

Sustainable Energy – without the hot air

David J.C. MacKay

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? Is nuclear power essential? Are windfarms "merely a gesture to prove our leaders' environmental credentials"?

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.

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*. These 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.



Photo by Terry Cavner.

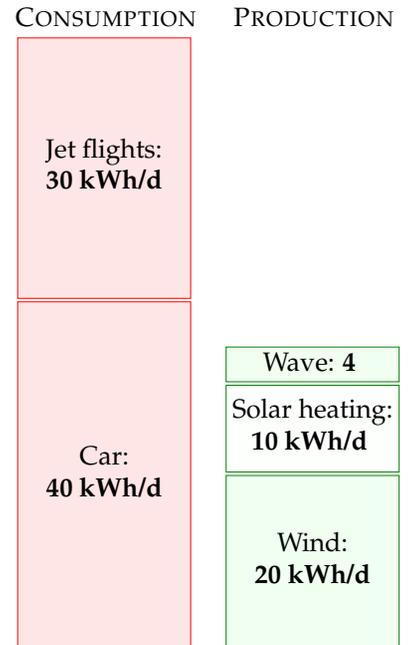


Figure 2. Comparisons of a couple of energy-consuming activities with conceivable renewable energy production from three UK sources.

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 yields 20 kWh per day per person; covering every south-facing roof with solar water-heating panels captures 10 kWh per day per person; and wave machines intercepting Atlantic waves over the entire 1000-km western coastline provide 4 kWh per day per person.

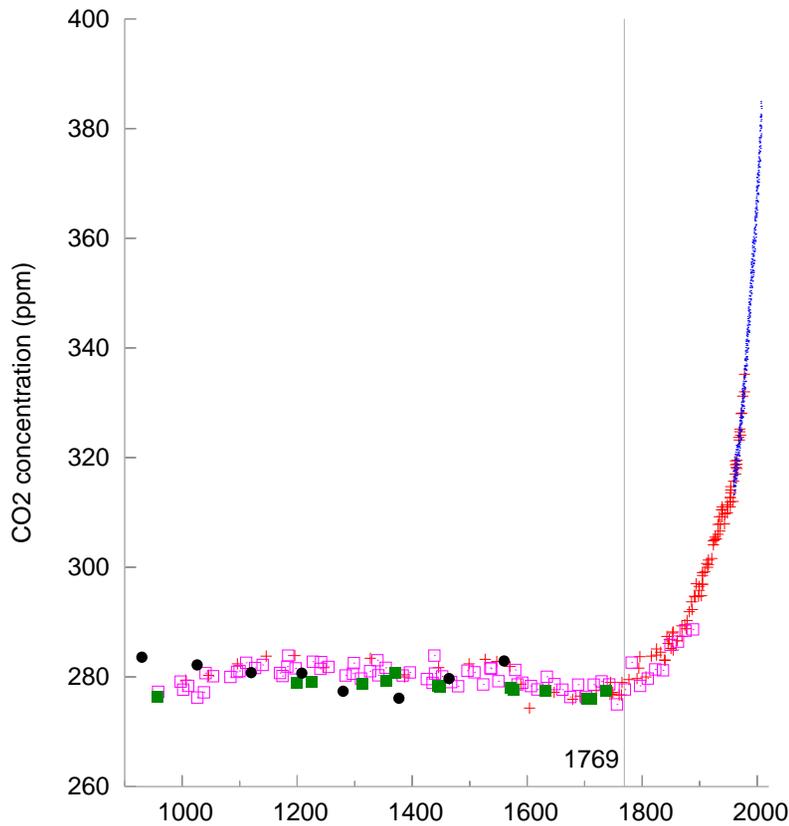
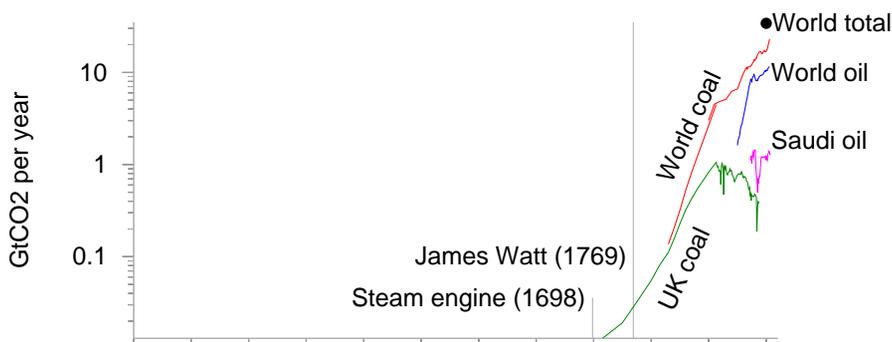
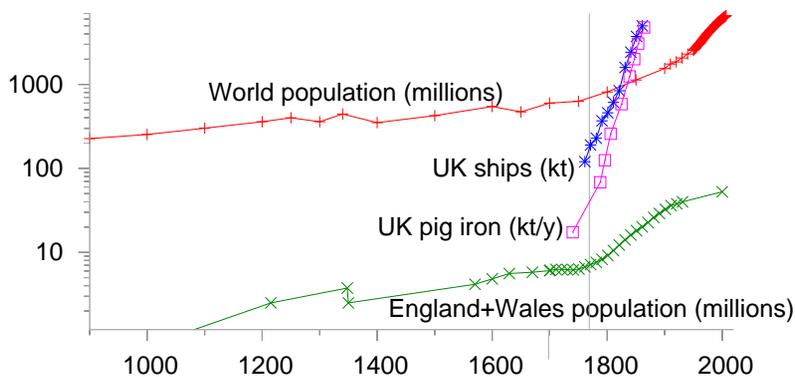


Figure 1. The climate-change motivation: burning fossil fuels causes greenhouse-gas concentrations to rise. The upper graph shows carbon dioxide (CO₂) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards). Do you think, just possibly, *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 seventy years earlier in 1698, but Watt's was much more efficient.)



The middle graph shows (on a logarithmic scale) the history of UK coal production, Saudi oil production, world coal production, world oil production, and (by the top right point) the total of all greenhouse gas emissions in the year 2000. All these production rates are shown in billions of tons of CO₂ – an incomprehensible unit, yes, but don't worry: it's personalized in the book.



The bottom graph shows (on a logarithmic scale) some consequences of the Industrial Revolution: sharp increases in the population of England, and, in due course, the world; and remarkable growth in British pig-iron production (in thousand tons per year); and in the tonnage of British ships (in thousand tons).

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. 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 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 audacious 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

This part 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 increase energy *supply*:

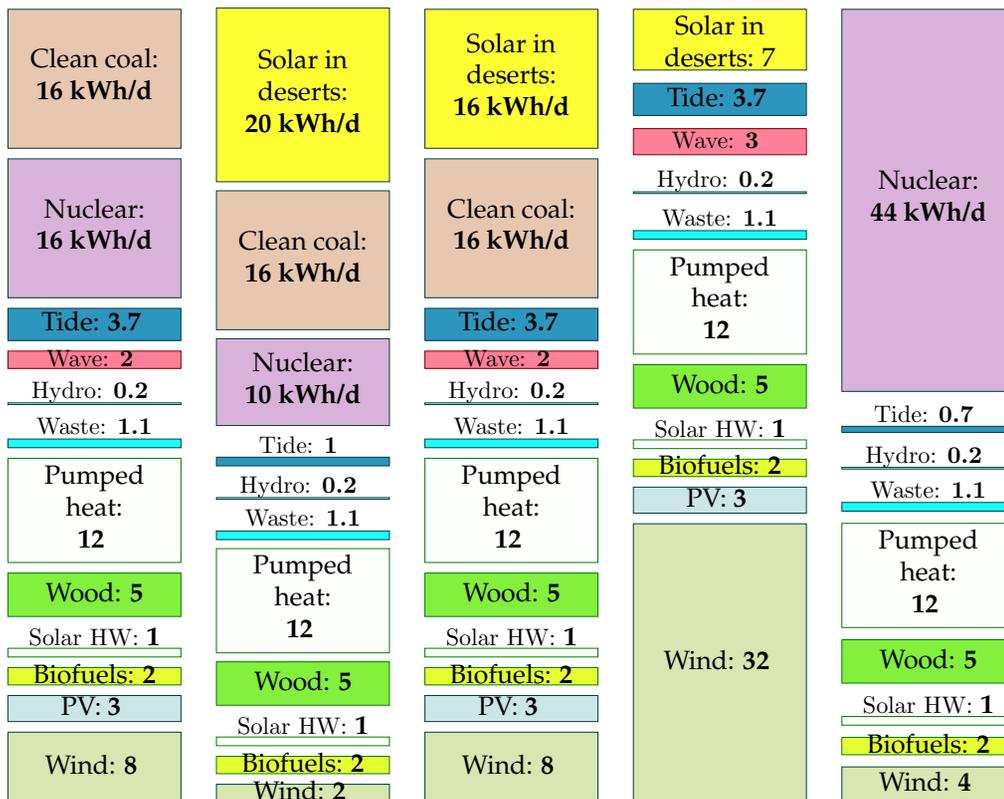
- “Sustainable fossil fuels” and “clean coal” are names given to carrying on burning coal, but in a different way, with carbon capture and storage. What power could we get from coal, “sustainably”?
- Nuclear power is another controversial option; is it just a stop-gap?
- A third way to get extra carbon-free 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?

The other strategies for eliminating the gap reduce energy *demand*:

- population reduction;
- lifestyle change;

POWER PER UNIT LAND OR WATER AREA	
Wind	2W/m ²
Offshore wind	3W/m ²
Tidal pools	3W/m ²
Tidal stream	6W/m ²
Solar PV panels	5W/m ²
Plants	0.5W/m ²
Rain-water	0.24W/m ²
Solar chimney	0.1W/m ²
Ocean thermal	5W/m ²
Concentrating solar power (desert)	14W/m²

Table 3. Renewable facilities have to be country-sized because all renewables are so diffuse.



- changing to more efficient *technology*.

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 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.

Figure 4. Five energy plans for Britain. All these supply-side plans assume that demand has been substantially reduced by efficiency savings in heating and transport.

Further information

This book is available in draft form at www.withouthotair.com and will remain free online when the book is published.

The bulk of the book is intended to be accessible to everyone who can add, multiply, and divide. There are also technical appendices aimed at readers who are comfortable with formulae like “ $\frac{1}{2}mv^2$.”

David MacKay is Professor of Natural Philosophy in the Department of Physics at the University of Cambridge.

June 28, 2008