How nuclear hydrogen production with cogeneration could support the integration of variable renewable energy into the grid.

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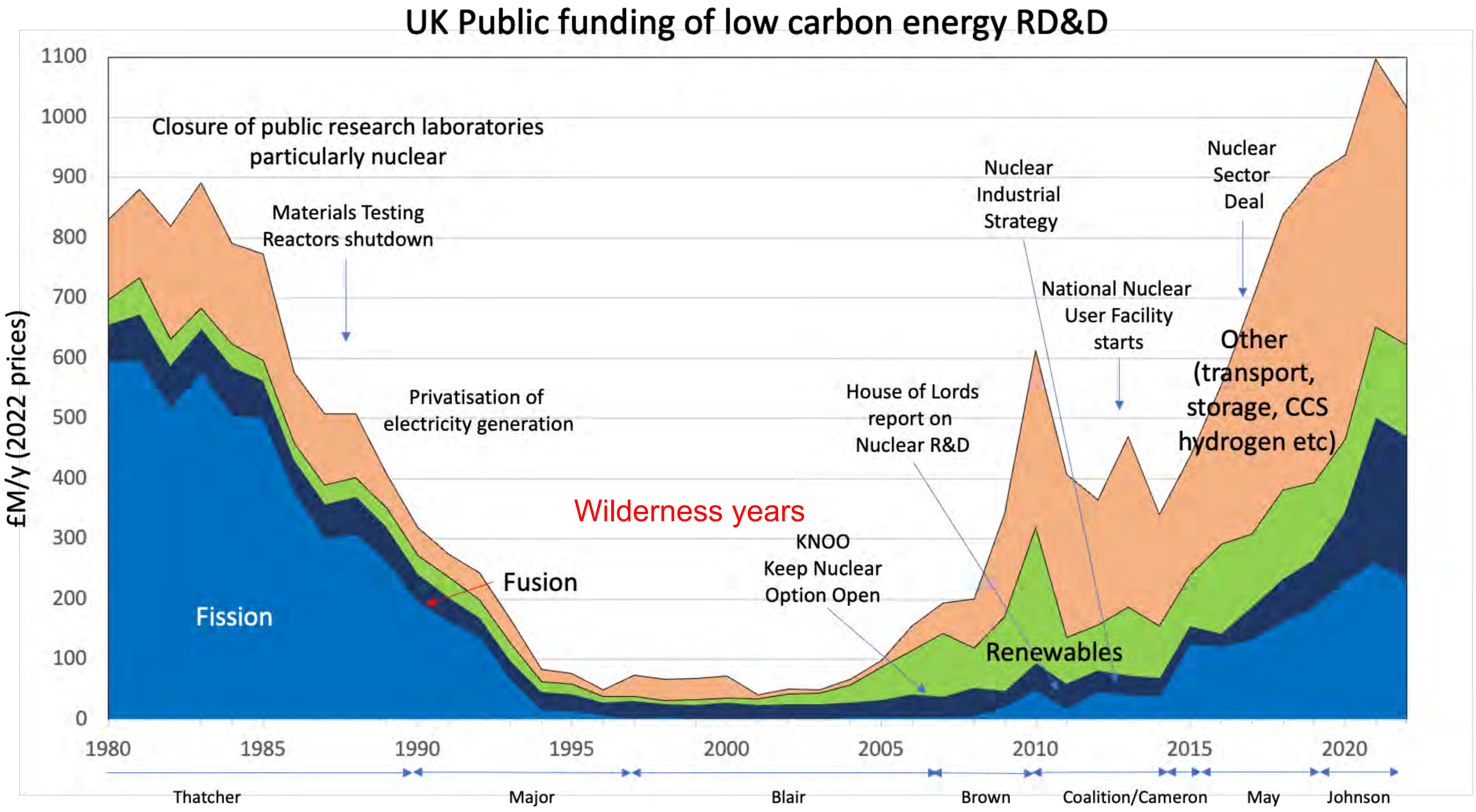
CURRENT UK NUCLEAR POLICY

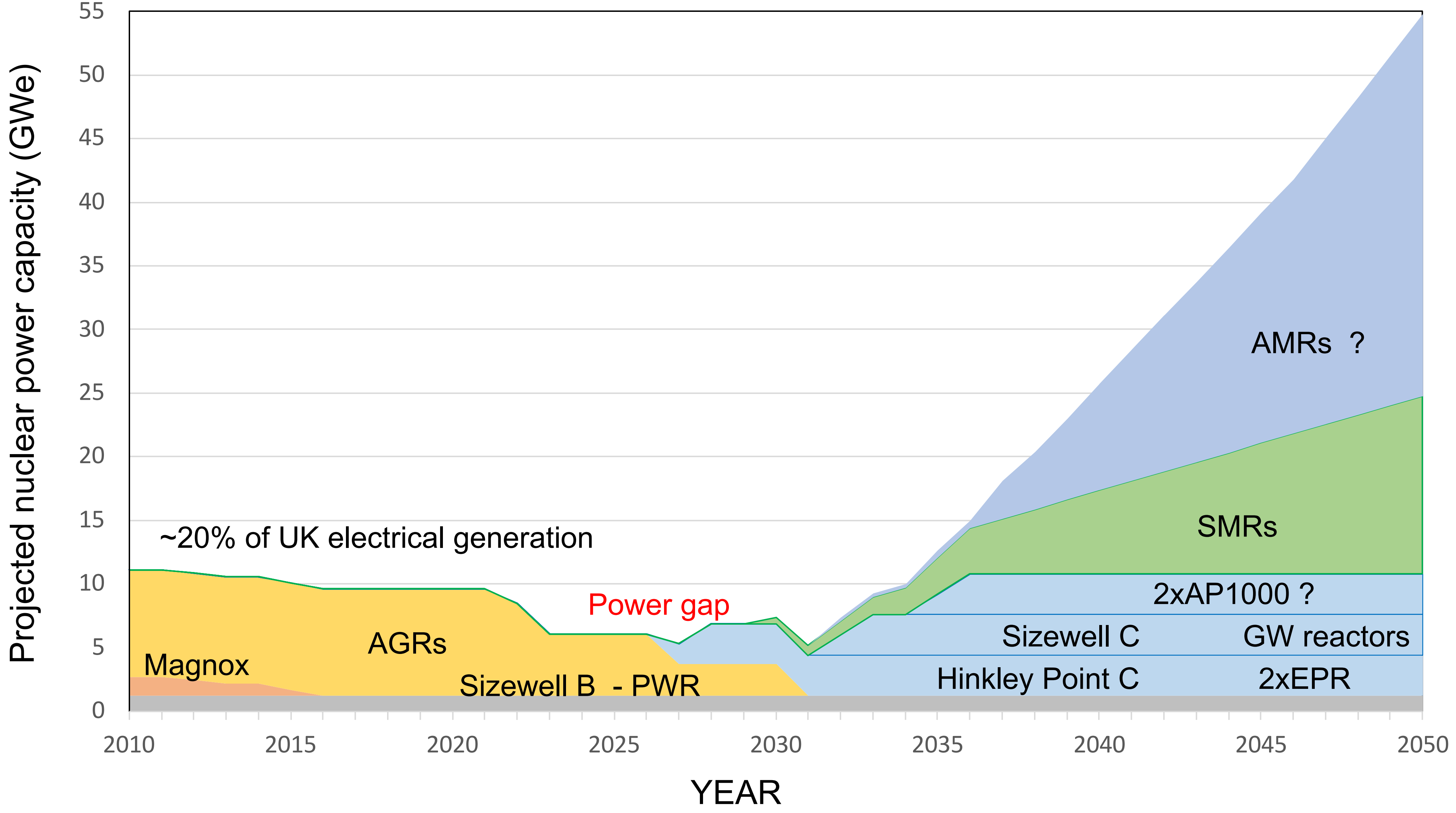
UK Nuclear environment

- The UK was previously a leading nuclear power nation that chose to develop its own gas cooled reactor designs – Magnox and AGR.
- Early 1980s the UK decided to switch to PWR technology, but only built Sizewell B. The rise of cheap natural gas resources meant nuclear power was too expensive and there was period of decline in nuclear R&D until ~2011.
- The construction of a new generation of nuclear reactors started with EdF leading around 2010, but finding investment in a deregulated environment was difficult.
- In 2023 there was a decision to start a SMR (Small Modular Reactor) programme and commitment to 24GWe of GW and SMR LWR stations . GBR (Great British Nuclear).
- AMR (Advanced Modular Reactor- UK definition of GEN IV SMR):
  2022 AMR RD&D project - plant to build a demonstration HTGR by early 2030s.
- Magnox reactors are all being decommissioned. AGRs are shut down or will shut down by early 2030s.

International Energy Agency data



UK historical and projected nuclear power



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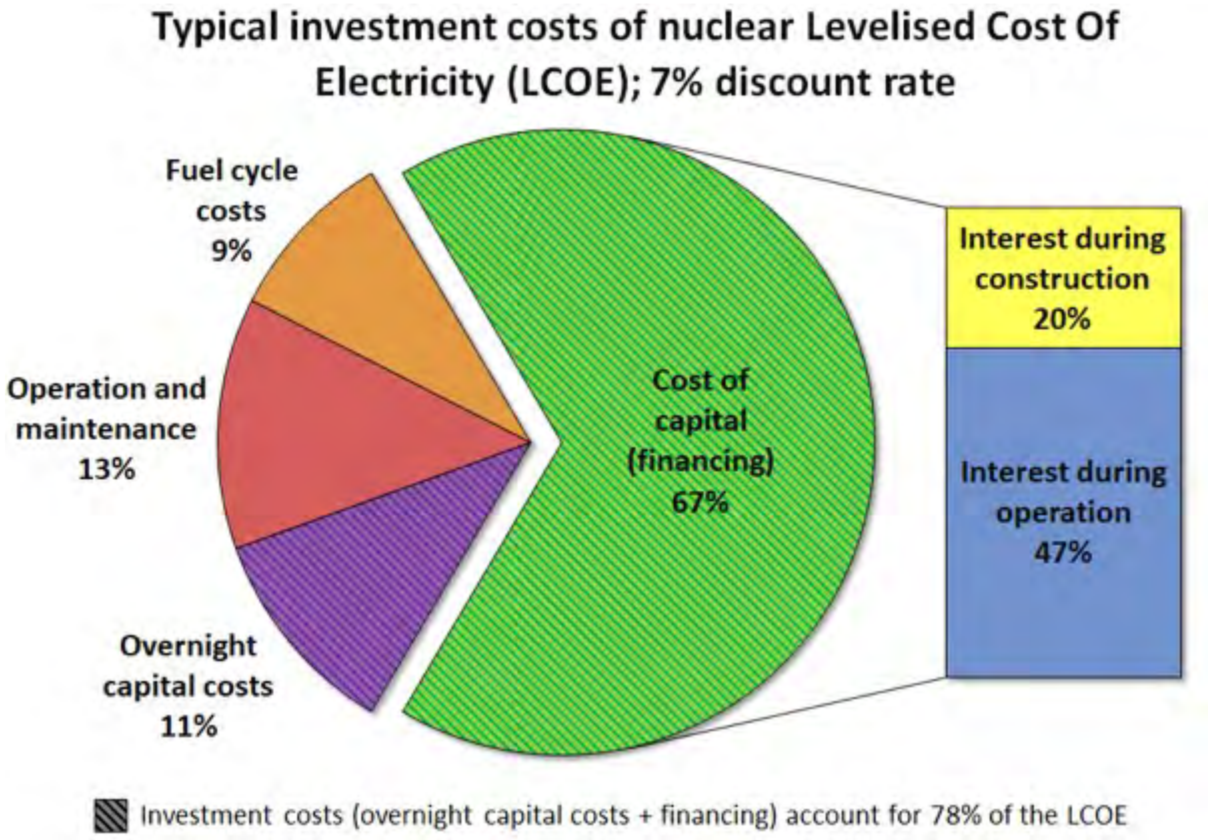
WHAT IS THE PROBLEM?

Four issues with nuclear power at the moment

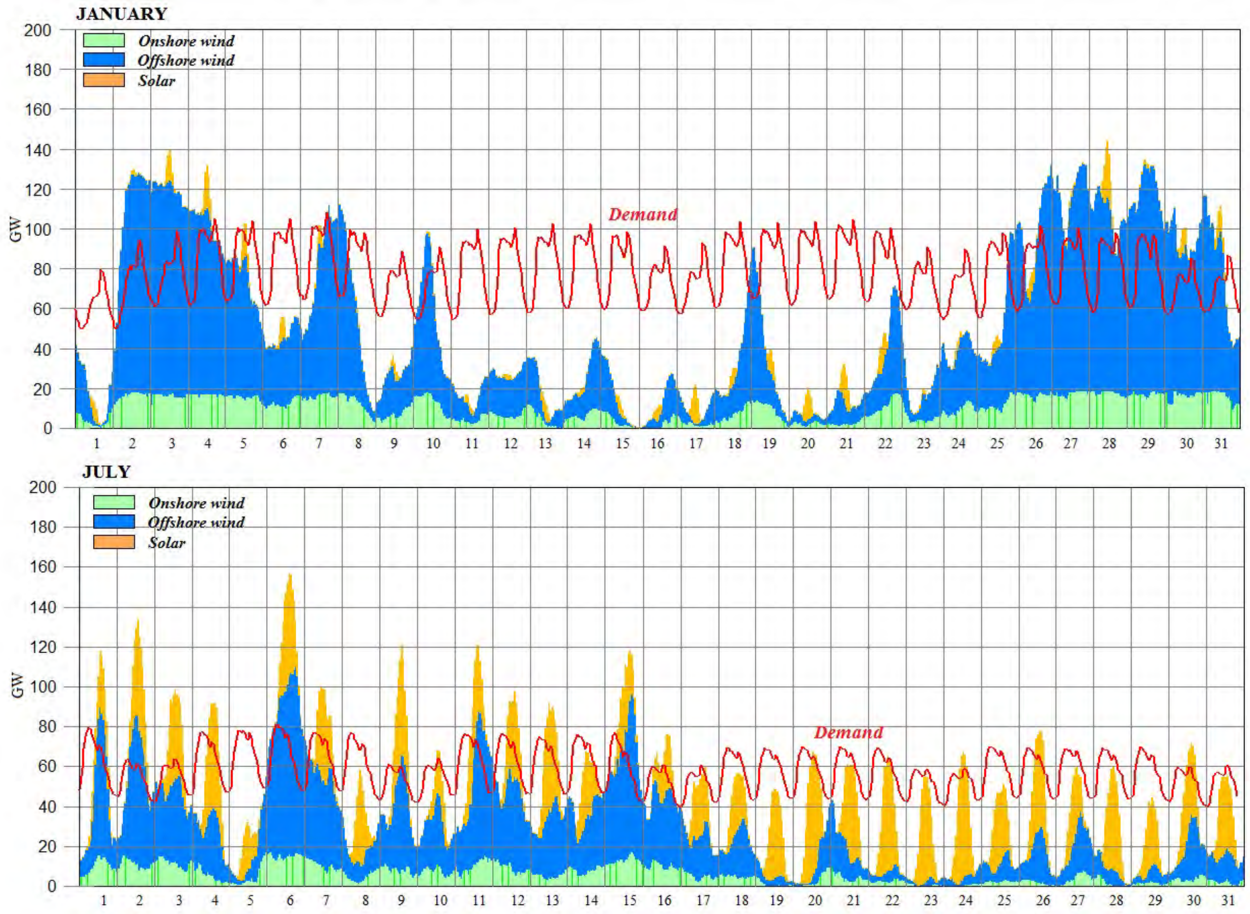
1. Too expensive – high capital cost and high unit cost leading to high rates of return on investment
2. Takes too long to construct – adds to costs through interest rates
3. Too inflexible - high capital costs mean that plant has to be run continuously to be cost effective
4. Currently focussed on supplying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



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

Five issues with renewables

1. Low availability in UK, solar around 10%, onshore 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. Require large areas of land or sea, limiting supply potential.
5. Large factions of intermittent renewables on the grid, without energy storage, increases the price of other power sources

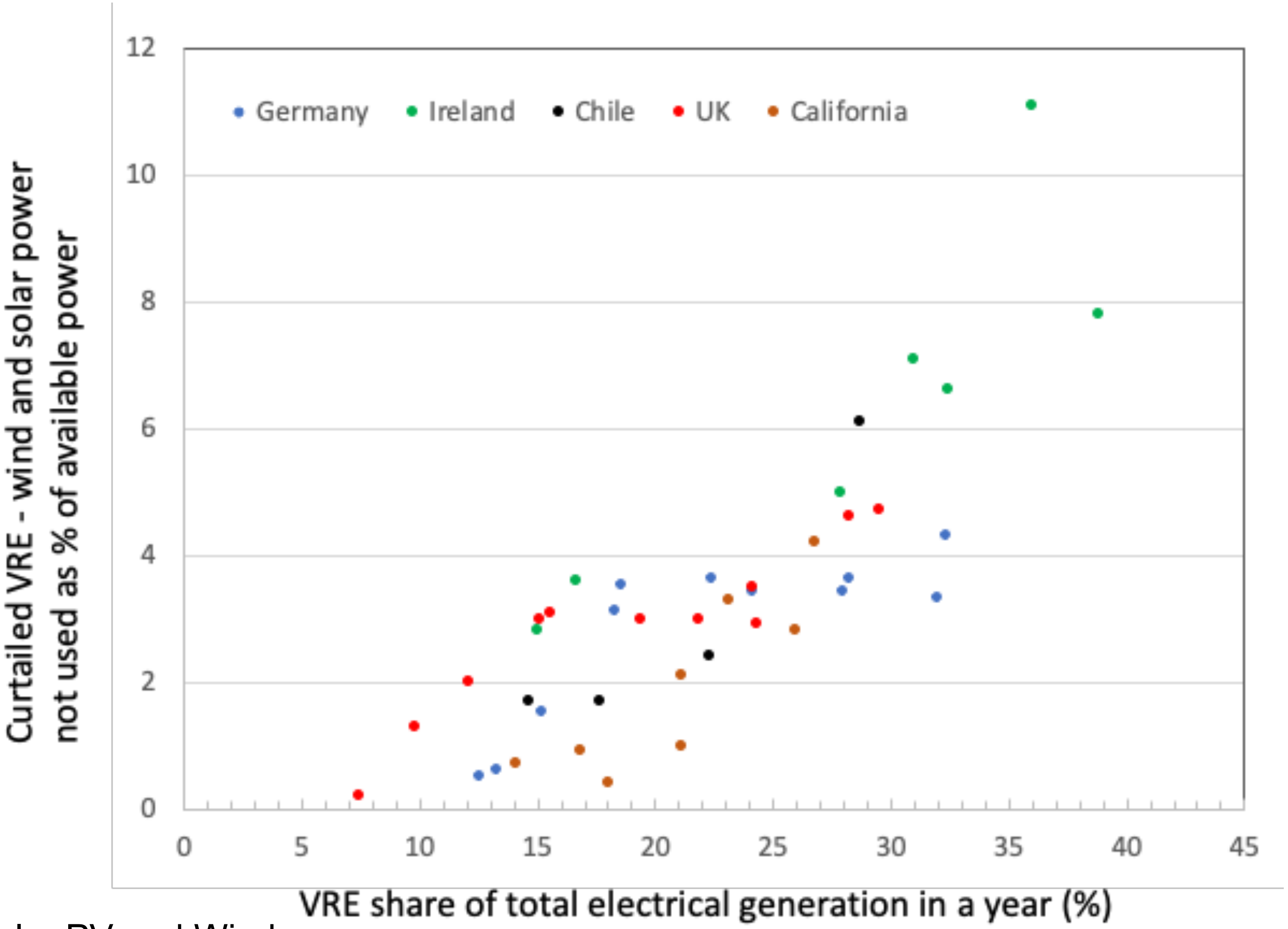


Demand and intermittent renewables supply scenario for the UK in 2050 using typical seasonal variations

From Euan Mearn’s Energy Matters

Data on curtailment of VRE since 2016

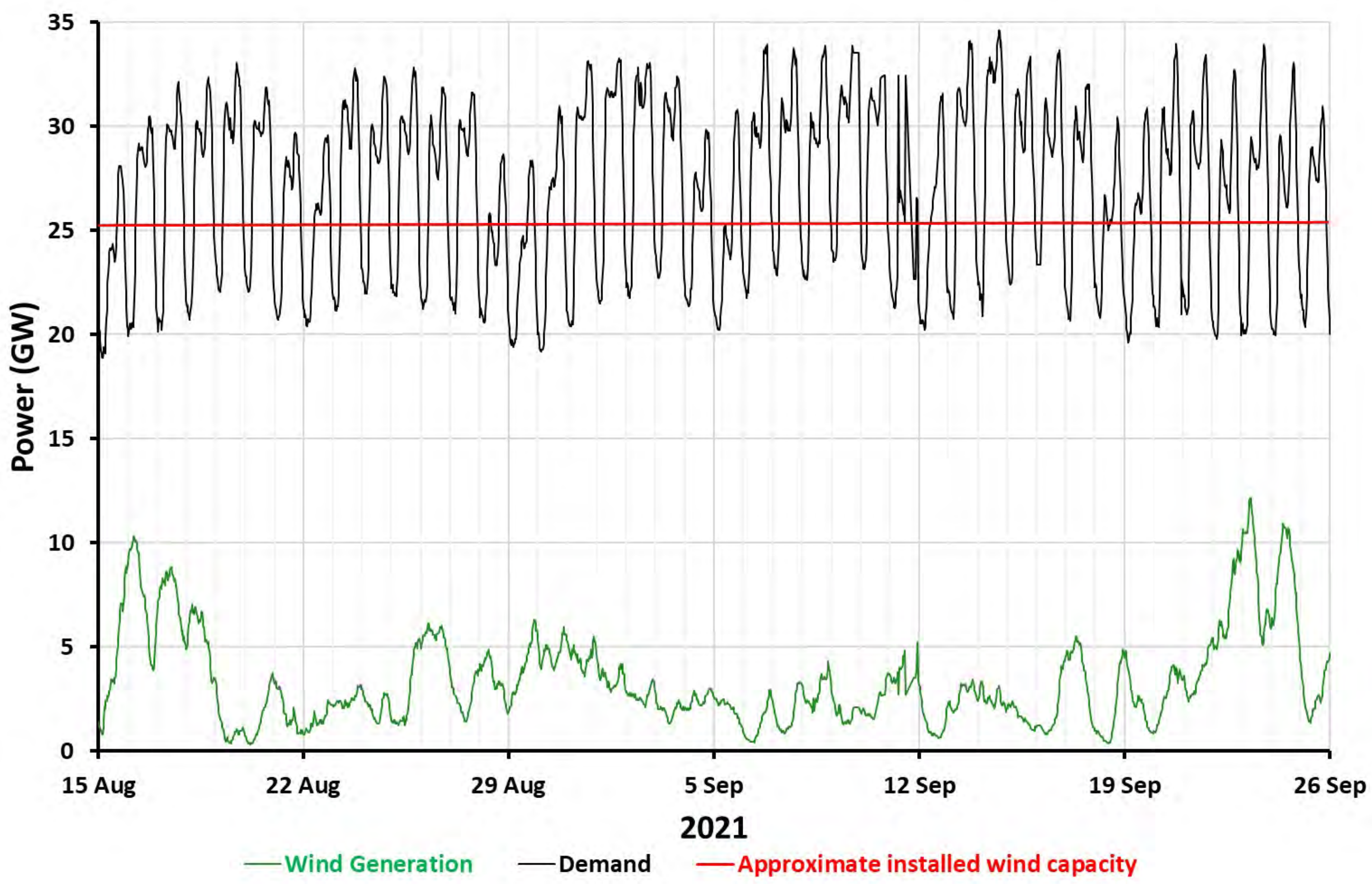
- Any capacity of VRE above the minimum summer level of demand will result in some of the electricity being curtailed (power rejected from grid).
- This increases costs by loss of ability to recover fixed costs, but in the UK renewable supply contracts often include payment if supply is refused.
- Up to now most curtailment is due to lack of adequate grid or distribution network connections
- In the future as VRE generation increases, curtailment could be become a serious problem. You can have too much VRE in your electricity generation



VRE = Variable Renewable Energy – largely Solar PV and Wind

An example of low wind availability in UK

- The UK is a windy country, particularly around the coast. However, the wind is very variable and only available for power production 25-50% of the time, depending on location.
- Occasionally there are long periods with very low levels of wind power. The figure shows an example from the summer, but such periods also occur during the winter.
- Solar power is only available during the day and in the UK and only produces power for ~11% of the time.
- Alternative power sources are needed with at least the capacity of the maximum demand.



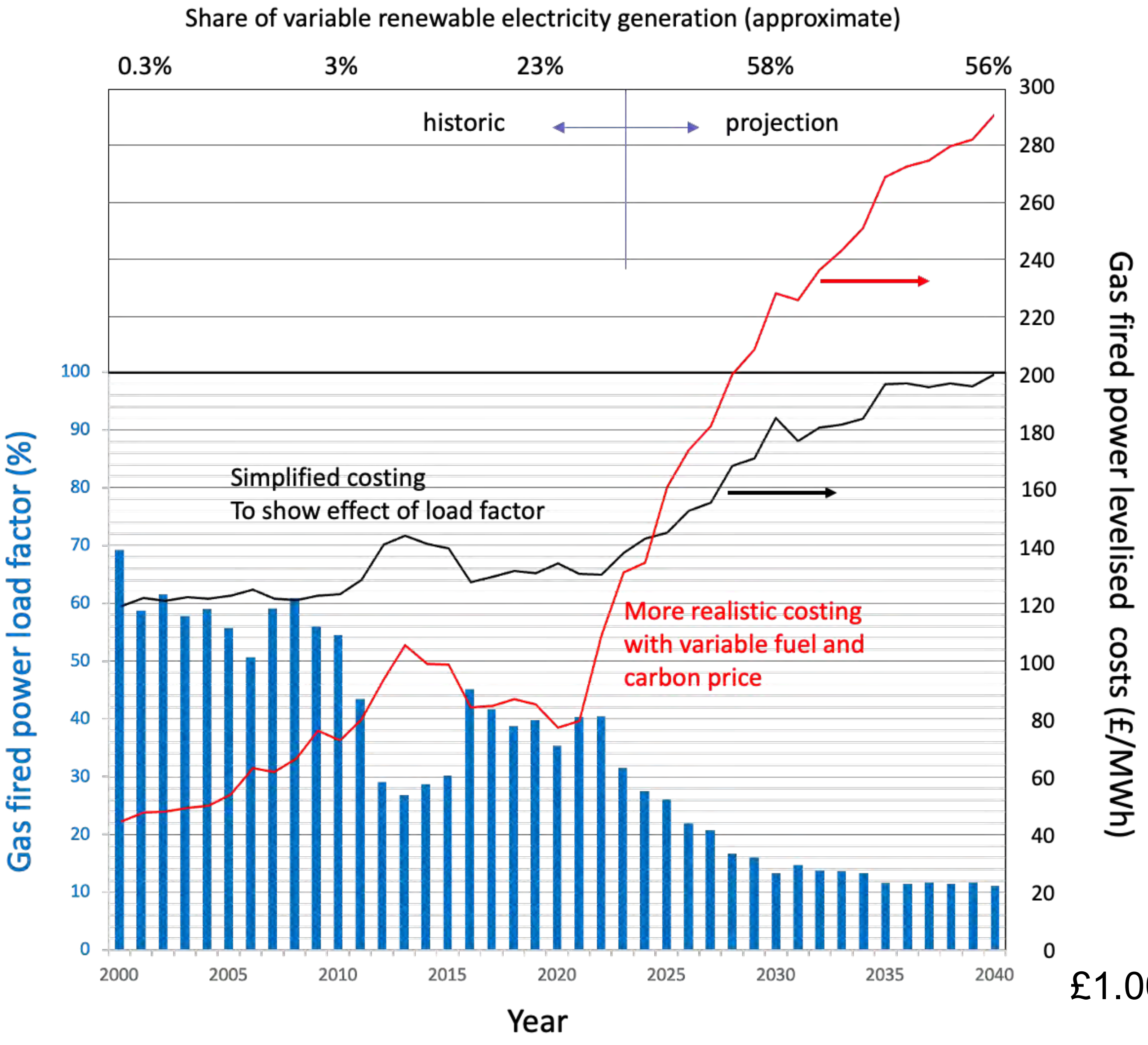
Seven issues with natural gas + CCS or CCUS

1. As the last two years have 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 March 2023!
3. If captured CO_2 is used to produce synfuels for transport then it is released to the atmosphere, only CO_2 captured from the atmosphere or from biofuel combustion can be carbon neutral or negative.
4. CCS is typically ~90% efficient in capturing CO_2, 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. Use of carbon negative sources to offset residual emissions from continued use of natural gas with CCS is expensive.

CCUS = Carbon Capture, Use and Storage

Effect of high variable renewable generation on gas load factor

- As the share of variable renewables increases inevitably there is a need for flexible generation to fill the gaps when the wind doesn't blow, and the sun doesn't shine. In the UK this has fallen on natural gas open cycle and combined cycle generation.
- The example here is a combination of UK historical generation and the official base case projections. Base case means what will happen if no new technology is introduced.
- The figure is complicated by the closing of coal generation recently that led to an increase in gas load factor



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Effect of load factor on generating cost – current technologies

- Reducing the load factor, for any technology, increases the levelised cost of generating electricity. This because of the increased charges on fixed costs, like minimum services but particularly repayment of capital costs with interest.
- Variable costs, like fuel charges are not affected, but these can fluctuate.
- Nuclear power and bio-energy, show sensitivity at quite high load factors.
- Gas is less sensitive hence its use in grid support.

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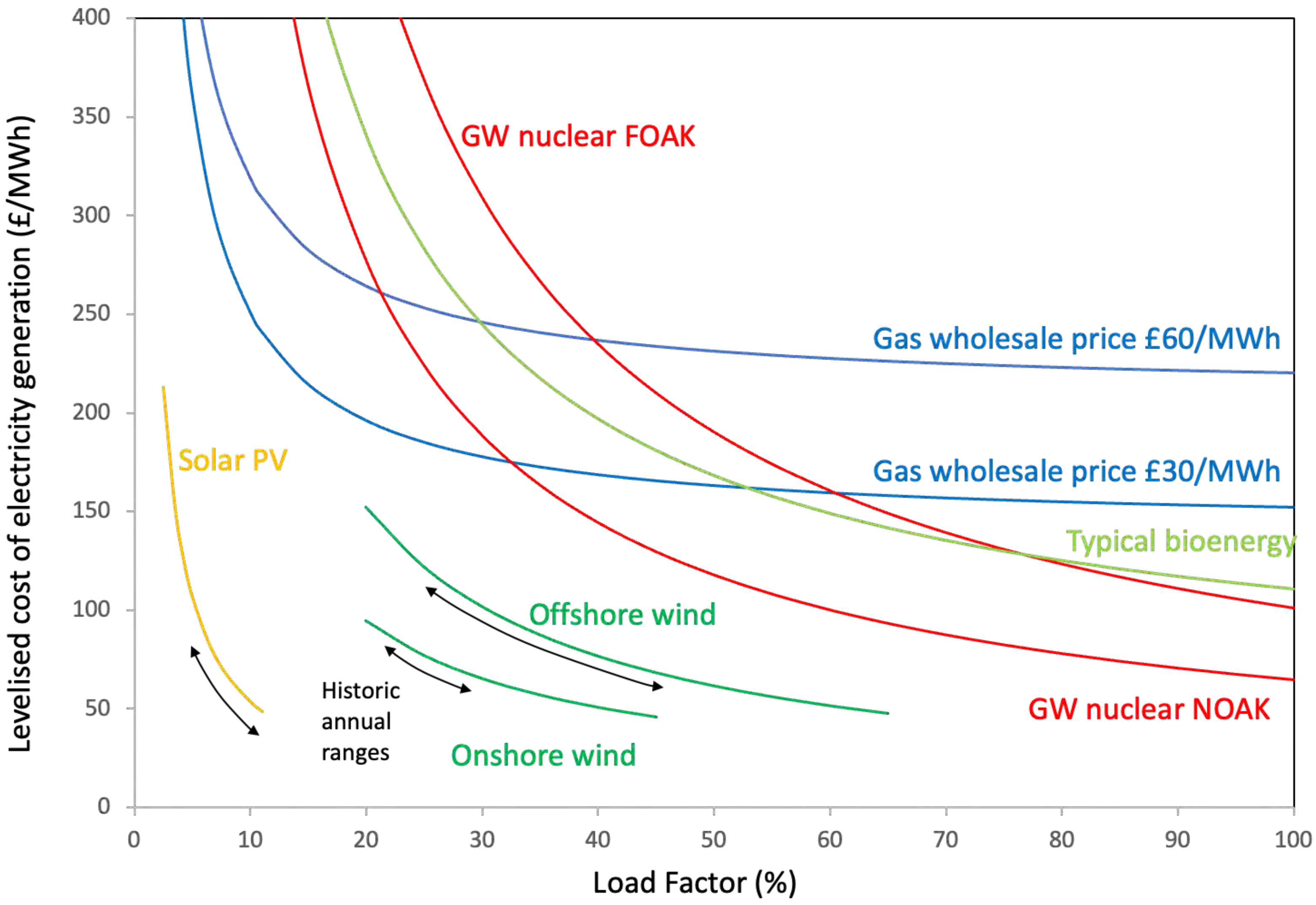

Effect of load factor on generating cost – future technologies

- The future projection introduce new options for storage, CCS and the use of hydrogen to support the electricity network.
- None of the technologies offers a low-cost solution to the problem of filling in the large capacity shortfall from low supply of variable renewables.
- Li-ion (and soon Na-ion) batteries are a good match for solar, but they are cost effective only for diurnal support.
- Hydrogen is better for longer support term support, but with some open cycle frequency support.

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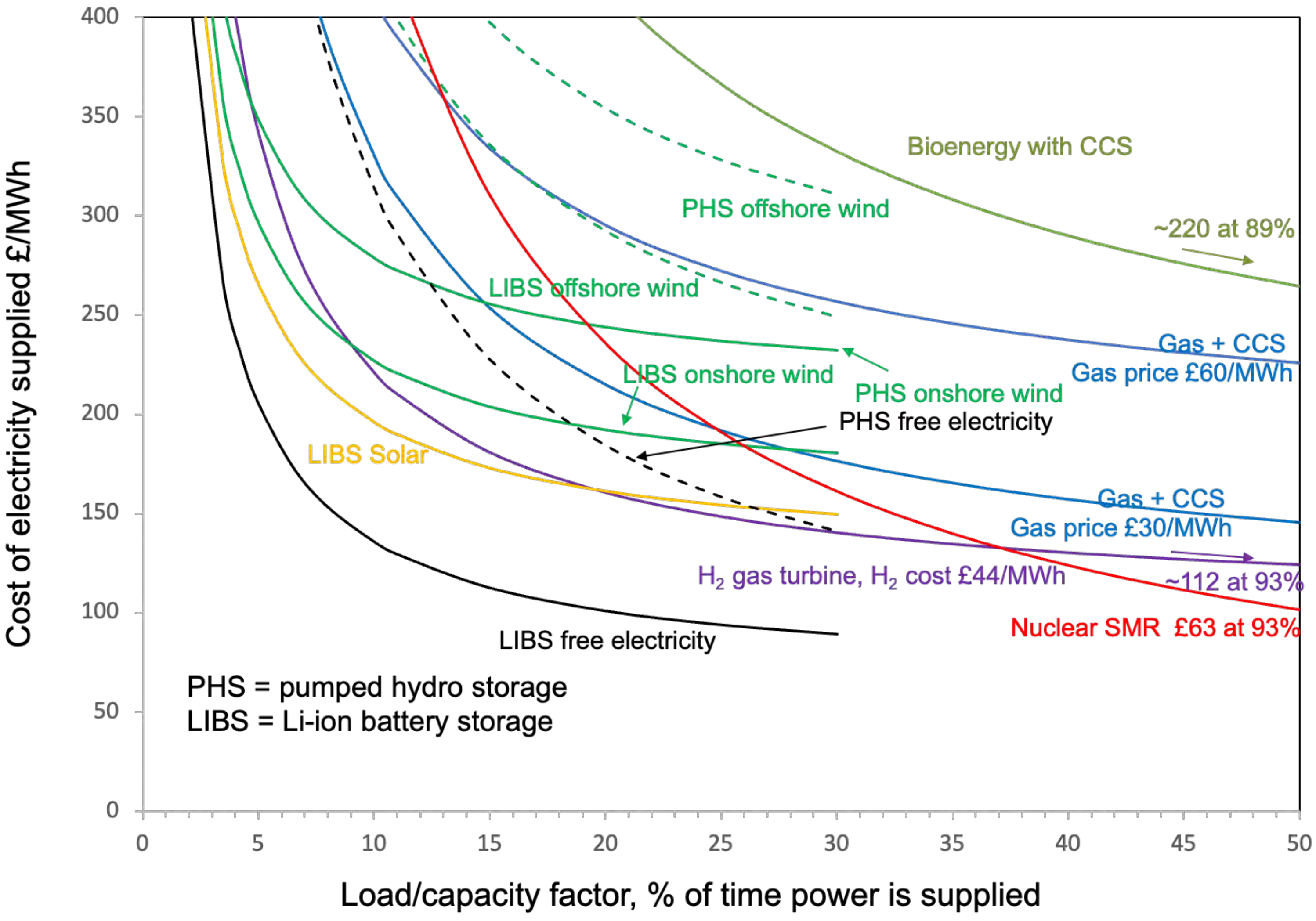

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HYDROGEN PRODUCTION

Current UK Hydrogen R&D and production projects

Apart from some production as part of oil refinery activities, so far there is no major hydrogen production in the UK, but a lot of research on steam reforming of methane and electrolysis. Both low temperature electrolysis and SOEC (Solid Oxide Electrolyser Cells) are under development. Ceres Power has developed a lower temperature SOEC process, which is being explored for nuclear applications.

The two main UK hydrogen production projects are both based on used on reforming of natural gas, capture of the CO_2 and disposal in spent offshore gas fields.

Humber Zero

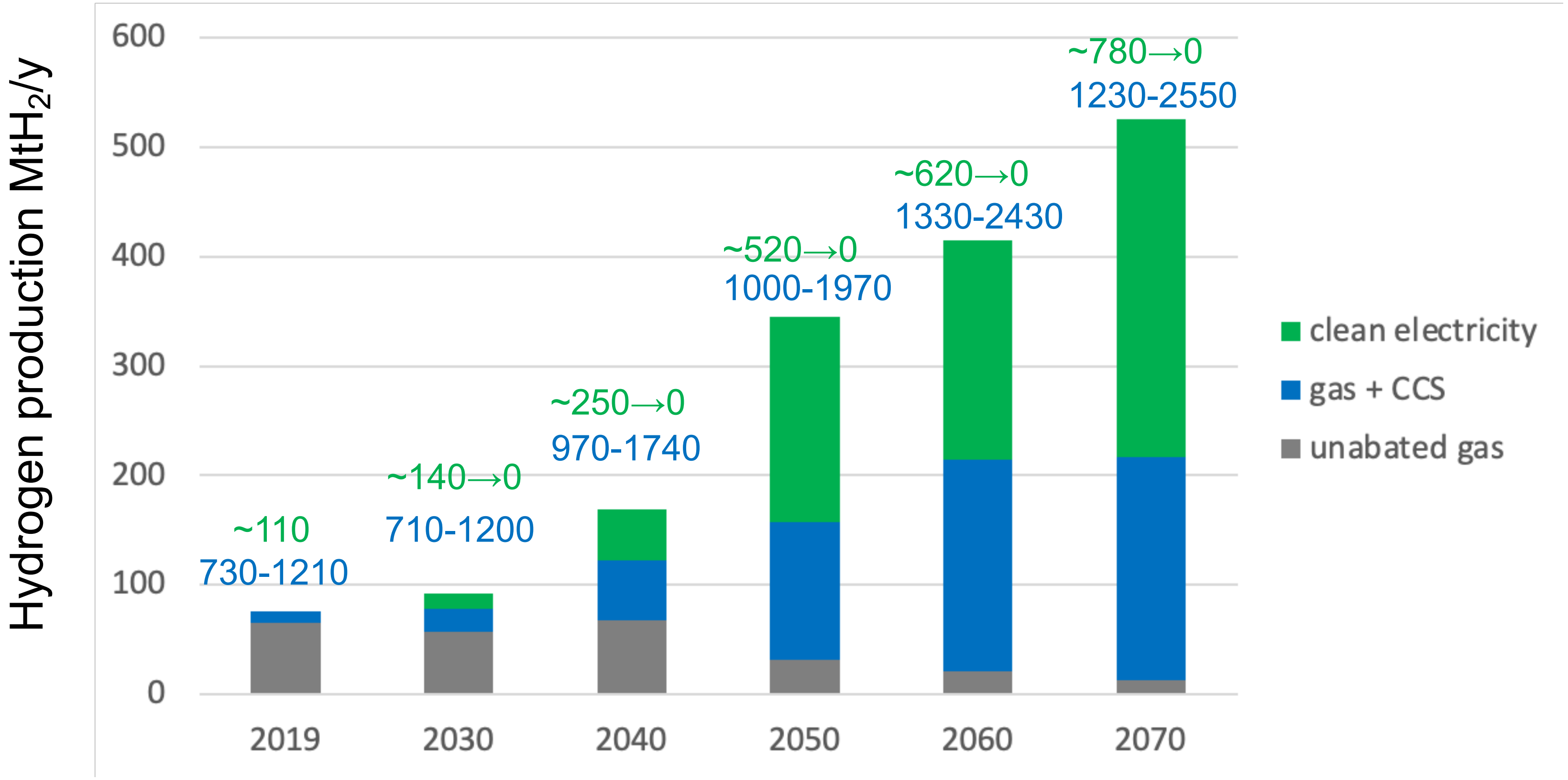
- The project is located at a Phillips oil refinery. The plan is to create a steam reforming plant with 0.173Mt/y production capacity and modify a gas turbine power station to use hydrogen. The CO2 will be piped 120 km to a depleted gas field.

HyNeT North West

- Similar to the Humber Zero project but based in Liverpool bay area and includes the use of auto-thermal reforming rather than steam reforming. The initial plan is to build two units each producing 0.3Mt/y.

CO_2 equivalent emissions from hydrogen production International Energy Agency projections (without nuclear)

Global hydrogen production in IEA Sustainable Development Scenario



Adapted from IEA "[Energy Technology Perspectives 2020]"
Special Report on CCUS Technologies
CO@ equiv. emissions data from
Parkinson, B., et al, [Energy & Environmental Science, 2019, 12, 19]

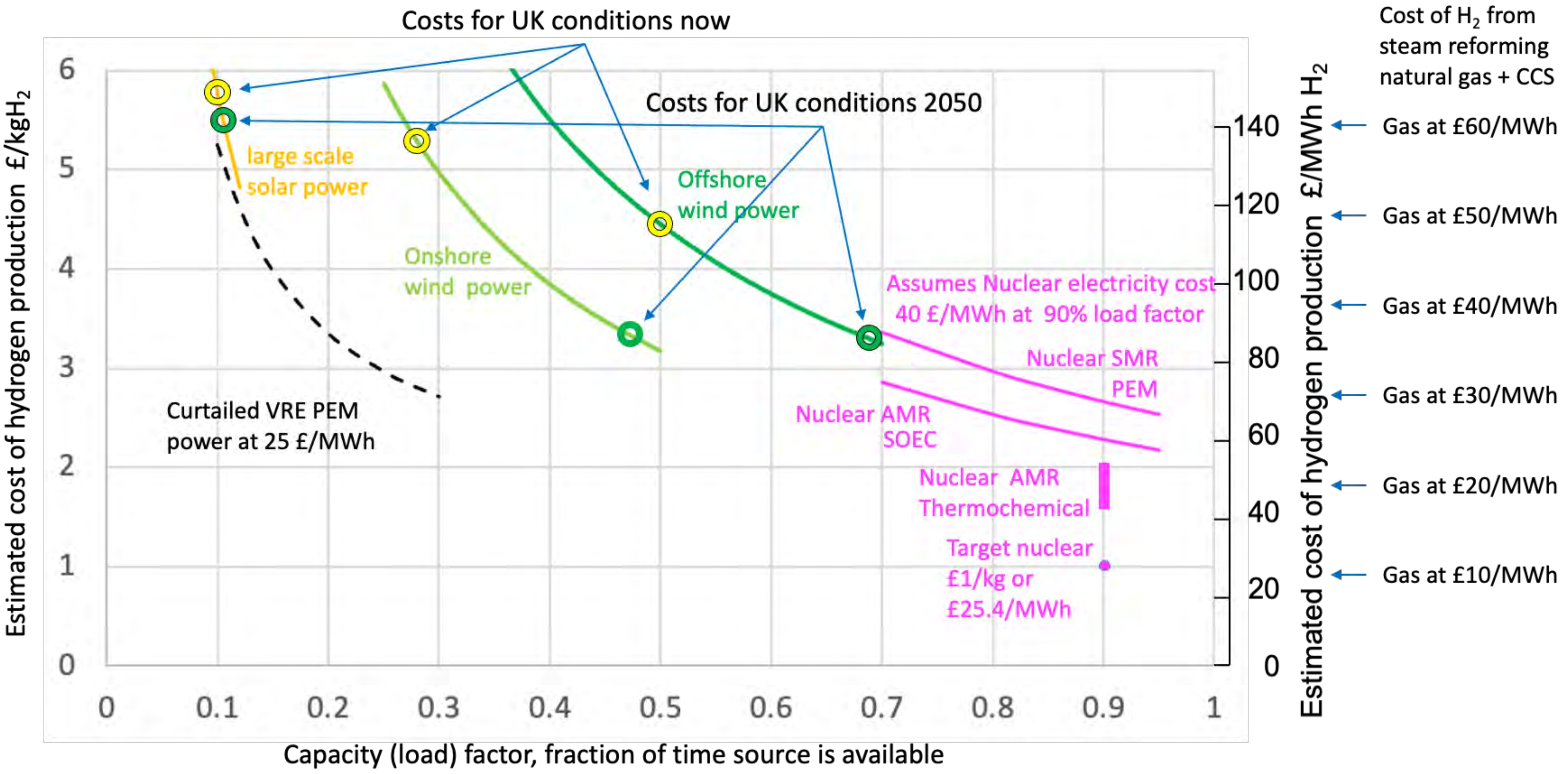
Looks OK?
Nearly 2000 tCO_2/y
Captured by 2070

But if we calculate the remaining CO_2 emissions ($MtCO_2e/y$) on a life cycle basis it is not so good.
Blue figures, the range reflects CH_4 emissions

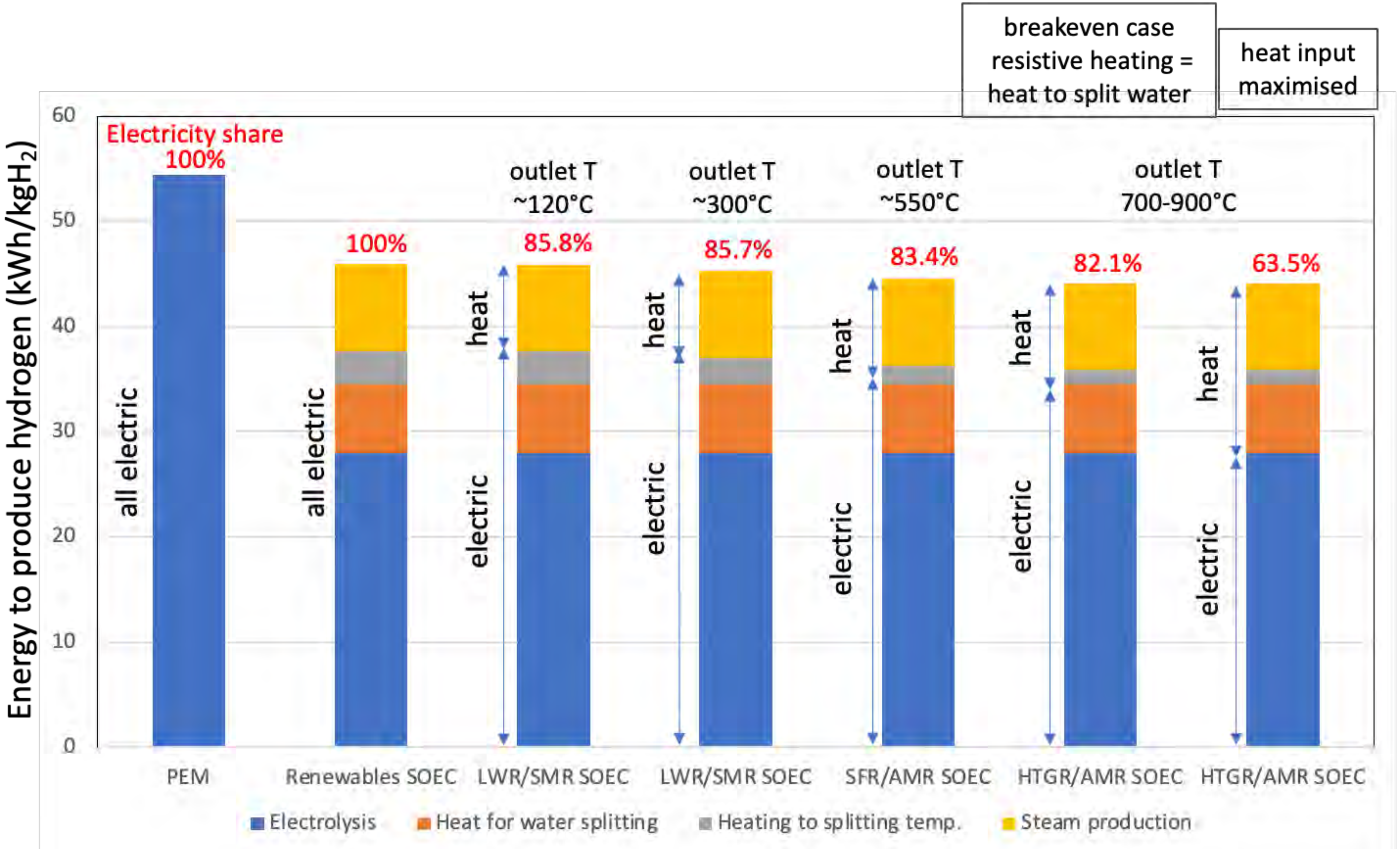
Green figures are if we just use wind or nuclear hydrogen

The green figures will reduce to zero as the world decarbonises, but the emissions from gas combustion remain.

Effect of load factor on hydrogen production



Comparison of PEM and SOEC with use of nuclear heat



Current UK programmes on nuclear hydrogen

Sizewell C Cogeneration Project

- Twin EPR station 3200 MWe capacity for EDF in final stages before construction.
- The project aims to develop and demonstrate hydrogen production using steam from the reactor and lower quality heat for DAC. The intention is to eventually use the hydrogen and CO_2 to produce aviation fuel.
- The nuclear cogeneration project started in 2020 and trails of technologies are being done.

Bay Area Hydrogen Hub Project at Heysham 2

- A twin AGR station 1250 MWe capacity for EDF, active but due to close by 2030.
- Cogeneration focussed on use of higher quality heat and electricity to produce hydrogen using SOECs. Steam is bled from the reactor low pressure turbines A demonstration is being completed and should be achieved by 2025
- Bay Hydrogen Hub – Hydrogen-4-Hanson, DESNZ Industrial Hydrogen Accelerator Programme report, March 2023

SOEC = Solid Oxide Electrolyzer Cell

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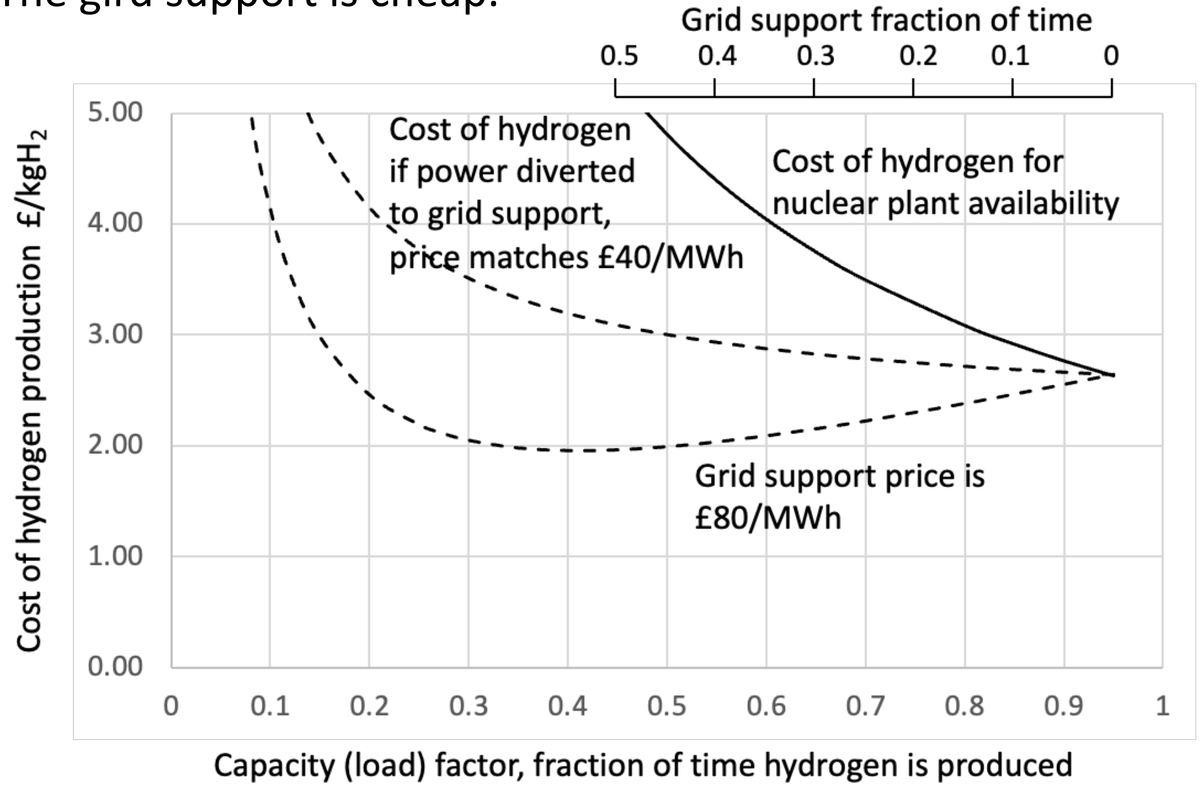
THE SOLUTION – NUCLEAR COGENERATION

The solution – nuclear power with cogeneration

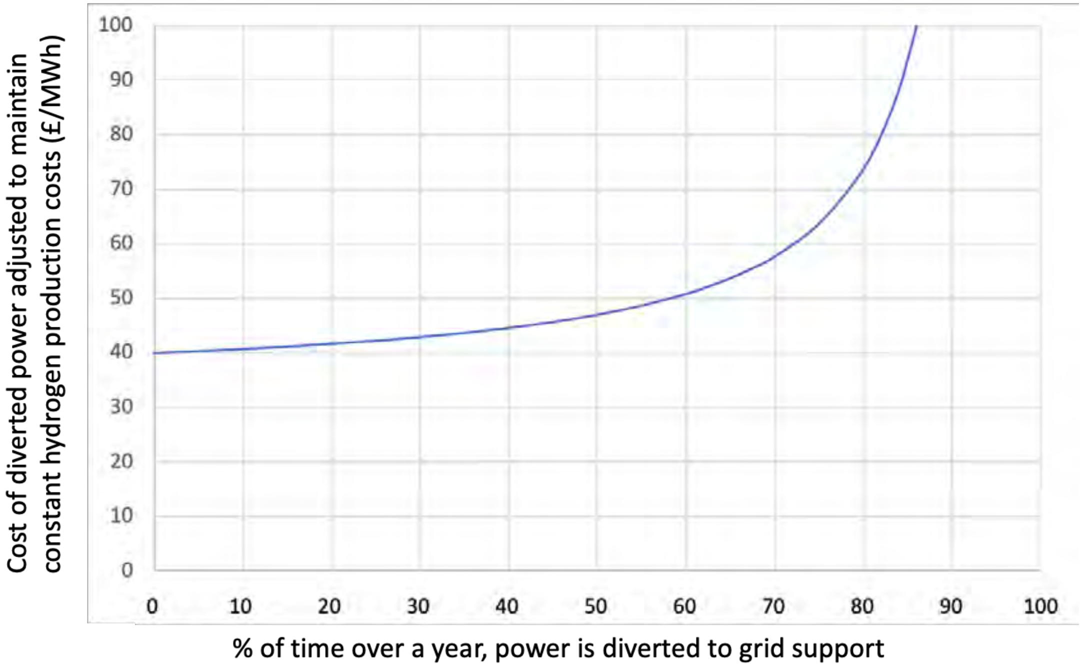
- A large capacity of flexible electricity generation is needed, but it turns out that the total amount of generation is not so large, and flexibility is more important.
- There are four elements:
  - A substantial amount of nuclear heat and electricity for other applications. In this example for simplicity, just hydrogen production is chosen, in reality a range of applications requiring different qualities of heat as well of electricity is ideal – air capture of CO2, production of synfuels, syngas, ammonia as well as hydrogen, pyrolysis of waste and biomass, etc.
  - For AMRs (Advanced Modular Reactors), reactors with higher outlet temperatures, use of molten salts for thermal energy storage can allow even more flexibility on on both when electricity and heat are used, But not only that, separating electricity generation from the reactor and the storage, allows a larger generating capacity to be provided.
  - The large use of heat and power, also allows curtailed variable renewable electricity to be used as part of the complex of application.
  - The production of clean hydrogen will allow rapid reaction and long endurance electricity generation to replace fossil fuels

The basis for low cost of grid support from cogeneration

- Usually with nuclear cogeneration you think of producing electricity for the grid and then some additional applications like hydrogen production. To understand how cogeneration works to allow low-cost grid support this has to be reversed.
- The application like hydrogen is the main activity, what we are doing is stealing some power to support the grid. Provided the grid support is the minor activity and the application has the largest share of the heat and power from the reactor. The gird support is cheap.



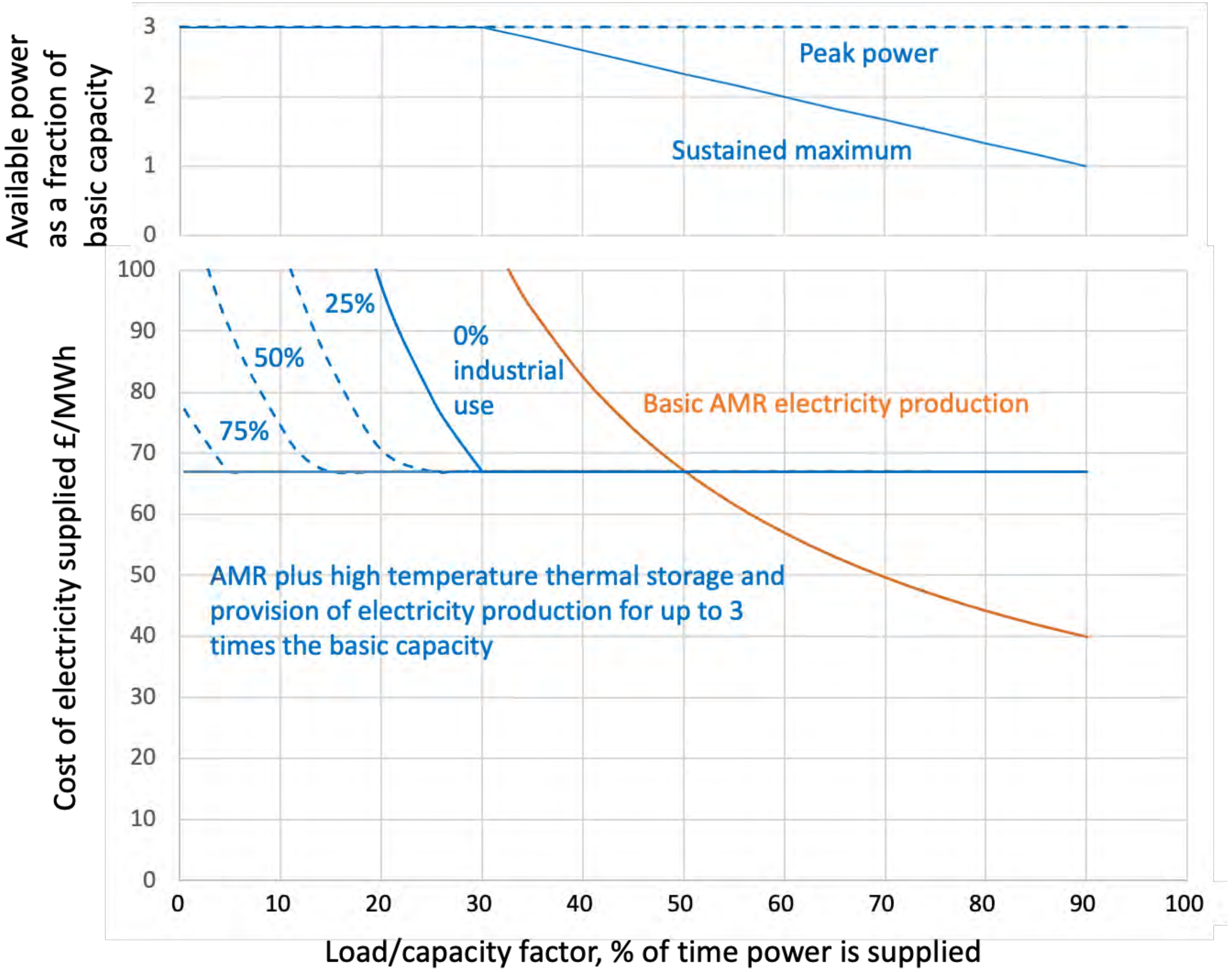
The point of view from the application, eg hydrogen production



The point of view from grid support

Thermal storage and higher generation capacity

- The idea is simple and used in solar thermal plants in sunnier countries.
- Use of molten salt and two large insulated thermal stores – one hot and one cooler. Generation is separated from the the heat source.
- In this idea for high temperature AMRs such as HTGRs, will have a power generation system say 3 times larger than the generator for the reactor directly connected, ie a 300MWe system with the thermal storage can produce 900MWe. How long it can do this for depends on the size of the thermal store.
- This has costs which raise the cost of the power, but if the system is built on a site that can use both heat and power for industrial applications the very high-capacity support can be used for short periods at the basic cost of the system, in this example ~£68/MWh compared to £40/MWh – the price of flexibility. This flexibility also allows use of curtailed variable renewable electricity.

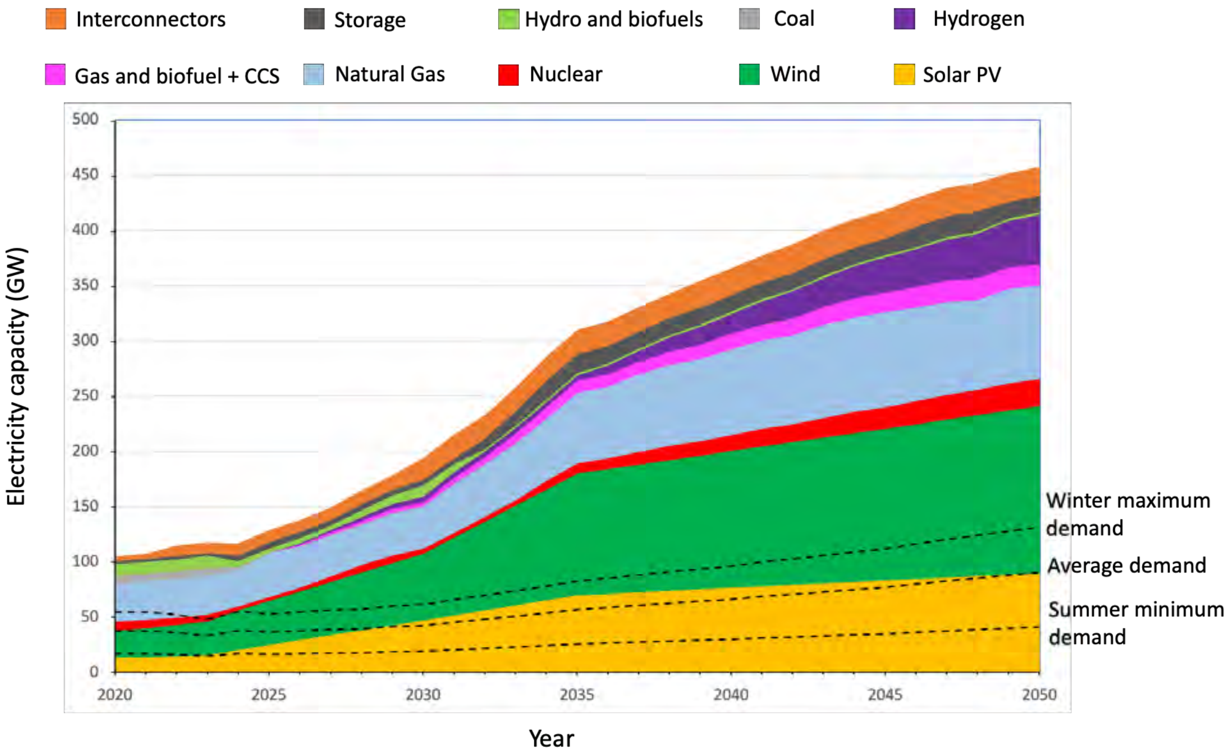


UK Government high electrification scenario

- The Department of Energy Security and Net Zero (DESNZ) issued a high electrification scenario which aims to use a higher share of low carbon electric power to support the move to an economy that would achieve an overall net zero with electrification of transport, domestic heating and many parts of industry.
- This scenario relies on very high capacities of solar and wind power (up to 90 and 150 GW), with a base load nuclear capacity of 25 GW of nuclear power. However, the constraints of the high wind generation results in the nuclear load factor dropping to ~80% with an associated increase in levelised costs.
- An important consequence of this scenario is the continued use of unmitigated gas generation, with a very high capacity (up to 85GW), but with very low load factors. Low load factors are also implied for hydrogen power and BECCS (Bioenergy + CCS). BECCS is very valuable as it provides the only negative contribution to CO_2 emissions in the scenario.
- The low load factors and construction of large underused plant means that the electricity costs and the CO2 emissions on a life cycle basis are high, despite the large fractions of relatively cheap and clean renewables.

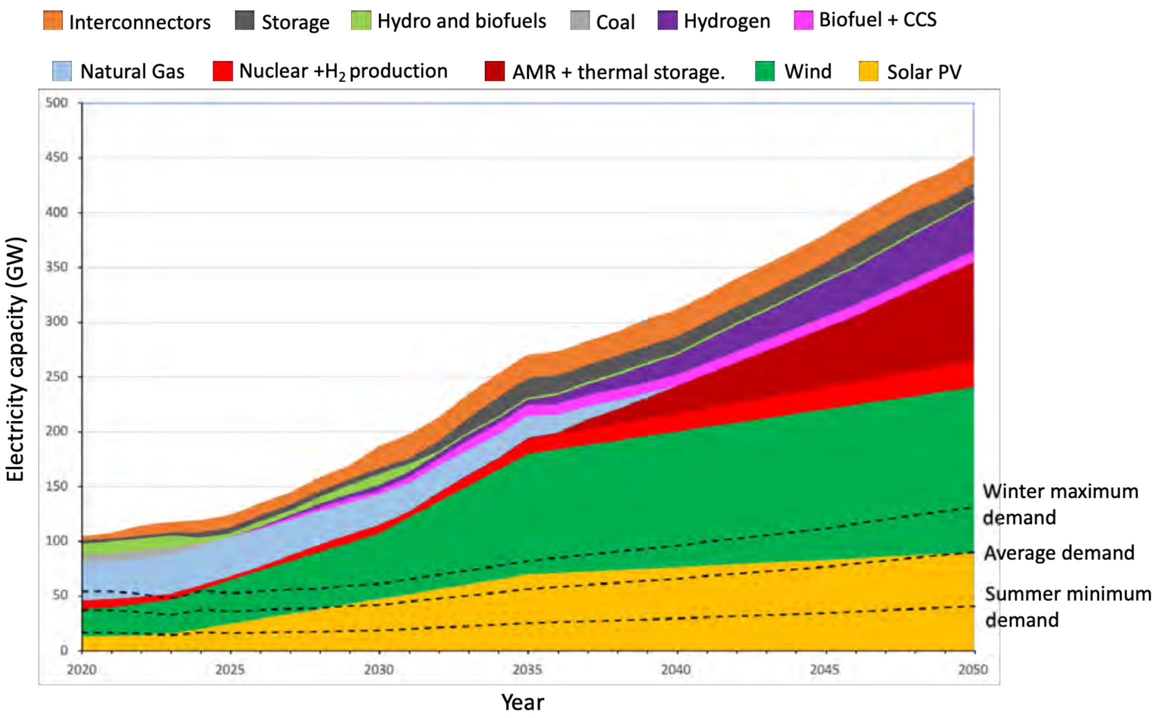
Comparison of high electrification scenarios - capacity

Original scenario using natural gas



Note the very large capacity from unmitigated gas and continued growth in gas capacity.

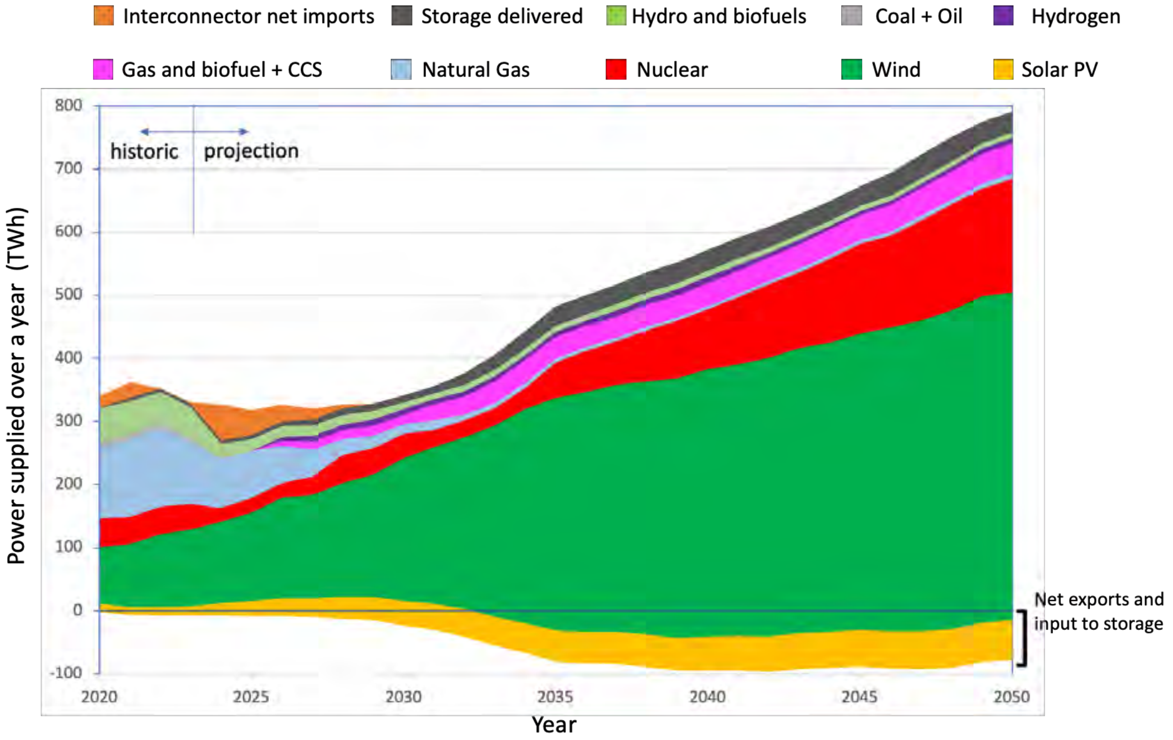
Alternative scenario using nuclear cogeneration



Note the larger capacity from nuclear and from the use of AMRs with thermal storage, where the capacity is boosted by the use of larger generators made possible by the storage.

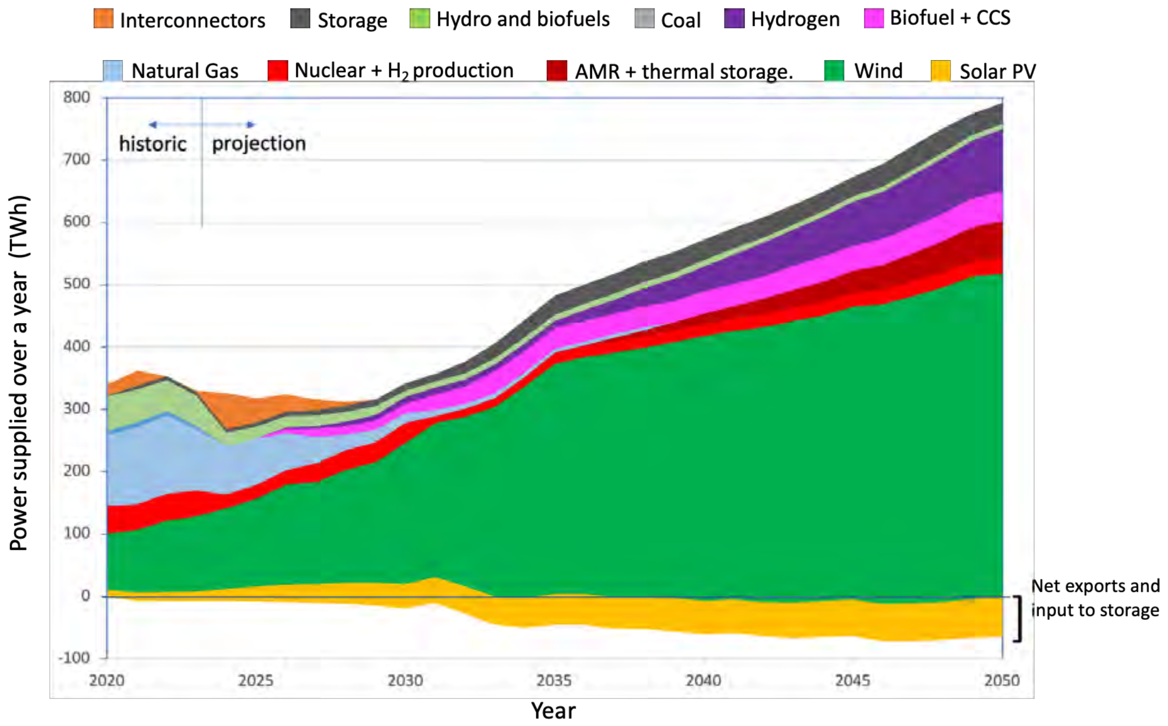
Comparison of high electrification scenarios – generation

Original scenario using natural gas



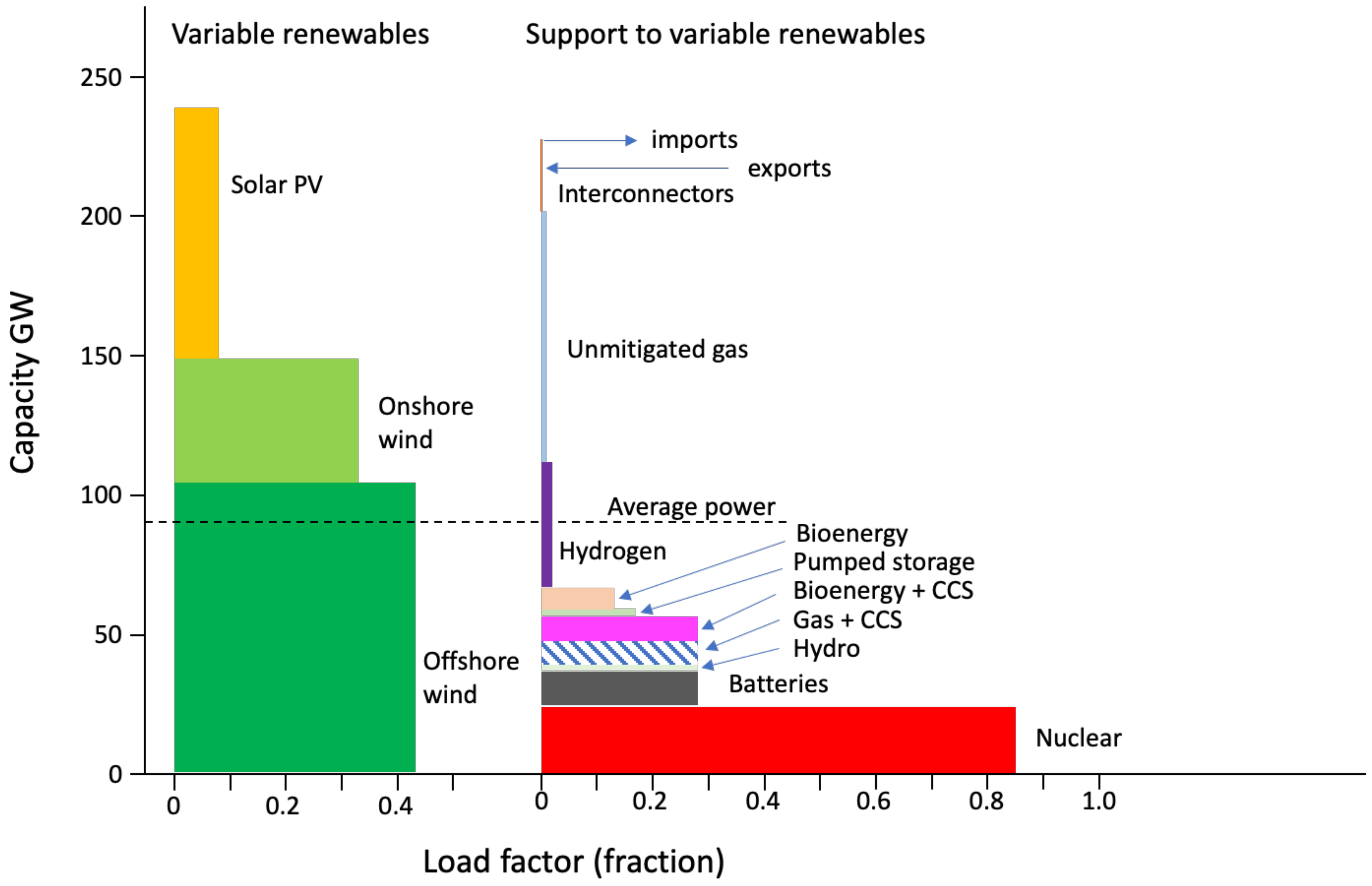
Note the very low generation from unmitigated gas this implies a load factor of 1.2% in 2050.
Note also the large generation from nuclear but this is not necessarily good thing.

Alternative scenario using nuclear cogeneration

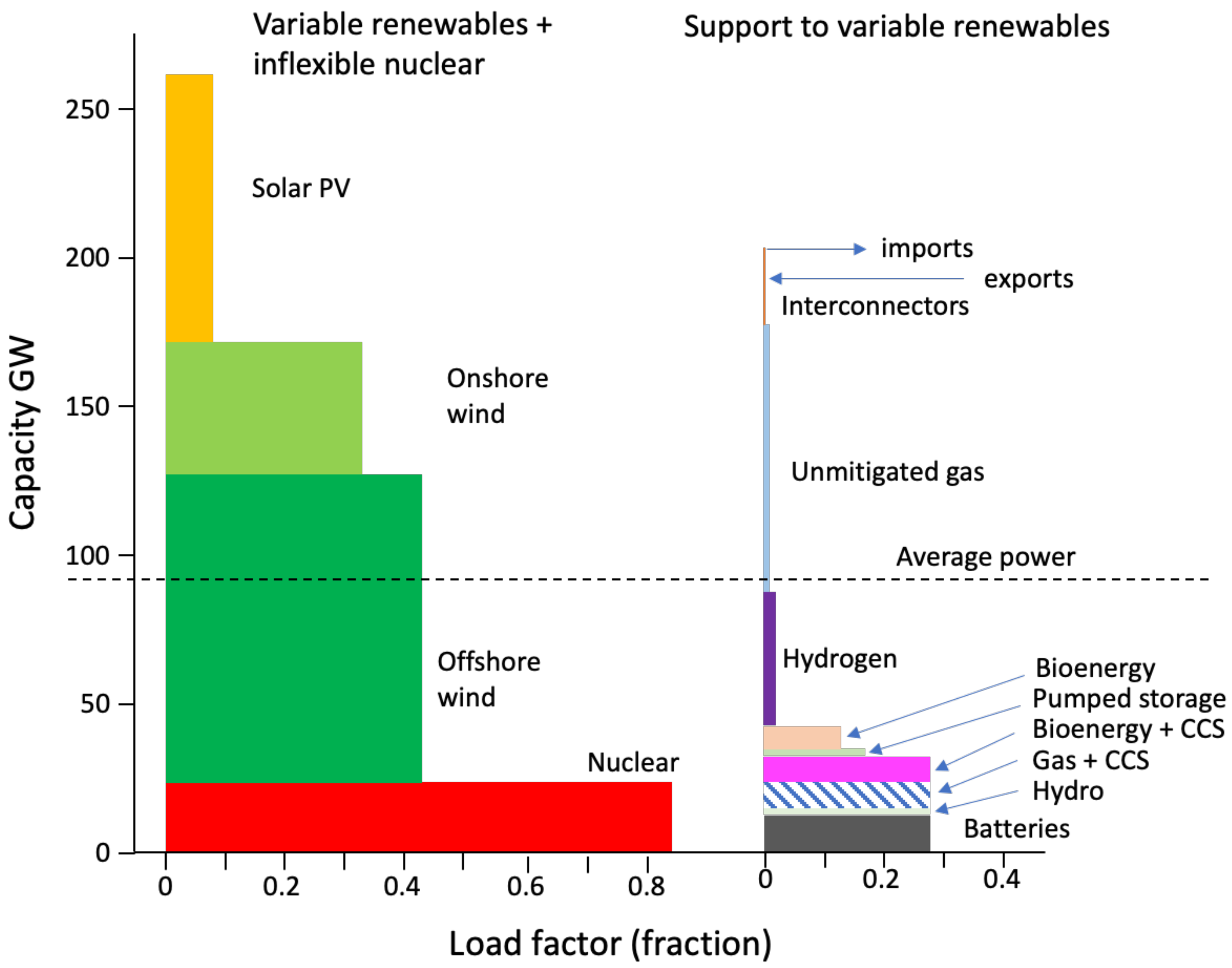


Note that that use of natural gas stops by 2040 and there is no generation from gas + CCS
Note also that generation form nuclear is supported by a larger contribution from nuclear hydrogen

The DESNZ high electrification scenario uses a large capacity of unmitigated gas at a very low load factor

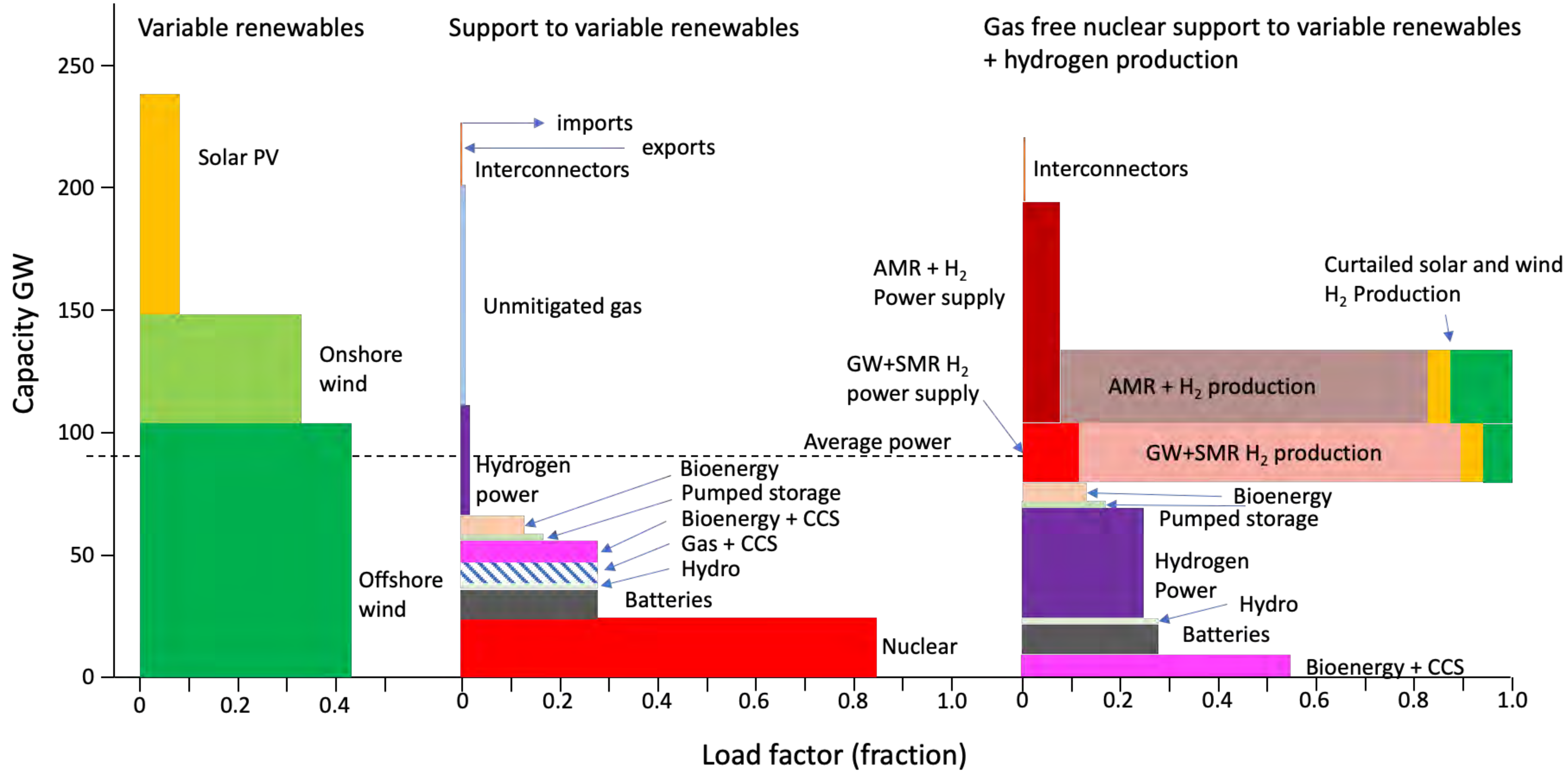


Adding nuclear capacity as base load, does not help the integration of VREs



Higher VRE curtailment or loss of nuclear efficiency.

Adding nuclear capacity as part of cogeneration and thermal energy storage enables the support of VRE without natural gas at lower costs and CO_2 eq. emissions



Comparison of costs and emissions in 2050
DESNZ high electrification scenario and nuclear modification

	Continued use of natural Gas	Nuclear with cogeneration and thermal storage
Cost of delivering ~840TWh of power to the grid £ billion	92	77
Averaged levelised cost of power £/MWh	105	90
Estimated emissions on a life cycle basis MtCO_2eq/y	49 (-18.5 from BECCS)	-22 (-43 from BECCS)
Nuclear electricity for cogeneration Nuclear heat for cogeneration TWh	~20 ~60	~400 ~1000
Nuclear waste heat some of which could be used TWh	~500-700	~1250
Amount of nuclear hydrogen that could be generated Mt/y	~15	~300 (~6Mt/y used for generation)
Emissions from hydrogen production tCO_2/tH_2	~<1 from nuclear ~ 6 from steam reforming + CCS	~<1

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