# A Plan with a time-line

Draft 3.4, May 12, 2010

Additional material to supplement the book:

**David J. C. MacKay.** *Sustainable Energy – Without the Hot Air*. UIT Cambridge, 2008. ISBN 9780954452933. Available free online from www.withouthotair.com.

# 1 *A plan with a time-line*

This plan starts in 2010 and aims to fully decarbonize Britain by 2050, and to keep the lights on along the way. (I say 'fully decarbonize' – to be precise, there may be some industries that are impossible to decarbonize, for example, agriculture, steel, concrete, aviation, and international shipping; so what I really mean is that *everything else* is fully decarbonized.)

This plan is called 'Plan C' – 'C' for 'consensus', and 'C' for 'constructive conversation'. Plan C is a suggested starting point for a single consensus plan.

Just like the six plans (D, L, N, G, E, M) presented in the book, plan C has several components that may seem ridiculous or infeasible in today's political climate. But the rules of the game are that one may criticise plan C only by proposing a replacement plan that adds up and that will have a better chance of achieving consensus.

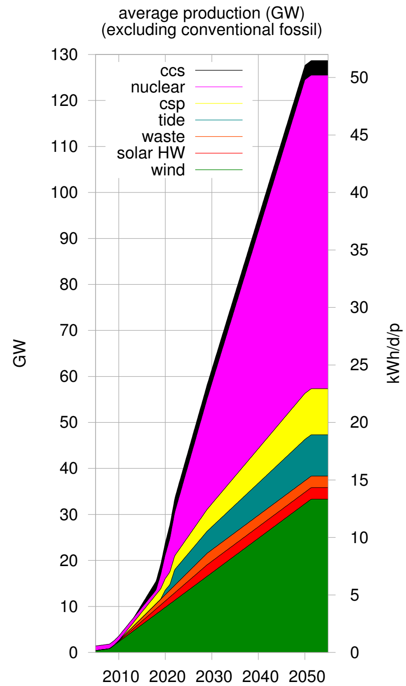



Figure 1.1. Where plan C gets its zero-carbon power from, on average. Hydroelectricity and photovoltaics are not shown because they are too small.

## Executive summary

> **We build almost *every* zero-carbon technology we possibly can, as fast as we possibly can, starting right away.**
>
> **The plan reduces energy consumption by between 30% and 50% (depending how the accounting is done) by adopting super-efficient technology for the two biggest consumers – transport and heating.**

## Overview

I'll describe everything in GW. (1 GW ↔ 0.4 kWh/d per person in the UK.) It's important to distinguish average power production and peak power production. I'll measure both in GW. "1 GWp" means 1 GW of peak power or capacity. For example, speaking of John Hutton's wind aspiration, we might say "33 GWp of wind power would deliver 10 GW on average."

For simplicity I will describe steady linear growth of all technologies. In reality of course most technologies will more naturally grow along an S-curve of some sort.

Britain's primary energy consumption today is about 300 GW, most of it fossil fuel. Roughly one third of energy consumption relates to transport and one third to heating. Plan C steadily reduces the energy demand of transport and heating by electrifying them and at the same time making them more efficient. By 2050, energy consumption for transport (excluding planes and shipping), heating (excluding industrial heating), and electricity is reduced to about 125 GW; almost all energy for heating and transport is supplied by electricity. This plan supplies this energy consumption by growing a diverse spread of technologies; most technologies are grown at the maximum rate I think is plausibly achievable. Renewables (domestic and imported) are increased roughly 20-fold, and nuclear power is increased 7-fold over 2008 levels. The electricity comes from the following sources. (The numbers given here are *average* outputs, not capacities.) Wind: 30 GW; tide: 8 GW; waste-to-energy: 2.5 GW; "clean coal" and biomass co-firing: 3.2 GW; nuclear: 70 GW; concentrating solar power in deserts: 10 GW. (That's a total of about 125 GW of electricity.) Solar panels will provide 2.5 GW of hot water and heat pumps (should we want to count them as an energy source) will pump on average about 40 GW of low-grade heat into buildings.

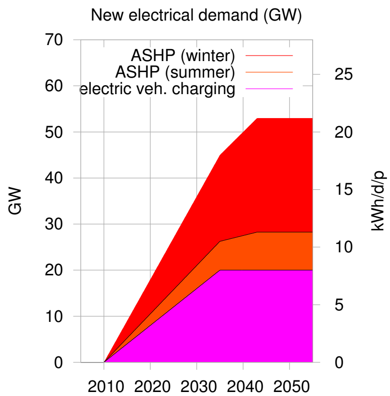



Figure 1.2. Plan C's new electrical demand from electrification of transport and of heating. The transport demand is largely easily-switch-off-and-on-able. Some of the heating demand could also be easily-switch-off-and-on-able too, using hot water tanks and other heat stores.

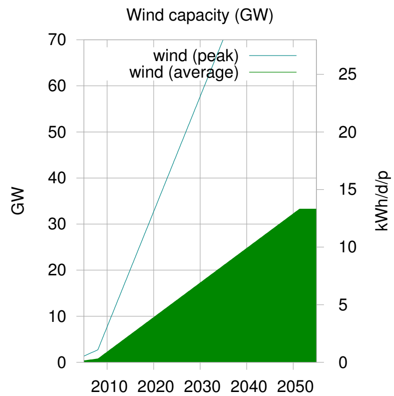



Figure 1.3. Plan C's wind capacity and average wind production. Capacity rises to 33 GW in 2020 and about 100 GW in 2050.

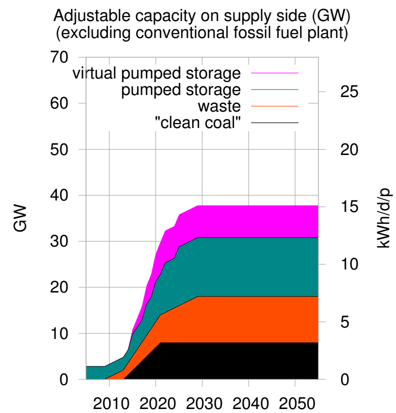



Figure 1.4. Plan C's adjustable capacity on the supply side. The new "clean coal" would especially play a role in compensating for summer/winter demand variations; the waste incinerators and pumped storage systems would compensate for daily demand variations; and the pumped storage systems would compensate for the wind variations, along with the adjustable demand of electric vehicles (figure 1.2).

## Some details

1. **Efficiency measures.** Obviously, we take all the low-hanging fruit. We provide mandatory free building insulation for all old buildings. We install smart meters that engage and inform building users. We switch all building lighting to LEDs, or equally efficient alternatives, by 2050. We promote car clubs, public transport, cycling, and walk-

ing. We promote "reduce, reuse, recycle" everywhere they make sense.

2. **Electric vehicles** will steadily replace fossil-fuel vehicles. 1.5 M new electric vehicles per year, each drawing an average power of 8 kWh/d, will create an additional electricity demand of 0.5 GW each year; vehicle-charging is a demand that is easily switch-off-and-onable. (These vehicles might initially be plug-in hybrids[1] then in due course all-electric vehicles; the replacement rate, 1.5 M per year, is roughly today's replacement rate of fossil cars.) All train lines will also be electrified over a period of 20 years. There will be an increase in rail freight. After 25 years the added electrical demand for electrified transport will amount to about 20 GW on average. One way of helping the growth of electric vehicles in cities will be to install power outlets for vehicle-charging in all lampposts that are near to parking places. Europe should agree on a standard for exchangeable batteries so that some high-use vehicles can refuel by battery exchange.

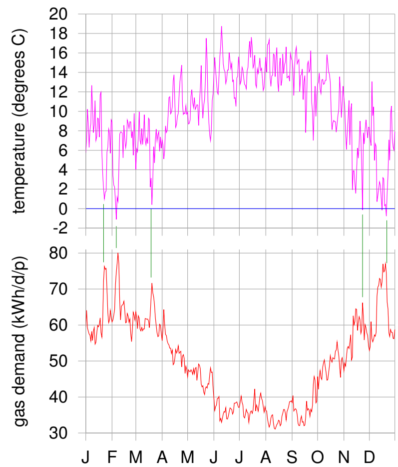



Figure 1.5. Gas demand (lower graph) and temperature (upper graph) in Britain during 2007. (1 kWh/d/p is equivalent to 2.5 GW. The vertical scale runs from 75 GW to 200 GW.)

3. **Air-source heat pumps** (high efficiency ones like the EcoCute from Japan, with average seasonal coefficient of performance better than 3.0) are installed in place of gas boilers and condensing gas boilers, which are phased out. These air-source heat pumps will eventually supply most building heating and water heating. The build rate will be 1 M units per year for a duration of 33 years. (This is roughly the rate at which fossil heating systems are currently being replaced.) Each unit will consume an average power of 1 kW in winter and 0.25 kW in summer. The additional new electricity demand thus created each year is 1 GW in winter and 0.25 GW in summer. After 33 years, the added electrical demand will be 33 GW in winter and 8 GW in summer. For some buildings, ground-source heat pumps may also be viable, but such buildings will be a minority – air-source heat pumps are easier to retrofit to existing high-density buildings in suburbs. Where forests can be grown close to buildings, there will be some use of wood for heating also, but for the majority of buildings wood won't be available.

4. **Solar hot water panels** will be installed on buildings at a steady rate such that by 2050 2.5 GW of average power is delivered in the form of hot water. (More in summer, less in winter.) This plan assumes 16 million units, each 3 $m^2$ in area, are installed.

5. **Wood** If we cover 15% of UK land with sustainable forests and willow and miscanthus plantations, 7.5 GW of heat can be supplied. (Today,

[1]By "plug-in hybrid" I mean a vehicle like the GM/Vauxhall Volt that runs entirely on electric power for short or medium-length trips, but has a small hydrocarbon-burning engine to give it extended range.

Britain's consumption of heat is roughly 100 GW on average.) These plantations could be up and running within two decades.

6. **Tide.** The Severn barrage is built and completed by 2022 (2 GW average output). Tidal lagoons are built in The Wash and off Blackpool, providing 1 GW of average output and some pumped storage capability, by 2020. A large investment (£20 bn of research and development) in tidal stream farms is made, with the goal of providing, by 2050, an average output of 5 GW. Assuming a lag of 10 years for development, most of this would be installed between 2020 and 2050.

Figure 1.6. Seagen (Strangford Lough), the only grid-connected tidal stream device in the UK. Capacity: 1.2 MW. Photo by Dr. I.J. Stevenson.

7. **Waste-to-energy (municipal and agricultural).** The target would be to produce an average power of 2.5 GW from waste-to-energy plants. The capacity would be increased steadily at a rate of 0.5 GWp per year to 10 GWp, so these power stations would run at a load factor of 25%. The purpose of this low load factor would be to make a substantial contribution to daily load-balancing on the grid. This plan requires *all* municipal waste that is not recycled to be incinerated or pyrolysed, and an equal amount of agricultural waste too.

8. **Wave power**. 0.75 GW could be produced from wave farms in the Atlantic, facing West, 130 km long. Whether this investment would be economic is not clear.

9. **Solar photovoltaic panels**. In 2006, PV produced 0.00075 GW, on average, in the UK. So if we assume that solar photovoltaic panels are increased one-thousand-fold, they would deliver 0.75 GW. Whether this investment would be economic is not clear. It is to be hoped that the cost of PV will come down. One potential benefit of decentralized power generation is the engagement and energy awareness it causes.

10. **Wind farms** are built at a rate of 2.5 GWp per year, stopping once 100 GWp is reached. (British wind farm capacity was about 2.7 GWp in 2008.) 100 GWp will produce 30 GW on average. This amount of wind would be roughly a 35-fold increase over 2009 levels. The land area occupied by wind farms would be roughly 5% of the country, or roughly half the area of Wales. The wind farms can be located onshore or offshore. Offshore wind farms would be significantly more expensive. Building wind farms offshore will require investment in jack-up barges: perhaps ten barges, costing £60 M each.

Figure 1.7. Red Tile wind farm, East Anglia.

11. **Pumped storage.** Alongside the growing wind farms, five new pumped storage facilities would be created – perhaps one in Wales (new build) and four in Scotland (by conversion of existing hydro facilities). Each would be similar in scale to Dinorwig with a peak output of 2 GW, and preferably storing a little more energy than Dinorwig, say 40 GWh

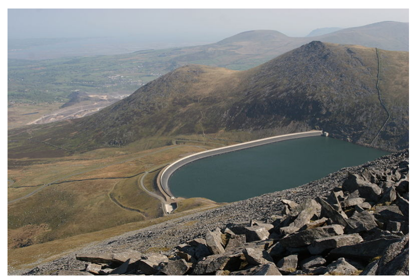


Figure 1.8. Marchlyn Mawr, the upper reservoir of the Dinorwig pumped storage facility. See Chapter 26 (pages 186–194) for further information.

each. This 10 GW rapidly-adjustable source, along with the rapidly-adjustable demand of the half-charged electric vehicles that are connected at any time (amounting to an easily-switch-off-and-on-able demand of 10 or 20 GW), and the rapidly-adjustable demand of heat-pumps for making hot water and heat pumps for winter-building-heating, will allow the balancing of fluctuating demand and intermittent renewables.

12. **Interconnectors.** Additional virtual pumped storage can be obtained from connections to countries with hydroelectricity. We build 5 GW of interconnectors between Britain and Norway (with cables from both Scotland and England); perhaps 1 GW to Denmark; and perhaps a 1 GW interconnector to Iceland, assuming that Iceland would increase its hydroelectric capacity. We also build 0.25 GW per year of new interconnector to France, so that by 2050 the connection to France is increased from 2 GW to 12 GW.

13. **Coal and gas with carbon capture and storage.** 8 GWp of "clean coal" power stations will be built at a rate of 1 GWp per year, providing an average output of 3 GW (more in winter, less in summer). This will require the import of roughly 11 GW of coal (assuming the power stations are 40% efficient and that capture and storage requires 25% of the power). For comparison, in 2006, the UK imported 70 GW of coal.

    The coal stations will also co-fire biomass, thus capturing some $CO_2$ and genuinely neutralizing the emissions associated with some continued fossil fuel use by air travel, industry, and international shipping. Market forces may lead to the building of *gas* power stations with carbon capture and storage, but I won't assume that these exist in 2050, since who knows where the price of gas is going. I think it safest to assume that cheap gas will be all gone by 2050. Plan C has no micro-CHP (micro-generation combined heat and power) because heat pumps are better, and allow decarbonization.

14. **Nuclear.** New stations are built at a rate of 2.2 GW per year, the first stations coming on line in 2018. By 2050 Britain would have 70 GW of nuclear power – roughly what France has today. This sustained build rate (2.2 GW per year) is similar to the historical build rate in France (3 GW per year).

Figure 1.9. Sizewell A and B. Plan C requires 70 new Sizewell B's.

15. **Imported renewable power from other countries**. Through international agreement and cooperation, **concentrating solar power stations** would be built in Mediterranean and North African deserts at an appropriate rate such that the power bought by Britain increases at a rate of 0.25 GW per year. By 2050, the power would be 10 GW. New power lines across Spain, Italy, and France would be required.

These power lines would be part of a European super-grid, useful for power-balancing across Europe and North Africa.

16. **Fluctuations of renewables and of demand; smart grids and storage**. Both wind power and nuclear power have difficulties tracking demand. (Modern nuclear power stations can be turned down, but they give the best economic return on investment if they are left on all the time.) It is therefore essential to implement **smart demand management** or **storage** or both, on a very large scale. The two main forms of demand that will be easily turn-off-and-on-able will be electric-vehicle-charging and electric heat-pumping. Wherever possible, buildings should have heat stores – the bigger the better – to help provide demand that can be moved in time by hours, days, or even months. Storage technologies deserve strong investment, because cheap storage will help any decarbonized energy plan, whatever its mix.

    *Without smart demand management, the expansion of wind and nuclear will not work.*

## Further details, options, risks and uncertainties

1. **Population**. This plan has made no allowance for population change.
2. **Wind / nuclear mix**. Plan C gets most of its power from wind and nuclear. The mix could be adjusted in response to economic or political preferences: the exchange rate is that each Sizewell B is equivalent (on average) to 2000 (2 MW) turbines, which would make up windfarms occupying an area of roughly 2000 km$^2$.
3. **Electric vehicles**. There are significant questions about batteries. Will it be possible to make batteries cheaper and lighter? Will it be easy to recycle old batteries into new batteries with only a small energy cost? Are there resource constraints that would make it difficult to deploy millions of electric vehicles? Plan C assumes that technical progress will resolve all these questions. There do seem to be promising signs of progress.
4. **'Vehicle-to-Grid'**. Plan C assumes that the charging of half-charged vehicles will be a big chunk of easily-switch-off-and-on-able demand. We could imagine going further, using electric vehicles not only as adjustable demand, but as occasional energy-sources too: using them as batteries for the benefit of the grid.

    Plan C did not assume this use of electric vehicles; it is possible that vehicle-to-grid might make economic sense.
5. **Hydrogen**. Plan C makes negligible use of hydrogen for transport because hydrogen vehicles use about four times more energy than

electric vehicles. We can't afford the energy! We're already very close to the buffers of plausible power production.

6. **Biofuels**. Plan C makes negligible use of biofuels for transport. Domestic production of biofuels at any useful scale would require too much land area, and it is not clear that environmentally-sound biofuels will ever be importable at significant scale from overseas. If biofuels are produced, their main use in a decarbonized-Britain plan should probably be in agricultural machinery, aviation, shipping, and long-distance road freight.

7. **Waste-to-energy**. In a decarbonized world, there is going to be a shortage of chemical feedstocks for manufacturing useful stuff. It will therefore be important to reuse and recycle stuff, especially carbon-containing stuff, rather than simply setting fire to it. At present we send roughly 1 kg per day per person of stuff to landfill. This will end. Plan C assumes that this waste stuff, and an equal amount of agricultural waste, is used in waste-to-energy facilities.

   Policies should recognise that the ideal waste-to-energy facilities are waste-to-chemicals facilities that preserve as much as possible of the carbon (and other useful lego bricks) in a form useful to the chemical and manufacturing industry. This means that the energy derived from waste may become smaller than plan C shows. *National Grid* have published ambitious plans for the turning of waste into methane gas for distribution to houses for use in heating and cooking. Perhaps a partial implementation of that idea would make sense, but I believe that society will come to think of methane as a resource that is too valuable to simply burn for domestic heating. We need a Chemical Feedstocks Plan for the post-fossil-fuel era.

8. **'Clean coal' with carbon capture and storage [CCS]**. 'Clean coal' is as yet an unproven low-carbon technology, with several uncertainties, therefore Plan C features only 8 GW of prototypes. If, by 2020, CCS is not proven to work, the coal in this plan could be replaced by additional nuclear build. If CCS works and if economics favours CCS over nuclear then the plan could be tilted in that direction.

9. **Solar photovoltaic panels**. In 2006, PV produced 0.000 75 GW (0.0003 kWh/d per person). It is to be hoped that the cost of PV will come down. One potential benefit of decentralized power generation is the engagement and energy awareness it causes. But for PV's contribution to actually show up on our charts (enabling the removal of, say, one power station), there would have to be more than a thousand-fold increase in PV over 2006 levels.

10. **Hydroelectricity**. In Plan C, there is no increase in hydroelectricity. Hydro continues to produce 0.5 GW on average, as it does today.

11. **International shipping** is quite an efficient user of fossil fuels, but perhaps we should plan to defossilize it too. (In 2002, Britain's share of international shipping used a power of 10 GW.) In this plan, Britain restarts President Dwight D. Eisenhower's *Atoms for Peace* initiative, building a new fleet of nuclear-powered container ships and passenger ships.

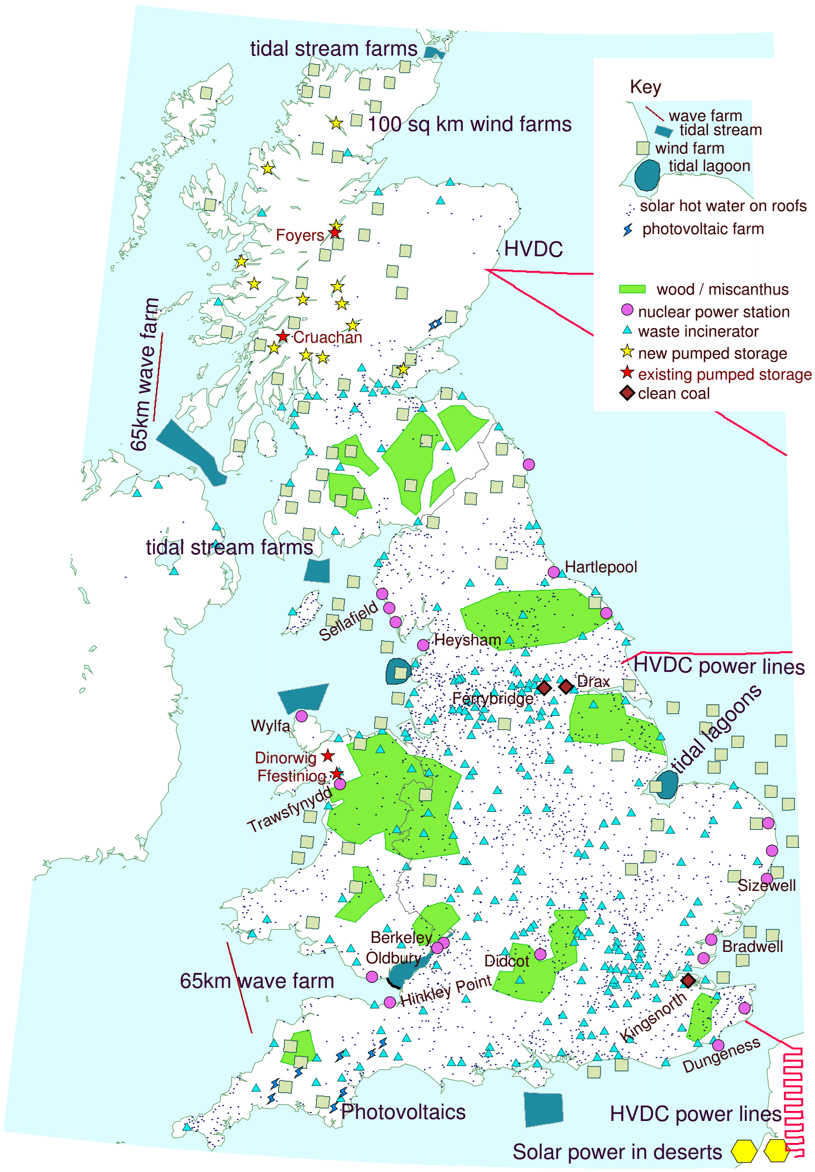
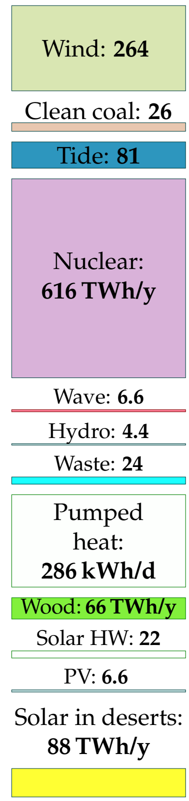



Figure 1.10. Plan C. Energy sources in 2050. The stack below shows the average energy contributed by each source in TWh per year.



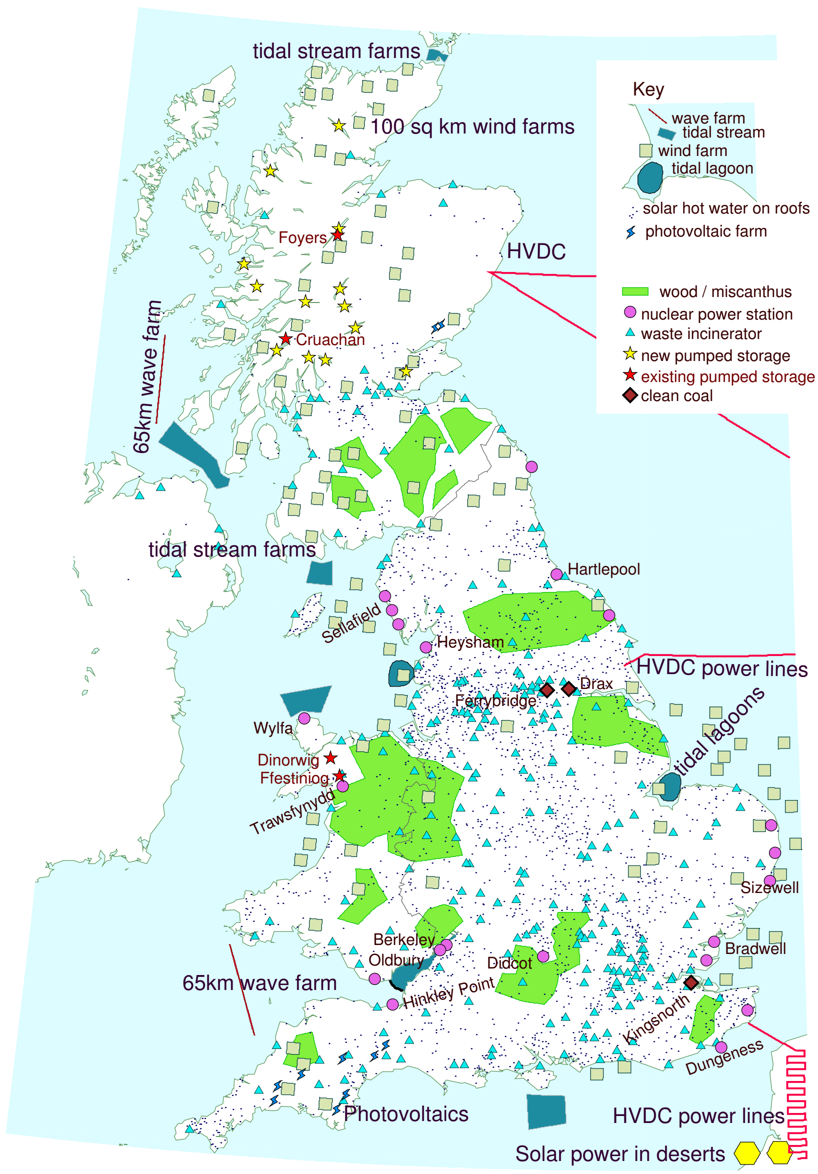



Figure 1.11. Plan C. Energy sources in 2050. The stack below shows the average energy contributed by each source in kWh per day per person.