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`.

Contents

1 A plan with a timeline

A plan with a detailed time-line

This plan starts in 2009 and aims to fully decarbonize Britain by 2050, and to keep the lights on along the way. An executive summary of the plan is:

> We build *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.

I'll describe everything in GW. (1 GW ↔ 0.4 kWh/d per person in the UK.) "1 GWp" means 1 GW of peak power or capacity. 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.

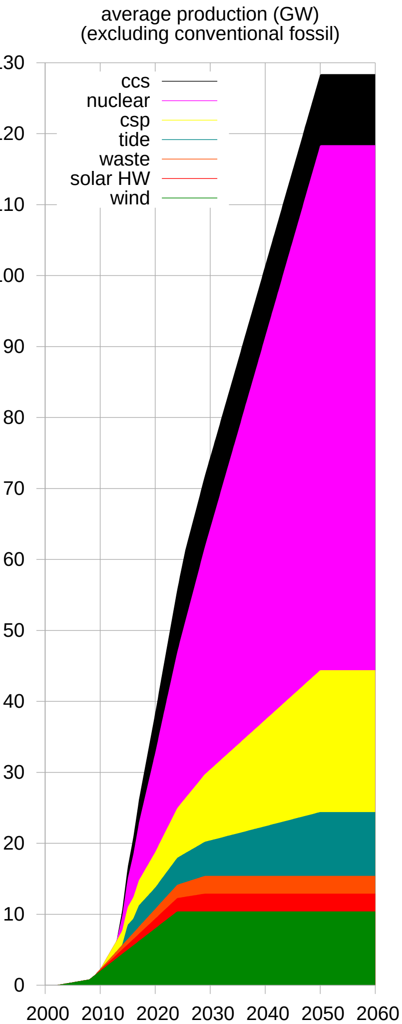

Figure 1.1. Where plan 7 gets its zero-carbon power from, on average. Hydroelectricity and photovoltaics are not shown because they are too small.

Overview

Britain's primary energy consumption today is about 250 GW, most of it fossil fuel. Roughly one third of energy consumption relates to transport and one third to heating. The plan that follows 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 is reduced to about 125 GW, almost all of which 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 twenty-fold, and nuclear power is increased seven-fold over 2008 levels. The electricity comes from the following sources. (The numbers given here are average outputs, not capacities.) Wind: 10 GW; tide: 8 GW; waste incineration: 2.5 GW; "clean coal" and biomass co-firing: 10 GW; nuclear: 72 GW; concentrating solar power in deserts: 20 GW. (That's a total of about 120 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.

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.

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; a demand that is easily switch-off-and-onable. (These vehicles might initially be plug-in hybrids 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.

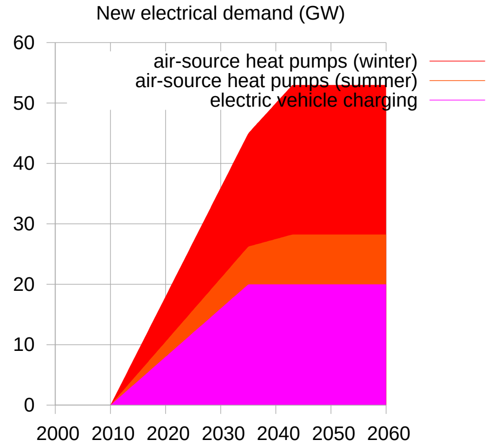

Figure 1.2. Plan 7's new electrical demand from electrification of transport and of heating. The transport demand is largely easily-switch-off-and-on-able.

3. **Air-source heat pumps** (high efficiency ones like the EcoCute from Japan) 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.

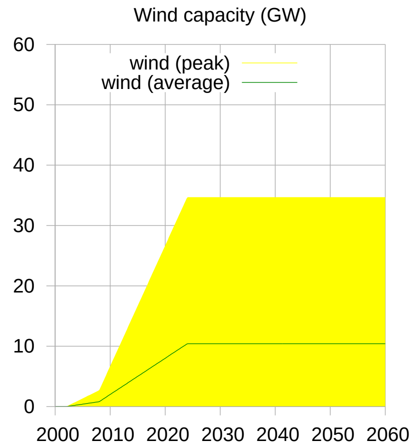

Figure 1.3. Plan 7's wind capacity and average wind production.

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.)

5. **Wind farms** are built at a rate of 2 GWp per year, stopping after 16 years once 33 GWp is reached. (British wind farm capacity was about 2.7 GWp in 2008.) 33 GWp will produce 10 GW on average. Building wind farms offshore will require investment in jack-up barges: perhaps ten barges, costing £60 M each.

6. **Tide.** The Severn barrage is built and completed by 2017 (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. 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.

7. **Waste incineration (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, and an equal amount of agricultural waste to be incinerated too.

8. **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 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) will allow the balancing of fluctuating demand and intermittent renewables.

9. **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 0.5 GW per year of new interconnector to France, so that by 2050 the connection to France is increased from 2 GW to 22 GW.

10. **Coal and gas with carbon capture and storage.** 25 GWp of "clean coal" power stations will be built at a rate of 2 GWp per year, providing an average output of 10 GW (more in winter, less in summer). 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 will also probably lead to the building of gas 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. My plan has no micro-CHP (microgeneration combined heat and power) because heat pumps are better, and allow defossilization.

11. **Nuclear.** New stations are built at a rate of 2 GW per year, the first stations coming on line in 2013. By 2050 Britain would have 75 GW

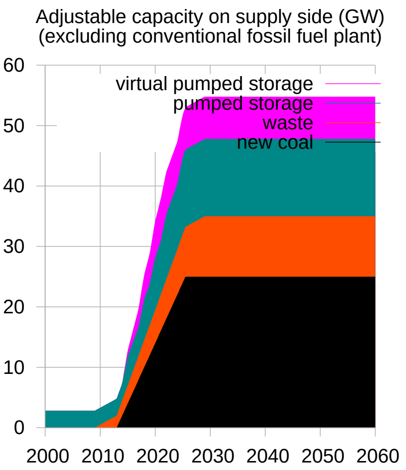

Figure 1.4. Plan 7's adjustable capacity on the supply side. The new "clean coal" would especially play a role in compensating for summer/winter demand variations; the waste incinerators and pumped storage systems would compensate for daily demand variations; and the pumped storage systems would compensate for the wind variations, along with the adjustable demand of electric vehicles (figure 1.2).

of nuclear power – a bit more than France has today. This sustained build rate (2 GW per year) is similar to the historical build rate in France (3 GW per year).

12. **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 0.5 GW per year. By 2050, the power would be 20 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.

13. **International shipping** is quite an efficient user of fossil fuels, but perhaps we should plan to defossilize it too. 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.