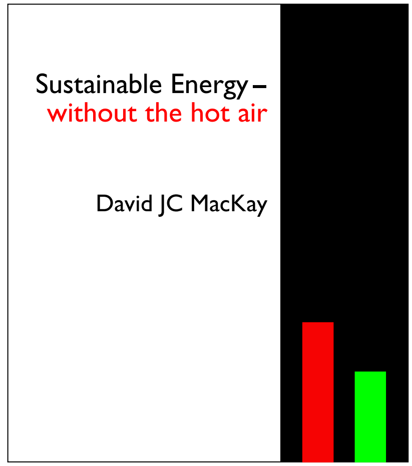
Sustainable Energy – without the hot air

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


Photo by Terry Cavner.

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.

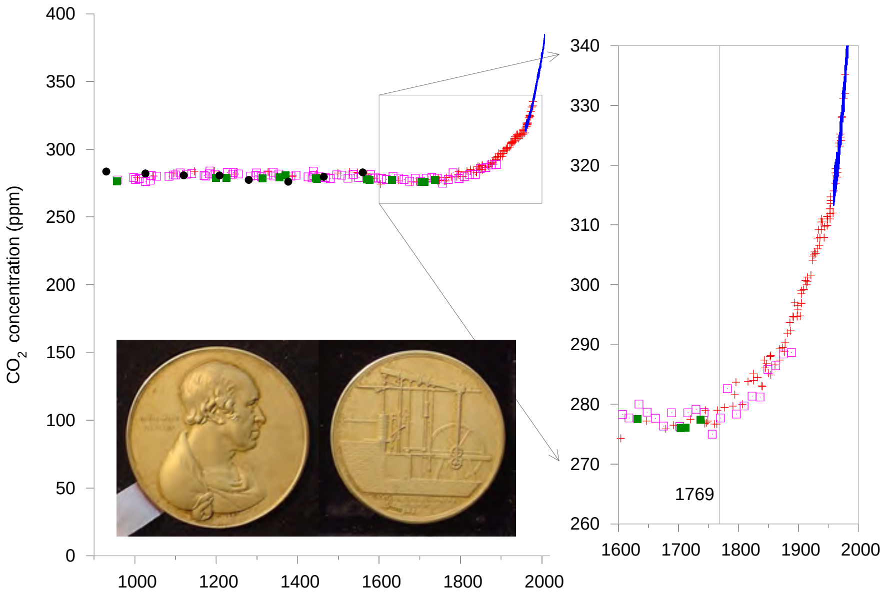


Figure 1. Carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards).

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

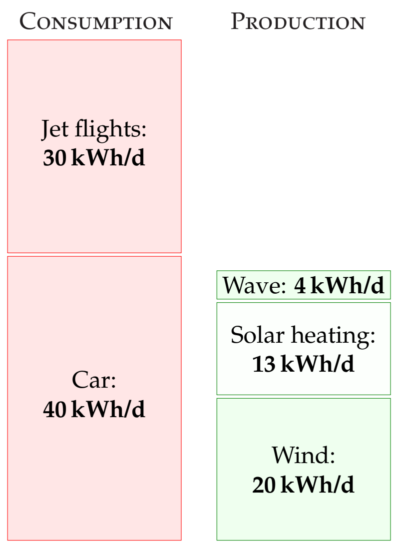


Figure 2. Comparisons of a couple of energy-consuming activities with conceivable renewable energy production from three UK sources. On the left, driving 50 km per day consumes 40 kWh per day, and taking an annual long-range flight by jet uses 30 kWh per day (averaged over the year). On the right, covering 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, 5 kWh/d per person; UK, 0.3 kWh/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 0.01 kWh per day. The amount of energy saved by switching off the phone charger, 0.01 kWh, 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.

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/m^2

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.

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?

Figure 5. Stirling dish engine. These beautiful concentrators deliver a power per unit land area of $14\,W/m^2$. Photo courtesy of Stirling Energy Systems. www.stirlingenergy.com

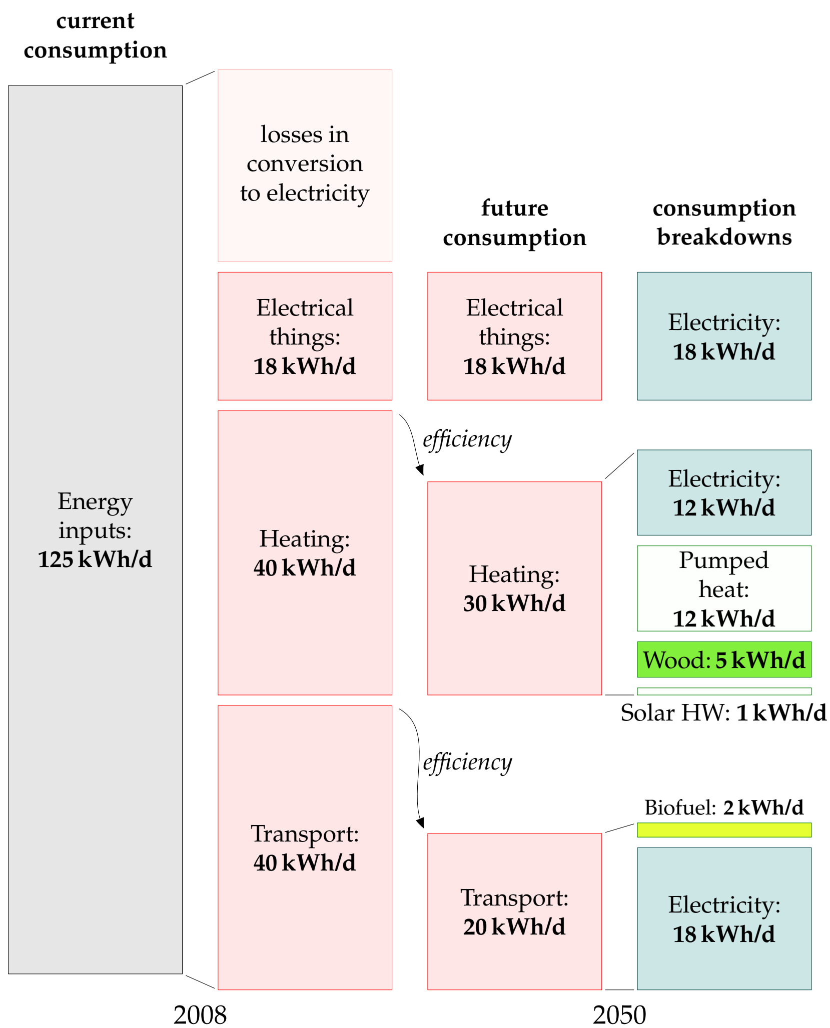


Figure 6. Current consumption per person in "cartoon Britain 2008" (left two columns), and a future consumption plan, along with a possible breakdown of fuels (right two columns). This plan requires that electricity supply be increased from 18 to 48 kWh/d per person of electricity.

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

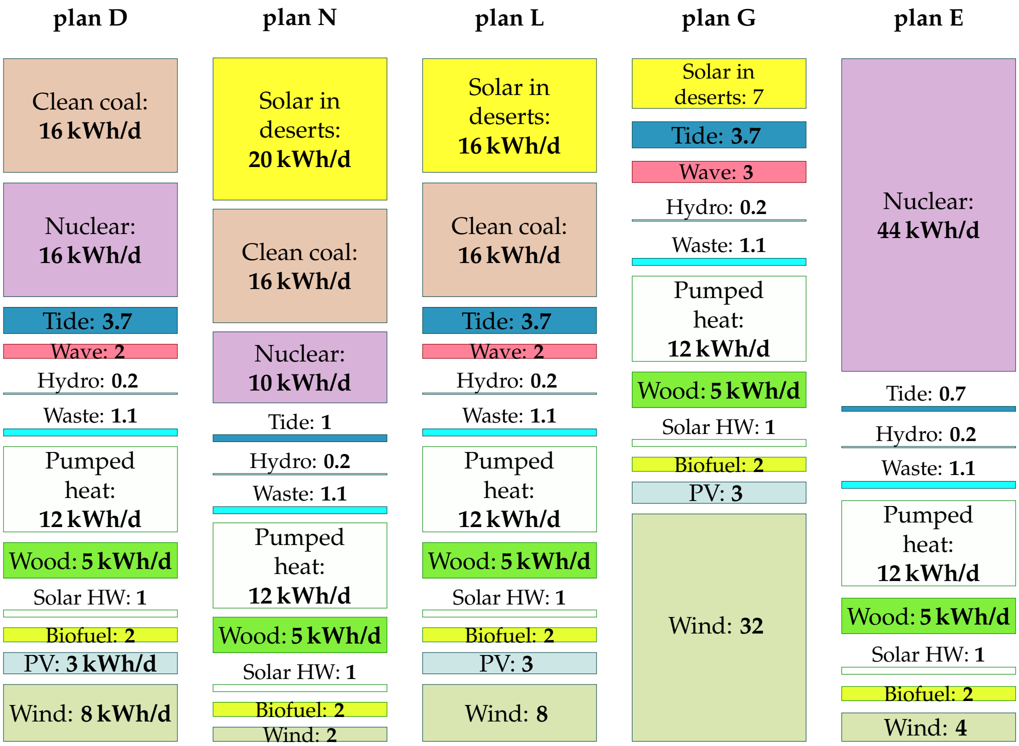


Figure 7. Five energy plans for Britain. All these supply-side plans assume that demand has been substantially reduced by efficiency savings in heating and transport.

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/m^2.
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.

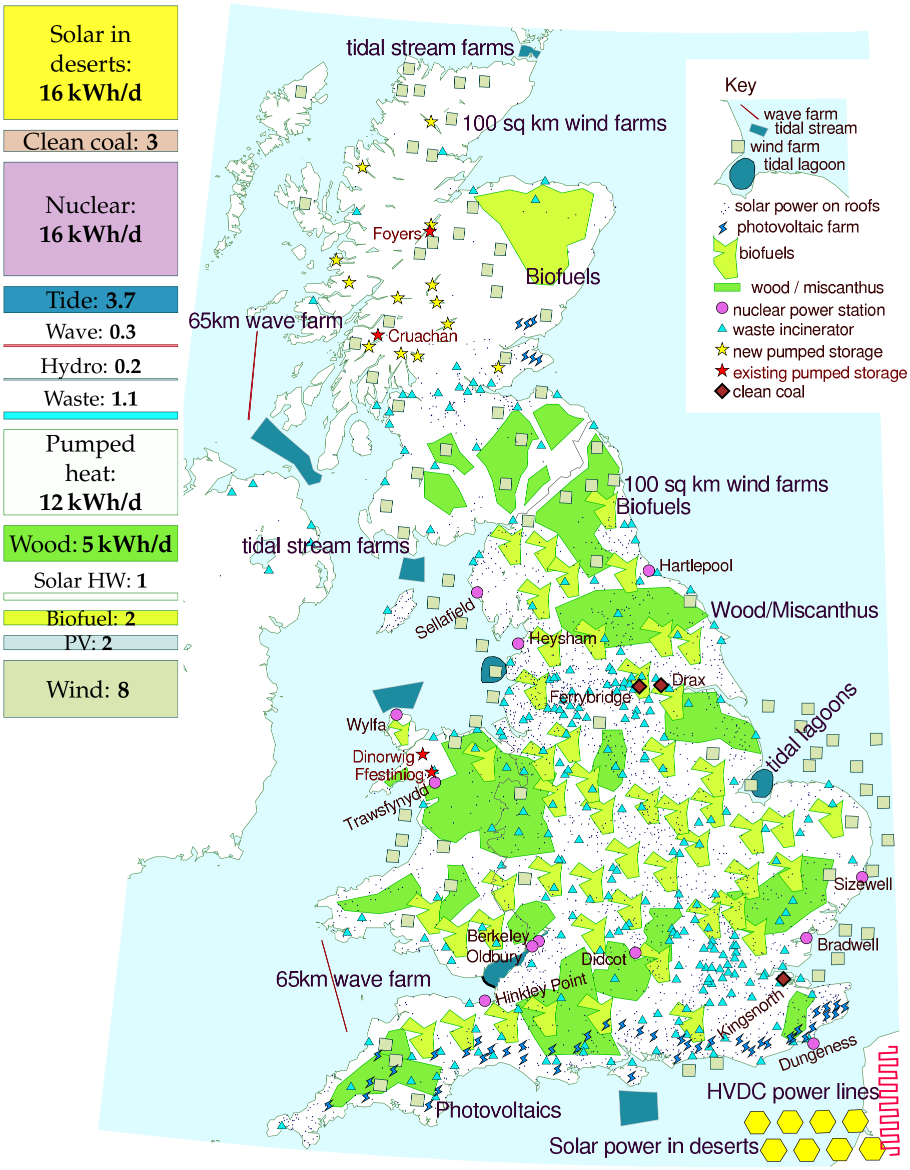


Figure 9. Plan M. A plan that adds up, for Scotland, England, and Wales. The grey-green squares are wind farms. Each is 100 km^2 in size and is shown to scale.
The red lines in the sea are wave farms, shown to scale.
Light-blue lightning-shaped polygons: solar photovoltaic farms – 20 km^2 each, shown 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 km^2 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.

My goal is not to pick winners, but to present honest quantitative facts about all the options. Having said that, I now highlight a few sacred cows that don't fare too well under the spotlight of quantitative attention, and a few that do.

Bad: **Hydrogen-powered vehicles** are a disaster. Most prototype hydrogen-powered vehicles use *more* energy than the fossil-fuel vehicle they replace. The BMW Hydrogen 7 uses 254 kWh per 100 km (while the average fossil car in Britain uses 80 kWh per 100 km). **Good**: In contrast, prototype

electric vehicles use ten times less energy: 20 kWh per 100 km or even 6 kWh per 100 km. Electric vehicles are far better than hybrid cars. Today's hybrid cars, which are typically at best about 30% better than fossil cars, should be viewed as a brief helpful stepping stone on the way to electric vehicles.

Figure 10. **Bad**: BMW Hydrogen 7. Energy consumption: 254 kWh per 100 km. Photo from BMW.

Figure 11. **Good**: The Tesla Roadster electric car. Energy consumption: 15 kWh per 100 km. www.teslamotors.com.

Figure 12. **Good**: The Aptera. 6 kWh per 100 km. Photo from www.aptera.com.

Bad: **Decentralized combined heat and power** is another looming mistake. Yes, combined heat and power (that is, putting individual power stations in each building, generating local electricity and heat to keep the buildings warm) can be a slightly more efficient way of using fossil fuels than the standard way (that is, centralized power stations and local condensing boilers). But they are only about 7% more efficient. And they use fossil fuels! Isn't the goal to get off fossil fuels? The fact is, there is a much better way to generate local heat: **heat pumps**. **Good**: Heat pumps are back-to-front refrigerators. Powered by electricity, they pump heat into the building from the outside – either from the air, or from the ground. The best heat pumps, recently developed in Japan, have a coefficient of performance of 4.9; this means that using 1 kWh of electricity, the heat pump delivers 4.9 kWh of heat in the form of hot air or hot water. This is a far more efficient way to use high-grade energy to make heat, than simply setting fire to high-grade chemicals, which achieves a coefficient of performance of only 0.9.

Figure 13. **Good**: The inner and outer bits of an air-source heat pump that has a coefficient of performance of 4. The inner bit is accompanied by a ball-point pen, for scale. One of these Fujitsu units can deliver 3.6 kW of heating when using just 0.845 kW of electricity. It can also run in reverse, delivering 2.6 kW of cooling when using 0.655 kW of electricity.

Figure 14. **Bad**: An Ampair "600 W" micro-turbine. The average power generated by this micro-turbine in Leamington Spa is 0.037 kWh per day (1.5 W).

Bad: **Roof-mounted micro-wind turbines** are an utter waste of resources. They never pay for themselves. **Good**: In contrast, **roof-mounted solar water heaters** are a no-brainer. They really work: even in Britain, where the sunniness is only about 30%, a modest 3-m^2 panel can supply half of a typical family's hot water.

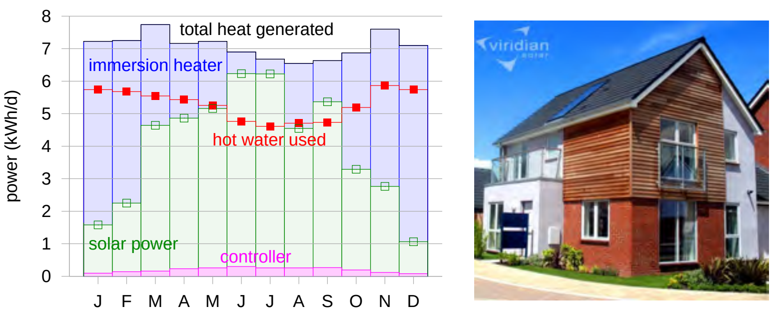


Figure 15. **Good**: Solar power generated by a 3 m^2 hot-water panel (green), and supplementary heat required (blue) to make hot water in the test house of Viridian Solar. (The photograph shows a house with the same model of panel on its roof.) The average solar power from 3 m^2 was 3.8 kWh/d. The experiment simulated the hot-water consumption of an average European household – 100 litres of hot (60 °C) water per day. The 1.5–2 kWh/d gap between the total heat generated (black line, top) and the hot water used (red line) is caused by heat-loss. The magenta line shows the electrical power required to run the solar system. The average power per unit area of these solar panels is 53 W/m^2.

Bad: **Turning phone chargers off** is a feeble gesture, like bailing the Titanic with a teaspoon. The widespread inclusion of "switching off phone chargers" in lists of "10 things you can do" is a *bad thing*, because it distracts attention from more-effective actions that people could be taking. **Good**: **Turning the thermostat down** is the single most effective energy-saving technology available to a typical person – every degree you turn it down will reduce your heating costs by 10%; and heating is likely to be the biggest form of energy consumption in most British buildings. Figure 16 shows data from my house.

This book isn't intended to be a definitive store of super-accurate numbers. Rather, it's intended to illustrate how to use approximate numbers as a part of constructive consensual conversations. This book doesn't advocate any particular energy plan or technology; rather, it tells you how many bricks are in the lego box, and how big each brick is, so the reader can figure out for himself how to make a plan that adds up.

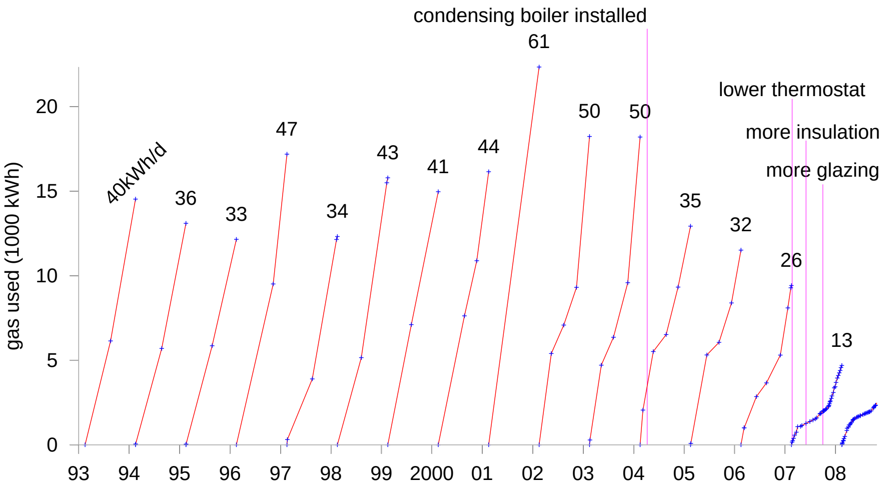


Figure 16. My domestic gas consumption, each year from 1993 to 2007. Each line shows the cumulative consumption during one year in kWh. The number at the end of each year is the average rate of consumption for that year, in kWh per day. Meter-readings are indicated by the blue points. Evidently, the more frequently I read my meter, the less gas I use!

Part III – Technical chapters

The third part of the book drills down to the physical foundations of energy consumption and energy production. Eight appendices show from first principles where the numbers in the first two parts come from. These appendices explain, for example, how cars can be made significantly more energy-efficient, and why planes cannot; and they explain how the power from wind farms, tide farms, and wave farms can all be calculated on the back of an envelope. Whereas the bulk of the book is intended to be accessible to everyone who can add, multiply, and divide, these technical appendices are aimed at readers who are comfortable with formulae like "$\frac{1}{2}mv^2$".

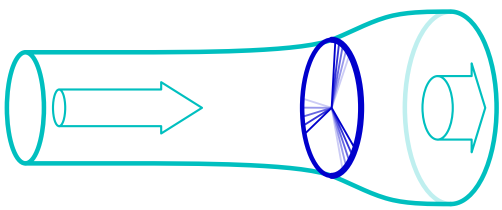


Figure 17. Flow of air past a windmill. The air is slowed down and splayed out by the windmill.

Part IV – Useful data

The final sixteen pages of the book contain further reference data and conversion factors, useful for applying the book's ideas to other countries, and for translating to and from units used by other organizations.

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Further information

The book is available for free online at www.withouthotair.com. The book is published by UIT Cambridge on 2nd December 2008 in the UK, and on 1st April 2009 in North America.

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