
Sustainable Energy – without the hot air

David J.C. MacKay

This remarkable book sets out, with enormous clarity and objectivity, the various alternative low-carbon pathways that are open to us.

Sir David King FRS

Chief Scientific Adviser to the UK Government, 2000–08

For anyone with influence on energy policy, whether in government, business or a campaign group, this book should be compulsory reading.

Tony Juniper

Former Executive Director, Friends of the Earth

At last a book that comprehensively reveals the true facts about sustainable energy in a form that is both highly readable and entertaining.

Robert Sansom

Director of Strategy and Sustainable Development, EDF Energy

A ten-page synopsis

We have an addiction to fossil fuels, and it's not sustainable. The developed world gets 80% of its energy from fossil fuels; Britain, 90%. And this is unsustainable for three reasons. First, easily-accessible fossil fuels will at some point run out, so we'll eventually have to get our energy from someplace else. Second, burning fossil fuels is having a measurable and very-probably dangerous effect on the climate. Avoiding dangerous climate change motivates an immediate change from our current use of fossil fuels. Third, even if we don't care about climate change, a drastic reduction in Britain's fossil fuel consumption would seem a wise move if we care about security of supply: continued rapid use of the North Sea oil and gas reserves will otherwise soon force fossil-addicted Britain to depend on imports from untrustworthy foreigners. (I hope you can hear my tongue in my cheek.)

How can we get off our fossil fuel addiction?

There's no shortage of advice on how to "make a difference," but the public is confused, uncertain whether these schemes are fixes or figleaves. People are rightly suspicious when companies tell us that buying their "green" product means we've "done our bit." They are equally uneasy about national energy strategy. Are "decentralization" and "combined heat and power," green enough, for example? The government would have us think so. But would these technologies really discharge Britain's duties regarding climate change? Are windfarms "merely a gesture to prove our leaders' environmental credentials"? Is nuclear power essential?

We need a plan that adds up. The good news is that such plans can be made. The bad news is that implementing them will not be easy.

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Photo by Terry Cavern.

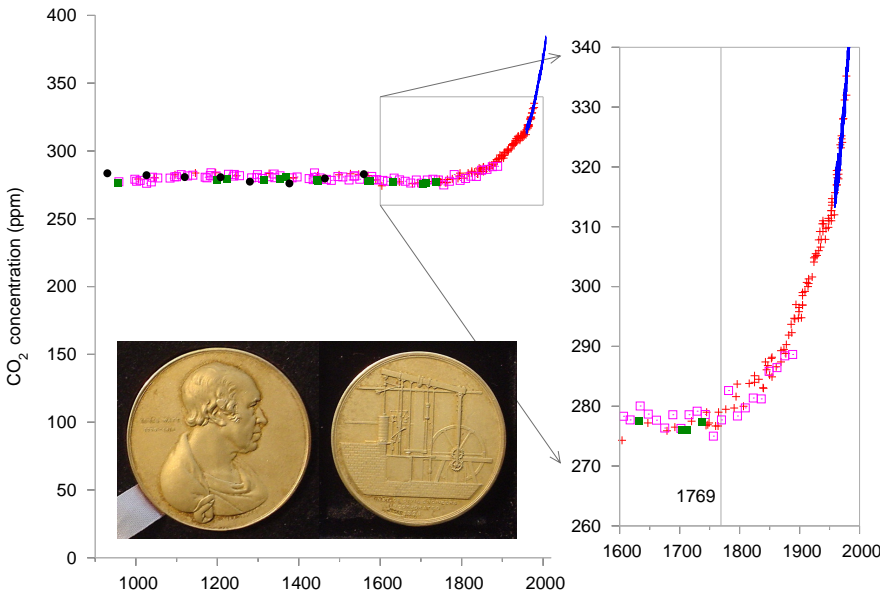


Figure 1. Carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards).

I think something new may have happened between 1800 AD and 2000 AD. I've marked the year 1769, in which James Watt patented his steam engine. (The first practical steam engine was invented 70 years earlier in 1698, but Watt's was much more efficient.)

Part I – Numbers, not adjectives

The first half of this book discusses whether a country like the United Kingdom, famously well endowed with wind, wave, and tidal resources, could live on its own renewables. We often hear that Britain's renewables are "huge." But it's not sufficient to know that a source of energy is "huge." We need to know how it compares with another "huge," namely our huge consumption. To make such comparisons, we need *numbers, not adjectives*.

Where numbers are used, their meaning is often obfuscated by enormousness. Numbers are chosen to impress, to score points in arguments, rather than to inform. In contrast, my aim here is to present honest, factual numbers in such a way that the numbers are comprehensible, comparable, and memorable. The numbers are made accessible by expressing them all in everyday *personal* units. Energies are expressed as quantities per person in kilowatt-hours (kWh), the same units that appear on household energy bills; and powers are expressed in kilowatt-hours per day (kWh/d), per person. Figure 2 illustrates a few quantities compared in these units. In red, for example, driving an average car 50 km per day uses **40 kWh per day**. In green on the right, some renewable resources are represented: covering 10% of the country with wind farms would yield **20 kWh per day per person** on average.

One reason for liking these personal units is that it makes it much easier to move from talking about the UK to talking about other countries or regions. For example, imagine we are discussing waste incineration and we learn that UK waste incineration delivers a power of 7 TWh per year and that Denmark's waste incineration delivers 10 TWh per year. (1 TWh (one terawatt-hour) is equal to one billion kWh.) Does this help us say whether Denmark incinerates "more" waste than the UK? While the total

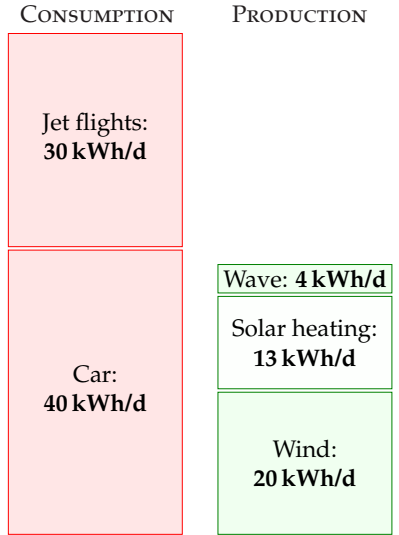


Figure 2. Comparisons of a couple of energy-consuming activities with conceivable renewable energy production from three UK sources. On the left, driving 50 km per day consumes 40 kWh per day, and taking an annual long-range flight by jet uses 30 kWh per day (averaged over the year). On the right, covering the windiest 10% of Britain with onshore windfarms would yield 20 kWh per day per person; covering every south-facing roof with solar water-heating panels would capture 13 kWh per day per person; and wave machines intercepting Atlantic waves over 500 km of coastline would provide 4 kWh per day per person.

power produced from waste in each country may be interesting, I think that what we usually want to know is the waste incineration *per person*. (For the record, that is: Denmark, 5kWh/d per person; UK, 0.3kWh/d per person. So Danes incinerate about 13 times as much waste as Brits.) By discussing everything per-person from the outset, we end up with a more transportable book, one that will hopefully be useful for sustainable energy discussions worldwide.

With simple honest numbers in place, we are able to answer questions such as:

- 1. Can a country like Britain conceivably live on its own renewable energy sources?
- 2. Will a switch to “advanced technologies” allow us to eliminate carbon dioxide pollution without changing our lifestyle?

Part I of *Sustainable Energy – without the hot air* builds up an illustrative red consumption stack, enumerating the energy cost of a range of energy-consuming activities; and a complete green stack, adding up all the potential renewable resources available in Britain.

While working out the numbers for the left-hand red consumption stack, we debunk several myths. For example, “leaving mobile phone chargers plugged in” is often held up as an example of a behavioural eco-crime, with people who switch their chargers off being praised for “doing their bit.” The truth is that a typical mobile phone charger consumes just 0.01kWh per day. The amount of energy saved by switching off the phone charger, 0.01kWh, is exactly the same as the energy used by driving an average car for one second. I’m not saying that you shouldn’t switch phone chargers off. But don’t be duped by the mantra “every little helps.” Obsessively switching off the phone-charger is like bailing the Titanic with a teaspoon. Do switch it off, but please be aware how tiny a gesture it is.

All the energy saved in switching off your charger for one day is used up in one second of car-driving.

The energy saved in switching off the charger for one year is equal to the energy in a single hot bath.

Your charger is only a tiny tiny fraction of your total energy consumption. If everyone does a little, we’ll achieve only a little.

Another memorable number is the contribution of long-distance flying to a person’s energy footprint. If you fly to Cape Town and back once per year, the energy you use in that trip is nearly as big as the energy used by driving an average car 50 km per day, every day, all year.

A significant item in the British energy footprint is stuff. Imported manufactured stuff is usually omitted from Britain’s energy footprint, since another country’s industry was responsible for expending the energy; but that overseas energy cost of making imported manufactured stuff (things like vehicles, machinery, white goods, electrical and electronic equipment, iron, steel, and dry bulk products) is at least 40 kWh per day per person.

STUFF FLOWS IN BRITAIN (kg per day, per person)	
IN	
Fossil fuels	16
coal	4
oil	4
gas	8
All imports	12.5
food imports	1.6
manufactured stuff	3.5
Water	160
OUT	
Carbon dioxide and other GHG pollution	30
Municipal waste	1.6
recycled	0.27
incinerated	0.13
landfilled	1.0
hazardous waste	0.2
food thrown away	0.3

Table 3. Sources: DEFRA, Eurostat, Office for National Statistics, Department for Transport.

The first half gives two clear conclusions. First, for any renewable facility to make an appreciable contribution – a contribution at all comparable to our current consumption – it has to be country-sized. To provide one quarter of our current energy consumption by growing energy crops, for example, would require 75% of Britain to be covered with biomass plantations. To provide 4% of our current energy consumption from wave power would require 500 km of Atlantic coastline to be completely filled with wave farms. Someone who wants to live on renewable energy, but expects the infrastructure associated with that renewable *not* to be large or intrusive, is deluding himself.

Second, *if economic constraints and public objections are set aside*, it would be possible for the average European energy consumption of 125 kWh/d per person to be provided from these country-sized renewable sources. The two hugest contributors would be photovoltaic panels, which, covering 5% or 10% of the country, would provide 50 kWh/d per person; and offshore wind farms, which, filling a sea-area twice the size of Wales, would provide another 50 kWh/d per person on average.

Such an immense panelling of the countryside and filling of British seas with wind machines (having a capacity five times greater than all the wind turbines in the world today) may be possible according to the laws of physics, but would the public accept and pay for such extreme arrangements? If we answer no, we are forced to conclude that *current consumption will never be met by British renewables*. We require either a radical reduction in consumption, or significant additional sources of energy – or, of course, both.

Part II – Energy plans that add up

The second part of *Sustainable Energy – without the hot air* explores six strategies for eliminating the gap between consumption and renewable production identified in the first part, then sketches several energy plans for Britain, each of which adds up.

The first three strategies for eliminating the gap reduce energy demand:

- population reduction;
- lifestyle change;
- changing to more efficient *technology*.

The other strategies for eliminating the gap increase energy supply:

- “Sustainable fossil fuels” and “clean coal” are names given to carrying on burning coal, but in a different way, with carbon capture and storage. What power could we get from coal, “sustainably”?
- Nuclear power is another controversial option; is it just a stop-gap?
- A third way to get extra carbon-free power would be to live on renewable energy from *other countries* – in particular, countries blessed with plentiful sunshine, large areas, and low population densities. What is the realistic potential of the Sahara desert?

POWER PER UNIT LAND OR WATER AREA	
Wind	2 W/m ²
Offshore wind	3 W/m ²
Tidal pools	3 W/m ²
Tidal stream	6 W/m ²
Solar PV panels	5–20 W/m ²
Plants	0.5 W/m ²
Rain-water (highlands)	0.24 W/m ²
Hydroelectric facility	11 W/m ²
Geothermal	0.017 W/m ²
Solar chimney	0.1 W/m ²
Ocean thermal	5 W/m ²
Concentrating solar power (desert)	15 W/m²

Table 4. Renewable facilities have to be country-sized because all renewables are so diffuse. This table lists the power per unit land-area or sea-area offered by a number of renewables.



Figure 5. Stirling dish engine. These beautiful concentrators deliver a power per unit land area of 14 W/m². Photo courtesy of Stirling Energy Systems. www.stirlingenergy.com

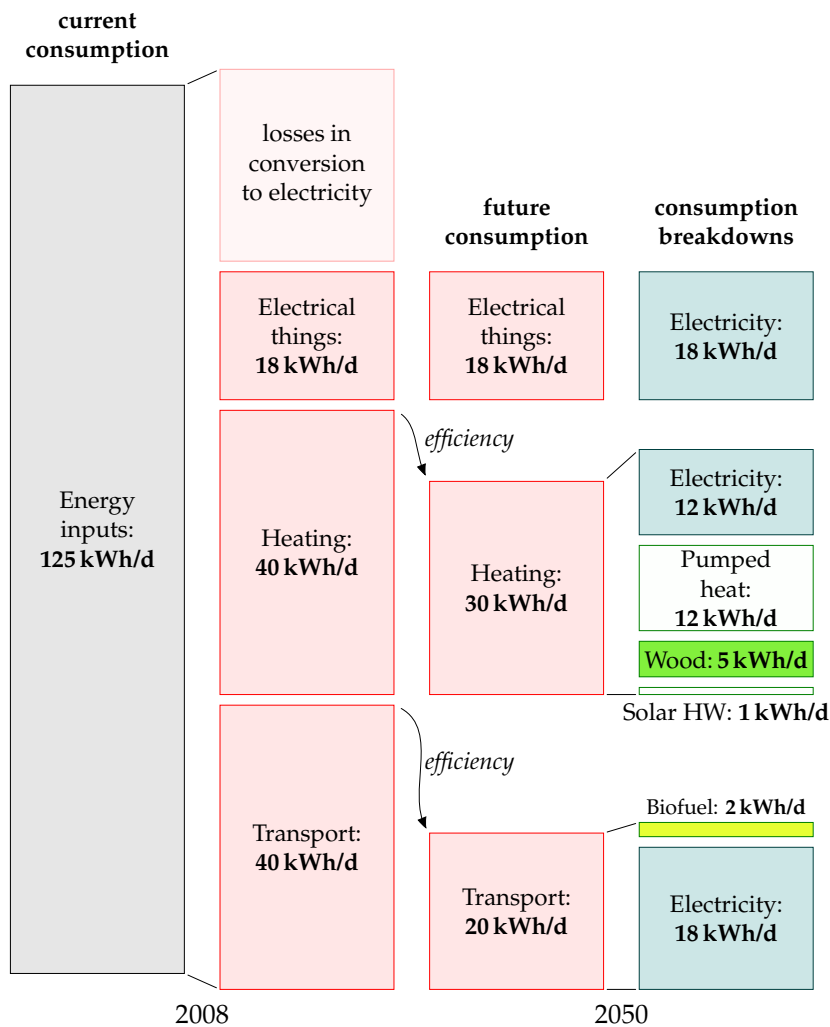


Figure 6. Current consumption per person in “cartoon Britain 2008” (left two columns), and a future consumption plan, along with a possible breakdown of fuels (right two columns). This plan requires that electricity supply be increased from 18 to 48 kWh/d per person of electricity.

To sharpen the discussion, this part of the book simplifies Britain into a cartoon featuring just three categories of consumption: transport, heating, and electricity.

Five energy plans for Britain are presented, all of which reduce the energy demand by electrifying transport and by electrifying heating (using heat pumps). Electric vehicles serve a second convenient function: the charging of their batteries is a large electricity demand that is easily turn-off-and-onable, so smart battery-charging would help match supply to demand in a renewable-heavy or nuclear-heavy electricity network.

The electrification of transport and heating of course requires a substantial increase in electricity generation. The five plans supply this required electricity using five different mixes of the carbon-free options. The mixes represent different political complexions, including plan G, the Green plan, which forgoes both “clean coal” and nuclear power; plan N, the NIMBY plan, which makes especially heavy use of *other* countries’ renewables; and plan E, the Economist’s plan, which focuses on the most economical

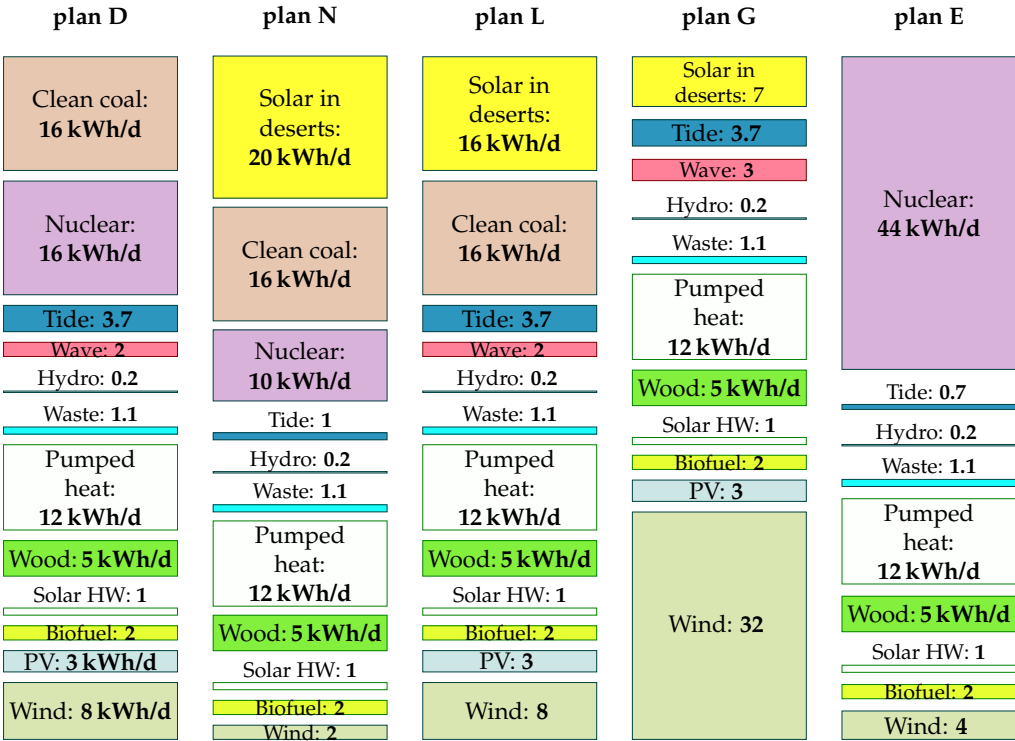


Figure 7. Five energy plans for Britain. All these supply-side plans assume that demand has been substantially reduced by efficiency savings in heating and transport.

carbon-free choices: onshore wind farms, nuclear power, and a handful of tidal lagoons.

These plans make clear the building blocks from which we must create our low-carbon future.

Any plan that doesn't make heavy use of nuclear power or "clean coal" has to make up the energy balance using renewable power bought in from other countries. The most promising renewable for large-scale development is concentrating solar power in deserts. Concentrating solar power uses various combinations of moving mirrors, molten salt, steam, and heat engines to generate electricity.



Figure 8. Andasol – a “100 MW” solar power station under construction in Spain. Excess thermal energy produced during the day will be stored in liquid salt tanks for up to seven hours, allowing a continuous and stable supply of electric power to the grid. The power per unit land area will be 10 W/m². Photo: IEA SolarPACES.

To convey the scale of energy plans that add up, figure 9 shows a map of Britain bearing a sixth plan. This sixth plan features every possible low-carbon energy source, and lies roughly in the middle of the first five, so I call it plan M.

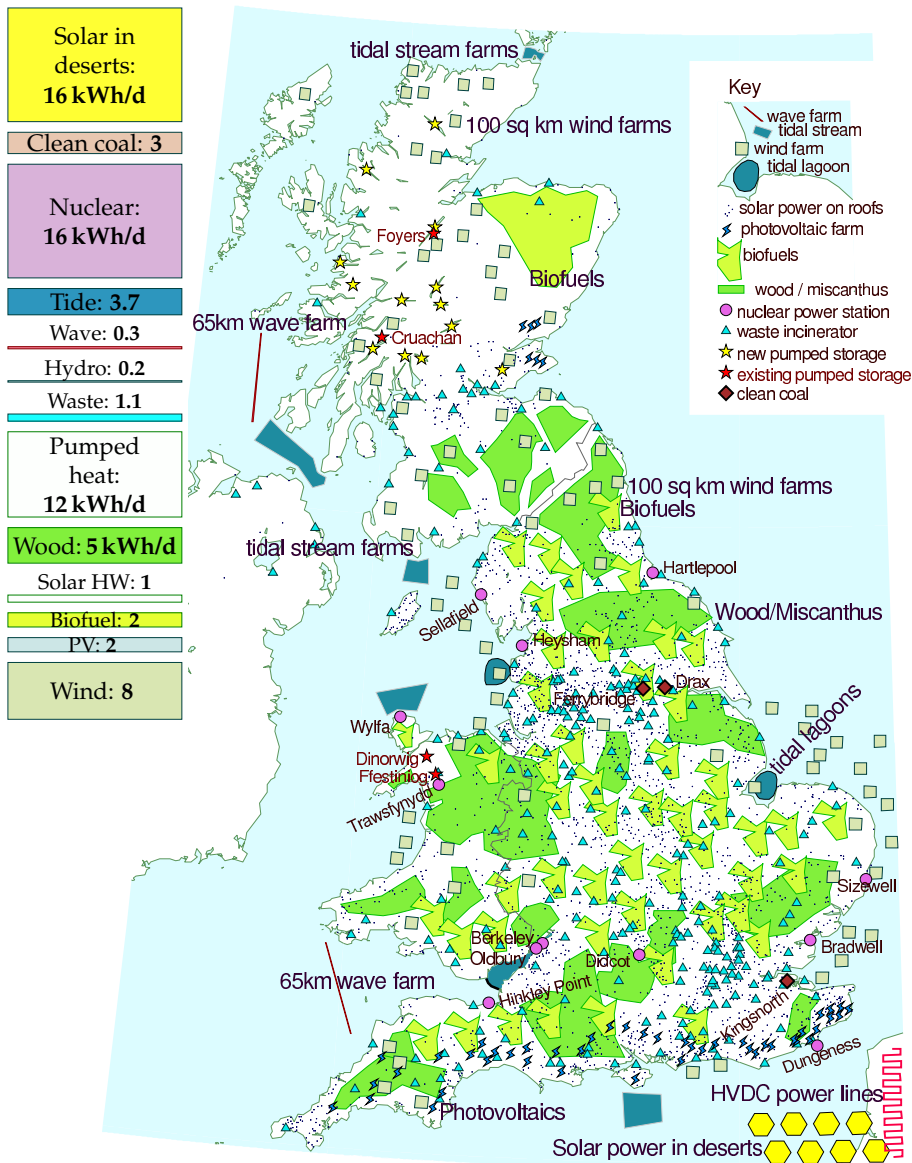


Figure 9. Plan M. A plan that adds up, for Scotland, England, and Wales. The grey-green squares are wind farms. Each is 100 km² in size and is shown to scale. The red lines in the sea are wave farms, shown to scale. Light-blue lightning-shaped polygons: solar photovoltaic farms – 20 km² each, shown to scale. Blue sharp-cornered polygons in the sea: tide farms. Blue blobs in the sea (Blackpool and the Wash): tidal lagoons. Light-green land areas: woods and short-rotation coppices (to scale). Yellow-green areas: biofuel (to scale). Small blue triangles: waste incineration plants (not to scale). Big brown diamonds: clean coal power stations, with cofiring of biomass, and carbon capture and storage (not to scale). Purple dots: nuclear power stations (not to scale) – 3.3 GW average production at each of 12 sites. Yellow hexagons across the channel: concentrating solar power facilities in remote deserts (to scale, 335 km² each). The pink wiggly line in France represents new HVDC lines, 2000 km long, conveying 40 GW from remote deserts to the UK. Yellow stars in Scotland: new pumped storage facilities. Red stars: existing pumped storage facilities. Blue dots: solar panels for hot water on all roofs.