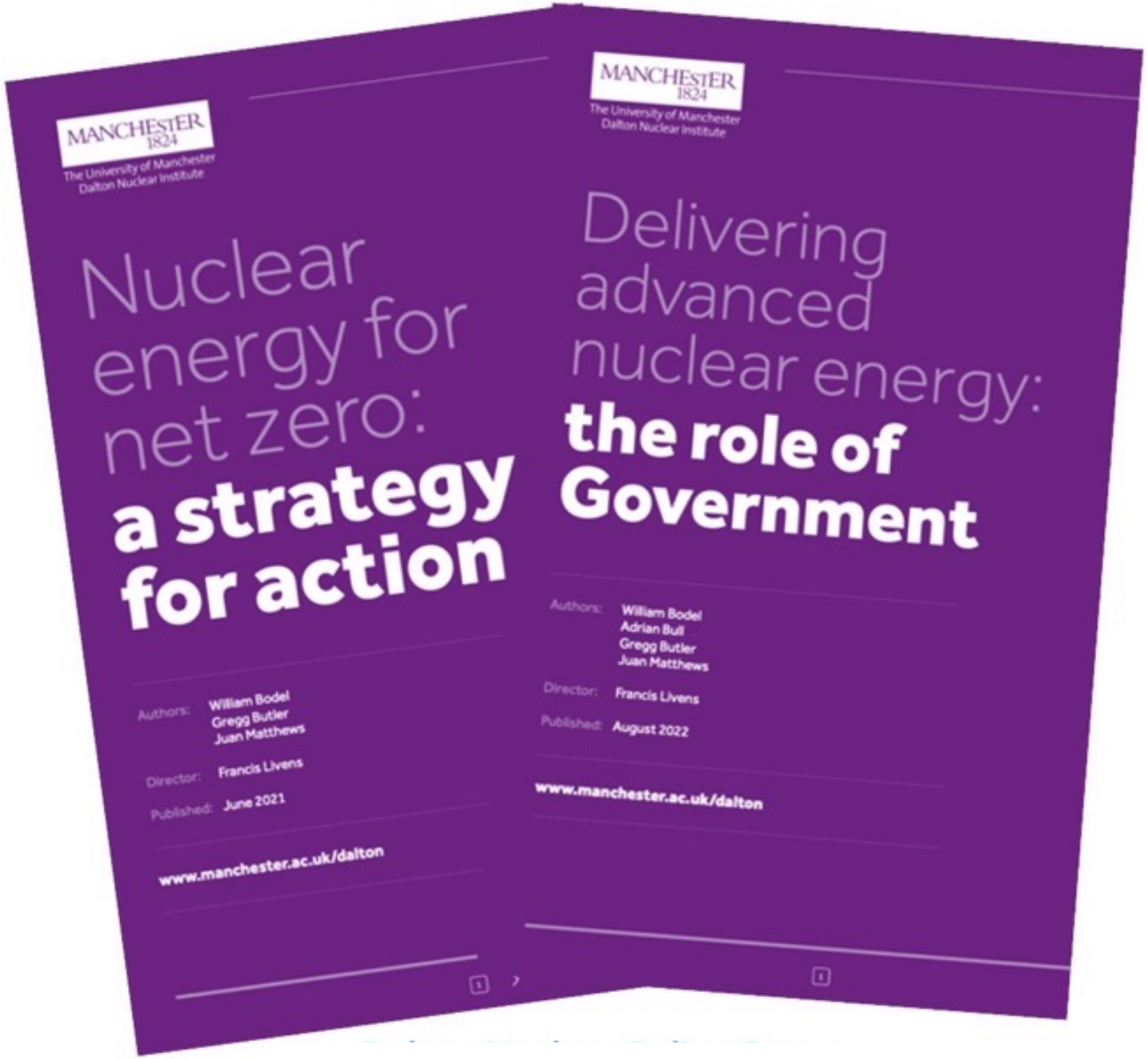
- Some AMR designs add a 3rd molten salt circuit to enable flexibility in electricity generation – Moltex SSR, MMR and the Natrium designs. This ideas comes from solar-thermal electrical generation and can be applied to any high temperature nuclear system. It is a solution that resolves the inflexibility of nuclear power but at a cost.
- The salt used is a mixture of Na and K nitrates, which has a sufficiently low melting temperature. For energy storage hot and cold heat sinks are required. These salts are limited to temperatures < 600°C as the nitrate salts start to decompose above this temperature. This form of storage also needs a lot of mass and so is only practical for a few hours capacity for diurnal cycling.

Higher temperature chloride salt storage systems

- Two other developments offer the possibility to improve the temperature range, capacity and costs of thermal energy storage.
- As already mentioned use of mixtures of MCl_2, NaCl and KCl, could to be a cheaper alternative to solar salts but also extend to the temperature range to 1000°C or higher. The main disadvantage is that solar salts already have a lot of experience from applications to solar thermal applications in hotter and sunnier locations than the UK and will be a big advantage to solar in those locations.
- The other possibility is to use the cheap HT chloride salts as a thermal energy vector and to make the actual storage in even cheaper solid stores.
- These could be rubble, gravel or sand. There is also the possibility of using geological strata for longer term storage to cope with summer/winter demand differences.
- These solutions offer a cheaper solution to the problem than generation and storage of hydrogen, which as a very low cycle efficiency (as low as 15%).

Achieving Net Zero through nuclear “refinery” and industry parks





[Dalton Policy Engagement]

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