

Practically Carbon Free

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Anthropogenic climate change is a present reality [1]. Any proposed solution must be politically tenable. If we insist that people give up items they have used for decades, there will be no public will for change. If we insist that growth in developed countries slows, there will be no political will for change. If we insist that other nations do not industrialise, there will be no global will for change.

To have a 3 in 4 chance of avoiding 2°C of warming, we must cut CO₂ emissions to 0.48 tonnes per person-year by 2050 [1]. The current global mean is 4.4 tonnes per person-year; the UK and US emit 8.3 and 17.7 tonnes per person-year respectively [2]. Indispensable processes currently emit too much CO₂. Steel, cement and fertiliser production emit 0.58 tonnes per person-year [3]. Human caused deforestation and forest fires emit 0.85 tonnes per person-year [3]. Ignoring fertilisers, agriculture emits 0.84 tonnes per person-year [3]. We must optimise every aspect of energy use for minimal emissions.

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To produce our energy needs whilst emitting less CO₂, we need to understand how energy is used and moved. We use 3 main types of energy: local heating, transport, and electricity. Heat can normally be produced from electricity or fuels. In some industrial use, hydrocarbons are required for speed of heating or chemical properties.

For transport, we could use electric vehicles, storing energy in batteries. Unfortunately, global lithium reserves are small. US trucks alone would consume 170% of global Lithium production. Global battery powered transport requires that the world give up private vehicles. Even given enough lithium, it takes around 15 years to replace all vehicles. It is not clear that we have this much time. We could use Hydrogen as fuel, but this requires vehicle replacement and either high pressure or cryogenic storage. Storage is dangerous in private vehicles, and rules out aviation. It is not clear that we can rely on the body politic to give them up.

More reasonable alternatives are methanol and dimethylether. These replace diesel and petrol, both chemically and in ease of storage. Fisher-Tropsch synthesis allows these fuels and methane to be produced from CO₂, hydrogen and heat. Amine gas scrubbing allows CO₂ to be removed from the atmosphere given waste heat. Hydrogen is currently produced from natural gas. The main alternatives are electrolysis and the Sulphur-Iodine process. Electricity is very low entropy, and so thermodynamics constrains electrical generation to around 40% efficiency. Electrolysis is worse overall. The Sulphur-Iodine process is closer to 65% efficient overall

[4]. Ultimately, solar thermal or nuclear power would be needed to actually produce heat. This would allow us to use hydrocarbons to store and transport energy, and use existing infrastructure at point of use.

Electricity is produced as required, so we need clean means of producing heat and electricity. Disregarding existing fossil fuelled plants, we have renewables, carbon capture and storage plants, and nuclear power. The UK has an abundance of renewable resources, but consumes an abundance of energy. MacKay [5] gives a numerate summary; disregarding any public dissent and devoting a majority of the UK's surface and seas to wind, photovoltaics, solar thermal, wave, tide and biocrops would not produce enough energy. Most of these renewables work less well at a global scale, as the UK has exceptional sites for many renewables.

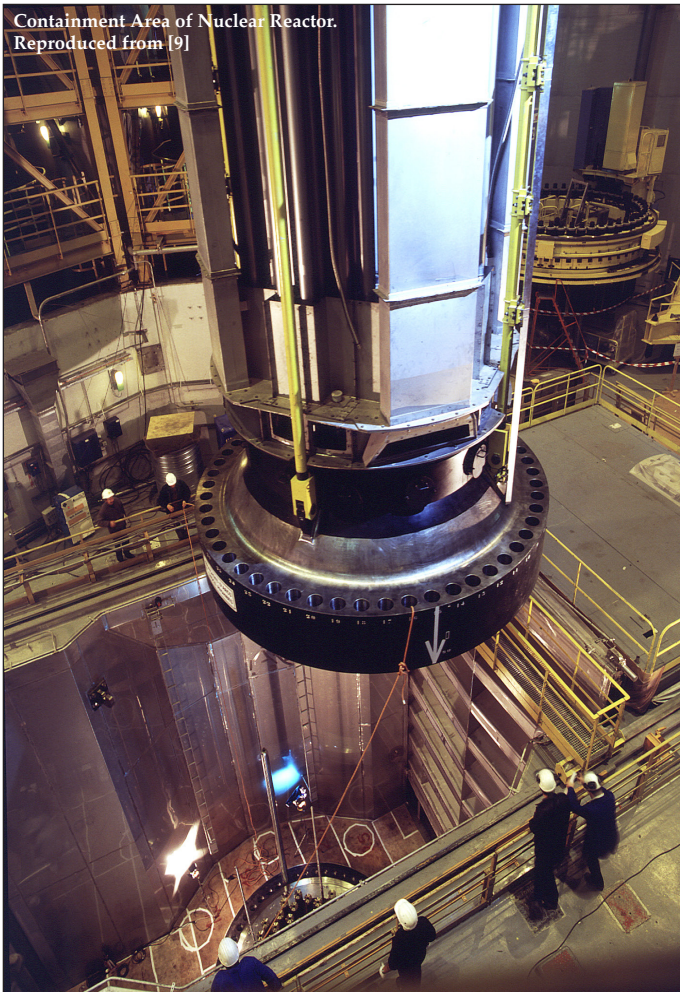
Another problem is the stability of electrical supply. Wind has the best statistical data, as it has the largest scale. In 2004 wind generated between 0.2% and 38% of German electricity on a day to day basis [7]. On their 7GW network, 8 hour predictions and actual supply differed by much as 6GW [7]. In the 2006 California heatwave, wind generation dropped to 4% of capacity for 10 days [6]. Electrical grids must balance supply and demand to avoid blackouts or melting their cables. Germany manages by importing and exporting from the French nuclear grid. At a national scale, renewables are unreliable. Generation capable of backing up all renewables at short notice is required.

Some propose carbon capture and storage. In practice, CCS has net emissions of 10-15% of normal fossil fuels, which is too high. CCS is more expensive than nuclear and has greater emissions. There is also the issue of finding stable geological stores. The emissions have far greater volume than the fuels burnt, and finding suitable large stable structures that are gas-tight is difficult.

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The remaining source is nuclear. Reactors can produce electricity and heat for hydrogen production. We want a reactor that has sound engineering, scales globally and is politically tenable. For this, society demands better waste properties, better safety and no risk of proliferation.

Coolant choice, canonically water, is a fundamental design driver. Unpressurised water boils too readily; interactions between pressure, temperature and boiling are the constraint leading to reactors that are sensitive to human error or natural disaster. High temperature steam is highly reactive, and so water cooled plants are limited to around 650°C. One known alternative is a mixture of unreactive metal fluorides. These are liquid between 400°C and 1400°C, and so high



Containment Area of Nuclear Reactor.
Reproduced from [9]

temperature reactors can be unpressurised. If spilt, the salts solidify and so are easily contained. High temperature also makes hydrogen production efficient.

Fuel choice has proliferation and waste implications. At present, enriched ^{235}U or the ^{238}U - ^{239}Pu Plutonium cycle are commonly used; both cause proliferation concerns. However, Indian reactors use the more common ^{232}Th , first turning it into ^{233}U . ^{232}U impurities are easy to detect and prevent weapons using ^{233}U without enrichment. Natural Thorium is pure ^{232}Th , so no enrichment or reprocessing is legitimate. The conversion process consumes neutrons, reducing the number leaving the core by a factor of 5-10. The neutrons used are low energy and thus less penetrating. As a result, decommissioning and maintenance are far easier. Long lived waste can be formed by repeat neutron absorption without fission. With ^{233}U as fuel, any nucleus gets 3 chances to fission before becoming waste. Other fuel's cycles give fewer chances, and so the ^{232}Th - ^{233}U cycle produces less long term waste.

Put together, we get the Liquid Fluoride Thorium Reactor (LFTR), a proposed Generation IV reactor. The fuel is dissolved in molten fluoride salt, and so gravity can move

the fuel to specialised storage tanks if anything appears wrong. The reactor is passively safe; as the reactor heats up, thermal expansion in the salt reduces the amount of fuel in the reactor, reducing heat output. Furthermore, it is easy to remove fission products [8], which in turn reduces the formation of long lived waste. As a result, the "high-level" waste from an LFTR is less active than natural rocks after 300 years.

LFTRs are safer, have better waste and are harder to abuse. LFTRs passively shut down before reaching excessive temperatures. There is no potential for physical explosions in the reactor. If there is a leak, the material freezes and is contained. The smaller quantity of waste is less active. There is no excuse for enrichment or reprocessing, preventing proliferation. Thorium itself is plentiful; LFTRs produce 10 times more energy from the thorium in coal than is obtained by burning the coal [8]. Thorium can be economically extracted from granite [8]. Experimental LFTRs have been in operation since the 1960s, developed initially for aircraft where plutonium production was not desirable.

“ Experimental LFTRs have been in operation since the 1960s. They are safe and can be exported ”

A wider plan can now be formulated. LFTRs are safe and can be exported. They use common fuel, securing energy supply. They can drive the Sulphur-Iodine process, Amine CO_2 extraction and Fisher-Tropsch synthesis. They can produce electricity. Hence we can achieve negligible net emissions without replacing our existing infrastructure. Producing hydrogen and electricity together also allows the electrical generation to be changed rapidly by balancing it out with hydrogen production. Hence the electrical grid can be made more responsive, and so traditional renewables can be used.

There are ways of reducing global emissions as required. The scope and politics of this problem are not well appreciated by the public. The canonical "environmental" line is renewables without CCS or nuclear. This fails to produce enough energy or be politically tenable. Politicians have made token local changes, but UK emissions must fall by about 90%, and we must find a global solution. Politicians and environmental advocates need to engage in numerate public discussion. One approach has been outlined above. It might not be ideal, but we must implement something soon. Reality will not wait. ■

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