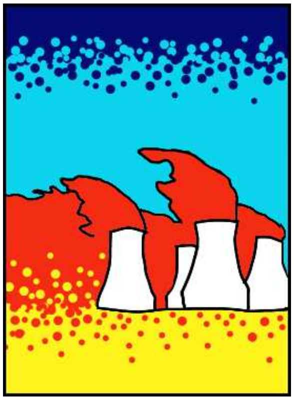
Part I

Numbers, not adjectives

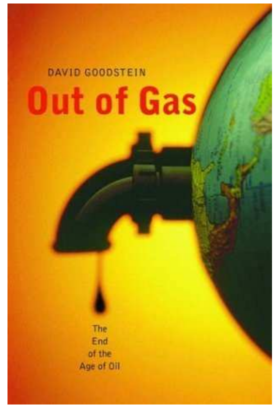


1 Motivations

We live at a time when emotions and feelings count more than truth, and there is a vast ignorance of science.

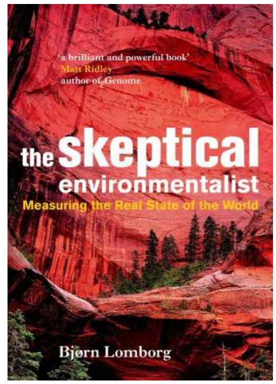
James Lovelock

I recently read two books, one by a physicist, and one by an economist. In *Out of Gas*, Caltech physicist David Goodstein describes an impending energy crisis brought on by The End of the Age of Oil. This crisis is coming soon, he predicts: the crisis will bite, not when the last drop of oil is extracted, but when oil extraction can't meet demand – perhaps as soon as 2015 or 2025. Moreover, even if we magically switched all our energy-guzzling to nuclear power right away, Goodstein says, the oil crisis would simply be replaced by a *nuclear* crisis in just twenty years or so, as uranium reserves also became depleted.



David Goodstein's *Out of Gas* (2004).

In *The Skeptical Environmentalist*, Bjørn Lomborg paints a completely different picture. "Everything is fine." Indeed, "everything is getting better." Furthermore, "we are not headed for a major energy crisis," and "there is plenty of energy."

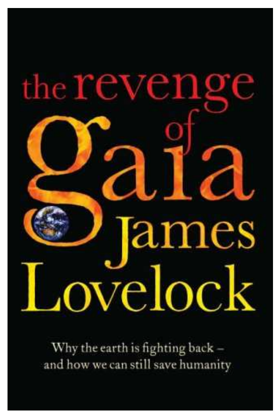


Bjørn Lomborg's *The Skeptical Environmentalist* (2001).

How could two smart people come to such different conclusions? I had to get to the bottom of this.

Energy made it into the British news in 2006. Kindled by tidings of great climate change and a tripling in the price of natural gas in just six years, the flames of debate are raging. How should Britain handle its energy needs? And how should the world?

"Wind or nuclear?", for example. Greater polarization of views among smart people is hard to imagine. During a discussion of the proposed expansion of nuclear power, Michael Meacher, former environment minister, said "if we're going to cut greenhouse gases by 60% . . . by 2050 there is no other possible way of doing that except through renewables;" Sir Bernard Ingham, former civil servant, speaking in favour of nuclear expansion, said "anybody who is relying upon renewables to fill the [energy] gap is living in an utter dream world and is, in my view, an enemy of the people."



The Revenge of Gaia: Why the earth is fighting back – and how we can still save humanity. James Lovelock (2006). © Allen Lane.

Similar disagreement can be heard within the ecological movement. All agree that *something* must be done urgently, but *what?* Jonathan Porritt, chair of the Sustainable Development Commission, writes: "there is no justification for bringing forward plans for a new nuclear power programme at this time, and . . . any such proposal would be incompatible with [the Government's] sustainable development strategy;" and "a non-nuclear strategy could and should be sufficient to deliver all the carbon savings we shall need up to 2050 and beyond, and to ensure secure access to reliable sources of energy." In contrast, environmentalist James Lovelock writes in his book, *The Revenge of Gaia*: "Now is much too late to establish sustainable development." In his view, power from nuclear fission, while not recommended as the long-term panacea for our ailing planet, is "the only effective medicine we have now." Onshore wind turbines are "merely ... a gesture to prove [our leaders'] environmental credentials."

This heated debate is fundamentally about numbers. How much energy could each source deliver, at what economic and social cost, and with what risks? But actual numbers are rarely mentioned. In public debates, people just say "Nuclear is a money pit" or "We have a *huge* amount of wave and wind." The trouble with this sort of language is that it's not sufficient to know that something is huge: we need to know how the one "huge" compares with another "huge," namely *our huge energy consumption*. To make this comparison, 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. "Los Angeles residents drive 142 million miles – the distance from Earth to Mars – every single day." "Each year, 27 million acres of tropical rainforest are destroyed." "14 billion pounds of trash are dumped into the sea every year." "British people throw away 2.6 billion slices of bread per year." "The waste paper buried each year in the UK could fill 103 448 double-decker buses."

If all the ineffective ideas for solving the energy crisis were laid end to end, they would reach to the moon and back. . . . I digress.

The result of this lack of meaningful numbers and facts? We are inundated with a flood of crazy innumerate codswallop. The BBC doles out advice on how we can do our bit to save the planet – for example "switch off your mobile phone charger when it's not in use;" if anyone objects that mobile phone chargers are not *actually* our number one form of energy consumption, the mantra "every little helps" is wheeled out. Every little helps? A more realistic mantra is:

if everyone does a little, we'll achieve only a little.

For the benefit of readers who speak American, rather than English, the translation of "every little helps" into American is "every little bit helps."

Companies also contribute to the daily codswallop as they tell us how wonderful they are, or how they can help us "do our bit." BP's website, for example, celebrates the reductions in carbon dioxide (CO_2) pollution they hope to achieve by changing the paint used for painting BP's ships. Does anyone fall for this? Surely everyone will guess that it's not the exterior paint job, it's the stuff *inside* the tanker that deserves attention, if society's CO_2 emissions are to be significantly cut? BP also created a web-based carbon absolution service, "`targetneutral.com`," which claims that they can "neutralize" all your carbon emissions, and that it "doesn't cost the earth" – indeed, that your CO_2 pollution can be cleaned up for just £40 per year. How can this add up? – if the true cost of fixing climate change were £40 per person then the government could fix it with the loose change in the Chancellor's pocket!

Even more reprehensible are companies that exploit the current concern for the environment by offering "water-powered batteries," "biodegradable mobile phones," "portable arm-mounted wind-turbines," and other pointless tat.

Campaigners also mislead. People who want to promote renewables over nuclear, for example, say "offshore wind power could power all UK homes;" then they say "new nuclear power stations will do little to tackle climate change" because 10 new nuclear stations would "reduce emissions only by about 4%." This argument is misleading because the playing field is switched half-way through, from the "number of homes powered" to "reduction of emissions." The truth is that the amount of electrical power generated by the wonderful windmills that "could power all UK homes" is *exactly the same* as the amount that would be generated by the 10 nuclear power stations! "Powering all UK homes" accounts for just 4% of UK emissions.

Perhaps the worst offenders in the kingdom of codswallop are the people who really should know better – the media publishers who promote the codswallop – for example, New Scientist with their article about the "water-powered car."*

*See this chapter's notes (p19) for the awful details. (Every chapter has endnotes giving references, sources, and details of arguments. To avoid distracting the reader, I won't include any more footnote marks in the text.)

In a climate where people don't understand the numbers, newspapers, campaigners, companies, and politicians can get away with murder.

We need simple numbers, and we need the numbers to be comprehensible, comparable, and memorable.

With numbers in place, we will be better placed to answer questions such as these:

1. Can a country like Britain conceivably live on its own renewable energy sources?
2. If everyone turns their thermostats one degree closer to the outside temperature, drives a smaller car, and switches off phone chargers when not in use, will an energy crisis be averted?
3. Should the tax on transportation fuels be significantly increased? Should speed-limits on roads be halved?
4. Is someone who advocates windmills over nuclear power stations "an enemy of the people"?
5. If climate change is "a greater threat than terrorism," should governments criminalize "the glorification of travel" and pass laws against "advocating acts of consumption"?
6. Will a switch to "advanced technologies" allow us to eliminate carbon dioxide pollution without changing our lifestyle?
7. Should people be encouraged to eat more vegetarian food?
8. Is the population of the earth six times too big?

Figure 1.1. This Greenpeace leaflet arrived with my junk mail in May 2006. Do beloved windmills have the capacity to displace hated cooling towers?

Why are we discussing energy policy?

Three different motivations drive today's energy discussions.

First, fossil fuels are a finite resource. It seems possible that cheap oil (on which our cars and lorries run) and cheap gas (with which we heat many of our buildings) will run out in our lifetime. So we seek alternative energy sources. Indeed given that fossil fuels are a valuable resource, useful for manufacture of plastics and all sorts of other creative stuff, perhaps we should save them for better uses than simply setting fire to them.

Second, we're interested in security of energy supply. Even if fossil fuels are still available somewhere in the world, perhaps we don't want to depend on them if that would make our economy vulnerable to the whims of untrustworthy foreigners. (I hope you can hear my tongue in my cheek.) Going by figure 1.2, it certainly looks as if "our" fossil fuels have peaked. The UK has a particular security-of-supply problem looming, known as the "energy gap." A substantial number of old coal power stations and nuclear power stations will be closing down during the next decade (figure 1.3), so there is a risk that electricity demand will sometimes exceed electricity supply, if adequate plans are not implemented.

Third, it's very probable that using fossil fuels changes the climate. Climate change is blamed on several human activities, but the biggest contributor to climate change is the increase in greenhouse effect produced by carbon dioxide (CO_2). Most of the carbon dioxide emissions come from fossil-fuel burning. And the main reason we burn fossil fuels is for energy. So to fix climate change, we need to sort out a new way of getting energy. The climate problem is mostly an energy problem.

Whichever of these three concerns motivates you, we need energy numbers, and policies that add up.

The first two concerns are straightforward selfish motivations for drastically reducing fossil fuel use. The third concern, climate change, is a more altruistic motivation – the brunt of climate change will be borne not by us but by future generations over many hundreds of years. Some people feel that climate change is not their responsibility. They say things like "What's the point in my doing anything? China's out of control!" So I'm going to discuss climate change a bit more now, because while writing this book I learned some interesting facts that shed light on these ethical questions. If you have no interest in climate change, feel free to fast-forward to the next section on page 16.

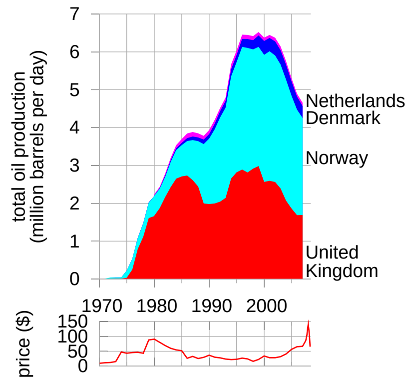


Figure 1.2. Are "our" fossil fuels running out? Total crude oil production from the North Sea, and oil price in 2006 dollars per barrel.

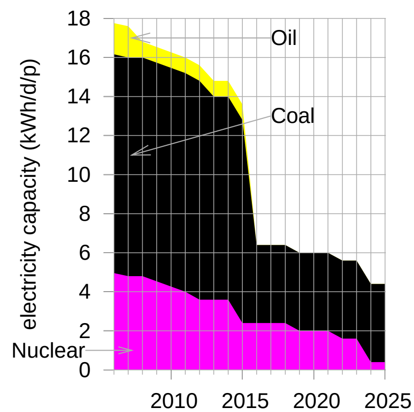


Figure 1.3. The energy gap created by UK power station closures, as projected by energy company EdF. This graph shows the predicted capacity of nuclear, coal, and oil power stations, in kilowatt-hours per day per person. The capacity is the maximum deliverable power of a source.

The climate-change motivation

The climate-change motivation is argued in three steps: one: human fossil-fuel burning causes carbon dioxide concentrations to rise; two: carbon dioxide is a greenhouse gas; three: increasing the greenhouse effect increases average global temperatures (and has many other effects).

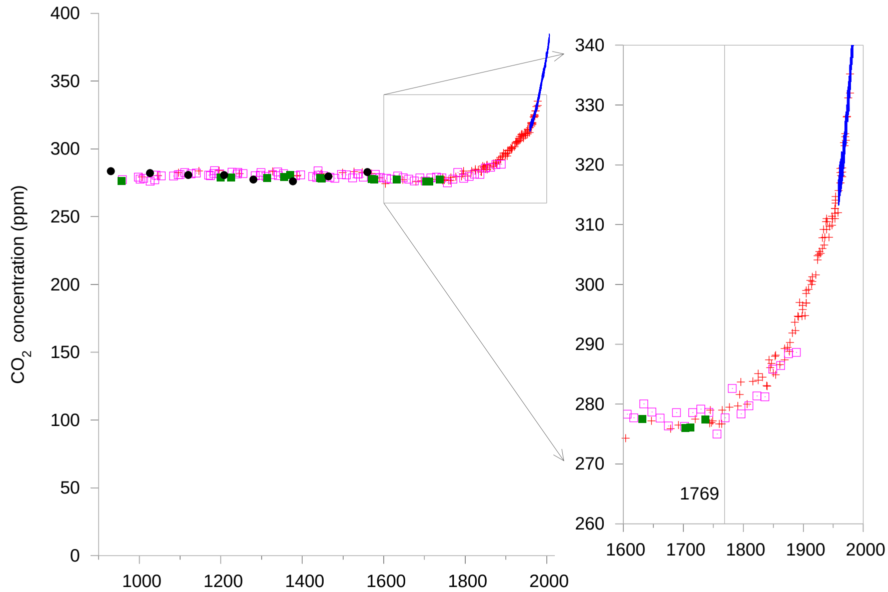


Figure 1.4. Carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards).

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.)

We start with the fact that carbon dioxide concentrations are rising. Figure 1.4 shows measurements of the CO_2 concentration in the air from the year 1000 AD to the present. Some "sceptics" have asserted that the recent increase in CO_2 concentration is a natural phenomenon. Does "sceptic" mean "a person who has not even glanced at the data"? Don't you think, just possibly, *something* may have happened between 1800 AD and 2000 AD? Something that was not part of the natural processes present in the preceding thousand years?

Something did happen, and it was called the Industrial Revolution. I've marked on the graph the year 1769, in which James Watt patented his steam engine. While the first practical steam engine was invented in 1698, Watt's more efficient steam engine really got the Industrial Revolution going. One of the steam engine's main applications was the pumping of water out of coal mines. Figure 1.5 shows what happened to British coal production from 1769 onwards. The figure displays coal production in units of billions of tons of CO_2 released when the coal was burned. In 1800, coal was used to make iron, to make ships, to heat buildings, to power locomotives and other machinery, and of course to power the pumps that enabled still more coal to be scraped up from inside the hills of England and Wales. Britain was terribly well endowed with coal: when the Revolution started, the amount of carbon sitting in coal under Britain was roughly the same as the amount sitting in oil under Saudi Arabia.

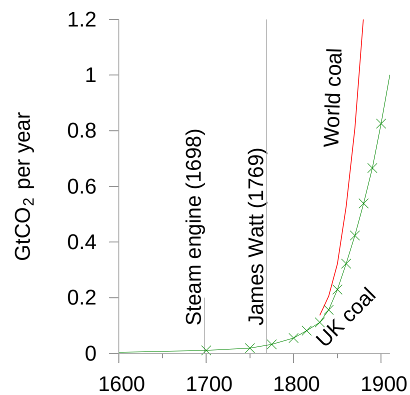
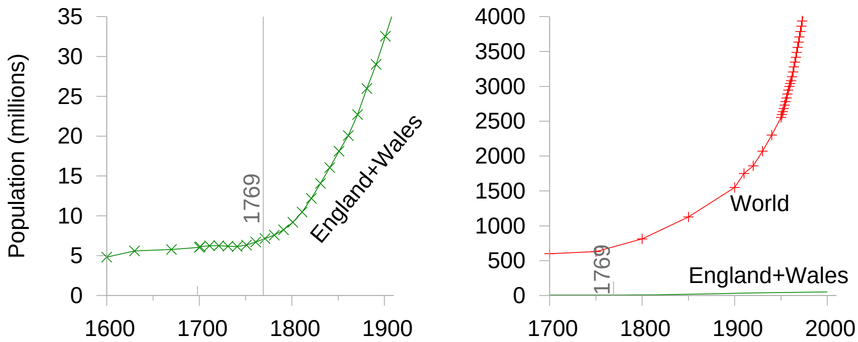
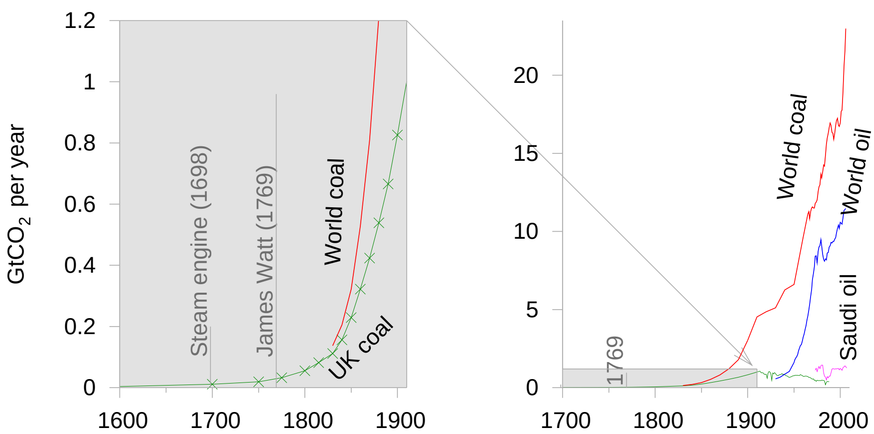


Figure 1.5. The history of UK coal production and world coal production from 1600 to 1910. Production rates are shown in billions of tons of CO_2 – an incomprehensible unit, yes, but don't worry: we'll personalize it shortly.

In the 30 years from 1769 to 1800, Britain's annual coal production doubled. After another 30 years (1830), it had doubled again. The next doubling of production-rate happened within *20* years (1850), and another doubling within 20 years of that (1870). This coal allowed Britain to turn the globe pink. The prosperity that came to England and Wales was reflected in a century of unprecedented population growth:



Eventually other countries got in on the act too as the Revolution spread. Figure 1.6 shows British coal production and world coal production on the same scale as figure 1.5, sliding the window of history 50 years later. British coal production peaked in 1910, but meanwhile world coal production continued to double every 20 years. It's difficult to show the history of coal production on a single graph. To show what happened in the *next* 50 years on the same scale, the book would need to be one metre tall! To cope with this difficulty, we can either scale down the vertical axis:



or we can squish the vertical axis in a non-uniform way, so that small quantities and large quantities can be seen at the same time on a single graph. A good way to squish the axis is called a logarithmic scale, and that's what I've used in the bottom two graphs of figure 1.7 (p9). On a logarithmic scale, all ten-fold increases (from 1 to 10, from 10 to 100, from 100 to 1000) are represented by equal distances on the page. On a logarithmic scale, a quantity that grows at a constant percentage per year (which is called "exponential growth") looks like a straight line. Logarithmic graphs are great

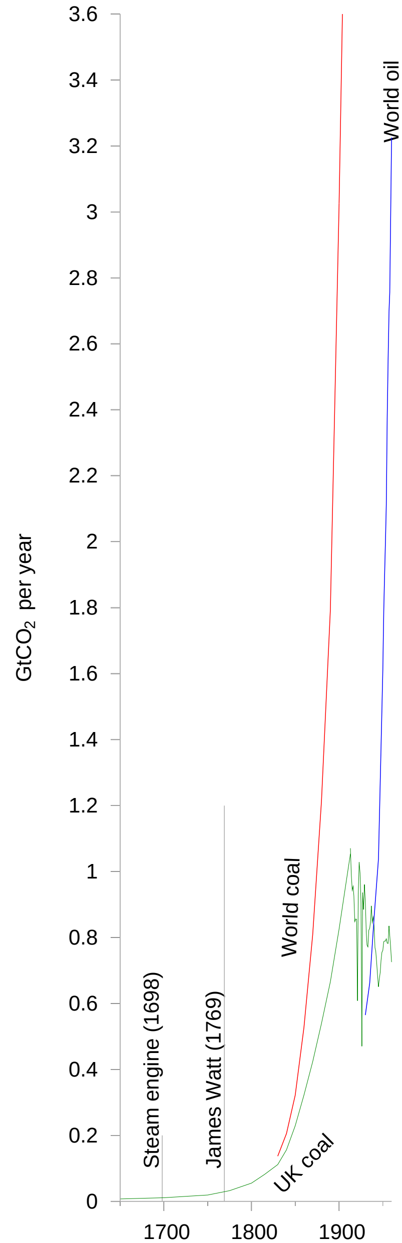


Figure 1.6. What happened next.
The history of UK coal production and world coal production from 1650 to 1960, on the same scale as figure 1.5.

for understanding growth. Whereas the ordinary graphs in the figures on pages 6 and 7 convey the messages that British and world coal production grew remarkably, and that British and world population grew remarkably, the relative growth rates are not evident in these ordinary graphs. The logarithmic graphs allow us to compare growth rates. Looking at the slopes of the population curves, for example, we can see that the world population's growth rate in the last 50 years was a little bigger than the growth rate of England and Wales in 1800.

From 1769 to 2006, world annual coal production increased 800-fold. Coal production is still increasing today. Other fossil fuels are being extracted too – the middle graph of figure 1.7 shows oil production for example – but in terms of CO_2 emissions, coal is still king.

The burning of fossil fuels is the principal reason why CO_2 concentrations have gone up. This is a fact, but, hang on: I hear a persistent buzzing noise coming from a bunch of climate-change inactivists. What are they saying? Here's Dominic Lawson, a columnist from the *Independent*:

> "The burning of fossil fuels sends about seven gigatons of CO_2 per year into the atmosphere, which sounds like a lot. Yet the biosphere and the oceans send about 1900 gigatons and 36 000 gigatons of CO_2 per year into the atmosphere – . . . one reason why some of us are sceptical about the emphasis put on the role of human fuel-burning in the greenhouse gas effect. Reducing man-made CO_2 emissions is megalomania, exaggerating man's significance. Politicians can't change the weather."

Now I have a lot of time for scepticism, and not everything that sceptics say is a crock of manure – but irresponsible journalism like Dominic Lawson's deserves a good flushing.

The first problem with Lawson's offering is that *all three numbers* that he mentions (seven, 1900, and 36 000) are *wrong!* The correct numbers are 26, 440, and 330. Leaving these errors to one side, let's address Lawson's main point, the relative smallness of man-made emissions.

Yes, natural flows of CO_2 *are* larger than the additional flow we switched on 200 years ago when we started burning fossil fuels in earnest. But it is terribly misleading to quantify only the large natural flows *into* the atmosphere, failing to mention the almost exactly equal flows *out* of the atmosphere back into the biosphere and the oceans. The point is that these *natural* flows in and out of the atmosphere have been almost exactly in balance for millenia. So it's not relevant at all that these natural flows are larger than human emissions. The natural flows *cancelled themselves out*. So the natural flows, large though they were, left the concentration of CO_2 in the atmosphere and ocean *constant*, over the last few thousand years. Burning fossil fuels, in contrast, creates a *new* flow of carbon that, though small, is *not cancelled*. Here's a simple analogy, set in the passport-control arrivals area of an airport. One thousand passengers arrive per hour, and

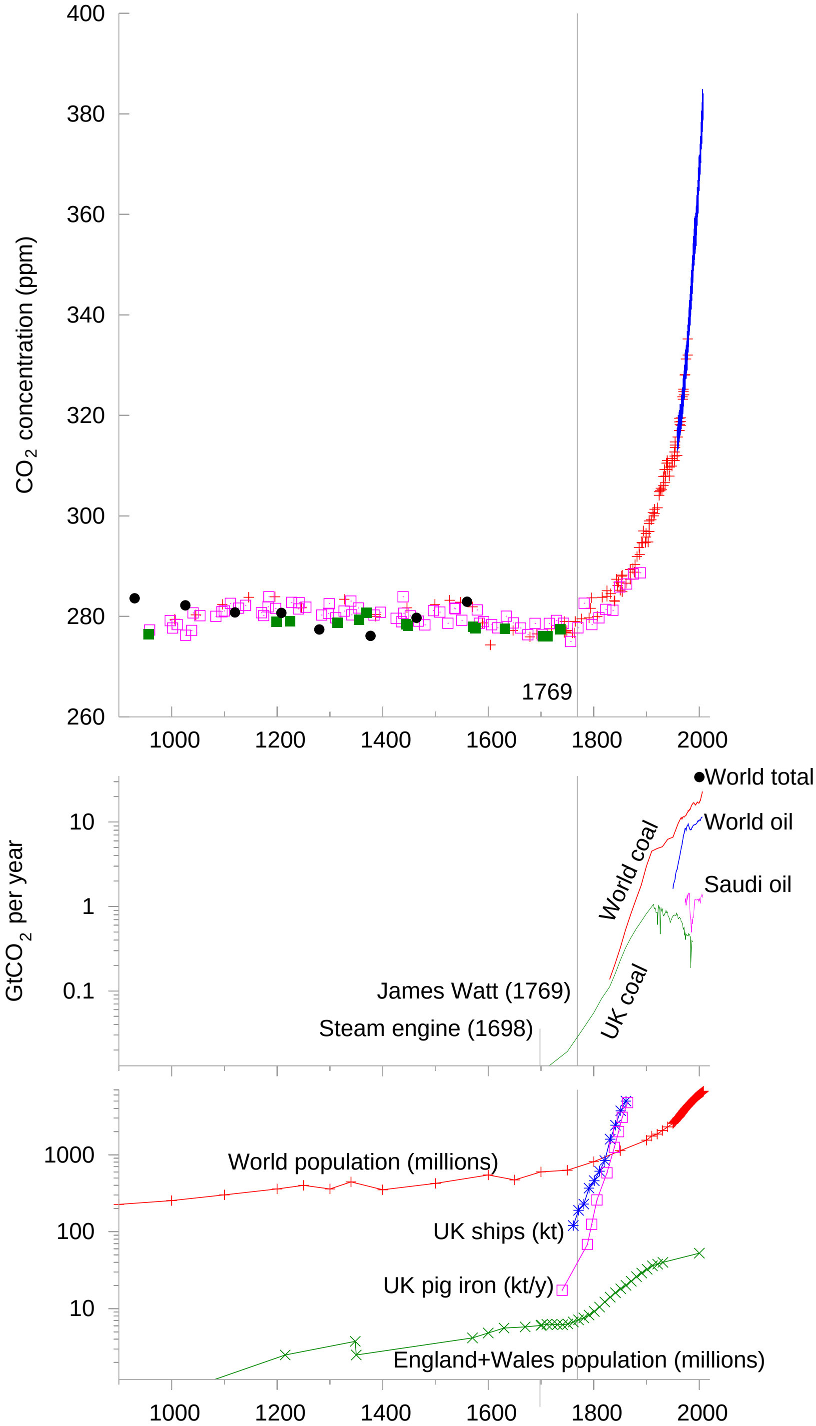


Figure 1.7. The upper graph shows carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years – the same data that was shown in figure 1.4.

Here's a portrait of James Watt and his 1769 steam engine.

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 production rates are expressed in units of the associated CO_2 emissions.

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 growth in the tonnage of British ships (in thousand tons).

In contrast to the ordinary graphs on the previous pages, the logarithmic scale allows us to show both the population of England and the population of the World on a single diagram, and to see interesting features in both.

there are exactly enough clockwork officials to process one thousand passengers per hour. There's a modest queue, but because of the match of arrival rate to service rate, the queue isn't getting any longer. Now imagine that owing to fog an extra stream of flights is diverted here from a smaller airport. This stream adds an extra 50 passengers per hour to the arrivals lobby – a small addition compared to the original arrival rate of one thousand per hour. Initially at least, the authorities don't increase the number of officials, and the officials carry on processing just one thousand passengers per hour. So what happens? Slowly but surely, *the queue grows*. Burning fossil fuels is undeniably increasing the CO_2 concentration in the atmosphere and in the surface oceans. No climate scientist disputes this fact. When it comes to CO_2 concentrations, man *is* significant.

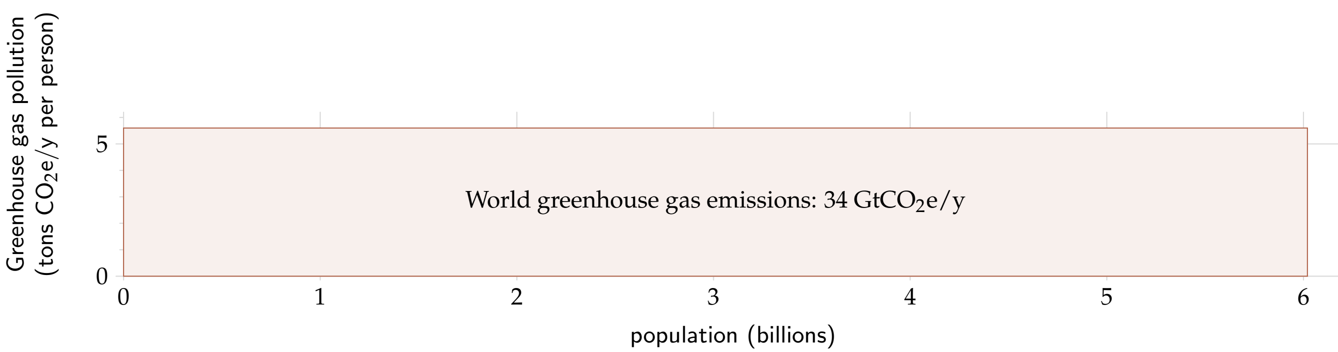
OK. Fossil fuel burning increases CO_2 concentrations significantly. But does it matter? "Carbon is nature!", the oilspinners remind us, "Carbon is life!" If CO_2 had no harmful effects, then indeed carbon emissions would not matter. However, carbon dioxide is a greenhouse gas. Not the strongest greenhouse gas, but a significant one nonetheless. Put more of it in the atmosphere, and it does what greenhouse gases do: it absorbs infrared radiation (heat) heading out from the earth and reemits it in a random direction; the effect of this random redirection of the atmospheric heat traffic is to impede the flow of heat from the planet, just like a quilt. So carbon dioxide has a warming effect. This fact is based not on complex historical records of global temperatures but on the simple physical properties of CO_2 molecules. Greenhouse gases are a quilt, and CO_2 is one layer of the quilt.

So, if humanity succeeds in doubling or tripling CO_2 concentrations (which is where we are certainly heading, under business as usual), what happens? Here, there is a lot of uncertainty. Climate science is difficult. The climate is a complex, twitchy beast, and exactly how much warming CO_2-doubling would produce is uncertain. The consensus of the best climate models seems to be that doubling the CO_2 concentration would have roughly the same effect as increasing the intensity of the sun by 2%, and would bump up the global mean temperature by something like 3 °C. This would be what historians call a Bad Thing. I won't recite the whole litany of probable drastic effects, as I am sure you've heard it before. The litany begins "the Greenland icecap would gradually melt, and, over a period of a few 100 years, sea-level would rise by about 7 metres." The brunt of the litany falls on future generations. Such temperatures have not been seen on earth for at least 100 000 years, and it's conceivable that the ecosystem would be so significantly altered that the earth would stop supplying some of the goods and services that we currently take for granted.

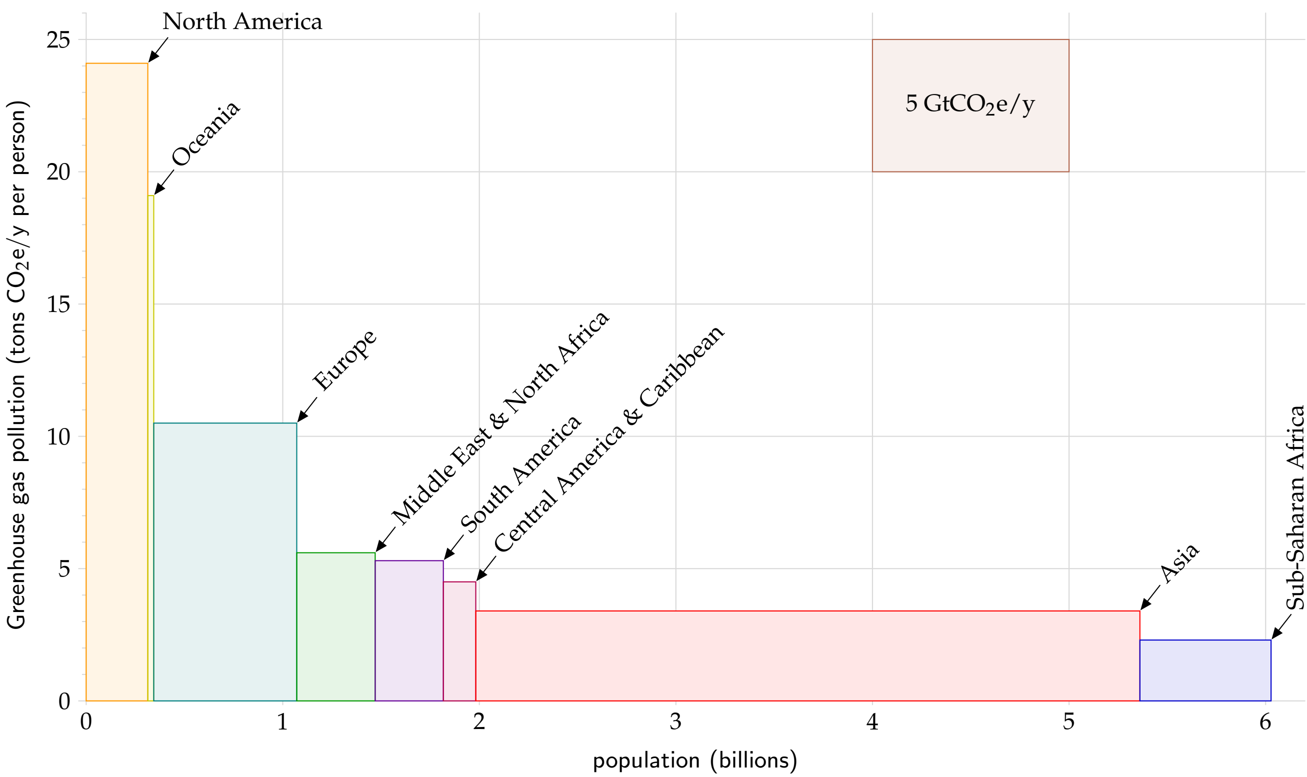
Climate modelling is difficult and is dogged by uncertainties. But uncertainty about exactly how the climate will respond to extra greenhouse gases is no justification for inaction. If you were riding a fast-moving motorcycle in fog near a cliff-edge, and you didn't have a good map of the cliff, would the lack of a map justify *not* slowing the bike down?

So, who should slow the bike down? Who should clean up carbon emissions? Who is responsible for climate change? This is an ethical question, of course, not a scientific one, but ethical discussions must be founded on facts. Let's now explore the facts about greenhouse gas emissions. First, a word about the units in which they are measured. Greenhouse gases include carbon dioxide, methane, and nitrous oxide; each gas has different physical properties; it's conventional to express all gas emissions in "equivalent amounts of carbon dioxide," where "equivalent" means "having the same warming effect over a period of 100 years." One ton of carbon-dioxide-equivalent may be abbreviated as "1 t CO_2e," and one billion tons (one thousand million tons) as "1 Gt CO_2e" (one gigaton). In this book 1 t means one metric ton (1000 kg). I'm not going to distinguish imperial tons, because they differ by less than 10% from the metric ton or tonne.

In the year 2000, the world's greenhouse gas emissions were about 34 billion tons of CO_2-equivalent per year. An incomprehensible number. But we can render it more comprehensible and more personal by dividing by the number of people on the planet, 6 billion, so as to obtain the greenhouse-gas pollution *per person*, which is about $5^1/_2$ tons CO_2e per year per person. We can thus represent the world emissions by a rectangle whose width is the population (6 billion) and whose height is the per-capita emissions.



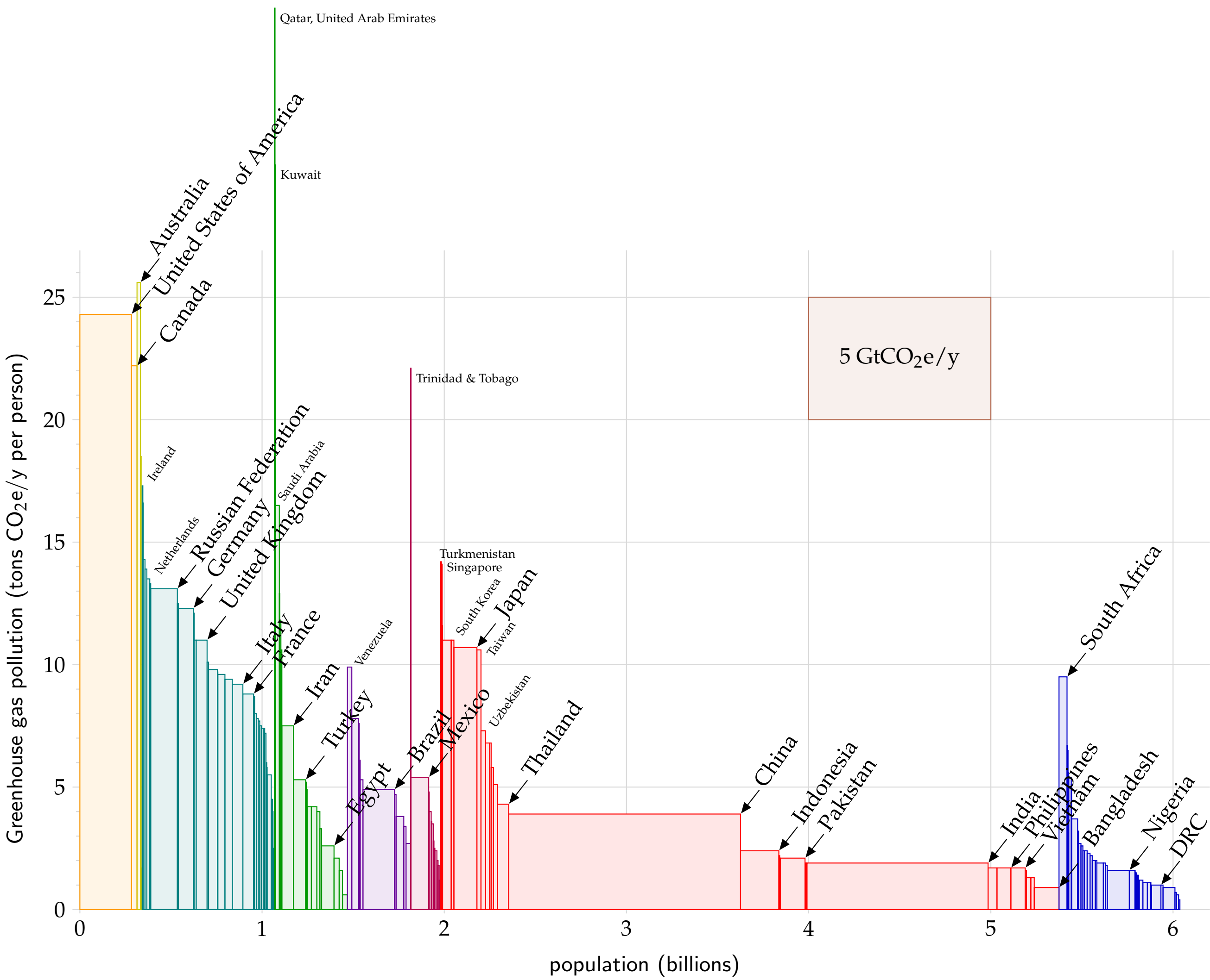
Now, all people are created equal, but we don't all emit 5½ tons of CO_2 per year. We can break down the emissions of the year 2000, showing how the 34-billion-ton rectangle is shared between the regions of the world:



This picture, which is on the same scale as the previous one, divides the world into eight regions. Each rectangle's area represents the greenhouse gas emissions of one region. The width of the rectangle is the population of the region, and the height is the average per-capita emissions in that region.

In the year 2000, Europe's per-capita greenhouse gas emissions were twice the world average; and North America's were four times the world average.

We can continue subdividing, splitting each of the regions into countries. This is where it gets really interesting:

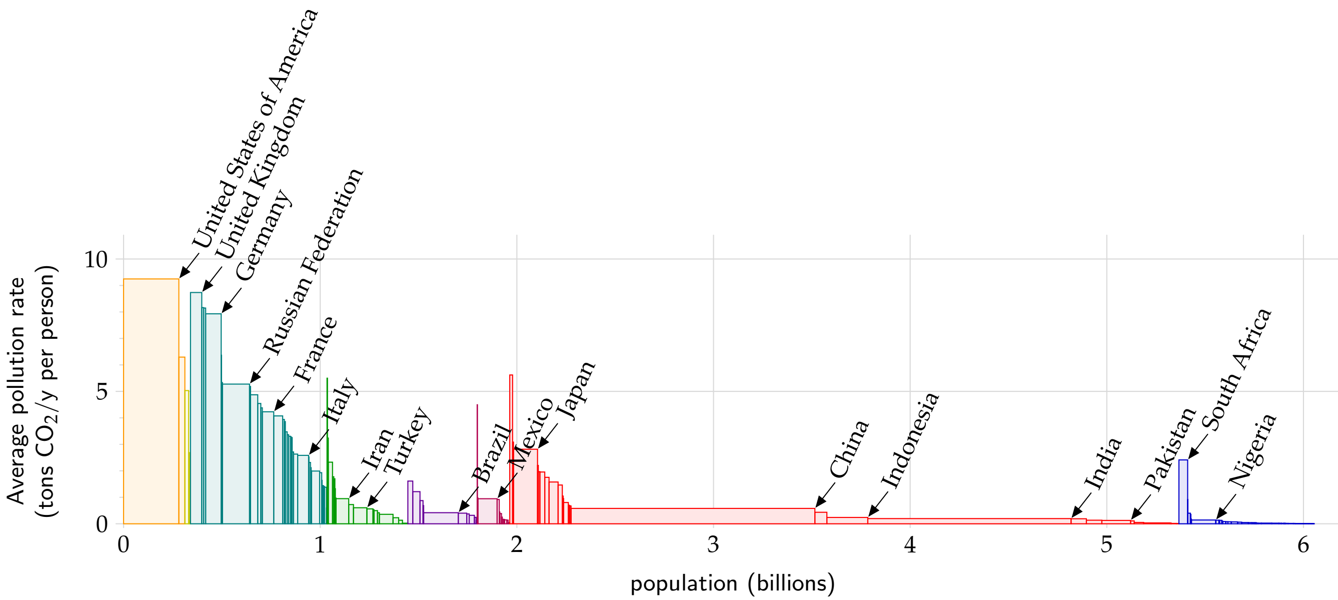


The major countries with the biggest per-capita emissions are Australia, the USA, and Canada. European countries, Japan, and South Africa are notable runners up. Among European countries, the United Kingdom is resolutely average. What about China, that naughty "out of control" country? Yes, the area of China's rectangle is about the same as the USA's, but the fact is that their per-capita emissions are *below* the world average. India's per-capita emissions are less than *half* the world average. Moreover, it's worth bearing in mind that much of the industrial emissions of China and India are associated with the manufacture of *stuff for rich countries*.

So, assuming that "something needs to be done" to reduce greenhouse gas emissions, who has a special responsibility to do something? As I said, that's an ethical question. But I find it hard to imagine any system of ethics that denies that the responsibility falls especially on the countries to the left hand side of this diagram – the countries whose emissions are two, three, or four times the world average. Countries that are most able to pay. Countries like Britain and the USA, for example.

Historical responsibility for climate impact

If we assume that the climate has been damaged by human activity, and that someone needs to fix it, who should pay? Some people say "the polluter should pay." The preceding pictures showed who's doing the polluting today. But it isn't the *rate* of CO_2 pollution that matters, it's the cumulative *total* emissions; much of the emitted carbon dioxide (about one third of it) will hang around in the atmosphere for at least 50 or 100 years. If we accept the ethical idea that "the polluter should pay" then we should ask how big is each country's historical footprint. The next picture shows each country's cumulative emissions of CO_2, expressed as an average emission rate over the period 1880–2004.



Congratulations, Britain! The UK has made it onto the winners' podium. We may be only an average European country today, but in the table of historical emitters, per capita, we are second only to the USA.

OK, that's enough ethics. What do scientists reckon needs to be done, to avoid a risk of giving the earth a 2 °C temperature rise (2 °C being the rise above which they predict lots of bad consequences)? The consensus is clear. We need to get off our fossil fuel habit, and we need to do so fast. Some countries, including Britain, have committed to at least a 60% reduction in greenhouse-gas emissions by 2050, but it must be emphasized that 60% cuts, radical though they are, are unlikely to cut the mustard. If the world's emissions were gradually reduced by 60% by 2050, climate scientists reckon it's more likely than not that global temperatures will rise by more than 2 °C. The sort of cuts we need to aim for are shown in figure 1.8. This figure shows two possibly-safe emissions scenarios presented by Baer and Mastrandrea (2006) in a report from the Institute for Public Policy Research. The lower curve assumes that a decline in emissions started in 2007, with total global emissions falling at roughly 5% per year. The upper curve assumes a brief delay in the start of the decline, and a 4% drop per year in global emissions. Both scenarios are believed to offer a modest chance of avoiding a 2 °C temperature rise above the pre-industrial level. In the lower scenario, the chance that the temperature rise will *exceed* 2 °C is estimated to be 9–26%. In the upper scenario, the chance of exceeding 2 °C is estimated to be 16–43%. These possibly-safe emissions trajectories, by the way, involve significantly sharper reductions in emissions than any of the scenarios presented by the Intergovernmental Panel on Climate Change (IPCC), or by the Stern Review (2007).

These possibly-safe trajectories require global emissions to fall by 70% or 85% by 2050. What would this mean for a country like Britain? If we subscribe to the idea of "contraction and convergence," which means that all countries aim eventually to have equal per-capita emissions, then Britain needs to aim for cuts greater than 85%: it should get down from its current 11 tons of CO_2e per year per person to roughly 1 ton per year per

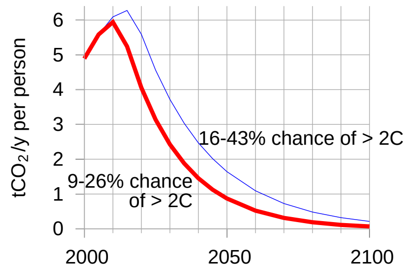


Figure 1.8. Global emissions for two scenarios considered by Baer and Mastrandrea, expressed in tons of CO_2 per year per person, using a world population of six billion. Both scenarios are believed to offer a modest chance of avoiding a 2 °C temperature rise above the pre-industrial level.

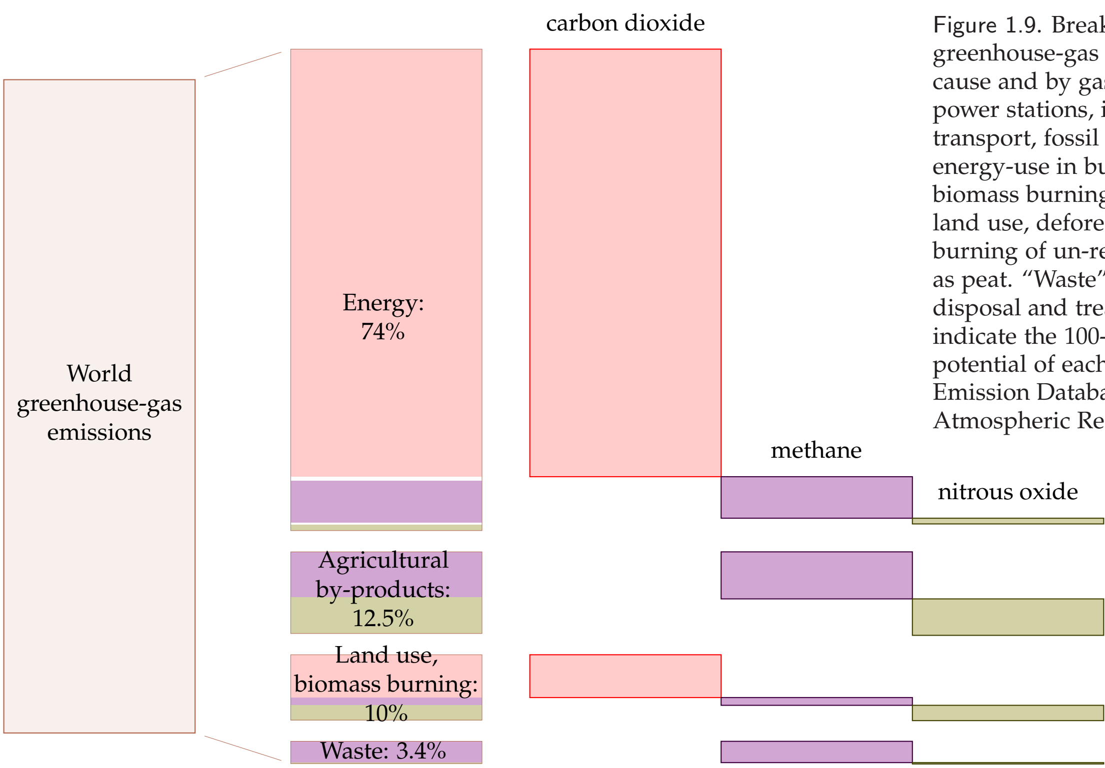


Figure 1.9. Breakdown of world greenhouse-gas emissions (2000) by cause and by gas. "Energy" includes power stations, industrial processes, transport, fossil fuel processing, and energy-use in buildings. "Land use, biomass burning" means changes in land use, deforestation, and the burning of un-renewed biomass such as peat. "Waste" includes waste disposal and treatment. The sizes indicate the 100-year global warming potential of each source. Source: Emission Database for Global Atmospheric Research.

person by 2050. This is such a deep cut, I suggest the best way to think about it is *no more fossil fuels*.

One last thing about the climate-change motivation: while a range of human activities cause greenhouse-gas emissions, the biggest cause by far is **energy use**. Some people justify not doing anything about their energy use by excuses such as "methane from burping cows causes more warming than jet travel." Yes, agricultural by-products contributed one eighth of greenhouse-gas emissions in the year 2000. But energy-use contributed three quarters (figure 1.9). The climate change problem is principally an energy problem.

Warnings to the reader

OK, enough about climate change. I'm going to assume we are motivated to get off fossil fuels. Whatever your motivation, the aim of this book is to help you figure out the numbers and do the arithmetic so that you can evaluate policies; and to lay a factual foundation so that you can see *which proposals add up*. I'm not claiming that the arithmetic and numbers in this book are new; the books I've mentioned by Goodstein, Lomborg, and Lovelock, for example, are full of interesting numbers and back-of-envelope calculations, and there are many other helpful sources on the internet too (see the notes at the end of each chapter).

What I'm aiming to do in this book is to make these numbers simple and memorable; to show you how you can figure out the numbers for yourself; and to make the situation so clear that any thinking reader will be able to draw striking conclusions. I don't want to feed you my own conclusions. Convictions are stronger if they are self-generated, rather than taught. Understanding is a creative process. When you've read this book I hope you'll have reinforced the confidence that you can figure anything out.

I'd like to emphasize that the calculations we will do are deliberately imprecise. Simplification is a key to understanding. First, by rounding the numbers, we can make them easier to remember. Second, rounded numbers allow quick calculations. For example, in this book, the population of the United Kingdom is 60 million, and the population of the world is 6 billion. I'm perfectly capable of looking up more accurate figures, but accuracy would get in the way of fluent thought. For example, if we learn that the world's greenhouse gas emissions in 2000 were 34 billion tons of CO_2-equivalent per year, then we can instantly note, without a calculator, that the average emissions per person are 5 or 6 tons of CO_2-equivalent per person per year. This rough answer is not exact, but it's accurate enough to inform interesting conversations. For instance, if you learn that a round-trip intercontinental flight emits nearly two tons of CO_2 per passenger, then knowing the average emissions yardstick (5-and-a-bit tons per year per person) helps you realize that just one such plane-trip per year corre-

"Look – it's Low Carbon Emission Man"

Figure 1.10. Reproduced by kind permission of PRIVATE EYE / Peter Dredge `www.private-eye.co.uk`.

sponds to over a third of the average person's carbon emissions.

I like to base my calculations on everyday knowledge rather than on trawling through impersonal national statistics. For example, if I want to estimate the typical wind speeds in Cambridge, I ask "is my cycling speed usually faster than the wind?" The answer is yes. So I can deduce that the wind speed in Cambridge is only rarely faster than my typical cycling speed of 20 km/h. I back up these everyday estimates with other peoples' calculations and with official statistics. (Please look for these in each chapter's end-notes.) 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.

In the calculations, I'll mainly use the United Kingdom and occasionally Europe, America, or the whole world, but you should find it easy to redo the calculations for whatever country or region you are interested in.

Let me close this chapter with a few more warnings to the reader. Not only will we make a habit of approximating the numbers we calculate; we'll also neglect all sorts of details that investors, managers, and economists have to attend to, poor folks. If you're trying to launch a renewable technology, just a 5% increase in costs may make all the difference between success and failure, so in business every detail must be tracked. But 5% is too small for this book's radar. This is a book about factors of 2 and factors of 10. It's about physical limits to sustainable energy, not current economic feasibility. While economics is always changing, the fundamental limits won't ever go away. We need to understand these limits.

Debates about energy policy are often confusing and emotional because people mix together *factual* assertions and *ethical* assertions.

Examples of **factual assertions** are "global fossil-fuel burning emits 34 billion tons of carbon dioxide equivalent per year;" and "if CO_2 concentrations are doubled then average temperatures will increase by 1.5–5.8°C in the next 100 years;" and "a temperature rise of 2°C would cause the Greenland ice cap to melt within 500 years;" and "the complete melting of the Greenland ice cap would cause a 7-metre sea-level rise."

A factual assertion is either true or false; figuring out *which* may be difficult; it is a scientific question. For example, the assertions I just gave are either true or false. But we don't know whether they are all true. Some of them are currently judged "very likely." The difficulty of deciding which factual assertions are true leads to debates in the scientific community. But given sufficient scientific experiment and discussion, the truth or falsity of most factual assertions can eventually be resolved, at least "beyond reasonable doubt."

Examples of **ethical assertions** are "it's wrong to exploit global resources in a way that imposes significant costs on future generations;" and "polluting should not be free;" and "we should take steps to ensure that it's unlikely that CO_2 concentrations will double;" and "politicians should agree a cap on CO_2 emissions;" and "countries with the biggest CO_2 emissions over the last century have a duty to lead action on climate change;" and "it is fair to share CO_2 emission rights equally across the world's population." Such assertions are not "either true or false." Whether we agree with them depends on our ethical judgment, on our values. Ethical assertions may be incompatible with each other; for example, Tony Blair's government declared a radical policy on CO_2 emissions: "the United Kingdom should reduce its CO_2 emissions by 60% by 2050;" at the same time Gordon Brown, while Chancellor in that government, repeatedly urged oil-producing countries to *increase* oil production.

This book is emphatically intended to be about facts, not ethics. I want the facts to be clear, so that people can have a meaningful debate about ethical decisions. I want everyone to understand how the facts constrain the options that are open to us. Like a good scientist, I'll try to keep my views on ethical questions out of the way, though occasionally I'll blurt something out – please forgive me.

Whether it's *fair* for Europe and North America to hog the energy cake is an ethical question; I'm here to remind you of the *fact* that we can't have our cake and eat it too; to help you weed out the pointless and ineffective policy proposals; and to help you identify energy policies that are compatible with your personal values.

We need a plan that adds up!

"Okay – it's agreed; we announce – 'to do nothing is not an option!' then we wait and see how things pan out. . . "

Figure 1.11. Reproduced by kind permission of PRIVATE EYE / Paul Lowe `www.private-eye.co.uk`.

Notes and further reading

At the end of each chapter I note details of ideas in that chapter, sources of data and quotes, and pointers to further information.

page no.

2 *". . . no other possible way of doing that except through renewables"*; *"anybody who is relying upon renewables to fill the [energy] gap is living in an utter dream world and is, in my view, an enemy of the people."* The quotes are from *Any Questions?*, 27 January 2006, BBC Radio 4 [`ydoobr`] . *Michael Meacher* was UK environment minister from 1997 till 2003. *Sir Bernard Ingham* was an aide to Margaret Thatcher when she was prime minister, and was Head of the Government Information Service. He is secretary of Supporters of Nuclear Energy.

– *Jonathan Porritt* (March 2006). *Is nuclear the answer?* Section 3. Advice to Ministers. `www.sd-commission.org.uk`

3 *"Nuclear is a money pit"*, *"We have a huge amount of wave and wind."* Ann Leslie, journalist. Speaking on *Any Questions?*, Radio 4, 10 February 2006.

– *Los Angeles residents drive . . . from Earth to Mars* – (The Earthworks Group, 1989, page 34).

– `targetneutral.com` charges just £4 per ton of CO_2 for their "neutralization." (A significantly lower price than any other "offsetting" company I have come across.) At this price, a typical Brit could have his 11 tons per year "neutralized" for just £44 per year! Evidence that BP's "neutralization" schemes don't really add up comes from the fact that its projects have not achieved the Gold Standard `www.cdmgoldstandard.org` (Michael Schlup, personal communication). Many "carbon offset" projects have been exposed as worthless by Fiona Harvey of the Financial Times [`2jhve6`].

4 *People who want to promote renewables over nuclear, for example, say "offshore wind power could power all UK homes."* At the end of 2007, the UK government announced that they would allow the building of offshore wind

turbines "enough to power all UK homes." Friends of the Earth's renewable energy campaigner, Nick Rau, said the group welcomed the government's announcement. "The potential power that could be generated by this industry is enormous," he said. [25e59w]. From the Guardian [5o7mxk]: John Sauven, the executive director of Greenpeace, said that the plans amounted to a "wind energy revolution." "And Labour needs to drop its obsession with nuclear power, which could only ever reduce emissions by about 4% at some time in the distant future." Nick Rau said: "We are delighted the government is getting serious about the potential for offshore wind, which could generate 25% of the UK's electricity by 2020." A few weeks later, the government announced that it would permit new nuclear stations to be built. "Today's decision to give the go-ahead to a new generation of nuclear power stations . . . will do little to tackle climate change," Friends of the Earth warned [5c4olc].

In fact, the two proposed expansions – of offshore wind and of nuclear – would both deliver just the same amount of electricity per year. The total permitted offshore wind power of 33 GW would on average deliver 10 GW, which is 4 kWh per day per person; and the replacement of all the retiring nuclear power stations would deliver 10 GW, which is 4 kWh per day per person. Yet in the same breath, anti-nuclear campaigners say that the nuclear option would "do little," while the wind option would "power all UK homes." The fact is, "powering all UK homes" and "only reducing emissions by about 4%" are the same thing.

4 *"water-powered car" New Scientist*, 29th July 2006, p. 35. This article, headlined "Water-powered car might be available by 2009," opened thus:

"Forget cars fuelled by alcohol and vegetable oil. Before long, you might be able to run your car with nothing more than water in its fuel tank. It would be the ultimate zero-emissions vehicle.

"While water is not at first sight an obvious power source, it has a key virtue: it is an abundant source of hydrogen, the element widely touted as the green fuel of the future."

The work *New Scientist* was describing was not ridiculous – it was actually about a car using *boron* as a fuel, with a boron/water reaction as one of the first chemical steps. Why did *New Scientist* feel the urge to turn this into a story suggesting that water was the fuel? Water is not a fuel. It never has been, and it never will be. It is already burned! The first law of thermodynamics says you can't get energy for nothing; you can only convert energy from one form to another. The energy in any engine must come from somewhere. Fox News peddled an even more absurd story [2fztd3].

– *Climate change is a far greater threat to the world than international terrorism*. Sir David King, Chief Scientific Advisor to the UK government, January, 2004. [26e8z]

– *the glorification of travel* – an allusion to the offence of "glorification" defined in the UK's Terrorism Act which came into force on 13 April, 2006. [ykhayj]

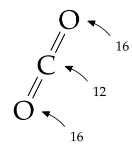
5 *Figure 1.2*. This figure shows production of crude oil including lease condensate, natural gas plant liquids, and other liquids, and refinery processing gain. Sources: EIA, and BP statistical review of world energy.

6 *The first practical steam engine was invented in 1698*. In fact, Hero of Alexandria described a steam engine, but given that Hero's engine didn't catch on in the following 1600 years, I deem Savery's 1698 invention the first *practical* steam engine.

– *Figures 1.4 and 1.7: Graph of carbon dioxide concentration*. The data are collated from Keeling and Whorf (2005) (measurements spanning 1958–2004); Neftel et al. (1994) (1734–1983); Etheridge et al. (1998) (1000–1978); Siegenthaler et al. (2005) (950–1888 AD); and Indermuhle et al. (1999) (from 11 000 to 450 years before present). This graph, by the way, should not be confused with the "hockey stick graph", which shows the history of global *temperatures*. Attentive readers will have noticed that the climate-change argument I presented makes no mention of *historical* temperatures.

Figures 1.5–1.7: Coal production numbers are from Jevons (1866), Malanima (2006), Netherlands Environmental Assessment Agency (2006), National Bureau of Economic Research (2001), Hatcher (1993), Flinn and Stoker (1984), Church et al. (1986), Supple (1987), Ashworth and Pegg (1986). Jevons was the first "Peak Oil" author. In 1865, he estimated Britain's easily-accessible coal reserves, looked at the history of exponential growth in consumption, and predicted the end of the exponential growth and the end of the British dominance of world industry. "We cannot long maintain our present rate of increase of consumption. ... the check to our progress must become perceptible within a century from the present time. ... the conclusion is inevitable, that our present happy progressive condition is a thing of limited duration." Jevons was right. Within a century British coal production indeed peaked, and there were two world wars.

8 *Dominic Lawson, a columnist from the Independent*. My quote is adapted from Dominic Lawson's column in the *Independent*, 8 June, 2007.
It is not a verbatim quote: I edited his words to make them briefer but took care not to correct any of his errors. *All three numbers he mentions are incorrect*. Here's how he screwed up. First, he says "carbon dioxide" but gives numbers for carbon: the burning of fossil fuels sends *26* gigatonnes of CO_2 per year into the atmosphere (not 7 gigatonnes). A common mistake. Second, he claims that the oceans send 36 000 gigatonnes of carbon per year into the atmosphere. This is a far worse error: 36 000 gigatonnes is the *total amount* of carbon in the ocean! The annual *flow* is much smaller – about 90 gigatonnes of carbon per year (330 Gt CO_2/y), according to standard diagrams of the carbon cycle [16y5g] (I believe this 90 Gt C/y is the estimated flow rate, were the atmosphere suddenly to have its CO_2 concentration reduced to zero.) Similarly his "1900 gigatonne" flow from biosphere to atmosphere is wrong. The correct figure according to the standard diagrams is about 120 gigatonnes of carbon per year (440 Gt CO_2/y).



The weights of an atom of carbon and a molecule of CO_2 are in the ratio 12 to 44, because the carbon atom weighs 12 units and the two oxygen atoms weigh 16 each. $12 + 16 + 16 = 44$.

Incidentally, the observed rise in CO_2 concentration is nicely in line with what you'd expect, assuming most of the human emissions of carbon remained in the atmosphere. From 1715 to 2004, roughly 1160 Gt CO_2 have been released to the atmosphere from the consumption of fossil fuels and cement production (Marland et al., 2007). If *all* of this CO_2 had stayed in the atmosphere, the concentration would have risen by 160 ppm (from 280 to 440 ppm). The actual rise has been about 100 ppm (from 275 to 377 ppm). So roughly 60% of what was emitted is now in the atmosphere.

10 *Carbon dioxide has a warming effect*. The over-emotional debate about this topic is getting quite tiresome, isn't it? "The science is now settled." "No it isn't!" "Yes it is!" I think the most helpful thing I can do here is direct anyone who wants a break from the shouting to a brief report written by Charney et al. (1979). This report's conclusions carry weight because the National Academy of Sciences (the US equivalent of the Royal Society) commissioned the report and selected its authors on the basis of their expertise, "and with regard for appropriate balance." The study group was convened "under the auspices of the Climate Research Board of the National Research Council to assess the scientific basis for projection of possible future climatic changes resulting from man-made releases of carbon dioxide into the atmosphere." Specifically, they were asked: "to identify the principal premises on which our current understanding of the question is based, to assess quantitatively the adequacy and uncertainty of our knowledge of these factors and processes, and to summarize in concise and objective terms our best present understanding of the carbon dioxide/climate issue for the benefit of policy-makers."
The report is just 33 pages long, it is free to download [5qfkaw], and I recommend it. It makes clear which bits of the science were already settled in 1979, and which bits still had uncertainty.
Here are the main points I picked up from this report. First, doubling the atmospheric CO_2 concentration would change the net heating of the troposphere, oceans, and land by an average power per unit area of roughly 4 W/m^2, if all other properties of the atmosphere remained unchanged. This heating effect can be compared with the average power absorbed by the atmosphere, land, and oceans, which is 238 W/m^2. So doubling CO_2 concentrations would have a warming effect equivalent to increasing the intensity of the sun by $4/238 = 1.7\%$. Second, the consequences of this CO_2-induced heating are hard to predict, on account of the complexity of the atmosphere/ocean system, but the authors predicted a global surface warming of between 2 °C and 3.5 °C, with greater increases at high latitudes. Finally, the authors summarize: "we have tried but have been unable to find any overlooked or underestimated physical effects that could reduce the currently estimated global warmings due to a doubling of atmospheric CO_2 to negligible proportions or reverse them altogether." They warn that, thanks to the ocean, "the great and ponderous flywheel of the global climate system," it is quite possible that the warming would occur sufficiently sluggishly that it

would be difficult to detect in the coming decades. Nevertheless "warming will eventually occur, and the associated regional climatic changes . . . may well be significant."
The foreword by the chairman of the Climate Research Board, Verner E. Suomi, summarizes the conclusions with a famous cascade of double negatives. "If carbon dioxide continues to increase, the study group finds no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible."

10 *The litany of probable drastic effects of climate change – I'm sure you've heard it before.* See [2z2xg7] if not.

12 *Breakdown of world greenhouse gas emissions by region and by country*. Data source: Climate Analysis Indicators Tool (CAIT) Version 4.0. (Washington, DC: World Resources Institute, 2007). The first three figures show national totals of all six major greenhouse gases (CO_2, CH_4, N_2O, PFC, HFC, SF_6), excluding contributions from land-use change and forestry. The figure on p14 shows cumulative emissions of CO_2 only.

14 *Congratulations, Britain! . . . in the table of historical emissions, per capita, we are second only to the USA*. Sincere apologies here to Luxembourg, whose historical per-capita emissions actually exceed those of America and Britain; but I felt the winners' podium should really be reserved for countries having both large per-capita and large total emissions. In total terms the biggest historical emitters are, in order, USA (322 Gt CO_2), Russian Federation (90 Gt CO_2), China (89 Gt CO_2), Germany (78 Gt CO_2), UK (62 Gt CO_2), Japan (43 Gt CO_2), France (30 Gt CO_2), India (25 Gt CO_2), and Canada (24 Gt CO_2). The per-capita order is: Luxembourg, USA, United Kingdom, Czech Republic, Belgium, Germany, Estonia, Qatar, and Canada.

– *Some countries, including Britain, have committed to at least a 60% reduction in greenhouse-gas emissions by 2050*. Indeed, as I write, Britain's commitment is being increased to an 80% reduction relative to 1990 levels.

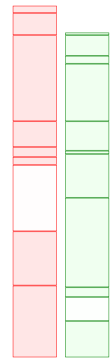
15 *Figure 1.8*. In the lower scenario, the chance that the temperature rise will exceed 2 °C is estimated to be 9–26%; the cumulative carbon emissions from 2007 onwards are 309 Gt C; CO_2 concentrations reach a peak of 410 ppm, CO_2e concentrations peak at 421 ppm, and in 2100 CO_2 concentrations fall back to 355 ppm. In the upper scenario, the chance of exceeding 2 °C is estimated to be 16–43%; the cumulative carbon emissions from 2007 onwards are 415 Gt C; CO_2 concentrations reach a peak of 425 ppm, CO_2e concentrations peak at 435 ppm, and in 2100 CO_2 concentrations fall back to 380 ppm. See also `hdr.undp.org/en/reports/global/hdr2007-2008/`.

16 *there are many other helpful sources on the internet.* I recommend, for example: BP's *Statistical Review of World Energy* [yyxq2m], the Sustainable Development Commission `www.sd-commission.org.uk`, the Danish Wind Industry Association `www.windpower.org`, Environmentalists For Nuclear Energy `www.ecolo.org`, Wind Energy Department, Risø University `www.risoe.dk/vea`, DEFRA `www.defra.gov.uk/environment/statistics`, especially the book *Avoiding Dangerous Climate Change* [dzcqq], the Pembina Institute `www.pembina.org/publications.asp`, and the DTI (now known as BERR) `www.dti.gov.uk/publications/`.

17 *factual assertions and ethical assertions. . .* Ethical assertions are also known as "normative claims" or "value judgments," and factual assertions are known as "positive claims." Ethical assertions usually contain verbs like "should" and "must," or adjectives like "fair," "right," and "wrong." For helpful further reading see Dessler and Parson (2006).

18 *Gordon Brown*. On 10th September, 2005, Gordon Brown said the high price of fuel posed a significant risk to the European economy and to global growth, and urged OPEC to raise oil production. Again, six months later, he said "we need . . . more production, more drilling, more investment, more petrochemical investment" (22nd April, 2006) [y98ys5]. Let me temper this criticism of Gordon Brown by praising one of his more recent initiatives, namely the promotion of electric vehicles and plug-in hybrids. As you'll see later, one of this book's conclusions is that electrification of most transport is a good part of a plan for getting off fossil fuels.

2 The balance sheet



Nature cannot be fooled.

Richard Feynman

Let's talk about energy consumption and energy production. At the moment, most of the energy the developed world consumes is produced from fossil fuels; that's not sustainable. Exactly how long we could keep living on fossil fuels is an interesting question, but it's not the question we'll address in this book. I want to think about *living without fossil fuels*.

We're going to make two stacks. In the left-hand, red stack we will add up our energy consumption, and in the right-hand, green stack, we'll add up sustainable energy production. We'll assemble the two stacks gradually, adding items one at a time as we discuss them.

The question addressed in this book is "can we *conceivably* live sustainably?" So, we will add up all *conceivable* sustainable energy sources and put them in the right-hand, green stack.

In the left-hand, red stack, we'll estimate the consumption of a "typical moderately-affluent person;" I encourage you to tot up an estimate of your *own* consumption, creating your own personalized left-hand stack too. Later on we'll also find out the current *average* energy consumption of Europeans and Americans.

Some key forms of consumption for the left-hand stack will be:

- transport
  - cars, planes, freight
- heating and cooling
- lighting
- information systems and other gadgets
- food
- manufacturing

In the right-hand sustainable-production stack, our main categories will be:

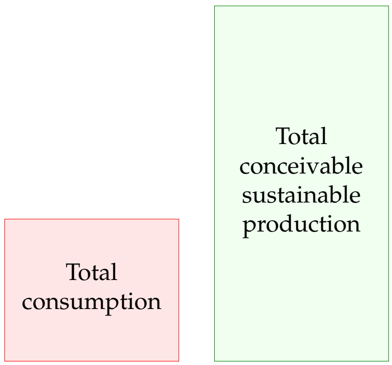
- wind
- solar
  - photovoltaics, thermal, biomass
- hydroelectric
- wave
- tide
- geothermal
- nuclear? (with a question-mark, because it's not clear whether nuclear power counts as "sustainable")

As we estimate our consumption of energy for heating, transportation, manufacturing, and so forth, the aim is not only to compute a number for the left-hand stack of our balance sheet, but also to understand what each number depends on, and how susceptible to modification it is.

In the right-hand, green stack, we'll add up the sustainable production estimates for the United Kingdom. This will allow us to answer the question "can the UK conceivably live on its own renewables?"

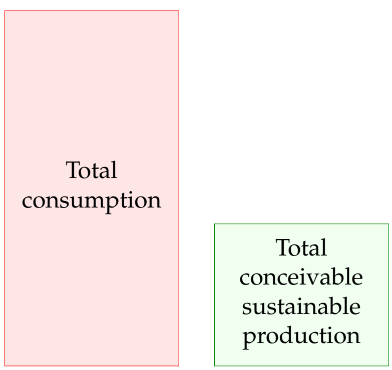
Whether the sustainable energy sources that we put in the right-hand stack are *economically* feasible is an important question, but let's leave that question to one side, and just add up the two stacks first. Sometimes people focus too much on economic feasibility and they miss the big picture. For example, people discuss "is wind cheaper than nuclear?" and forget to ask "how *much* wind is available?" or "how much uranium is left?"

The outcome when we add everything up might look like this:



If we find consumption is much less than conceivable sustainable production, then we can say "good, *maybe* we can live sustainably; let's look into the economic, social, and environmental costs of the sustainable alternatives, and figure out which of them deserve the most research and development; if we do a good job, there *might* not be an energy crisis."

On the other hand, the outcome of our sums might look like this:



– a much bleaker picture. This picture says "it doesn't matter what the economics of sustainable power are: there's simply *not enough* sustainable power to support our current lifestyle; massive change is coming."

Energy and power

Most discussions of energy consumption and production are confusing because of the proliferation of *units* in which energy and power are measured, from "tons of oil equivalent" to "terawatt-hours" (TWh) and "exajoules" (EJ). Nobody but a specialist has a feeling for what "a barrel of oil" or "a million BTUs" means in human terms. In this book, we'll express everything in a single set of personal units that everyone can relate to.

Figure 2.1. Distinguishing energy and power. Each of these 60 W light bulbs has a *power* of 60 W when switched on; it doesn't have an "energy" of 60 W. The bulb uses 60 W of electrical *power* when it's on; it emits 60 W of *power* in the form of light and heat (mainly the latter).

The unit of **energy** I have chosen is the kilowatt-hour (kWh). This quantity is called "one unit" on electricity bills, and it costs a domestic user about 10p in the UK in 2008. As we'll see, most individual daily choices involve amounts of energy equal to small numbers of kilowatt-hours.

When we discuss **powers** (rates at which we use or produce energy), the main unit will be the kilowatt-hour per day (kWh/d). We'll also occasionally use the watt (40 W $\simeq$ 1 kWh/d) and the kilowatt (1 kW = 1000 W = 24 kWh/d), as I'll explain below. The kilowatt-hour per day is a nice human-sized unit: most personal energy-guzzling activities guzzle at a rate of a small number of kilowatt-hours per day. For example, one 40 W lightbulb, kept switched on all the time, uses **one** kilowatt-hour per day. Some electricity companies include graphs in their electricity bills, showing energy consumption in kilowatt-hours per day. I'll use the same unit for all forms of power, not just electricity. Petrol consumption, gas consumption, coal consumption: I'll measure all these powers in kilowatt-hours per day. Let me make this clear: for some people, the word "power" means only *electrical* energy consumption. But this book concerns *all* forms of energy consumption and production, and I will use the word "power" for all of them.

One kilowatt-hour per day is roughly the power you could get from one human servant. The number of kilowatt-hours per day you use is thus the effective number of servants you have working for you.

People use the two terms energy and power interchangeably in ordinary speech, but in this book we must stick rigorously to their scientific definitions. *Power is the rate at which something uses energy.*

volume is measured in litres	flow is measured in litres per minute
energy is measured in kWh	power is measured in kWh per day

Maybe a good way to explain energy and power is by an analogy with water and water-flow from taps. If you want a drink of water, you want a *volume* of water – one litre, perhaps (if you're thirsty). When you turn on a tap, you create a *flow* of water – one litre per minute, say, if the tap yields only a trickle; or 10 litres per minute, from a more generous tap. You can get the same volume (one litre) either by running the trickling tap for one minute, or by running the generous tap for one tenth of a minute. The *volume* delivered in a particular time is equal to the *flow* multiplied by the *time*:

$$\text{volume} = \text{flow} \times \text{time}.$$

We say that a *flow* is a *rate* at which *volume* is delivered. If you know the volume delivered in a particular time, you get the flow by dividing the volume by the time:

$$\text{flow} = \frac{\text{volume}}{\text{time}}.$$

Here's the connection to energy and power. *Energy* is like water *volume*: *power* is like water *flow*. For example, whenever a toaster is switched on, it starts to consume *power* at a rate of one kilowatt. It continues to consume one kilowatt until it is switched off. To put it another way, the toaster (if it's left on permanently) consumes one kilowatt-hour (kWh) of energy per hour; it also consumes 24 kilowatt-hours per day.

The longer the toaster is on, the more energy it uses. You can work out the energy used by a particular activity by multiplying the power by the duration:

$$\text{energy} = \text{power} \times \text{time}.$$

The joule is the standard international unit of energy, but sadly it's far too small to work with. The kilowatt-hour is equal to 3.6 million joules (3.6 megajoules).

Powers are so useful and important, they have something that water flows don't have: they have their own special units. When we talk of a flow, we might measure it in "litres per minute," "gallons per hour," or "cubic-metres per second;" these units' names make clear that the flow is "a volume per unit time." A power of *one joule per second* is called *one watt*. 1000 joules per second is called one kilowatt. Let's get the terminology straight: the toaster uses one kilowatt. It doesn't use "one kilowatt per second." The "per second" is already built in to the definition of the kilowatt: one kilowatt means "one kilojoule per second." Similarly we say "a nuclear power station generates one gigawatt." One gigawatt, by the way, is one billion watts, one million kilowatts, or 1000 megawatts. So one gigawatt is a million toasters. And the "g"s in gigawatt are pronounced hard, the same as in "giggle." And, while I'm tapping the blackboard, we capitalize the "g" and "w" in "gigawatt" only when we write the abbreviation "GW."

Please, never, ever say "one kilowatt per second," "one kilowatt per hour," or "one kilowatt per day;" none of these is a valid measure of power. The urge that people have to say "per something" when talking about their toasters is one of the reasons I decided to use the "kilowatt-hour per day" as my unit of power. I'm sorry that it's a bit cumbersome to say and to write.

Here's one last thing to make clear: if I say "someone used a gigawatt-hour of energy," I am simply telling you *how much* energy they used, not *how fast* they used it. Talking about a gigawatt-hour *doesn't* imply the

energy
is measured in
kWh
or
MJ

power
is measured in
kWh per day
or
kW
or
W (watts)
or
MW (megawatts)
or
GW (gigawatts)
or
TW (terawatts)

energy was used *in one hour*. You could use a gigawatt-hour of energy by switching on one million toasters for one hour, or by switching on 1000 toasters for 1000 hours.

As I said, I'll usually quote powers in kWh/d *per person*. 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. Does this help us say whether Denmark incinerates "more" waste than the UK? While the total 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.) To save ink, I'll sometimes abbreviate "per person" to "/p". 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.

1 TWh (one terawatt-hour) is equal to one billion kWh.

Picky details

Isn't energy conserved? We talk about "using" energy, but doesn't one of the laws of nature say that energy can't be created or destroyed?

Yes, I'm being imprecise. This is really a book about *entropy* – a trickier thing to explain. When we "use up" one kilojoule of energy, what we're really doing is taking one kilojoule of energy in a form that has *low entropy* (for example, electricity), and *converting* it into an exactly equal amount of energy in another form, usually one that has much higher entropy (for example, hot air or hot water). When we've "used" the energy, it's still there; but we normally can't "use" the energy over and over again, because only *low entropy* energy is "useful" to us. Sometimes these different grades of energy are distinguished by adding a label to the units: one kWh(e) is one kilowatt-hour of electrical energy – the highest grade of energy. One kWh(th) is one kilowatt-hour of thermal energy – for example the energy in ten litres of boiling-hot water. Energy lurking in higher-temperature things is more useful (lower entropy) than energy in tepid things. A third grade of energy is chemical energy. Chemical energy is high-grade energy like electricity.

It's a convenient but sloppy shorthand to talk about the energy rather than the entropy, and that is what we'll do most of the time in this book. Occasionally, we'll have to smarten up this sloppiness; for example, when we discuss refrigeration, power stations, heat pumps, or geothermal power.

Are you comparing apples and oranges? Is it valid to compare different

forms of energy such as the chemical energy that is fed into a petrol-powered car and the electricity from a wind turbine?

By comparing consumed energy with conceivable produced energy, I do not wish to imply that all forms of energy are equivalent and interchangeable. The electrical energy produced by a wind turbine is of no use to a petrol engine; and petrol is no use if you want to power a television. In principle, energy can be converted from one form to another, though conversion entails losses. Fossil-fuel power stations, for example, guzzle *chemical energy* and produce *electricity* (with an efficiency of 40% or so). And aluminium plants guzzle *electrical energy* to create a product with high *chemical energy* – aluminium (with an efficiency of 30% or so).

In some summaries of energy production and consumption, all the different forms of energy are put into the same units, but multipliers are introduced, rating electrical energy from hydroelectricity for example as being worth 2.5 times more than the chemical energy in oil. This bumping up of electricity's effective energy value can be justified by saying, "well, 1 kWh of electricity is equivalent to 2.5 kWh of oil, because if we put that much oil into a standard power station it would deliver 40% of 2.5 kWh, which is 1 kWh of electricity." In this book, however, I will usually use a one-to-one conversion rate when comparing different forms of energy. It is *not* the case that 2.5 kWh of oil is inescapably equivalent to 1 kWh of electricity; that just happens to be the perceived exchange rate in a world-view where oil is used to make electricity. Yes, conversion of chemical energy to electrical energy is done with this particular inefficient exchange rate. But electrical energy can also be converted to chemical energy. In an alternative world (perhaps not far-off) with relatively plentiful electricity and little oil, we might use electricity to make liquid fuels; in that world we would surely not use the same exchange rate – each kWh of gasoline would then cost us something like 3 kWh of electricity! I think the timeless and scientific way to summarize and compare energies is to hold 1 kWh of chemical energy equivalent to 1 kWh of electricity. My choice to use this one-to-one conversion rate means that some of my sums will look a bit different from other people's. (For example, BP's *Statistical Review of World Energy* rates 1 kWh of electricity as equivalent to $100/38 \simeq 2.6$ kWh of oil; on the other hand, the government's *Digest of UK Energy Statistics* uses the same one-to-one conversion rate as me.) And I emphasize again, this choice does not imply that I'm suggesting you could convert either form of energy directly into the other. Converting chemical energy into electrical energy always wastes energy, and so does converting electrical into chemical energy.

Physics and equations

Throughout the book, my aim is not only to work out numbers indicating our current energy consumption and conceivable sustainable production, but also to make clear *what these numbers depend on*. Understanding what the numbers depend on is essential if we are to choose sensible policies to change any of the numbers. Only if we understand the physics behind energy consumption and energy production can we assess assertions such as "cars waste 99% of the energy they consume; we could redesign cars so that they use 100 times less energy." Is this assertion true? To explain the answer, I will need to use equations like

$$\text{kinetic energy} = \frac{1}{2}mv^2.$$

However, I recognize that to many readers, such formulae are a foreign language. So, here's my promise: *I'll keep all this foreign-language stuff in technical chapters at the end of the book.* Any reader with a high-school/secondary-school qualification in maths, physics, or chemistry should enjoy these technical chapters. The main thread of the book (from page 2 to page 250) is intended to be accessible to everyone who can add, multiply, and divide. It is especially aimed at our dear elected and unelected representatives, the Members of Parliament.

One last point, before we get rolling: I don't know everything about energy. I don't have all the answers, and the numbers I offer are open to revision and correction. (Indeed I expect corrections and will publish them on the book's website.) The one thing I *am* sure of is that the answers to our sustainable energy questions will involve *numbers*; any sane discussion of sustainable energy requires numbers. This book's got 'em, and it shows how to handle them. I hope you enjoy it!

Notes and further reading

page no.

25 *The "per second" is already built in to the definition of the kilowatt.* Other examples of units that, like the watt, already have a "per time" built in are the knot – "our yacht's speed was ten knots!" (a knot is one nautical mile *per* hour); the hertz – "I could hear a buzzing at 50 hertz" (one hertz is a frequency of one cycle *per* second); the ampere – "the fuse blows when the current is higher than 13 amps" (*not* 13 amps per second); and the horsepower – "that stinking engine delivers 50 horsepower" (*not* 50 horsepower per second, nor 50 horsepower per hour, nor 50 horsepower per day, just 50 horsepower).

– *Please, never, ever say "one kilowatt per second."* There are specific, rare exceptions to this rule. If talking about a growth in demand for power, we might say "British demand is growing at one gigawatt per year." In Chapter 26 when I discuss fluctuations in wind power, I will say "one morning, the power delivered by Irish windmills fell at a rate of 84 MW per hour." Please take care! Just one accidental syllable can lead to confusion: for example, your electricity meter's reading is in kilowatt-hours (kWh), *not* 'kilowatts-per-hour'.

I've provided a chart on p368 to help you translate between kWh per day per person and the other major units in which powers are discussed.

3 Cars

For our first chapter on consumption, let's study that icon of modern civilization: the car with a lone person in it.

How much power does a regular car-user consume? Once we know the conversion rates, it's simple arithmetic:

$$\text{energy used per day} = \frac{\text{distance travelled per day}}{\text{distance per unit of fuel}} \times \text{energy per unit of fuel.}$$

For the **distance travelled per day**, let's use 50 km (30 miles).

For the **distance per unit of fuel**, also known as the **economy** of the car, let's use 33 miles per UK gallon (taken from an advertisement for a family car):

$$33\,\text{miles per imperial gallon} \simeq 12\,\text{km per litre.}$$

(The symbol "$\simeq$" means "is approximately equal to.")

What about the **energy per unit of fuel** (also called the **calorific value** or **energy density**)? Instead of looking it up, it's fun to estimate this sort of quantity by a bit of lateral thinking. Automobile fuels (whether diesel or petrol) are all hydrocarbons; and hydrocarbons can also be found on our breakfast table, with the calorific value conveniently written on the side: roughly 8 kWh per kg (figure 3.2). Since we've estimated the economy of the car in miles per unit *volume* of fuel, we need to express the calorific value as an energy per unit *volume*. To turn our fuel's "8 kWh per kg" (an energy per unit *mass*) into an energy per unit volume, we need to know the density of the fuel. What's the density of butter? Well, butter just floats on water, as do fuel-spills, so its density must be a little less than water's, which is 1 kg per litre. If we guess a density of 0.8 kg per litre, we obtain a calorific value of:

$$8\,\text{kWh per kg} \times 0.8\,\text{kg per litre} \simeq 7\,\text{kWh per litre.}$$

Rather than willfully perpetuate an inaccurate estimate, let's switch to the actual value, for petrol, of 10 kWh per litre.

$$\begin{aligned}\text{energy per day} &= \frac{\text{distance travelled per day}}{\text{distance per unit of fuel}} \times \text{energy per unit of fuel}\\ &= \frac{50\,\text{km/day}}{12\,\text{km/litre}} \times 10\,\text{kWh/litre}\\ &\simeq 40\,\text{kWh/day}.\end{aligned}$$

Congratulations! We've made our first estimate of consumption. I've displayed this estimate in the left-hand stack in figure 3.3. The red box's height represents 40 kWh per day per person.

Figure 3.1. Cars. A red BMW dwarfed by a spaceship from the planet Dorkon.

Figure 3.2. Want to know the energy in car fuel? Look at the label on a pack of butter or margarine. The calorific value is 3000 kJ per 100 g, or about 8 kWh per kg.

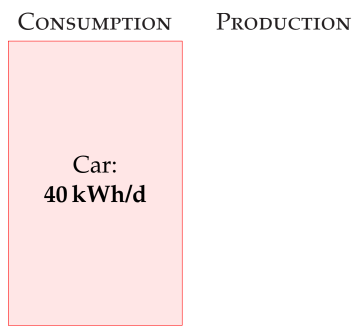


Figure 3.3. Chapter 3's conclusion: a typical car-driver uses about 40 kWh per day.

This is the estimate for a typical car-driver driving a typical car today. Later chapters will discuss the *average* consumption of all the people in Britain, taking into account the fact that not everyone drives. We'll also discuss in Part II what the consumption *could* be, with the help of other technologies such as electric cars.

Why does the car deliver 33 miles per gallon? Where's that energy going? Could we manufacture cars that do 3300 miles per gallon? If we are interested in trying to reduce cars' consumption, we need to understand the physics behind cars' consumption. These questions are answered in the accompanying technical chapter A (p254), which provides a cartoon theory of cars' consumption. I encourage you to read the technical chapters if formulae like $\frac{1}{2}mv^2$ don't give you medical problems.

Chapter 3's conclusion: a typical car-driver uses about 40 kWh per day. Next we need to get the sustainable-production stack going, so we have something to compare this estimate with.

Queries

What about the energy-cost of* producing *the car's fuel?

Good point. When I estimate the energy consumed by a particular activity, I tend to choose a fairly tight "boundary" around the activity. This choice makes the estimation easier, but I agree that it's a good idea to try to estimate the full energy impact of an activity. It's been estimated that making each unit of petrol requires an input of 1.4 units of oil and other primary fuels (Treloar et al., 2004).

***What about the energy-cost of manufacturing the* car?**

Yes, that cost fell outside the boundary of this calculation too. We'll talk about car-making in Chapter 15.

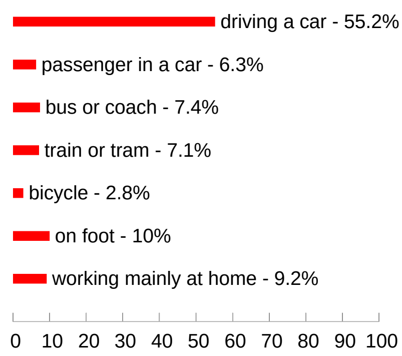


Figure 3.4. How British people travel to work, according to the 2001 census.

Notes and further reading

page no.

29 *For the distance travelled per day, let's use 50 km.* This corresponds to 18 000 km (11 000 miles) per year. Roughly half of the British population drive to work. The total amount of car travel in the UK is 686 billion passenger-km per year, which corresponds to an "average distance travelled by car per British person" of 30 km per day. Source: Department for Transport [5647rh]. As I said on p22, I aim to estimate the consumption of a "typical moderately-affluent person" – the consumption that many people aspire to. Some people don't drive much. In this chapter, I want to estimate the energy consumed by someone who chooses to drive, rather than depersonalize the answer by reporting the UK average, which mixes together the drivers and non-drivers. If I said "the average use of energy for car driving

in the UK is 24 kWh/d per person," I bet some people would misunderstand and say: "I'm a car driver so I guess I use 24 kWh/d."

29 *... let's use 33 miles per UK gallon.* In the European language, this is 8.6 litres per 100 km. 33 miles per gallon was the average for UK cars in 2005 [27jdc5]. Petrol cars have an average fuel consumption of 31 mpg; diesel cars, 39 mpg; new petrol cars (less than two years old), 32 mpg (Dept. for Transport, 2007). Honda, "the most fuel-efficient auto company in America," records that its fleet of new cars sold in 2005 has an average top-level fuel economy of 35 miles per UK gallon [28abpm].

29 *Let's guess a density of 0.8 kg per litre.* Petrol's density is 0.737. Diesel's is 0.820–0.950 [nmn4l].

– *... the actual value of 10 kWh per litre.* ORNL [2hcgdh] provide the following calorific values: diesel: 10.7 kWh/l; jet fuel: 10.4 kWh/l; petrol: 9.7 kWh/l. When looking up calorific values, you'll find "gross calorific value" and "net calorific value" listed (also known as "high heat value" and "low heat value"). These differ by only 6% for motor fuels, so it's not crucial to distinguish them here, but let me explain anyway. The gross calorific value is the actual chemical energy released when the fuel is burned. One of the products of combustion is water, and in most engines and power stations, part of the energy goes into vaporizing this water. The net calorific value measures how much energy is left over assuming this energy of vaporization is discarded and wasted.

When we ask "how much energy does my lifestyle consume?" the gross calorific value is the right quantity to use. The net calorific value, on the other hand, is of interest to a power station engineer, who needs to decide which fuel to burn in his power station. Throughout this book I've tried to use gross calorific values.

A final note for party-pooping pedants who say "butter is not a hydrocarbon": OK, butter is not a *pure* hydrocarbon; but it's a good approximation to say that the main component of butter is long hydrocarbon chains, just like petrol. The proof of the pudding is, this approximation got us within 30% of the correct answer. Welcome to guerrilla physics.

calorific values	
petrol	10 kWh per litre
diesel	11 kWh per litre

4 Wind

The UK has the best wind resources in Europe.

Sustainable Development Commission

Wind farms will devastate the countryside pointlessly.

James Lovelock

How much wind power could we plausibly generate?

We can make an estimate of the potential of *on-shore* (land-based) wind in the United Kingdom by multiplying the average power per unit land-area of a wind farm by the area per person in the UK:

$$\text{power per person} = \text{wind power per unit area} \times \text{area per person}.$$

Chapter B (p263) explains how to estimate the power per unit area of a wind farm in the UK. If the typical windspeed is 6 m/s (13 miles per hour, or 22 km/h), the power per unit area of wind farm is about 2 W/m^2.

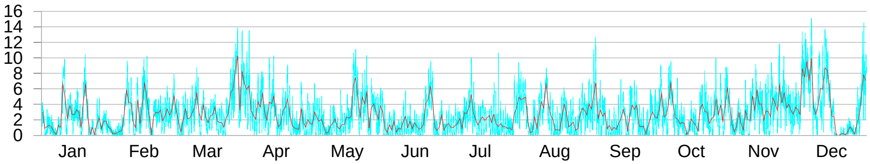
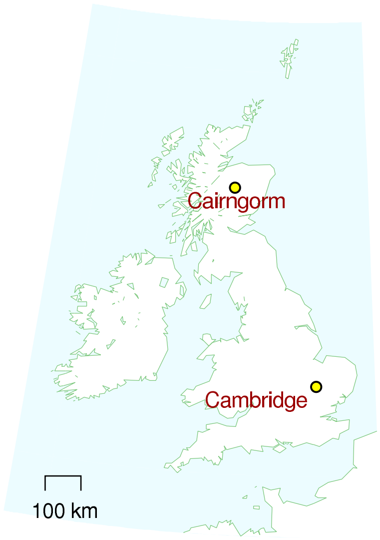


Figure 4.1. Cambridge mean wind speed in metres per second, daily (red line), and half-hourly (blue line) during 2006. See also figure 4.6.

This figure of 6 m/s is probably an over-estimate for many locations in Britain. For example, figure 4.1 shows daily average windspeeds in Cambridge during 2006. The daily average speed reached 6 m/s on only about 30 days of the year – see figure 4.6 for a histogram. But some spots do have windspeeds above 6 m/s – for example, the summit of Cairngorm in Scotland (figure 4.2).

Plugging in the British population density: 250 people per square kilometre, or 4000 square metres per person, we find that wind power could



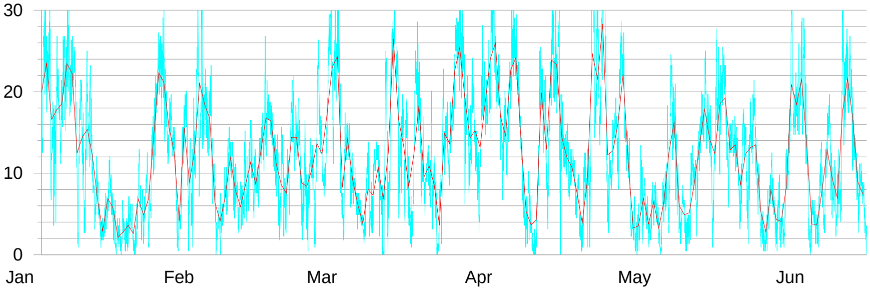


Figure 4.2. Cairngorm mean wind speed in metres per second, during six months of 2006.

generate

$$2\,\mathrm{W/m^2} \times 4000\,\mathrm{m^2/person} = 8000\,\mathrm{W\ per\ person},$$

if wind turbines were packed across the *whole* country, and assuming $2\,\mathrm{W/m^2}$ is the correct power per unit area. Converting to our favourite power units, that's 200 kWh/d per person.

Let's be realistic. What fraction of the country can we really imagine covering with windmills? Maybe 10%? Then we conclude: if we covered the windiest 10% of the country with windmills (delivering $2\,\mathrm{W/m^2}$), we would be able to generate 20 kWh/d per person, which is ***half*** of the power used by driving an average fossil-fuel car 50 km per day.

Britain's onshore wind energy resource may be "huge," but it's evidently not as huge as our huge consumption. We'll come to offshore wind later.

I should emphasize how generous an assumption I'm making. Let's compare this estimate of British wind potential with current installed wind power worldwide. The windmills that would be required to provide the UK with 20 kWh/d per person amount to 50 times the entire wind hardware of Denmark; 7 times all the wind farms of Germany; and double the entire fleet of all wind turbines in the world.

Please don't misunderstand me. Am I saying that we shouldn't bother building wind farms? Not at all. I'm simply trying to convey a helpful fact, namely that if we want wind power to truly make a difference, the wind farms must cover a very large area.

This conclusion – that the maximum contribution of onshore wind, albeit "huge," is much less than our consumption – is important, so let's check the key figure, the assumed power per unit area of wind farm ($2\,\mathrm{W/m^2}$), against a real UK wind farm.

The Whitelee wind farm being built near Glasgow in Scotland has 140 turbines with a combined *peak* capacity of 322 MW in an area of $55\,\mathrm{km^2}$. That's $6\,\mathrm{W/m^2}$, *peak*. The average power produced is smaller because the turbines don't run at peak output all the time. The ratio of the average power to the peak power is called the "load factor" or "capacity factor," and it varies from site to site, and with the choice of hardware plopped on the site; a typical factor for a good site with modern turbines is 30%. If we assume Whitelee has a load factor of 33% then the average power production per unit land area is $2\,\mathrm{W/m^2}$ – exactly the same as the power density we assumed above.

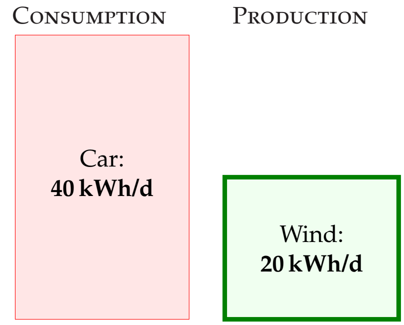


Figure 4.3. Chapter 4's conclusion: the maximum plausible production from on-shore windmills in the United Kingdom is 20 kWh per day per person.

POWER PER UNIT AREA	
wind farm (speed 6 m/s)	$2\,\mathrm{W/m^2}$

Table 4.4. Facts worth remembering: wind farms.

POPULATION DENSITY OF BRITAIN
250 per $\mathrm{km^2}$ $\leftrightarrow$ 4000 $\mathrm{m^2}$ per person

Table 4.5. Facts worth remembering: population density. See page 338 for more population densities.

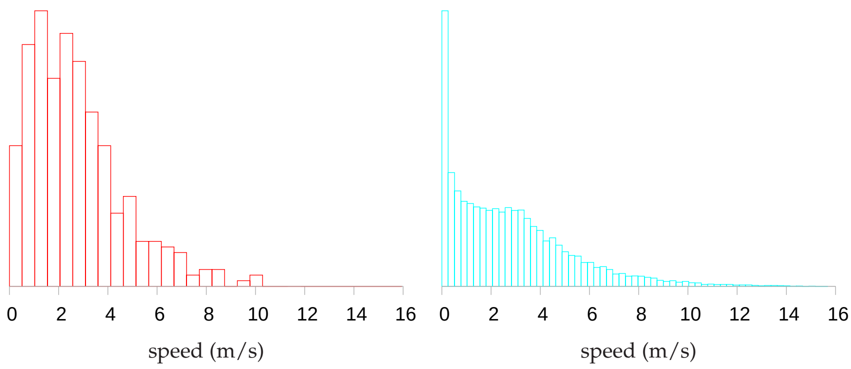


Figure 4.6. Histogram of Cambridge average wind speed in metres per second: daily averages (left), and half-hourly averages (right).

Queries

Wind turbines are getting bigger all the time. Do bigger wind turbines change this chapter's answer?

Chapter B explains. Bigger wind turbines deliver financial economies of scale, but they don't greatly increase the total power per unit land area, because bigger windmills have to be spaced further apart. A wind farm that's twice as tall will deliver roughly 30% more power.

Wind power fluctuates all the time. Surely that makes wind less useful?

Maybe. We'll come back to this issue in Chapter 26, where we'll look at wind's intermittency and discuss several possible solutions to this problem, including energy storage and demand management.

Notes and further reading

page no.

32 *Figure 4.1 and figure 4.6*. Cambridge wind data are from the Digital Technology Group, Computer Laboratory, Cambridge [`vxhhj`]. The weather station is on the roof of the Gates building, roughly 10 m high. Wind speeds at a height of 50 m are usually about 25% bigger. Cairngorm data (*figure 4.2*) are from Heriot–Watt University Physics Department [`tdvml`].

33 *The windmills required to provide the UK with 20 kWh/d per person are 50 times the entire wind power of Denmark*. Assuming a load factor of 33%, an average power of 20 kWh/d per person requires an installed capacity of 150 GW. At the end of 2006, Denmark had an installed capacity of 3.1 GW; Germany had 20.6 GW. The world total was 74 GW (`wwindea.org`). Incidentally, the load factor of the Danish wind fleet was 22% in 2006, and the average power it delivered was 3 kWh/d per person.

5 Planes

Imagine that you make one intercontinental trip per year by plane. How much energy does that cost?

A Boeing 747-400 with 240 000 litres of fuel carries 416 passengers about 8 800 miles (14 200 km). And fuel's calorific value is 10 kWh per litre. (We learned that in Chapter 3.) So the energy cost of one full-distance round-trip on such a plane, if divided equally among the passengers, is

$$\frac{2 \times 240\,000 \text{ litre}}{416 \text{ passengers}} \times 10 \text{ kWh/litre} \simeq 12\,000 \text{ kWh per passenger.}$$

If you make one such trip per year, then your average energy consumption per day is

$$\frac{12\,000 \text{ kWh}}{365 \text{ days}} \simeq 33 \text{ kWh/day.}$$

14 200 km is a little further than London to Cape Town (10 000 km) and London to Los Angeles (9000 km), so I think we've slightly overestimated the distance of a typical long-range intercontinental trip; but we've also overestimated the fullness of the plane, and the energy cost per person is more if the plane's not full. Scaling down by 10 000 km/14 200 km to get an estimate for Cape Town, then up again by 100/80 to allow for the plane's being 80% full, we arrive at 29 kWh per day. For ease of memorization, I'll round this up to 30 kWh per day.

Let's make clear what this means. Flying once per year has an energy cost slightly bigger than leaving a 1 kW electric fire on, non-stop, 24 hours a day, all year.

Just as Chapter 3, in which we estimated consumption by cars, was accompanied by Chapter A, offering a model of where the energy goes in cars, this chapter's technical partner (Chapter C, p269), discusses where the energy goes in planes. Chapter C allows us to answer questions such as "would air travel consume significantly less energy if we travelled in slower planes?" The answer is **no**: in contrast to wheeled vehicles, which *can* get more efficient the slower they go, planes are already almost as energy-efficient as they could possibly be. Planes unavoidably have to use energy for two reasons: they have to throw air down in order to stay up, and they need energy to overcome air resistance. No redesign of a plane is going to radically improve its efficiency. A 10% improvement? Yes, possible. A doubling of efficiency? I'd eat my complimentary socks.

Queries

Aren't turboprop aircraft* far *more energy-efficient?

No. The "comfortably greener" Bombardier Q400 NextGen, "the most technologically advanced turboprop in the world," according to its manu-

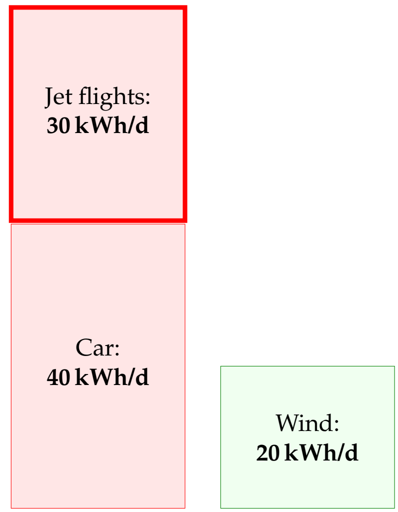


Figure 5.1. Taking one intercontinental trip per year uses about 30 kWh per day.

Figure 5.2. Bombardier Q400 NextGen. `www.q400.com`.

facturers [www.q400.com], uses 3.81 litres per 100 passenger-km (at a cruise speed of 667 km/h), which is an energy cost of 38 kWh per 100 p-km. The full 747 has an energy cost of 42 kWh per 100 p-km. So both planes are twice as fuel-efficient as a single-occupancy car. (The car I'm assuming here is the average European car that we discussed in Chapter 3.)

	energy per distance (kWh per 100 p-km)
Car (4 occupants)	20
Ryanair's planes, year 2007	37
Bombardier Q400, full	38
747, full	42
747, 80% full	53
Ryanair's planes, year 2000	73
Car (1 occupant)	80

Table 5.3. Passenger transport efficiencies, expressed as energy required per 100 passenger-km.

Is flying extra-bad for climate change in some way?

Yes, that's the experts' view, though uncertainty remains about this topic [3fbufz]. Flying creates other greenhouse gases in addition to CO_2, such as water and ozone, and indirect greenhouse gases, such as nitrous oxides. If you want to estimate your carbon footprint in tons of CO_2-equivalent, then you should take the actual CO_2 emissions of your flights and bump them up two- or three-fold. This book's diagrams don't include that multiplier because here we are focusing on our *energy* balance sheet.

> *The best thing we can do with environmentalists is shoot them.*
>
> Michael O'Leary, CEO of Ryanair [3asmgy]

Notes and further reading

page no.

35 *Boeing 747-400* – data are from [9ehws].

Planes today are not completely full. Airlines are proud if their average fullness is 80%. Easyjet planes are 85% full on average. (Source: thelondonpaper Tuesday 16th January, 2007.) An 80%-full 747 uses about 53 kWh per 100 passenger-km.

What about short-haul flights? In 2007, Ryanair, "Europe's greenest airline," delivered transportation at a cost of 37 kWh per 100 p-km [3exmgv]. This means that flying across Europe with Ryanair has much the same energy cost as having all the passengers drive to their destination in cars, two to a car. (For an indication of what other airlines might be delivering, Ryanair's fuel burn rate in 2000, before their environment-friendly investments, was above 73 kWh per 100 p-km.) London to Rome is 1430 km; London to Malaga is 1735 km. So a round-trip to Rome with the greenest airline has an energy cost of 1050 kWh, and a round-trip to Malaga costs 1270 kWh. If you pop over to Rome and to Malaga once per year, your average power consumption is 6.3 kWh/d with the greenest airline, and perhaps 12 kWh/d with a less green one.

What about frequent flyers? To get a silver frequent flyer card from an intercontinental airline, it seems one must fly around 25 000 miles per year in economy class. That's about 60 kWh per day, if we scale up the opening numbers from this chapter and assume planes are 80% full.

Here are some additional figures from the Intergovernmental Panel on Climate Change [yrnmum]: a full 747-400 travelling 10 000 km with low-density seating (262 seats) has an energy consumption of 50 kWh per 100 p-km. In a high-density seating configuration (568 seats) and travelling 4000 km, the

Figure 5.4. Ryanair Boeing 737-800. Photograph by Adrian Pingstone.

same plane has an energy consumption of 22 kWh per 100 p-km. A short-haul Tupolev-154 travelling 2235 km with 70% of its 164 seats occupied consumes 80 kWh per 100 p-km.

35 *No redesign of a plane is going to radically improve its efficiency.* Actually, the Advisory Council for Aerospace Research in Europe (ACARE) target is for an overall 50% reduction in fuel burned per passenger-km by 2020 (relative to a 2000 baseline), with 15–20% improvement expected in engine efficiency. As of 2006, Rolls Royce is half way to this engine target [36w5gz].
Dennis Bushnell, chief scientist at NASA's Langley Research Center, seems to agree with my overall assessment of prospects for efficiency improvements in aviation. The aviation industry is mature. "There is not much left to gain except by the glacial accretion of a per cent here and there over long time periods." (New Scientist, 24 February 2007, page 33.)
The radically reshaped "Silent Aircraft" [silentaircraft.org/sax40], if it were built, is predicted to be 16% more efficient than a conventional-shaped plane (Nickol, 2008).
If the ACARE target is reached, it's presumably going to be thanks mostly to having fuller planes and better air-traffic management.

Figure 5.5. Two short-haul trips on the greenest short-haul airline: 6.3 kWh/d. Flying enough to qualify for silver frequent flyer status: 60 kWh/d.

6 Solar

We are estimating how our consumption stacks up against conceivable sustainable production. In the last three chapters we found car-driving and plane-flying to be bigger than the plausible on-shore wind-power potential of the United Kingdom. Could solar power put production back in the lead?

The power of raw sunshine at midday on a cloudless day is 1000 W per square metre. That's 1000 W per m^2 of area oriented towards the sun, not per m^2 of land area. To get the power per m^2 of *land area* in Britain, we must make several corrections. We need to compensate for the tilt between the sun and the land, which reduces the intensity of midday sun to about 60% of its value at the equator (figure 6.1). We also lose out because it is not midday all the time. On a cloud-free day in March or September, the ratio of the *average* intensity to the midday intensity is about 32%. Finally, we lose power because of cloud cover. In a typical UK location the sun shines during just 34% of daylight hours.

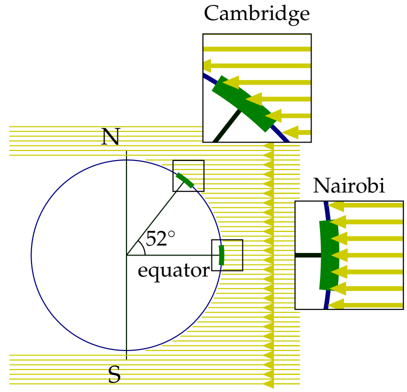


Figure 6.1. Sunlight hitting the earth at midday on a spring or autumn day. The density of sunlight per unit land area in Cambridge (latitude 52°) is about 60% of that at the equator.

The combined effect of these three factors and the additional complication of the wobble of the seasons is that the average raw power of sunshine per square metre of south-facing roof in Britain is roughly 110 W/m^2, and the average raw power of sunshine per square metre of flat ground is roughly 100 W/m^2.

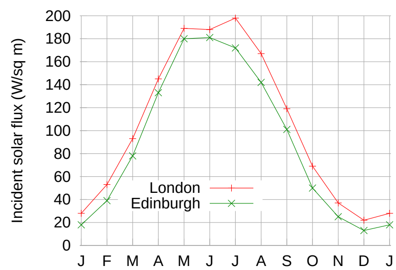


Figure 6.2. Average solar intensity in London and Edinburgh as a function of time of year. The average intensity, per unit land area, is 100 W/m^2.

We can turn this raw power into useful power in four ways:

1. Solar thermal: using the sunshine for direct heating of buildings or water.

2. Solar photovoltaic: generating electricity.

3. Solar biomass: using trees, bacteria, algae, corn, soy beans, or oilseed to make energy fuels, chemicals, or building materials.

4. Food: the same as solar biomass, except we shovel the plants into humans or other animals.

(In a later chapter we'll also visit a couple of other solar power techniques appropriate for use in deserts.)

Let's make quick rough estimates of the maximum plausible powers that each of these routes could deliver. We'll neglect their economic costs, and the energy costs of manufacturing and maintaining the power facilities.

Solar thermal

The simplest solar power technology is a panel making hot water. Let's imagine we cover *all* south-facing roofs with solar thermal panels – that

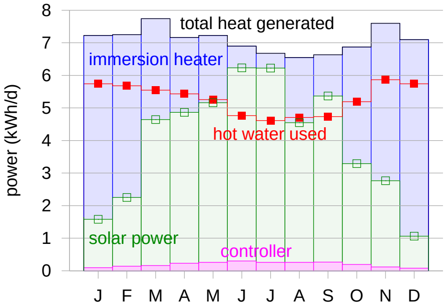


Figure 6.3. Solar power generated by a $3\,m^2$ hot-water panel (green), and supplementary heat required (blue) to make hot water in the test house of Viridian Solar. (The photograph shows a house with the same model of panel on its roof.) The average solar power from $3\,m^2$ was 3.8 kWh/d. The experiment 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 $53\,W/m^2$.

would be about $10\,m^2$ of panels per person – and let's assume these are 50%-efficient at turning the sunlight's $110\,W/m^2$ into hot water (figure 6.3). Multiplying

$$50\% \times 10\,m^2 \times 110\,W/m^2$$

we find solar heating could deliver

13 kWh per day per person.

I colour this production box white in figure 6.4 to indicate that it describes production of low-grade energy – hot water is not as valuable as the high-grade electrical energy that wind turbines produce. Heat can't be exported to the electricity grid. If you don't need it, then it's wasted. We should bear in mind that much of this captured heat would not be in the right place. In cities, where many people live, residential accommodation has less roof area per person than the national average. Furthermore, this power would be delivered non-uniformly through the year.

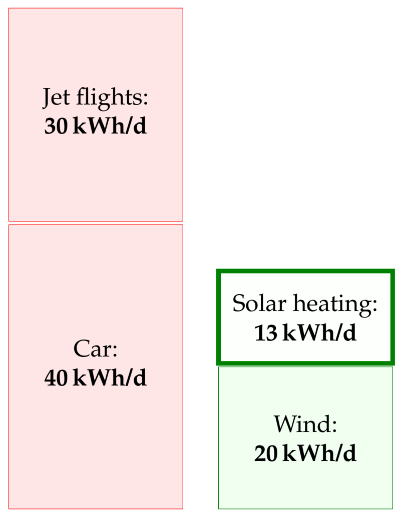


Figure 6.4. Solar thermal: a $10\,m^2$ array of thermal panels can deliver (on average) about 13 kWh per day of thermal energy.

Solar photovoltaic

Photovoltaic (PV) panels convert sunlight into electricity. Typical solar panels have an efficiency of about 10%; expensive ones perform at 20%. (Fundamental physical laws limit the efficiency of photovoltaic systems to at best 60% with perfect concentrating mirrors or lenses, and 45% without concentration. A mass-produced device with efficiency greater than 30% would be quite remarkable.) The average power delivered by south-facing 20%-efficient photovoltaic panels in Britain would be

$$20\% \times 110\,W/m^2 = 22\,W/m^2.$$

Figure 6.5 shows data to back up this number. Let's give every person $10\,m^2$ of expensive (20%-efficient) solar panels and cover all south-facing roofs. These will deliver

5 kWh per day per person.

Since the area of all south-facing roofs is 10 m^2 per person, there certainly isn't space on our roofs for these photovoltaic panels as well as the solar thermal panels of the last section. So we have to choose whether to have the photovoltaic contribution or the solar hot water contribution. But I'll just plop both these on the production stack anyway. Incidentally, the present cost of installing such photovoltaic panels is about four times the cost of installing solar thermal panels, but they deliver only half as much energy, albeit high-grade energy (electricity). So I'd advise a family thinking of going solar to investigate the solar thermal option first. The smartest solution, at least in sunny countries, is to make combined systems that deliver both electricity and hot water from a single installation. This is the approach pioneered by Heliodynamics, who reduce the overall cost of their systems by surrounding small high-grade gallium arsenide photovoltaic units with arrays of slowly-moving flat mirrors; the mirrors focus the sunlight onto the photovoltaic units, which deliver both electricity and hot water; the hot water is generated by pumping water past the back of the photovoltaic units.

The conclusion so far: covering your south-facing roof at home with photovoltaics may provide enough juice to cover quite a big chunk of your personal average electricity consumption; but roofs are not big enough to make a huge dent in our total *energy* consumption. To do more with PV, we need to step down to terra firma. The solar warriors in figure 6.6 show the way.

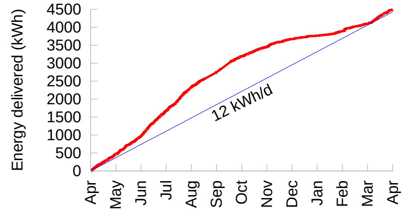


Figure 6.5. Solar photovoltaics: data from a 25-m^2 array in Cambridgeshire in 2006. The peak power delivered by this array is about 4 kW. The average, year-round, is 12 kWh per day. That's 20 W per square metre of panel.

Figure 6.6. Two solar warriors enjoying their photovoltaic system, which powers their electric cars and home. The array of 120 panels (300 W each, 2.2 m^2 each) has an area of 268 m^2, a peak output (allowing for losses in DC–to–AC conversion) of 30.5 kW, and an average output – in California, near Santa Cruz – of 5 kW (19 W/m^2). Photo kindly provided by Kenneth Adelman.
www.solarwarrior.com

Fantasy time: solar farming

If a breakthrough of solar technology occurs and the cost of photovoltaics came down enough that we could deploy panels all over the countryside, what is the maximum conceivable production? Well, if we covered 5% of the UK with 10%-efficient panels, we'd have

$$\begin{aligned} & 10\% \times 100\,\mathrm{W/m^2} \times 200\,\mathrm{m^2}\text{ per person} \\ \simeq\ & 50\,\mathrm{kWh/day/person}. \end{aligned}$$

I assumed only 10%-efficient panels, by the way, because I imagine that solar panels would be mass-produced on such a scale only if they were very cheap, and it's the lower-efficiency panels that will get cheap first. The power density (the power per unit area) of such a solar farm would be

$$10\% \times 100\,\mathrm{W/m^2} = 10\,\mathrm{W/m^2}.$$

This power density is twice that of the Bavaria Solarpark (figure 6.7).

Could this flood of solar panels co-exist with the army of windmills we imagined in Chapter 4? Yes, no problem: windmills cast little shadow, and ground-level solar panels have negligible effect on the wind. How audacious is this plan? The solar power capacity required to deliver this 50 kWh per day per person in the UK is more than 100 times all the photovoltaics in the whole world. So should I include the PV farm in my sustainable production stack? I'm in two minds. At the start of this book I said I wanted to explore what the laws of physics say about the limits of sustainable energy, assuming money is no object. On those grounds, I should certainly go ahead, industrialize the countryside, and push the PV farm onto the stack. At the same time, I want to help people figure out what we should be doing between *now* and 2050. And today, electricity from solar farms would be four times as expensive as the market rate. So I feel a bit irresponsible as I include this estimate in the sustainable production stack in figure 6.9 – paving 5% of the UK with solar panels seems beyond the bounds of plausibility in so many ways. If we seriously contemplated doing such a thing, it would quite probably be better to put the panels in a two-fold sunnier country and send some of the energy home by power lines. We'll return to this idea in Chapter 25.

Figure 6.7. A solar photovoltaic farm: the 6.3 MW (peak) Solarpark in Mühlhausen, Bavaria. Its average power per unit land area is expected to be about $5\,\mathrm{W/m^2}$. Photo by SunPower.

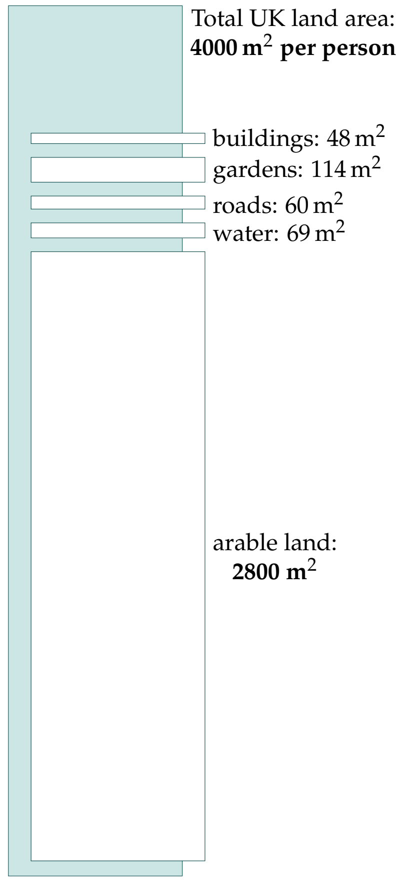


Figure 6.8. Land areas per person in Britain.

Mythconceptions

Manufacturing a solar panel consumes more energy than it will ever deliver.

False. The *energy yield ratio* (the ratio of energy delivered by a system over its lifetime, to the energy required to make it) of a roof-mounted, grid-connected solar system in Central Northern Europe is 4, for a system with a lifetime of 20 years (Richards and Watt, 2007); and more than 7 in a sunnier spot such as Australia. (An energy yield ratio bigger than one means that a system is A Good Thing, energy-wise.) Wind turbines with a lifetime of 20 years have an energy yield ratio of 80.

Aren't photovoltaic panels going to get more and more efficient as technology improves?

I am sure that photovoltaic panels will become ever *cheaper*; I'm also sure that solar panels will become ever less energy-intensive to *manufacture*, so their energy yield ratio will improve. But this chapter's photovoltaic estimates weren't constrained by the economic cost of the panels, nor by the energy cost of their manufacture. This chapter was concerned with the maximum conceivable power delivered. Photovoltaic panels with 20% efficiency are already close to the theoretical limit (see this chapter's endnotes). I'll be surprised if this chapter's estimate for roof-based photovoltaics ever needs a significant upward revision.

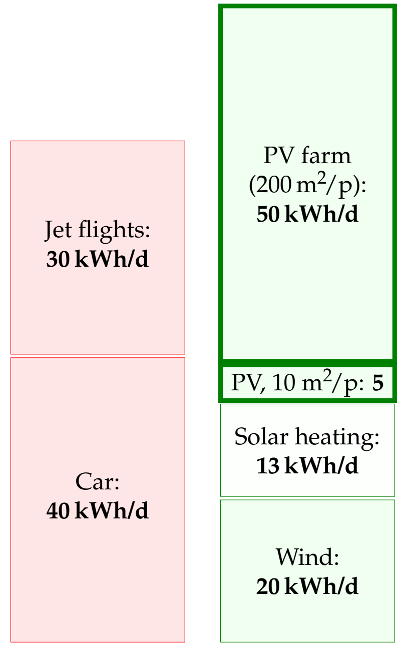


Figure 6.9. Solar photovoltaics: a $10\,m^2$ array of building-mounted south-facing panels with 20% efficiency can deliver about 5 kWh per day of electrical energy. If 5% of the country were coated with 10%-efficient solar panels ($200\,m^2$ of panels per person) they would deliver 50 kWh/day/person.

Solar biomass

> *All of a sudden, you know, we may be in the energy business by being able to grow grass on the ranch! And have it harvested and converted into energy. That's what's close to happening.*
>
> George W. Bush, February 2006

All available bioenergy solutions involve first growing green stuff, and then doing something with the green stuff. How big could the energy collected by the green stuff possibly be? There are four main routes to get energy from solar-powered biological systems:

1. We can grow specially-chosen plants and burn them in a power station that produces electricity or heat or both. We'll call this "coal substitution."

2. We can grow specially-chosen plants (oil-seed rape, sugar cane, or corn, say), turn them into ethanol or biodiesel, and shove that into cars, trains, planes or other places where such chemicals are useful. Or we might cultivate genetically-engineered bacteria, cyanobacteria, or algae that directly produce hydrogen, ethanol, or butanol, or even electricity. We'll call all such approaches "petroleum substitution."

3. We can take by-products from other agricultural activities and burn them in a power station. The by-products might range from straw (a by-product of Weetabix) to chicken poo (a by-product of McNuggets). Burning by-products is coal substitution again, but using ordinary plants, not the best high-energy plants. A power station that burns agricultural by-products won't deliver as much power per unit area of farmland as an optimized biomass-growing facility, but it has the

advantage that it doesn't monopolize the land. Burning methane gas from landfill sites is a similar way of getting energy, but it's sustainable only as long as we have a sustainable source of junk to keep putting into the landfill sites. (Most of the landfill methane comes from wasted food; people in Britain throw away about 300 g of food per day per person.) Incinerating household waste is another slightly less roundabout way of getting power from solar biomass.

4. We can grow plants and feed them directly to energy-requiring humans or other animals.

For all of these processes, the first staging post for the energy is in a chemical molecule such as a carbohydrate in a green plant. We can therefore estimate the power obtainable from any and all of these processes by estimating how much power could pass through that first staging post. All the subsequent steps involving tractors, animals, chemical facilities, landfill sites, or power stations can only lose energy. So the power at the first staging post is an upper bound on the power available from all plant-based power solutions.

So, let's simply estimate the power at the first staging post. (In Chapter D, we'll go into more detail, estimating the maximum contribution of each process.) The average harvestable power of sunlight in Britain is 100 W/m^2. The most efficient plants in Europe are about 2%-efficient at turning solar energy into carbohydrates, which would suggest that plants might deliver 2 W/m^2; however, their efficiency drops at higher light levels, and the best performance of any energy crops in Europe is closer to 0.5 W/m^2. Let's cover 75% of the country with quality green stuff. That's 3000 m^2 per person devoted to bio-energy. This is the same as the British land area

Figure 6.10. Some *Miscanthus* grass enjoying the company of Dr Emily Heaton, who is 5′4″ (163 cm) tall. In Britain, *Miscanthus* achieves a power per unit area of 0.75 W/m^2. Photo provided by the University of Illinois.

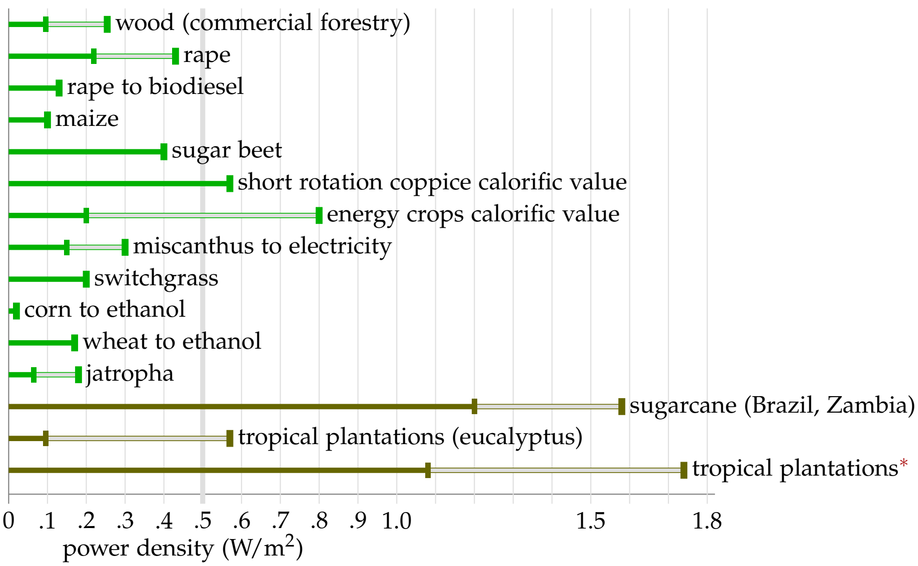


Figure 6.11. Power production, per unit area, achieved by various plants. For sources, see the end-notes. These power densities vary depending on irrigation and fertilization; ranges are indicated for some crops, for example wood has a range from 0.095–0.254 W/m^2. The bottom three power densities are for crops grown in tropical locations. The last power density (tropical plantations*) assumes genetic modification, fertilizer application, and irrigation. In the text, I use 0.5 W/m^2 as a summary figure for the best energy crops in NW Europe.

currently devoted to agriculture. So the maximum power available, ignoring all the additional costs of growing, harvesting, and processing the greenery, is

$$0.5\,\mathrm{W/m^2} \times 3000\,\mathrm{m^2} \text{ per person} \quad = \quad 36\,\mathrm{kWh/d} \text{ per person.}$$

Wow. That's not very much, considering the outrageously generous assumptions we just made, to try to get a big number. If you wanted to get biofuels for cars or planes from the greenery, all the other steps in the chain from farm to spark plug would inevitably be inefficient. I think it'd be optimistic to hope that the overall losses along the processing chain would be as small as 33%. Even burning dried wood in a good wood boiler loses 20% of the heat up the chimney. So surely the true potential power from biomass and biofuels cannot be any bigger than 24 kWh/d per person. And don't forget, we want to use some of the greenery to make food for us and for our animal companions.

Could genetic engineering produce plants that convert solar energy to chemicals more efficiently? It's conceivable; but I haven't found any scientific publication predicting that plants in Europe could achieve net power production beyond $1\,\mathrm{W/m^2}$.

I'll pop 24 kWh/d per person onto the green stack, emphasizing that I think this number is an over-estimate – I think the true maximum power that we could get from biomass will be smaller because of the losses in farming and processing.

I think one conclusion is clear: *biofuels can't add up* – at least, not in countries like Britain, and not as a replacement for all transport fuels. Even leaving aside biofuels' main defects – that their production competes with food, and that the additional inputs required for farming and processing often cancel out most of the delivered energy (figure 6.14) – biofuels made from plants, in a European country like Britain, can deliver so little power, I think they are scarcely worth talking about.

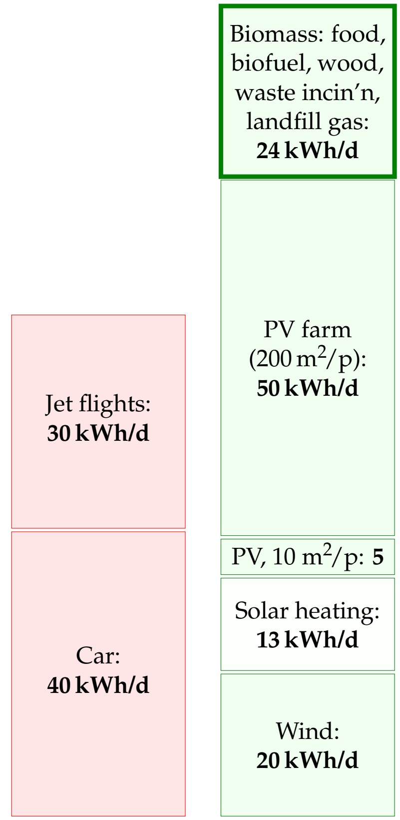


Figure 6.12. Solar biomass, including all forms of biofuel, waste incineration, and food: 24 kWh/d per person.

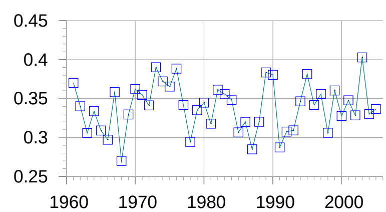


Figure 6.13. Sunniness of Cambridge: the number of hours of sunshine per year, expressed as a fraction of the total number of daylight hours.

Notes and further reading

page no.

38 *...compensate for the tilt between the sun and the land.* The latitude of Cambridge is $\theta = 52°$; the intensity of midday sunlight is multiplied by $\cos\theta \simeq 0.6$. The precise factor depends on the time of year, and varies between $\cos(\theta + 23°) = 0.26$ and $\cos(\theta - 23°) = 0.87$.

– *In a typical UK location the sun shines during one third of daylight hours.* The Highlands get 1100 h sunshine per year – a sunniness of 25%. The best spots in Scotland get 1400 h per year – 32%. Cambridge: 1500 ± 130 h per year – 34%. South coast of England (the sunniest part of the UK): 1700 h per year – 39%. [2rqloc] Cambridge data from [2szckw]. See also figure 6.16.

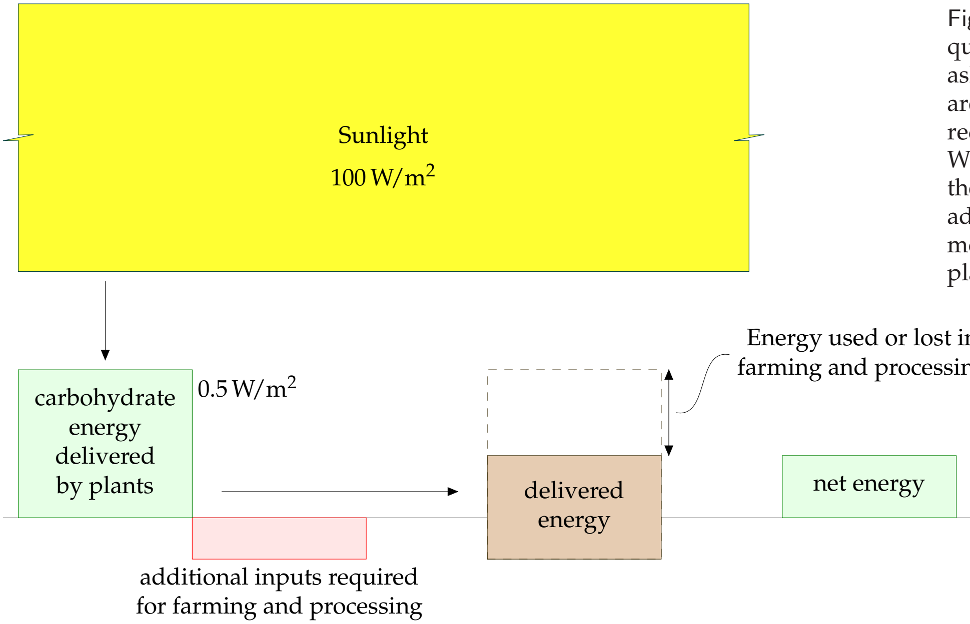


Figure 6.14. This figure illustrates the quantitative questions that must be asked of any proposed biofuel. What are the additional energy inputs required for farming and processing? What is the delivered energy? What is the *net* energy output? Often the additional inputs and losses wipe out most of the energy delivered by the plants.

38 *The average raw power of sunshine per square metre of south-facing roof in Britain is roughly 110 W/m², and of flat ground, roughly 100 W/m².* Source: NASA "Surface meteorology and Solar Energy" [5hrxls]. Surprised that there's so little difference between a tilted roof facing south and a horizontal roof? I was. The difference really is just 10% [6z9epq].

39 *...that would be about 10 m² of panels per person.* I estimated the area of south-facing roof per person by taking the area of land covered by buildings per person (48 m² in England – table I.6), multiplying by 1/4 to get the south-facing fraction, and bumping the area up by 40% to allow for roof tilt. This gives 16 m² per person. Panels usually come in inconvenient rectangles so some fraction of roof will be left showing; hence 10 m² of panels.

– *The average power delivered by photovoltaic panels...*
There's a myth going around that states that solar panels produce almost as much power in cloudy conditions as in sunshine. This is simply not true. On a bright but cloudy day, solar photovoltaic panels and plants do continue to convert some energy, but much less: photovoltaic production falls roughly ten-fold when the sun goes behind clouds (because the intensity of the incoming sunlight falls ten-fold). As figure 6.15 shows, the power delivered by photovoltaic panels is almost exactly proportional to the intensity of the sunlight – at least, if the panels are at 25 °C. To complicate things, the power delivered depends on temperature too – hotter panels have reduced power (typically 0.38% loss in power per °C) – but if you check data from real panels, e.g. at www.solarwarrior.com, you can confirm the main point: output on a cloudy day is *far less* than on a sunny day. This issue is obfuscated by some solar-panel promoters who discuss how the "efficiency" varies with sunlight. "The panels are more efficient in cloudy conditions," they say; this

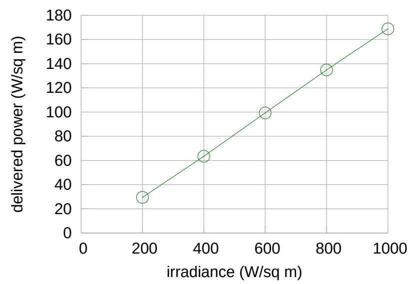


Figure 6.15. Power produced by the Sanyo HIP-210NKHE1 module as a function of light intensity (at 25 °C, assuming an output voltage of 40 V). Source: datasheet, www.sanyo-solar.eu.

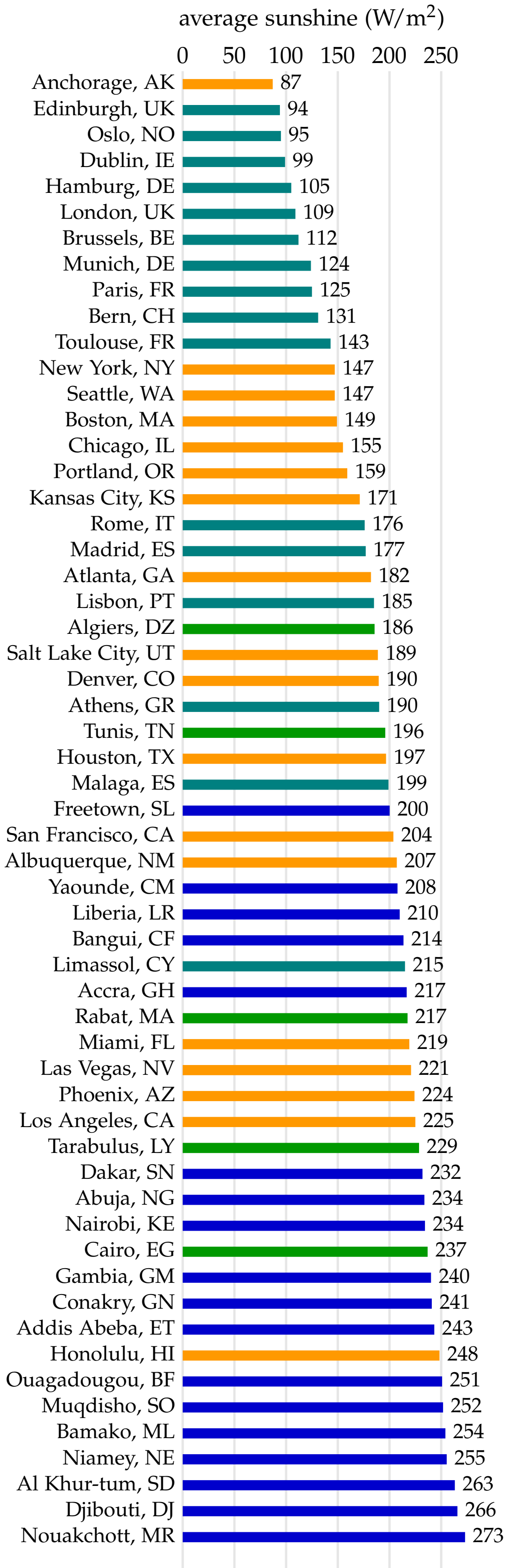


Figure 6.16. Average power of sunshine falling on a horizontal surface in selected locations in Europe, North America, and Africa.

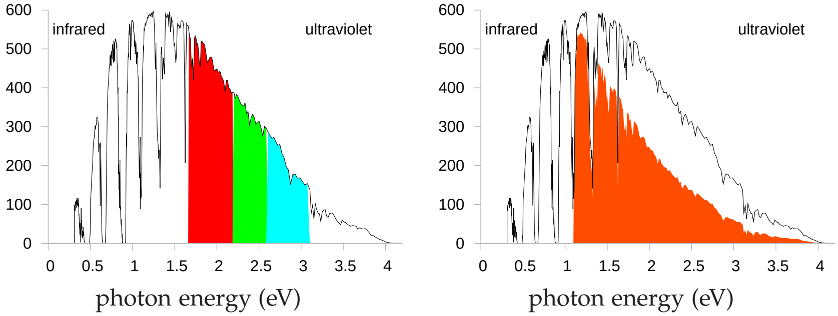


Figure 6.17. Part of Shockley and Queisser's explanation for the 31% limit of the efficiency of simple photovoltaics.
Left: the spectrum of midday sunlight. The vertical axis shows the power density in W/m^2 per eV of spectral interval. The visible part of the spectrum is indicated by the coloured section.
Right: the energy captured by a photovoltaic device with a single band-gap at 1.1 eV is shown by the tomato-shaded area. Photons with energy less than the band-gap are lost. Some of the energy of photons above the band-gap is lost; for example half of the energy of every 2.2 eV photon is lost.
Further losses are incurred because of inevitable radiation from recombining charges in the photovoltaic material.

may be true, but efficiency should not be confused with delivered power.

39 *Typical solar panels have an efficiency of about 10%; expensive ones perform at 20%.* See figure 6.18. Sources: Turkenburg (2000), Sunpower `www.sunpowercorp.com`, Sanyo `www.sanyo-solar.eu`, Suntech.

– *A device with efficiency greater than 30% would be quite remarkable*. This is a quote from Hopfield and Gollub (1978), who were writing about panels without concentrating mirrors or lenses. The theoretical limit for a standard "single-junction" solar panel without concentrators, the Shockley–Queisser limit, says that at most 31% of the energy in sunlight can be converted to electricity (Shockley and Queisser, 1961). (The main reason for this limit is that a standard solar material has a property called its band-gap, which defines a particular energy of photon that that material converts most efficiently. Sunlight contains photons with many energies; photons with energy *below* the band-gap are not used at all; photons with energy *greater* than the band-gap may be captured, but all their energy in excess of the band-gap is lost. Concentrators (lenses or mirrors) can both reduce the cost (per watt) of photovoltaic systems, and increase their efficiency. The Shockley–Queisser limit for solar panels with concentrators is 41% efficiency. The only way to beat the Shockley–Queisser limit is to make fancy photovoltaic devices that split the light into different wavelengths, processing each wavelength-range with its own personalized band-gap. These are called multiple-junction photovoltaics. Recently multiple-junction photovoltaics with optical concentrators have been reported to be about 40% efficient. [`2tl7t6`], `www.spectrolab.com`. In July 2007, the University of Delaware reported 42.8% efficiency with 20-times concentration [`6hobq2`], [`2lsx6t`]. In August 2008, NREL reported 40.8% efficiency with 326-times concentration [`62ccou`]. Strangely, both these results were called world efficiency records. What multiple-junction devices are available on the market? Uni-solar sell a thin-film triple-junction 58 W(peak) panel with an area of 1 m^2. That implies an efficiency, in full sunlight, of only 5.8%.

40 *Figure 6.5: Solar PV data*. Data and photograph kindly provided by Jonathan Kimmitt.

– *Heliodynamics* – `www.hdsolar.com`. See figure 6.19.
A similar system is made by Arontis `www.arontis.se`.

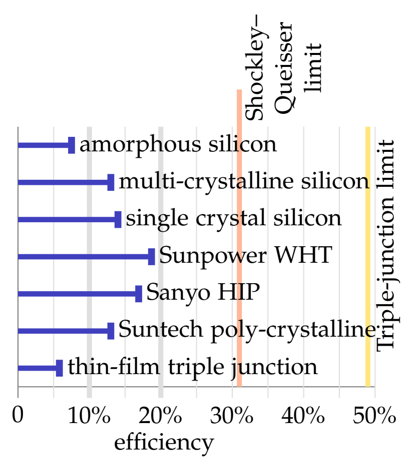


Figure 6.18. Efficiencies of solar photovoltaic modules available for sale today. In the text I assume that roof-top photovoltaics are 20% efficient, and that country-covering photovoltaics would be 10% efficient. In a location where the average power density of incoming sunlight is 100 W/m^2, 20%-efficient panels deliver 20 W/m^2.

41 *The Solarpark in Muhlhausen, Bavaria*. On average this 25-hectare farm is expected to deliver 0.7 MW (17 000 kWh per day).
New York's Stillwell Avenue subway station has integrated amorphous silicon thin-film photovoltaics in its roof canopy, delivering 4 W/m^2 (Fies et al., 2007).
The Nellis solar power plant in Nevada was completed in December, 2007, on 140 acres, and is expected to generate 30 GWh per year. That's 6 W/m^2 [5hzs5y].
Serpa Solar Power Plant, Portugal (PV), "the world's most powerful solar power plant," [39z5m5] [2uk8q8] has sun-tracking panels occupying 60 hectares, i.e., 600 000 m^2 or 0.6 km^2, expected to generate 20 GWh per year, i.e., 2.3 MW on average. That's a power per unit area of 3.8 W/m^2.

41 *The solar power capacity required to deliver 50 kWh/d per person in the UK is more than 100 times all the photovoltaics in the whole world*. To deliver 50 kWh/d per person in the UK would require 125 GW average power, which requires 1250 GW of capacity. At the end of 2007, world installed photovoltaics amounted to 10 GW peak; the build rate is roughly 2 GW per year.

– *...paving 5% of this country with solar panels seems beyond the bounds of plausibility*. My main reason for feeling such a panelling of the country would be implausible is that Brits like using their countryside for farming and recreation rather than solar-panel husbandry. Another concern might be price. This isn't a book about economics, but here are a few figures. Going by the price-tag of the Bavarian solar farm, to deliver 50 kWh/d per person would cost €91 000 per person; if that power station lasted 20 years without further expenditure, the wholesale cost of the electricity would be €0.25 per kWh. Further reading: David Carlson, BP solar [2ahecp].

43 *People in Britain throw away about 300 g of food per day.* Source: Ventour (2008).

– *Figure 6.10*. In the USA, *Miscanthus* grown without nitrogen fertilizer yields about 24 t/ha/y of dry matter. In Britain, yields of 12–16 t/ha/y are reported. Dry *Miscanthus* has a net calorific value of 17 MJ/kg, so the British yield corresponds to a power density of 0.75 W/m^2. Sources: Heaton et al. (2004) and [6kqq77]. The estimated yield is obtained only after three years of undisturbed growing.

– *The most efficient plants are about 2% efficient; but the delivered power per unit area is about 0.5 W/m^2*. *At low light intensities*, the best British plants are 2.4% efficient in well-fertilized fields (Monteith, 1977) but at higher light intensities, their conversion efficiency drops. According to Turkenburg (2000) and Schiermeier et al. (2008), the conversion efficiency of solar to biomass energy is less than 1%.
Here are a few sources to back up my estimate of *0.5 W/m^2* for vegetable power in the UK. The Royal Commission on Environmental Pollution's estimate of the potential delivered power density from energy crops in Britain is 0.2 W/m^2 (Royal Commission on Environmental Pollution, 2004). On page 43 of the Royal Society's biofuels document (Royal Society working group on biofuels, 2008), *Miscanthus* tops the list, delivering about 0.8 W/m^2 of chemical power.

Figure 6.19. A combined-heat-and-power photovoltaic unit from Heliodynamics. A reflector area of 32 m^2 (a bit larger than the side of a double-decker bus) delivers up to 10 kW of heat and 1.5 kW of electrical power. In a sun-belt country, one of these one-ton devices could deliver about 60 kWh/d of heat and 9 kWh/d of electricity. These powers correspond to average fluxes of 80 W/m^2 of heat and 12 W/m^2 of electricity (that's per square metre of device surface); these fluxes are similar to the fluxes delivered by standard solar heating panels and solar photovoltaic panels, but Heliodynamics's concentrating design delivers power at a lower cost, because most of the material is simple flat glass. For comparison, the total power consumption of the average European person is 125 kWh/d.

In the World Energy Assessment published by the UNDP, Rogner (2000) writes: "Assuming a 45% conversion efficiency to electricity and yields of 15 oven dry tons per hectare per year, 2 km^2 of plantation would be needed per megawatt of electricity of installed capacity running 4,000 hours a year." That is a power per unit area of 0.23 W(e)/m^2. (1 W(e) means 1 watt of electrical power.)

Energy for Sustainable Development Ltd (2003) estimates that short-rotation coppices can deliver over 10 tons of dry wood per hectare per year, which corresponds to a power density of 0.57 W/m^2. (Dry wood has a calorific value of 5 kWh per kg.)

According to Archer and Barber (2004), the instantaneous efficiency of a healthy leaf in optimal conditions can approach 5%, but the long-term energy-storage efficiency of modern crops is 0.5–1%. Archer and Barber suggest that by genetic modification, it might be possible to improve the storage efficiency of plants, especially *C4 plants*, which have already naturally evolved a more efficient photosynthetic pathway. C4 plants are mainly found in the tropics and thrive in high temperatures; they don't grow at temperatures below 10 °C. Some examples of C4 plants are sugarcane, maize, sorghum, finger millet, and switchgrass. Zhu et al. (2008) calculate that the theoretical limit for the conversion efficiency of solar energy to biomass is 4.6% for C3 photosynthesis at 30 °C and today's 380 ppm atmospheric CO_2 concentration, and 6% for C4 photosynthesis. They say that the highest solar energy conversion efficiencies reported for C3 and C4 crops are 2.4% and 3.7% respectively; and, citing Boyer (1982), that the average conversion efficiencies of major crops in the US are 3 or 4 times lower than those record efficiencies (that is, about 1% efficient). One reason that plants don't achieve the theoretical limit is that they have insufficient capacity to use all the incoming radiation of bright sunlight. Both these papers (Zhu et al., 2008; Boyer, 1982) discuss prospects for genetic engineering of more-efficient plants.

43 *Figure 6.11.* The numbers in this figure are drawn from Rogner (2000) (net energy yields of wood, rape, sugarcane, and tropical plantations); Bayer Crop Science (2003) (rape to biodiesel); Francis et al. (2005) and Asselbergs et al. (2006) (jatropha); Mabee et al. (2006) (sugarcane, Brazil); Schmer et al. (2008) (switchgrass, marginal cropland in USA); Shapouri et al. (1995) (corn to ethanol); Royal Commission on Environmental Pollution (2004); Royal Society working group on biofuels (2008); Energy for Sustainable Development Ltd (2003); Archer and Barber (2004); Boyer (1982); Monteith (1977).

44 *Even just setting fire to dried wood in a good wood boiler loses 20% of the heat up the chimney.* Sources: Royal Society working group on biofuels (2008); Royal Commission on Environmental Pollution (2004).

7 Heating and cooling

This chapter explores how much power we spend controlling the temperature of our surroundings – at home and at work – and on warming or cooling our food, drink, laundry, and dirty dishes.

Figure 7.1. A flock of new houses.

Domestic water heating

The biggest use of hot water in a house might be baths, showers, dishwashing, or clothes-washing – it depends on your lifestyle. Let's estimate first the energy used by taking a hot bath.

The volume of bath-water is 50 cm × 15 cm × 150 cm ≃ 110 litre. Say the temperature of the bath is 50 °C (120 F) and the water coming into the house is at 10 °C. The heat capacity of water, which measures how much energy is required to heat it up, is 4200 J per litre per °C. So the energy required to heat up the water by 40 °C is

$$4200\,\mathrm{J/litre/^\circ C} \times 110\,\mathrm{litre} \times 40\,^\circ\mathrm{C} \simeq 18\,\mathrm{MJ} \simeq 5\,\mathrm{kWh}.$$

So taking a bath uses about 5 kWh. For comparison, taking a shower (30 litres) uses about 1.4 kWh.

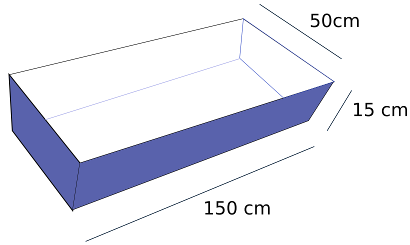


Figure 7.2. The water in a bath.

Kettles and cookers

Britain, being a civilized country, has a 230 volt domestic electricity supply. With this supply, we can use an electric kettle to boil several litres of water in a couple of minutes. Such kettles have a power of 3 kW. Why 3 kW? Because this is the biggest power that a 230 volt outlet can deliver without the current exceeding the maximum permitted, 13 amps. In countries where the voltage is 110 volts, it takes twice as long to make a pot of tea.

$$230\,\mathrm{V} \times 13\,\mathrm{A} = 3000\,\mathrm{W}$$

If a household has the kettle on for 20 minutes per day, that's an average power consumption of 1 kWh per day. (I'll work out the next few items "per household," with 2 people per household.)

One small ring on an electric cooker has the same power as a toaster: 1 kW. The higher-power hot plates deliver 2.3 kW. If you use two rings of the cooker on full power for half an hour per day, that corresponds to 1.6 kWh per day.

A microwave oven usually has its cooking power marked on the front: mine says 900 W, but it actually *consumes* about 1.4 kW. If you use the microwave for 20 minutes per day, that's 0.5 kWh per day.

A regular oven guzzles more: about 3 kW when on full. If you use the oven for one hour per day, and the oven's on full power for half of that time, that's 1.5 kWh per day.

Microwave:
1400 W peak

Fridge-freezer:
100 W peak,
18 W average

Figure 7.3. Power consumption by a heating and a cooling device.

Device	power	time per day	energy per day
Cooking			
– kettle	3 kW	1/3 h	1 kWh/d
– microwave	1.4 kW	1/3 h	0.5 kWh/d
– electric cooker (rings)	3.3 kW	1/2 h	1.6 kWh/d
– electric oven	3 kW	1/2 h	1.5 kWh/d
Cleaning			
– washing machine	2.5 kW		1 kWh/d
– tumble dryer	2.5 kW	0.8 h	2 kWh/d
– airing-cupboard drying			0.5 kWh/d
– washing-line drying			0 kWh/d
– dishwasher	2.5 kW		1.5 kWh/d
Cooling			
– refrigerator	0.02 kW	24 h	0.5 kWh/d
– freezer	0.09 kW	24 h	2.3 kWh/d
– air-conditioning	0.6 kW	1 h	0.6 kWh/d

Table 7.4. Energy consumption figures for heating and cooling devices, per household.

Hot clothes and hot dishes

A clothes washer, dishwasher, and tumble dryer all use a power of about 2.5 kW when running.

A clothes washer uses about 80 litres of water per load, with an energy cost of about 1 kWh if the temperature is set to 40 °C. If we use an indoor airing-cupboard instead of a tumble dryer to dry clothes, heat is still required to evaporate the water – roughly 1.5 kWh to dry one load of clothes, instead of 3 kWh.

Totting up the estimates relating to hot water, I think it's easy to use about 12 kWh per day per person.

Hot water:
12 kWh/d

Figure 7.5. The hot water total at both home and work – including bathing, showering, clothes washing, cookers, kettles, microwave oven, and dishwashing – is about 12 kWh per day per person. I've given this box a light colour to indicate that this power could be delivered by low-grade thermal energy.

Hot air – at home and at work

Now, does more power go into making hot water and hot food, or into making hot air via our buildings' radiators?

One way to estimate the energy used per day for hot air is to imagine a building heated instead by electric fires, whose powers are more familiar to us. The power of a small electric bar fire or electric fan heater is 1 kW (24 kWh per day). In winter, you might need one of these per person to keep toasty. In summer, none. So we estimate that on average one modern person *needs* to use 12 kWh per day on hot air. But most people use more than they need, keeping several rooms warm simultaneously (kitchen, living room, corridor, and bathroom, say). So a plausible consumption figure for hot air is about double that: 24 kWh per day per person.

This chapter's companion Chapter E contains a more detailed account of where the heat is going in a building; this model makes it possible to

Figure 7.6. A big electric heater: 2 kW.

predict the heat savings from turning the thermostat down, double-glazing the windows, and so forth.

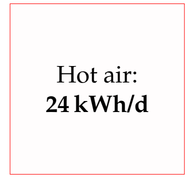


Figure 7.7. Hot air total – including domestic and workplace heating – about 24 kWh per day per person.

Warming the outdoors, and other luxuries

There's a growing trend of warming the outdoors with patio heaters. Typical patio heaters have a power of 15 kW. So if you use one of these for a couple of hours every evening, you are using an extra 30 kWh per day.

A more modest luxury is an electric blanket. An electric blanket for a double bed uses 140 W; switching it on for one hour uses 0.14 kWh.

Cooling

Fridge and freezer

We control the temperatures not only of the hot water and hot air with which we surround ourselves, but also of the cold cupboards we squeeze into our hothouses. My fridge-freezer, pictured in figure 7.3, consumes 18 W on average – that's roughly 0.5 kWh/d.

Air-conditioning

In countries where the temperature gets above 30 °C, air-conditioning is viewed as a necessity, and the energy cost of delivering that temperature control can be large. However, this part of the book is about British energy consumption, and Britain's temperatures provide little need for air-conditioning (figure 7.8).

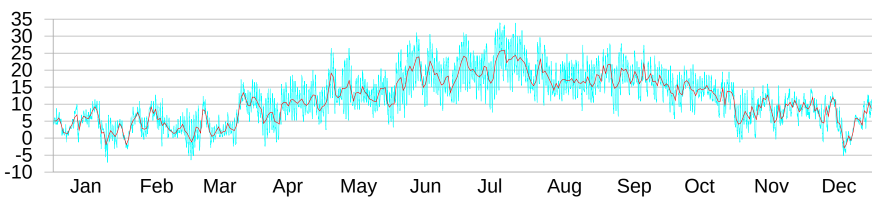


Figure 7.8. Cambridge temperature in degrees Celsius, daily (red line), and half-hourly (blue line) during 2006.

An economical way to get air-conditioning is an air-source heat pump. A window-mounted electric air-conditioning unit for a single room uses 0.6 kW of electricity and (by heat-exchanger) delivers 2.6 kW of cooling. To estimate how much energy someone might use in the UK, I assumed they might switch such an air-conditioning unit on for about 12 hours per day on 30 days of the year. On the days when it's on, the air-conditioner uses 7.2 kWh. The average consumption over the whole year is 0.6 kWh/d.

This chapter's estimate of the energy cost of cooling – 1 kWh/d per person – includes this air-conditioning and a domestic refrigerator. Society

Figure 7.9. Cooling total – including a refrigerator (fridge/freezer) and a little summer air-conditioning – 1 kWh/d.

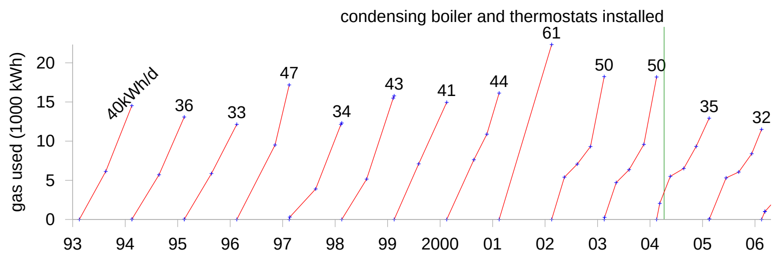


Figure 7.10. My domestic cumulative gas consumption, in kWh, each year from 1993 to 2005. The number at the top of each year's line is the average rate of energy consumption, in kWh per day. To find out what happened in 2007, keep reading!

also refrigerates food on its way from field to shopping basket. I'll estimate the power cost of the food-chain later, in Chapter 15.

Total heating and cooling

Our rough estimate of the total energy that one person might spend on heating and cooling, including home, workplace, and cooking, is 37 kWh/d per person (12 for hot water, 24 for hot air, and 1 for cooling).

Evidence that this estimate is in the right ballpark, or perhaps a little on the low side, comes from my own domestic gas consumption, which for 12 years averaged 40 kWh per day (figure 7.10). At the time I thought I was a fairly frugal user of heating, but I wasn't being attentive to my actual power consumption. Chapter 21 will reveal how much power I saved once I started paying attention.

Since heating is a big item in our consumption stack, let's check my estimates against some national statistics. Nationally, the average *domestic* consumption for space heating, water, and cooking in the year 2000 was 21 kWh per day per person, and consumption in the *service sector* for heating, cooling, catering, and hot water was 8.5 kWh/d/p. For an estimate of workplace heating, let's take the gas consumption of the University of Cambridge in 2006–7: 16 kWh/d per employee.

Totting up these three numbers, a second guess for the national spend on heating is $21 + 8.5 + 16 \simeq 45$ kWh/d per person, if Cambridge University is a normal workplace. Good, that's reassuringly close to our first guess of 37 kWh/d.

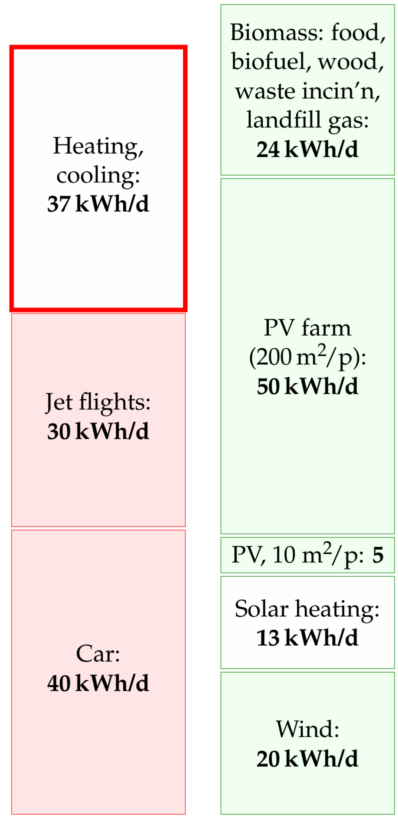


Figure 7.11. Heating and cooling – about 37 units per day per person. I've removed the shading from this box to indicate that it represents power that could be delivered by low-grade thermal energy.

Notes and further reading

page no.

50 *An oven uses 3 kW*. Obviously there's a range of powers. Many ovens have a maximum power of 1.8 kW or 2.2 kW. Top-of-the-line ovens use as much as 6 kW. For example, the Whirlpool AGB 487/WP 4 Hotplate Electric Oven Range has a 5.9 kW oven, and four 2.3 kW hotplates.
`www.kcmltd.com/electric_oven_ranges.shtml`
`www.1stforkitchens.co.uk/kitchenovens.html`

51 *An airing cupboard requires roughly 1.5 kWh to dry one load of clothes.* I worked this out by weighing my laundry: a load of clothes, 4 kg when dry, emerged from my Bosch washing machine weighing 2.2 kg more (even after a good German spinning). The latent heat of vaporization of water at 15 °C is roughly 2500 kJ/kg. To obtain the daily figure in table 7.4 I assumed that one person has a load of laundry every three days, and that this sucks valuable heat from the house during the cold half of the year. (In summer, using the airing cupboard delivers a little bit of air-conditioning, since the evaporating water cools the air in the house.)

53 *Nationally, the average domestic consumption was 21 kWh/d/p; consumption in the service sector was 8.5 kWh/d/p.* Source: Dept. of Trade and Industry (2002a).

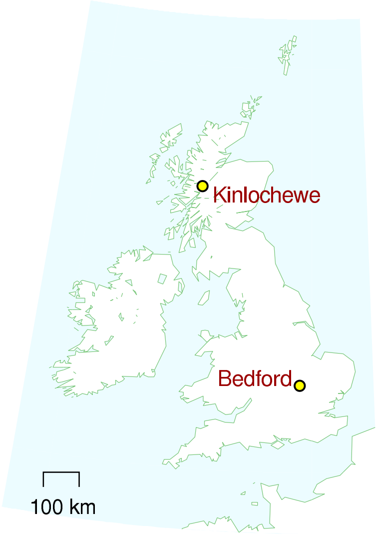
– *In 2006–7, Cambridge University's gas consumption was 16 kWh/d per employee.* The gas and oil consumption of the University of Cambridge (not including the Colleges) was 76 GWh in 2006–7. I declared the University to be the place of work of 13 300 people (8602 staff and 4667 postgraduate researchers). Its electricity consumption, incidentally, was 99.5 GWh. Source: University utilities report.

8 Hydroelectricity

Figure 8.1. Nant-y-Moch dam, part of a 55 MW hydroelectric scheme in Wales. Photo by Dave Newbould, www.origins-photography.co.uk.

To make hydroelectric power, you need altitude, and you need rainfall. Let's estimate the total energy of all the rain as it runs down to sea-level.

For this hydroelectric forecast, I'll divide Britain into two: the lower, dryer bits, which I'll call "the lowlands;" and the higher, wetter bits, which I'll call "the highlands." I'll choose Bedford and Kinlochewe as my representatives of these two regions.



Let's do the lowlands first. To estimate the gravitational power of lowland rain, we multiply the rainfall in Bedford (584 mm per year) by the density of water (1000 kg/m^3), the strength of gravity (10 m/s^2) and the typical lowland altitude above the sea (say 100 m). The power per unit area works out to 0.02 W/m^2. That's the power per unit area of land on which rain falls.

When we multiply this by the area per person (2700 m^2, if the lowlands are equally shared between all 60 million Brits), we find an average raw power of about 1 kWh per day per person. This is the absolute upper limit for lowland hydroelectric power, if every river were dammed and every drop perfectly exploited. Realistically, we will only ever dam rivers with substantial height drops, with catchment areas much smaller than the whole country. Much of the water evaporates before it gets anywhere near a turbine, and no hydroelectric system exploits the full potential energy of the water. We thus arrive at a firm conclusion about lowland water power. People may enjoy making "run-of-the-river" hydro and other small-scale hydroelectric schemes, but such lowland facilities can never deliver more than 1 kWh per day per person.

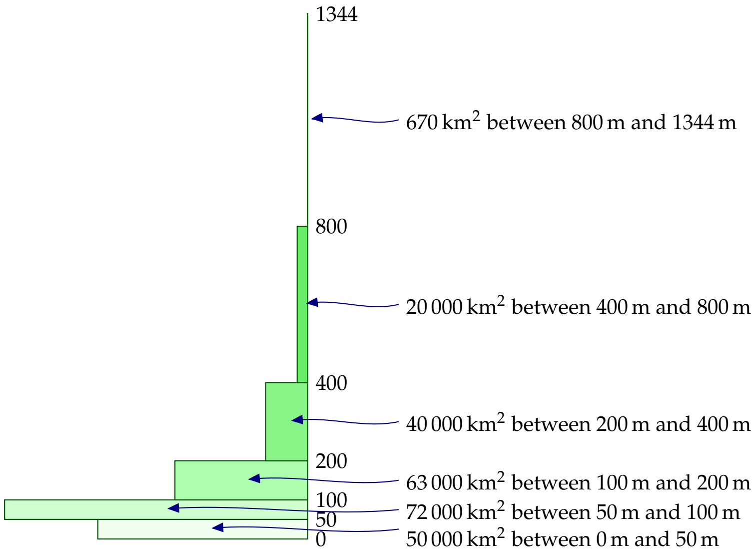


Figure 8.2. Altitudes of land in Britain. The rectangles show how much land area there is at each height.

Let's turn to the highlands. Kinlochewe is a rainier spot: it gets 2278 mm per year, four times more than Bedford. The height drops there are bigger too – large areas of land are above 300 m. So overall a twelve-fold increase in power per square metre is plausible for mountainous regions. The raw power per unit area is roughly 0.24 W/m^2. If the highlands generously share their hydro-power with the rest of the UK (at 1300 m^2 area per person), we find an upper limit of about 7 kWh per day per person. As in the lowlands, this is the upper limit on raw power if evaporation were outlawed and every drop were perfectly exploited.

What should we estimate is the plausible practical limit? Let's guess 20% of this – 1.4 kWh per day, and round it up a little to allow for production in the lowlands: 1.5 kWh per day.

The actual power from hydroelectricity in the UK today is 0.2 kWh/d per person, so this 1.5 kWh/d per person would require a seven-fold increase in hydroelectric power.

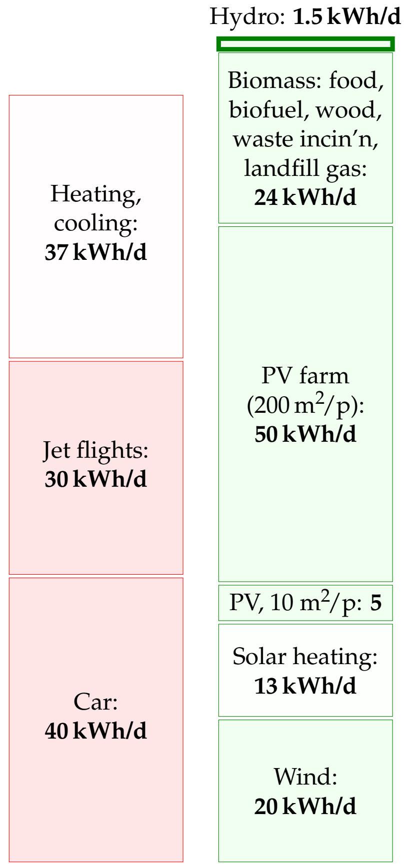


Figure 8.3. Hydroelectricity.

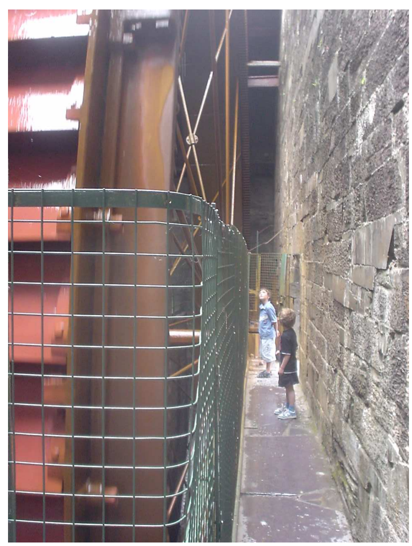


Figure 8.4. A 60 kW waterwheel.

Notes and further reading

55 *Rainfall* statistics are from the BBC weather centre.

56 *The raw power per unit area [of Highland rain] is roughly* 0.24 W/m^2. We can check this estimate against the actual power density of the Loch Sloy hydro-electric scheme, completed in 1950 (Ross, 2008). The catchment area of Loch Sloy is about 83 km^2; the rainfall there is about 2900 mm per year (a bit higher than the 2278 mm/y of Kinlochewe); and the electricity output in 2006 was 142 GWh per year, which corresponds to a power density of 0.2 W per m^2 of catchment area. Loch Sloy's surface area is about 1.5 km^2, so the hydroelectric facility itself has a per unit lake area of 11 W/m^2. So the hillsides, aqueducts, and tunnels bringing water to Loch Sloy act like a 55-fold power concentrator.

– *The actual power from hydroelectricity in the UK today is 0.2 kWh per day per person.* Source: MacLeay et al. (2007). In 2006, large-scale hydro produced 3515 GWh (from plant with a capacity of 1.37 GW); small-scale hydro, 212 GWh (0.01 kWh/d/p) (from a capacity of 153 MW).
In 1943, when the growth of hydroelectricity was in full swing, the North of Scotland Hydroelectricity Board's engineers estimated that the Highlands of Scotland could produce 6.3 TWh per year in 102 facilities – that would correspond to 0.3 kWh/d per person in the UK (Ross, 2008).
Glendoe, the first new large-scale hydroelectric project in the UK since 1957, will add capacity of 100 MW and is expected to deliver 180 GWh per year. Glendoe's catchment area is 75 km^2, so its power density works out to 0.27 W per m^2 of catchment area. Glendoe has been billed as "big enough to power Glasgow." But if we share its 180 GWh per year across the population of Glasgow (616 000 people), we get only 0.8 kWh/d per person. That is just 5% of the average electricity consumption of 17 kWh/d per person. The 20-fold exaggeration is achieved by focusing on Glendoe's *peak* output rather than its *average*, which is 5 times smaller; and by discussing "homes" rather than the total electrical power of Glasgow (see p329).

9 *Light*

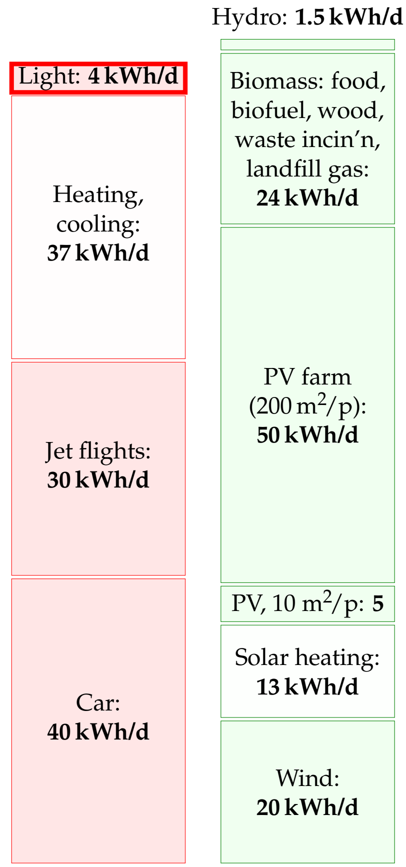


Figure 9.1. Lighting – 4 kWh per day per person.

Lighting home and work

The brightest domestic lightbulbs use 250 W, and bedside lamps use 40 W. In an old-fashioned incandescent bulb, most of this power gets turned into heat, rather than light. A fluorescent tube can produce an equal amount of light using one quarter of the power of an incandescent bulb.

How much power does a moderately affluent person use for lighting? My rough estimate, based on table 9.2, is that a typical two-person home with a mix of low-energy and high-energy bulbs uses about 5.5 kWh per day, or 2.7 kWh per day per person. I assume that each person also has a workplace where they share similar illumination with their colleagues; guessing that the workplace uses 1.3 kWh/d per person, we get a round figure of 4 kWh/d per person.

Street-lights and traffic lights

Do we need to include public lighting too, to get an accurate estimate, or do home and work dominate the lighting budget? Street-lights in fact use about 0.1 kWh per day per person, and traffic lights only 0.005 kWh/d per person – both negligible, compared with our home and workplace lighting. What about other forms of public lighting – illuminated signs and bollards, for example? There are fewer of them than street-lights; and street-lights already came in well under our radar, so we don't need to modify our overall estimate of 4 kWh/d per person.

Lights on the traffic

In some countries, drivers must switch their lights on whenever their car is moving. How does the extra power required by that policy compare with the power already being used to trundle the car around? Let's say the car has four incandescent lights totalling 100 W. The electricity for those bulbs is supplied by a 25%-efficient engine powering a 55%-efficient generator, so the power required is 730 W. For comparison, a typical car going at an average speed of 50 km/h and consuming one litre per 12 km

Device	Power	Time per day	Energy per day per home
10 incandescent lights	1 kW	5 h	5 kWh
10 low-energy lights	0.1 kW	5 h	0.5 kWh

Table 9.2. Electric consumption for domestic lighting. A plausible total is 5.5 kWh per home per day; and a similar figure at work; perhaps 4 kWh per day per person.

has an average power consumption of 42 000 W. So having the lights on while driving requires 2% extra power.

What about the future's electric cars? The power consumption of a typical electric car is about 5000 W. So popping on an extra 100 W would increase its consumption by 2%. Power consumption would be smaller if we switched all car lights to light-emitting diodes, but if we pay any more attention to this topic, we will be coming down with a severe case of every-little-helps-ism.

The economics of low-energy bulbs

Generally I avoid discussing economics, but I'd like to make an exception for lightbulbs. Osram's 20 W low-energy bulb claims the same light output as a 100 W incandescent bulb. Moreover, its lifetime is said to be 15 000 hours (or "12 years," at 3 hours per day). In contrast a typical incandescent bulb might last 1000 hours. So during a 12-year period, you have this choice (figure 9.3): buy 15 incandescent bulbs and 1500 kWh of electricity (which costs roughly £150); or buy one low-energy bulb and 300 kWh of electricity (which costs roughly £30).

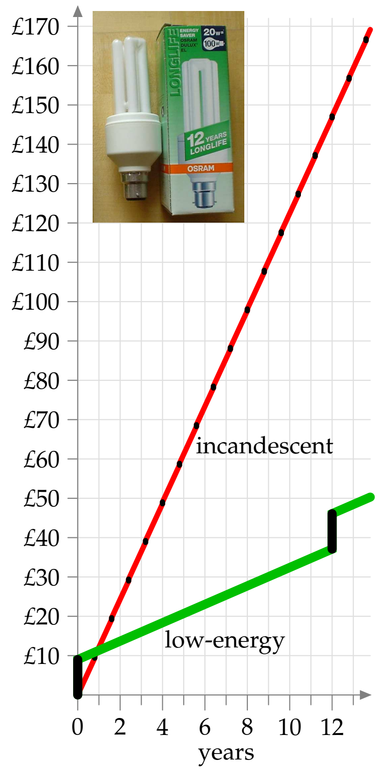


Figure 9.3. Total cumulative cost of using a traditional incandescent 100 W bulb for 3 hours per day, compared with replacing it *now* with an Osram Dulux Longlife Energy Saver (pictured). Assumptions: electricity costs 10p per kWh; replacement traditional bulbs cost 45p each; energy-saving bulbs cost £9. (I know you can find them cheaper than this, but this graph shows that even at £9, they're much more economical.)

Should I wait until the old bulb dies before replacing it?

It feels like a waste, doesn't it? Someone put resources into making the old incandescent lightbulb; shouldn't we cash in that original investment by using the bulb until it's worn out? But the economic answer is clear: *continuing to use an old lightbulb is throwing good money after bad*. If you can find a satisfactory low-energy replacement, replace the old bulb now.

What about the mercury in compact fluorescent lights? Are LED bulbs better than fluorescents?

Researchers say that LED (light-emitting diode) bulbs will soon be even more energy-efficient than compact fluorescent lights. The efficiency of a light is measured in *lumens per watt*. I checked the numbers on my latest purchases: the Philips Genie 11 W compact fluorescent bulb (figure 9.4) has a brightness of 600 lumens, which is an efficiency of **55 lumens per watt**; regular incandescent bulbs deliver **10 lumens per watt**; the Omicron 1.3 W lamp, which has 20 white LEDs hiding inside it, has a brightness of 46 lumens, which is an efficiency of **35 lumens per watt**. So this LED bulb is almost as efficient as the fluorescent bulb. The LED industry still has a little catching up to do. In its favour, the LED bulb has a life of 50 000 hours, eight times the life of the fluorescent bulb. As I write, I see that `www.cree.com` is selling LEDs with a power of **100 lumens per watt**. It's projected that in the future, white LEDs will have an efficiency of over 150 lumens per watt [`ynjzej`]. I expect that within another couple of years, the best advice, from the point of view of both energy efficiency and avoiding mercury pollution, will be to use LED bulbs.

Figure 9.4. Philips 11 W alongside Omicron 1.3 W LED bulb.

Mythconceptions

"There is no point in my switching to energy-saving lights. The "wasted" energy they put out heats my home, so it's not wasted."

This myth is addressed in Chapter 11, p71.

Bulb type	efficiency (lumens/W)
incandescent	10
halogen	16–24
white LED	35
compact fluorescent	55
large fluorescent	94
sodium street-light	150

Table 9.5. Lighting efficiencies of commercially-available bulbs. In the future, white LEDs are expected to deliver 150 lumens per watt.

Notes and further reading

page no.

57 *Street-lights use about 0.1 kWh per day per person...* There's roughly one sodium street-light per 10 people; each light has a power of 100 W, switched on for 10 hours per day. That's 0.1 kWh per day per person.

– *...and traffic lights only 0.005 kWh/d per person.* Britain has 420 000 traffic and pedestrian signal light bulbs, consuming 100 million kWh of electricity per year. Shared between 60 million people, 100 million kWh per year is 0.005 kWh/d per person.

– *There are fewer signs and illuminated bollards than street-lights.* [www.highwayelectrical.org.uk]. There are 7.7 million lighting units (street lighting, illuminated signs and bollards) in the UK. Of these, roughly 7 million are street-lights and 1 million are illuminated road signs. There are 210 000 traffic signals.
According to DUKES 2005, the total power for public lighting is 2095 GWh/y, which is 0.1 kWh/d per person.

– *55%-efficient generator* – source: en.wikipedia.org/wiki/Alternator. Generators in power stations are much more efficient at converting mechanical work to electricity.

10 Offshore wind

The London Array offshore wind farm will make a crucial contribution to the UK's renewable energy targets.

James Smith, chairman of Shell UK

Electric power is too vital a commodity to be used as a job-creation programme for the wind turbine industry.

David J. White

At sea, winds are stronger and steadier than on land, so offshore wind farms deliver a higher power per unit area than onshore wind farms. The Kentish Flats wind farm in the Thames Estuary, about 8.5 km offshore from Whitstable and Herne Bay, which started operation at the end of 2005, was predicted to have an average power per unit area of 3.2 W/m^2. In 2006, its average power per unit area was 2.6 W/m^2.

I'll assume that a power per unit area of 3 W/m^2 (50% larger than our onshore estimate of 2 W/m^2) is an appropriate figure for offshore wind farms around the UK.

We now need an estimate of the area of sea that could plausibly be covered with wind turbines. It is conventional to distinguish between *shallow* offshore wind and *deep* offshore wind, as illustrated in figure 10.2. Conventional wisdom seems to be that *shallow* offshore wind (depth less than 25–30 m), while roughly twice as costly as land-based wind, is economically feasible, given modest subsidy; and *deep* offshore wind is at present not economically feasible. As of 2008, there's just one deep offshore windfarm in UK waters, an experimental prototype sending all its electricity to a nearby oilrig called Beatrice.

Figure 10.1. Kentish Flats – a shallow offshore wind farm. Each rotor has a diameter of 90 m centred on a hub height of 70 m. Each "3 MW" turbine weighs 500 tons, half of which is its foundation.
Photos © Elsam (`elsam.com`). Used with permission.

Shallow offshore

Within British territorial waters, the shallow area is about 40 000 km^2, most of it off the coast of England and Wales. This area is about two Waleses.

The average power available from shallow offshore wind farms occupying the whole of this area would be 120 GW, or 48 kWh/d per person. But it's hard to imagine this arrangement being satisfactory for shipping. Substantial chunks of this shallow water would, I'm sure, remain off-limits for wind farms. The requirement for shipping corridors and fishing areas must reduce the plausibly-available area; I propose that we assume the available fraction is one third (but please see this chapter's end-notes for a more pessimistic view!). So we estimate the maximum plausible power from shallow offshore wind to be 16 kWh/d per person.

Before moving on, I want to emphasize the large area – two thirds of a Wales – that would be required to deliver this 16 kWh/d per person. If

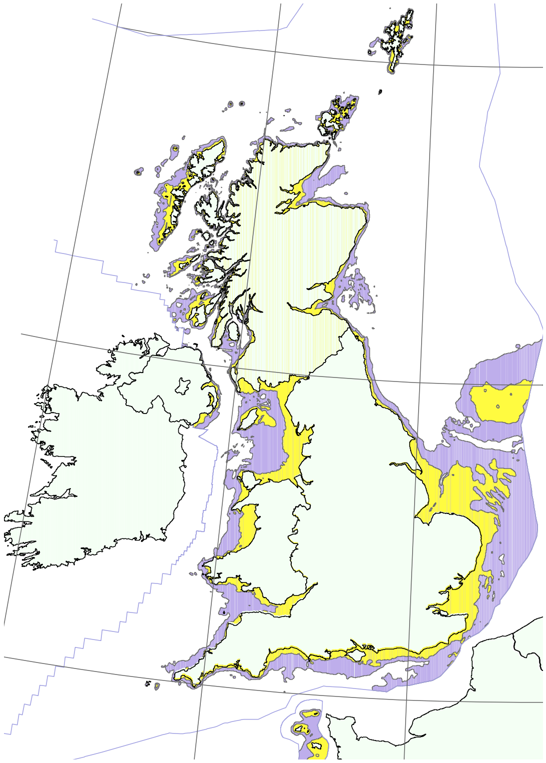
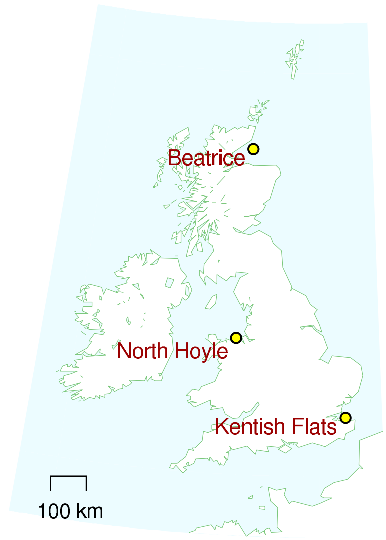


Figure 10.2. UK territorial waters with depth less than 25 m (yellow) and depth between 25 m and 50 m (purple). Data from DTI Atlas of Renewable Marine Resources. © Crown copyright.



we take the total coastline of Britain (length: 3000 km), and put a strip of turbines 4 km wide all the way round, that strip would have an area of 13 000 km^2. That is the area we must fill with turbines to deliver 16 kWh/d per person. To put it another way, consider the number of turbines required. 16 kWh/d per person would be delivered by 44 000 "3 MW" turbines, which works out to 15 per kilometre of coastline, if they were evenly spaced around 3000 km of coast.

Offshore wind is tough to pull off because of the corrosive effects of sea water. At the big Danish wind farm, Horns Reef, all 80 turbines had to be dismantled and repaired after only 18 months' exposure to the sea air. The Kentish Flats turbines seem to be having similar problems with their gearboxes, one third needing replacement during the first 18 months.

Deep offshore

The area with depths between 25 m and 50 m is about 80 000 km^2 – the size of Scotland. Assuming again a power per unit area of 3 W/m^2, "deep" offshore wind farms could deliver another 240 GW, or 96 kWh/d per person, if turbines completely filled this area. Again, we must make corridors for shipping. I suggest as before that we assume we can use one third of the area for wind farms; this area would then be about 30% bigger than Wales, and much of it would be further than 50 km offshore. The outcome: if an area equal to a 9 km-wide strip all round the coast were filled with turbines, deep offshore wind could deliver a power of 32 kWh/d per person. A huge amount of power, yes; but still no match for our huge consumption. And we haven't spoken about the issue of wind's intermittency. We'll come back to that in Chapter 26.

I'll include this potential deep offshore contribution in the production stack, with the proviso, as I said before, that wind experts reckon deep offshore wind is prohibitively expensive.

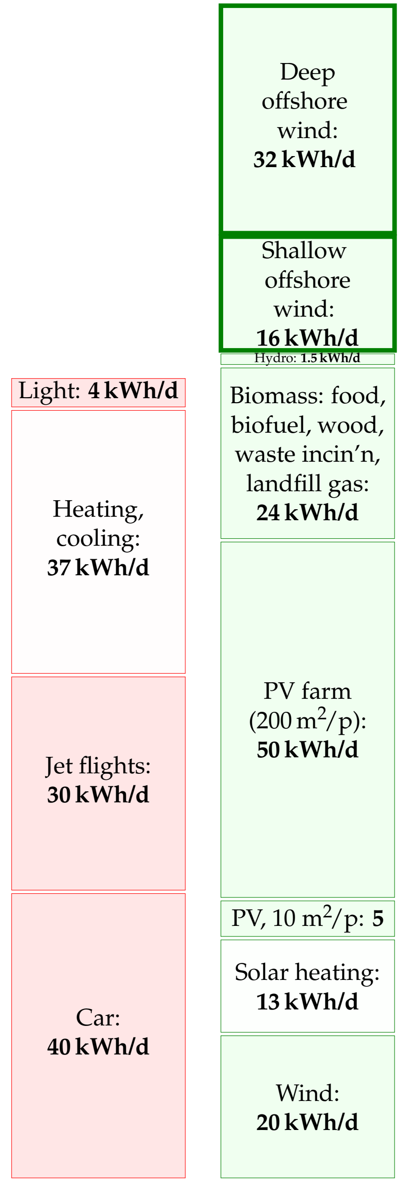


Figure 10.3. Offshore wind.

Some comparisons and costs

So, how's our race between consumption and production coming along? Adding both shallow and deep offshore wind to the production stack, the green stack has a lead. Something I'd like you to notice about this race, though, is this contrast: how *easy* it is to toss a bigger log on the consumption fire, and how *difficult* it is to grow the production stack. As I write this paragraph, I'm feeling a little cold, so I step over to my thermostat and turn it up. It's so simple for me to consume an extra 30 kWh per day. But squeezing an extra 30 kWh per day per person from renewables requires an industrialization of the environment so large it is hard to imagine.

To create 48 kWh per day of offshore wind per person in the UK would require 60 million tons of concrete and steel – one ton per person. Annual world steel production is about 1200 million tons, which is 0.2 tons per person in the world. During the second world war, American shipyards built 2751 Liberty ships, each containing 7000 tons of steel – that's a total of 19 million tons of steel, or 0.1 tons per American. So the building of 60 million tons of wind turbines is not off the scale of achievability; but don't kid yourself into thinking that it's easy. Making this many windmills is as big a feat as building the Liberty ships.

For comparison, to make 48 kWh per day of nuclear power per person in the UK would require 8 million tons of steel and 0.14 million tons of concrete. We can also compare the 60 million tons of offshore wind hardware that we're trying to imagine with the existing fossil-fuel hardware already sitting in and around the North Sea (figure 10.4). In 1997, 200 installations and 7000 km of pipelines in the UK waters of the North Sea contained 8 million tons of steel and concrete. The newly built Langeled gas pipeline from Norway to Britain, which will convey gas with a power of 25 GW (10 kWh/d/p), used another 1 million tons of steel and 1 million tons of concrete (figure 10.5).

The UK government announced on 10th December 2007 that it would permit the creation of 33 GW of offshore wind capacity (which would deliver on average 10 GW to the UK, or 4.4 kWh per day per person), a plan branded "pie in the sky" by some in the wind industry. Let's run with a round figure of 4 kWh per day per person. This is one quarter of my shallow 16 kWh per day per person. To obtain this average power requires roughly 10 000 "3 MW" wind turbines like those in figure 10.1. (They have a capacity of "3 MW" but on average they deliver 1 MW. I pop quotes round "3 MW" to indicate that this is a capacity, a peak power.)

What would this "33 GW"' of power cost to erect? Well, the "90 MW" Kentish Flats farm cost £105 million, so "33 GW" would cost about £33 billion. One way to clarify this £33 billion cost of offshore wind delivering 4 kWh/d per person is to share it among the UK population; that comes out to £550 per person. This is a much better deal, incidentally, than micro-turbines. A roof-mounted microturbine currently costs about £1500 and, even at a very optimistic windspeed of 6 m/s, delivers only 1.6 kWh/d. In reality, in a typical urban location in England, such microturbines deliver 0.2 kWh per day.

Another bottleneck constraining the planting of wind turbines is the special ships required. To erect 10 000 wind turbines ("33 GW") over a period of 10 years would require roughly 50 jack-up barges. These cost £60 million each, so an extra capital investment of £3 billion would be required. Not a show-stopper compared with the £33bn price tag already quoted, but the need for jack-up barges is certainly a detail that requires some forward planning.

Figure 10.4. The Magnus platform in the northern UK sector of the North Sea contains 71 000 tons of steel. In the year 2000 this platform delivered 3.8 million tons of oil and gas – a power of 5 GW. The platform cost £1.1 billion.
Photos by Terry Cavner.

Costs to birds

Do windmills kill "huge numbers" of birds? Wind farms recently got adverse publicity from Norway, where the wind turbines on Smola, a set of islands off the north-west coast, killed 9 white-tailed eagles in 10 months. I share the concern of BirdLife International for the welfare of rare birds. But I think, as always, it's important to do the numbers. It's been estimated that 30 000 birds per year are killed by wind turbines in Denmark, where windmills generate 9% of the electricity. Horror! Ban windmills! We also learn, moreover, that *traffic* kills *one million* birds per year in Denmark. Thirty-times-greater horror! Thirty-times-greater incentive to ban cars! And in Britain, 55 million birds per year are killed by *cats* (figure 10.6).

Figure 10.5. Pipes for Langeled. From Bredero–Shaw [`brederoshaw.com`].

Going on emotions alone, I would like to live in a country with virtually no cars, virtually no windmills, and with plenty of cats and birds (with the cats that prey on birds perhaps being preyed upon by Norwegian white-tailed eagles, to even things up). But what I really hope is that decisions about cars and windmills are made by careful rational thought, not by emotions alone. Maybe we do need the windmills!

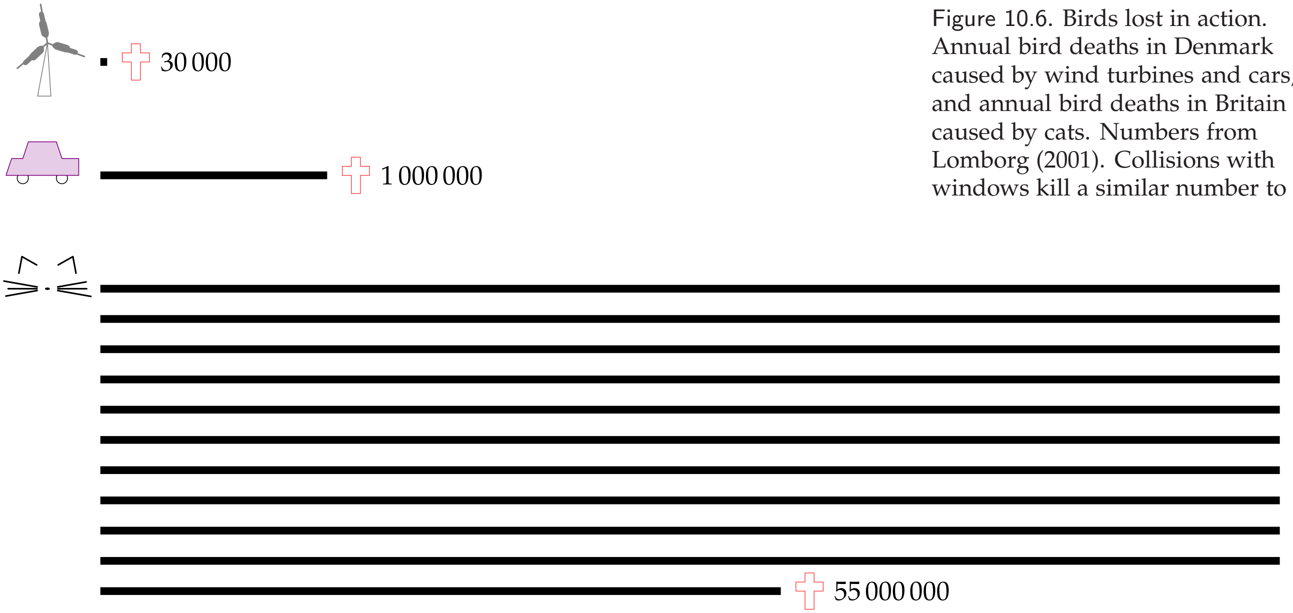


Figure 10.6. Birds lost in action. Annual bird deaths in Denmark caused by wind turbines and cars, and annual bird deaths in Britain caused by cats. Numbers from Lomborg (2001). Collisions with windows kill a similar number to cats.

Notes and further reading

page no.

60 *The Kentish Flats wind farm in the Thames Estuary...*
See `www.kentishflats.co.uk`. Its 30 Vestas V90 wind turbines have a total peak output of 90 MW, and the predicted average output was 32 MW (assuming a load factor of 36%). The mean wind speed at the hub height is 8.7 m/s. The turbines stand in 5 m-deep water, are spaced 700 m apart, and occupy an area of 10 km². The power density of this offshore wind farm was thus predicted to be 3.2 W/m². In fact, the average output was 26 MW, so the average load factor in 2006 was 29% [`wbd8o`]. This works out to a power density of 2.6 W/m². The North Hoyle wind farm off Prestatyn, North Wales, had a higher load factor of 36% in 2006. Its thirty 2 MW turbines occupy 8.4 km². They thus had an average power density of 2.6 W/m².

– *...shallow offshore wind, while roughly twice as costly as onshore wind, is economically feasible, given modest subsidy.* Source: Danish wind association `windpower.org`.

– *...deep offshore wind is at present not economically feasible.*
Source: British Wind Energy Association briefing document, September 2005, `www.bwea.com`. Nevertheless, a deep offshore demonstration project in 2007 put two turbines adjacent to the Beatrice oil field, 22 km off the east coast of Scotland (figure 10.8). Each turbine has a "capacity" of 5 MW and sits in a water depth of 45 m. Hub height: 107 m; diameter 126 m. All the electricity generated will be used by the oil platforms. Isn't that special! The 10 MW project cost £30 million – this price-tag of £3 per watt (peak) can be

Region	depth 5 to 30 metres		depth 30 to 50 metres	
	area (km^2)	potential resource (kWh/d/p)	area (km^2)	potential resource (kWh/d/p)
North West	3 300	6	2 000	4
Greater Wash	7 400	14	950	2
Thames Estuary	2 100	4	850	2
Other	14 000	28	45 000	87
TOTAL	27 000	52	49 000	94

Table 10.7. Potential offshore wind generation resource in proposed strategic regions, if these regions were *entirely filled* with wind turbines. From Dept. of Trade and Industry (2002b).

compared with that of Kentish Flats, £1.2 per watt (£105 million for 90 MW). `www.beatricewind.co.uk`
It's possible that *floating* wind turbines may change the economics of deep offshore wind.

60 *The area available for offshore wind.*
The Department of Trade and Industry's (2002) document "Future Offshore" gives a detailed breakdown of areas that are useful for offshore wind power. Table 10.7 shows the estimated resource in 76 000 km^2 of shallow and deep water. The DTI's estimated power contribution, if these areas were *entirely* filled with windmills, is 146 kWh/d per person (consisting of 52 kWh/d/p from the shallow and 94 kWh/d/p from the deep). But the DTI's estimate of the potential offshore wind generation resource is just 4.6 kWh per day per person. It might be interesting to describe how they get down from this potential resource of 146 kWh/d per person to 4.6 kWh/d per person. Why a final figure so much lower than ours? First, they imposed these limits: the water must be within 30 km of the shore and less than 40 m deep; the sea bed must not have gradient greater than 5°; shipping lanes, military zones, pipelines, fishing grounds, and wildlife reserves are excluded. Second, they assumed that only 5% of potential sites will be developed (as a result of seabed composition or planning constraints); they reduced the capacity by 50% for all sites less than 10 miles from shore, for reasons of public acceptability; they further reduced the capacity of sites with wind speed over 9 m/s by 95% to account for "development barriers presented by the hostile environment;" and other sites with average wind speed 8–9 m/s had their capacities reduced by 5%.

61 *...if we take the total coastline of Britain (length: 3000 km), and put a strip of turbines 4 km wide all the way round...* Pedants will say that "the coastline of Britain is not a well-defined length, because the coast is a fractal." Yes, yes, it's a fractal. But, dear pedant, please take a map and put a strip of turbines 4 km wide around mainland Britain, and see if it's not the case that your strip is indeed about 3000 km long.

– *Horns Reef* (Horns Rev). The difficulties with this "160 MW" Danish wind farm off Jutland [`www.hornsrev.dk`] are described by Halkema (2006).

When it is in working order, Horns Reef's load factor is 0.43 and its average power per unit area is 2.6 W/m^2.

62 *Liberty ships* – www.liberty-ship.com/html/yards/introduction.html

– *...fossil fuel installations in the North Sea contained 8 million tons of steel and concrete* – Rice and Owen (1999).

– *The UK government announced on 10th December 2007 that it would permit the creation of 33 GW of offshore capacity...* [25e59w].

– *... "pie in the sky"*. Source: Guardian [2t2vjq].

63 *What would "33 GW" of offshore wind cost?* According to the DTI in November 2002, electricity from offshore wind farms costs about £50 per MWh (5p per kWh) (Dept. of Trade and Industry, 2002b, p21). Economic facts vary, however, and in April 2007 the estimated cost of offshore was up to £92 per MWh (Dept. of Trade and Industry, 2007, p7). By April 2008, the price of offshore wind evidently went even higher: Shell pulled out of their commitment to build the London Array. It's because offshore wind is so expensive that the Government is having to increase the number of ROCs (renewable obligation certificates) per unit of offshore wind energy. The ROC is the unit of subsidy given out to certain forms of renewable electricity generation. The standard value of a ROC is £45, with 1 ROC per MWh; so with a wholesale price of roughly £40/MWh, renewable generators are getting paid £85 per MWh. So 1 ROC per MWh is not enough subsidy to cover the cost of £92 per MWh. In the same document, estimates for other renewables (medium levelized costs in 2010) are as follows. Onshore wind: £65–89/MWh; co-firing of biomass: £53/MWh; large-scale hydro: £63/MWh; sewage gas: £38/MWh; solar PV: £571/MWh; wave: £196/MWh; tide: £177/MWh.

"Dale Vince, chief executive of green energy provider Ecotricity, which is engaged in building onshore wind farms, said that he supported the Government's [offshore wind] plans, but only if they are not to the detriment of onshore wind. 'It's dangerous to overlook the fantastic resource we have in this country... By our estimates, it will cost somewhere in the region of £40bn to build the 33 GW of offshore power Hutton is proposing. We could do the same job onshore for £20bn'." [57984r]

– *In a typical urban location in England, microturbines deliver 0.2 kWh per day*. Source: *Third Interim Report*, www.warwickwindtrials.org.uk/2.html. Among the best results in the Warwick Wind Trials study is a Windsave WS1000 (a 1-kW machine) in Daventry mounted at a height of 15 m above the ground, generating 0.6 kWh/d on average. But some microturbines deliver only 0.05 kWh per day – Source: Donnachadh McCarthy: "My carbon-free year," *The Independent*, December 2007 [6oc3ja]. The Windsave WS1000 wind turbine, sold across England in B&Q's shops, won an Eco-Bollocks award from *Housebuilder's Bible* author Mark Brinkley: "Come on, it's time to admit that the roof-mounted wind turbine industry is a complete fiasco. Good money is being thrown at an invention that doesn't work. This is the Sinclair C5 of the Noughties." [5soql2]. The Met Office and Carbon Trust published a report in July 2008 [6g2jm5], which estimates that, if small-scale

Figure 10.8. Construction of the Beatrice demonstrator deep offshore windfarm. Photos kindly provided by Talisman Energy (UK) Limited.

Figure 10.9. Kentish Flats. Photos © Elsam (elsam.com). Used with permission.

turbines were installed at all houses where economical in the UK, they would generate in total roughly 0.7 kWh/d/p. They advise that roof-mounted turbines in towns are usually worse than useless: "in many urban situations, roof-mounted turbines may not pay back the carbon emitted during their production, installation and operation."

63 *Jack-up barges cost £60 million each.*
Source: news.bbc.co.uk/1/hi/magazine/7206780.stm. I estimated that we would need roughly 50 of them by assuming that there would be 60 work-friendly days each year, and that erecting a turbine would take 3 days.

Further reading: UK wind energy database [www.bwea.com/ukwed/].

11 Gadgets

One of the greatest dangers to society is the phone charger. The BBC News has been warning us of this since 2005:

> "The nuclear power stations will all be switched off in a few years. How can we keep Britain's lights on? ... **unplug your mobile-phone charger when it's not in use**."

Sadly, a year later, Britain hadn't got the message, and the BBC was forced to report:

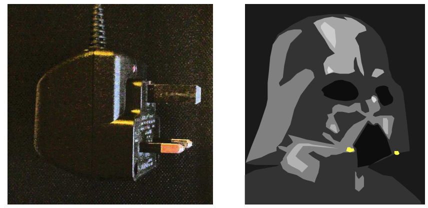
> "**Britain tops energy waste league**."

And how did this come about? The BBC rams the message home:

> "65% of UK consumers leave chargers on."

From the way reporters talk about these planet-destroying black objects, it's clear that they are roughly as evil as Darth Vader. But how evil, exactly?

In this chapter we'll find out the truth about chargers. We'll also investigate their cousins in the gadget parade: computers, phones, and TVs. Digital set-top boxes. Cable modems. In this chapter we'll estimate the power used in running them and charging them, but not in manufacturing the toys in the first place – we'll address that in the later chapter on "stuff."



Vader Charger

Figure 11.1. Planet destroyers. Spot the difference.

Figure 11.2. These five chargers – three for mobile phones, one for a pocket PC, and one for a laptop – registered less than one watt on my power meter.

The truth about chargers

Modern phone chargers, when left plugged in with no phone attached, use about half a watt. In our preferred units, this is a power consumption of about 0.01 kWh per day. For anyone whose consumption stack is over 100 kWh per day, the BBC's advice, *always unplug the phone charger*, could potentially reduce their energy consumption by one hundredth of one percent (if only they would do it).

> *Every little helps!*

I don't think so. 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. Let me put it this way:

> 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.

Admittedly, some older chargers use more than half a watt – if it's warm to the touch, it's probably using one watt or even three (figure 11.3). A three-watt-guzzling charger uses 0.07 kWh per day. I think that it's a good idea to switch off such a charger – it *will* save you three pounds per year. But don't kid yourself that you've "done your bit" by so doing. 3 W is only a tiny fraction of total energy consumption.

OK, that's enough bailing the Titanic with a teaspoon. Let's find out where the electricity is really being used.

Figure 11.3. This wasteful cordless phone and its charger use 3 W when left plugged in. That's **0.07 kWh/d**. If electricity costs 10p per kWh then a 3 W trickle costs £3 per year.

Gadgets that really suck

Table 11.4 shows the power consumptions, in watts, of a houseful of gadgets. The first column shows the power consumption when the device is actually being used – for example, when a sound system is actually playing sound. The second column shows the consumption when the device is switched on, but sitting doing nothing. I was particularly shocked to find that a laser-printer sitting idle consumes 17 W – the same as the average consumption of a fridge-freezer! The third column shows the consumption when the gadget is explicitly asked to go to sleep or standby. The fourth shows the consumption when it is completely switched off – but still left plugged in to the mains. I'm showing all these powers in watts – to convert back to our standard units, remember that 40 W is 1 kWh/d. A nice rule of thumb, by the way, is that each watt costs about one pound per year (assuming electricity costs 10p per kWh).

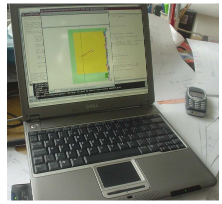
The biggest guzzlers are the computer, its screen, and the television, whose consumption is in the hundreds of watts, when on. Entertainment systems such as stereos and DVD players swarm in the computer's wake, many of them consuming 10 W or so. A DVD player may cost just £20 in the shop, but if you leave it switched on all the time, it's costing you another £10 per year. Some stereos and computer peripherals consume several watts even when switched off, thanks to their mains-transformers. To be sure that a gadget is truly off, you need to switch it off at the wall.

Powering the hidden tendrils of the information age

According to Jonathan Koomey (2007), the computer-servers in US data-centres and their associated plumbing (air conditioners, backup power systems, and so forth) consumed 0.4 kWh per day per person – just over 1% of US electricity consumption. That's the consumption figure for 2005, which, by the way, is twice as big as the consumption in 2000, because the number of servers grew from 5.6 million to 10 million.

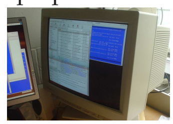
Gadget	Power consumption (W)			
	on and active	on but inactive	standby	off
Computer and peripherals:				
computer box	80	55		2
cathode-ray display	110		3	0
LCD display	34		2	1
projector	150		5	
laser printer	500	17		
wireless & cable-modem	9			
Laptop computer	16	9		0.5
Portable CD player	2			
Bedside clock-radio	1.1	1		
Bedside clock-radio	1.9	1.4		
Digital radio	9.1		3	
Radio cassette-player	3	1.2		1.2
Stereo amplifier	6			6
Stereo amplifier II	13			0
Home cinema sound	7	7	4	
DVD player	7	6		
DVD player II	12	10	5	
TV	100		10	
Video recorder	13		1	
Digital TV set top box	6		5	
Clock on microwave oven	2			
Xbox	160		2.4	
Sony Playstation 3	190		2	
Nintendo Wii	18		2	
Answering machine		2		
Answering machine II		3		
Cordless telephone		1.7		
Mobile phone charger	5	0.5		
Vacuum cleaner	1600			

Table 11.4. Power consumptions of various gadgets, in watts. 40 W is 1 kWh/d.

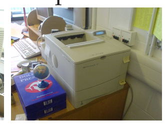


Laptop: 16 W

Computer: 80 W



LCD 31 W CRT 108 W



Printer: 17 W (on, idle)

Projector: 150 W

Digital radio: 8 W

Other gadgets

A vacuum cleaner, if you use it for a couple of hours per week, is equivalent to about 0.2 kWh/d. Mowing the lawn uses about 0.6 kWh. We could go on, but I suspect that computers and entertainment systems are the big suckers on most people's electrical balance-sheet.

This chapter's summary figure: it'll depend how many gadgets you have at home and work, but a healthy houseful or officeful of gadgets left on all the time could easily use 5 kWh/d.

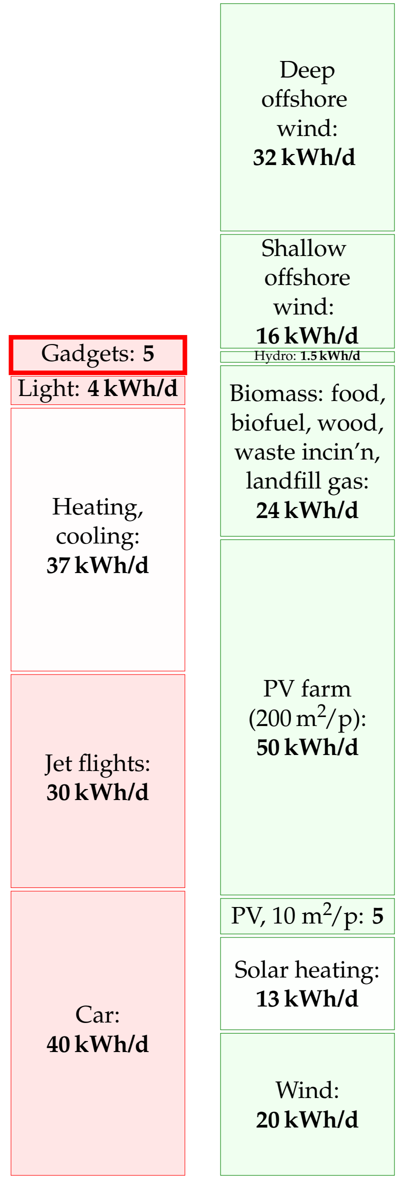


Figure 11.5. Information systems and other gadgets.

Mythconceptions

"There is no point in my switching off lights, TVs, and phone chargers during the winter. The 'wasted' energy they put out heats my home, so it's not wasted."

This myth is *True* for a few people, but only during the winter; but *False* for most.

If your house is being heated by electricity through ordinary bar fires or blower heaters then, yes, it's much the same as heating the house with any electricity-wasting appliances. But if you are in this situation, you should change the way you heat your house. Electricity is high-grade energy, and heat is low-grade energy. *It's a waste to turn electricity into heat.* To be precise, if you make only one unit of heat from a unit of electricity, that's a waste. Heaters called air-source heat pumps or ground-source heat pumps can do much better, delivering 3 or 4 units of heat for every unit of electricity consumed. They work like back-to-front refrigerators, pumping heat into your house from the outside air (see Chapter 21).

For the rest, whose homes are heated by fossil fuels or biofuels, it's a good idea to avoid using electrical gadgets as a heat source for your home – at least for as long as our increases in electricity-demand are served from fossil fuels. It's better to burn the fossil fuel at home. The point is, if you use electricity from an ordinary fossil power station, more than half of the energy from the fossil fuel goes sadly up the cooling tower. Of the energy that gets turned into electricity, about 8% is lost in the transmission system. If you burn the fossil fuel in your home, more of the energy goes directly into making hot air for you.

Notes and further reading

page no.

68 *The BBC News has been warning us … unplug your mobile-phone charger.* The BBC News article from 2005 said: "the nuclear power stations will all be switched off in a few years. How can we keep Britain's lights on? Here's three ways you can save energy: switch off video recorders when they're not in use; don't leave televisions on standby; and unplug your mobile-phone charger when it's not in use."

68 *Modern phone chargers, when left plugged in with no phone attached, use about half a watt.* The Maplin power meter in figure 11.2 is not accurate enough to measure this sort of power. I am grateful to Sven Weier and Richard McMahon of Cambridge University Engineering Department who measured a standard Nokia charger in an accurate calorimeter; they found that, when not connected to the mobile, it wastes 0.472 W. They made additional interesting measurements: the charger, when connected to a fully-charged mobile phone, wastes 0.845 W; and when the charger is doing what it's meant to do, charging a partly-charged Nokia mobile, it wastes 4.146 W as heat. Pedants sometimes ask "what about the *reactive power* of the charger?" This is a technical niggle, not really worth our time. For the record, I measured the reactive power (with a crummy meter) and found it to be about 2 VA per charger. Given that the power loss in the national grid is 8% of the delivered power, I reckon that the power loss associated with the reactive power is at most 0.16 W. When actually making a phone-call, the mobile uses 1 W.

Further reading: Kuehr (2003).

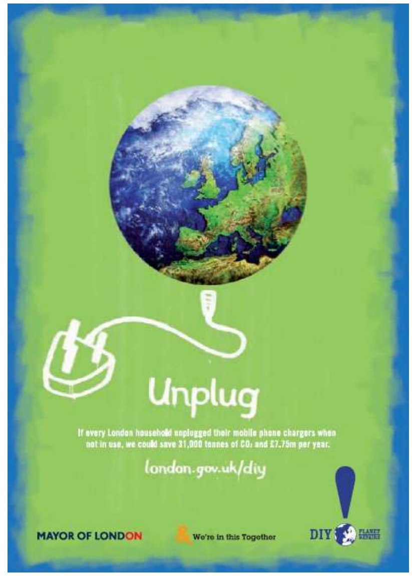


Figure 11.6. Advertisement from the "DIY planet repairs" campaign. The text reads "**Unplug**. If every London household unplugged their mobile-phone chargers when not in use, we could save 31,000 tonnes of CO_2 and £7.75m per year." `london.gov.uk/diy/`

12 Wave

If wave power offers hope to any country, then it must offer hope to the United Kingdom and Ireland – flanked on the one side by the Atlantic Ocean, and on the other by the North Sea.

First, let's clarify where waves come from: *sun makes wind and wind makes waves*.

Most of the sunlight that hits our planet warms the oceans. The warmed water warms the air above it, and produces water vapour. The warmed air rises; as it rises it cools, and the water eventually re-condenses, forming clouds and rain. At its highest point, the air is cooled down further by the freezing blackness of space. The cold air sinks again. This great solar-powered pump drives air round and round in great convection rolls. From our point of view on the surface, these convection rolls produce the winds. Wind is second-hand solar energy. As wind rushes across open water, it generates waves. Waves are thus third-hand solar energy. (The waves that crash on a beach are nothing to do with the tides.)

In open water, waves are generated whenever the wind speed is greater than about 0.5 m/s. The wave crests move at about the speed of the wind that creates them, and in the same direction. The *wavelength* of the waves (the distance between crests) and the *period* (the time between crests) depend on the speed of the wind. The longer the wind blows for, and the greater the expanse of water over which the wind blows, the greater the *height* of the waves stroked up by the wind. Thus since the prevailing winds over the Atlantic go from west to east, the waves arriving on the Atlantic coast of Europe are often especially big. (The waves on the east coast of the British Isles are usually much smaller, so my estimates of potential wave power will focus on the resource in the Atlantic Ocean.)

Waves have long memory and will keep going in the same direction for days after the wind stopped blowing, until they bump into something. In seas where the direction of the wind changes frequently, waves born on different days form a superposed jumble, travelling in different directions.

If waves travelling in a particular direction encounter objects that absorb energy from the waves – for example, a row of islands with sandy beaches – then the seas beyond the object are calmer. The objects cast a shadow, and there's less energy in the waves that get by. So, whereas sunlight delivers a power per unit *area*, waves deliver a power per unit *length* of coastline. You can't have your cake and eat it. You can't collect wave energy two miles off-shore *and* one mile off-shore. Or rather, you can try, but the two-mile facility will absorb energy that would have gone to the one-mile facility, and it won't be replaced. The fetch required for wind to stroke up big waves is thousands of miles.

We can find an upper bound on the maximum conceivable power that could be obtained from wave power by estimating the incoming power

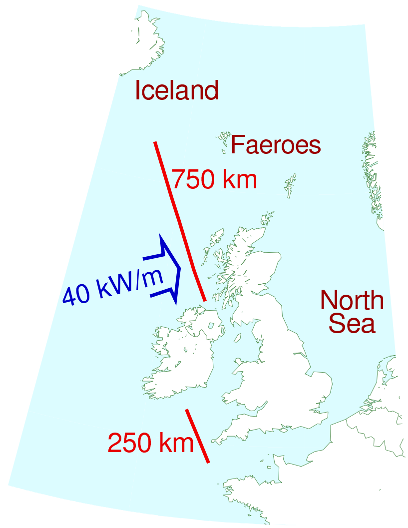


Figure 12.1. A Pelamis wave energy collector is a sea snake made of four sections. It faces nose-on towards the incoming waves. The waves make the snake flex, and these motions are resisted by hydraulic generators. The peak power from one snake is 750 kW; in the best Atlantic location one snake would deliver 300 kW on average. Photo from Pelamis wave power `www.pelamiswave.com`.

per unit length of exposed coastline, and multiplying by the length of coastline. We ignore the question of what mechanism could collect all this power, and start by working out how much power it is.

The power of Atlantic waves has been measured: it's about 40 kW per metre of exposed coastline. That sounds like a lot of power! If everyone owned a metre of coastline and could harness their whole 40 kW, that would be plenty of power to cover modern consumption. However, *our population is too big*. There is not enough Atlantic-facing coastline for everyone to have their own metre.

As the map on p73 shows, Britannia rules about 1000 km of Atlantic coastline (one million metres), which is $^1/_{60}$ m per person. So the total raw incoming power is 16 kWh per day per person. If we extracted all this power, the Atlantic, at the seaside, would be as flat as a millpond. Practical systems won't manage to extract all the power, and some of the power will inevitably be lost during conversion from mechanical energy to electricity. Let's assume that brilliant wave-machines are 50%-efficient at turning the incoming wave power into electricity, and that we are able to pack wave-machines along 500 km of Atlantic-facing coastline. That would mean we could deliver 25% of this theoretical bound. That's 4 kWh per day per person. As usual, I'm intentionally making pretty extreme assumptions to boost the green stack – I expect the assumption that we could line *half of the Atlantic coastline* with wave absorbers will sound bananas to many readers.

How do the numbers assumed in this calculation compare with today's technology? As I write, there are just three wave machines working in deep water: three Pelamis wave energy collectors (figure 12.1) built in Scotland and deployed off Portugal. No actual performance results have been published, but the makers of the Pelamis ("designed with survival as the key objective before power capture efficiency") predict that a two-kilometre-long wave-farm consisting of 40 of their sea-snakes would deliver 6 kW per metre of wave-farm. Using this number in the previous calculation, the power delivered by 500 kilometres of wave-farm is reduced to 1.2 kWh per day per person. While wave power may be useful for small communities on remote islands, I suspect it can't play a significant role in the solution to Britain's sustainable energy problem.

What's the weight of a Pelamis, and how much steel does it contain? One snake with a maximum power of 750 kW weighs 700 tons, including 350 tons of ballast. So it has about 350 tons of steel. That's a weight-to-power ratio of roughly 500 kg per kW (peak). We can compare this with the steel requirements for offshore wind: an offshore wind-turbine with a maximum power of 3 MW weighs 500 tons, including its foundation. That's a weight-to-power ratio of about 170 kg per kW, one third of the wave machine's. The Pelamis is a first prototype; presumably with further investment and development in wave technology, the weight-to-power ratio would fall.

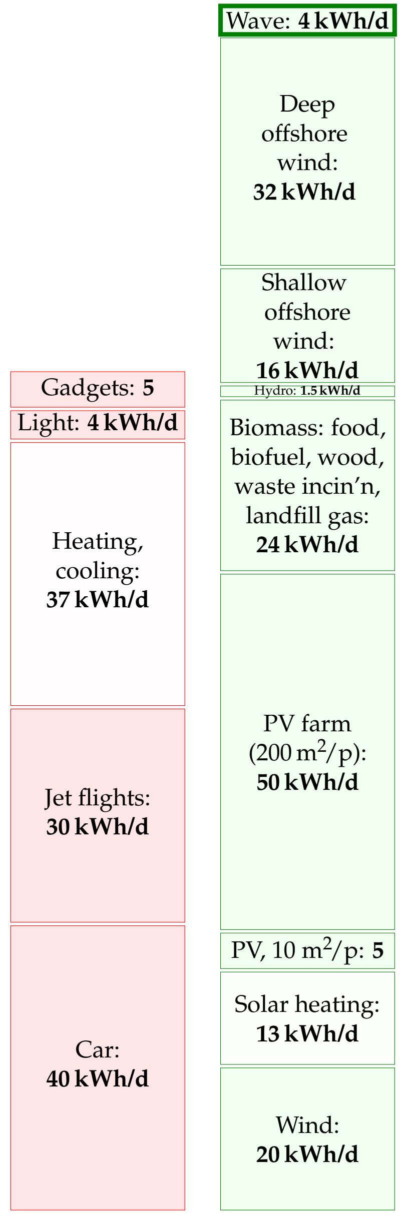


Figure 12.2. Wave.

Notes and further reading

page no.

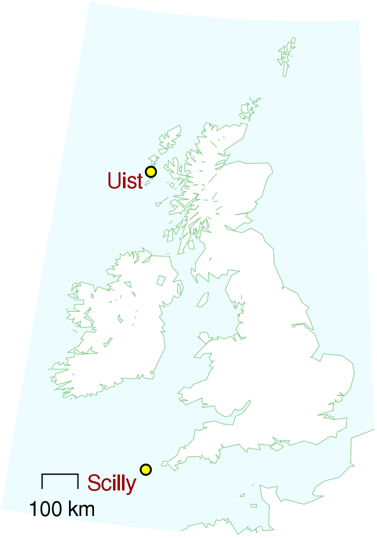
73 *Waves are generated whenever the wind speed is greater than about 0.5 m/s. The wave crests move at about the speed of the wind that creates them.* The simplest theory of wave-production (Faber, 1995, p. 337) suggests that (for small waves) the wave crests move at about half the speed of the wind that creates them. It's found empirically however that, the longer the wind blows for, the longer the wavelength of the dominant waves present, and the greater their velocity. The characteristic speed of fully-developed seas is almost exactly equal to the wind-speed 20 metres above the sea surface (Mollison, 1986).

– *The waves on the east coast of the British Isles are usually much smaller*. Whereas the wave power at Lewis (Atlantic) is 42 kW/m, the powers at the east-coast sites are: Peterhead: 4 kW/m; Scarborough: 8 kW/m; Cromer: 5 kW/m. Source: Sinden (2005). Sinden says: "The North Sea Region experiences a very low energy wave environment."

74 *Atlantic wave power is 40 kW per metre of exposed coastline.* (Chapter F explains how we can estimate this power using a few facts about waves.) This number has a firm basis in the literature on Atlantic wave power (Mollison et al., 1976; Mollison, 1986, 1991). From Mollison (1986), for example: "the large scale resource of the NE Atlantic, from Iceland to North Portugal, has a net resource of 40–50 MW/km, of which 20–30 MW/km is potentially economically extractable." At any point in the open ocean, three powers per unit length can be distinguished: the total power passing through that point in all directions (63 kW/m on average at the Isles of Scilly and 67 kW/m off Uist); the net power intercepted by a directional collecting device oriented in the optimal direction (47 kW/m and 45 kW/m respectively); and the power per unit coastline, which takes into account the misalignment between the optimal orientation of a directional collector and the coastline (for example in Portugal the optimal orientation faces northwest and the coastline faces west).

– *Practical systems won't manage to extract all the power, and some of the power will inevitably be lost during conversion from mechanical energy to electricity*. The UK's first grid-connected wave machine, the Limpet on Islay, provides a striking example of these losses. When it was designed its conversion efficiency from wave power to grid power was estimated to be 48%, and the average power output was predicted to be 200 kW. However losses in the capture system, flywheels and electrical components mean the actual average output is 21 kW – just 5% of the predicted output (Wavegen, 2002).

Photo by Terry Cavner.



13 Food and farming

Modern agriculture is the use of land to convert petroleum into food.

Albert Bartlett

Figure 13.1. A salad Niçoise.

Minimum: **3 kWh/d**

Figure 13.2. Minimum energy requirement of one person.

We've already discussed in Chapter 6 how much sustainable power could be *produced* through greenery; in this chapter we discuss how much power is currently *consumed* in giving us our daily bread.

A moderately active person with a weight of 65 kg consumes food with a chemical energy content of about 2600 "Calories" per day. A "Calorie," in food circles, is actually 1000 chemist's calories (1 kcal). 2600 "Calories" per day is about 3 kWh per day. Most of this energy eventually escapes from the body as heat, so one function of a typical person is to act as a space heater with an output of a little over 100 W, a medium-power lightbulb. Put 10 people in a small cold room, and you can switch off the 1 kW convection heater.

How much energy do we actually consume in order to get our 3 kWh per day? If we enlarge our viewpoint to include the inevitable upstream costs of food production, then we may find that our energy footprint is substantially bigger. It depends if we are vegan, vegetarian or carnivore.

The vegan has the smallest inevitable footprint: 3 kWh per day of energy from the plants he eats.

The energy cost of drinking milk

I love milk. If I drinka-pinta-milka-day, what energy does that require? A typical dairy cow produces 16 litres of milk per day. So my one pint per day (half a litre per day) requires that I employ $^1/_{32}$ of a cow. Oh, hang on – I love cheese too. And to make 1 kg of Irish Cheddar takes about 9 kg of milk. So consuming 50 g of cheese per day requires the production of an extra 450 g of milk. OK: my milk and cheese habit requires that I employ $^1/_{16}$ of a cow. And how much power does it take to run a cow? Well, if a cow weighing 450 kg has similar energy requirements per kilogram to a human (whose 65 kg burns 3 kWh per day) then the cow must be using about 21 kWh/d. Does this extrapolation from human to cow make you uneasy? Let's check these numbers: `www.dairyaustralia.com.au` says that a suckling cow of weight 450 kg needs 85 MJ/d, which is 24 kWh/d. Great, our guess wasn't far off! So my $^1/_{16}$ share of a cow has an energy consumption of about 1.5 kWh per day. This figure ignores other energy costs involved in persuading the cow to make milk and the milk to turn to cheese, and of getting the milk and cheese to travel from her to me. We'll cover some of these costs when we discuss freight and supermarkets in Chapter 15.

Milk, cheese: **1.5 kWh/d**

Figure 13.3. Milk and cheese.

Eggs

A "layer" (a chicken that lays eggs) eats about 110 g of chicken feed per day. Assuming that chicken feed has a metabolizable energy content of 3.3 kWh per kg, that's a power consumption of 0.4 kWh per day per chicken. Layers yield on average 290 eggs per year. So eating two eggs a day requires a power of 1 kWh per day. Each egg itself contains 80 kcal, which is about 0.1 kWh. So from an energy point of view, egg production is 20% efficient.

Figure 13.4. Two eggs per day.

The energy cost of eating meat

Let's say an enthusiastic meat-eater eats about half a pound a day (227 g). (This is the average meat consumption of Americans.) To work out the power required to maintain the meat-eater's animals as they mature and wait for the chop, we need to know for how long the animals are around, consuming energy. Chicken, pork, or beef?

Chicken, sir? Every chicken you eat was clucking around being a chicken for roughly 50 days. So the steady consumption of half a pound a day of chicken requires about 25 pounds of chicken to be alive, preparing to be eaten. And those 25 pounds of chicken consume energy.

Pork, madam? Pigs are around for longer – maybe 400 days from birth to bacon – so the steady consumption of half a pound a day of pork requires about 200 pounds of pork to be alive, preparing to be eaten.

Cow? Beef production involves the longest lead times. It takes about 1000 days of cow-time to create a steak. So the steady consumption of half a pound a day of beef requires about 500 pounds of beef to be alive, preparing to be eaten.

Figure 13.5. Eating meat requires extra power because we have to feed the queue of animals lining up to be eaten by the human.

To condense all these ideas down to a single number, let's assume you eat half a pound (227 g) per day of meat, made up of equal quantities of chicken, pork, and beef. This meat habit requires the perpetual sustenance of 8 pounds of chicken meat, 70 pounds of pork meat, and 170 pounds of cow meat. That's a total of 110 kg of meat, or 170 kg of animal (since about two thirds of the animal gets turned into meat). And if the 170 kg of animal has similar power requirements to a human (whose 65 kg burns 3 kWh/d) then the power required to fuel the meat habit is

$$170\,\text{kg} \times \frac{3\,\text{kWh/d}}{65\,\text{kg}} \simeq 8\,\text{kWh/d}.$$

I've again taken the physiological liberty of assuming "animals are like humans;" a more accurate estimate of the energy to make chicken is in this chapter's endnotes. No matter, I only want a ballpark estimate, and here it is. The power required to make the food for a typical consumer of vegetables, dairy, eggs, and meat is $1.5 + 1.5 + 1 + 8 = 12$ kWh per day. (The daily calorific balance of this rough diet is 1.5 kWh from vegetables;

0.7 kWh from dairy; 0.2 kWh from eggs; and 0.5 kWh from meat – a total of 2.9 kWh per day.)

This number does not include any of the power costs associated with farming, fertilizing, processing, refrigerating, and transporting the food. We'll estimate some of those costs below, and some in Chapter 15.

Do these calculations give an argument in favour of vegetarianism, on the grounds of lower energy consumption? It depends on where the animals feed. Take the steep hills and mountains of Wales, for example. Could the land be used for anything other than grazing? Either these rocky pasturelands are used to sustain sheep, or they are not used to help feed humans. You can think of these natural green slopes as maintenance-free biofuel plantations, and the sheep as automated self-replicating biofuel-harvesting machines. The energy losses between sunlight and mutton are substantial, but there is probably no better way of capturing solar power in such places. (I'm not sure whether this argument for sheep-farming in Wales actually adds up: during the worst weather, Welsh sheep are moved to lower fields where their diet is supplemented with soya feed and other food grown with the help of energy-intensive fertilizers; what's the true energy cost? I don't know.) Similar arguments can be made in favour of carnivory for places such as the scrublands of Africa and the grasslands of Australia; and in favour of dairy consumption in India, where millions of cows are fed on by-products of rice and maize farming.

On the other hand, where animals are reared in cages and fed grain that humans could have eaten, there's no question that it would be more energy-efficient to cut out the middlehen or middlesow, and feed the grain directly to humans.

Figure 13.6. Will harvest energy crops for food.

Fertilizer and other energy costs in farming

The embodied energy in Europe's fertilizers is about 2 kWh per day per person. According to a report to DEFRA by the University of Warwick, farming in the UK in 2005 used an energy of 0.9 kWh per day per person for farm vehicles, machinery, heating (especially greenhouses), lighting, ventilation, and refrigeration.

The energy cost of Tiddles, Fido, and Shadowfax

Animal companions! Are you the servant of a dog, a cat, or a horse?

There are perhaps 8 million cats in Britain. Let's assume you look after one of them. The energy cost of Tiddles? If she eats 50 g of meat per day (chicken, pork, and beef), then the last section's calculation says that the power required to make Tiddles' food is just shy of 2 kWh per day. A vegetarian cat would require less.

Similarly if your dog Fido eats 200 g of meat per day, and carbohydrates

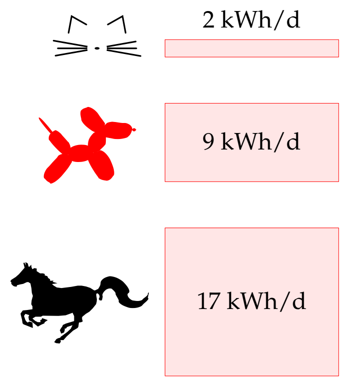


Figure 13.7. The power required for animal companions' food.

amounting to 1 kWh per day, then the power required to make his food is about 9 kWh per day.

Shadowfax the horse weighs about 400 kg and consumes 17 kWh per day.

Mythconceptions

I heard that the energy footprint of food is so big that "it's better to drive than to walk."

Whether this is true depends on your diet. It's certainly possible to find food whose fossil-fuel energy footprint is bigger than the energy delivered to the human. A bag of crisps, for example, has an embodied energy of 1.4 kWh of fossil fuel per kWh of chemical energy eaten. The embodied energy of meat is higher. According to a study from the University of Exeter, the typical diet has an embodied energy of roughly 6 kWh per kWh eaten. To figure out whether driving a car or walking uses less energy, we need to know the transport efficiency of each mode. For the typical car of Chapter 3, the energy cost was 80 kWh per 100 km. Walking uses a net energy of 3.6 kWh per 100 km – 22 times less. So if you live entirely on food whose footprint is greater than 22 kWh per kWh then, yes, the energy cost of getting you from A to B in a fossil-fuel-powered vehicle is less than if you go under your own steam. But if you have a typical diet (6 kWh per kWh) then "it's better to drive than to walk" is a myth. Walking uses one quarter as much energy.

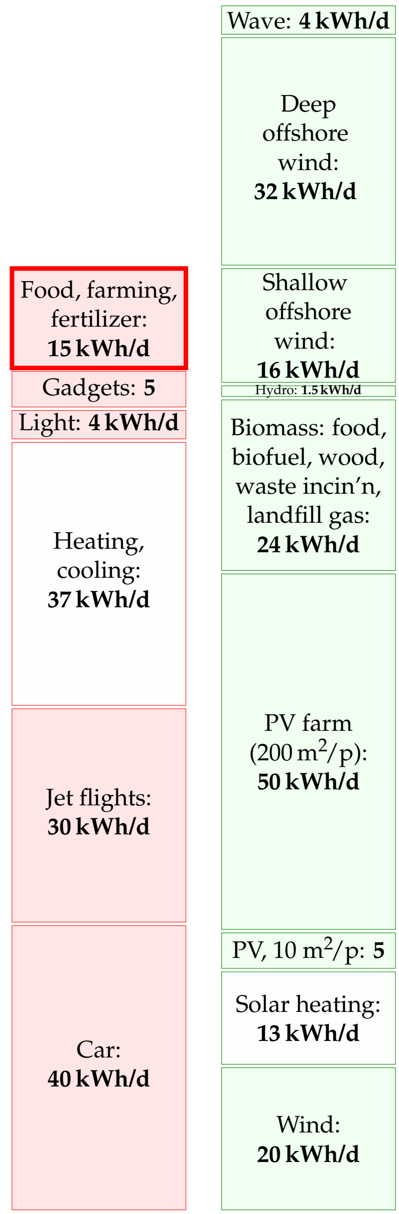


Figure 13.8. Food and farming.

Notes and further reading

page no.

76 *A typical dairy cow produces 16 litres of milk per day.* There are 2.3 million dairy cows in the UK, each producing around 5900 litres per year. Half of all milk produced by cows is sold as liquid milk. `www.ukagriculture.com`, `www.vegsoc.org/info/cattle.html`

77 *It takes about 1000 days of cow-time to create a steak.* 33 months from conception to slaughterhouse: 9 months' gestation and 24 months' rearing. `www.shabdenparkfarm.com/farming/cattle.htm`

– *Chicken.* A full-grown (20-week old) layer weighs 1.5 or 1.6 kg. Its feed has an energy content of 2850 kcal per kg, which is 3.3 kWh per kg, and its feed consumption rises to 340 g per week when 6 weeks old, and to 500 g per week when aged 20 weeks. Once laying, the typical feed required is 110 g per day.
Meat chickens' feed has an energy content of 3.7 kWh per kg. Energy consumption is 400–450 kcal per day per hen (0.5 kWh/d per hen), with 2 kg being a typical body weight. A meat chicken weighing 2.95 kg consumes a total of 5.32 kg of feed [`5h69fm`]. So the embodied energy of a meat chicken is about 6.7 kWh per kg of animal, or 10 kWh per kg of eaten meat.

If I'd used this number instead of my rough guess, the energy contribution of the chicken would have been bumped up a little. But given that the mixed-meat diet's energy footprint is dominated by the beef, it really doesn't matter that I underestimated the chickens. Sources: Subcommittee on Poultry Nutrition, National Research Council (1994), `www.nap.edu/openbook.php?isbn=0309048923`, MacDonald (2008), and `www.statistics.gov.uk/statbase/datasets2.asp`.

77 *let's assume you eat half a pound (227 g) a day of meat, made up of equal quantities of chicken, pork, and beef.* This is close to the average meat consumption in America, which is 251 g per day – made up of 108 g chicken, 81 g beef, and 62 g pork (MacDonald, 2008).

78 *The embodied energy in Europe's fertilizers is about 2 kWh per day per person.* In 1998–9, Western Europe used 17.6 Mt per year of fertilizers: 10 Mt of nitrates, 3.5 Mt of phosphate and 4.1 Mt potash. These fertilizers have energy footprints of 21.7, 4.9, and 3.8 kWh per kg respectively. Sharing this energy out between 375 million people, we find a total footprint of 1.8 kWh per day per person. Sources: Gellings and Parmenter (2004), International Fertilizer Industry Association [`5pwojp`].

– *Farming in the UK in 2005 used an energy of 0.9 kWh per day per person.* Source: Warwick HRI (2007).

79 *A bag of crisps has an embodied energy of 1.4 kWh of fossil fuel per kWh of chemical energy eaten*. I estimated this energy from the carbon footprint of a bag of crisps: 75 g CO_2 for a standard 35 g bag [`5bj8k3`]. Of this footprint, 44% is associated with farming, 30% with processing, 15% packaging, and 11% transport and disposal. The chemical energy delivered to the consumer is 770 kJ. So this food has a carbon footprint of 350 g per kWh. Assuming that most of this carbon footprint is from fossil fuels at 250 g CO_2 per kWh, the energy footprint of the crisps is 1.4 kWh of fossil fuel per kWh of chemical energy eaten.

– *The typical diet has an embodied energy of roughly 6 kWh per kWh eaten*. Coley (2001) estimates the embodied energy in a typical diet is 5.75 times the derived energy. Walking has a CO_2 footprint of 42 g/km; cycling, 30 g/km. For comparison, driving an average car emits 183 g/km.

– *Walking uses 3.6 kWh per 100 km*. A walking human uses a total of 6.6 kWh per 100 km [`3s576h`]; we subtract off the resting energy to get the energy footprint of walking (Coley, 2001).

Further reading: Weber and Matthews (2008).

14 Tide

The moon and earth are in a whirling, pirouetting dance around the sun. Together they tour the sun once every year, at the same time whirling around each other once every 28 days. The moon also turns around once every 28 days so that she always shows the same face to her dancing partner, the earth. The prima donna earth doesn't return the compliment; she pirouettes once every day. This dance is held together by the force of gravity: every bit of the earth, moon, and sun is pulled towards every other bit of earth, moon, and sun. The sum of all these forces is *almost* exactly what's required to keep the whirling dance on course. But there are very slight imbalances between the gravitational forces and the forces required to maintain the dance. It is these imbalances that give rise to the tides.

The imbalances associated with the whirling of the moon and earth around each other are about three times as big as the imbalances associated with the earth's slower dance around the sun, so the size of the tides varies with the phase of the moon, as the moon and sun pass in and out of alignment. At full moon and new moon (when the moon and sun are in line with each other) the imbalances reinforce each other, and the resulting big tides are called *spring tides*. (Spring tides are *not* "tides that occur at spring-time;" spring tides happen every two weeks like clockwork.) At the intervening half moons, the imbalances partly cancel and the tides are smaller; these smaller tides are called *neap tides*. Spring tides have roughly twice the amplitude of neap tides: the spring high tides are twice as high above mean sea level as neap high tides, the spring low tides are twice as low as neap low tides, and the tidal currents are twice as big at springs as at neaps.

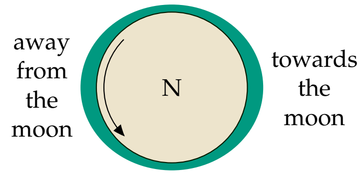


Figure 14.1. An ocean covering a billiard-ball earth. We're looking down on the North pole, and the moon is 60 cm off the page to the right. The earth spins once per day inside a rugby-ball-shaped shell of water. The oceans are stretched towards and away from the moon because the gravitational forces supplied by the moon don't perfectly match the required centripetal force to keep the earth and moon whirling around their common centre of gravity.
Someone standing on the equator (rotating as indicated by the arrow) will experience two high waters and two low waters per day.

Why are there two high tides and two low tides per day? Well, if the earth were a perfect sphere, a smooth billiard ball covered by oceans, the tidal effect of the earth-moon whirling would be to deform the water slightly towards and away from the moon, making the water slightly rugby-ball shaped (figure 14.1). Someone living on the equator of this billiard-ball earth, spinning round once per day within the water cocoon, would notice the water level going up and down twice per day: up once as he passed under the nose of the rugby-ball, and up a second time as he passed under its tail. This cartoon explanation is some way from reality. In reality, the earth is not smooth, and it is not uniformly covered by water (as you may have noticed). Two humps of water cannot whoosh round the earth once per day because the continents get in the way. The true behaviour of the tides is thus more complicated. In a large body of water such as the Atlantic Ocean, tidal crests and troughs form but, unable to whoosh round the earth, they do the next best thing: they whoosh around the perimeter of the Ocean. In the North Atlantic there are two crests and two troughs, all circling the Atlantic in an anticlockwise direction once a day. Here in Britain we don't directly see these Atlantic crests and troughs – we are set back from the Atlantic proper, separated from it by a few hundred miles of paddling pool called the continental shelf. Each time one of the crests whooshes by in the Atlantic proper, it sends a crest up our paddling pool. Similarly each Atlantic trough sends a trough up the paddling pool. Consecutive crests and troughs are separated by six hours. Or to be more precise, by six and a quarter hours, since the time between moon-rises is about 25, not 24 hours.

The speed at which the crests and troughs travel varies with the depth of the paddling pool. The shallower the paddling pool gets, the slower the crests and troughs travel and the larger they get. Out in the ocean, the tides are just a foot or two in height. Arriving in European estuaries, the tidal range is often as big as four metres. In the northern hemisphere, the Coriolis force (a force, associated with the rotation of the earth, that acts only on moving objects) makes all tidal crests and troughs tend to hug the right-hand bank as they go. For example, the tides in the English channel are bigger on the French side. Similarly, the crests and troughs entering the North Sea around the Orkneys hug the British side, travelling down to the Thames Estuary then turning left at the Netherlands to pay their respects to Denmark.

Tidal energy is sometimes called lunar energy, since it's mainly thanks to the moon that the water sloshes around so. Much of the tidal energy, however, is really coming from the rotational energy of the spinning earth. The earth is very gradually slowing down.

So, how can we put tidal energy to use, and how much power could we extract?

Rough estimates of tidal power

When you think of tidal power, you might think of an artificial pool next to the sea, with a water-wheel that is turned as the pool fills or empties (figures 14.2 and 14.3). Chapter G shows how to estimate the power available from such tide-pools. Assuming a range of 4 m, a typical range in many European estuaries, the maximum power of an artificial tide-pool that's filled rapidly at high tide and emptied rapidly at low tide, generating power from both flow directions, is about 3 W/m^2. This is the same as the power per unit area of an offshore wind farm. And we already know how big offshore wind farms need to be to make a difference. *They need to be country-sized.* So similarly, to make tide-pools capable of producing power comparable to Britain's total consumption, we'd need the total area of the tide-pools to be similar to the area of Britain.

Amazingly, Britain is already supplied with a natural tide-pool of just the required dimensions. This tide-pool is known as the North Sea (figure 14.5). If we simply insert generators in appropriate spots, significant power can be extracted. The generators might look like underwater wind-

Figure 14.2. Woodbridge tide-pool and tide-mill. Photos kindly provided by Ted Evans.

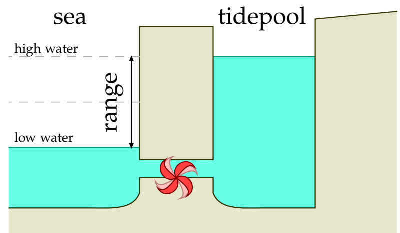


Figure 14.3. An artificial tide-pool. The pool was filled at high tide, and now it's low tide. We let the water out through the electricity generator to turn the water's potential energy into electricity.

tidal range	power density
2 m	1 W/m^2
4 m	**3** W/m^2
6 m	7 W/m^2
8 m	13 W/m^2

Table 14.4. Power density (power per unit area) of tide-pools, assuming generation from both the rising and the falling tide.

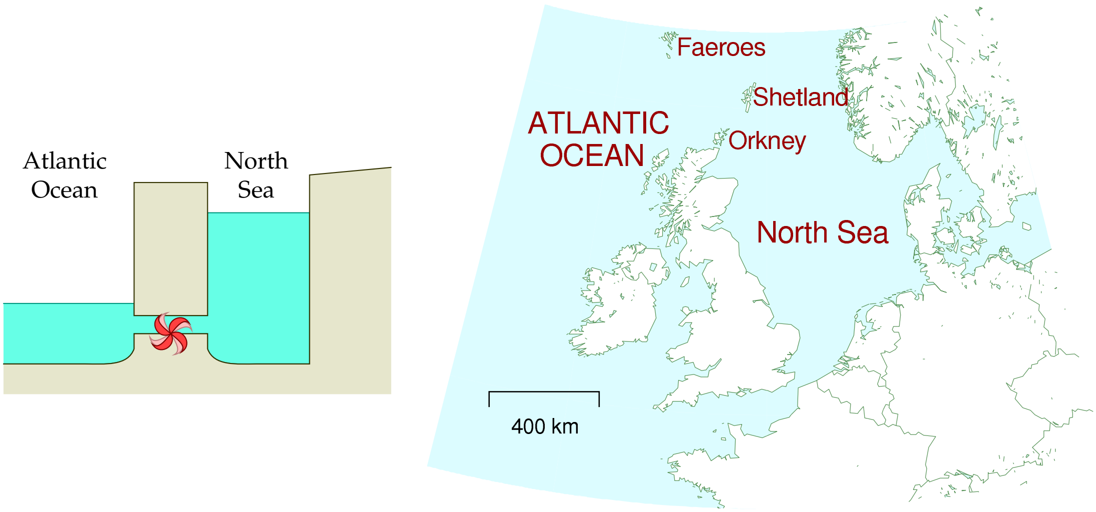


Figure 14.5. The British Isles are in a fortunate position: the North Sea forms a natural tide-pool, in and out of which great sloshes of water pour twice a day.

mills. Because the density of water is roughly 1000 times that of air, the power of water flow is 1000 times greater than the power of wind at the same speed. We'll come back to tide farms in a moment, but first let's discuss how much raw tidal energy rolls around Britain every day.

Raw incoming tidal power

The tides around Britain are genuine tidal waves – unlike tsunamis, which are called "tidal waves," but are nothing to do with tides. Follow a high tide as it rolls in from the Atlantic. The time of high tide becomes progressively later as we move east up the English channel from the Isles of Scilly to Portsmouth and on to Dover. The crest of the tidal wave progresses up the channel at about 70 km/h. (The crest of the wave moves much faster than the water itself, just as ordinary waves on the sea move faster than the water.) Similarly, a high tide moves clockwise round Scotland, rolling down the North Sea from Wick to Berwick and on to Hull at a speed of about 100 km/h. These two high tides converge on the Thames Estuary. By coincidence, the Scottish crest arrives about 12 hours later than the crest that came via Dover, so it arrives in near-synchrony with the next high tide via Dover, and London receives the normal two high tides per day.

The power we can extract from tides can never be more than the total power of these tidal waves from the Atlantic. The total power crossing the lines in figure 14.6 has been measured; on average it amounts to 100 kWh per day per person. If we imagine extracting 10% of this incident energy, and if the conversion and transmission processes are 50% efficient, the average power delivered would be 5 kWh per day per person.

This is a tentative first guess, made without specifying any technical

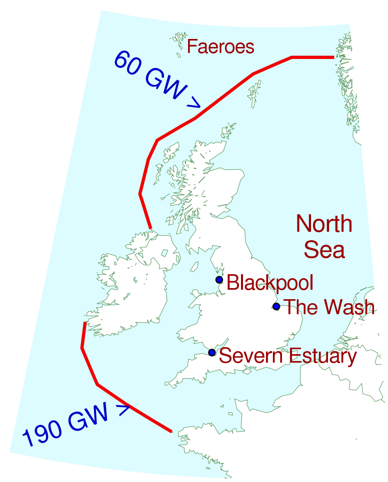


Figure 14.6. The average incoming power of lunar tidal waves crossing these two lines has been measured to be 250 GW. This raw power, shared between 60 million people, is 100 kWh per day per person.

details. Now let's estimate the power that could be delivered by three specific solutions: tide farms, barrages, and offshore tidal lagoons.

Tidal stream farms

One way to extract tidal energy would be to build tide farms, just like wind farms. The first such underwater windmill, or "tidal-stream" generator, to be connected to the grid was a "300 kW" turbine, installed in 2003 near the northerly city of Hammerfest, Norway. Detailed power production results have not been published, and no-one has yet built a tide farm with more than one turbine, so we're going to have to rely on physics and guesswork to predict how much power tide farms could produce. Assuming that the rules for laying out a sensible tide farm are similar to those for wind farms, and that the efficiency of the tide turbines will be like that of the best wind turbines, table 14.7 shows the power of a tide farm for a few tidal currents.

Given that tidal currents of 2 to 3 knots are common, there are many places around the British Isles where the power per unit area of tide farm would be 6 W/m^2 or more. This power per unit area can be compared to our estimates for wind farms (2–3 W/m^2) and for photovoltaic solar farms (5–10 W/m^2).

Tide power is not to be sneezed at! How would it add up, if we assume that there are no economic obstacles to the exploitation of tidal power at all the hot spots around the UK? Chapter G lists the flow speeds in the best areas around the UK, and estimates that 9 kWh/d per person could be extracted.

speed (m/s)	speed (knots)	power density (W/m^2)
0.5	1	1
1	2	8
2	4	60
3	6	200
4	8	500
5	10	1000

Table 14.7. Tide farm power density (in watts per square metre of sea-floor) as a function of flow speed. (1 knot = 1 nautical mile per hour = 0.514 m/s.)

Barrages

Tidal barrages are a proven technology. The famous barrage at La Rance in France, where the tidal range is a whopping 8 metres on average, has produced an average power of 60 MW since 1966. The tidal range in the Severn Estuary is also unusually large. At Cardiff the range is 11.3 m at spring tides, and 5.8 m at neaps. If a barrage were put across the mouth of the Severn Estuary (from Weston-super-Mare to Cardiff), it would make a 500 km^2 tide-pool (figure 14.8). Notice how much bigger this pool is than the estuary at La Rance. What power could this tide-pool deliver, if we let the water in and out at the ideal times, generating on both the flood and the ebb? According to the theoretical numbers from table 14.4, when the range is 11.3 m, the average power contributed by the barrage (at 30 W/m^2) would be at most 14.5 GW, or **5.8 kWh/d per person**. When the range is 5.8 m, the average power contributed by the barrage (at 8 W/m^2) would be at most 3.9 GW, or **1.6 kWh/d per person**. These numbers assume that the water is let in in a single pulse at the peak of high tide, and let out in a single pulse at low tide. In practice, the in-flow and out-flow would be spread over a few hours, which would reduce the power delivered a little.

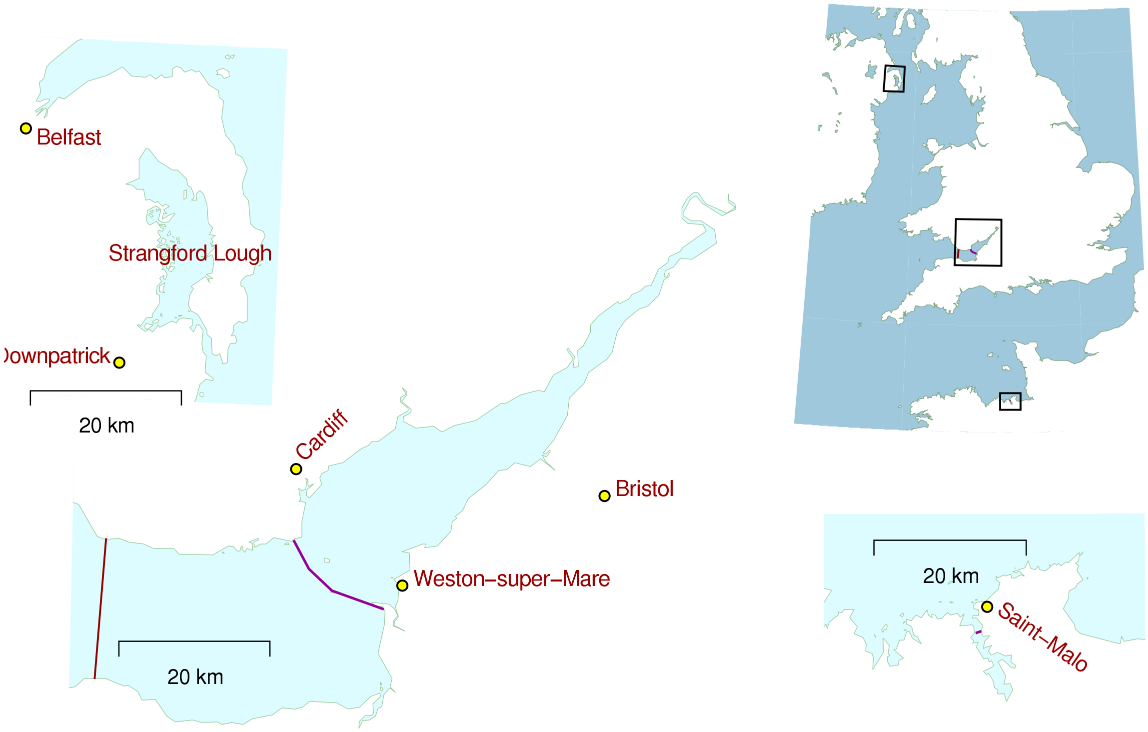


Figure 14.8. The Severn barrage proposals (bottom left), and Strangford Lough, Northern Ireland (top left), shown on the same scale as the barrage at La Rance (bottom right).
The map shows two proposed locations for a Severn barrage. A barrage at Weston-super-Mare would deliver an average power of 2 GW (0.8 kWh/d per person). The outer alternative would deliver twice as much.
There is a big tidal resource in Northern Ireland at Strangford Lough. Strangford Lough's area is 150 km^2; the tidal range in the Irish Sea outside is 4.5 m at springs and 1.5 m at neaps – sadly not as big as the range at La Rance or the Severn. The raw power of the natural tide-pool at Strangford Lough is roughly 150 MW, which, shared between the 1.7 million people of Northern Ireland, comes to 2 kWh/d per person. Strangford Lough is the location of the first grid-connected tidal stream generator in the UK.

The current proposals for the barrage will generate power in one direction only. This reduces the power delivered by another 50%. The engineers' reports on the proposed Severn barrage say that, generating on the ebb alone, it would contribute 0.8 kWh/d per person on average. The barrage would also provide protection from flooding valued at about £120M per year.

Tidal lagoons

Tidal lagoons are created by building walls in the sea; they can then be used like artificial estuaries. The required conditions for building lagoons are that the water must be shallow and the tidal range must be large. Economies of scale apply: big tidal lagoons make cheaper electricity than small ones. The two main locations for large tidal lagoons in Britain are the Wash on the east coast, and the waters off Blackpool on the west coast (figure 14.9). Smaller facilities could be built in north Wales, Lincolnshire, southwest Wales, and east Sussex.

If two lagoons are built in one location, a neat trick can be used to boost the power delivered and to enable the lagoons to deliver power on demand at any time, independent of the state of the tide. One lagoon can be designated the "high" lagoon, and the other the "low" lagoon. At low tide, some power generated by the emptying high lagoon can be used to pump water *out* of the low lagoon, making its level even lower than low water. The energy required to pump down the level of the low lagoon is then repaid with interest at high tide, when power is generated by letting water into the low lagoon. Similarly, extra water can be pumped into the high lagoon at high tide, using energy generated by the low lagoon. Whatever state the tide is in, one lagoon or the other would be able to generate power. Such a pair of tidal lagoons could also work as a pumped storage facility, storing excess energy from the electricity grid.

The average power per unit area of tidal lagoons in British waters could be $4.5\,\mathrm{W/m^2}$, so if tidal lagoons with a total area of $800\,\mathrm{km}^2$ were created (as indicated in figure 14.9), the power generated would be 1.5 kWh/d per person.

Figure 14.9. Two tidal lagoons, each with an area of $400\,\mathrm{km}^2$, one off Blackpool, and one in the Wash. The Severn estuary is also highlighted for comparison.

Beauties of tide

Totting everything up, the barrage, the lagoons, and the tidal stream farms could deliver something like 11 kWh/d per person (figure 14.10).

Tide power has never been used on an industrial scale in Britain, so it's hard to know what economic and technical challenges will be raised as we build and maintain tide-turbines – corrosion, silt accumulation, entanglement with flotsam? But here are seven reasons for being excited about tidal power in the British Isles. 1. Tidal power is completely predictable; unlike wind and sun, tidal power is a renewable on which one could depend; it works day and night all year round; using tidal lagoons, energy can be stored so that power can be delivered on demand. 2. Successive high and low tides take about 12 hours to progress around the British Isles, so the strongest currents off Anglesey, Islay, Orkney and Dover occur at different times from each other; thus, together, a collection of tide farms could produce a more constant contribution to the electrical grid than one tide farm, albeit a contribution that wanders up and down with the phase of the moon. 3. Tidal power will last for millions of years. 4. It doesn't require high-cost hardware, in contrast to solar photovoltaic power. 5. Moreover, because the power density of a typical tidal flow is greater than the power density of a typical wind, a 1 MW tide turbine is smaller in size than a 1 MW wind turbine; perhaps tide turbines could therefore be cheaper than wind turbines. 6. Life below the waves is peaceful; there is no such thing as a freak tidal storm; so, unlike wind turbines, which require costly engineering to withstand rare windstorms, underwater tide turbines will not require big safety factors in their design. 7. Humans mostly live on the land, and they can't see under the sea, so objections to the visual impact of tide turbines should be less strong than the objections to wind turbines.

Mythconceptions

Tidal power, while clean and green, should not be called renewable. Extracting power from the tides slows down the earth's rotation. We definitely can't use tidal power long-term.

False. The natural tides already slow down the earth's rotation. The natural rotational energy loss is roughly 3 TW (Shepherd, 2003). Thanks to natural tidal friction, each century, the day gets longer by 2.3 milliseconds. Many tidal energy extraction systems are just extracting energy that would have been lost anyway in friction. But even if we *doubled* the power extracted from the earth–moon system, tidal energy would still last more than a billion years.

Notes and further reading

page no.

82 *The power of an artificial tide-pool.* The power per unit area of a tide-pool is derived in Chapter G, p311.

– *Britain is already supplied with a natural tide-pool … known as the North Sea.* I should not give the impression that the North Sea fills and empties just like a tide-pool on the English coast. The flows in the North Sea are more complex because the time taken for a bump in water level to propagate across the Sea is similar to the time between tides. Nevertheless, there are whopping tidal currents in and out of the North Sea, and within it too.

83 *The total incoming power of lunar tidal waves crossing these lines has been measured to be 100 kWh per day per person.* Source: Cartwright et al. (1980). For readers who like back-of-envelope models, Chapter G shows how to estimate this power from first principles.

84 *La Rance* generated 16 TWh over 30 years. That's an average power of 60 MW. (Its peak power is 240 MW.) The tidal range is up to 13.5 m; the impounded area is 22 km^2; the barrage 750 m long. Average power density: 2.7 W/m^2. Source: [6xrm5q].

85 *The engineers' reports on the Severn barrage… say 17 TWh/year.* (Taylor, 2002b). This (2 GW) corresponds to 5% of current UK total electricity consumption, on average.

86 *Power per unit area of tidal lagoons could be 4.5 W/m^2.* MacKay (2007a).

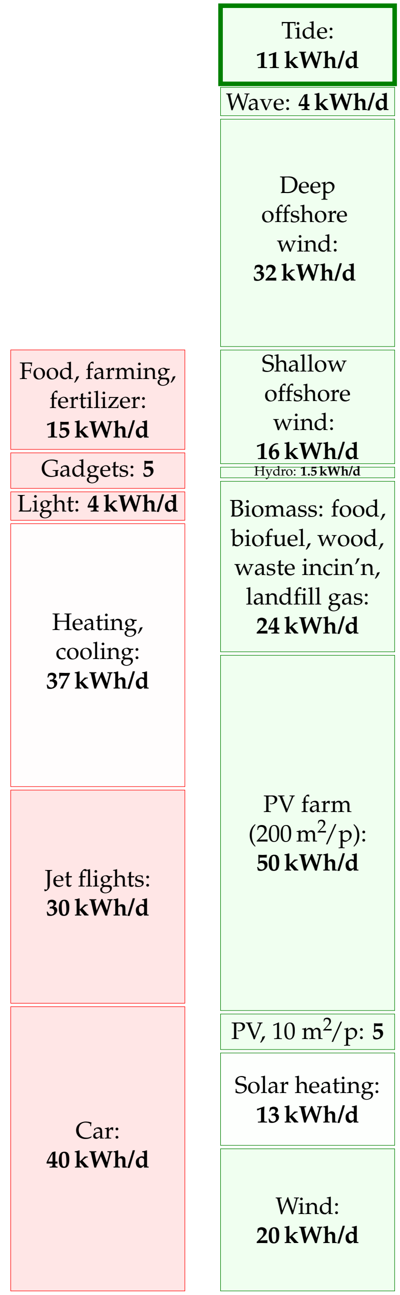


Figure 14.10. Tide.

15 Stuff

One of the main sinks of energy in the "developed" world is the creation of stuff. In its natural life cycle, stuff passes through three stages. First, a new-born stuff is displayed in shiny packaging on a shelf in a shop. At this stage, stuff is called "goods." As soon as the stuff is taken home and sheds its packaging, it undergoes a transformation from "goods" to its second form, "clutter." The clutter lives with its owner for a period of months or years. During this period, the clutter is largely ignored by its owner, who is off at the shops buying more goods. Eventually, by a miracle of modern alchemy, the clutter is transformed into its final form, rubbish. To the untrained eye, it can be difficult to distinguish this "rubbish" from the highly desirable "good" that it used to be. Nonetheless, at this stage the discerning owner pays the dustman to transport the stuff away.

Let's say we want to understand the full energy-cost of a stuff, perhaps with a view to designing better stuff. This is called life-cycle analysis. It's conventional to chop the energy-cost of anything from a hair-dryer to a cruise-ship into four chunks:

Phase R: Making **raw materials**. This phase involves digging minerals out of the ground, melting them, purifying them, and modifying them into manufacturers' lego: plastics, glasses, metals, and ceramics, for example. The energy costs of this phase include the transportation costs of trundling the raw materials to their next destination.

Phase P: Production. In this phase, the raw materials are processed into a manufactured product. The factory where the hair-dryer's coils are wound, its graceful lines moulded, and its components carefully snapped together, uses heat and light. The energy costs of this phase include packaging and more transportation.

Phase U: Use. Hair-dryers and cruise-ships both guzzle energy when they're used as intended.

Phase D: Disposal. This phase includes the energy cost of putting the stuff back in a hole in the ground (landfill), or of turning the stuff back into raw materials (recycling); and of cleaning up all the pollution associated with the stuff.

To understand how much energy a stuff's life requires, we should estimate the energy costs of all four phases and add them up. Usually one of these four phases dominates the total energy cost, so to get a reasonable estimate of the total energy cost we need accurate estimates only of the cost of that dominant phase. If we wish to redesign a stuff so as to reduce its total energy cost, we should usually focus on reducing the cost of the dominant phase, while making sure that energy-savings in that phase

Figure 15.1. Selfridges' rubbish advertisement.

	embodied energy (kWh per kg)
fossil fuel	10
wood	5
paper	10
glass	7
PET plastic	30
aluminium	40
steel	6

Table 15.2. Embodied energy of materials.

aren't being undone by accompanying increases in the energy costs of the other three phases.

Rather than estimating in detail how much power the perpetual production and transport of all stuff requires, let's first cover just a few common examples: drink containers, computers, batteries, junk mail, cars, and houses. This chapter focuses on the energy costs of phases R and P. These energy costs are sometimes called the "embodied" or "embedded" energy of the stuff – slightly confusing names, since usually that energy is neither literally embodied nor embedded in the stuff.

Aluminium: **3 kWh/d**

Packaging: **4 kWh/d**

Figure 15.3. Five aluminium cans per day is 3 kWh/d. The embodied energy in other packaging chucked away by the average Brit is 4 kWh/d.

Drink containers

Let's assume you have a coke habit: you drink five cans of multinational chemicals per day, and throw the aluminium cans away. For this stuff, it's the raw material phase that dominates. The production of metals is energy intensive, especially for aluminium. Making one aluminium drinks-can needs 0.6 kWh. So a five-a-day habit wastes energy at a rate of 3 kWh/d.

As for a 500 ml water bottle made of PET (which weighs 25 g), the embodied energy is 0.7 kWh – just as bad as an aluminium can!

Other packaging

The average Brit throws away 400 g of packaging per day – mainly food packaging. The embodied energy content of packaging ranges from 7 to 20 kWh per kg as we run through the spectrum from glass and paper to plastics and steel cans. Taking the typical embodied energy content to be 10 kWh/kg, we deduce that the energy footprint of packaging is 4 kWh/d. A little of this embodied energy is recoverable by waste incineration, as we'll discuss in Chapter 27.

Chips: **2.5 kWh/d**

Figure 15.4. She's making chips. Photo: ABB.
Making one personal computer every two years costs 2.5 kWh per day.

Computers

Making a personal computer costs 1800 kWh of energy. So if you buy a new computer every two years, that corresponds to a power consumption of 2.5 kWh per day.

Batteries

The energy cost of making a rechargeable nickel-cadmium AA battery, storing 0.001 kWh of electrical energy and having a mass of 25 g, is 1.4 kWh (phases R and P). If the energy cost of disposable batteries is similar, throwing away two AA batteries per month uses about 0.1 kWh/d. The energy cost of batteries is thus likely to be a minor item in your stack of energy consumption.

Newspapers, magazines, and junk mail

A 36-page newspaper, distributed for free at railway stations, weighs 90 g. The Cambridge Weekly News (56 pages) weighs 150 g. *The Independent* (56 pages) weighs 200 g. A 56-page property-advertising glossy magazine and Cambridgeshire Pride Magazine (32 pages), both delivered free at home, weigh 100 g and 125 g respectively.

This river of reading material and advertising junk pouring through our letterboxes contains energy. It also costs energy to make and deliver. Paper has an embodied energy of 10 kWh per kg. So the energy embodied in a typical personal flow of junk mail, magazines, and newspapers, amounting to 200 g of paper per day (that's equivalent to one *Independent* per day for example) is about 2 kWh per day.

Paper recycling would save about half of the energy of manufacture; waste incineration or burning the paper in a home fire may make use of some of the contained energy.

Newspapers, junk mail, magazines: **2 kWh/d**

Bigger stuff

The largest stuff most people buy is a house.

In Chapter H, I estimate the energy cost of making a new house. Assuming we replace each house every 100 years, the estimated energy cost is 2.3 kWh/d. This is the energy cost of creating the *shell* of the house only – the foundation, bricks, tiles, and roof beams. If the average house occupancy is 2.3, the average energy expenditure on house building is thus estimated to be 1 kWh per day per person.

House-building: **1 kWh/d**

What about a car, and a road? Some of us own the former, but we usually share the latter. A new car's embodied energy is 76 000 kWh – so if you get one every 15 years, that's an average energy cost of 14 kWh per day. A life-cycle analysis by Treloar, Love, and Crawford estimates that building an Australian road costs 7600 kWh per metre (a continuously reinforced concrete road), and that, including maintenance costs, the total cost over 40 years was 35 000 kWh per metre. Let's turn this into a ballpark figure for the energy cost of British roads. There are 28 000 miles of trunk roads and class-1 roads in Britain (excluding motorways). Assuming 35 000 kWh per metre per 40 years, those roads cost us 2 kWh/d per person.

Car-making: **14 kWh/d**

Road-building: **2 kWh/d**

Transporting the stuff

Up till now I've tried to make estimates of *personal* consumption. "If you chuck away five coke-cans, that's 3 kWh; if you buy *The Independent*, that's 2 kWh." From here on, however, things are going to get a bit less personal. As we estimate the energy required to transport stuff around the country and around the planet, I'm going to look at national totals and divide them by the population.

Figure 15.5. Food-miles – Pasties, hand-made in Helston, Cornwall, shipped 580 km for consumption in Cambridge.

Freight transport is measured in ton-kilometres (t-km). If one ton of Cornish pasties are transported 580 km (figure 15.5) then we say 580 t-km of freight transport have been achieved. The energy intensity of road transport in the UK is about 1 kWh per t-km.

When the container ship in figure 15.6 transports 50 000 tons of cargo a distance of 10 000 km, it achieves 500 million t-km of freight transport. The energy intensity of freight transport by this container ship is 0.015 kWh per t-km. Notice how much more efficient transport by container-ship is than transport by road. These energy intensities are displayed in figure 15.8.

Figure 15.6. The container ship *Ever Uberty* at Thamesport Container Terminal. Photo by Ian Boyle `www.simplonpc.co.uk`.

Transport of stuff by road

In 2006, the total amount of road transport in Britain by heavy goods vehicles was 156 billion t-km. Shared between 60 million, that comes to 7 t-km per day per person, which costs 7 kWh per day per person (assuming an energy intensity of 1 kWh per ton-km). One quarter of this transport, by the way, was of food, drink, and tobacco.

Road freight: **7 kWh/d**

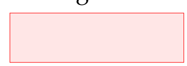
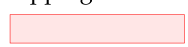


Figure 15.7. The lorry delivereth and the lorry taketh away. Energy cost of UK road freight: 7 kWh/d per person.

Transport by water

In 2002, 560 million tons of freight passed through British ports. The Tyndall Centre calculated that Britain's share of the energy cost of international shipping is 4 kWh/d per person.

Shipping: **4 kWh/d**



Transport of water; taking the pee

Water's not a very glamorous stuff, but we use a lot of it – about 160 litres

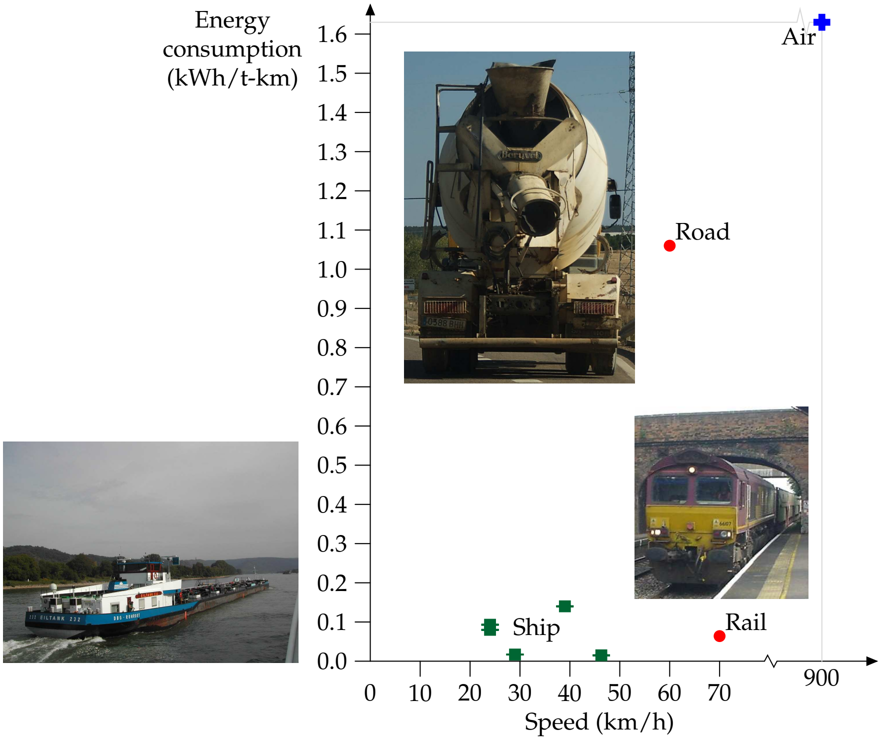


Figure 15.8. Energy requirements of different forms of freight-transport. The vertical coordinate shows the energy consumed in kWh per net ton-km, (that is, the energy per t-km of freight moved, not including the weight of the vehicle).
See also figure 20.23 (energy requirements of passenger transport).

Water transport requires energy because boats make waves. Nevertheless, transporting freight by ship is surprisingly energy efficient.

per day per person. In turn, we provide about 160 litres per day per person of sewage to the water companies. The cost of pumping water around the country and treating our sewage is about 0.4 kWh per day per person.

Desalination

At the moment the UK doesn't spend energy on water desalination. But there's talk of creating desalination plants in London. What's the energy cost of turning salt water into drinking water? The least energy-intensive method is reverse osmosis. Take a membrane that lets through only water, put salt water on one side of it, and pressurize the salt water. Water reluctantly oozes through the membrane, producing purer water – reluctantly, because pure water separated from salt has low entropy, and nature prefers high entropy states where everything is mixed up. We must pay high-grade energy to achieve unmixing.

The Island of Jersey has a desalination plant that can produce 6000 m^3 of pure water per day (figure 15.10). Including the pumps for bringing the water up from the sea and through a series of filters, the whole plant uses a power of 2 MW. That's an energy cost of 8 kWh per m^3 of water produced. At a cost of 8 kWh per m^3, a daily water consumption of 160 litres would require 1.3 kWh per day.

Water delivery
and removal:
0.4 kWh/d

Figure 15.9. Water delivery: 0.3 kWh/d; sewage processing: 0.1 kWh/d.

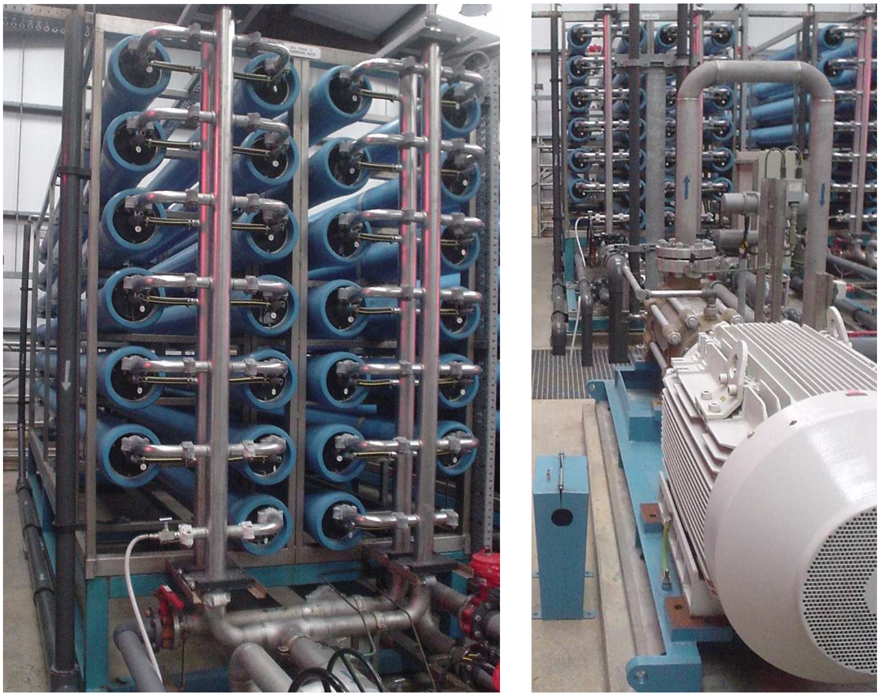


Figure 15.10. Part of the reverse-osmosis facility at Jersey Water's desalination plant. The pump in the foreground, right, has a power of 355 kW and shoves seawater at a pressure of 65 bar into 39 spiral-wound membranes in the banks of blue horizontal tubes, left, delivering 1500 m^3 per day of clean water. The clean water from this facility has a total energy cost of 8 kWh per m^3.

Stuff retail

Supermarkets:
0.5 kWh/d

Supermarkets in the UK consume about 11 TWh of energy per year. Shared out equally between 60 million happy shoppers, that's a power of 0.5 kWh per day per person.

The significance of imported stuff

In standard accounts of "Britain's energy consumption" or "Britain's carbon footprint," imported goods are *not* counted. Britain used to make its own gizmos, and our per-capita footprint in 1910 was as big as America's is today. Now Britain doesn't manufacture so much (so our energy consumption and carbon emissions have dropped a bit), but we still love gizmos, and we get them made for us by other countries. Should we ignore the energy cost of making the gizmo, because it's imported? I don't think so. Dieter Helm and his colleagues in Oxford estimate that under a correct account, allowing for imports and exports, Britain's carbon footprint is nearly *doubled* from the official "11 tons CO_2e per person" to about 21 tons. This implies that the biggest item in the average British person's energy footprint is the energy cost of making imported stuff.

In Chapter H, I explore this idea further, by looking at the weight of Britain's imports. Leaving aside our imports of fuels, we import a little over 2 tons per person of stuff every year, of which about 1.3 tons per person are processed and manufactured stuff like vehicles, machinery, white goods, and electrical and electronic equipment. That's about 4 kg per day per person of processed stuff. Such goods are mainly made of materials whose production required at least 10 kWh of energy per kg of stuff. I thus estimate that this pile of cars, fridges, microwaves, computers, photocopiers and televisions has an embodied energy of at least 40 kWh per day per person.

To summarize all these forms of stuff and stuff-transport, I will put on the consumption stack 48 kWh per day per person for the making of stuff (made up of at least 40 for imports, 2 for a daily newspaper, 2 for road-making, 1 for house-making, and 3 for packaging); and another 12 kWh per day per person for the transport of the stuff by sea, by road, and by pipe, and the storing of food in supermarkets.

Work till you shop.

Traditional saying

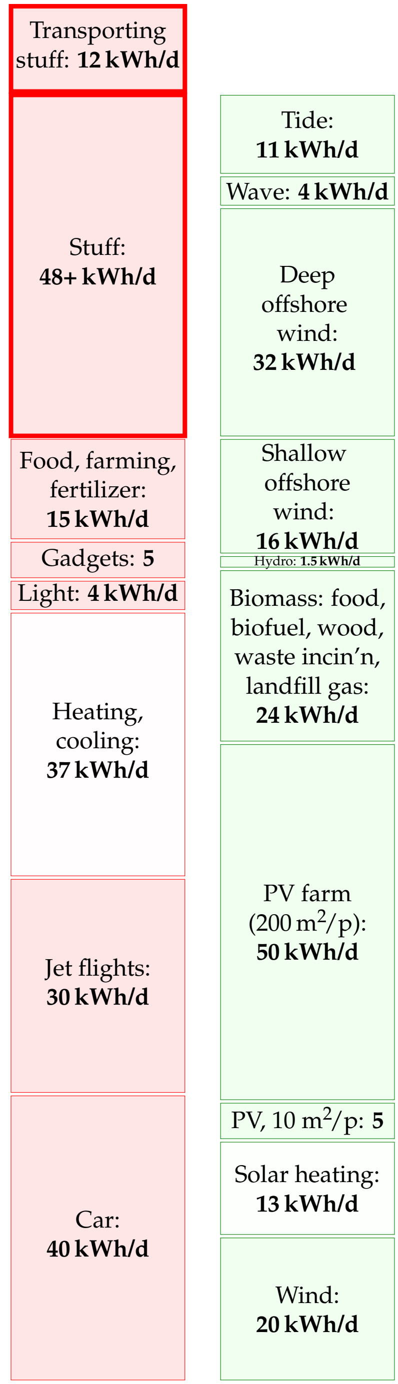


Figure 15.11. Making our stuff costs at least 48 kWh/d. Delivering the stuff costs 12 kWh/d.

Notes and further reading

page no.

89 *One aluminium drinks can costs 0.6 kWh.* The mass of one can is 15 g. Estimates of the total energy cost of aluminium manufacture vary from 60 MJ/kg to 300 MJ/kg. [yx7zm4], [r22oz], [yhrest]. The figure I used is from The Aluminum Association [y5as53]: 150 MJ per kg of aluminium (40 kWh/kg).

– *The embodied energy of a water bottle made of PET.* Source: Hammond and Jones (2006) – PET's embodied energy is 30 kWh per kg.

– *The average Brit throws away 400 g of packaging per day.* In 1995, Britain used 137 kg of packaging per person (Hird et al., 1999).

– *A personal computer costs 1800 kWh of energy.* Manufacture of a PC requires (in energy and raw materials) the equivalent of about 11 times its own weight of fossil fuels. Fridges require 1–2 times their weight. Cars require 1–2 times their weight. Williams (2004); Kuehr (2003).

– *. . . a rechargeable nickel-cadmium battery.* Source: Rydh and Karlström (2002).

– *. . . steel. . .* From Swedish Steel, "The consumption of coal and coke is 700 kg per ton of finished steel, equal to approximately 5320 kWh per ton of finished steel. The consumption of oil, LPG and electrical power is 710 kWh per ton finished product. Total [primary] energy consumption is thus approx. 6000 kWh per ton finished steel." (6 kWh per kg.) [y2ktgg]

90 *A new car's embodied energy is 76 000 kWh.* Source: Treloar et al. (2004). Burnham et al. (2007) give a lower figure: 30 500 kWh for the net life-cycle energy cost of a car. One reason for the difference may be that the latter life-cycle analysis assumes the vehicle is recycled, thus reducing the net materials cost.

90 *Paper has an embodied energy of 10 kWh per kg.* Making newspaper from virgin wood has an energy cost of about 5 kWh/kg, and the paper itself has an energy content similar to that of wood, about 5 kWh/kg. (Source: Ucuncu (1993); Erdincler and Vesilind (1993); see p284.) Energy costs vary between mills and between countries. 5 kWh/kg is the figure for a Swedish newspaper mill in 1973 from Norrström (1980), who estimated that efficiency measures could reduce the cost to about 3.2 kWh/kg. A more recent full life-cycle analysis (Denison, 1997) estimates the net energy cost of production of newsprint in the USA from virgin wood followed by a typical mix of landfilling and incineration to be 12 kWh/kg; the energy cost of producing newsprint from recycled material and recycling it is 6 kWh/kg.

91 *The energy intensity of road transport in the UK is about 1 kWh per t-km.* Source: `www.dft.gov.uk/pgr/statistics/datatablespublications/energyenvironment`.

– *The energy intensity of freight transport by this container ship is 0.015 kWh per ton-km.* The *Ever Uberty* – length 285 m, breadth 40 m – has a capacity of 4948 TEUs, deadweight 63 000 t, and a service speed of 25 knots; its engine's normal delivered power is 44 MW. One TEU is the size of a small 20-foot container – about 40 m^3. Most containers you see today are 40-foot containers with a size of 2 TEU. A 40-foot container weighs 4 tons and can carry 26 tons of stuff. Assuming its engine is 50%-efficient, this ship's energy consumption works out to 0.015 kWh of chemical energy per ton-km. `www.mhi.co.jp/en/products/detail/container_ship_ever_uberty.html`

– *Britain's share of international shipping...* Source: Anderson et al. (2006).

92 *Figure 15.8.* **Energy consumptions of ships.** The five points in the figure are a container ship (46 km/h), a dry cargo vessel (24 km/h), an oil tanker (29 km/h), an inland marine ship (24 km/h), and the NS Savannah (39 km/h).

Dry cargo vessel 0.08 kWh/t-km. A vessel with a grain capacity of 5200 m^3 carries 3360 deadweight tons. (Deadweight tonnage is the mass of cargo that the ship can carry.) It travels at speed 13 kn (24 km/h); its one engine with 2 MW delivered power consumes 186 g of fuel-oil per kWh of delivered energy (42% efficiency). `conoship.com/uk/vessels/detailed/page7.htm`

Oil tanker A modern oil tanker uses 0.017 kWh/t-km [`61brab`]. Cargo weight 40 000 t. Capacity: 47 000 m^3. Main engine: 11.2 MW maximum delivered power. Speed at 8.2 MW: 15.5 kn (29 km/h). The energy contained in the oil cargo is 520 million kWh. So 1% of the energy in the oil is used in transporting the oil one-quarter of the way round the earth (10 000 km).

Roll-on, roll-off carriers The ships of Wilh. Wilhelmsen shipping company deliver freight-transport with an energy cost between 0.028 and 0.05 kWh/t-km [`5ctx4k`].

92 *Water delivery and sewage treatment costs 0.4 kWh/d per person*. The total energy use of the water industry in 2005–6 was 7703 GWh. Supplying 1 m^3 of water has an energy cost of 0.59 kWh. Treating 1 m^3 of sewage has an energy cost of 0.63 kWh. For anyone interested in greenhouse-gas emissions, water supply has a footprint of 289 g CO_2 per m^3 of water delivered, and wastewater treatment, 406 g CO_2 per m^3 of wastewater.
Domestic water consumption is 151 litres per day per person. Total water consumption is 221 l/d per person. Leakage amounts to 57 litres per day per person. Sources: Parliamentary Office of Science and Technology [`www.parliament.uk/documents/upload/postpn282.pdf`], Water UK (2006).

93 *Supermarkets in the UK consume 11 TWh/y.* [`yqbzl3`]

– *Helm et al. suggest that, allowing for imports and exports, Britain's carbon footprint is nearly **doubled** to about 21 tons.* Helm et al. (2007).

16 Geothermal

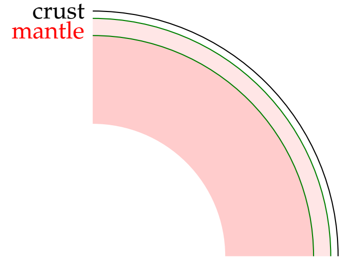


Figure 16.1. An earth in section.

Figure 16.2. Some granite.

Geothermal energy comes from two sources: from radioactive decay in the crust of the earth, and from heat trickling through the mantle from the earth's core. The heat in the core is there because the earth used to be red-hot, and it's still cooling down and solidifying; the heat in the core is also being topped up by tidal friction: the earth flexes in response to the gravitational fields of the moon and sun, in the same way that an orange changes shape if you squeeze it and roll it between your hands.

Geothermal is an attractive renewable because it is "always on," independent of the weather; if we make geothermal power stations, we can switch them on and off so as to follow demand.

But how much geothermal power is available? We could estimate geothermal power of two types: the power available at an ordinary location on the earth's crust; and the power available in special hot spots like Iceland (figure 16.3). While the right place to first develop geothermal technology is definitely the special hot spots, I'm going to assume that the greater total resource comes from the ordinary locations, since ordinary locations are so much more numerous.

The difficulty with making *sustainable* geothermal power is that the speed at which heat travels through solid rock limits the rate at which heat can be sustainably sucked out of the red-hot interior of the earth. It's like trying to drink a crushed-ice drink through a straw. You stick in the straw, and suck, and you get a nice mouthful of cold liquid. But after a little more sucking, you find you're sucking air. You've extracted all the liquid from the ice around the tip of the straw. Your initial rate of sucking wasn't sustainable.

If you stick a straw down a 15-km hole in the earth, you'll find it's nice and hot there, easily hot enough to boil water. So, you could stick two straws down, and pump cold water down one straw and suck from the other. You'll be sucking up steam, and you can run a power station. Limitless power? No. After a while, your sucking of heat out of the rock will have reduced the temperature of the rock. You weren't sucking sustainably. You now have a long wait before the rock at the tip of your straws warms up again. A possible attitude to this problem is to treat geothermal heat the same way we currently treat fossil fuels: as a resource to be mined rather than collected sustainably. Living off geothermal heat in this way might be better for the planet than living unsustainably off fossil fuels; but perhaps it would only be another stop-gap giving us another 100 years of unsustainable living? In this book I'm most interested in *sustainable* energy, as the title hinted. Let's do the sums.

Figure 16.3. Geothermal power in Iceland. Average geothermal electricity generation in Iceland (population, 300 000) in 2006 was 300 MW (24 kWh/d per person). More than half of Iceland's electricity is used for aluminium production. Photo by Gretar Ívarsson.

Geothermal power that would be sustainable forever

First imagine using geothermal energy sustainably by sticking down straws to an appropriate depth, and sucking *gently*. Sucking at such a rate that the rocks at the end of the our straws don't get colder and colder. This means sucking at the natural rate at which heat is already flowing out of the earth.

As I said before, geothermal energy comes from two sources: from radioactive decay in the crust of the earth, and from heat trickling through the mantle from the earth's core. In a typical continent, the heat flow from the centre coming through the mantle is about 10 mW/m^2. The heat flow at the surface is 50 mW/m^2. So the radioactive decay has added an extra 40 mW/m^2 to the heat flow from the centre.

one milliwatt (1 mW) is 0.001 W.

So at a typical location, the maximum power we can get per unit area is 50 mW/m^2. But that power is not high-grade power, it's low-grade heat that's trickling through at the ambient temperature up here. We presumably want to make electricity, and that's why we must drill down. Heat is useful only if it comes from a source at a higher temperature than the ambient temperature. The temperature increases with depth as shown in figure 16.4, reaching a temperature of about 500 °C at a depth of 40 km. Between depths of 0 km where the heat flow is biggest but the rock temperature is too low, and 40 km, where the rocks are hottest but the heat flow is 5 times smaller (because we're missing out on all the heat generated from radioactive decay) there is an optimal depth at which we should suck. The exact optimal depth depends on what sort of sucking and power-station machinery we use. We can bound the maximum sustainable power

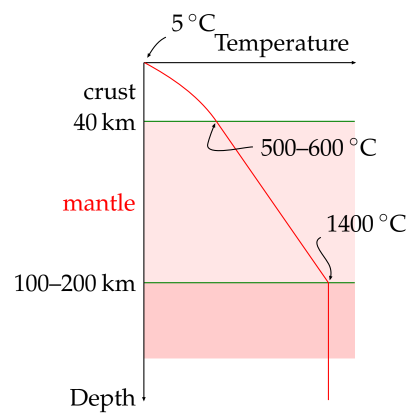


Figure 16.4. Temperature profile in a typical continent.

by finding the optimal depth assuming that we have an ideal engine for turning heat into electricity, and that drilling to any depth is free.

For the temperature profile shown in figure 16.4, I calculated that the optimal depth is about 15 km. Under these conditions, an ideal heat engine would deliver 17 mW/m^2. At the world population density of 43 people per square km, that's 10 kWh per person per day, if *all* land area were used. In the UK, the population density is 5 times greater, so wide-scale geothermal power of this sustainable-forever variety could offer at most 2 kWh per person per day.

This is the sustainable-forever figure, ignoring hot spots, assuming perfect power stations, assuming every square metre of continent is exploited, and assuming that drilling is free. And that it is possible to drill 15-km-deep holes.

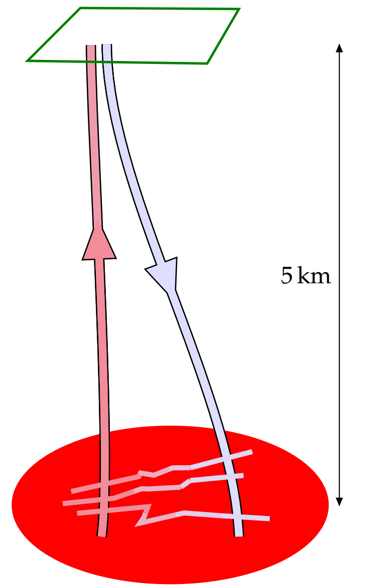
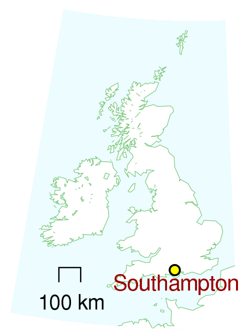


Figure 16.5. Enhanced geothermal extraction from hot dry rock. One well is drilled and pressurized to create fractures. A second well is drilled into the far side of the fracture zone. Then cold water is pumped down one well and heated water (indeed, steam) is sucked up the other.

Geothermal power as mining

The other geothermal strategy is to treat the heat as a resource to be mined. In "enhanced geothermal extraction" from hot dry rocks (figure 16.5), we first drill down to a depth of 5 or 10 km, and fracture the rocks by pumping in water. (This step may create earthquakes, which don't go down well with the locals.) Then we drill a second well into the fracture zone. Then we pump water down one well and extract superheated water or steam from the other. This steam can be used to make electricity or to deliver heat. What's the hot dry rock resource of the UK? Sadly, Britain is not well endowed. Most of the hot rocks are concentrated in Cornwall, where some geothermal experiments were carried out in 1985 in a research facility at Rosemanowes, now closed. Consultants assessing these experiments concluded that "generation of electrical power from hot dry rock was unlikely to be technically or commercially viable in Cornwall, or elsewhere in the UK, in the short or medium term." Nonetheless, what is the resource? The biggest estimate of the hot dry rock resource in the UK is a total energy of 130 000 TWh, which, according to the consultants, could conceivably contribute 1.1 kWh per day per person of electricity for about 800 years.

Other places in the world have more promising hot dry rocks, so if you want to know the geothermal answers for other countries, be sure to ask a local. But sadly for Britain, geothermal will only ever play a tiny part.



Doesn't Southampton use geothermal energy already? How much does that deliver?

Yes, Southampton Geothermal District Heating Scheme was, in 2004 at least, the only geothermal heating scheme in the UK. It provides the city with a supply of hot water. The geothermal well is part of a combined heat, power, and cooling system that delivers hot and chilled water to customers, and sells electricity to the grid. Geothermal energy contributes about 15% of the 70 GWh of heat per year delivered by this system. The population of Southampton at the last census was 217 445, so the geothermal power being delivered there is **0.13 kWh/d** per person in Southampton.

Notes and further reading

page no.

97 *The heat flow at the surface is 50 mW/m²*. Massachusetts Institute of Technology (2006) says 59 mW/m² average, with a range, in the USA, from 25 mW to 150 mW. Shepherd (2003) gives 63 mW/m².

98 *"Generation of electrical power from hot dry rock was unlikely to be technically or commercially viable in the UK"*. Source: MacDonald et al. (1992). See also Richards et al. (1994).

– *The biggest estimate of the hot dry rock resource in the UK . . . could conceivably contribute 1.1 kWh per day per person of electricity for about 800 years*. Source: MacDonald et al. (1992).

– *Other places in the world have more promising hot dry rocks*. There's a good study (Massachusetts Institute of Technology, 2006) describing the USA's hot dry rock resource. Another more speculative approach, researched by Sandia National Laboratories in the 1970s, is to drill all the way down to magma at temperatures of 600–1300 °C, perhaps 15 km deep, and get power there. The website `www.magma-power.com` reckons that the heat in pools of magma under the US would cover US energy consumption for 500 or 5000 years, and that it could be extracted economically.

– *Southampton Geothermal District Heating Scheme*. `www.southampton.gov.uk`.

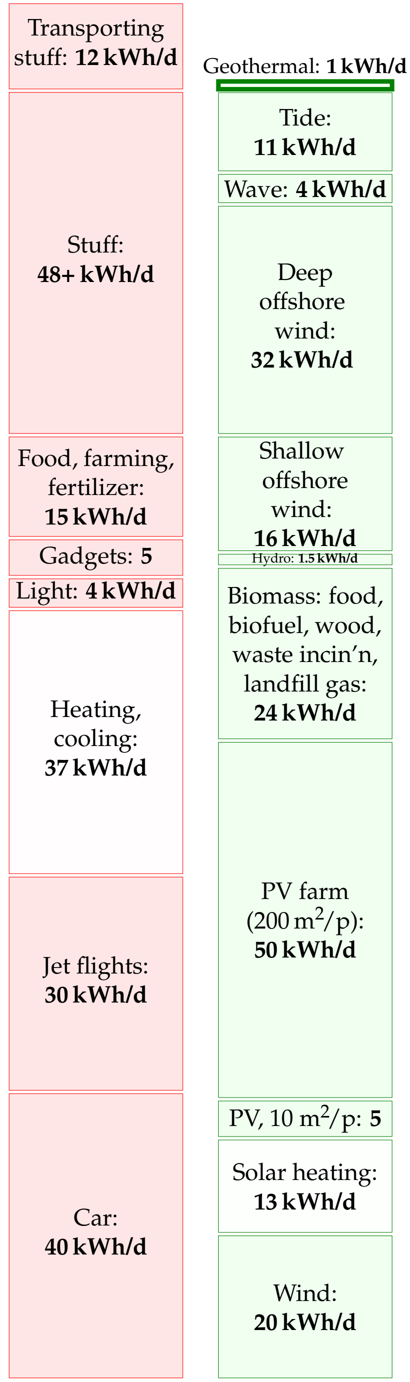


Figure 16.6. Geothermal.

17 Public services

Every gun that is made, every warship launched, every rocket fired signifies, in the final sense, a theft from those who hunger and are not fed, those who are cold and are not clothed.

This world in arms is not spending money alone. It is spending the sweat of its laborers, the genius of its scientists, the hopes of its children.

President Dwight D. Eisenhower – April, 1953

The energy cost of "defence"

Let's try to estimate how much energy we spend on our military.

In 2007–8, the fraction of British central government expenditure that went to defence was £33 billion/£587 billion = 6%. If we include the UK's spending on counter-terrorism and intelligence (£2.5 billion per year and rising), the total for defensive activities comes to £36 billion.

As a crude estimate we might guess that 6% of this £36 billion is spent on energy at a cost of 2.7p per kWh. (6% is the fraction of GDP that is spent on energy, and 2.7p is the average price of energy.) That works out to about 80 TWh per year of energy going into defence: making bullets, bombs, nuclear weapons; making devices for delivering bullets, bombs, and nuclear weapons; and roaring around keeping in trim for the next game of good-against-evil. In our favourite units, this corresponds to 4 kWh per day per person.

The cost of nuclear defence

The financial expenditure by the USA on manufacturing and deploying nuclear weapons from 1945 to 1996 was $5.5 trillion (in 1996 dollars).

Nuclear-weapons spending over this period exceeded the combined total federal spending for education; agriculture; training, employment, and social services; natural resources and the environment; general science, space, and technology; community and regional development (including disaster relief); law enforcement; and energy production and regulation.

If again we assume that 6% of this expenditure went to energy at a cost of 5¢ per kWh, we find that the energy cost of having nuclear weapons was 26 000 kWh per American, or 1.4 kWh per day per American (shared among 250 million Americans over 51 years).

What energy would have been delivered to the lucky recipients, had all those nuclear weapons been used? The energies of the biggest thermonuclear weapons developed by the USA and USSR are measured in megatons of TNT. A ton of TNT is 1200 kWh. The bomb that destroyed Hiroshima had the energy of 15 000 tons of TNT (18 million kWh). A *megaton* bomb delivers an energy of 1.2 billion kWh. If dropped on a city of one million, a megaton bomb makes an energy donation of 1200 kWh per person, equivalent to 120 litres of petrol per person. The total energy of the USA's nuclear arsenal today is 2400 megatons, contained in 10 000 warheads. In the good old days when folks really took defence seriously, the arsenal's energy was 20 000 megatons. These bombs, if used, would have delivered an energy of about 100 000 kWh per American. That's equivalent to 7 kWh per day per person for a duration of 40 years – similar to all the electrical energy supplied to America by nuclear power.

Energy cost of making nuclear materials for bombs

The main nuclear materials are plutonium, of which the USA has produced 104 t, and high-enriched uranium (HEU), of which the USA has produced 994 t. Manufacturing these materials requires energy.

The most efficient plutonium-production facilities use 24 000 kWh of heat when producing 1 gram of plutonium. So the direct energy-cost of making the USA's 104 tons of plutonium (1945–1996) was at least 2.5 trillion kWh which is 0.5 kWh per day per person (if shared between 250 million Americans).

The main energy-cost in manufacturing HEU is the cost of enrichment. Work is required to separate the ^{235}U and ^{238}U atoms in natural uranium in order to create a final product that is richer in ^{235}U. The USA's production of 994 tons of highly-enriched uranium (the USA's total, 1945–1996) had an energy cost of about 0.1 kWh per day per person.

> *"Trident creates jobs." Well, so does relining our schools with asbestos, but that doesn't mean we should do it!*
>
> Marcus Brigstocke

Universities

According to Times Higher Education Supplement (30 March 2007), UK universities use 5.2 billion kWh per year. Shared out among the whole population, that's a power of 0.24 kWh per day per person.

So higher education and research seem to have a much lower energy cost than defensive war-gaming.

There may be other energy-consuming public services we could talk about, but at this point I'd like to wrap up our race between the red and green stacks.

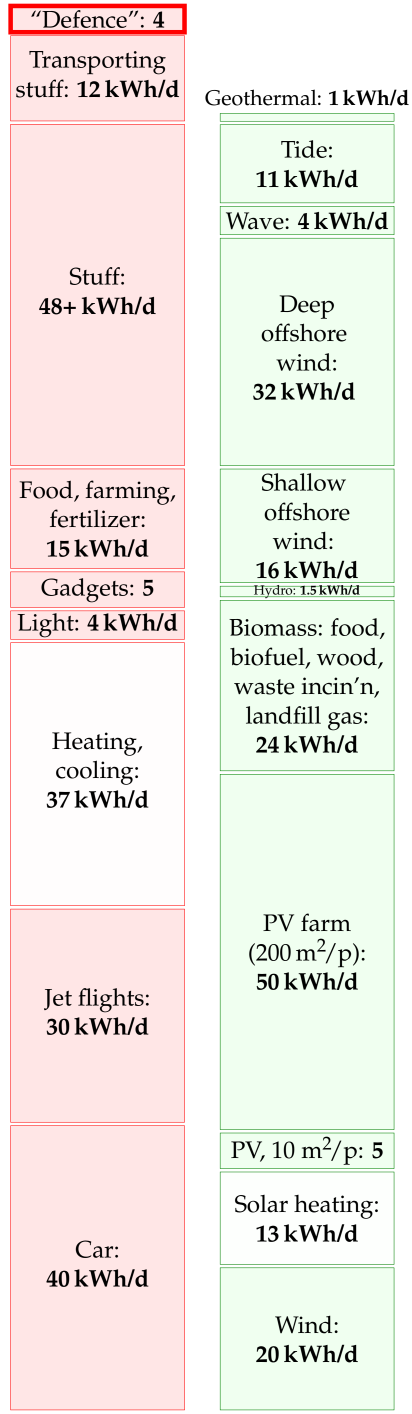


Figure 17.1. The energy cost of defence in the UK is estimated to be about 4 kWh per day per person.

Notes and further reading

page no.

100 *military energy budget*. The UK budget can be found at [yttg7p]; defence gets £33.4 billion [fcqfw] and intelligence and counter-terrorism £2.5 billion per year [2e4fcs]. According to p14 of the Government's Expenditure Plans 2007/08 [33x5kc], the "total resource budget" of the Department of Defence is a bigger sum, £39 billion, of which £33.5 billion goes for "provision of defence capability" and £6 billion for armed forces pay and pensions and war pensions. A breakdown of this budget can be found here: [35ab2c]. See also [yg5fsj], [yfgjna], and www.conscienceonline.org.uk.

The US military's energy consumption is published: "The Department of Defense is the largest single consumer of energy in the United States. In 2006, it spent $13.6 billion to buy 110 million barrels of petroleum fuel [roughly 190 billion kWh] and 3.8 billion kWh of electricity" (Dept. of Defense, 2008). This figure describes the direct use of fuel and electricity and doesn't include the embodied energy in the military's toys. Dividing by the US population of 300 million, it comes to 1.7 kWh/d per person.

– *The financial expenditure by the USA on manufacturing and deploying nuclear weapons from 1945 to 1996 was $5.5 trillion (in 1996 dollars)*. Source: Schwartz (1998).

101 *Energy cost of plutonium production*. [slbae].

– *The USA's production of 994 tons of HEU...* Material enriched to between 4% and 5% ^{235}U is called low-enriched uranium (LEU). 90%-enriched uranium is called high-enriched uranium (HEU). It takes three times as much work to enrich uranium from its natural state to 5% LEU as it does to enrich LEU to 90% HEU. The nuclear power industry measures these energy requirements in a unit called the separative work unit (SWU). To produce a kilogram of ^{235}U as HEU takes 232 SWU. To make 1 kg of ^{235}U as LEU (in 22.7 kg of LEU) takes about 151 SWU. In both cases one starts from natural uranium (0.71% ^{235}U) and discards depleted uranium containing 0.25% ^{235}U.

The commercial nuclear fuel market values an SWU at about $100. It takes about 100 000 SWU of enriched uranium to fuel a typical 1000 MW commercial nuclear reactor for a year. Two uranium enrichment methods are currently in commercial use: gaseous diffusion and gas centrifuge. The gaseous diffusion process consumes about 2500 kWh per SWU, while modern gas centrifuge plants require only about 50 kWh per SWU. [yh45h8], [t2948], [2ywzee]. A modern centrifuge produces about 3 SWU per year.

The USA's production of 994 tons of highly-enriched uranium (the USA's total, 1945–1996) cost 230 million SWU, which works out to 0.1 kWh/d per person (assuming 250 million Americans, and using 2500 kWh/SWU as the cost of diffusion enrichment).

18 Can we live on renewables?

The red stack in figure 18.1 adds up to 195 kWh per day per person. The green stack adds up to about 180 kWh/d/p. A close race! But please remember: in calculating our production stack we threw all economic, social, and environmental constraints to the wind. Also, some of our green contributors are probably incompatible with each other: our photovoltaic panels and hot-water panels would clash with each other on roofs; and our solar photovoltaic farms using 5% of the country might compete with the energy crops with which we covered 75% of the country. If we were to lose just one of our bigger green contributors – for example, if we decided that deep offshore wind is not an option, or that panelling 5% of the country with photovoltaics at a cost of £200 000 per person is not on – then the production stack would no longer match the consumption stack.

Furthermore, even if our red consumption stack were lower than our green production stack, it would not necessarily mean our energy sums are adding up. You can't power a TV with cat food, nor can you feed a cat from a wind turbine. Energy exists in different forms – chemical, electrical, kinetic, and heat, for example. For a sustainable energy plan to add up, we need both the forms and amounts of energy consumption and production to match up. Converting energy from one form to another – from chemical to electrical, as at a fossil-fuel power station, or from electrical to chemical, as in a factory making hydrogen from water – usually involves substantial losses of useful energy. We will come back to this important detail in Chapter 27, which will describe some energy plans that do add up.

Here we'll reflect on our estimates of consumption and production, compare them with official averages and with other people's estimates, and discuss how much power renewables could plausibly deliver in a country like Britain.

The questions we'll address in this chapter are:

1. Is the size of the red stack roughly correct? What is the *average* consumption of Britain? We'll look at the official energy-consumption numbers for Britain and a few other countries.

2. Have I been unfair to renewables, underestimating their potential? We'll compare the estimates in the green stack with estimates published by organizations such as the Sustainable Development Commission, the Institution of Electrical Engineers, and the Centre for Alternative Technology.

3. What happens to the green stack when we take into account social and economic constraints?

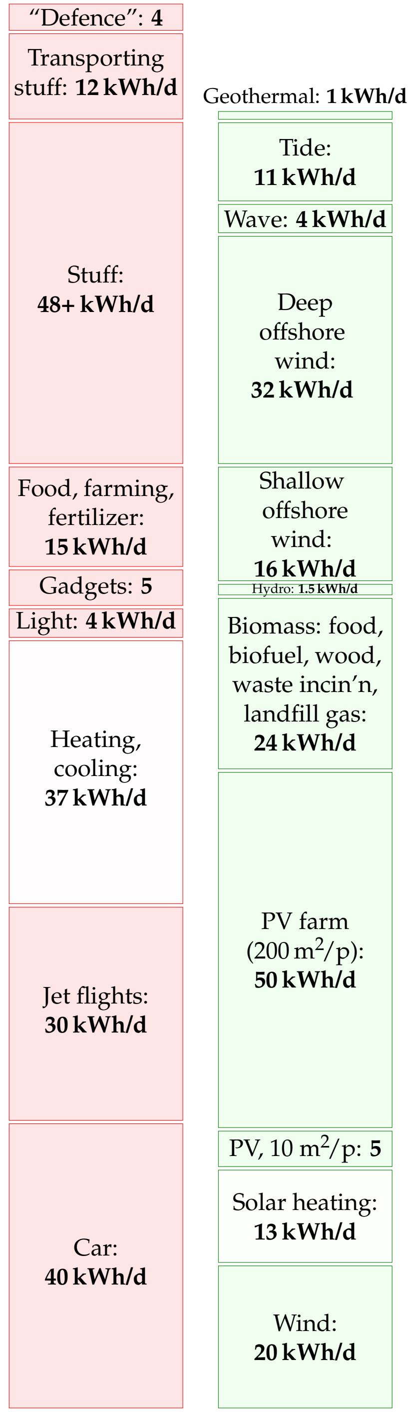


Figure 18.1. The state of play after we added up all the traditional renewables.

Red reflections

Our estimate of a typical affluent person's consumption (figure 18.1) has reached 195 kWh per day. It is indeed true that many people use this much energy, and that many more aspire to such levels of consumption. The *average* American consumes about **250 kWh per day**. If we all raised our standard of consumption to an average American level, the green production stack would definitely be dwarfed by the red consumption stack.

What about the average European and the average Brit? Average European consumption of "primary energy" (which means the energy contained in raw fuels, plus wind and hydroelectricity) is about 125 kWh per day per person. The UK average is also 125 kWh per day per person.

These official averages do not include two energy flows. First, the "embedded energy" in *imported* stuff (the energy expended in making the stuff) is not included at all. We estimated in Chapter 15 that the embedded energy in imported stuff is at least 40 kWh/d per person. Second, the official estimates of "primary energy consumption" include only industrial energy flows – things like fossil fuels and hydroelectricity – and don't keep track of the natural embedded energy in food: energy that was originally harnessed by photosynthesis.

Another difference between the red stack we slapped together and the national total is that in most of the consumption chapters so far we tended to ignore the energy lost in converting energy from one form to another, and in transporting energy around. For example, the "car" estimate in Part I covered only the energy in the petrol, not the energy used at the oil refinery that makes the petrol, nor the energy used in trundling the oil and petrol from A to B. The national total accounts for all the energy, before any conversion losses. Conversion losses in fact account for about 22% of total national energy consumption. Most of these conversion losses happen at power stations. Losses in the electricity transmission network chuck away 1% of total national energy consumption.

When building our red stack, we tried to imagine how much energy a typical affluent person uses. Has this approach biased our perception of the importance of different activities? Let's look at some official numbers. Figure 18.2 shows the breakdown of energy consumption by end use. The top two categories are transport and heating (hot air and hot water). Those two categories also dominated the red stack in Part I. Good.

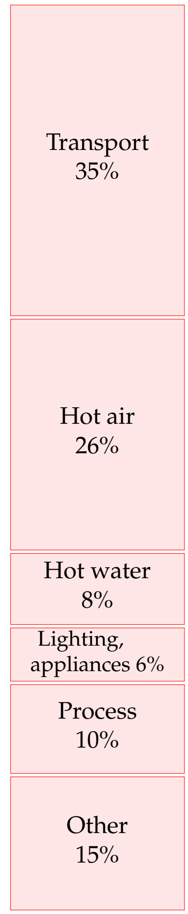


Figure 18.2. Energy consumption, broken down by end use, according to the Department for Trade and Industry.

Road transport	Petroleum	22.5
Railways	Petroleum	0.4
Water transport	Petroleum	1.0
Aviation	Petroleum	7.4
All modes	Electricity	0.4
All energy used by transport		31.6

Table 18.3. 2006 breakdown of energy consumption by transport mode, in kWh/d per person.
Source: Dept. for Transport (2007).

Figure 18.4. Power consumption per capita, versus GDP per capita, in purchasing-power-parity US dollars. Squares show countries having "high human development;" circles, "medium" or "low." Figure 30.1 (p231) shows the same data on logarithmic scales.

Let's look more closely at transport. In our red stack, we found that the energy footprints of driving a car 50 km per day and of flying to Cape Town once per year are roughly equal. Table 18.3 shows the relative importances of the different transport modes in the national balance-sheet. In the national averages, aviation is smaller than road transport.

How do Britain's official consumption figures compare with those of other countries? Figure 18.4 shows the power consumptions of lots of countries or regions, versus their gross domestic products (GDPs). There's an evident correlation between power consumption and GDP: the higher a country's GDP (per capita), the more power it consumes per capita. The UK is a fairly typical high-GDP country, surrounded by Germany, France, Japan, Austria, Ireland, Switzerland, and Denmark. The only notable exception to the rule "big GDP implies big power consumption" is Hong Kong. Hong Kong's GDP per capita is about the same as Britain's, but

Figure 18.5. Hong Kong. Photo by Samuel Louie and Carol Spears.

Hong Kong's power consumption is about 80 kWh/d/p.

The message I take from these country comparisons is that the UK is a fairly typical European country, and therefore provides a good case study for asking the question "How can a country with a high quality of life get its energy sustainably?"

Green reflections

People often say that Britain has plenty of renewables. Have I been mean to green? Are my numbers a load of rubbish? Have I underestimated sustainable production? Let's compare my green numbers first with several estimates found in the Sustainable Development Commission's publication *The role of nuclear power in a low carbon economy. Reducing CO_2 emissions – nuclear and the alternatives.* Remarkably, even though the Sustainable Development Commission's take on sustainable resources is very positive ("We have huge tidal, wave, biomass and solar resources"), *all the estimates in the Sustainable Development Commission's document are smaller than mine!* (To be precise, all the estimates of the renewables total are smaller than my total.) The Sustainable Development Commission's publication gives estimates from four sources detailed below (IEE, Tyndall, IAG, and PIU). Figure 18.6 shows my estimates alongside numbers from these four sources and numbers from the Centre for Alternative Technology (CAT). Here's a description of each source.

IEE The Institute of Electrical Engineers published a report on renewable energy in 2002 – a summary of possible contributions from renewables in the UK. The second column of figure 18.6 shows the "technical potential" of a variety of renewable technologies for UK electricity generation – "an upper limit that is unlikely ever to be exceeded even with quite dramatic changes in the structure of our society and economy." According to the IEE, the total of all renewables' technical potential is about 27 kWh/d per person.

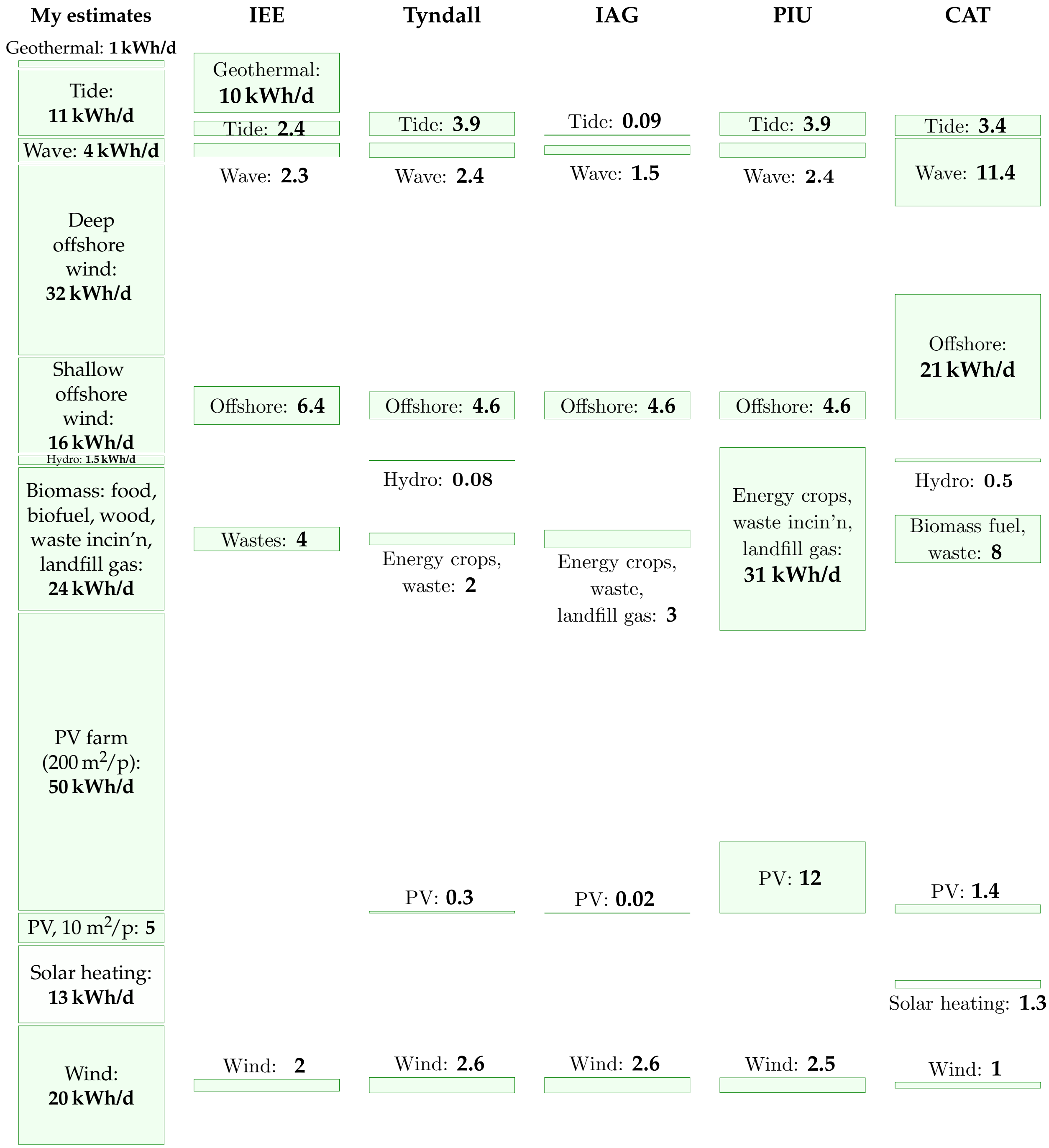


Figure 18.6. Estimates of theoretical or practical renewable resources in the UK, by the Institute of Electrical Engineers, the Tyndall Centre, the Interdepartmental Analysts Group, and the Performance and Innovation Unit; and the proposals from the Centre for Alternative Technology's "Island Britain" plan for 2027.

Tyndall The Tyndall Centre's estimate of the total practicable renewable-energy resource is 15 kWh per day per person.

IAG The Interdepartmental Analysts Group's estimates of renewables, take into account economic constraints. Their total practical *and* economical resource (at a retail price of 7p/kWh) is 12 kWh per day per person.

PIU The "PIU" column shows the "indicative resource potential for renewable electricity generation options" from the DTI's contribution to the PIU review in 2001. For each technology I show their "practical maximum," or, if no practical maximum was given, their "theoretical maximum."

CAT The final column shows the numbers from the Centre for Alternative Technology's "Island Britain" plan Helweg-Larsen and Bull (2007).

Bio-powered Europe

Sometimes people ask me "surely we used to live on renewables just fine, before the Industrial Revolution?" Yes, but don't forget that two things were different then: lifestyles, and population densities.

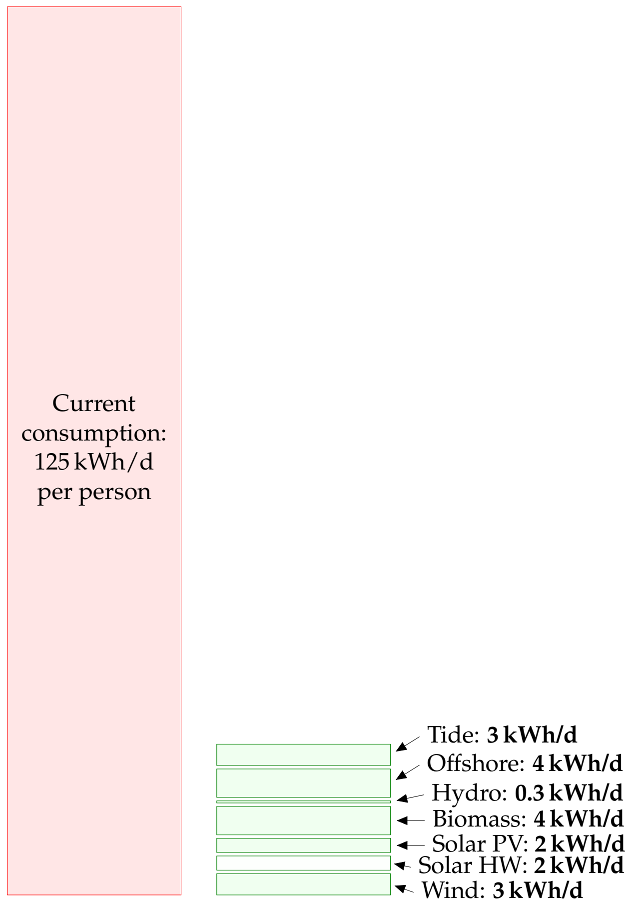
Turning the clock back more than 400 years, Europe lived almost entirely on sustainable sources: mainly wood and crops, augmented by a little wind power, tidal power, and water power. It's been estimated that the average person's lifestyle consumed a power of 20 kWh per day. The wood used per person was 4 kg per day, which required 1 hectare (10 000 m^2) of forest per person. The area of land per person in Europe in the 1700s was 52 000 m^2. In the regions with highest population density, the area per person was 17 500 m^2 of arable land, pastures, and woods. Today the area of Britain per person is just 4000 m^2, so even if we reverted to the lifestyle of the Middle Ages and completely forested the country, we could no longer live sustainably here. Our population density is far too high.

Green ambitions meet social reality

Figure 18.1 is bleak news. Yes, technically, Britain has "huge" renewables. But realistically, I don't think Britain can live on its own renewables – at least not the way we currently live. I am partly driven to this conclusion by the chorus of opposition that greets any major renewable energy proposal. People love renewable energy, *unless it is bigger than a figleaf*. If the British are good at one thing, it's saying "no."

Wind farms?	"No, they're ugly noisy things."
Solar panels on roofs?	"No, they would spoil the visual amenity of the street."

Figure 18.7. The state of play after we add up all the traditional renewables, *and then have a public consultation.*



After the public consultation. I fear the maximum Britain would ever get from renewables is in the ballpark of 18 kWh/d per person. (The left-hand consumption number, 125 kWh/d per person, by the way, is the average British consumption, excluding imports, and ignoring solar energy acquired through food production.)

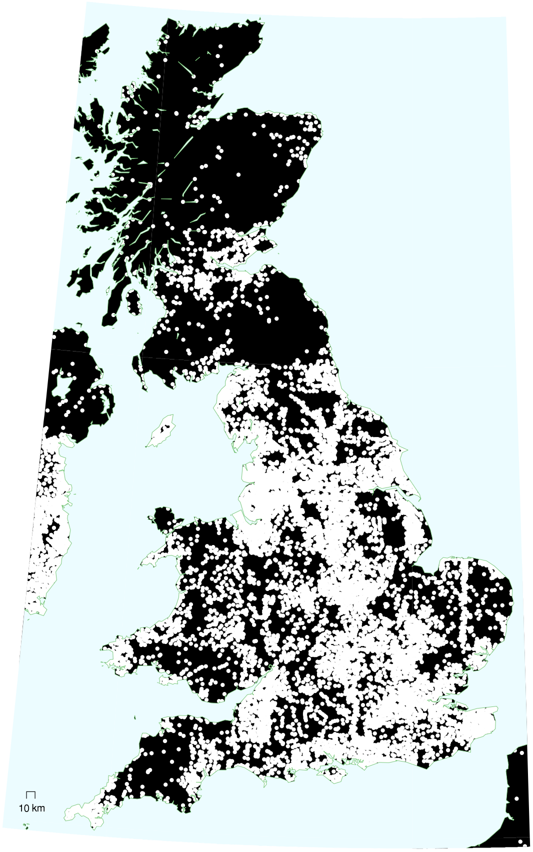


Figure 18.8. Where the wild things are. One of the grounds for objecting to wind farms is the noise they produce. I've chopped out of this map of the British mainland a 2-km-radius exclusion zone surrounding every hamlet, village, and town. These white areas would presumably be excluded from wind-farm development. The remaining black areas would perhaps also be largely excluded because of the need to protect tranquil places from industrialization. Settlement data from `www.openstreetmap.org`.

More forestry? "No, it ruins the countryside."

Waste incineration? "No, I'm worried about health risks, traffic congestion, dust and noise."

Hydroelectricity? "Yes, but not *big* hydro – that harms the environment."

Offshore wind? "No, I'm more worried about the ugly powerlines coming ashore than I was about a Nazi invasion."

Wave or geothermal power? "No, far too expensive."

After all these objections, I fear that the maximum Britain would ever get from renewables would be something like what's shown in the bottom right of figure 18.7.

Figure 18.8 offers guidance to anyone trying to erect wind farms in Britain. On a map of the British mainland I've shown in white a 2-km-radius exclusion zone surrounding every hamlet, village, and town. These white areas would presumably be excluded from wind-farm development because they are too close to the humans. I've coloured in black all regions

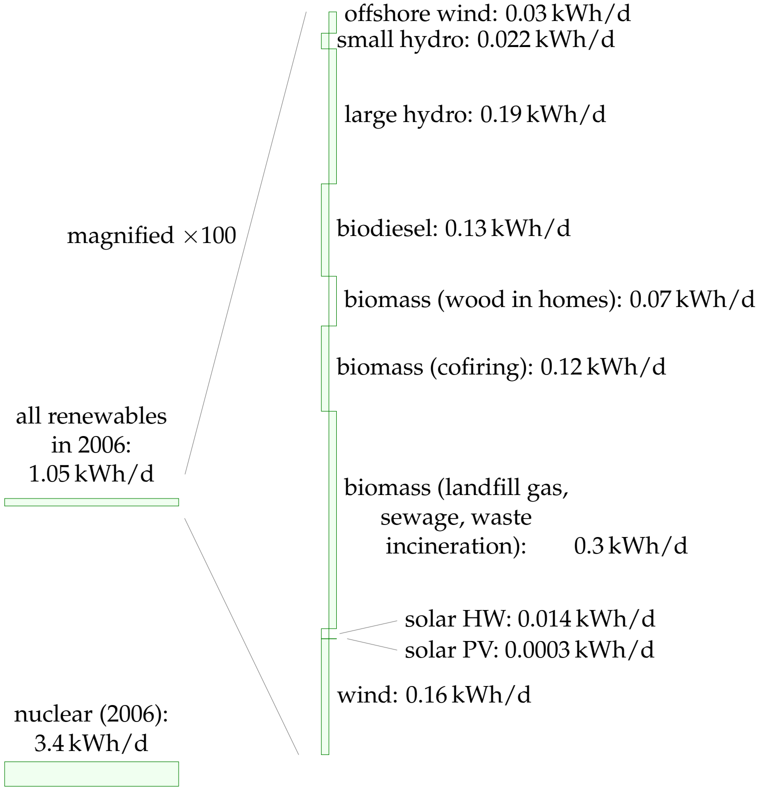


Figure 18.9. Production of renewables and nuclear energy in the UK in 2006. All powers are expressed per-person, as usual. The breakdown of the renewables on the right hand side is scaled up 100-fold vertically.

that are *more than 2 km* from any human settlement. These areas are largely excluded from wind-farm development because they are *tranquil*, and it's essential to protect tranquil places from industrialization. If you want to avoid objections to your wind farm, pick any piece of land that is not coloured black or white.

> *Some of these environmentalists who have good hearts but confused minds are almost a barrier to tackling climate change.*
>
> Malcolm Wicks, Minister of State for Energy

We are drawing to the close of Part I. The assumption was that we want to get off fossil fuels, for one or more of the reasons listed in Chapter 1 – climate change, security of supply, and so forth. Figure 18.9 shows how much power we currently get from renewables and nuclear. They amount to just 4% of our total power consumption.

The two conclusions we can draw from Part I are:

1. *To make a difference, renewable facilities have to be country-sized.*

   For any renewable facility to make a contribution comparable to our current consumption, *it has to be country-sized*. To get a big contribution from wind, we used wind farms with the area of Wales. To get a big contribution from solar photovoltaics, we required half the area of Wales. To get a big contribution from waves, we imagined wave farms covering 500 km of coastline. To make energy crops with a big contribution, we took 75% of the whole country.

Renewable facilities have to be country-sized because all renewables are so diffuse. Table 18.10 summarizes most of the powers-per-unit-area that we encountered in Part I.

To sustain Britain's lifestyle on its renewables alone would be very difficult. A renewable-based energy solution will necessarily be large and intrusive.

2. *It's not going to be easy* to make a plan that adds up using renewables alone. If we are serious about getting off fossil fuels, Brits are going to have to learn to start saying "yes" to something. Indeed to several somethings.

In Part II I'll ask, "assuming that we can't get production from renewables to add up to our current consumption, what are the other options?"

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

Table 18.10. Renewable facilities have to be country-sized because all renewables are so diffuse.

Notes and further reading

page no.

104 *UK average energy consumption is 125 kWh per day per person.* I took this number from the UNDP Human Development Report, 2007.
The DTI (now known as DBERR) publishes a Digest of United Kingdom Energy Statistics every year. [uzek2]. In 2006, according to DUKES, total primary energy demand was 244 million tons of oil equivalent, which corresponds to 130 kWh per day per person.
I don't know the reason for the small difference between the UNDP number and the DUKES number, but I can explain why I chose the slightly lower number. As I mentioned on p27, DUKES uses the same energy-summing convention as me, declaring one kWh of chemical energy to be equal to one kWh of electricity. But there's one minor exception: DUKES defines the "primary energy" produced in nuclear power stations to be the thermal energy, which in 2006 was 9 kWh/d/p; this was converted (with 38% efficiency) to 3.4 kWh/d/p of supplied electricity; in my accounts, I've focused on the electricity produced by hydroelectricity, other renewables, and nuclear power; this small switch in convention reduces the nuclear contribution by about 5 kWh/d/p.

– *Losses in the electricity transmission network chuck away 1% of total national energy consumption*. To put it another way, the losses are 8% of the electricity generated. This 8% loss can be broken down: roughly 1.5% is lost in the long-distance high-voltage system, and 6% in the local public supply system. Source: MacLeay et al. (2007).

105 *Figure 18.4.* Data from UNDP Human Development Report, 2007. [3av4s9]

108 *In the Middle Ages, the average person's lifestyle consumed a power of 20 kWh per day.* Source: Malanima (2006).

110 *"I'm more worried about the ugly powerlines coming ashore than I was about a Nazi invasion."* Source: [6frj55].