Sustainable Energy – without the hot air

David J.C. MacKay

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Department of Physics
University of Cambridge

http://www.withouthotair.com/
http://www.inference.phy.cam.ac.uk/mackay/

Back-cover blurb

Sustainable energy — without the hot air

Category: Science.

We're often told that '*huge* amounts of renewable power are available' – wind, wave, tide, and so forth. But our current power consumption is also huge! To understand our sustainable energy crisis, we need to know how the one 'huge' compares with the other. We need numbers, not adjectives.

In this book, David MacKay, Professor in Physics at Cambridge University, shows how to estimate the numbers, and what those numbers depend on. As a case study, the presentation focuses on the United Kingdom, asking first "could Britain live on sustainable energy resources alone?" and second "how can Britain make a realistic post-carbon energy plan that adds up?"

These numbers bring home the size of the changes that society must undergo if sustainable living is to be achieved.

Don't be afraid of this book's emphasis on numbers. It's all basic stuff, accessible to high school students, policy-makers and the educated public. To have a meaningful discussion of sustainable energy, you need numbers.

The author enjoying a sunny day in Venice.

This is **Draft 2.1.5** (May 12, 2008). You are looking at the low-resolution edition (*i.e.*, some images are low-resolution to save bandwidth). Feedback welcome. Thanks!

What's this book about?

I'm concerned about cutting UK emissions of twaddle – twaddle about sustainable energy. Everyone claims to be concerned, and everyone is encouraged to 'make a difference', but many of the things that allegedly make a difference don't add up.

Twaddle emissions are high at the moment because people get emotional (for example about wind or nuclear) and no-one talks about numbers. Or if they do mention numbers, they select them to sound big, to make an impression, and to score points in arguments, rather than to aid thoughtful discussion.

This is a straight-talking book about the numbers. The aim is to guide the reader around the claptrap to actions that really make a difference and to policies that add up.

How to operate this book

Some chapters begin with a quotation. Please don't assume that my quoting someone means that I agree with them. Think of these quotes as provocations, as hypotheses to be critically assessed.

Many of the early chapters (numbered 1, 2, 3, ...) have longer technical chapters (A, B, C, ...) associated with them. These technical chapters start on page 244.

At the end of each chapter are further notes and pointers to sources and references. The text also contains pointers to web resources.

When a web-pointer is monstrously long, I've used the TinyURL service, and put the tiny code in the text like this – [yh8xse] – and the full pointer at the end of the book on page 368. yh8xse is a shorthand for a tiny URL, in this case: http://tinyurl.com/yh8xse.

A complete list of all the URLs in this book is provided at http://tinyurl.com/yh8xse.

If you find a URL doesn't work any more, you may be able to find the page on the Wayback Machine internet archive [f754].

An electronic version of this book is available for free on the website www.withouthotair.com. This book used to be longer. The removed material (roughly 100 pages on carbon, climate change, and the many strategies people use to try to mislead or to win arguments) is available in draft form on the same website.

I welcome feedback and corrections. I expect that as I continue to learn about sustainable energy, I'll update some of the numbers in this book.

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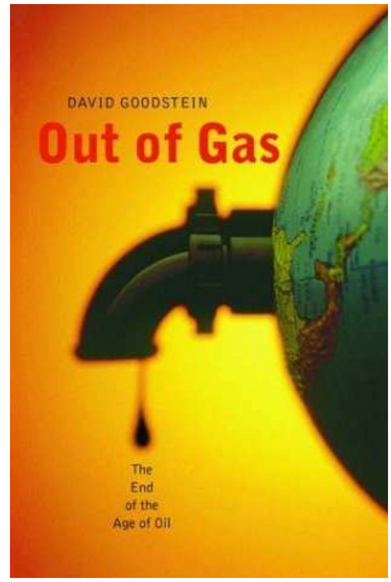
Preface



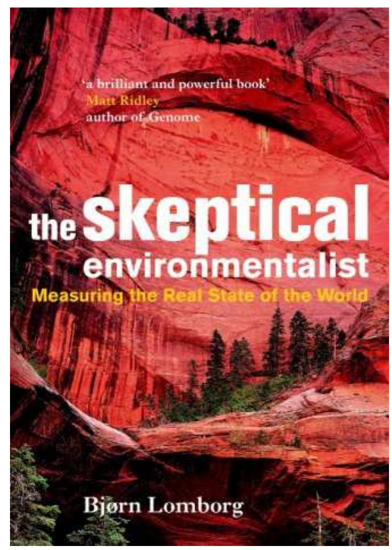


Figure 1. David Goodstein's *Out of Gas* (2004).
Bjørn Lomborg's *The Skeptical Environmentalist* (2001).

> *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, the oil crisis would simply be replaced by a *nuclear* crisis in just twenty years or so, as uranium reserves also became depleted.

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."

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."

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, Prof. James Lovelock F.R.S., "the founding historical and cultural leader of environmentalism" knocks both "sustainable development" and "business as usual" 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."

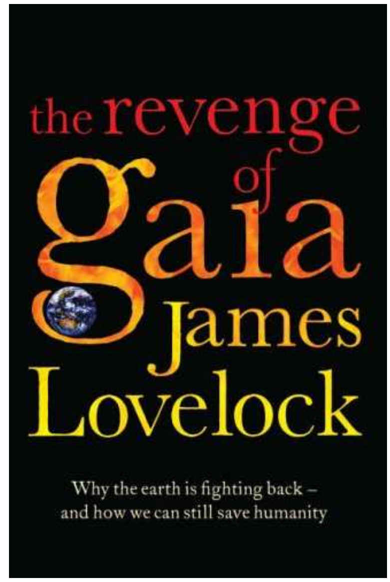


Figure 2. The Revenge of Gaia: Why the Earth Is Fighting Back – and How We Can Still Save Humanity. James Lovelock (2006). © Allen Lane.

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 enormity. 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. I'm sure some people realise a more realistic mantra is:

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

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 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 are also the creators of 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. This has to be a scam – 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," "recyclable mobile phones," "environment-friendly phone calls," and other pointless tat.

Campaigners also mislead. People who want to promote renewables over nuclear, for example, often say "renewables could supply 80% of our electricity"; then they say "nuclear power would only reduce our emissions by . . . " This argument is misleading because the playing field is switched half-way through, from "electricity" to "emissions". I think many people confuse "electricity" and "energy"; but electricity is only one way in which we get energy; most of us get most of our energy in forms other than electricity – natural gas and petrol, for example (for heating and transport, respectively). In fact electricity accounts for only one fifth of our energy consumption, so even if renewables could supply 80% of our electricity, that would represent less than one fifth of our current energy demand.

Perhaps the worst offenders in the kingdom of codswallop are the people who really should know better – the media publishers who promote the codswallop. A couple that spring to mind: New Scientist for their "water-powered car"; and Nature magazine for their column praising Arnold Schwarzenegger for filling up a hydrogen-powered Hummer.

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, stops driving a 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'?

Figure 3. This Greepeace leaflet arrived in my junk mail in May 2006. Do beloved windmills have the capacity to displace hated cooling towers?

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 earth six times too big?

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 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.) The UK has a particular security-of-supply problem looming, known as the "energy gap". Because a substantial number of old coal power stations and nuclear power stations will be closing down during the next decade, there is a risk that electricity demand will sometimes exceed electricity supply, if adequate plans are not implemented. At the same time, Britain's North Sea fossil fuel supply is dwindling.

Third, using fossil fuels changes the climate. Climate change is blamed on several human activities, but the biggest contributor to climate change is the 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.

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.

The climate change motivation runs 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.

We start with the fact that carbon dioxide (CO_2) concentrations are rising. The upper graph in figure 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 caused by solar activity. 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 steam engine was invented in 1698, Watt's more efficient steam engine really got the Industrial Revolution going. One of its main applications was the pumping of water out of coal mines. The middle graph shows what happened to British coal production from 1769 onwards, and to world coal production one hundred years later as the Revolution spread. In 1800, coal was used to make iron, to make ships, to heat buildings, to power trains and other machinery, and of course to power the pumps that enabled still more coal to be scraped up from deep inside the hills of England and Wales. England was terribly well endowed with coal. When the Revolution started, the amount of carbon sitting in coal under England was roughly the same as the amount sitting in oil under Saudi Arabia. This coal allowed Britain to turn the globe red. The prosperity that came to England and Wales was reflected in a century of unprecented population growth, as the third graph in figure 4 shows. This rate of population growth may have been impressive, but the rate at which coal production grew was even greater. As the middle graph shows, British coal production, which was essentially the same thing as world coal production, doubled every twenty years. Eventually other countries got in on the act too. British coal production peaked in 1910, but meanwhile world coal production continued to doubled every twenty years, a doubling that continued for a total of two hundred years. Coal production is still increasing today. Other fossil fuels are being extracted too – the middle graph in figure 4 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, do you hear what I hear? I hear a persistent angry buzzing noise coming from a bunch of self-styled sceptics. What can they be saying? Here's Dominic Lawson, a columnist from the *Independent*:

> "The burning of fossil fuels sends about seven gigatonnes of CO_2 per year into the atmosphere, which sounds like a

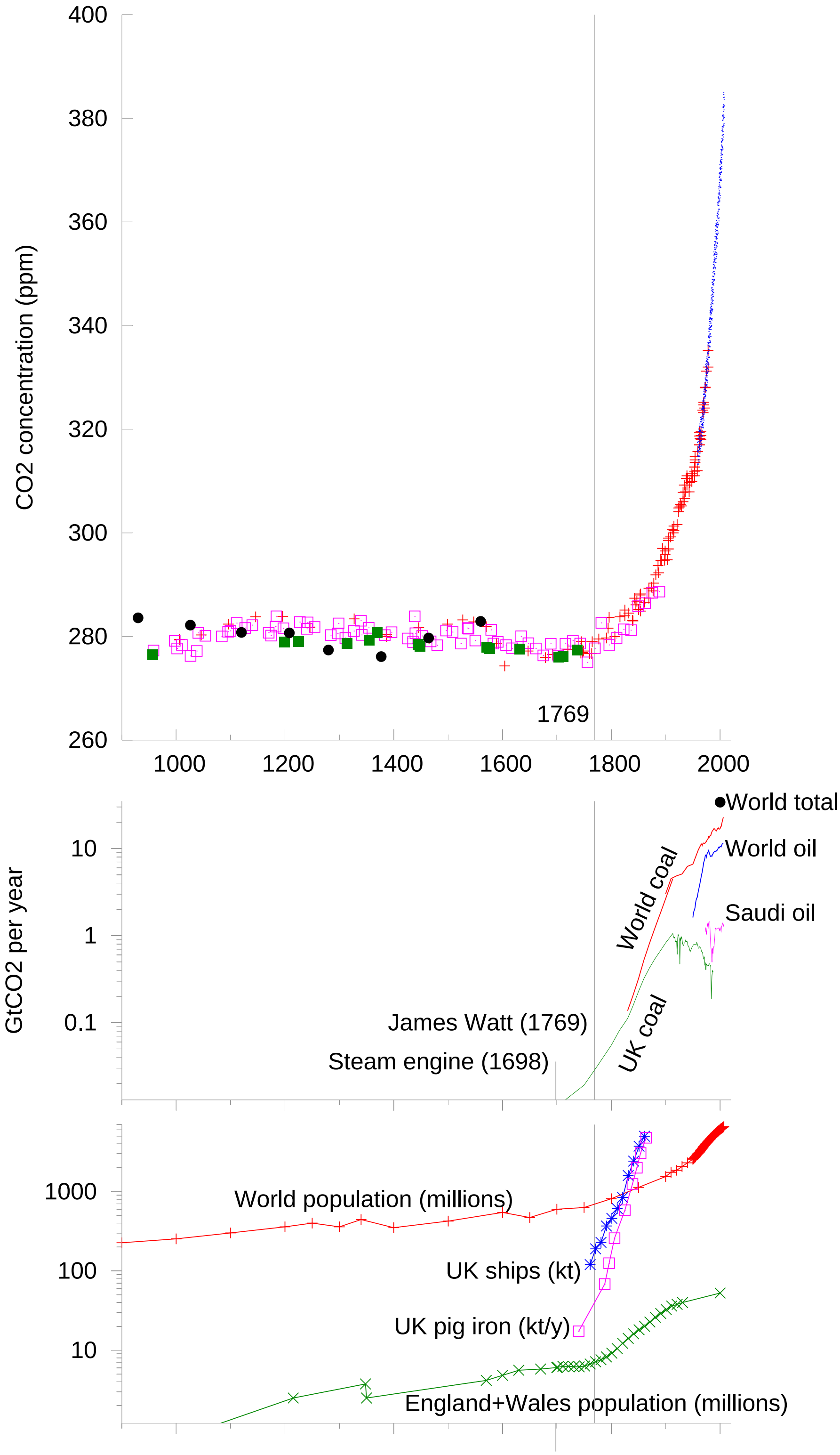


Figure 4. The upper graph shows carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards). Do you think, just possibly, *something new* may have happened between 1800 AD and 2000 AD?

I've marked the year 1769, in which James Watt patented his steam engine. (The first steam engine was invented seventy years earlier in 1698, but Watt's was much more efficient.)

The middle graph shows (on a logarithmic scale) the history of UK coal production, Saudi oil production, world coal production, world oil production, and (by the top right point) the total of all greenhouse gas emissions in the year 2000. All these production rates are shown in billions of tons of CO_2 – an incomprehensible unit, yes, but don't worry: we'll personalize it shortly.

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).

> lot. Yet the biosphere and the oceans send about 1900 gigatonnes and 36 000 gigatonnes 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.

Yes, natural flows of CO_2 *are* much larger than the additional flow we switched on two hundred 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 the large *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 much 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*. Burning fossil fuels creates a *new* flow of carbon that, though small, is *not cancelled*. Burning fossil fuels is therefore undeniably changing the CO_2 concentration in the atmosphere and in the surface oceans. No scientist disputes this fact. When it comes to CO_2 concentrations, man *is* significant.

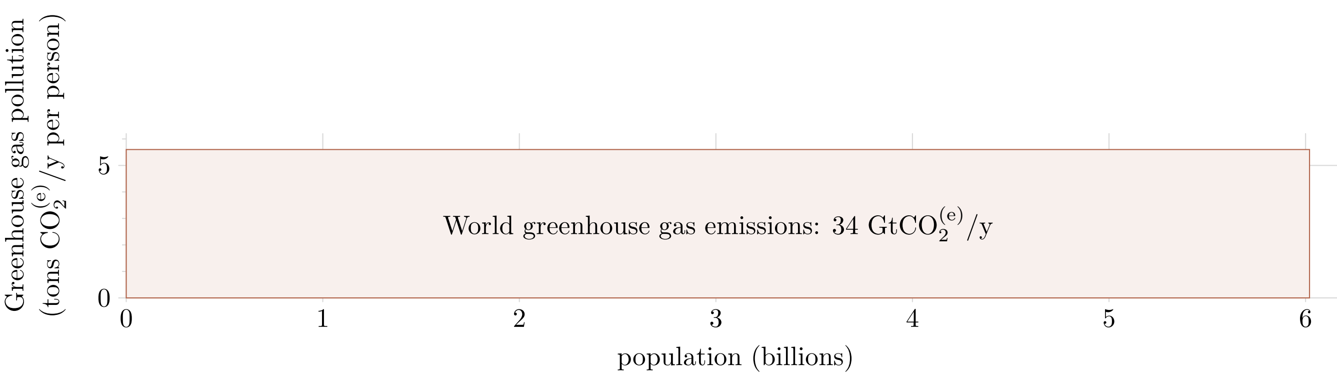
OK. Fossil fuel burning increases CO_2 concentrations dramatically. Does it matter? "Carbon is nature!", the oilspinners remind us, "Carbon is life!" If CO_2 had no harmful effects, then it would not matter. However, carbon dioxide is a greenhouse gas. Not the strongest greenhouse gas, but a significant 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 slightly impede the flow of heat from the planet. Carbon dioxide has a warming effect. This fact is based not on historical records of global temperatures but on the known physical properties of CO_2 molecules. Greenhouse gases are a duvet, and CO_2 is one layer of the duvet.

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 effect CO_2-doubling would have 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 litany of probable drastic effects, as I am sure you've heard it before. (See [2z2xg7] if not.) The litany begins "the Greenland icecap would gradually melt, and, over a period of a few hundred 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 3 million years, and it's conceivable that the ecosystem will be so significantly altered that the earth would stop providing some of the goods and services that we currently take for granted.

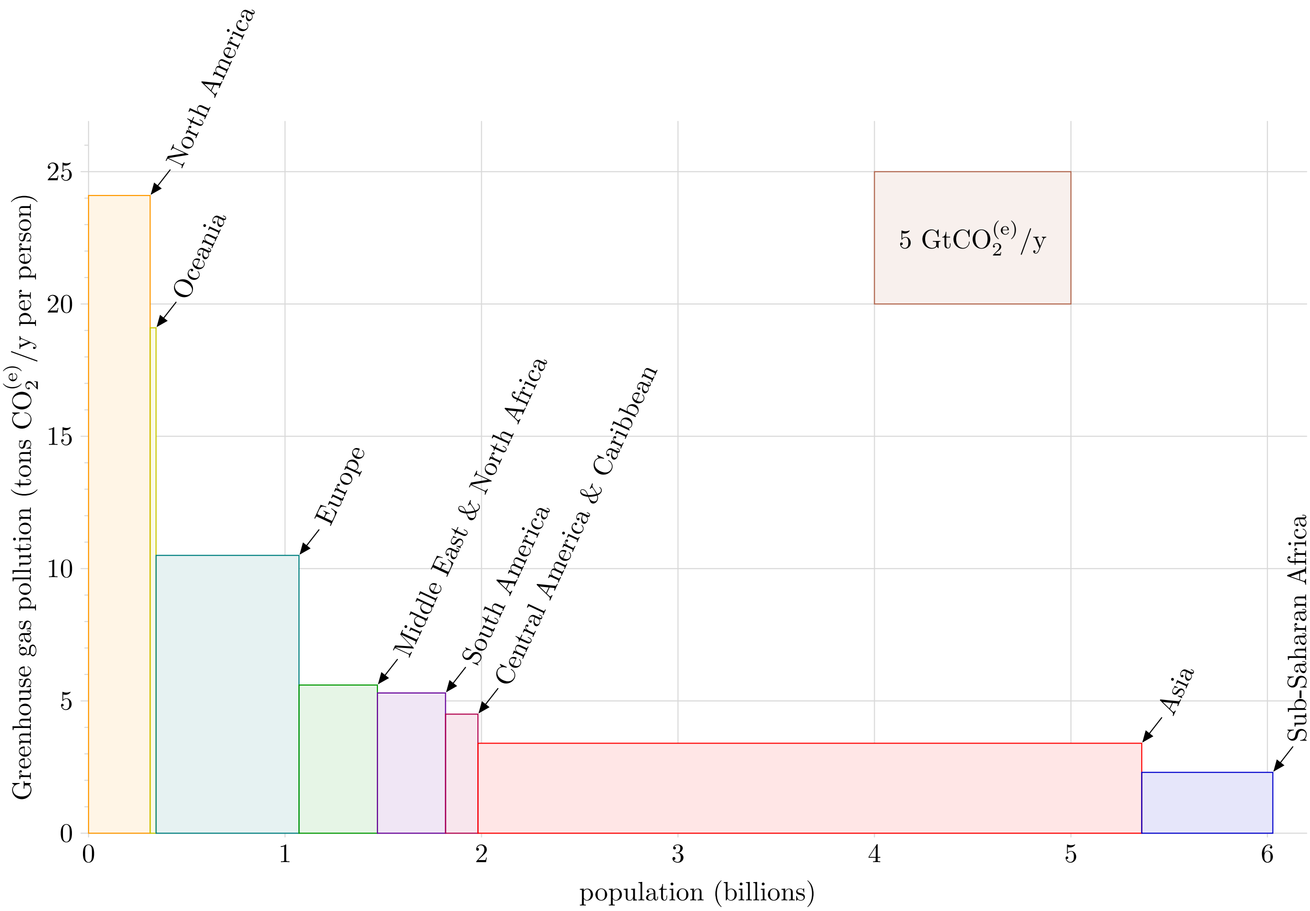
Climate modelling is very difficult, and I doubt that any of the models yet made are accurate. But uncertainty about exactly how the climate will respond to extra greenhouse gases is no justification for inaction. If you were riding a fast-moving motorcycle in fog near a cliff-edge, and you didn't have a very 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 is responsible for 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. So let's now explore the facts about present and past greenhouse gas emissions.

In the year 2000, world greenhouse gas emissions stood at 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 or 6 tons 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.



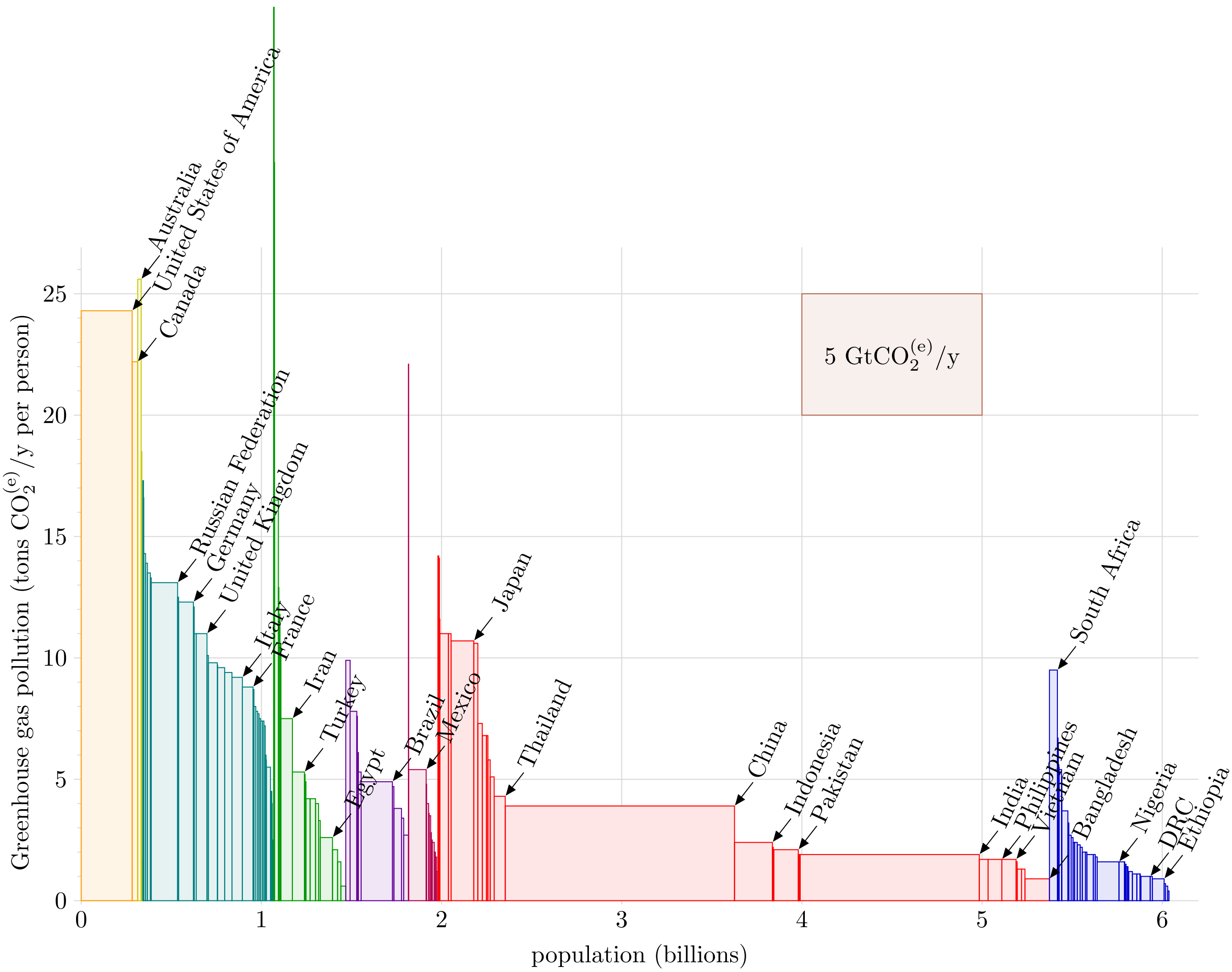
Six tons per year per person is equivalent to every person burning one and a half tons of coal per year. Now, all people are created equal, but some are more equal than others. We don't all emit 6 tons per year. We can break down the emissions of the year 2000, showing how the 34 billion-ton rectangle is shared between the regions of the world.



In this picture I've broken the world down into eight regions. Each rectangle 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.

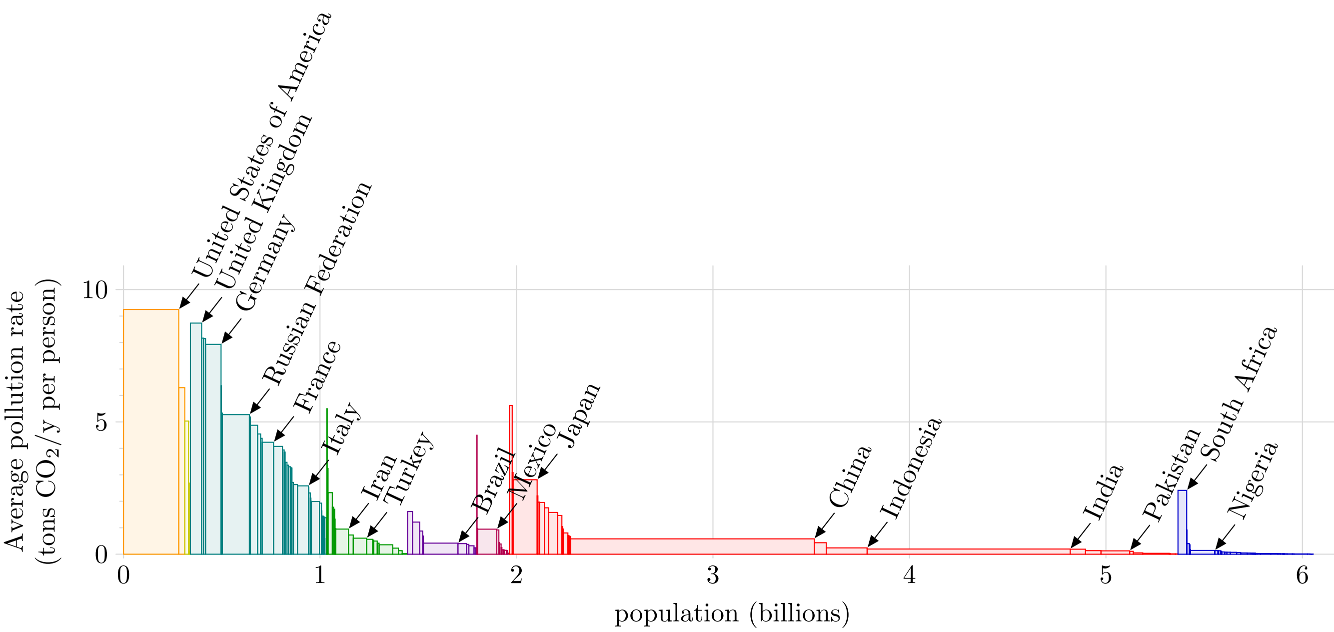


The major countries with the biggest per-capita emissions are Australia, the USA, and Canada. European countries and Japan are notable runners up. Among European countries, the United Kingdom is resolutely average. What about China, that naughty 'out of control' country? Yes, the area of China's rectangle 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.

So, assuming that 'something needs to be done' about climate change, assuming that the world needs to reduce greenhouse gas emissions, who has a special responsibility to do something? Well, 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 ones whose emissions are two, three, or four times the world average. Countries like Britain and America for example.

Historical responsibility for climate impact

There's another factual foundation I'd like to explore. 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 so much as the cumulative total emissions – much of the emitted carbon dioxide will hang out in the atmosphere for at least 50 or 100 years. We might therefore 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 emissions, per capita, we are second only to the USA. [In absolute terms the biggest historical emitters are, in order, USA (322 $GtCO_2$), Russian Federation (90 $GtCO_2$), China (89 $GtCO_2$), Germany (78 $GtCO_2$), UK (62 $GtCO_2$), Japan (43 $GtCO_2$), France (30 $GtCO_2$), India (25 $GtCO_2$), and Canada (24 $GtCO_2$).]

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? 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 a 60% reduction in greenhouse-gas emissions by 2050, but we must be clear that such 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 5. 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 starts immediately 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. 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 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 get down from its current 10 or so tons of CO_2 per year per person to roughly 1 ton per year per person by 2050. This is such a deep cut, I suggest the best way to think about it is 'no more fossil fuels'.

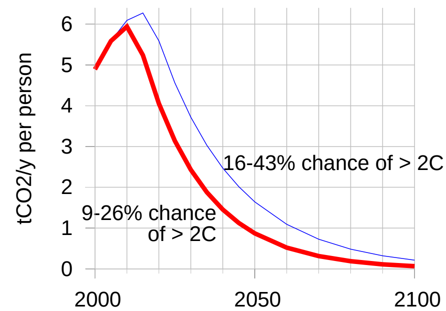


Figure 5. Global emissions for two scenarios considered by Baer and Mastrandrea, expressed in tons of CO_2 per person, using a world population of six billion. Both scenarios are believed to offer a modest chance of avoiding a 2°C temperature rise.

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 more 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 inaccurate. 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 fossil fuel emissions are currently 7 billion tons of carbon per year, then we can instantly note, without a calculator, that the average emissions per person are just a little more than 1 ton of carbon per person per year. (Because 7 divided by 6 is 1.) This is a useful yardstick to remember:

Yardstick number 1
"average **current** emissions are 1 ton of carbon per year per person."

By the way, one ton of carbon is equivalent to roughly 4 tons of CO_2 (44/12 tons, to be precise);

this yardstick's figure of 4 tons of CO_2 per year is a bit smaller than the 5.6 tons of $CO_2^{(e)}$ per year mentioned a few pages back because the 5.6 tons included all greenhouse-gas emissions.

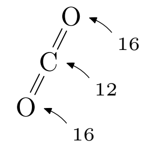


Figure 6. The weights of an atom of carbon and a molecule of CO_2 are in the ratio 12 to 44, because the carbon atom weighs 12 units and the two oxygen atoms weigh 16 each. $12 + 16 + 16 = 44$.

If you also learn that a round-trip intercontinental flight emits nearly two tons of CO_2 per passenger (which is about half a ton of carbon), then the yardstick helps you realise that just one such plane-trip per year corresponds to half of the average person's carbon emissions.

Did it bother you that I said that 7 divided by 6 is 1? This mistake really is deliberate. If the yardstick said 'average personal emissions are 1.167 tons of carbon per year', it would no longer be a yardstick. A yardstick is easy to handle. It's hard to remember '1.167' tons. One ton is much easier to remember, and it's easier to work with: everyone can divide or multiply by 1 without the help of a calculator.

Continuing the example, if you also learn that a safe, sustainable level of fossil fuel emissions for the next century is not 7 billion tons of carbon per year but 2 billion tons of carbon per year, we deduce

Yardstick number 2
'we need average emissions to be ⅓ ton of carbon per year per person'.

(Two billion divided by six billion.) So, if you want everyone to have equal pollution rights, you now know that that round-trip flight in the 747 uses up more than one year's allowance!

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 (5.6 m/s, or 12 miles per hour). I back up these everyday estimates with other peoples' calculations and with statistics from official sources.

Let me close this preface 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 fundamental limits to sustainable energy, not current economic feasibility. Economics is always changing, but the fundamental limits won't ever go away. We need to understand them.

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

A final note before we start: discussions about energy policy involve two sorts of claims: *factual* assertions, and *ethical* assertions.

Examples of factual assertions are "global fossil-fuel burning emits 7 billion tons of carbon 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"; and "the melting of the Greenland ice cap would eventually cause a 7 m sea level rise."

A factual assertion is either true or false; figuring out *which* may be difficult; it is a scientific question. The difficulty of deciding factual assertions leads to debates in the scientific community. But given sufficient scientific experiment and discussion, the truth or falsity of 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.

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

Figure 7. Lowe cartoon from Private Eye.

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

Notes

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

1 *"...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. *Michael Meacher* was UK environment minister from 1997 till 2003. *Sir Bernard Ingham* was an aide to Margaret Thatcher when she was prime minister. [`ydoobr`]

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

2 *"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.

2 *Lovelock.* `http://www.ecolo.org/lovelock/`

2 *Los Angeles residents drive ... from Earth to Mars* – [The Earthworks Group, 1989, page 34].

3 *`targetneutral.com`* charge just £4 per ton of CO_2 for their 'neutralization'. (A significantly lower price than any other 'offsetting' company I have come across.) So, if this were not a scam, a typical Brit could have his ten tons per year 'neutralized' for £40 per year. Further evidence that BP's 'neutralization' schemes are a scam comes from the fact that its projects have not achieved the Gold Standard `http://www.cdmgoldstandard.org/` (Michael Schlup, personal communication). Many 'carbon offset' projects have been exposed as worthless by award-winning journalist Fiona Harvey [`2jhve6`].

3 *"water-powered car" New Scientist*, 29th July 2006, p. 35. This awful 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."
Fox News pedalled an even more absurd story [`2fztd3`].

3 *Arnold Schwarzenegger ... filling up a hydrogen-powered Hummer. Nature* **438**, 24 November 2005. Nature's article in praise of California uncritically reported that Arnold's vision is to see hydrogen-powered cars "replace the polluting models on the road", and quoted a commentator saying that "the governor is a real-life climate action hero today." The critical question that needs to be asked when such hydrogen heroism is on display is "where is the *energy* to come from to make the hydrogen?"

4 *Climate change is a far greater threat to the world than international terrorism.* Sir David King, Chief Scientific Advisor to the UK government, Friday 9th January, 2004. [`26e8z`]

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

6 *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); and 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' – that's a graph of global temperatures, which doesn't have such a clear upward kink (yet).
Coal production figures 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. He

estimated Britain's easily-accessible coal reserves, looked at the history of exponential growth in consumption, and predicted, in 1865, 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.

9 *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).

12 *Figure 5.* 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 GtC; CO_2 concentrations reach a peak of 410 ppm, $CO_2^{(e)}$ 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 GtC; CO_2 concentrations reach a peak of 425 ppm, $CO_2^{(e)}$ concentrations peak at 435 ppm, and in 2100 CO_2 concentrations fall back to 380 ppm.

12 *there are many more 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 `www.dti.gov.uk/publications/`.

14 *factual assertions and ethical assertions . . .* Ethical assertions are also known as 'normative claims', and factual assertions are known as 'positive claims'. Notice that the ethical assertions usually contain verbs like 'should' and 'must', or adjectives like 'fair', 'right', and 'wrong'. For helpful reading in this area see Dessler and Parson [2006].

14 *Gordon Brown.* On Saturday 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' (April 22 2006). [y98ys5]

5 *Dominic Lawson, a columnist from the* Independent. My quote is adapted from Dominic Lawson's column in the *Independent*, Friday 8 June 2007. It is not a verbatim quote: I edited his words to make them briefer but I took care not to correct any of his pungent errors.

Part I

Numbers, not adjectives

1

The balance sheet

Nature cannot be fooled.

Richard Feynman

The first part of this book is about energy consumption and energy production.

We're going to make a table with two columns. In the left-hand column we will add up our energy consumption, and in the right-hand column, we'll add up sustainable 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.

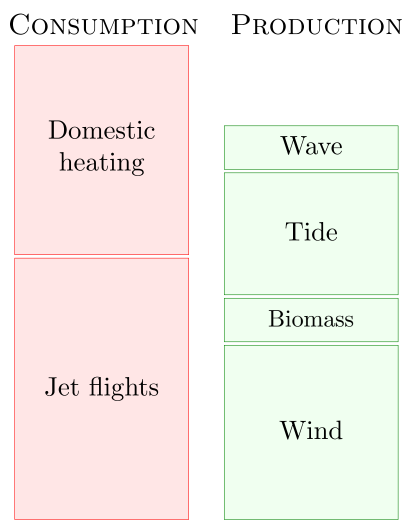


Figure 1.1. Our balance sheet. This picture shows what it might look like after we've added two forms of consumption and four forms of sustainable production.

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 column.

In the left-hand column, 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 column too. Later on we'll also find out the current average energy consumption of Europeans and Americans.

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 column of our balance sheet, but also to understand what each number depends on, and how susceptible to modification it is.

In the right-hand column, 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 column are *economically* feasible is an important question, but let's leave that question to one side, and just add up the two columns 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?"

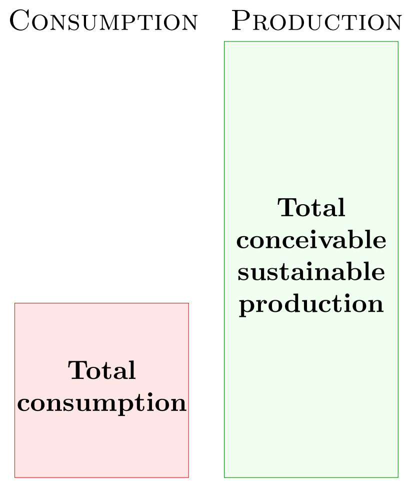
Some key forms of consumption for the left-hand column will be:

- Transport
  - cars, planes, freight
- Heating and cooling
- Lighting
- Information systems and other gadgets
- Food
- Manufacturing

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

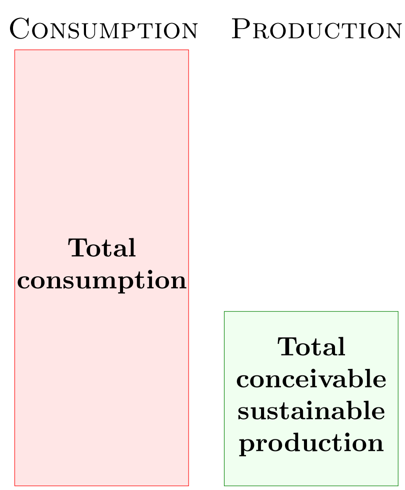
- Wind
- Solar
  - photovoltaics, thermal, biomass
- Hydroelectric
- Wave
- Tide
- Geothermal
- Nuclear? (with a question-mark, because it's not clear whether nuclear power counts as 'sustainable')

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."

Most discussions of energy consumption and production are confusing because of the proliferation of **units** in which energy and power are measured, from 'tonnes of oil equivalent' to 'terawatthours' (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 get everything into a single set of personal units that everyone can relate to.

The unit of **energy** I have chosen is the kilowatt-hour (kWh). This quantity, coincidentally, is called 'one unit' on electricity bills, and it costs a domestic user about 10p in the UK in 2007. As we'll see, 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 of power 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 that comes out to 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.

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.

Energy and power

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 a rate at which you use energy.*

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, say (if you're thirsty). When you turn on a tap, you create a *flow* of water – one litre per minute, perhaps, if the tap yields only a trickle; or ten 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 can 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. Water *volume* is like *energy*: water *flow* is like *power*.

If someone throws a jug of water into the garden, we say "they threw away a *volume* of water (perhaps a litre)." Similarly if someone sets fire to a can of petrol, we could say "they wasted a lot of *energy* there! (perhaps 40 kWh of energy)."

If someone leaves a tap trickling, we might say "that *flow* is wasting one litre per minute!" Similarly if someone leaves a lightbulb switched on, we might say "the *power* wasted by that bulb is about one kilowatt-hour per day".

When a tap is set trickling, a *flow* is created. A trickling flow might deliver one litre per minute; or, to put it another way, it delivers sixty litres per hour. Similarly, 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) per hour; it also consumes twenty-four kilowatt-hours per day.

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).

Figure 1.4. 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).

Powers are so useful and important, they have something that 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*. One thousand 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." 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.

Other examples of units that, like the watt, already have a "per" 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 bigger 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). Similarly we say "a nuclear power station generates one gigawatt." One gigawatt, by the way, is one million kilowatts, or a thousand 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'.

Here's one last example: 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 was used *in one hour*. You could indeed use a gigawatt-hour of energy by switching on one million toasters for one hour; but you could also use a gigawatt-hour by switching on one thousand toasters for one thousand hours.

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 cold 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 energy.

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 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. Most fossil-fuel power stations guzzle chemical energy and produce electricity (with an efficiency of 40% or so). Many aluminium plants guzzle electrical energy to create a product with high chemical energy – pure aluminium.

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 fundamentally equivalent to 1 kWh of electricity; that just happens to be the perceived exchange rate from the point of view of one present-day technology. In an alternative world with plentiful electricity and very little oil, we would surely not use the same exchange rate. I think the timeless and scientific way to summarise 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. 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 one hundred times less energy'. Is this assertion true? To explain the answer, I like to use equations like

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

However, I recognise that to many readers, such formulae are a foreign language. So, here's my promise: *I'll keep all the foreign-language stuff in technical chapters at the end of the book.* Any reader with a high-school qualification in maths, physics, or chemistry should enjoy the technical chapters. The main thread of the book 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 and the Lords.

One last point, before we get rolling: I'm not an expert in any of the topics in this book. I don't have all the answers, and the numbers I offer are open to revision and correction. (Indeed I expect corrections and plan to 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

22 *Please, never, ever say "one kilowatt per second."* There are exceptions to this rule. If you run a solar-power factory that manufactures solar power stations then it would be natural to describe your factory's output by saying 'we produce one gigawatt per year'. Similarly, if talking about a growth in demand for power, we might say 'British demand is growing at one gigawatt per year'. In chapter 25 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 terrible confusion: for example, your electricity meter's reading is in kilowatt-hours (kWh), *not* 'kilowatts-per-hour'.

I've provided a chart on p.386 to help you translate between kWh per day per person and the other major units in which powers are discussed.

The most commonly used units in public documents discussing power options are:

terawatt-hours per year (TWh/y). 1000 TWh/y per United Kingdom is roughly equal to 45 kWh/d per person.

gigawatts (GW). 2.5 GW per UK is precisely 1 kWh/d per person.

million tonnes of oil equivalent per year (Mtoe/y). 2 Mtoe/y per UK is roughly 1 kWh/d per person.

1 Mtoe/y per UK is roughly 0.53 kWh/d per person.

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 discusing waste incineration and we learn, in the standard units, that UK waste incineration delivers a power of 7 TWh/y and that Denmark's waste incineration delivers 10 TWh/y.

Does this help us say whether Denmark does "more" waste incineration than the UK? While the total amount of energy produced from waste in each country may be interesting, and indeed Denmark's total is a little bigger, I think that what we usually want to know is the amount of waste incineration *per person.* (For the record, that's Denmark: 5 kWh/d per person; UK: 0.3 kWh/d per person.) 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.

2

Cars

Figure 2.1. Cars. A red BMW dwarfed by a spaceship from the planet Dorkon.

For our first chapter on consumption, let's study that icon of modern civilization: the car.

How much power does a daily 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).

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

Figure 2.2. 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.

We can estimate the **energy per unit of fuel** (also called the **calorific value** or **energy density**) 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: 30 000 kJ per kg. 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 '30 000 kJ per kg' (an energy per unit *mass*) into an energy per unit volume, we need to know the density of our 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 and assume butter and diesel are the same, we obtain a calorific value of

$$30\,000\,\text{kJ per kg} \times 0.8\,\text{kg per litre} = 24\,000\,\text{kJ per litre}.$$

Putting this into our preferred energy unit, the kilowatt-hour (1 kWh = 3600 kJ), the calorific value of fuel is estimated to be about 7 kWh per litre. Rather than wilfully perpetuate an inaccurate estimate, let's switch to the official value of 10 kWh per litre.

calorific values

petrol	10 kWh per litre
diesel	11 kWh per litre

Table 2.3. Facts worth remembering: passenger transport efficiencies.

Energy per distance car doing 33 mpg (12 km per litre)	
Occupants	
1	80 kWh per 100 person-km
4	20 kWh per 100 person-km

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

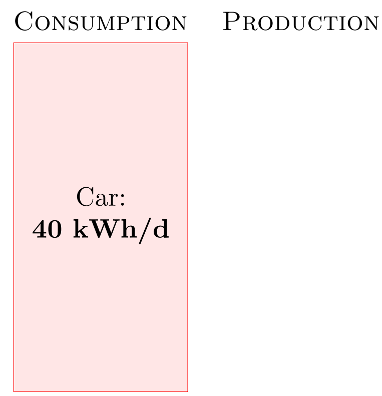


Figure 2.4. Chapter 2's conclusion: a typical car-driver uses about 40 kWh per day. Now we need to find out about sustainable production.

Congratulations! We've made our first estimate of consumption.

Why does the car deliver 33 miles per gallon? Where's that energy going? Could we make 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 (p. 244), 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.

Notes

26 *For the distance travelled per day, let's use 50 km.* This corresponds to 18 000 km per year or 11 000 miles per year. Roughly half of the British population drive to work. The total amount of car travel of the UK is 686 billion passenger km, which corresponds to an 'average distance travelled by car per British person', of 30 km per day. Source: Department for Transport – `http://www.dft.gov.uk/pgr/statistics/datatablespublications/tsgb/`. As I said on page 18, 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. I want to estimate the energy consumed by someone who chooses to drive, rather than depersonalise 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."

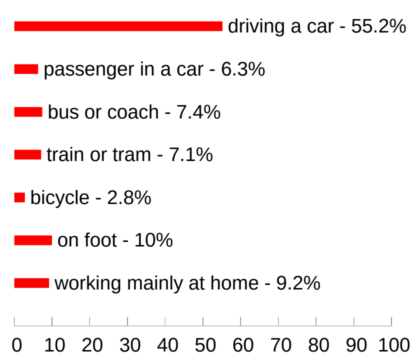


Figure 2.5. How British people travel to work, according to the 2001 census.

26 *let's use 33 miles per UK gallon (I got this number from an advertisement for a family car).* 33 miles per gallon was the average for UK cars in 2005. [`27jdc5`] For comparison, the website of 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`]

26 *Let's guess a density of 0.8 kg per litre.* Gasoline's density is 0.737. Diesel's is 0.820–0.950 [`nmn41`].

26 *the official 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. These differ by only 6% for motor fuels, so it's not important to distinguish them, but let me explain anyway. The gross calorific value is the actual 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 wasted energy is discarded.

When we ask 'how much energy does my lifestyle consume?' I think 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 new power station.

A final note for 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. The proof of the pudding is, this approximation got us within 30% of the correct answer.

3

Wind

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 (p.252) explains how to estimate the power per unit area of a windfarm 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 windfarm is about $2\,\text{W/m}^2$. This figure of 6 m/s is probably an over-estimate for many locations in Britain. For example, figure 3.2 shows daily average windspeeds at Cambridge during 2006. The daily average speed reached 6 m/s on only about 30 days of the year. But some spots do have windspeeds above 6 m/s – for example, the summit of Cairngorm in Scotland (figure 3.3).

Power per unit area	
Windfarm (speed 6 m/s)	$2\,\text{W/m}^2$

Table 3.1. Facts worth remembering: windfarms.

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

$$2\,\text{W/m}^2 \times 4000\,\text{m}^2/\text{person} \;=\; 8\,\text{kW per person},$$

if wind turbines were packed at the maximum possible density across the *whole* country. Converting to our favourite power units, that's

$$\text{maximum conceivable wind power} \;\simeq\; 200\,\text{kWh/d per person}.$$

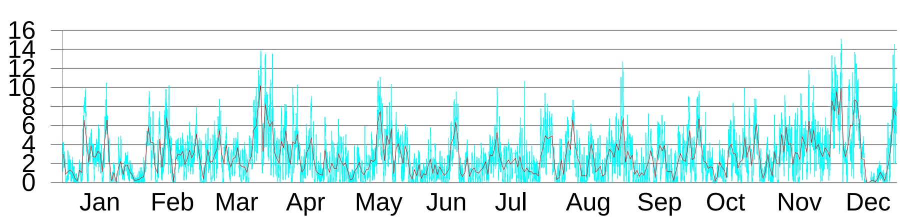


Figure 3.2. Cambridge mean wind speed in metres per second, daily (heavy line), and half-hourly (light line) during 2006.

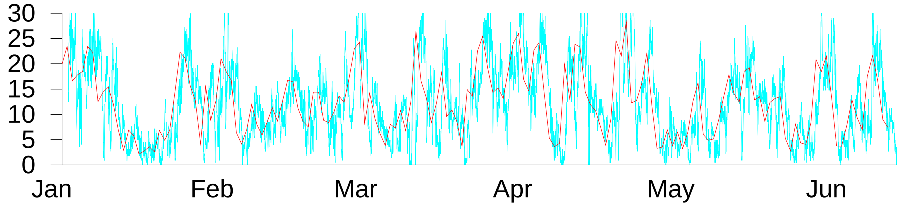


Figure 3.3. Cairngorm mean wind speed in metres per second, daily (heavy line), and half-hourly (light line), during six months of 2006.

Let's be realistic. What fraction of the country can we really imagine covering with windmills? Maybe 10%? Taking 10% of the maximum conceivable wind power, we obtain

$$\text{maximum conceivable wind power (assuming 6 m/s and 10\% filling)} \\ = 20\,\text{kWh/d per person.}$$

Our conclusion: if we covered the windiest 10% of the country with windmills, we might be able to generate ***half*** of the energy used by driving a car 50 km per day each.

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

I should emphasize how audacious an assumption I'm making. Let's compare this estimate of British wind potential with current installed wind power worldwide. The windmills required to provide the UK with 20 kWh/d per person are fifty times the entire wind hardware of Denmark; seven times all the windfarms of Germany; and double the entire fleet of all wind turbines in the world.

This conclusion – that the greatest that onshore wind could add up to, albeit 'huge', is much less than our consumption – is important, so let's check the key figure, the assumed power per unit area of windfarm (2 W/m^2), against a real UK windfarm.

The standard windmill of today is typically a machine with a rotor diameter of around 54 metres centred at a height of 80 metres; such a machine has a 'capacity' of 1 MW. The 'capacity' or 'peak capacity' is the *maximum* power the windmill can generate in optimal conditions. Usually, wind turbines are designed to start running at wind speeds around 3 to 5 m/s and to stop if the wind speed reaches gale speeds of 25 m/s. The actual average power delivered differs from the capacity by a factor that describes the fraction of the time that wind conditions are near optimal. This factor, sometimes called the 'load factor' or 'capacity factor', 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%.

The Whitelee windfarm being built near Glasgow in Scotland has 140 turbines with a combined peak capacity of 322 MW in an area of 55 km^2. That's 6 W/m^2, *peak*. If we assume a capacity factor of 33% then the average power production per unit land area is 2 W/m^2. This is just the same as the power density we assumed earlier.

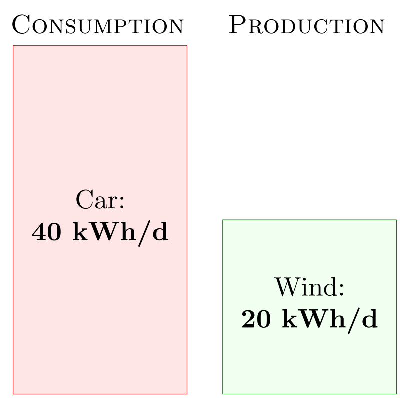


Figure 3.4. Chapter 3's conclusion: the maximum plausible production from on-shore windmills in the United Kingdom is 20 kWh per day per person.

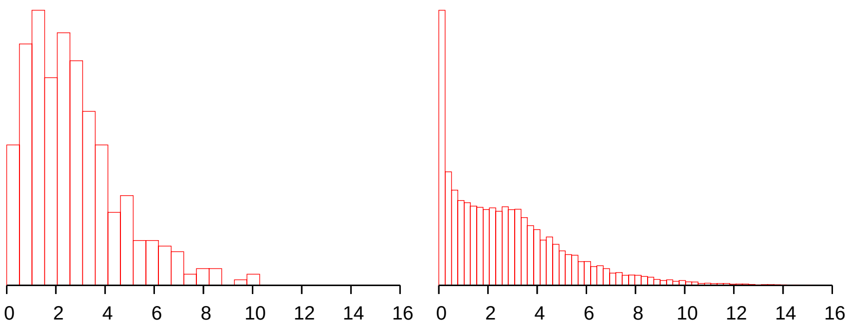


Figure 3.5. Histogram of Cambridge average wind speed in metres per second: daily averages (left), and half-hourly averages (right).

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 economies of scale – a good idea, financially – but they don't much increase the total power per unit 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?

May be. We'll come back to this issue in chapter 25, where we'll look at wind's intermittency and discuss two possible solutions to this problem: energy storage, and demand management.

Population density of Britain
250 per km^2 $\leftrightarrow$ 4000 m^2/person

Table 3.6. Facts worth remembering: population density

Notes

Population densities

Region	Population	Area (km^2)	Density (persons per km^2)	Area each (m^2)
World	6 440 000 000	148 000 000	43	23 100
Scotland	5 050 000	78 700	64	15 500
European Union	496 000 000	4 330 000	115	8 720
Wales	2 910 000	20 700	140	7 110
United Kingdom	59 500 000	244 000	243	4 110
England	49 600 000	130 000	380	2 630

Table 3.7. Some regions, ordered by their population density. See pages 174 and 326 for more population densities.

29 Cambridge wind data (figure 3.2 and figure 3.5) 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 3.3) are from Heriot–Watt University Physics Department [tdvml].

30 *Usually, wind turbines are designed to start running at wind speeds around 3 to 5 m/s.* [ymfbsn].

30 *The windmills required to provide the UK with 20 kWh/d per person are fifty 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 they delivered was 3 kWh/d per person.

30 *a typical load factor for a* good *site is 30%.* In 2005, the average load factor of all major UK windfarms was 28.4% [`ypvbvd`]. The load factor varied during the year, with a low of 17% in June and July. The load factor for the best region in the country – Caithness, Orkney and the Shetlands – was 33%. The load factors of the two offshore windfarms operating in 2005 were 36% for North Hoyle (off North Wales) and 29% for Scroby Sands (off Great Yarmouth). Average load factors in 2006 for ten regions were: Cornwall 25%; Mid-Wales 27%; Cambridgeshire and Norfolk 25%; Cumbria 25%; Durham 16%; Southern Scotland 28%; Orkney and Shetlands 35%; Northeast Scotland 26%; Northern Ireland 31%; Offshore 29%. Average of all: 27% [`wbd8o`].

4

Planes

Figure 4.1. A Boeing 747, yesterday.

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 2.) 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

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

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 being 80% full, we arrive at 29 kWh per day. For ease of memorization, I'll round this up to **30 kWh per day**.

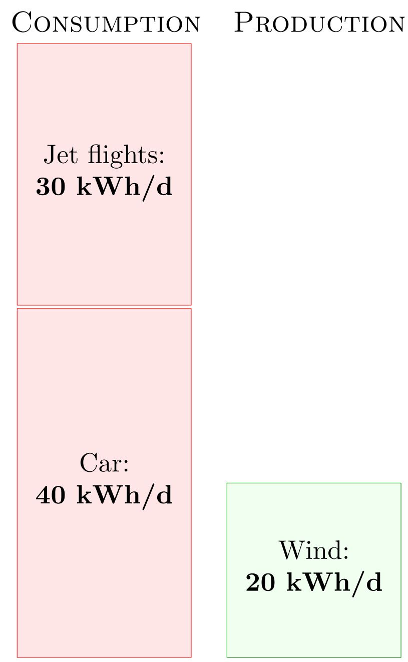


Figure 4.2. Chapter 4's conclusion: taking one intercontinental trip per year uses about 30 kWh per day.

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 2, 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 (p. 260), discusses where the energy goes in planes. This discussion allows us to answer questions such as 'would air travel consume much less energy if we travelled in slower propellor-driven planes?' [The answer is **no**: planes are already almost as 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.]

What about short-haul flights?

In 2007, Ryanair, 'Europe's greenest airline', delivered transportation at a cost of 3.5 litres per 100 passenger-km (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 7 litres per 100 passenger-km (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.

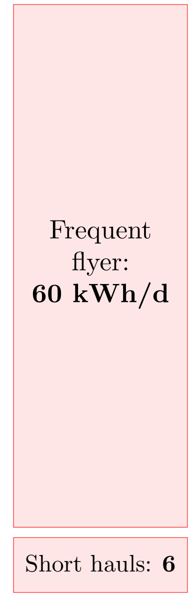


Figure 4.3. Two short-haul trips on the greenest short-haul airline: 6.3 kWh/d. Flying enough to qualify for silver frequent flyer status: 60 kWh/d.

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.

Figure 4.4. Ryanair Boeing 737-800. Photograph by Adrian Pingstone.

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

Yes, that's the experts' view. Flying creates other greenhouse gases too. If you want to estimate your carbon footprint in tonnes of CO_2-equivalent, then you should take the actual CO_2 emissions of your flights and bump them up by a factor of two or three. The precise factor depends on whether the flight is daytime or nighttime. This book's diagrams don't include that factor because here we are focussing on our energy balance sheet.

Notes

33 *Boeing 747-400* facts are from [9ehws]. Incidentally, using these figures we can obtain the fuel efficiency of the completely-full 747. It works out to 42 kWh per 100 passenger-km – twice as fuel-efficient as a single-occupancy car.
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. Some additional figures from the IPCC [yrnmum]: A full 747-400 travelling 10 000 km with low-density seating (262 seats) has an

energy per distance in kWh per 100 p-km	
Car (4 occupants)	20
Ryanair, 2007	37
747, full	42
747, 80% full	53
Ryanair, 2000	73
Car (1 occupant)	80

Table 4.5. Passenger transport efficiencies, expressed as energy required per unit of transport.

energy consumption of 50 kWh per 100 p-km. In a high-density seating configuration (568 seats) and travelling 4000 km, the 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.

34 *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 are half way to this engine target [36w5gz].
Dennis Bushnell, chief scientist at NASA's Langley Research Centre, 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' SAX-40, if it were built, is predicted to be 16% more efficient than a conventional-shaped plane Nickol [2008] http://silentaircraft.org/sax40/.

5

Solar

Figure 5.1. A solar water heater providing hot water for a family in Michigan. The system's pump is powered by the small photovoltaic panel on the left.

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

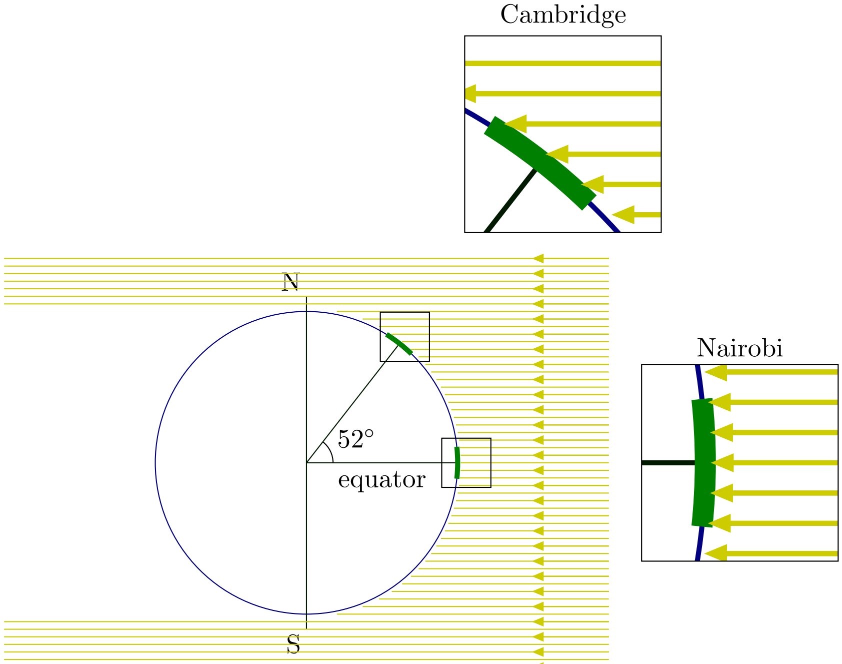


Figure 5.2. Sunlight hitting the earth at midday on a spring or autumn day. The density of sunlight per unit land area in Cambridge (latitude 52°) is about 60% of that at the equator.

The 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 by multiplying by a factor of 0.6. I'll call this the latitude factor. We also lose out because it is not midday all the time. It's a fair approximation to say that it's midday about 1/4 of the time, and dark the other 3/4. So we have a daylight factor of 1/4. Finally, we lose power because of cloud cover. In a typical

UK location we should include a sunniness factor of 1/3.

To estimate the average raw power of sunshine per square metre of south-facing roof, we multiply by the daylight factor and the sunniness factor (but not the latitude factor – we'll assume that the roof is tilted at roughly 52°):

$$\begin{array}{rccccc} & \text{power of midday sunshine} & \times & \text{daylight factor} & \times & \text{sunniness} \\ = & 1000\,\text{W/m}^2 & \times & \frac{1}{4} & \times & \frac{1}{3} \\ \simeq & & 80\,\text{W/m}^2. & & & \end{array}$$

The average raw power of sunshine per square metre of flat ground is

$$\begin{array}{rcccc} & 80\,\text{W/m}^2 \times \text{latitude factor} & & & \\ = & 80\,\text{W/m}^2 \times & 0.6 & \simeq & 50\,\text{W/m}^2. \end{array}$$

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 energy fuels 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 each of these routes could deliver. We'll neglect their economic costs, and the energy costs of manufacturing and maintaining the power facilities.

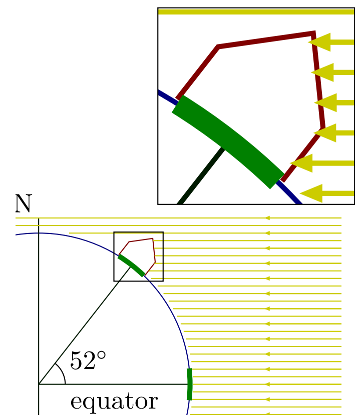


Figure 5.3. If you have a South-facing sloping roof, the density of sunlight per unit roof-area is about $1000\,\text{W/m}^2$ at midday on a spring or autumn day – the same as the density at the equator.

Solar thermal

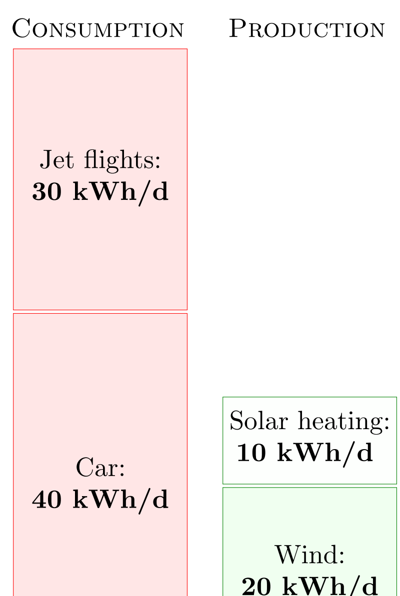
Let's imagine we cover *all* south-facing roofs with solar thermal panels – that would be about $10\,\text{m}^2$ of panels per person – and let's assume these are 50% efficient at turning the sunlight's $80\,\text{W/m}^2$ into hot water. Multiplying

$$50\% \times 10\,\text{m}^2 \times 80\,\text{W/m}^2$$

we find solar heating could deliver

$$10\,\text{kWh per day per person.}$$

I colour this production box white 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, 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.



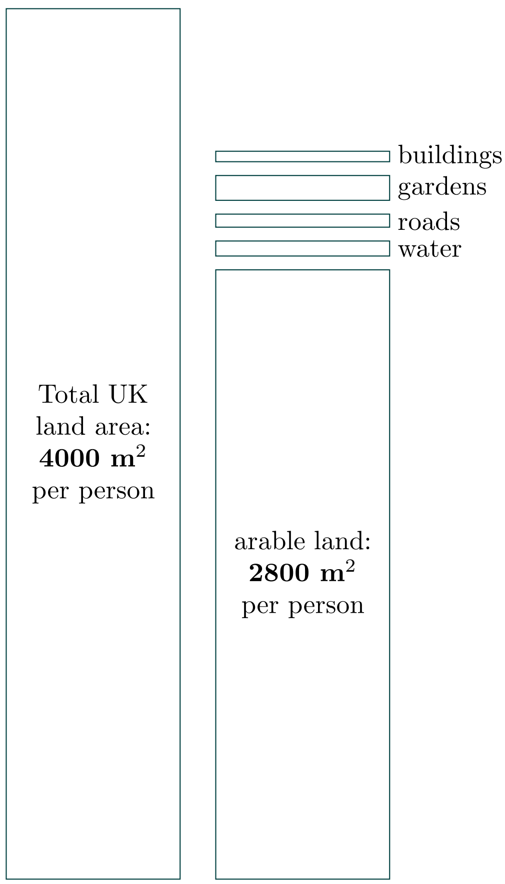


Figure 5.4. Land areas in Britain.

	area per person (m^2)
domestic buildings	30
other buildings	18
domestic gardens	114
roads	60
rail	4
path	3

Solar photovoltaic

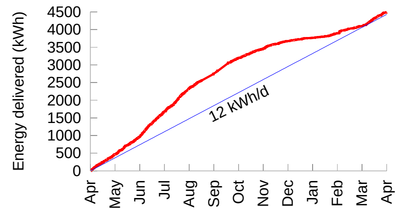


Figure 5.6. Solar photovoltaic: data from a 25-m^2 array in Cambridgeshire in 2006. The peak power delivered by this array is about 4 kW. The average, year-round, is 12 kWh per day. That's 20 W per square metre of panel.

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'.)

Let's give everyone 10 m^2 of expensive (20%-efficient) solar panels and put them on a south-facing roof. These will deliver

$$4\,\text{kWh per day per person.}$$

Since the area of all south-facing roofs is 10 m^2 per person, there's certainly not 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 – or, best of all, buy integrated photovoltaic/hot-water panels. 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 electricity and hot water.

Fantasy time: solar farming

Figure 5.7. Solar photovoltaic farms: The 6.3 MW (peak) Solarpark in Mühlhausen, Bavaria. On average this 25-hectare farm is expected to deliver 0.7 MW (17 000 kWh per day). Its average power per unit land area is about 5 W/m^2.

If a miracle 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 10% of the UK with 10%-efficient panels, we'd have

$$\begin{aligned} & 10\% \times 50\,\text{W/m}^2 \times 400\,\text{m}^2 \text{ per person} \\ \simeq\ & 50\,\text{kWh/day/person.} \end{aligned}$$

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 of such a solar farm, incidentally, is

$$10\% \times 50\,\text{W/m}^2 = 5\,\text{W/m}^2.$$

This number is confirmed by the specifications of the Bavarian Solarpark figure 5.7. Could these solar panels co-exist with the army of windmills we imagined in chapter 3? Yes, no problem: windmills cast little shadow, and ground-level solar panels have negligible effect on the wind. How audacious is this plan? Well, the solar power capacity required to deliver this 50 kWh/d per person in the UK is more than one hundred 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 over this. At the start of the 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 make helpful comments for today's society, to help people figure out what we should be doing *now*. And today, electricity from solar farms would be four times as expensive the market rate. So it feels a bit irresponsible to include this estimate in our total conceivable sustainable production – paving 10% of this country with solar panels seems beyond the bounds of plausibility in so many ways. If we seriously contemplated doing such a thing, it would quite likely be better to put the panels in a three-times sunnier country and send home some of the energy by power lines. We'll return to this idea in chapter 24.

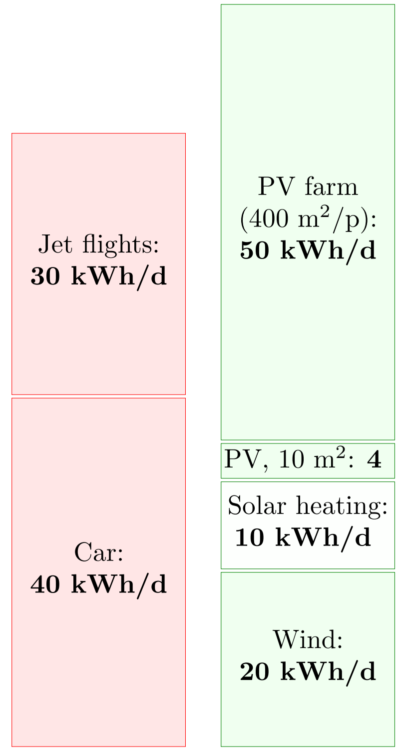


Figure 5.8. Solar photovoltaic: a $10\,\mathrm{m}^2$ array of building-mounted south-facing panels with 20% efficiency can deliver about 4 kWh per day of electrical energy. If 10% of the country were coated with 10%-efficient solar panels ($400\,\mathrm{m}^2$ of panels per person) they would deliver 50 kWh/day/person.

Mythconceptions

"The energy required to make a solar panel is much bigger than the energy it'll 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 was A Good Thing, energy-wise.]

Wind turbines with a lifetime of 20 years have an energy yield ratio of 80.

Figure 5.9. Two trees, yesterday.

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*

There are four main ways to get energy from solar-powered biological systems:

1. We can grow specially-chosen plants and burn them in a power station which 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 not using specially-chosen 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 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, I'm told.) 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.

Figure 5.11. Some *Miscanthus* grass enjoying the company of Dr. Emily Heaton, who is 5'4" tall (163 cm). 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. Photo provided by the University of Illinois.

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 is passing through that first staging post. All the subsequent steps involving tractors, animals, chemical plants, landfill sites, and 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.

In this chapter, 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.

All available biomass solutions involve first growing green stuff, and then doing something with the green stuff. We skip over the details of that second step and work out what the energy collected by the green stuff could possibly be. We worked out that the average harvestable power of sunlight in Britain is 50 W/m^2. The most efficient plants are about 1% efficient at turning solar energy into carbohydrates, so they deliver an average power of 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 currently devoted to agriculture. So the maximum energy available, ignoring all the additional costs of growing, harvesting, and processing the greenery, is

$$\begin{aligned} & 0.5\,\mathrm{W/m^2} \times 3000\,\mathrm{m^2} \text{ per person} \\ = & \;1500\,\mathrm{W} \text{ per person} \\ = & \;36\,\mathrm{kWh/d} \text{ per person.} \end{aligned}$$

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 sparkplug 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.

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. Chapter D looks in a little more detail at specific bio-solar solutions.

(To back up these estimates, refer to Royal Commission wood estimates.)

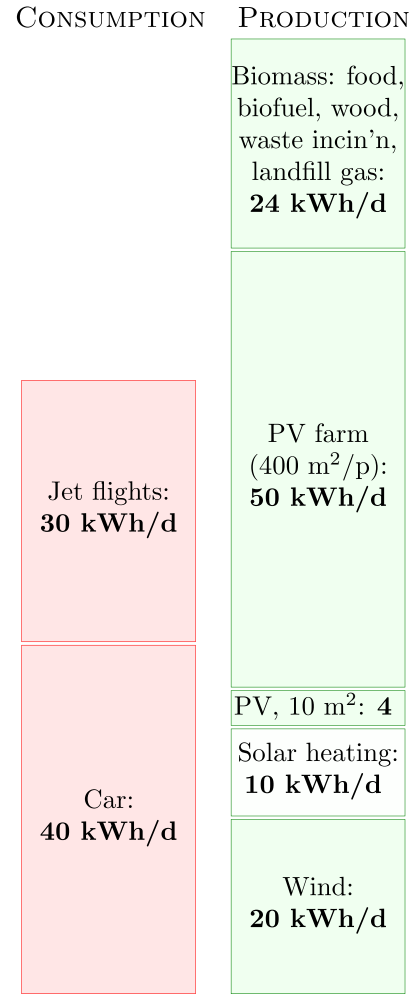


Figure 5.12. Solar biomass, including all forms of biofuel, waste incineration, and food: 24 kWh/d per person.

Bio-powered Europe

Turning the clock back more than four hundred 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 8 kWh per day. The wood used per person was 4 kg per day, which required 1 hectare (10 000 $\mathrm{m^2}$) of forest per person. Today the area of Britain per person is just 4000 $\mathrm{m^2}$, so even if we reverted to the lifestyle of the Middle Ages, we could no longer live sustainably here. Our population density is far too high.

Statistics for agricultural productivity

In the UK, wheat yield is 8000 kg per ha per year. Barley: 5800 kg per ha per year. Livestock per 1000 ha of utilized agricultural land: 668 cows, 1695 sheep, and 365 pigs.

Criticisms of biofuel farms

"Biofuel farms make CO_2 emissions worse."

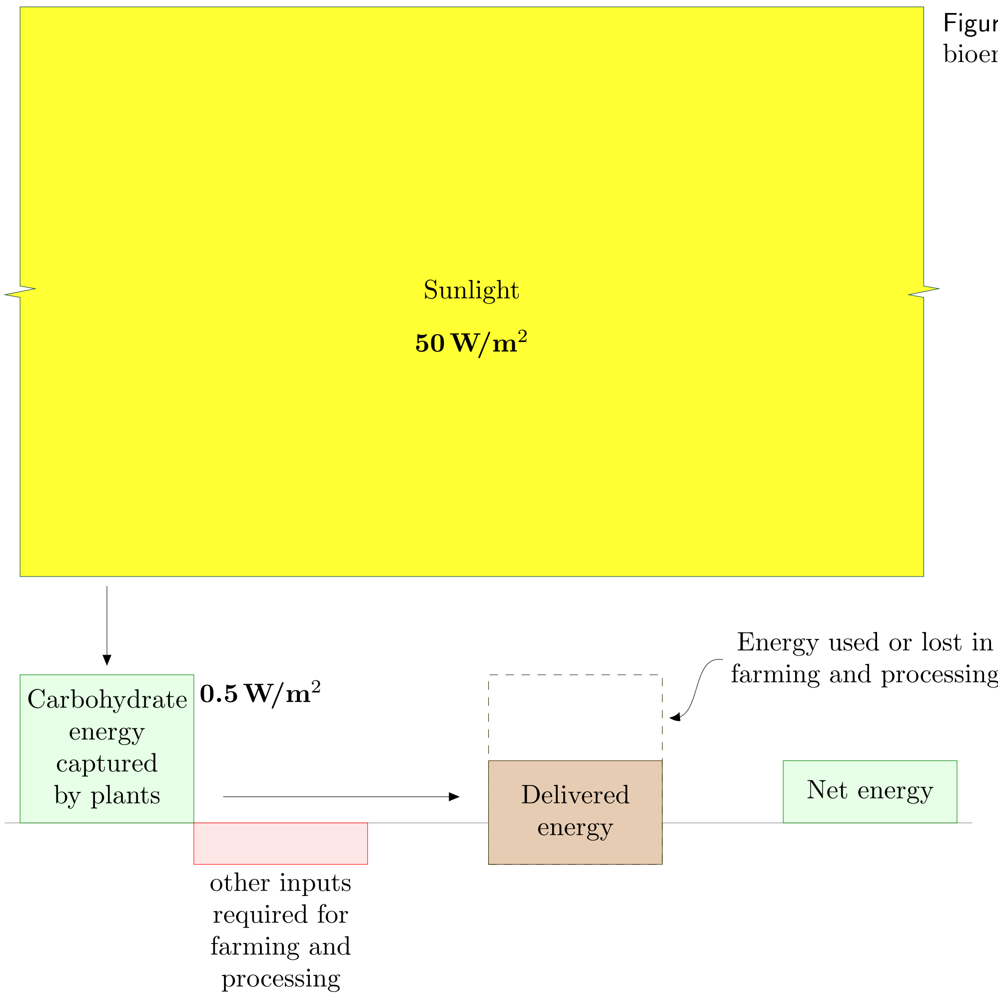


Figure 5.13. From solar energy to bioenergy.

New biofuel diagrams

Example facility in Scotland. Steven's Croft, 44 MW(e), is the largest wood-fired power station in the UK. Uses 480 000 tonnes of fuel per year: 60% sawmill co-products and small round wood; 20% short rotation coppice (willow); 20% recycled fibre (from wood product manufacture).

The company has already set itself a target for 2009 of generating 10% of its electricity by burning biomass fuels. Drax says that if it were to use one and a half million tonnes of biomass a year that would require 20 lorries an hour at peak times.

Notes

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

37 *In a typical* UK *location we should include a sunniness factor of* 1/3. 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 parts of the UK): 1700 h per year – 39%. [2rqloc]
Cambridge data from [2szckw]. See also table 5.15.
When using these sunniness figures to work out solar power, I've assumed that when it's 'sunny', solar collectors work at their peak efficiency, and when it's 'not sunny', they deliver nothing. Both these assumptions are inaccurate, but I expect that they roughly cancel each other out. 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. The power delivered by photovoltaic panels is almost exactly proportional to the intensity of the sunlight (source: Sanyo 210 datasheet).

37 *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), multiplying by 1/4 to get the south-facing fraction, and bumping the answer 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.

37 *assume solar thermal panels are 50% efficient. . .* Source: Salter, Scottish Executive document quoted 40%. The solar panels release a load of the heat they absorb into the air.

39 *solar farming* – Numbers from a Serpa Solar Power Plant, Portugal (PV): 'The world's most powerful solar power plant'. [39z5m5] [2uk8q8] Its sun-tracking panels occupy 60 hectares, i.e. 600 000 m² or 0.6 km², and are expected to generate 20 GWh per year, *i.e.*, 2.3 MW

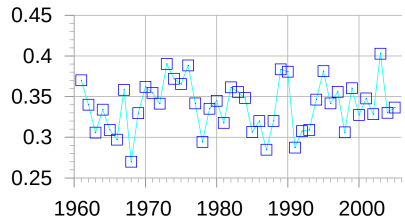


Figure 5.14. Sunniness of Cambridge: the number of hours of sunshine per year, expressed as a fraction of the total number of daylight hours.

	sunniness
Sheffield	28%
Edinburgh	30%
Manchester	31%
Cork	32%
London	34%
Cologne	35%
Copenhagen	38%
Munich	38%
Paris	39%
Berlin	42%
Wellington, NZ	43%
Seattle	46%
Toronto	46%
Detroit, MI	54%
Winnipeg	55%
Beijing	55%
Sydney	56%
Pula, Croatia	57%
Nice, France	58%
Boston, MA	58%
Bangkok, Thailand	60%
Chicago	60%
New York	61%
Lisbon, Portugal	61%
Kingston, Jamaica	62%
San Antonio	62%
Seville, Spain	66%
Nairobi, Kenya	68%
Johannesburg, SA	71%
Tel Aviv	74%
Los Angeles	77%

Land use	area per person (m^2)	percentage
– domestic buildings	30	1.1
– domestic gardens	114	4.3
– non-domestic buildings	18	0.66
– road	60	2.2
– rail	3.6	0.13
– path	2.9	0.11
– greenspace	2335	87.5
– water	69	2.6
– other land uses	37	1.4
Total	2670	100

Table 5.16. Land areas, in England, devoted to different uses. Source: Generalised Land Use Database Statistics for England 2005. [3b7zdf]

on average. That's a power density of 3.8 W/m^2. Cost $75 million. ($33 000 per kW.)

39 *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 concentrators (mirrors or lenses). The theoretical limit for a standard single-material solar panel without concentrators, the Shockley–Queisser limit, says that at most 31% of the energy in sunlight can be converted to electricity. (The reason for this limit is that a standard solar material has a property called its band-gap, which defines a particular energy of photon for which that material is most efficient. 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 can both reduce the cost (per watt) of photovoltaic systems, and increase their efficiency. Recently multi-junction photovoltaics with optical concentrators have been reported to be about 40% efficient. [2tl7t6] `http://www.spectrolab.com/` The University of Delaware reports 42% efficiency with 20-times concentration. `http://www.azonano.com/news.asp?newsID=4546`

39 *Solar PV data* Figure 5.6: Data and photograph kindly provided by Jonathan Kimmitt.

Further data on a family's solar panels in California are available from `http://www.solarwarrior.com/`. Their 268 m^2 South-facing solar panels located at latitude 37° have a peak production of 27 kW, and an average production of 110 kWh/d, which corresponds to 17 W/m^2.

39 *Heliodynamics* – `http://www.hdsolar.com/`

40 *paving 10% 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's a few figures. Going by the price-tag of the Bavarian solar

Figure 5.17. 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.

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, The sales price of solar PV panels is about $3/W(peak) at the moment (2007). Nanosolar `http://www.nanosolar.com/` announced in December 2007 that their systems cost $2/W(peak). `http://www.enews20.com/news_Nanosolar_Starts_Shipping_Revolutionary_Solar_Panels_04604.html` If current trends continue, the price is expected to be about $1/W(peak) by 2027. A 400 m^2 array, at 120 W(peak)/m^2, would cost $48 000. [If we ask it to pay for itself in 10 years, the value of the electricity delivered would have to be about 25¢ per kWh.] Reckless extrapolation suggests the price of the array in 2050 could be five times smaller ($10 000). So maybe by 2050, solar PV will be cost-effective. But the area of the UK will still be just the same. Source: David Carlson, BP solar [2ahecp].

41 Figure 5.11. *Miscanthus* data are from Heaton, Voigt & Long (2004) Biomass and Bioenergy, 27:21-30 2004 and `http://www.defra.gov.uk/erdp/pdfs/ecs/miscanthus-guide.pdf`. The estimated yield is obtained only after three years of undisturbed growing.

41 *Let's cover 75% of the country with quality green stuff.* We currently devote 75% of our verdant country to food production or other forms of agriculture (185 000 km^2 out of a total area of 244 000 km^2).

41 *The most efficient plants are about 1% efficient*, and the delivered power per unit area is about 0.5 W/m^2. Here are a few sources to back up this power estimate for the UK. First, 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]. Second, in the table on page 43 of the Royal Society's biofuels document, Miscanthus tops the list, delivering about 0.8 W/m^2 of chemical energy. My figure of 0.5 W/m^2 is the average of these two.
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 [2004] 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 concentrated in the tropics and thrive in high temperatures. Some examples of C4 plants are sugarcane, maize, sorghum, finger millet, and switchgrass.

42 *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]

See also biodiesel.tex for further notes.

6

Heating and cooling

Figure 6.1. A flock of new houses, yesterday.

We spend about one third of our energy on controlling the temperature of our surroundings – at home and at work – and on warming or cooling food, drink, laundry, and dirty dishes.

Domestic water heating

The biggest use of hot water in a house might be baths, showers, dish-washing, or clothes-washing – it depends on your lifestyle. Some people have one hot bath per day. Let's estimate the power used by this habit.

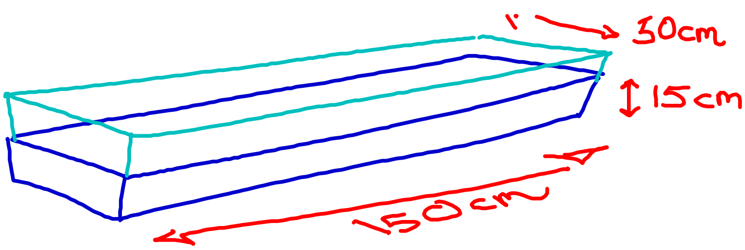


Figure 6.2. The water in a bath.

Bathing

The volume of bathwater is $50\,\text{cm} \times 15\,\text{cm} \times 150\,\text{cm} \simeq 110\,\text{litre}$.

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

$$4200\,\text{J/litre/°C} \times 110\,\text{litre} \times 40\text{°C} \simeq 18\,\text{MJ} \simeq 5\,\text{kWh}.$$

So taking a bath uses about **5 kWh**.

Hot water:
13

Figure 6.3. Hot water total – including bathing, showering, clothes washing, cookers, kettles, microwave oven, dishwashing – about 13 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.

Kettles and cookers

Britain, being a civilized country, has a 230 V 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

$$\begin{aligned}\text{Electrical power} &= \text{Voltage} \times \text{Current}\\ &= 230\,\text{V} \times 13\,\text{A}\\ &= 3000\,\text{W}\end{aligned}$$

Box 6.4. Kettle calculation: a fast-boiling kettle has a power of 3 kW.

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)	2 kW	1/2 h	1 kWh/d
– electric oven	6 kW	1/3 h	2 kWh/d
Cleaning			
– tumble dryer	2.5 kW	1/3 h	0.8 kWh/d
– airing-cupboard drying			0.25 kWh/d
– washing machine	2.5 kW	1/3 h	0.8 kWh/d
– dishwasher	2.5 kW	2/3 h	1.6 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 6.5. Electrical consumption figures for heating and cooling, per person.

3 kW? Because this is the biggest power that a 230 V outlet can deliver without the current exceeding 13 A (Box 6.4). In countries where the voltage is 110 V, it takes twice as long to make a pot of tea.

If you have the kettle on for 20 minutes per day, that's an average power consumption of **1 kWh per day**.

One ring on an electric cooker has the same power as a toaster: 1 kW. If you use two rings of the cooker on full power for half an hour per day, that corresponds to **1 kWh per day**.

A microwave oven usually has its cooking power marked on the front: mine says 900 W, which is nearly a kilowatt; 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 6 kW (when on full). If you use the oven for two hours every six days, that's **2 kWh per day**.

Hot clothes and hot dishes

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

Totting up the estimates relating to hot water, I think it's easy to use about 13 kWh per day per person. As usual, this is not an estimate of *average* consumption – not everyone takes a daily bath, nor does everyone use clothes-washers and tumble-dryers this heavily.

Hot air

Now, does more power go into making hot water and hot food, or into making hot air via the house's radiators, which are heated by burning natural gas?

One way to estimate the energy used per day for hot air is to imagine a house heated instead by electric fires, whose powers we know. 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.

Another way to estimate the energy for hot air is to think how many hours per day your central heating is on, and look up the power of the boiler. My condensing boiler delivers 35 kW. In the winter it's on for perhaps a couple of hours per day, so it's using 70 kWh/d (perhaps more at weekends, less on weekdays). If this winter behaviour lasts half the year, the average consumption per house is about 35 kWh per day. If the house is shared between two, then their hot-air power requirement is about 18 kWh/d each. When making these estimates, we mustn't forget our workplace; so I think 24 kWh/d per person for space heating is a good guess. This chapter's companion chapter E contains a more detailed account of where the heat is going in a house; this model makes it possible to predict the heat savings from turning the thermostat down, double-glazing the windows, and so forth.

Figure 6.6. A big electric heater: 2 kW.

Hot air:
24

Figure 6.7. Hot air total – including domestic and workplace heating – about 24 kWh per day per person. I've given this box a light colour to indicate that this energy is, or could be, low-grade thermal energy – heat from burning gas, for example.

Cooling

Fridge and freezer

Our urge to control temperatures is manifested not only in the hot water and hot air with which we surround ourselves, but also in the cold cupboards we squeeze into our hothouses. My fridge-freezer, pictured in figure 6.8, consumes 18 W on average – that's roughly 0.5 kWh/d.

Microwave: 1400 W peak

Fridge-freezer: 100 W peak, 18 W average

Figure 6.8. Power consumption by a heating and a cooling device.

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 very large. However, this part of the book is about British energy consumption, and Britain's temperatures give little need for air-conditioning (figure 6.10).

Cooling: **1**

Figure 6.9. Cooling total – including a refrigerator (fridge/freezer) and a little

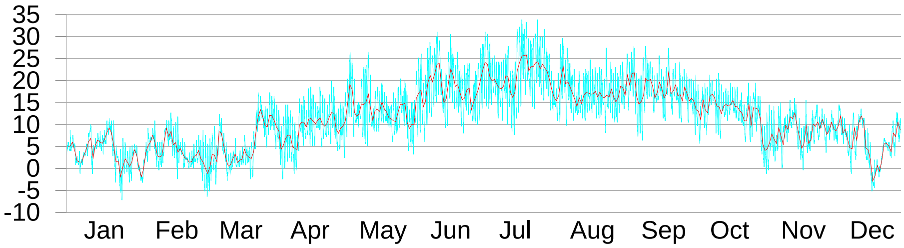


Figure 6.10. Cambridge temperature in degrees Celsius, daily (heavy line), and half-hourly (light line) during 2006.

Microwave oven's clock	2 W
Microwave oven (nominally 900 W)	1400 W
Fridge average	18 W
Fridge when active	100 W
Electric blanket	140 W
Electric convection heater	2000 W

Table 6.11. Power consumptions.

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, which corresponds to 1 h per day on average. So that averages out to 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 also refrigerates food on its way from field to shopping basket. I'll estimate the power cost of the foodchain later in chapter 14.

Total heating and cooling, both home and workplace, including cooking

13 for hot water, 24 for hot air, 1 for cooling – a total of 38 kWh/d per person.

Finish this summary.

Japan 'CoolBiz' rules for civil servants: air-conditioning set to 28°C (82F).

	Volume	Energy
Bath	110 litre	5 kWh
Shower	25 litre	1 kWh
Clothes washing machine	80 litre	4 kWh

Table 6.13. The water table. Volumes of hot-water consumption activities, and their energy costs assuming a temperature rise of 40°C.

Warming outdoors

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 30 kWh per day.

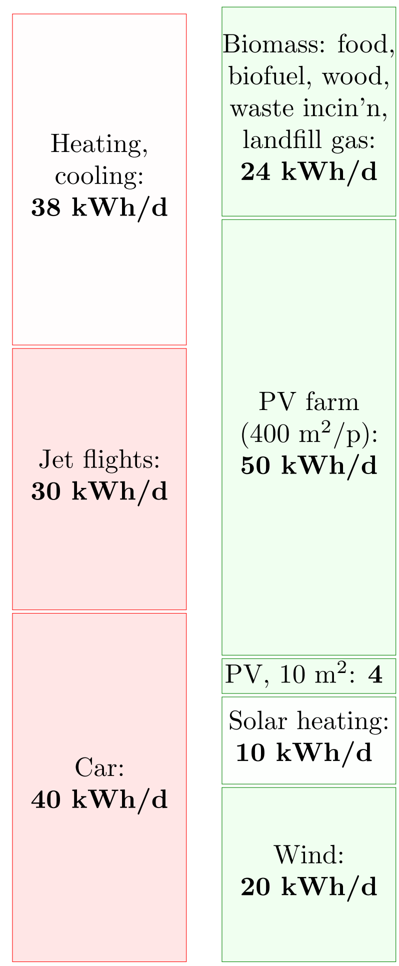


Figure 6.12. Heating and cooling – about 40 units per day per person. I've removed the shading from this box to indicate that it represents power that could be delivered by low-grade thermal energy. Low-grade energy could be provided by solar heat. It could also be provided by heat pumps at an electrical-energy cost significantly lower than the heat delivered.

Notes

48 *An airing cupboard requires roughly 1.5 kWh to dry one load of clothes.* I worked this out by weighing my laundry: a 4 kg load of dry clothes emerged from the washing machine with an extra 2.2 kg of weight (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 the table 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.)

Some national averages from Department of Trade and Industry [2002a] – Average domestic consumption for space heating, water, and cooking (2000): 21 kWh/d/p. Consumption in the service sector for heating, cooling, catering, hot water (2000): 8.5 kWh/d/p.

Some examples of workplace energy consumption figures: At a famous British university, the total bill for water, gas and electricity was £3.2 million in 2005/6. This includes a total of 22 710 000 kWh of electricity, of which 1 354 000 kWh were used in the Department of Physics – an average electrical consumption rate of 18.5 kWh/day for each of the 200 staff in the building. This is a figure for 'gadgets' more than 'heating'.

November 2000	'primary units' (the first 22 kWh/d)	1.35 p/kWh
	'secondary units' (the rest)	1.93 p/kWh
January 2007	the first 12 kWh/d	5.25 p/kWh
	the rest	2.94 p/kWh

Table 6.14. Domestic gas charges for British Gas customers in Cambridge, including tax.

7

Hydroelectricity

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 the country into two: the lower, dryer bits, which I'll call 'the lowlands'; and the higher, wetter bits, which I'll call 'the highlands' – understood to include places like the Lake District, the Pennines, and Wales. 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 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 altitude above the sea of England (say $h = 100$ m). The power works out to 0.02 W/m^2.

When we multiply this by the area per person (2500 m^2, when 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 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.

Let's turn to the highlands. Kinlochewe is a rainier spot: 2278 mm per year, four times more than Bedford. The height drops there are also bigger – 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 density 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 each), 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 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

Figure 7.1. A 60 kW waterwheel in Dinorwig, North Wales. With diameter 50 feet, it's the largest working waterwheel in Britain. From 1870 to 1925 this waterwheel powered virtually all the machinery of the Dinorwig slateworks.

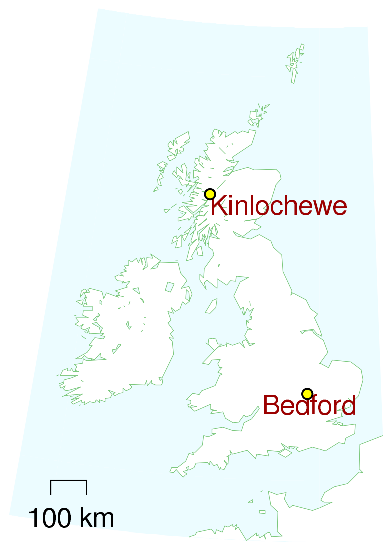


Figure 7.4. Nant-y-Moch dam, part of a 55 MW hydroelectric scheme

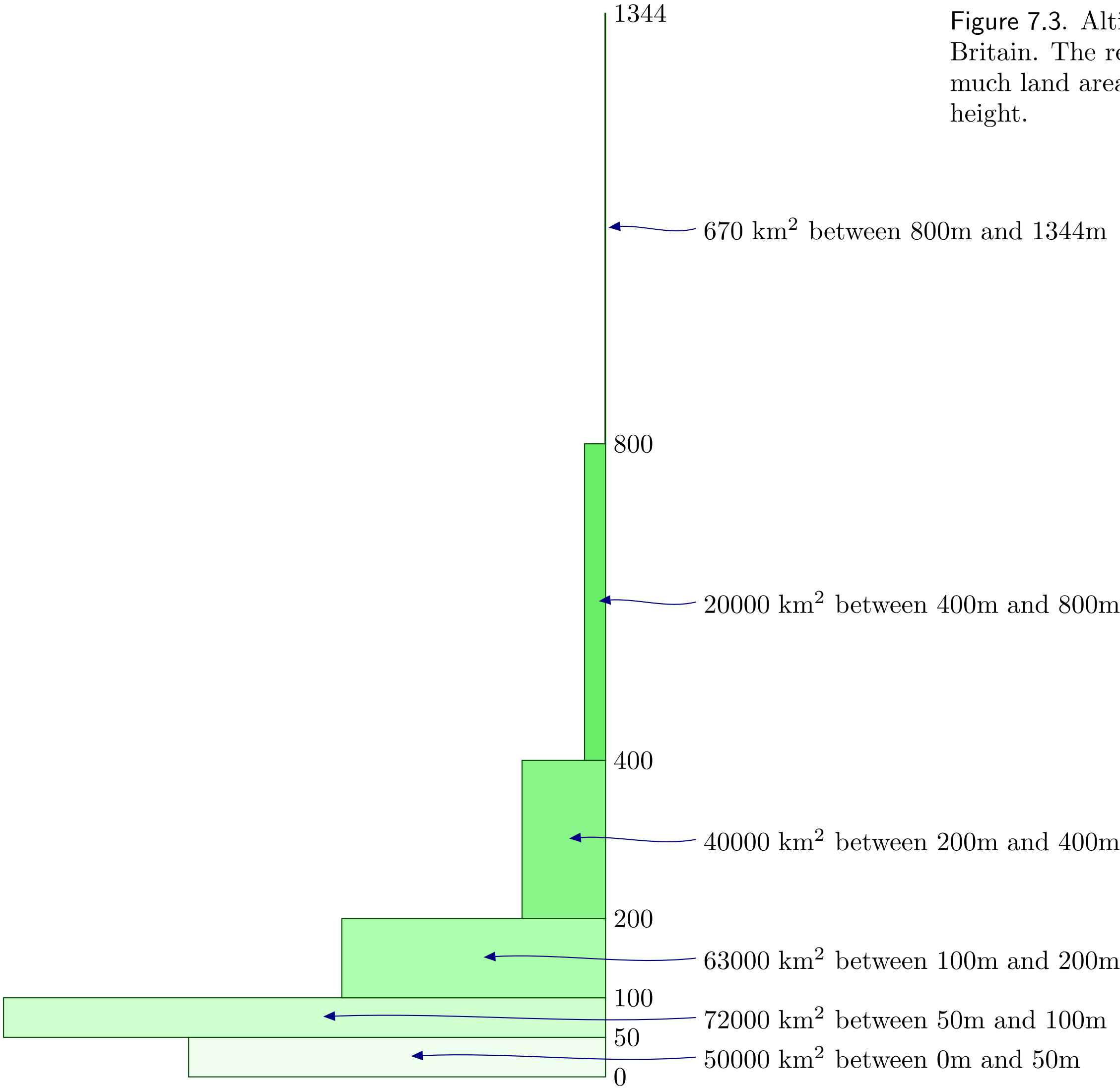


Figure 7.3. Altitudes of land in Britain. The rectangles show how much land area there is at each height.

per day per person, so this guess of 1.5 kWh/d/p would be nearly a ten-fold increase in hydroelectric power.

Notes

55 *The actual power from hydroelectricity in the UK today is 0.2 kWh per day per person.* Source: Dukes07, actual production of hydroelectricity in 2006 was: large-scale hydro, 3515 GWh (from plant with a capacity of 1.37 GW); small-scale hydro, 212 GWh (from a capacity of 153 MW).
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 is billed in the news as 'big enough to power every home in a city the size of Glasgow'. I bet that people get the impression from this that Glendoe will provide enough electricity 'to power Glasgow'. But this is a long way from the truth. If we take 180 GWh per year and share it between Glasgow (616 000 people), we get 0.8 kWh/d per person. That is just 5% of the average electricity consumption of 16 kWh/d per person.

8

Light

Figure 8.1. Lighting – 4 units per day per person.

Lighting home and work

The brightest domestic lightbulbs use 250W, 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 that produces an equal amount of light uses one quarter of the power of an incandescent bulb.

How much power does a moderately affluent person use on lighting? My rough estimate, based on table 8.2, 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; if we guess 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?

There's roughly one sodium streetlight per ten people, each with a power of 100 W, switched on for 10 h/d. That's 0.1 kWh per person per day.

Britain apparently has 420 000 traffic and pedestrian signal light bulbs, consuming 100 million kWh of electricity per year. Let's personalise these data. Shared between 60 million people, 100 million kWh per year is the same as 0.005 kWh/d per person.

What about other forms of public lighting – illuminated signs, bol-

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 8.2. 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.

	2006	2007
'Primary units' (the first 2 kWh/d)	10.73 p/kWh	17.43 p/kWh
'Secondary units' (the rest)	8.13 p/kWh	9.70 p/kWh

Table 8.3. Domestic electricity charges (2006, 2007) for Powergen customers in Cambridge, including tax.

lards, 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 have lights on their car whenever it's moving. How does the extra power required for 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. A typical car going at an average speed of 50 km/h and consuming one litre per 12 km has an average power consumption of 42 000 W. So the extra power consumed by having the lights on is 2%.

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 paid any more attention to this topic, we would be coming down with a case of every-little-helps-ism.

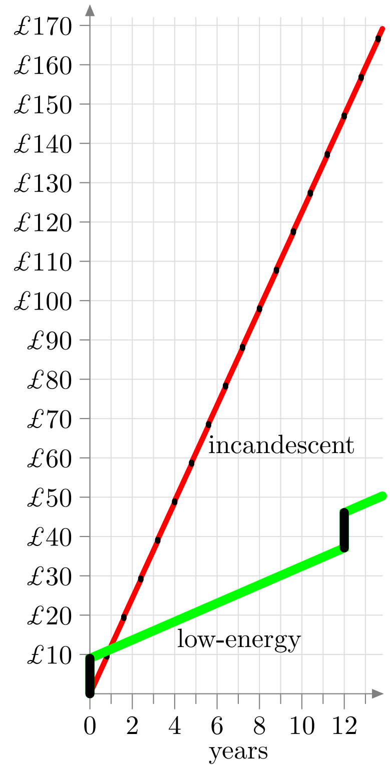


Figure 8.4. Total cumulative cost of using a traditional incandescent 100 W bulb for 3 hours per day, compared with replacing it *now* with an Osram Dulux Longlife Energy Saver. Assumptions: electricity costs 10p per kWh; traditional bulbs cost 45p each; energy-saving bulbs cost £9. (I know you can find them cheaper than this, but this graph shows that even at £9, they're much more economical.)

The economics of low-energy bulbs

Generally I avoid discussion of 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: 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).

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? 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?

Researchers say that LED (light-emitting diode) bulbs will soon be even more energy efficient than compact fluorescent lights. I checked the numbers on my latest purchases: the Philips Genie 11 W compact fluorescent bulb 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. 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 land-fill pollution, will be to use LED bulbs.

Figure 8.6. Philips 11 W alongside Omicron 1.3 W LED bulb.

Bulb type	Efficiency (lumens/W)
incandescent	10
halogen	16–24
white LED	35
compact fluorescent	55
large fluorescent	94
sodium streetlight	150

Table 8.7. Lighting efficiencies of commercially-available bulbs. In the future, white LEDs are expected to deliver 150 lumens per watt.

Notes

57 `http://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 going to public lighting is 2095 GWh/y, which is 0.1 kWh/d per person.
In the US, lighting uses 220 TWh/y residential, 110 TWh/y industrial, and 410 TWh/y commercial, which is 7 kWh/d per person in total.
Further information: `http://www.bchydro.com/powersmart/elibrary/elibrary680.html`

57 *55%-efficient generator* – source: `http://en.wikipedia.org/wiki/Alternator`

9

Offshore wind

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 windfarms deliver a higher power per unit area than onshore windfarms. The Kentish Flats windfarm 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 density of 3.2 W/m^2. In 2006, its average power density was 2.6 W/m^2.

I'll assume that a power density of 3 W/m^2 (which is 50% larger than our onshore estimate of 2 W/m^2) is an appropriate figure for all offshore windfarms 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. Conventional wisdom seems to be that *shallow* offshore wind (depth less than 25–30 m), while roughly twice as costly as onshore wind, is economically feasible, given modest subsidy; and *deep* offshore wind is at present not economically feasible. As of 2007, there's just one deep offshore windfarm, an experimental prototype sending all its electricity to a nearby oilrig.

Figure 9.1. Kentish Flats. 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 © by Elsam (`elsam.com`). Used with permission.

Shallow offshore

Within British territorial waters, the shallow area (5–25 m) is about 40 000 km^2 – most of it off the coast of England and Wales. This area is about two Waleses.

The power available from shallow offshore windfarms 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 windfarms. The requirement for shipping corridors and fishing areas must cut down the plausibly-available area by some factor – I propose a factor of three (but please see this chapter's end-notes for a

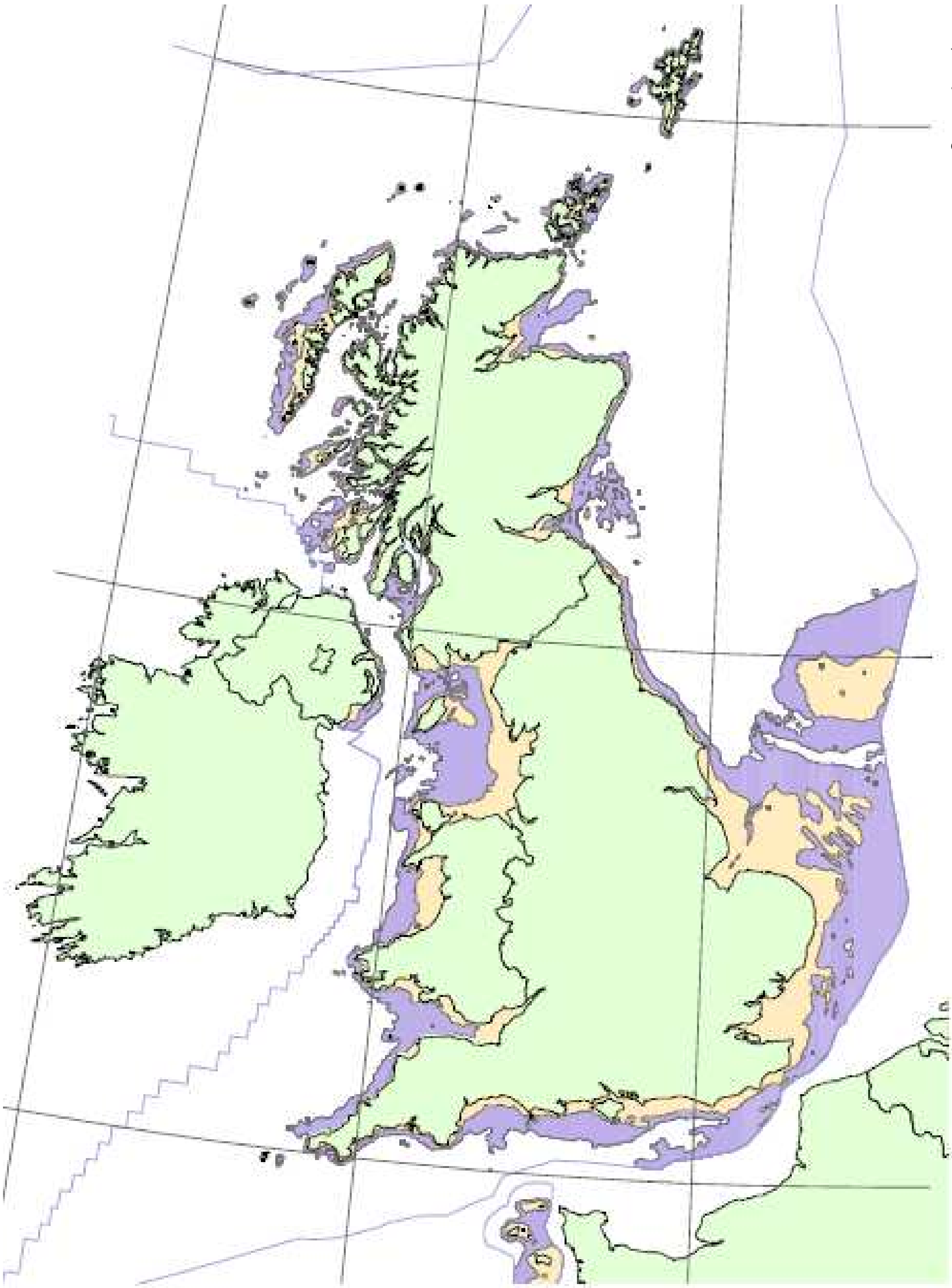


Figure 9.2. UK territorial waters with depth less than 25 m (yellow) and depth between 25 m and 50 m (magenta). Data from DTI Atlas of Renewable Marine Resources. © Crown copyright.

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 audaciously large area – two thirds of a Wales – that would be required to deliver this 16 kWh/d per person. If 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 fifteen 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 windfarm, Horns Reef, all 80 turbines had to be completely 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, with one third of them 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. So 'deep' offshore windfarms 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 cut the area by a factor of three; the area occupied 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 25. *(check ref)*

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 not economically feasible.

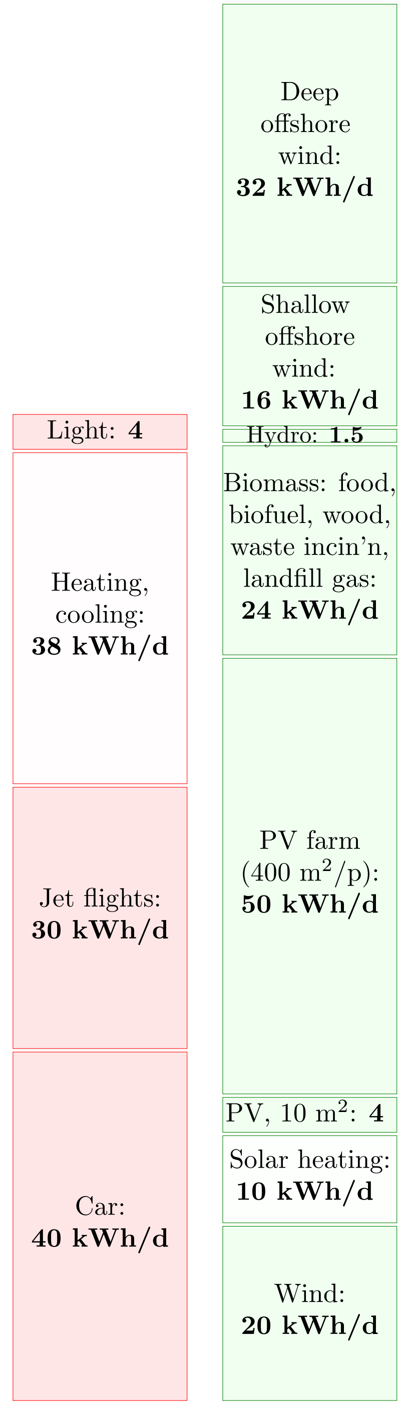


Figure 9.3. Offshore wind.

Costing offshore wind

For comparison, the DTI's estimate of the potential offshore wind generation resource is 4.6 kWh per day per person, from both shallow and deep waters. The UK government announced on 10th December 2007 that it would permit the creation of 33 GW of offshore capacity (which would deliver on average 4.4 kWh/d per person), a plan branded 'pie in the sky' by some in the wind industry [2t2vjq]. So, let's run with a figure of 4 kWh per day per person. This is the same as 10 GW per UK on average, and it's 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 9.1. (They're called '3 MW' but on average they deliver 1 MW.)

What would this 10 GW of power cost to erect? Well, the 32 MW Kentish Flats farm cost £105 million, so 10 GW would cost about £33 billion. This statement violates my rules of comprehensibility – who has got a good feeling for what a billion means? But "£3 million per MW" or "£3 billion per GW" is something we might compare with nuclear power. Nuclear power stations cost about £1.25 billion per GW to build. So at present prices the capital cost of offshore wind is greater than the capital cost of nuclear power. However, we're not really comparing like with like here. The 1 GW delivered by a typical nuclear power station is always on; the power delivered by wind farms is bursty. Nuclear power and wind power have different clean-up costs and different risks. I'm not trying to advocate nuclear over wind – I'm just reporting the numbers as honestly as I can.

Another bottleneck constraining the planting of wind turbines is the special ships required. If Britain were to erect 10 000 wind turbines over a period of 5 years then roughly 100 jack-up barges would be required. These cost £60 million each, so an extra capital investment of £6 billion would be required. Not a show-stopper compared with the £33b price tag we already quoted, but the need for jack-up barges is certainly a detail that requires some forward planning.

A second way of expressing the £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 better deal, incidentally, than microturbines. A microturbine currently costs about £1500 and delivers only 1.6 kWh/d even at an optimistic windspeed of 6 m/s.

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 nine white-tailed eagles in ten months. I share the concern of BirdLife International for the welfare of birds, especially 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 9.5).

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

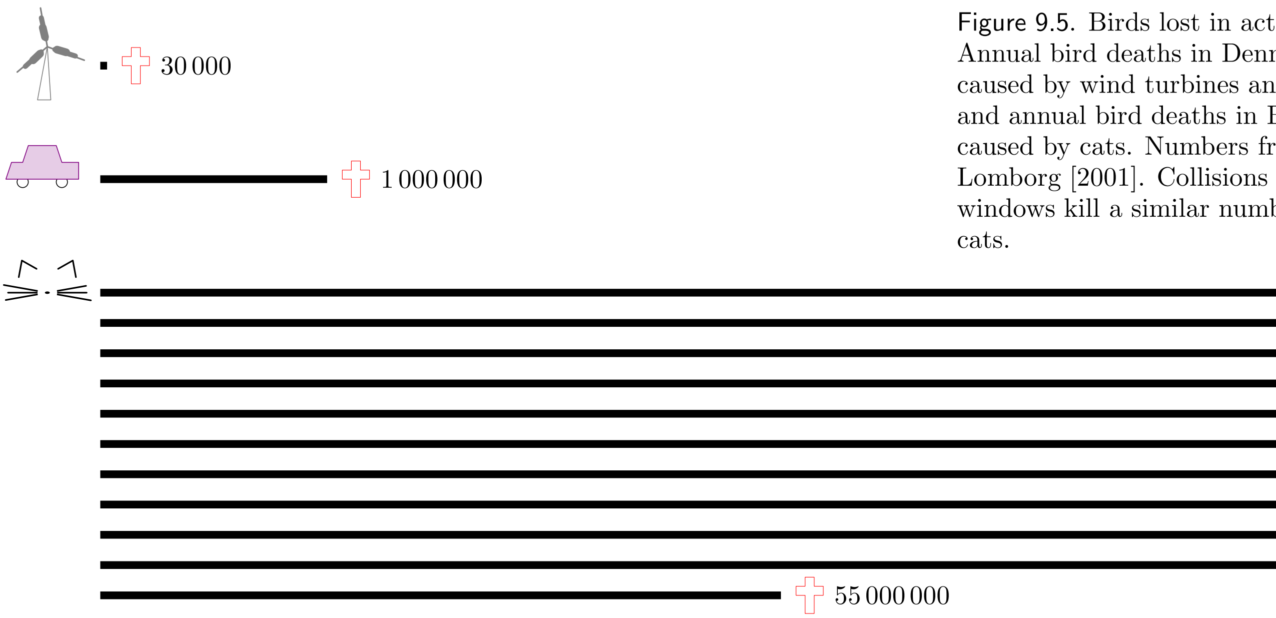


Figure 9.5. Birds lost in action. Annual bird deaths in Denmark caused by wind turbines and cars, and annual bird deaths in Britain caused by cats. Numbers from Lomborg [2001]. Collisions with windows kill a similar number to cats.

So, how's our race between consumption and production coming along? Adding both shallow and deep offshore wind to the production stack, it's neck and neck. 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 tonnes, which is 0.2 tons per person. During world war II, American shipyards built 2751 Liberty ships, each containing 7000 tons of steel – that's a total of 19 million tons of steel. 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. In 1997, 200 installations in the UK waters of the North Sea and 7000 km of pipelines 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(thermal), used another million tonnes of steel and a million tonnes of concrete.

Figure 9.6. 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.

Notes

59 *The Kentish Flats windfarm 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 km^2. The power density of this offshore windfarm was thus predicted to be 3.2 MW/km^2. In fact, the average load factor in 2006 was 29% (227 279 MWh delivered, compared with a capacity of 8760 × 90 MWh) [wbd8o]. This is a power density of 2.6 W/m^2. 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 km^2. They thus had an average power density of 2.6 W/m^2.

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

59 *deep offshore wind is not at present at all 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. 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 pricetag of £3 per watt (peak) can be compared with that of Kentish Flats, £1.2 per watt (£105 million for 90 MW). http://www.beatricewind.co.uk/

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.

61 *Horns Reef* (Horns Rev). The difficulties with this '160 MW' Danish wind farm off Jutland www.hornsrev.dk are described in halkema-windenergyfactfiction.pdf
When it is working, its load factor is 0.43 and its average power per unit area is 2.6 W/m^2.

61 *The UK government announced on 10th December 2007...* [25e59w].

61 *the DTI's estimate of the potential offshore wind generation resource is 4.6 kWh per day per person*
The Department of Trade and Industry's [2002] document 'Future Offshore' gives a detailed breakdown of areas that are useful for offshore wind power. Shallow water (5–30m) area of 27 000 km^2. Deeper water (30–50m) area of 50 000 km^2. Their estimated power contribution,

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	3 345	6	2 067	4
Greater Wash	7 391	14	946	2
Thames Estuary	2 099	4	848	2
Other	14 431	28	45 441	87
TOTAL	27 266	52	49 302	94

Table 9.8. Potential offshore wind generation resource in proposed strategic regions, if these regions were *entirely filled* with wind turbines. From Department of Trade and Industry [2002b].

if these areas were *entirely* filled with windmills, is 146 kWh/d per person (consisting of 52 from the shallow and 94 from the deep).

It might be interesting to describe how they get down from this potential resource of 140 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 degrees; 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'; finally other sites with average wind speed 8-9 m/s had their capacities reduced by 5%.

62 *Jack-up barges cost £60 million each.* `http://news.bbc.co.uk/1/hi/magazine/7206780.stm`. I estimated that we'd need roughly 100 of them by assuming that there would be 60 work-friendly days each year, and that erecting a turbine would take 3 days.

Cost of offshore wind According to the DTI in November 2002, electricity from offshore windfarms costs about £50 per MWh (5p per kWh) [Department of Trade and Industry, 2002b, p. 21]. Economic facts vary, however, and in April 2007 the estimated cost of offshore was up to £92 per MWh [Department of Trade and Industry, 2007, p. 7]. It's because offshore wind is so expensive that the government is having to increase the number of ROCs per unit of offshore wind energy. The ROC (renewable obligation certificate) 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. In the same document, estimates for other renewables (medium levelised 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.

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

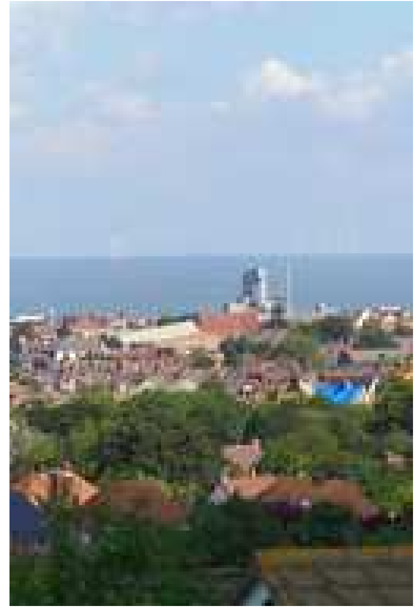


Figure 9.9. Kentish Flats. Photos © by Elsam (elsam.com). Used with permission.

63 *Liberty ships* – http://www.liberty-ship.com/html/yards/introduction.html

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

10

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 were 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."

Vader Charger

Figure 10.1. Planet destroyers. Spot the difference.

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. Running them and charging them. (But not manufacturing the toys in the first place, we address that in the later chapter on 'stuff'.)

The truth about chargers

Figure 10.2. 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.

Modern phone chargers, when left plugged in with no phone attached, use about one third of 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!*

Admittedly, some older chargers are worse – if it's warm to the touch, it's probably using one watt or even two (figure 10.3). A two-watt-guzzling charger uses 0.05 kWh per day. I think that it's a good idea to switch off such a charger – it *will* save you two pounds per year. But don't kid yourself that you've 'done your bit' by so doing. 2 W is only a small fraction of total energy consumption.

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

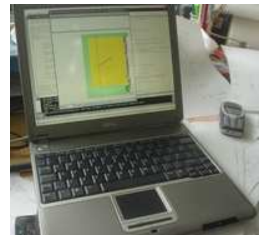
Table 10.4 shows the power consumptions, in watts, of a houseful of gadgets. The first column shows the power consumption when the device is actually being used – for example, when a sound system is actually playing sound. The second column shows the consumption when the device is switched on, but sitting doing nothing. I was particularly shocked to find that a laser-printer sitting idle consumes 17 W – the same as a fridge-freezer! The third column shows the consumption when the gadget is asked to go to sleep or to 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.

The biggest guzzler is the computer and its screen, whose consumption is in the hundreds of watts. Entertainment systems such as stereos and DVD players swarm in the computer's wake, many of them consuming 10 W or so. Some stereos consume several watts even when switched off, thanks to their mains-transformers. 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.

Figure 10.3. This lousy cordless phone and its charger use 2 W when left plugged in. That's **0.05 kWh/d**. If electricity costs 10p per kWh then a 2 W trickle costs £2 per year.

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			
Bedside clock-radio	1.6			
Digital radio	8		3	
Radio cassette-player	3	1		1
Stereo amplifier	6			6
Stereo amplifier	13			0
Home cinema sound	7	7	4	
DVD player	7	6		
DVD player	12	10	5	
TV	100		10	
Video recorder	13		1	
Digital TV set top box	6		5	
Xbox	160		2.4	
Sony Playstation 3	190		2	
Nintendo Wii	18		2	
Answering machine		2		
Answering machine		3		
Cordless telephone		1.7		
Mobile phone charger		0.3		

Table 10.4. Power consumptions of various gadgets, in watts. 40 W is 1 kWh/d. Consumption when 'off' is the pwer measured when the gadget was switched off but plugged in to the mains.



Laptop: 16 W

Computer: 80 W

LCD 31 W CRT 108 W

Printer: 17 W (on, idle)

Projector: 150 W

Digital radio: 8 W

Device	Power	Time per day	Energy per day
Television	0.1 kW	4 h	0.4 kWh
Computer	0.1 kW	24 h	2.4 kWh
Power adaptors, chargers, stereos	0.005 kW	24 h ×8	1 kWh

Table 10.5. Electric consumption by domestic information systems. I assumed five power adaptors: chargers for cordless phones, mobile phones, pocket computers; adaptor for answering machine, bedside radios. A plausible total is 5 kWh per home per day; a similar figure at the workplace; perhaps 3 kWh per person per day.

Notes

Further reading: Kuehr [2003]

67 *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.’
See charger.tex for another 2007 sighting of this same BBC-ism.

Somewhere I need to include other household gadgets – vacuum cleaner (1.4 kWh/week), lawn mower (notes in electricity.tex).

When making the call, the mobile uses 1 W.

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.”

True for a few people, and only during the winter. *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.* Heaters called air-source heat pumps or ground-source heat pumps can deliver 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.

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 electricity is mainly generated from fossil fuels. 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.

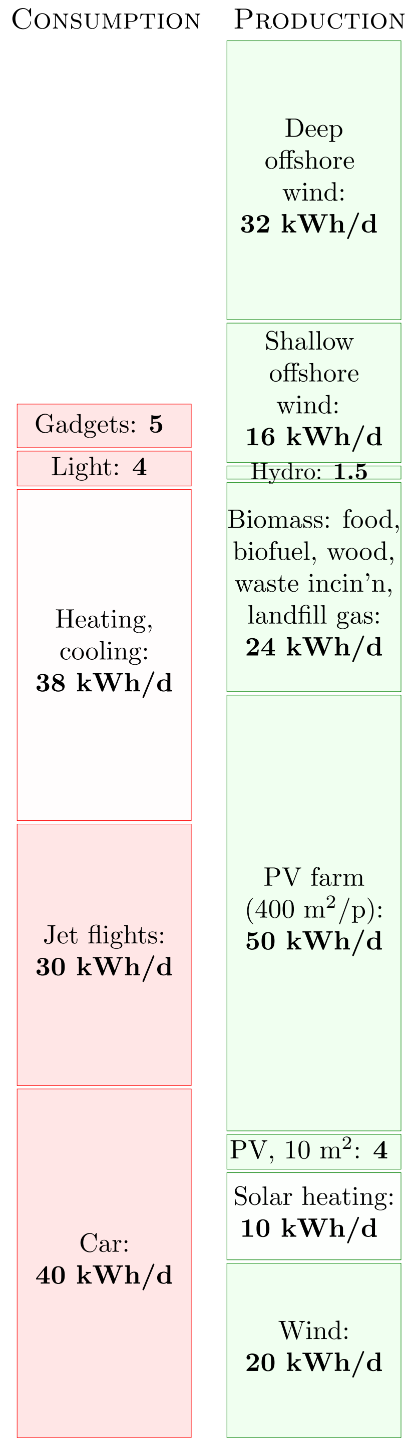
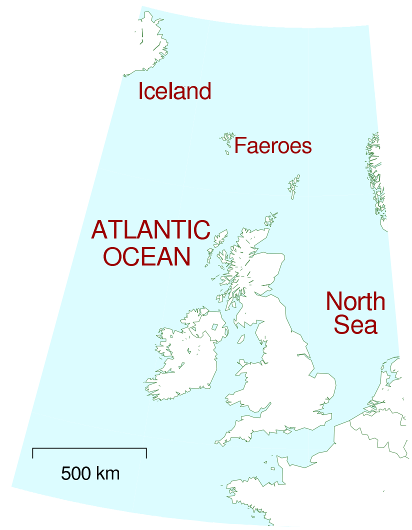


Figure 10.6. Information systems and other gadgets

11

Waves



If wave power offers hope to any country, then it must offer hope to the United Kingdom and Eire – 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 releases 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

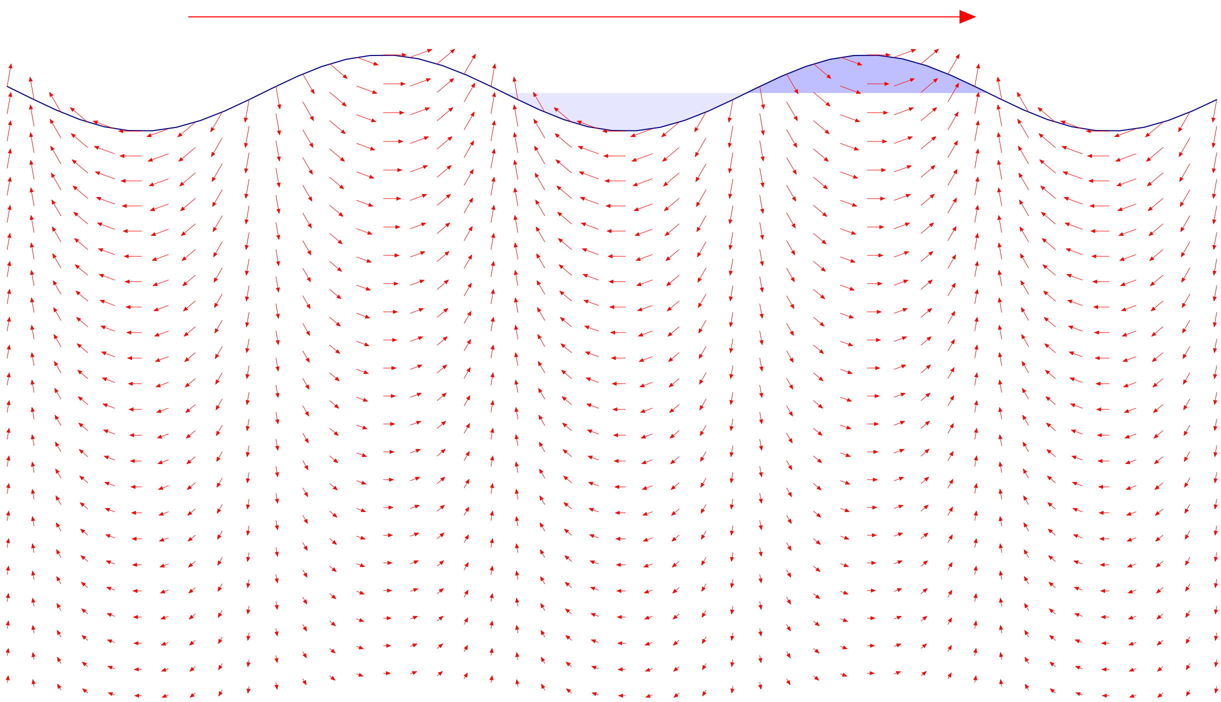


Figure 11.1. A wave has energy in two forms: potential energy associated with raising water out of the light-shaded troughs into the heavy-shaded crests; and kinetic energy of all the water moving around as indicated by the small arrows. The speed of the wave, travelling from left to right, is indicated by the bigger arrow at the top.

absorb energy from the wave – 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, while sunlight delivers a power per unit *area*, waves deliver a power per unit *length* of coastline.

We can find an upper bound on the maximum conceivable power that could be obtained from wave power by estimating the incoming power 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 prevailing winds are westerly, so let's think about waves rolling in from the Atlantic.

The power of Atlantic waves has been measured: it's about 40 kW per metre of exposed coastline. (Chapter F explains how we can estimate this power using a few facts about waves.)

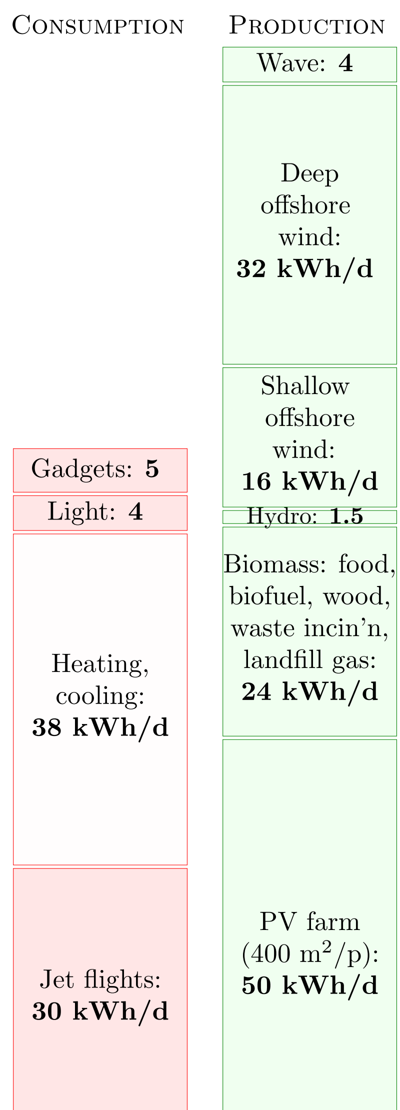
That sounds like a lot of power! If everyone owned a metre of coastline and could harness their whole 40 kW, that would be plenty of power to cover modern consumption. However, *our population is too big.* There is not enough Atlantic-facing coastline for everyone to have their own metre.

The total exposed coastline is something like one thousand kilometres (one million metres), which is 1/60 m each. 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 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 incident power into electricity, and that we are able to pack wave-machines along 50% of the coastline. That would mean we could deliver 25% of this theoretical bound. That's 4 kWh **per day per person**.

How do the numbers assumed in this calculation compare with today's technology? As I write, there are still no wave energy collectors working in deep water; a Pelamis wave energy collector is sitting coyly on the shore in Portugal but there's no news of its having been deployed. The makers of the Pelamis ('designed with survival as the key objective before power capture efficiency') describe a two-kilometre-long wave-farm consisting of 40 of their sea-snakes, delivering 6 kW per metre. Using this figure in the previous calculation, the power delivered by 500 kilometres of wave-farm is reduced to **1.2 kWh/d 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? It weighs 700 tons, including 350 or 400 tons of ballast. So it has about 350 tons of steel. 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. So this wave-machine has a steel-weight-to-power ratio of half a ton per kW, roughly three times bigger than that of a wind-turbine. In 500 kilometres of wave-farm, delivering 1.2 kWh/d per person, there would be 3 million tons of steel. That's roughly 40 times the mass of the Magnus oil platform shown on page 11. (Which delivers 5 GW; let's turn this into mass per MW shall we? Should include an engine too – the Wartsila-Sulzer weighs 2300 tons, is 52% efficient and delivers 80 MW. The Magnus–engine oil-chain has a weight-to-delivered-power ratio of 56 tons per MW; 56 kg per kW. So the prototype wave machine has roughly ten times the weight-to-power ratio of the evolved fossil fuel solution.) The Pelamis is a first prototype; presumably with further investment and development in wave technology, the weight-to-power ratio would fall.

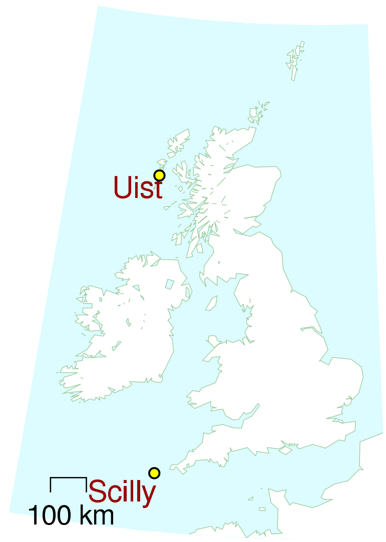
Figure 11.2. A Pelamis wave energy collector. The Pelamis sea snake is made of four sections. It faces nose-on towards the incoming waves. The waves make the snake flex, and these motions are resisted by hydraulic generators. The peak power from one snake is 750 kW; in the best Atlantic location one snake would deliver 300 kW on average. From Pelamis wave power `www.pelamiswave.com`.



Notes

71 *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].

72 *Atlantic wave power is* 40 kW *per metre of exposed coastline.* 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 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).



How do this chapter's estimates compare with those of other bodies? The IEE's 2002 estimate of the 'technical potential' of wave – "an upper limit that is unlikely ever to be exceeded even with quite dramatic changes in the structure of our society and economy" – was 2.3 kWh/d/p. The Tyndall Centre estimated the 'theoretical potential' of offshore wave power to be 32 kWh/d/p, and the 'practicable resource' to be 2.3 kWh/d/p. The Interdepartmental Analysts Group estimated that wave power could contribute an average of 1.5 kWh/d/p at a cost of 7p/kWh. All three of these estimates are similar to my figure of 4 kWh/d/p.

I speculate that overestimates may have been made by other bodies who have got their wave-power estimate from the Atlas of Marine Resources, because some people don't realise that *waves are a resource 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.

72 *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 0.48, 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. Source: Islay Limpet Project Monitoring Final Report,

http://www.wavegen.co.uk/pdf/art.1707.pdf.

Photo by Terry Cavner.

12

Food and farming

Figure 12.1. A salad nicoise, yesterday.

Minimum: **3**

Figure 12.2. Minimum energy requirement of one person.

> *Modern agriculture is the use of land to convert petroleum into food.*
>
> Albert Bartlett

We've already discussed in chapter 5 how much sustainable power could be produced in the form of 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 1000 chemist's calories, which is 4200 joules of energy. So 2600 'Calories' per day is about 3 kWh per day. One function of a typical person is thus to act as a space heater with an output of a little over 100 W, a medium-power lightbulb. Put ten 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? It depends if we are vegan, vegetarian or carnivore.

Let's start with the vegan. 3 kWh/d of energy in the plants.

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 if I consume 50 g of cheese per day, that 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/day, 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/d. 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 these costs in chapter 14.

Milk, cheese: **1.5**

Figure 12.3. Milk and cheese.

Eggs

A 'layer' (a chicken that lays eggs) eats about 110 g of chicken feed per day. Assuming 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/d. (Each egg itself contains 80 kcal, which is about 0.1 kWh.)

Eggs: **1**

Figure 12.4. Two eggs per day.

The energy cost of eating meat

Let's say an enthusiastic meat-eater eats about half a pound a day (220 g). 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 half-pound of chicken you eat was clucking around being a half-pound of 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 take about 1000 days 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.

Carnivory: **8**

Figure 12.5. Eating meat requires extra power because we have to feed energy to 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) a 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

$$170\,\text{kg} \times \frac{3\,\text{kWh/d}}{65\,\text{kg}} \simeq 8\,\text{kWh/d}. \tag{12.1}$$

I've used the 'animals are like humans' assumption again; this physiological liberty may mean I've underestimated the cow's contribution and overestimated the chicken's. 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 calorific balance of this rough diet is 1.5 kWh/d from vegetables; 0.7 kWh from dairy; 0.2 kWh from eggs; and 0.5 kWh from meat.)

This number does not include any of the power costs associated with fertilizing, processing, refrigerating, and transporting the food. We'll estimate those costs elsewhere.

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. Similar arguments can be made in favour of carnivory for places such as the scrublands of Africa and the grasslands of Australia.

On the other hand, where animals are reared in cages and fed grain that could have fed humans, 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.

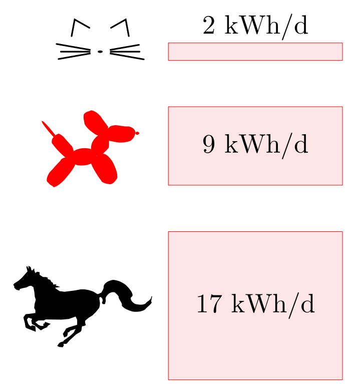


Figure 12.6. The power required for animal companions' food.

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 eight 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, then the last section's calculation (assuming Tiddles eats chicken, pork, and beef in equal proportions) says that the power required to make her food is just shy of 2 kWh/d.

Similarly if your dog Fido eats 200 g of meat per day, and carbohydrates amounting to 1 kWh per day, then the power required to make his food is something like 9 kWh per day.

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

Fertilizer costs (under construction)

`http://www.idsia.ch/~juergen/haberbosch.html`

"Nearly one century after its invention, the process is still applied all over the world to produce 500 million tons of artificial fertilizer per year. 1% of the world's energy supply is used for it (Science 297(1654), Sep 2002); it still sustains roughly 40% of the population (M. D. Fryzuk, Nature 427, p 498, 5 Feb 2004)."

Total energy spent by the UK on fertilizer is . . . (see Smil). (I'm not sure yet.)

But 'non-energy' uses of natural gas and petroleum products are probably dominated by fertilizer creation. They call it 'non-energy', but turning butane or methane into ammonia *does* use the chemical energy of the butane or methane! From DUKES: In 2006, the UK's non-energy use of natural gas was 9.5 TWh, which is 0.43 kWh/d per person; the non-energy use of petroleum products was 10.6 million tons, which is 5.6 kWh/d per person. If we guess that half of the non-energy use of these fossil fuels is for fertilizer creation, we get 3 kWh/d per person.

In 2006 DUKES 'industrial consumption', total natural gas used for 'food' was 27.6 TWh (1.26 kWh/d/p). I wonder if that includes fertilizers? Use for 'chemicals' was 39.2 TWh (1.8 kWh/d/p).

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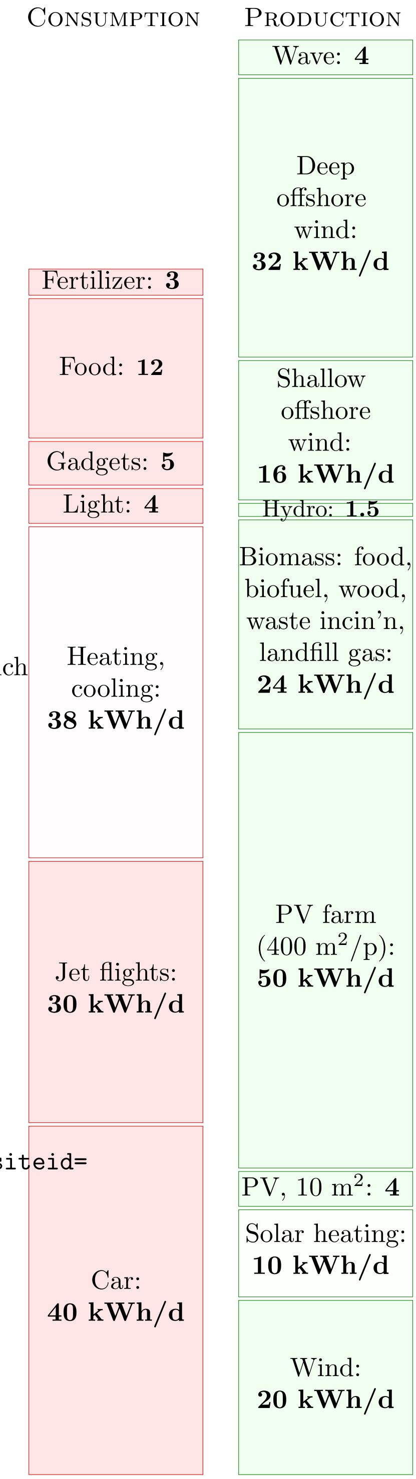


Figure 12.7. Food and farming.

Notes

Carbon footprint of a bag of crisps: 75 g CO_2 for a standard 35 g bag. `http://www.walkerscarbonfootprint.co.uk/walkers_carbon_footprint.html` of which 44% is farming, 30% is processing, 15% packaging, and 11% transport and disposal. The chemical energy 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. If all one's 3 kWh per day of (vegetarian!) food had the same fossil energy footprint then the food's fossil energy footprint would be 4.2 kWh/d.

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

Meat `http://icwales.icnetwork.co.uk/farming/farming/tm_headline=am-criticises-nz-lamb-study&method=full&objectid=19281105&siteid=50082-name_page.html` Other people's estimates of the footprint of meat. Lamb reared in New Zealand and transported to the UK: 700 kg per tonne of lamb, according to a report from Lincoln University, New Zealand.

More of the same, but including methane impact From Daily Telegraph: "Eating beef 'is less green than driving'".

Producing 1 kg of beef generates as much greenhouse gas as driving a car non-stop for three hours, it was claimed yesterday. Japanese scientists used a range of data to calculate the environmental impact of a single purchase of beef. Taking into account all the processes involved, they said, four average sized steaks generated greenhouse gases with a warming potential equivalent to 36 kg of carbon dioxide. This also consumed 47 kWh of energy. [I expect this means consumption of 'primary' energy (energy fuels, but not food).] [My estimate was 8 kWh for the food energy for roughly 1/6 kg of beef, *i.e.*, 48 kWh for 1kg.]

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 annum. Half of all milk produced by cows is sold as liquid milk. http://www.ukagriculture.com/ http://www.vegsoc.org/info/cattle.html

77 *Chicken* Source: Subcommittee on Poultry Nutrition, National Research Council [1994] http://www.nap.edu/openbook.php?isbn=0309048923
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 3200 kcal per kg, which is 3.7 kWh per kg. Energy consumption is 400–450 kcal per day per hen, or 0.5 kWh/d per hen, with 2 kg being a typical body weight.
Other sources: statistics.gov.uk/STATBASE

The energy costs of walking and cycling have been estimated by ..... SWEEG SCIENTISTS' ANNUAL REPORT 2000-2001 Centre for Energy and the Environment Exeter The embodied energy in typical diet is 5.75 times the derived energy. Walking is 42 g/km. Cycling is 30 g/km. (cf Driving a car, 183 g/km.)

13

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 every 28 days. The moon also turns around once every 28 days so that she always shows the same dutiful face to her dancing partner, the earth. The prima donna earth doesn't return the complement; 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.

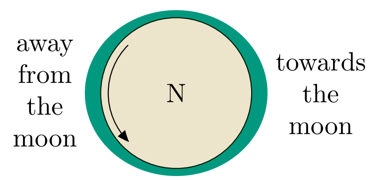


Figure 13.1. An ocean covering a billiard-ball earth. We're looking down on the North pole, and the moon is 60 cm off the page to the right. The earth spins once per day inside a rugby-ball-shaped shell of water. The oceans are stretched towards and away from the moon because the gravitational forces 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.

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 earth's slower dance around the sun, so the size of the tides varies with the phase of the moon. At full moon and new moon the imbalances reinforce each other, and the resulting big tides are called spring tides. Spring tides are not tides that occur at spring time; they 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 (relative to mean sea level), the spring low tides are twice as low, and the tidal currents are twice as big at springs.

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. 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. 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 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 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. Consecutive crests and troughs are separated by six hours. Or to be more precise, by six and a bit hours, since the time between two moon-rises is about 25, not 24 hours.

The speed at which the crests and troughs travel depends on 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. Tidal crests and troughs move up the English channel at roughly 70 km/h, round the north of Scotland at about 150 km/h, and down the North Sea at about 100 km/h. In the northern hemisphere, the Coriolis force 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. (That is, the vertical amplitude is bigger.) 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 kinetic energy of the spinning earth. The earth is very gradually slowing down. Each century, the day gets longer by 2.3 milliseconds, thanks to tidal friction. Tidal energy is a renewable that will be with us for a billion years.

Figure 13.2. Woodbridge tidemill. [Get better picture.]

So, how can we put tidal energy to use?

When you think of tidal power, you might think of an artificial pool next to the sea, with a waterwheel that is turned as the pool fills or empties. We'll start by estimating the power available from such tide pools. Every twelve-and-a-bit hours, there's a high tide (in most European ports, at least). Six hours later, there's a low tide. What range between high and low tide shall we assume for our artificial tide pool? The range between high and low tide depends on the phase of the moon and on your location. Let's assume a range of 4 m. This is a typical range in many European estuaries; in a few special spots – the Severn estuary, Blackpool, and The Wash – the range is sometimes 7 m or more. The power of an artificial tide pool that's filled rapidly at high tide and

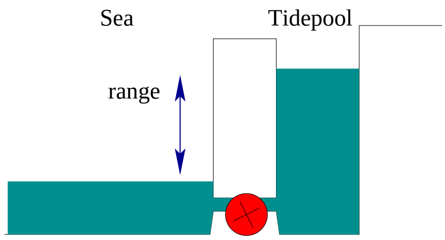


Figure 13.3. An artificial tide pool. The pool was filled at high tide, and now it's low tide. We let the water out through the electricity generator to turn the water's potential energy into electricity.

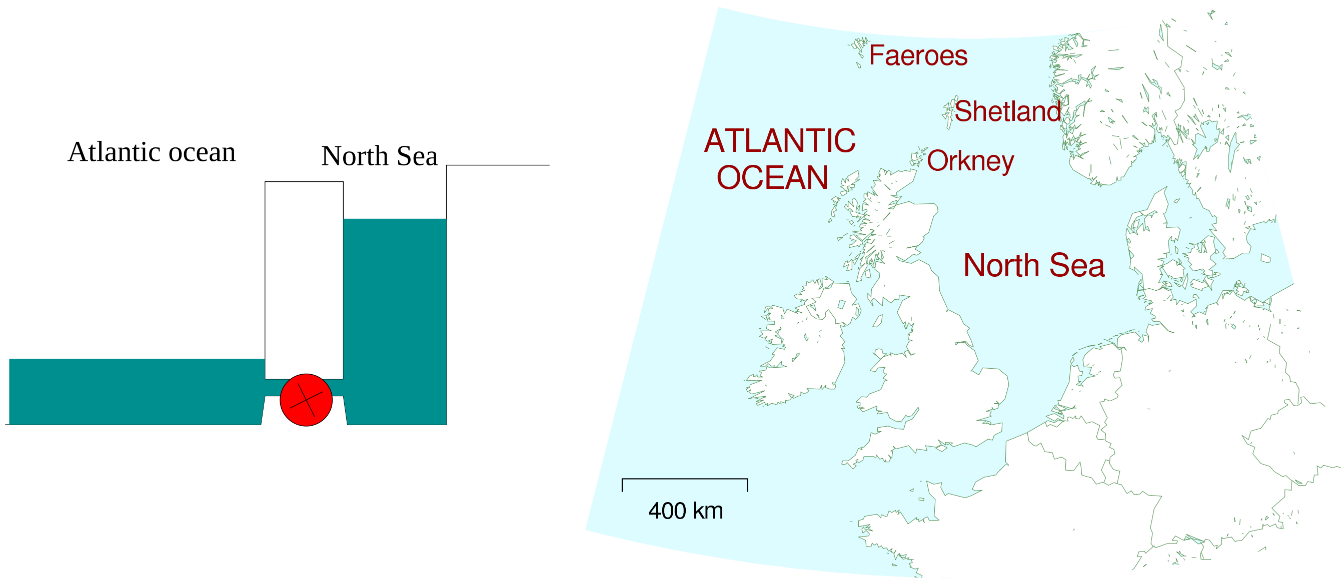


Figure 13.4. A natural tide pool. The British Isles are in a fortunate position. The North Sea forms a natural tide pool, in and out of which great sloshes of water pour twice a day.

emptied rapidly at low tide, generating power from both flow directions, is about 3 W/m^2. This is only a little bigger than the power per unit area of a wind-farm. That means, to make tidepools 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 tidepool of just the required dimensions. This tidepool is known as the North Sea (figure 13.4). All we need to do is insert the generators in appropriate spots, and significant power can be extracted. The generators might look like underwater windmills. Because the density of water is roughly a thousand times that of air, the power of water flow is one thousand 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 estimate how much tidal energy rolls around Britain every day.

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 per hour. (The crest of the

tidal range	power per unit area
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 13.5. Power density of tide-pools, assuming generation from both the rising and the falling tide.

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

Table 13.7. Tide-farm power (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.)

wave moves much faster than the water itself, just like ordinary waves on the sea.) 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 per hour. 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. This total power crossing the lines in figure 13.6 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 details. Now let's estimate the power that could be delivered by three specific solutions: tide-farms, barrages, and offshore tidal lagoons.

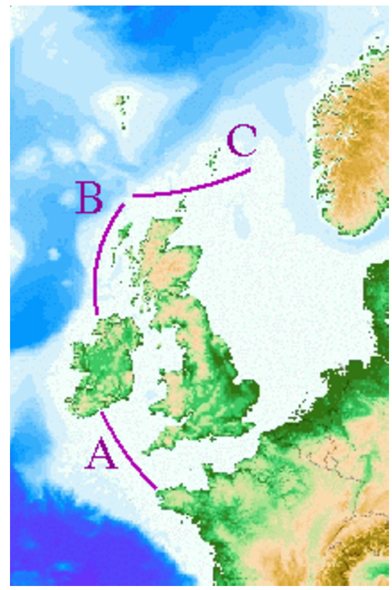


Figure 13.6. Three lines near the edge of the continental shelf. The total incoming power of lunar tidal waves crossing these lines has been measured to be 100 kWh per day per person, of which 76 kWh/d/p comes over line A, and the other 24 kWh/d comes over lines B and C.

Tidal stream

One way to extract tidal energy would be to build tide-farms, just like wind-farms. 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 13.7 shows the power of a tide-farm for a few tidal currents.

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 density can be compared to our estimates of the power densities of wind-farms (2–3 W/m^2) and of photovoltaic solar farms (5 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?

[Finish this bit off by stealing from p.307.]

Answer:

14 kWh/d per person.

Barrages

The tidal range in the Bristol channel is 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 Bristol channel (from Weston super Mare to Cardiff), it would make a 500 km^2 tide-pool. 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? 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**. This calculation assumes that the water is let in all in one pulse at the peak of high tide, and let out all in one pulse at low tide. In practice, the in-flow and out-flow would have to be spread over a few hours, which would reduce the power delivered a little; and the turbines would not extract all the potential energy perfectly: a 10 or 20% loss is likely. [On the other hand, a sneaky trick might be used to boost the power: when the tide is high, pumps could shove a little *extra* water behind the barrage; the energy required to create this small head is recovered, with interest, when the water is let out at low tide. This trick, and the complementary trick at low tide, could be used to significantly boost the power delivered at neap tides. I'll discuss this pumping trick later.] 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.

Insert estimates of tidal lagoons here: 64 TWh/y available in six sea locations: Lancashire, North Wales, Lincolnshire, Southwest Wales, East Sussex, and The Wash. 64 TWh/y is 7.3 GW, or 3 kWh/d per person.

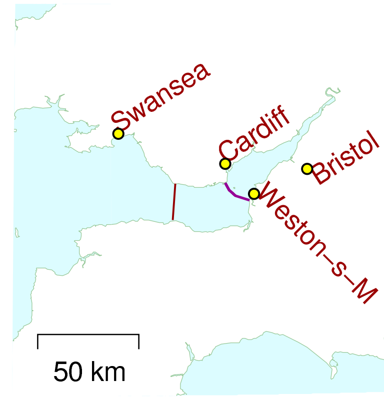
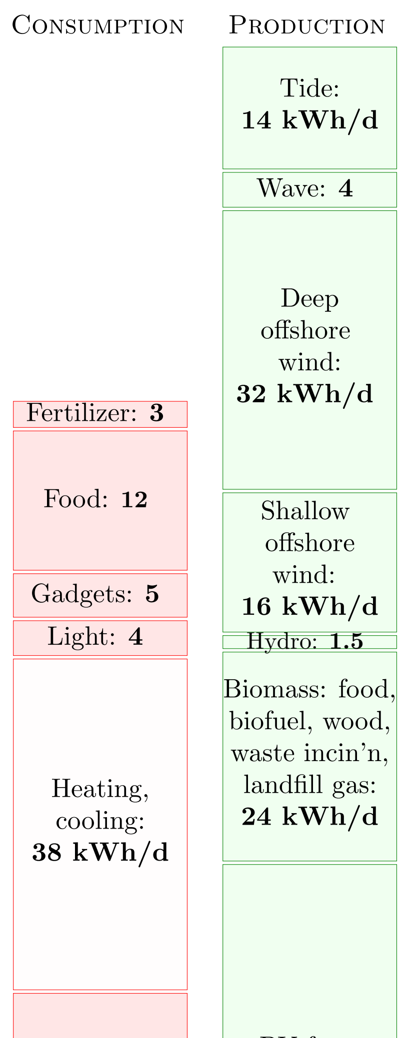


Figure 13.8. Two proposed locations for a Severn barrage. A barrage at Weston-super-Mare would deliver an average power of 2 GW. The outer alternative would deliver twice as much.

Should include maps of good locations of tidal lagoons and diagrams of the two possible flows.



Beauties of tide

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 roll in from the Atlantic and 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 much 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 water flow is greater than the power density of a typical wind, a 60 kW tide turbine would have a smaller size than a 60 kW wind turbine. Perhaps tide turbines could 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 than the corresponding objections to wind turbines.

Mythconceptions

"Tidal power is not renewable."

"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 energy of the spinning earth is 2×10^{29} J

Total world power consumption is 15 TW. If we sucked all this power out of the earth's rotation then after one million years, the rotational energy energy of the earth would be reduced by less than 1%.

Natural rotational energy loss is roughly 3 TW Shepherd [2003].

Natural slowing rate of the earth owing to tidal friction is 2.3 ms/day per century.

Many tidal energy extraction systems are just extracting energy that would have been lost anyway in bottom friction. But even if we did *double* the energy extracted from the earth–moon system, how long would tidal energy last?

Answer: more than a billion years. In two million years, the length of a day would be longer by two minutes instead of one minute.

Notes

82 *The power of an artificial tide pool.* The power per unit area of a tide pool is derived on p.300.

83 *Britain is already supplied with a natural tidepool ... known as the North Sea.* I should not give the impression that the North Sea fills and empties just like a tidepool on the English coast. The flows in the North Sea are more complex because the time taken for an increase 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.

84 *The total incoming power of lunar tidal waves crossing these lines has been measured to be 100 kWh per day per person.* Cartwright et al. [1980] found (by measuring currents and depths along the edge of the continental shelf) that the average power transmission was 60 GW between Malin Head (Eire) and Floro (Norway) and 190 GW between Valentia (Eire) and the Brittany coast near Ouessant. The power entering the Irish Sea was found to be 45 GW, and entering the North Sea via the Dover Straits, 16.7 GW. For readers who like back-of-envelope models, chapter G shows how to estimate these powers from first principles.

85 *The engineers' reports on the proposed Severn barrage...* say 17 TWh/year, which is 0.8 kWh/d per person Taylor [2002].This corresponds to 5% of current electricity consumption, or to 2 GW.

Check-up

How do this chapter's estimates compare with those of government offices?

Estimates vary. According to the DTI Digest of Energy, 2004, 'a recent study estimated that the available UK tidal resource is up to 22 TWh per year' (1 kWh/d per person) – significantly smaller than my estimate of 14 kWh/d per person. But the Scottish Executive in 2001 estimated that Scotland alone has a potential 7.5 GW of tidal power (3 kWh/d per person if shared across the UK).

Notes

La Rance: generated 16 TWh over 30 years. That's an average power of 60 MW. Tidal range up to 13.5 m; impounded area 22 km^2. Barrage 750 m long. Average power density: 2.7 W/m^2.

[2cfgle] an explanation of how Atlantic tides work. Crests and troughs rotate anticlockwise around the Ocean. High tide in France precedes Ireland by 40 minutes, and Iceland by 2 hours.

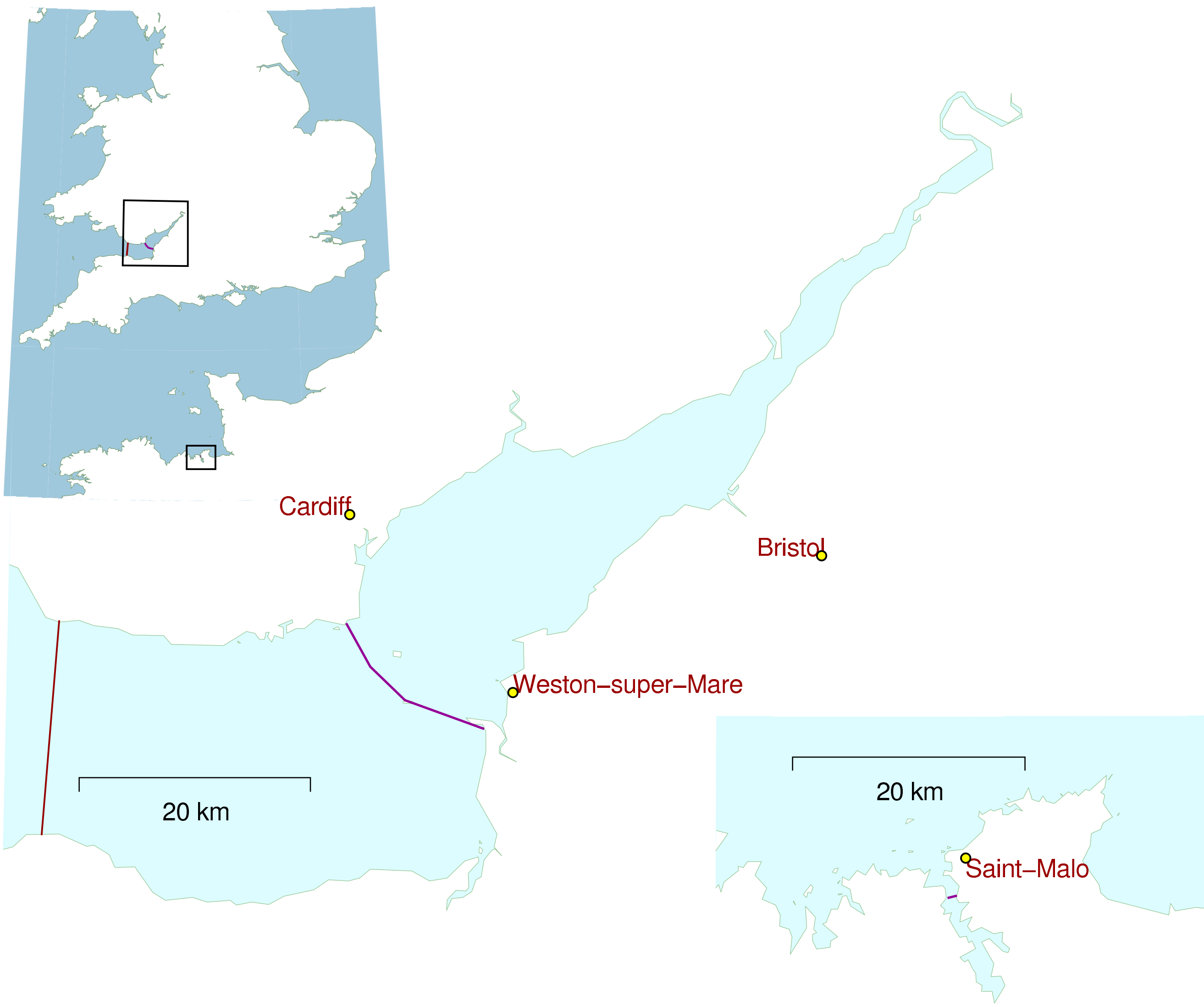


Figure 13.10. The Severn barrage proposals, shown on the same scale as the barrage at la Rance.

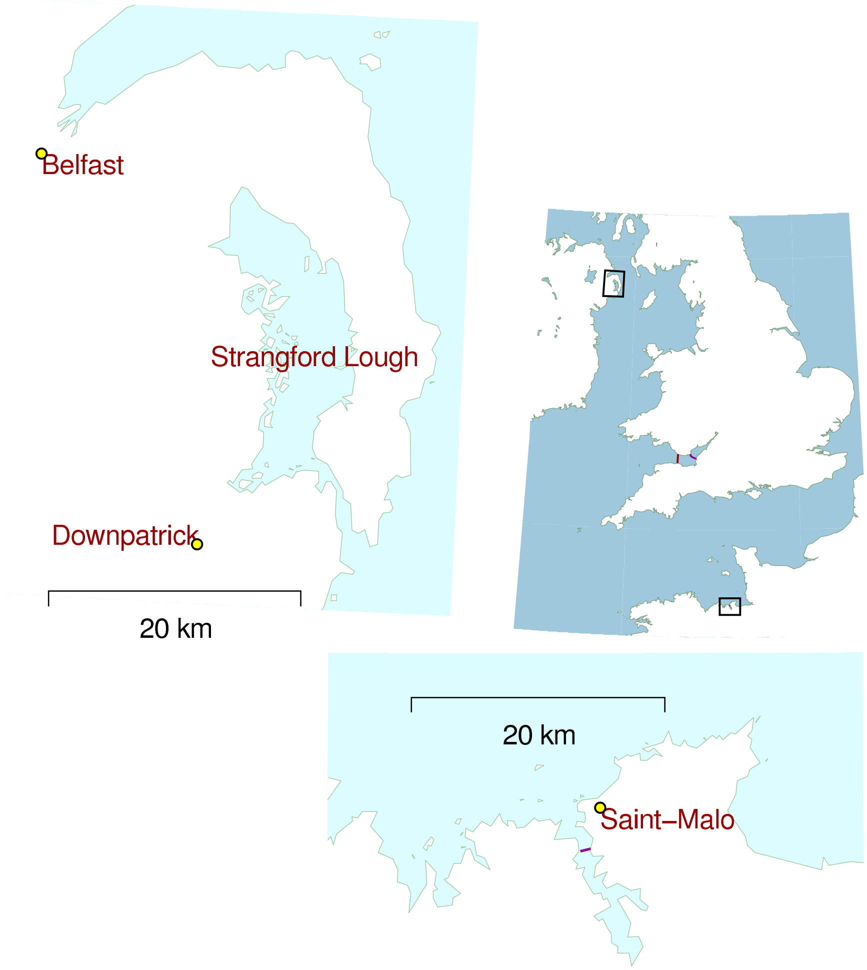


Figure 13.11. Strangford Lough, Northern Ireland, on the same scale as la Rance. Strangford Lough's area is $150\,\text{km}^2$; the tidal range in the Irish Sea outside is 4.5 m at springs and 1.5 m at neaps – sadly not as big as the range at la Rance or the Severn. The raw power of this natural tidepool is roughly 150 MW, which, shared between the 1.7 million people of Northern Ireland comes to 2 kWh/d per person.

Turbines are about 90% efficient for heads of 3.7 m or more. Baker et al. [2006].

14

Stuff

Figure 14.1. Selfridges' rubbish advertisement.

The polluter is not the producer, but rather the consumer.

Dieter Helm

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 known by the name 'goods'. The moment 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, with a view perhaps 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: [cite Mike Ashby]

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

Rather than estimating in detail how much energy the production and transport of stuff costs, let's just cover a few common examples: drink containers, computers, junk mail, cars, and houses.

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 Evian water bottle made of PET (which weighs 25 g), the energy value of the raw materials is the value of 25 g of crude oil, which (at an exchange rate of 10 kWh per kilogram) is 0.25 kWh.

A personal computer costs 250 kg of fossil fuels. Assume that's 2500 kWh. If you buy a new computer every two years, that's 4 kWh per day.

Chips: **4**
Aluminium: **3**

Figure 14.2. Five aluminium cans per day is 3 kWh/d; one personal computer every two years is 4 kWh/d.

Batteries

I wonder what the energy cost of making AAs is?

Here is the answer for a rechargeable Nickel-Cadmium battery, storing 1 Wh of electrical energy and having a mass of 25 g. The energy cost of raw materials and manufacture is 1.4 kWh per AA battery. The energy cost of batteries is unlikely to be a significant item in your stack of energy consumption. Throwing away two AA batteries per month uses 0.1 kWh/d.

Figure 14.3. She's making chips. Photo: ABB.

Newspapers, magazines, and junk mail

A 36-page newspaper, as 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. Making newspaper from virgin wood has an energy cost of about 5 kWh per kg, and the paper itself has an energy content similar to that of wood, about 5 kWh per kg. That's a total of 10 kWh embodied energy per kg of paper.

Let's estimate how much energy is embodied in a typical personal flow of junk mail, magazines, and newspapers. Imagine that our typical person acquires, voluntarily or involuntarily, 200 g of newspaper per day – that's equivalent to one Independent per day for example – and that they pop this paper in with the rubbish that heads off to landfill. The total power going into this stream of paper 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

Figure 14.4. Paper materials.

Packaging

From foodmiles document: 1995: 137 kg packaging used per person. 25 million tonnes of waste was produced in 1997 in the UK and a third of this was food packaging. That's a number worth remembering: Waste production: 400 kg per person per year, or roughly 1 kg per day.

Dajnak and Lockwood [2000] says 490 kg of municipal solid waste per urban inhabitant in the UK in 1996. Four tonnes of municipal solid waste (MSW) contains as much energy as 1 tonne of coal – 8000 kWh of heat. Gross calorific value of MSW: 6500–10,000 kJ/kg. 1800–2800 kWh/kg. Electricity produced: 1–1.4 kWh/kg. 200 000 t MSW per year → 21.5 MW. My graph (waste.eps) indicated 200 000 t MSW per year → 18 MW.

Bigger stuff

The largest stuff most people buy is a house.

In chapter H I estimate the energy cost of making a house, assuming you make a new one every 100 years. The estimated energy cost is 2.3 kWh/d. This is the energy cost of the *shell* of the house only – the bricks, tiles, 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.

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, including maintenance costs, the total cost of over 40 years was 126 GJ/m. 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.

Transporting the stuff

To do: move all my transport estimates here.

See industry.tex for the cost of supermarkets.

HGVs do 2 miles per litre. (10 mpg)

Transport of stuff by road

Total road transport in Britain by heavy goods vehicles was 156 billion t-km in 2006. Shared between 60 million, that comes to 2500 t-km per person per year, or (assuming 1 kWh per ton-km) 7 kWh per day per person. (In this chapter's notes I derive 1.06 kWh/tkm for UK road freight.) One quarter of the transport, by the way, was of food, drink and tobacco.

Transport by water

International shipping (2002, UK share – 560 million tonnes of freight): 7.5 Mtoe [Anderson et al., 2006] (6.2 MtC, 23 $MtCO_2$).

So **4 kWh/d per person**.

Transport of water

Water's not a very glamorous stuff, but we use a lot of it – about 160 kg per day per person. The UK emits 3 million tonnes of carbon dioxide pumping water around the country every year.

[`yhcttw`] Putting into kWh at a conversion rate of 0.5 kg/kWh(e): 100 kWh per year each, or 0.3 kWh/d each.

What's the conversion rate for a domestic user? [`35dlrb`] In 1997/98 the UK consumed just over 16.8 billion cubic metres of water.

Non-domestic usage accounted for 13.5 billion cubic metres while 3.3 billion cubic metres were used by households through the public water supply network.

Public water supply amounted to 7.2 billion cubic metres of which 1.8 million was lost through leakage. Domestic use accounted for nearly 45 per cent of the public water supply with the remainder spread fairly evenly across the manufacturing and services sectors.

(end quote)

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

Figure 14.5. Food-miles – Pasties, hand-made in Helston, Cornwall, shipped 360 miles for consumption in Cambridge.

	embodied energy (kWh per kg)
fossil fuel	10
wood	5
paper	10
aluminium	
steel	6

Table 14.6. Embodied energy of materials.

Road freight: **7**

Figure 14.7. Energy cost of UK road freight: 7 kWh/d per person.

	Energy consumed	Emissions of CO_2

cost of turning salt water into drinking water? The least energy-intensive method for desalination 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. There must be a payment of high-grade energy to bribe nature to permit unmixing.

The Island of Jersey has a desalination plant that can produce 6000 m^3 of pure water per day. The reverse osmosis filters are driven at a pressure of 65 bar. 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 cubic meter of water produced.

At a cost of 8 kWh per m^3, a daily water consumption of 160 l requires 1.3 kWh per day.)

Taking the pee

10 billion litres per day of sewage are produced in England and Wales (about 200 l per person), requiring 6.3 GWh of energy to process. That's 0.1 kWh per day per person.

Total waste per person: (Europe?) 610 kg/capita (2003).

UK Waste dumped in landfill per year per person is 375 kg per person (2005). (Denmark incinerates 363 kg; Netherlands 197; UK 45 kg, producing 0.5 Mtoe.)

Stuff retail

Supermarkets currently consume about 11 TWh of energy per year and have a carbon footprint of 4.1 M tonnes CO_2 (3% of all UK emissions). [yqbzl3]

Shared out equally between 60 million happy shoppers, that's a power of **0.5 kWh/d** per person.

The significance of imported stuff

In standard accounts of 'Britain's primary energy consumption' or 'Britain's carbon footprint', imported goods are *not* counted. Britain used to make its own gizmos, and our footprint used to be huge. 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 the gizmo, because it's imported? I don't think so. Dieter Helm and his colleagues in Oxford suggest that under a correct account, allowing for imports and exports, Britain's carbon footprint is nearly *doubled* from the official '11 tons $CO_2^{(e)}$ per person' to about 21 tonnes. If they are right, this

Figure 14.12. Part of the reverse osmosis facility at Jersey Water's desalination plant. The pump in the foreground has a power of 355 kW and shoves seawater into 39 spiral-wound membranes in the banks of blue horizontal tubes, top, 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.

Supermarkets:

implies that a typical British person's energy footprint is dominated by the energy cost of making imported stuff.

In chapter H I explore this idea further, confirming Dieter Helm's estimate by looking at the weight of Britain's imports. Leaving aside our imports of fuels, we import a little over two tons per person of stuff every year, of which about 1.3 tons per person are made up of processed and manufactured stuff like vehicles, machinery, white goods, electrical and electronic equipment. Such goods are mainly made of materials whose production required at least 10 kWh of energy per kg of stuff. I 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 summarise 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 (at least 40 for imports, 2 for a daily newspaper, 2 for road-making, 2.3 for house-making, and 3 for packaging) and 12 kWh per day per person for the transport of the stuff by sea and by road, and the storing of food in supermarkets.

Work till you shop

Anon

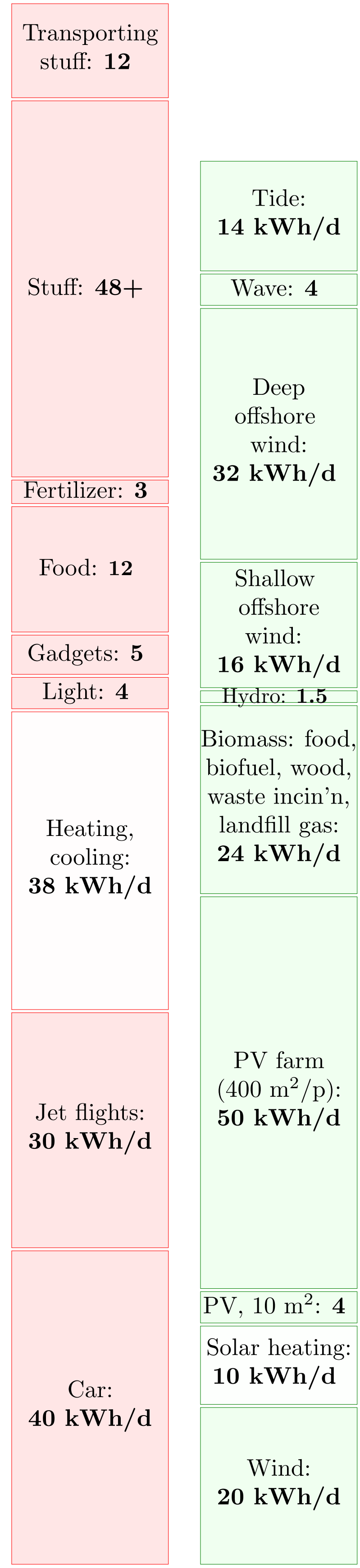


Figure 14.15. Making our stuff

Notes

91 *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. The figure I used is from The Aluminum Association [y5as53]: 150 MJ per kg of Aluminium (40 kWh/kg). Higher figures such as 230 MJ/kg can also be found [r22oz],[yhrest]. Lower figures such as 60 MJ/kg [yx7zm4] are presumably based on the electrolysis cost alone. The energy cost of electrolysing Aluminium ore to produce Aluminium is about 15 kWh/kg (54 MJ/kg). In addition, the electrolysis burns up carbon electrodes: 1.5 to 2.2 tons of carbon dioxide are emitted for each ton of aluminum produced. If we value the electrodes at 27 GJ/tonne of carbon (the same as coal), the electrodes are worth another 11–16 MJ/kg of aluminium. The remaining 80 MJ/kg in the Aluminum Association figure of 150 MJ per kg presumably comes from mining, processing and transport.

91 *A personal computer costs 250 kg of fossil fuels.* Manufacture of a PC requires (in energy and raw materials) the equivalent of about 10 times its own weight of fossil fuels. Fridges, cars, etc generally take 1-2 times their weight.

?? *steel. . .* From Swedish Steel, 'The consumption of coal and coke is 700 kg per ton of finished steel, equal to approx. 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.' [y2ktgg]

Corus say they use 18 GJ/ton of steel (5,000 kWh/ton, or 5 kWh/kg) [y55ppn].

92 *Making newspaper from virgin wood has an energy cost of about 5 kWh per kg.* Energy costs vary between mills and between countries. 5 kWh per kg is the figure for a Swedish newspaper mill in 1973 from a paper [Norrström, 1980] which estimated that efficiency measures could reduce the cost to about 3.2 kWh per kg – part heat, part electricity. A more recent full lifecycle 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. From a greenhouse-gas point of view, incidentally, the worst of all is virgin paper production followed by landfilling: in landfill about half of the paper's carbon is turned into methane, which is a stronger greenhouse gas than CO_2.

92 *the paper itself has an energy content similar to that of wood.* Source: Ucuncu [1993], Erdincler and Vesilind [1993]; see p. 278.

94 *10 billion litres per day of sewage are produced in England and Wales, requiring 6.3 GWh of energy to process.* Source: Parliamentary Office of Science and Technology. `http://www.parliament.uk/documents/upload/postpn282.pdf`

91 *a rechargeable Nickel-Cadmium battery.* This estimate is from Rydh and Karlström [2002]. Here are some details of how the 1.4 kWh breaks down. Energy of making a NiCd rechargeable battery: 44% is for production of raw materials; 55% is for manufacture of battery from the raw materials. Extracting and refining Cadmium: 70 MJ/kg (20 kWh/kg). Nickel: 159 MJ/kg (44 kWh/kg). Manufacturing: 140 MJ per kg of battery (40 kWh/kg).
The energy associated with using a rechargeable battery may be 2–32 times greater than energy of manufacture, depending on the efficiency of the battery charger, and on whether the charger is left plugged in. Recycling is a good idea, in life-cycle analysis terms, for 90% of batteries (*i.e.*, don't bother transporting in every single battery, but cast the net wide enough to get 90%). Recycling Cadmium and Nickel from batteries uses respectively 46% and 75% less energy than extracting and refining virgin metal. Making a battery from recycled cadmium and nickel costs 16% less primary energy than making it from virgin metals.
Metal intensity of a lithium-based battery is 0.14–0.52 kg/kWh. Lithium batteries are the best rechargeable batteries in terms of metal mass required.

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

?? What is the pressure required to get reverse osmosis to go? According to the laws of physics, it's got to be at least the osmotic pressure of the seawater, which is proportional to the concentration of solute in the solution. Seawater's osmotic pressure is 26.75 bar. Cl^- 0.546 mol/kg.

Na^+ 0.469 mol/kg. Others: 0.105 mol/kg. Total: 1.12 mol/kg. Density is 1.025 kg/l, so molar density is 1.148 mol/l = 1148 mol/m^3. (Assuming full dissociation.) $R = 8.314$ J/K/mol. With $T = 293$ K, $RT = 2436$ J/mol So $p = cRT = 28$ bar. Pressure is an energy per unit volume, so we can also write this as 2.8 MJ/m^3 = 0.78 kWh/m^3. This is the unavoidable energy-cost per unit volume for desalination. This pressure is the pressure associated with a 280 m column of water. In practice, the pressure used is roughly double the osmotic pressure, so a pressure of 50–60 bars is required, or a head of 560 m. Coincidentally this is exactly the head between the Dead Sea and the high point of the proposed 'two seas canal', which would deliver water from the Red Sea to the Dead Sea. It's proposed that the water would be desalinated and pumped up the initial hill and would generate hydroelectricity as it went down the greater drop into the Red Sea. I wonder if they could instead put the desalination membrane at the *bottom* of the pipe; this would cut out the need for electrically-powered pressurization equipment and for the entire hydroelectric power station.

15

Geothermal

Figure 15.1. Geothermal power in Iceland. Average geothermal electricity generation in Iceland in 2006 was 300 MW (24 kWh/d/person). More than half of Iceland's electricity is used for aluminium extraction. Photo by Gretar Ívarsson.

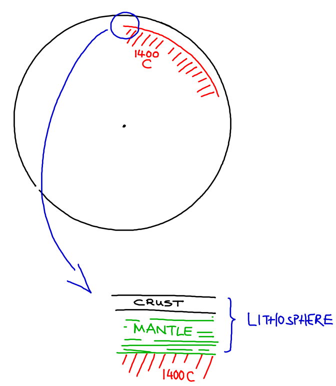


Figure 15.2. An earth, yesterday.

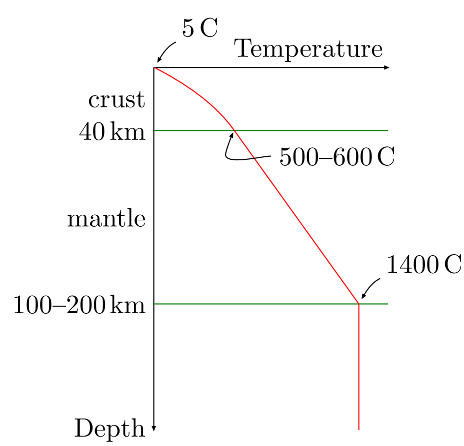


Figure 15.3. Temperature profile in a typical continent.

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; 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, and 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 can estimate geothermal power of two types: the typical geothermal power available at an ordinary location on the earth's crust; and the power available in a few special hot spots like Iceland. 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 energy 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 one of those crushed-ice drinks 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. If you stop sucking, you now have a long wait before the rock at the end of your straws warms up again. A possible attitude to this problem is to treat geothermal energy the same way we currently treat fossil fuels: as a resource to be mined until it runs out. Living off geothermal energy 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? Let's do the sums. In this book I'm most interested in sustainable energy, as the title hinted. So let's first work out the sustainable power we could get from geothermal energy.

One way to use geothermal energy sustainably would be to stick down straws to an appropriate depth, and suck *gently*. Suck 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. We'll discuss this option first.

Then we'll discuss the second option, namely pushing the straw steadily deeper so as to use up all the accessible geothermal energy over, say, 1000 years.

[Should I move most of the following material to a technical chapter?]

First let's estimate the naturally-available heat-flow. In a few hot-spots around the world, the natural heat-flow is big, and we find hot-springs and volcanos. But in this section, I'm going to look at ordinary areas of continent. Here there are hot rocks too, we just have to drill deeper to go and suck from them.

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 flux from the centre coming through the mantle is about $10\,\mathrm{mW/m^2}$. The heat flux at the surface is $50\,\mathrm{mW/m^2}$. So the radioactive decay has added an extra $40\,\mathrm{mW/m^2}$ to the heat flux from the centre.

So at a typical location, the maximum energy we can get per unit area is $50\,\mathrm{mW/m^2}$. But that energy is not useful work, that's the heat that's trickling through at room temperature. 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 room temperature. The temperature increases with depth as shown in figure 15, reaching a temperature of about 500°C at a depth of 40 km. In 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 flux is five 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 set a bound on the maximum power sustainably deliverable by geothermal energy by finding the optimal depth assuming that we have an ideal heat engine that works on temperature difference.

For the temperature profile shown in figure 15, the optimal depth is about 15 km. Here, the temperature is about 270 C, and the heat flux is about 70% of the flux at the surface. The work flux is $17\,\mathrm{mW/m^2}$. At the

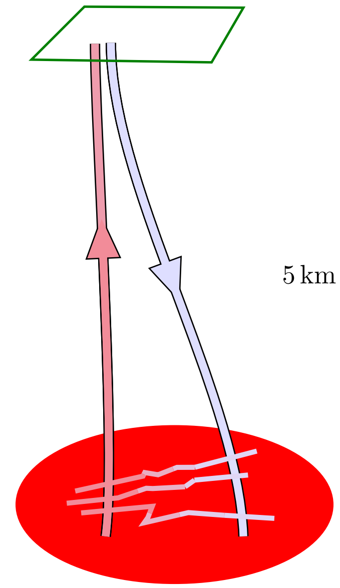


Figure 15.4. Enhanced geothermal extraction from hot dry rock. One well is drilled and pressurised to create fractures. A second well is drilled and cold water is pumped down one well; heated water is sucked up the other well.

world population density of 43 people per square km, that's 10 kWh per person per day. In the UK, the population density is 5 times greater, so widescale geothermal energy could offer at most 2 kWh per person per day.

These are the indefinitely-sustainable figures, 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-kilometre-deep holes. These are electricity figures. In addition to the electricity, a roughly equal amount of heat would be produced as a by-product, which could be used for heating buildings or for pre-heating domestic water.

Figure 15.5. Some granite, yesterday.

MIT strategy [Massachusetts Institute of Technology, 2006] is to drill vertically to 3 km anywhere, then drill horizontally, with many drives from a single bore-hole; and fracture the rocks by pumping in water. 'EGS' means 'Enhanced Geothermal Systems' (not 'high-grade hydrothermal resources', which are much more sparsely distributed). "We focussed our efforts on what it would take for geothermal resources to provide 100 GW(e)'. (Current US 'capacity' is 1000 GW(e).) Have to supply porosity by pressurizing to crack rocks; have to supply water. "Even in the most promising areas, however, drilling must reach depths of 5,000 feet or more in the west, and much deeper in the eastern United States." Drilling into these rocks, fracturing them and pumping water in to produce steam. `http://web.mit.edu/newsoffice/2007/geothermal.html` This could deliver at least 10% of U.S. electricity. 'With a reasonable investment in R&D, EGS could provide 100 GWe or more of cost-competitive generating capacity in the next 50 years. Further, EGS provides a secure source of power for the long term.' 'We have estimated the total EGS resource base to be more than 13 million exajoules (EJ) (thermal). Using reasonable assumptions regarding how heat would be mined from stimulated EGS reservoirs, we also estimated the extractable portion to be about 280,000 EJ or about 2000 times the annual consumption of primary energy in the United States in 2005.' [For comparison, the hydrothermal resource is estimated to be at most 10 000 EJ.] To extract thermal energy economically, one must drill to depths where the rock temperatures are sufficiently high: for generating electricity, the MIT report indicates rock temperatures exceeding 150°C to 200°C are required. At a depth of 6.5 km, almost all of the USA is above 100°C; only a small fraction is above 200°C. At a depth of 10 km, almost all of the USA is above 150°C and roughly half is above 200°C.

Let's assume the continent of the USA is representative of the world as a whole, and run with the figure of 280 000 EJ above, converting it into personal units. Let's assume we're aiming for electricity. Geothermal energy to electricity conversion is about 10% efficient. (Remember, hot water's energy is a lower grade of energy than electricity.) So the extractable energy per unit area is

$$28\,000\,\mathrm{EJ}/9\,600\,000\,\mathrm{km}^2 = 800\,\mathrm{kWh/m}^2$$

Steady extraction of this energy over a period of 1000 years would correspond to a flux of

$$0.1\,\mathrm{W/m^2}.$$

With an area per person of $23\,000\,\mathrm{m^2}$, this steady extraction would deliver

$$50\,\mathrm{kWh/d}\text{ per person,}$$

if every square metre of continent were exploited. Quite a nice sum! [On the other hand, with an area per person of $4000\,\mathrm{m^2}$, geothermal offers only 9 kWh/d per person. (And the UK doesn't have good rock temperatures.)]

More to come here: estimate the extraction cost (pumping and drilling).

Would living on geothermal energy produce a shortage of another resource such as water? Let's assume production of 50 kWh/d per person. This much power can be carried by a flow of 400 litres per day of water, assuming a temperature change of 100°C. Assuming that 10% of the water pumped down a well is lost, extraction of electrical power at this rate would require water-topping-up at a rate of 40 litres per day per person. That's a significant amount, but not impossible in wet countries: for comparison, Britain's consumption of piped purified water is 160 litres per day per person.

What's the area required? A 100 MW(e) plant mining a subsurface reservoir of $5\,\mathrm{km^3}$ would require a surface area of $2.1\,\mathrm{km^2}$ for its bits and bobs. That's $50\,\mathrm{W/m^2}$. Compare that with the flux $0.1\,\mathrm{W/m^2}$, I deduce that 1/500 of the land area would be taken up by geothermal plant.

Magma

What I've just described is known as the 'hot dry rock' approach to large-scale geothermal power. Another approach, researched by Sandia Labs in the 1970s, is to drill all the way down to magma at temperatures of 600–1300°C, 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. In contrast to hot dry rocks, which contain a finite resource which our mining might exhaust over 1000 years or so, magma-power enthusiasts talk of getting power from *circulating* magma, which could be tapped for millions of years.

Boise

The first district heating system in the USA was in Boise, where in 1890 natural hot springs were used to heat over 200 buildings and a swimming pool. The current city system heats several million square feet of building including the City Hall.

(I have more details in notes.)

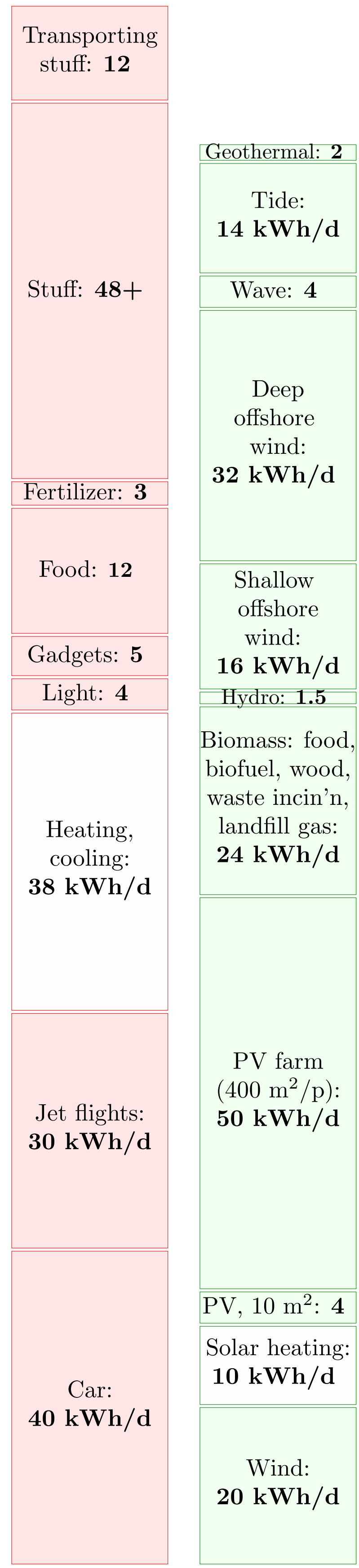
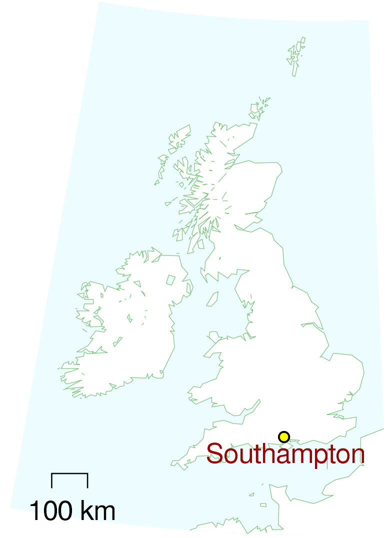


Figure 15.6. Geothermal

The biggest estimate of the hot dry rock resource in the UK is 130 000 TWh (total energy). It's estimated that of this, 1880 TWh might be accessible, most of it in Cornwall, and could be extracted at a rate of 75 TWh/y, which is 3.4 kWh/d per person for 25 years – not a very sustainable duration! And we haven't taken into account the energy lost in conversion to electricity and in pumping and drilling. If the whole 130 000 TWh were magically extracted over 1000 years without loss, that would amount to 6 kWh/d per person.



Southampton Geothermal District Heating Scheme

Southampton, Hampshire

(In 2004 this was the only geothermal heating scheme in the UK)

The Southampton Geothermal District Heating Scheme provides the city with a supply of hot water. How much does it supply?

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 heat delivered by this system.

Their CHP system produces 70 GWh of energy per year according to `www.southampton.gov.uk`.

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.

Mid-ocean geothermal power

What if we went to the place where the earth's crust is thinnest? – where it is being formed. Black smokers are mid-ocean hydrothermal vents out of which superheated water pours. The raw power of all black smokers on the planet is roughly 7 TW, which is 30 kWh/d/p.

Notes

102 The heat flux at the surface is 50 mW/m^2. (Massachusetts Institute of Technology [2006] says 59 mW/m^2 average, with a range, in the U.S.A., from 25 mW to 150 mW.) Shepherd [2003] says 63 mW/m^2.

There is a super animation at [`2cv3ry`].

Figure 15.8. Geothermal power in Iceland. Photo by Rosie Ward.

Useful facts: Heat capacity of Silicon (typical solid?) 711 J/kg/K. Density 2.33 g/cm^3.

MIT report says – water requirements of geothermal may be a problem.

16

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 D.D. Eisenhower – April, 1953

'Defence': **4**

Figure 16.1. The energy cost of 'defence' in the UK is estimated to be about 4 kWh per day per person.

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 'defense'

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). [I use 250 million rather than the current 300 million to represent the typical USA population during 1945–1996.]

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. A ton of TNT is 4.2 gigajoules or 1200 kWh. A megaton bomb delivers an energy of 1.2 billion kWh. If dropped on a city of one million, a megaton bomb makes and 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 defense seriously, it 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.

Other facts

Hiroshima was 15 kt, Nagasaki was 22 kt.

The bomb that destroyed Hiroshima had the energy of 15 000 tons of TNT or 15 kilotons – that's 45 kWh per resident of Hiroshima.

The cost of not making nuclear weapons

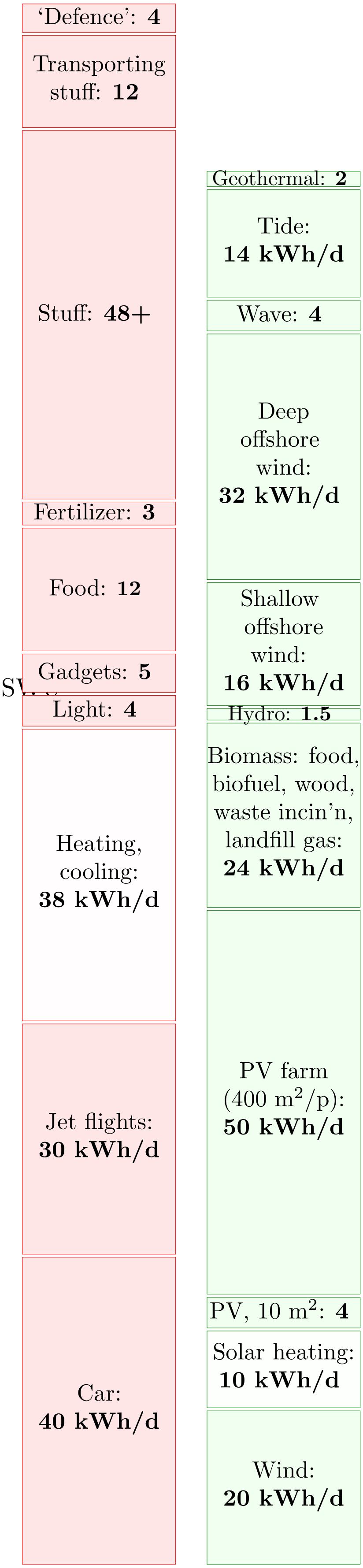
Today, the US Department of Energy's budget allocates at least $4.5 billion per year to "stockpile stewardship" activities to maintain the nuclear stockpile *without* nuclear testing and *without* large-scale production of new weapons.

Energy cost of making nuclear materials for bombs

Plutonium production: the most efficient plutonium–production facilities produce 1 gram of plutonium per megawatt day (thermal). [`slbae`].

So the direct energy-cost of making the USA's 104 tons of plutonium (1945–1996) was at least 2.5×10^{12} kWh which is 0.5 kWh/d per person (assuming 250 million Americans).

A SWU (separative work unit) is a unit of measurement used in the nuclear power industry. It measures the work needed to separate the U-235 and U-238 atoms in natural uranium in order to create a final product that is richer in U-235 atoms. Material enriched to between 4% and 5% U-235 is called low-enriched uranium (LEU). 90%-enriched



uranium is called high-enriched uranium (HEU). It typically takes three times as much work to enrich uranium from its natural state to 5 percent LEU as it does to enrich LEU to 90 percent HEU. If you begin with 100 kilograms of natural uranium, it takes about 60 SWU to produce 10 kilograms of uranium enriched in U-235 content to 4.5%. The number of SWU that would normally be used to produce a kilogram of U-235 as HEU is 232 SWU. The number of SWU required to make 1 kg of U-235 as LEU (in 22.7 kg of LEU) is about 151 SWU. In both cases one starts from natural uranium (0.71 percent U-235) and discards depleted uranium with 0.25 percent U-235.

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 megawatt (MW) commercial nuclear reactor for a year. [yh45h8]

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. [t2948]

A modern centrifuge produces about 3 SWU per year.

OK, so the USA’s production of 994 tons of highly-enriched uranium (the USA’s total, 1945–1996) cost 230 million SWU, which was 0.1 kWh/d per person (assuming 250 million Americans). [Using 2500 kWh/SWU as the cost of diffusion enrichment.]

Arguments

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

Notes

220: *wars and preparation for wars* www.conscienceonline.org.uk UK budget: [yttg7p] of which ‘defence’ is £33.4 billion [fcqfw] and intelligence and counter-terrorism: [2e4fcs]. According to page 14 the Government’s Expenditure Plans 2007/08 [], 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]. [yg5fsj] [yfgjna]
The US military’s energy consumption is known: “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." Department 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 population of 300 million, it comes to **1.7 kWh/d per person**.

103 *The financial expenditure by the USA on manufacturing and deploying nuclear weapons from 1945 to 1996 was \$5.5 trillion (in 1996 dollars).* `http://www.brook.edu/fp/projects/nucwcost/schwartz.htm`.

?? Smil [1999] V. Smil 1999.

Universities

According to Times Higher Education Supplement (March 30th 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.

EPSRC is now responsible via HECToR for a continuous waste heat production of circa 1 MW. (Cray's website lists power consumption as 15–22.5 kW per cabinet and there are 60 cabinets).

Total staff of University of Cambridge number 8602. Student numbers: 11 729 full-time equivalent undergraduates, 1626+4667 postgraduates. Total: 18 022.

Gas and oil consumption of the University of Cambridge (not including its Colleges) was 76 GWh in 2006–7. Electricity: 99.5 GWh. Electricity consumption per unit floor-area is 186 kWh/m^2 per year. If we judge the University to be the place of work of 13 300 people (8602 staff and 4667 postgraduate researchers) then this workplace consumption comes to: 16 kWh/d per person of gas, and 21 kWh/d per person of electricity. Example department: Chemical Laboratory: Area 27 603 m^2. Gas: 7895 MWh. Elec: 9890 MWh. Per person, that's 35 kWh/d of gas and 44 kWh/d of electricity.

How does a newly-built building perform? The Computer Laboratory houses 250 people in 11 110 m^2, and uses 1982 MWh of electricity per year. That's 22 kWh/d per person.

17

Can we live on renewables?

A close race! But please remember: in calculating our production stack we threw all economic constraints to the wind. Also, some of our green contributors are probably incompatible with each other: with our solar PV farm we assumed that we'd use 10% of the country, then with our energy crops 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 10% of the country with photovoltaics is not on – the production stack would no longer match the consumption stack. Our estimate of a typical affluent person's consumption has reached **200 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 **300 kWh per day**. There are other forms of consumption yet to enumerate – we've scarcely touched industry, for example – but I propose that we take a break now and look at some official average figures.

These official averages do not include two energy flows: First, the 'embedded energy' in imported stuff. Embedded energy means the upstream energy expended in making the stuff. We estimated that the embedded energy in imported stuff is at least 40 kWh/d per person. Second, the official estimates of 'primary energy consumption' only include industrial energy flows – things like fossil fuels and hydroelectricity – and don't keep track of the natural embedded energy in food: energy harnessed by photosynthesis. Our estimate of the energy required to keep the food chain going was something like 16 kWh/d per person.

Average European consumption of 'primary energy' is about 125 kWh per day. The UK average is similar to the European average.

If we all raised our standard of consumption to an American level, the green production stack would be utterly dwarfed by the consumption stack.

`http://www.eia.doe.gov/emeu/cabs/United_Kingdom/Full.html` says 2003 consumption was 133 kWh/d per person.

DTI (now known as DBERR) Digest of United Kingdom Energy Statistics Primary demand is 247.3 Mtoe. (Of which about 1.5% is lost

in distribution.) And 53.5 Mtoe of energy value is lost in the process of converting energy from one form to another (for example producing electricity, which chucks heat up cooling towers). So final users actually use 65% of the “primary demand”.

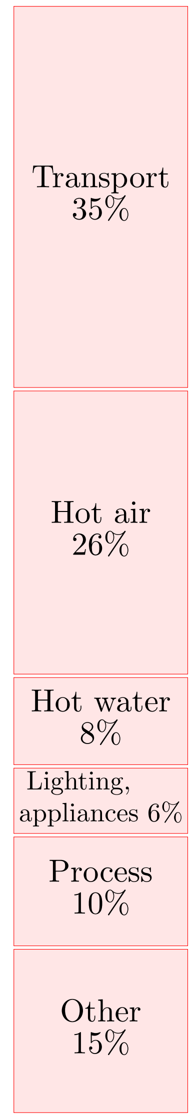
Breakdown of final energy consumption by sector: Transport 33% Domestic 28% Industry 19.5% (of which 1% is iron and steel) Commerce 6% Non-energy use 7%

From government white paper 2003.

Energy use by sector	
Transport	36%
Domestic	30%
Industry	21%
Other	13%

Energy by end use	
Transport	35%
Space heating	26%
Hot water	8%
Lighting, appliances	6%
Process	10%
Other	15%

Consumption by end use



How are we feeling?

Figure 17.1 is a reminder of the production estimates we have made so far. These are not estimates of what would be *easy* to achieve; nor have I considered economic, social, or environmental constraints. These are estimates of maximum plausible sustainable production.

I consider this figure to be bleak news. No single sustainable source matches our current consumption, even if much of the country were industrialized; and even all of onshore wind, shallow offshore wind, solar heating, solar PV at 12 m^2 per person, biomass, food, hydro, tide, wave, and geothermal together don’t reach 90 kWh/d. We can achieve a total substantially bigger than 125 kWh/d only by calling on deep offshore wind (covering an area bigger than Wales) *and* vast photovoltaic arrays (covering an area bigger than Wales).

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 very good at one thing, it’s saying “no.” Wind farms across the country? “No, they’re ugly noisy things.” Solar panels on roofs? “No, that would spoil the visual amenity of the street.” An expansion of forestry? “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 environ-

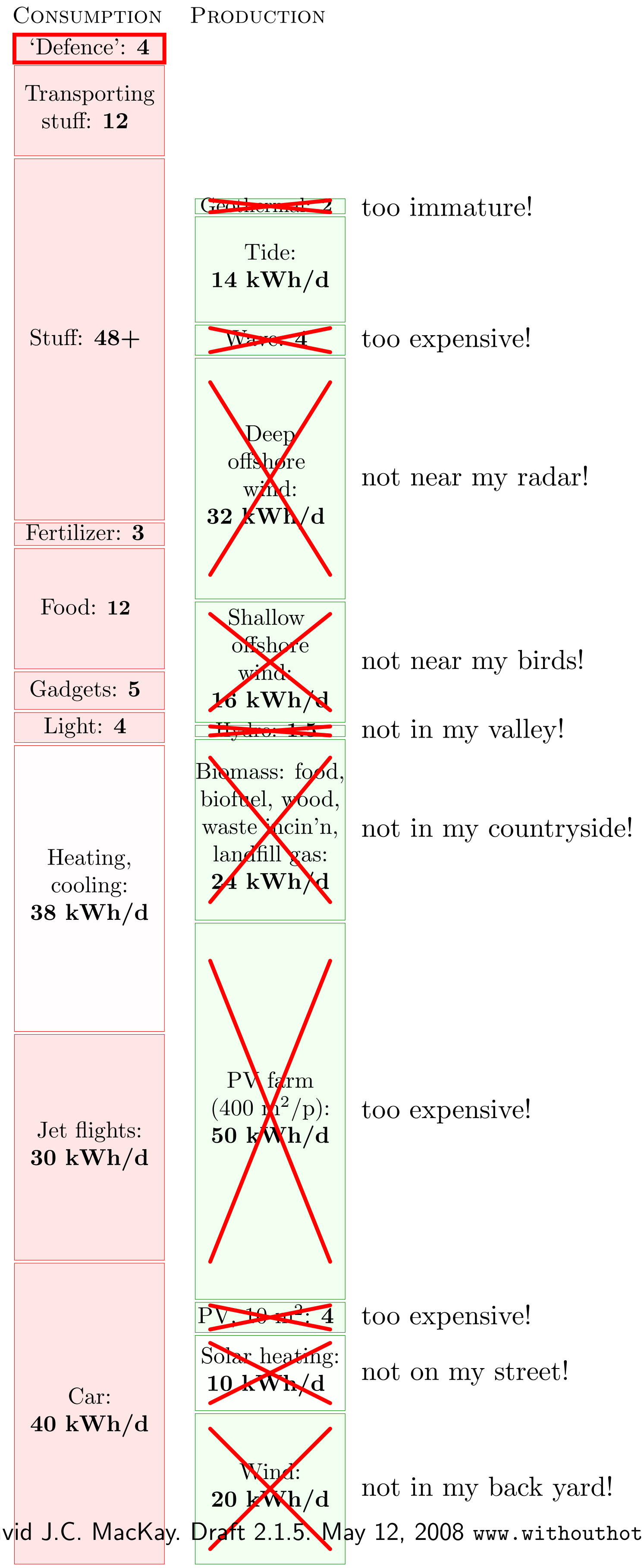


Figure 17.3. The state of play after we add up all the traditional renewables, *and then have a public consultation.*

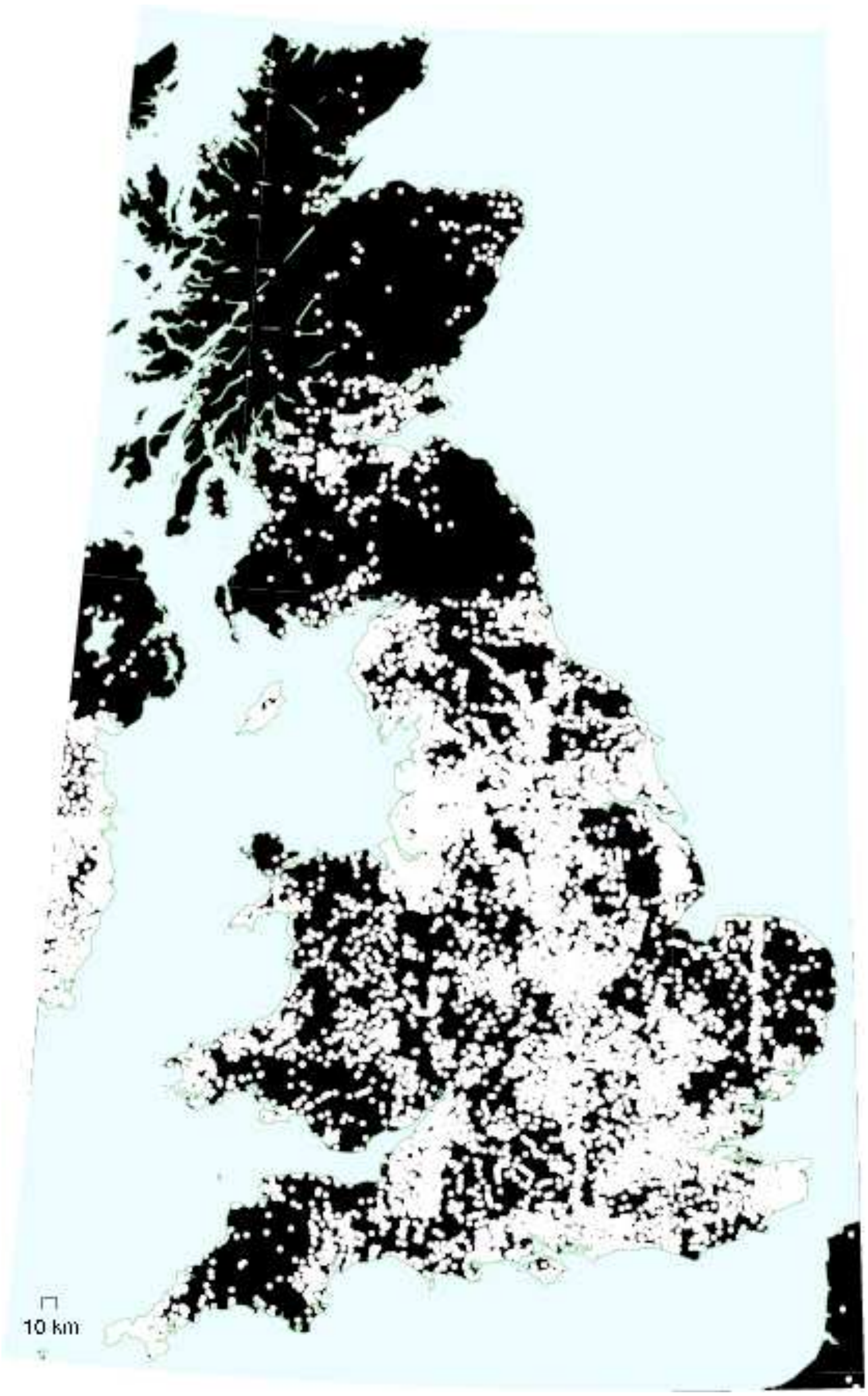


Figure 17.4. Where the wild things are. One of the grounds for objecting to wind farms is the noise they produce. I've chopped out of this map of the British mainland a 2-km-radius exclusion zone surrounding every hamlet, village, and town listed in the openstreetmap database. These white areas would 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.

ment". Offshore wind? "No, I'm more worried about the 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 figure 17.5.

We are drawing to the close of the first part of this book. The premise of the first half was that we want to get off fossil fuels, for one or more of the reasons listed in the preface – climate change, security of supply, and so forth.

The conclusion I expect you to draw from part I is that it's not going to be easy to make a plan that adds up using renewables. 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 of the book I'll ask "assuming that we can't get production from renewables to add up to our current consumption what are the other options?"

Before we address this question, however, perhaps you would like to double-check the conclusion of part I. 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 them with other organizations' 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 total offered by renewables are smaller than my total.) Figure **??** shows figures from the Sustainable Development Commission's publication as a green stack alongside the national average consumption of 125 kWh/d per person.

The Institute of Electrical Engineers published a report on renewable energy in 2002. Table 17.6 shows their summary figures in kWh per day per person. According to the IEE, the total of all renewables' technical potential is about 27 kWh/d per person. The table does not include any contribution from solar energy except biomass. Their figures for biomass and wave all agree with mine; their estimates for tide and wind are quite a lot smaller than mine; The only figure in their list that is bigger than mine is geothermal, where I would readily admit my estimate was not founded on any knowledge of UK geology.

Table 17.7 shows the Tyndall Centre's estimates of renewable energy resources. Their total practicable resource is 15 kWh per day per person.

Table 17.8 shows the Interdepartmental Analysts Group's estimates of renewables, which take into account economic constraints. Their total practical *and* economical resource (at a retail price of 7p/kWh) is

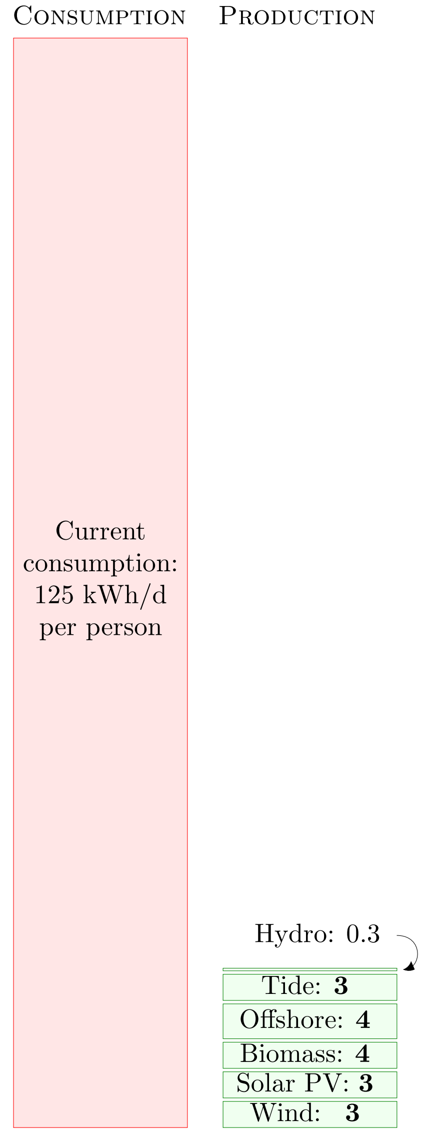


Figure 17.5. After the public consultation. (The left-hand consumption figure, 125 kWh/d per person, by the way, is the average British consumption, excluding imports, and ignoring solar energy acquired through food production.)

Technology	Technical potential (kWh/d/p)
Onshore wind power	2
Offshore wind power	6.4
Biofuels	
– wet and dry wastes	2
– forestry	At least 2
Small-scale hydro	0.09
Tidal power	2.4
Wave power	2.3
Geothermal	10
Total	**27**

Table 17.6. The IEE's 2002 Summary of possible contributions from renewables in the UK. 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".

Technology	Theoretical potential (kWh/d/p)	Practicable resource (kWh/d/p)
Onshore wind	15	2.6
Offshore wind	140	4.6
Solar photovoltaics	12	0.3
Energy crops	9	0.78
Forestry and agricultural wastes		0.6
Municipal solid waste combustion		0.6
Tidal		
– tidal stream		1.6
– barrage		2.3
Wave		
– shoreline	0.09	0.02
– near-shore	6	0.09
– offshore	32	2.3
Hydro power	1.8	0.08
Total		15

Table 17.7. Tyndall Centre – renewable energy resource estimates in the UK. For solar PV, the theoretical potential assumes the use of all suitable buildings in the UK; the practicable resource assumes that solar PV is installed only on new-build projects. Most of these numbers are copies of DTI-commissioned estimates by ETSU from 2000.

Technology	Resource (kWh/d/p)
Onshore wind power	2.6
Offshore wind power	4.6
Solar photovoltaics	0.02
Energy crops	1.5
Agricultural and forestry residues	0.9
Landfill gas	0.3
Municipal solid waste	0.3
Tidal power	0.09
Wave power	1.5
Total	**12**

Table 17.8. Interdepartmental Analysts Group's estimate of "maximum practicable resource in 2025, for electricity to be generated at price under **7p/kWh**." (The retail price of electricity is currently about 2–3p/kWh.)

Technology	Theoretical max (kWh/d/p)	Practical max (kWh/d/p)
Onshore wind	15	2.5
Offshore wind	180	4.6
Solar PV	12	
Energy crops	30	
Municipal waste	0.6	
Landfill gas		0.2
Hydro	1.8	
Tidal stream	1.6	
Tidal barrage	2.3	
Wave nearshore	4.6	0.1
Wave offshore	27	2.3

Table 17.9. DTI-PIU: "Indicative resource potential for renewable electricity generation options" – based on ETSU data.

12 kWh per day per person.

Table 17.9 shows figures from the DTI's contribution to the PIU review in 2001.

All these numbers are summarised in figure 17.10, along with the numbers from the Centre for Alternative Technology's 'Island Britain' plan.

Reach for the sky

> "Europe became the world leader in tackling climate change yesterday when 27 governments agreed to cut greenhouse gas emissions by 20% and commit the EU to generating a fifth of its energy from renewable sources within 13 years."
>
> Guardian, Saturday March 10, 2007.

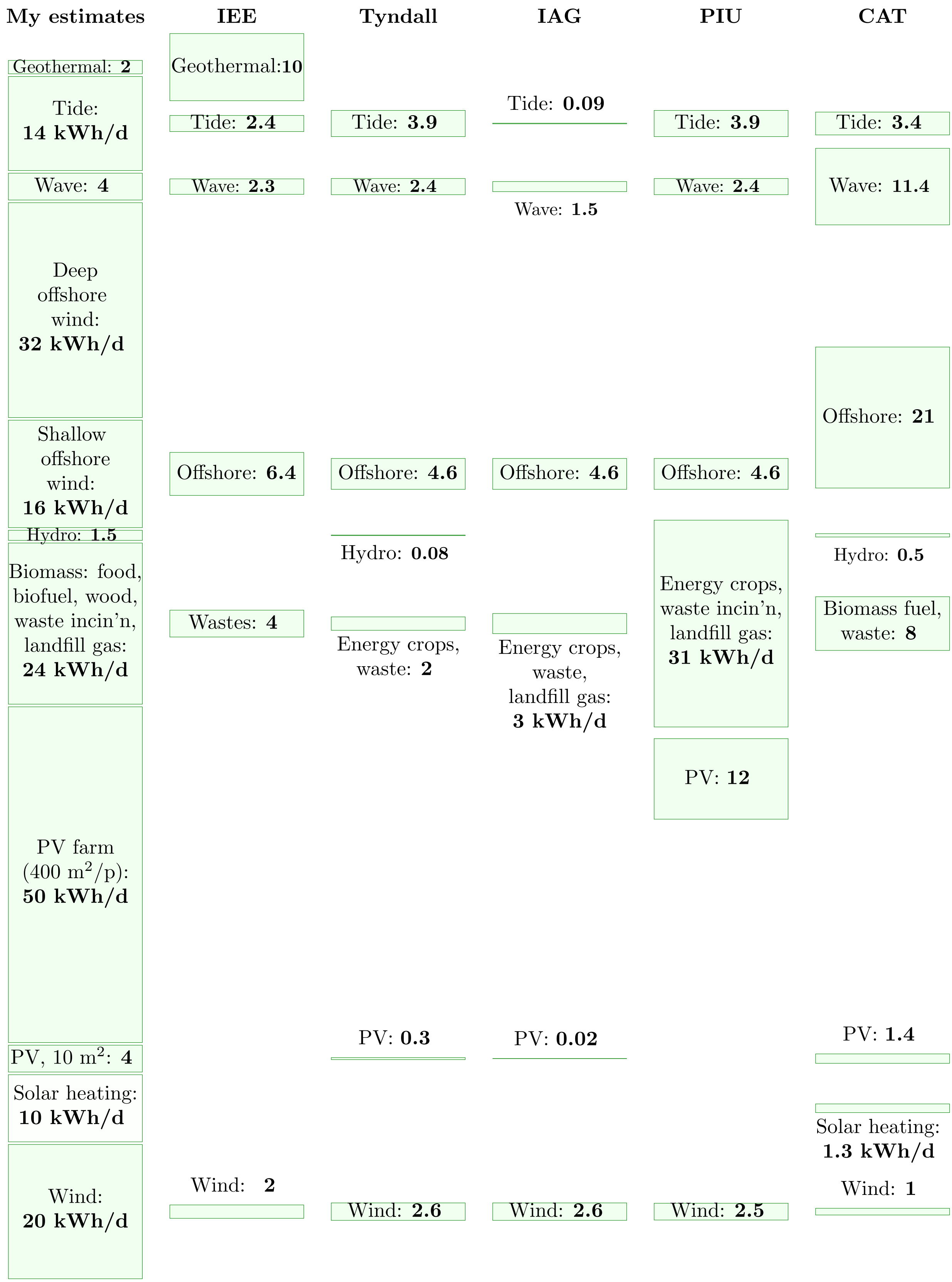


Figure 17.10. Estimates of theoretical or practical renewable resources in the UK, by the Institute of Electrical Engineers, the Tyndall Centre, the Interdepartmental Analysts Group, and the Performance and Innovation Unit; and the proposals from the Centre for Alternative

Primary fuel	kWh/d/p		kWh(e)/d/p
Oil	43		
Natural gas	47		
Coal	20		
Nuclear	9	→	3.4
Hydro			0.2
Other renewables			0.8?

Table 17.11. Breakdown of primary energy sources in the UK (2004–2006).

Can Europe get one fifth of all its energy from renewables by 2020? Reading this headline, I assumed that the journalists had made the standard slip of confusing 'energy' with 'electricity'. Surely Europe was only aiming to get one fifth of *electricity* from renewables? But no. Reading their statement [2aanbx], it is clear that European governments really did mean one fifth of *all energy consumption* – which means roughly 24 kWh/d per person. In the light of the economic estimates of renewables given in this chapter, it will be interesting to see how Britain will achieve this target.

Are we comparing like with like? Are the renewables interchangeable?

I've plopped all the conceivable green contributions in a single stack and compared their total with the red consumption stack. But we should be clear that getting the red consumption stack to be lower than a green production stack would not necessarily mean our sums are adding up. You can't power a TV with cat food, nor can you feed a cat on electricity 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 the forms of energy consumption and production to match up too. Converting energy from one form to another – from chemical to electrical, as at a 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 a later chapter, which will describe some energy plans that do add up.

Summary

Stop saying "we've got huge renewables," and do the sums.

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 windfarms with the area of Wales. To get a big contribution from solar photovoltaics, we required the area of Wales. To get a big contribution from waves, we imagined wavefarms covering

500 km of coastline. To make energy crops with a big contribution, we took 75% of the whole country.

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

"Nuclear or wind?" is the wrong question. We need everything we can get our hands on – all the wind, and all the nuclear – and even then, we're still in trouble.

Notes

The DTI's Digest of United Kingdom Energy Statistics gives a slightly larger figure for primary demand in 2004: 247.3 Mtoe (132 kWh/d). (Of which about 1.5% is lost in distribution.) And 53.5 Mtoe of energy is lost in the process of converting energy from one form to another (for example producing electricity). So users actually use 65% of the "primary demand".

I'm going to split the difference between the BP figure and the DTI figure and say that the average UK citizen uses 125 kWh/d.

1 toe = 11.6 MWh = 42 GJ

Electricity demand total: 402 TWh. Losses = 8% of electricity. (Breakdown: 1.5% in high-voltage system, 6% on public supply system.) Energy industry itself used 8% of electricity.

Nuclear power stations' thermal efficiency is 38%. Nuclear delivers 19% of electricity. Electricity power stations give 30% of CO_2 emissions.

Renewables: 3.81 Mtoe, of which 84% biofuels and 10.5% hydro. (But note this is the input energy, not the output energy; biofuels contribute less than hydro when we go to output energy.)

Biofuels breakdown: landfill gas 35% sewage gas 5% Domestic wood 5% Industrial wood 7% Co-firing 9% Waste combustion 12% Other biofuels 11%

See figure 19.2, which should probably move here.

Digest of United Kingdom Energy Statistics [uzek2].

Part II

Making a difference

18

Every BIG helps

"We were going to have a wind turbine but they're not very efficient"

Figure 18.1. Robert Thompson cartoon from Private Eye April 2007.

What now?

We've established that the UK's present lifestyle can't be sustained on the UK's own renewables (except at huge cost and with the industrialization of country-sized areas of land and sea). So, what are our options, if we wish to live sustainably? We can balance the energy budget of a country like Britain either by reducing demand, or by increasing supply, or, of course, by doing both.

Demand for energy could be reduced in three ways:

1. by reducing our population;

2. by changing our lifestyle;

3. by keeping our lifestyle, but reducing its energy intensity through 'efficiency' and 'technology'.

Supply could be increased above the limits of renewables in three ways.

1. We could get off fossil fuels by investing in 'clean coal' technology. Oh. Oops! Coal is a fossil fuel. Well, never mind – let's take a look at it. If we used coal 'sustainably', how much power could it offer? If we don't care about sustainability and just want 'security of supply', can coal offer that?

2. We could invest in nuclear fission. Is current nuclear technology 'sustainable'? Is it at least a stop-gap that might last for one hundred years?

3. We could buy, beg, or steal renewable energy from other countries – bearing in mind that most countries will be in the same boat as Britain and will have no renewable energy to spare; and also bearing in mind that getting renewable energy from another country won't magically reduce the size of the renewable power facilities required to deliver power comparable to Britain's needs. If we import renewable energy from other countries in order to avoid building renewable facilities the size of Wales in our country,

we must have no illusions: we will probably have to build facilities the size of Wales in those other countries.

The next chapters address the 'efficiency' and 'technology' options on the demand side.

Once we've figured out by how much demand can plausibly be reduced, we can then turn back to the supply side, and quantify how much energy we need to get from nuclear power, or from other people's renewables, if we want to get off fossil fuels and live sustainably.

There are many books describing '100 things you can do to save the planet'. I don't want to bore you to death with a long list of all the things that might make a helpful contribution. I'm also worried that such lists encourage the notion that 'every little helps'.

In the chapters that follow, I won't mention all the good ideas. I'll just discuss the big ideas.

Cartoon Britain

To simplify and streamline our discussion of demand reduction, I propose to work with a cartoon of British energy consumption, omitting lots of details in order to focus on the big picture. Here's how my cartoon works. Cartoon–Britain consumes energy in just three forms: heating, transport, and electricity. The heating consumption of cartoon–Britain is 40 kWh per day per person (currently all supplied by fossil fuels); the transport consumption is also 40 kWh per day per person (currently all supplied by fossil fuels); and the electricity consumption is 18 kWh(e) per day per person; the electricity is currently almost all generated from fossil fuels, with a fossil-fuel input of 45 kWh per day per person. This simplification ignores some fairly sizeable details, such as agriculture and industry, and the embodied energy of imported goods! But I'd like to be able to have a *quick* conversation about the main things we need to do to get off fossil fuels. Heating, transport, and electricity account for more than half of our energy consumption, so if we can come up with a plan that delivers heating, transport, and electricity sustainably, then we have made a good step on the way to a more detailed plan that adds up.

Having adopted this cartoon of Britain, our discussions of how to reduce demand will have just three bits. First, how can we reduce heating's energy-demand and eliminate all fossil fuel use for heating? Second, how can we reduce transport's energy-demand and eliminate all fossil fuel use for transport? Third, what about electricity? (This third bit will discuss how to cope with fluctuations in demand and fluctuations in renewable power production.)

I could spend many pages discussing 'fifty things you can do to make a difference', but I think this cartoon approach, chasing the three biggest fish, may lead to more effective policies.

What about 'stuff'? According to part I, the embodied energy in imported stuff might be the biggest fish of all! Yes, perhaps that fish is

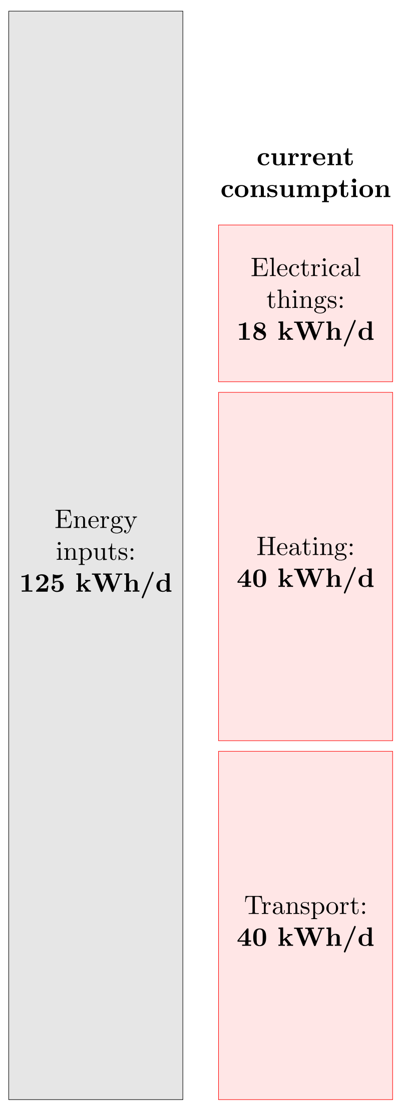


Figure 18.2. Current consumption in 'cartoon Britain 2008'.

the elephant in the room. But let's leave discussion of defossilizing that elephant to one side, and focus on the things over which we have the most direct control.

So, here we go: our big fish are heating, transport, and electricity, and we are going to attack them first on the supply side and then on the demand side.

Lampoon 'every little helps'?

Every little helps

This mantra, *"Little changes can make a big difference"*, is bunkum, when applied to climate change and power. It may be true that "many people doing a little adds up to a lot", if all those 'littles' are somehow focused into a single 'lot' – for example, if one million people donate £10 to *one* accident-victim, then the victim receives £10 million. That's a lot. But power is a very different thing. We all use power. So to achieve a "big difference" in total power consumption, you need almost everyone to make a "big" difference to their own power consumption. If everyone does a little, all that we will get is a little.

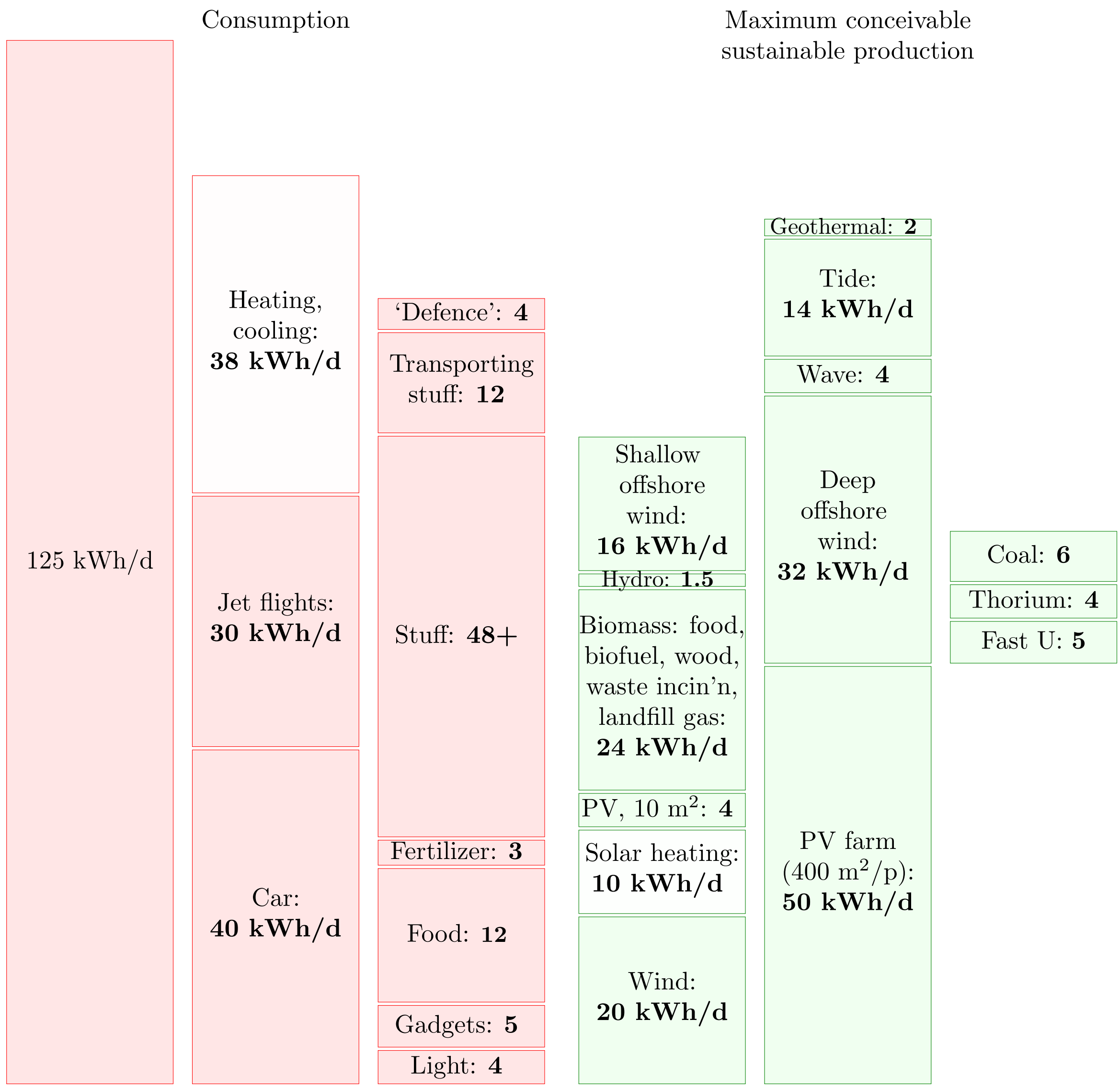
Making a difference

Honda: "This year, our Formula One car will race to raise awareness of environmental issues and to encourage people everywhere to **make a difference** to the world around them. By pledging to make **small changes** to our lifestyle . . . we can all make our Earth dreams a reality." `http://myearthdream.com/`

"The Honda Racing F1 Team's new 2007 Formula One car features a beautiful piece of artwork highlighting our planet Earth."

"On this site we will ask you to make a pledge to change something in your lifestyle in order to help the environment. **Small changes really can make a huge difference**."

"After you have made your pledge your name will appear, not only in a pixel on the digital car, but also as a teeny part of the artwork on the real F1 car."


Consumption
Maximum conceivable sustainable production
125 kWh/d
Heating, cooling: 38 kWh/d
Jet flights: 30 kWh/d
Car: 40 kWh/d
'Defence': 4
Transporting stuff: 12
Stuff: 48+
Fertilizer: 3
Food: 12
Gadgets: 5
Light: 4
Shallow offshore wind: 16 kWh/d
Hydro: 1.5
Biomass: food, biofuel, wood, waste incin'n, landfill gas: 24 kWh/d
PV, 10 m²: 4
Solar heating: 10 kWh/d
Wind: 20 kWh/d
Geothermal: 2
Tide: 14 kWh/d
Wave: 4
Deep offshore wind: 32 kWh/d
PV farm (400 m²/p): 50 kWh/d
Coal: 6
Thorium: 4
Fast U: 5

19

Reflections on sustainable production

Our present happy progressive condition is a thing of limited duration.

William Stanley Jevons, 1865

But first, let's reflect on how we got into this pickle. Could it have anything to do with population growth?

While the footprint of each individual cannot be reduced to zero, the absence of an individual does do so.

Chris Rapley, former head of the British Antarctic Survey

We need fewer people, not greener ones.

Daily Telegraph

Democracy cannot survive overpopulation. Human dignity cannot survive overpopulation.

Isaac Asimov

Figure 19.3. Population growth and emissions... Cartoon from New Scientist.

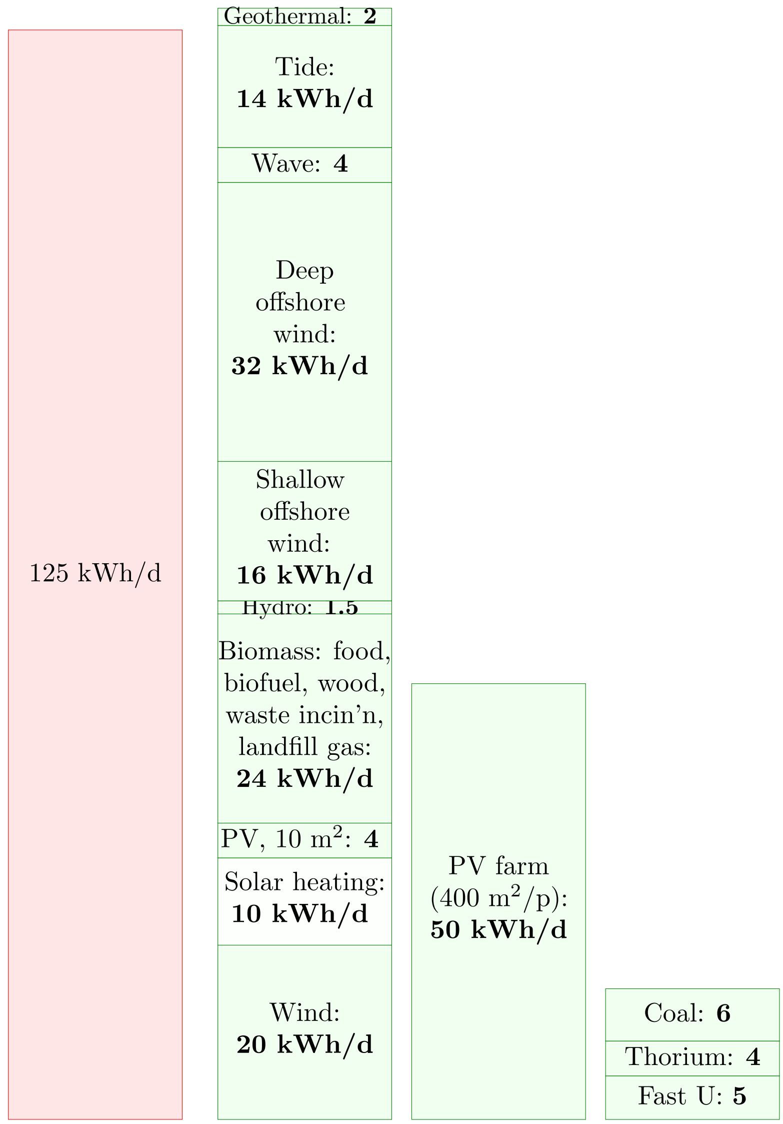


Figure 19.1. Our estimates of maximum plausible sustainable production, alongside an average consumption of 125 kWh per day per person.

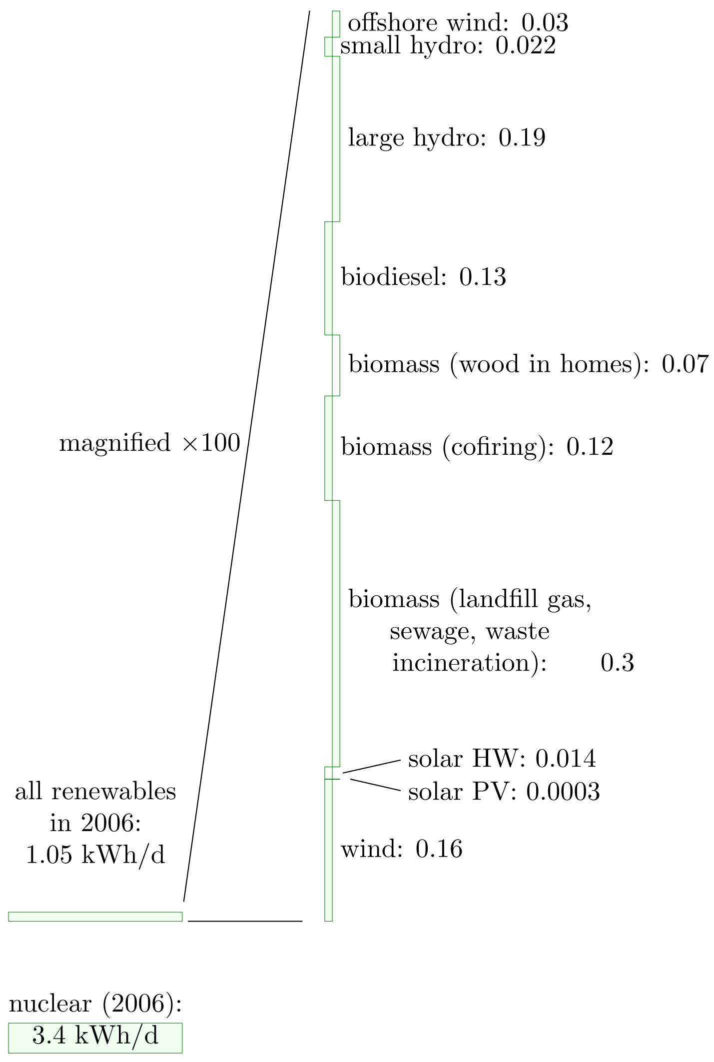


Figure 19.2. Production of renewables and nuclear energy in the UK in 2006. The breakdown of the renewables on the right hand side is scaled up one hundred-fold vertically compared with all the other diagrams in this book.

20

Better transport

Modern vehicle technology can reduce climate change emissions without changing the look, feel or performance that owners have come to expect.

California Air Resources Board

Roughly one third of our energy goes into transportation. Can *technology* deliver a reduction in consumption?

Electric cars. Switching freight from road to rail. Integrated public transport. Magnetic levitation. More-efficient planes. Do any of these ideas add up?

Summary: there's a mix of lifestyle changes and alternative technologies – sometimes difficult to separate: is going by train rather than car a lifestyle change or a technology change? The underlying principles are: reduce frontal area per person; reduce the vehicle's weight per person; when travelling, go at a steady speed; travel slower; travel less; and make the energy chain more efficient.

A widely quoted statistic says something along the lines of "Only *1 percent* of fuel energy in a car goes into moving the driver." – the implication being that, surely, by being a bit smarter, could we not make cars *one hundred* times more efficient? The answer is yes, almost, but only by applying the principles of vehicle design and vehicle use, listed above, to extreme degrees.

One illustration of extreme vehicle design is an eco-car, which has small frontal area and low weight, and – if any records are to be broken – must be driven at low speed. The *Team Crocodile* eco-car does 2184 miles per gallon (1.3 kWh per 100 km) at 24 km per hour. Weighing 50 kg and shorter in height than a traffic cone, It comfortably accommodates one teenage driver. To achieve this performance, the driver must be careful to drive at steady speed.

Here are two other extreme vehicle designs which are more efficient than a standard petrol car by a factor of 25 or more: the bicycle, and the train. The bicycle's performance (in terms of energy per distance) is pretty much the same as the eco-car's. Its speed is the same, its mass is lower than the eco-car's, and its effective frontal area is higher, because

Figure 20.1. Team Crocodile's eco-car. Photo kindly provided by Team Crocodile.
http://www.teamcrocodile.com/

the bike and rider are not so well streamlined as the eco-car. In contrast to the eco-car and the bicycle, trains manage to achieve high efficiency without travelling slowly, and without having a low weight. They make up for their high speed and heavy frame by exploiting the principle of small frontal area per person. Whereas a cyclist and a regular car have effective frontal areas of about $0.8\,\mathrm{m}^2$ and $0.5\,\mathrm{m}^2$ respectively, a full commuter train from Cambridge to London has a frontal area per passenger of $0.02\,\mathrm{m}^2$.

Don't forget where the energy is going. In *long-distance travel* by train or automobile, most of the energy goes into making air swirl around. The key strategies for consuming less in this sort of transportation are therefore to move slower, and to move less, and to use long, thin vehicles.

In *short-distance travel*, the energy mainly goes into speeding up the vehicle and its contents. Key strategies for consuming less in this sort of transportation are therefore to weigh less, and to go further between stops. Regenerative braking may help too. In addition, as above, it helps to move slower, and to move less.

Speed laws

An easy way to reduce energy consumption from transport is to reduce the speed at which people drive. Possibly unnecessary if there is a sufficiently big energy tax, and drivers are educated and informed about the way that fuel consumption increases with speed. But energy taxes won't persuade the rich to drive slowly, so it might be a good idea to introduce 50 mph speed limits on roads, 65 mph on motorways, and 25 mph in built-up areas.

(Quantify expected energy savings – see later in this chapter.)

Vehicle frontal area restrictions

Increased tax for vehicles higher than 4 feet. (Side-benefit: increases visibility of pedestrians and cyclists, and ability of pedestrians and cyclists to see clearly.)

Special lower speed limit, like the current 60 mph speed limit for heavy goods vehicles, for all large vehicles.

Tax incentives favouring cars with lower-power engines.

Include an up-front tax on new cars, proportional to the expected lifetime carbon emissions of the vehicle.

Figure 20.2. Monstercars not only use more fuel – they are also just tall enough to completely obscure the view of pedestrians, and to obscure pedestrians from the view of other drivers.

Coaches for long-distance journeys

Make sure to mention that they are roughly as good as trains in energy terms. Though they are not so easily electrified, they are more flexible in route.

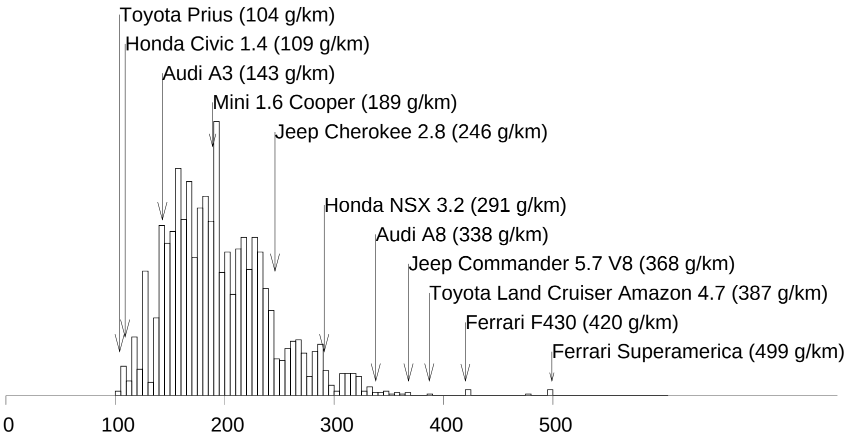


Figure 20.5. Carbon pollution, in grams CO_2 per km, of a selection of ordinary cars for sale in the UK. The horizontal axis shows the emission rate, and the height of the histogram indicates the number of models on sale with those emissions. Source: `http://www.newcarnet.co.uk/`.

Congestion reduction

Stopping and starting, speeding up and slowing down, is a much less efficient way to get around than driving smoothly. Idling in stationary traffic is an especially poor deliverer of miles per gallon.

Congestion can be reduced by providing good alternatives (cycle lanes, public transport), and by charging road users extra if they contribute in congestion.

Figure 20.4. Prius.

Electric cars and hybrids

Transportation guzzles energy, and *the faster we go, the more it guzzles*. Now, let me remind you, I'm not trying to tell anyone what to do. I'm trying to make the numbers clear so you can evaluate alternative suggested policies. So, just in case you are interested in reducing transportation costs, let's sum up policies that would reduce energy consumption significantly.

Reducing the mass of the car makes a difference to consumption during city driving, but not motorway driving.

Regenerative brakes make a difference during city driving, not motorway driving. Using the brakes less in the city makes a similar difference; how can you use the brakes less? By using the accelerator less. So measures that smooth traffic flow, reducing a car's variations in speed, will help.

Reducing the frontal area of cars, and enhancing stream-lining make a difference to motorway energy consumption. The best drag coefficient of cars on the market is 0.25. When comparing cars' drags, don't forget to multiply their drag coefficient by the frontal area. Small cars are better.

Hybrid cars such as the Toyota Prius have more-efficient engines (figure 20.5). The Prius emits about 100 g of CO_2 per km, whereas the typical new car in the UK emits 189 g.

To have the biggest impact on your energy consumption, sell the

Energy-per-distance	
Car doing 33 mpg	73 kWh/(100 km)
Electric car at optimal speed	11 kWh$^{(e)}$/(100 km)
Bicycle at 20 km/h	1.6 kWh/(100 km)

Table 20.7. Facts worth remembering: car energy consumption.

car, and ride a bike. If you insist on keeping a car, you can have a huge impact on your consumption by *driving slower*. If everyone who drives for one hour per day relocated their home such that they could drive at half the speed for the same duration (perhaps in an appropriately lower-powered vehicle), energy consumption by transportation would fall by a factor of 8; stinky emissions would fall by a factor of 8; and serious injuries to pedestrians and cyclists would fall by an even bigger factor.

Figure 20.6. Are electric vehicles a good idea? Top left: the G-Wiz. Top right: the rotting corpse of a Sinclair C5. Middle: an electric Citroën Berlingo. Bottom: the Elettrica.

Electric vehicles

The REVA electric car was launched in June 2001 in Bangalore and is exported to the UK as the G-Wiz. The G-Wiz's electric motor has a peak power of 13 kW, and can produce a sustained power of 4.8 kW. The motor provides regenerative braking. It is powered by eight 6-volt lead acid batteries, which when fully charged give a range of 'up to 77 km'. A full charge consumes 9.7 kWh of electricity. These figures correspond to 13 kWh per 100 km.

How does this compare with the consumption of an ordinary petrol-powered car? At `www.goinggreen.co.uk`, they claim that the G-Wiz does '600 miles per gallon', but that's misleading. At 9.7 kWh per 77 km, the energy consumption is 220 miles per gallon – about 7 times better than a typical car that does 33 miles per gallon. This comparison treats a unit of electrical energy as having equal value to a unit of chemical energy. If you prefer to redo the comparison with the exchange rate achieved by a 40%-efficient fossil-fuel power station, 2.5 kWh of chemical energy for 1 kWh of electricity, you'll find that the G-Wiz is equivalent to a 90 miles-per-gallon car.

More electric cars

The Berlingo Electrique 500E, an urban delivery van, has 27 nicad batteries and a 28 kW motor. It can transport a payload of 500 kg. Top speed: 100 km/h; range: 100 km. 25 kWh per 100 km. (Estimate kindly supplied by a Berlingo owner.) [`4wm2w4`]

The GM EV1 did 6 km per kWh, or 17 kWh/100 km.

The 'i MiEV' electric car from Mitsubishi is projected to have a range of 160 km with a 16 kWh battery pack. That's 10 kWh per 100 km, like the G-Wiz – but whereas it's hard to fit two adult Europeans in a G-Wiz, the Mitsubishi prototype has four doors and four full-size seats. `http://www.greencarcongress.com/2008/02/mitsubishi-moto.html`

Figure 20.8. The i MiEV. From Mitsubishi Motors Corporation. It has a 47 kW motor, weighs 1080 kg, and has a top speed of 130 km/h.

More electric car

The two-seater General Motors EV1 had a range of 120 to 240 km per charge, with nickel-metal hydride batteries holding 26.4 kWh. That's an energy consumption of between 22 and 11 kWh per 100 km.

The eBox has a Lithium ion battery with a capacity of 35 kWh and a weight of 280 kg; and a range of 140–180 miles. Its motor's power is 120 kW peak and 50 kW continuous. Normal charge time is 5 h. Efficiency: 12 kWh per 100 km if carrying a single occupant; 3 kWh per 100 seat-km if four seats are used. (Same as a high-speed train.)

Prototype tZero (precursor of Venturi, Tesla, and Wrightspeed.) Lithium ion battery gives 4 times the range, and is slightly more efficient than lead acid. tZero does 11 kWh/100 km.

Note I haven't included embodied energy, *i.e.*, the energy required to make the electric car, especially its battery.

(Move details from here to the notes, just retain the summary figures.)

What about other non-fossil-fuel cars?

Yep, there's the compressed-air car. I think in terms of energy efficiency the compressed-air technique for storing energy isn't as good as electric batteries. The problem is that compressing the air generates *heat* that's unlikely to be used efficiently; and expanding the air generates *cold*, another byproduct that is unlikely to be used efficiently. But compressed air may be a superior technology to electric batteries in other ways. For example, air can be compressed thousands of times and doesn't wear out! It's interesting to note, however, that the first product sold by the Aircar company (also known as MDI) is actually an *electric* scooter. `http://www.theaircar.com/acf/`

Assume 300 bar pressure and compare the energy per kilogram and per unit volume with that of batteries. Include in the storage diagram.

Compressed air is used for regenerative braking in big trucks.

Notes

AVT-100E `www.avt.uk.com` Range: 100 miles with lithium ion batteries. 15 kW motor. Top speed over 100 mph.

Electric Smart Car "The electric version is powered by a 40 bhp motor, can go up to 70 miles before the battery goes flat and has a top speed of 70 mph.

Recharging is done through a standard electrical power point and costs about £1.20, producing the equivalent of 60g/km of carbon dioxide emissions at the power station, Smart says.

A full recharge takes about eight hours, but the battery can be topped up from 80% drained to 80% charged in about three-and-a-half hours.” http://www.whatcar.com/news-article.aspx?NA=226488
(cf equivalent petrol-powered Smart: 116 g/km.)

Toyota RAV4 EV This vehicle – an all-electric mini-SUV – was sold by Toyota between 1997 and 2003. The RAV4EV has 24 12-volt 95Ah NiMH batteries capable of storing 27.4 kWh of energy. Range of 130 to 190 km. So that’s an energy consumption of 14–21 kWh per 100 km. The RAV4EV was popular with Jersey Police force.

Figure 20.9. Toyota RAV4 EV. Photo by Kenneth Adelman, http://www.solarwarrior.com/.

Phoenix SUT – a five-seat ‘sport utility truck’ made in California – has a range of ‘up to 130 miles’ from a 35 kWh lithium-ion battery pack. (That’s 17 kWh per 100 km.) The batteries can be recharged from a special outlet in 10 minutes. http://www.gizmag.com/go/7446/

Electric trams Battery-powered electric trams – http://www.tdi.uk.com/

Electric minibus From http://www.smithelectricvehicles.com/: 40 kWh Lithium Ion battery pack. 90 kW motor with regenerative brakes. Range ‘up to 100 miles’. 15 seats. Vehicle kerb weight 3026 kg. Payload 1224 kg. That’s a vehicle-performance of at best 25 kWh per 100 km. If the vehicle is fully occupied, it could deliver transportation at an impressive cost of 2 kWh per 100 passenger-km.

Electric coach The Thunder Sky bus has a range of 180 miles and a recharge time of three hours. http://www.thunder-sky.com/

Range Only 8.3 per cent of commuters travel over 30 km to their workplace. Eddington

You’ve shown that electric cars are more energy-efficient than fossil cars. But are they better if our objective is to reduce CO_2 emissions, and the eletricity is still generated by fossil power-stations?

This is quite an easy calculation to do. Assume the electric vehicle’s energy cost is 20 kWh(e) per 100 km. (I think 15 kWh per 100 km is perfectly possible, but let’s play sceptical in this calculation.) If grid electricity has a carbon footprint of 500 g per kWh(e) then the effective emissions of this vehicle are **100 gCO_2 per km**, which is as good as the best fossil cars. So I conclude that switching to electric cars is *already* a good idea, even before we green our electricity supply.

about 500 passengers, weighs 410 tons and uses a power of 3.4 MW when travelling at 125 mph.
The Class 91 electric train on the left travels at 140 mph (225 km/h) and uses

Trains

The UK national railways consume 2700 GWh per year for traction – which is 0.12 kWh per day per person. But that average figure isn't really what we want to know, is it? We want to know how train compares with other forms of transport.

How much could consumption be reduced by a switch from personal gas-guzzlers to excellent integrated public transport?

High-speed train

Imagine switching from driving 100 km per day by car (which costs 80 kWh/d) to riding 100 km per day on a high-speed train. If the train is full, the energy cost per passenger is 3 kWh per 100 seat-km. So such travel has a cost of **3 kWh per day**.

What about other types of train? Lower-speed trains, and trains that aren't full?

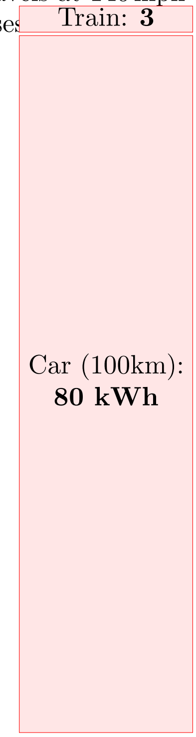


Figure 20.11. 100 km on a fully-occupied high-speed train, compared with 100 km in a single-person car.

Public transport

Energy efficiencies (per passenger)	
Car (doing 33 mpg):	
single occupant	80 kWh per 100 km
share between 4 seats	20 kWh per 100 seat-km
Electric car:	
single occupant	11 kWh(e) per 100 km
Plane: 747 (cruise speed 900 km/h)	42 kWh per 100 seat-km
Fast trains: ICE at 200 km/h (125mph)	3 kWh(e) per 100 seat-km
Victoria line (underground),	
average speed 48 km/h (30 mph)	4 kWh(e) per 100 passenger-km
London transport trains, average speed 33 km/h (20 mph),	
total cost including lighting, lifts, depots, workshops	70 kWh per 100 actual passenger-km
London buses, average speed 18 km/h (11 mph)	24 kWh per 100 actual passenger-km

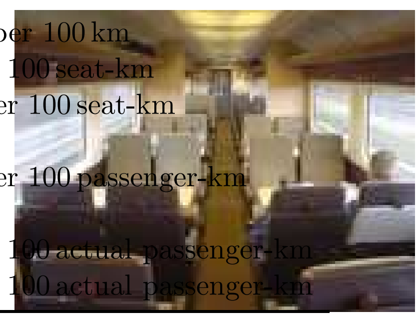


Figure 20.12. Some trains aren't full. Three men and a cello – the sole occupants of this carriage of the 10.30 from Edinburgh to Kings Cross.

All London transport trains, average speed 33 km/h (20 mph), total cost including lighting, lifts, depots, workshops. 70 kWh per 100 actual passenger-km. Occupancy per vehicle: 11.8, distance between stops: 1.8 km

All London buses, average speed 18 km/h (11 mph) 24 kWh per 100 actual passenger-km. occupancy per vehicle: 14.4, distance between stops: 0.3 km Ridley and Catling [1982]

Buses are more energy-efficient than underground trains (in terms of kWh per passenger-km) but the trains deliver higher speeds and the staff costs are significantly less.

Updated figures from Transport for London: `http://www.tfl.gov.uk/assets/downloads/corporate/Environment-Report-2006.pdf` cars, 124

Figure 20.13. With congestion like this, it's faster to walk.

g/pkm (low due to load factor), buses 103 g/pkm, and underground 55 g/pkm, although maybe they don't include running the stations?

Tube trains

Figure 20.14. Tubes, inner and outer.

Victoria line train consists of eight cars: four 30.5 ton and four 20.5 ton cars (the former having four motors each). Laden, an average train weighs 228 tons. Ridley and Catling [1966] The maximum speed is 45 mile/h. The average speed is 31 mph. A train with most seats occupied carries about 350 passengers; crush-loaded, the train takes about 620. The energy consumption at peak times is about 4.4 kWh per 100 passenger km. This doesn't include any regenerative braking, though the line does use 'mechanical regeneration' (*i.e.*, gravity: hump-back stations). The gravity principle provides an energy saving of 5% and a reduction in inter-station run time of 9%.

Weights: 0.57t per seat (underground train); 0.14t per seat (bus); 0.50t (modern tram).

Regenerative braking has been introduced to some London Underground lines since 1992.

Tram and trolleybus

Figure 20.15. A Polish Solaris trolleybus in Landskrona, Sweden. Photo by Carl–Johan Aberger.

`http://www.tbus.org.uk` `http://www.scottishelectrictransit.org.uk`

Figure 20.16. Trolleybuses in San Francisco.

Figure 20.17. Tram 147 in Blackpool. Photo from `www.blackpool.gov.uk`.

Coach

A diesel-powered coach, carrying 49 passengers and doing 10 miles per gallon at 65 miles per hour. That's 6 kWh per 100 pkm.

Conclusion

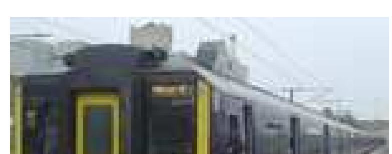
Trains and buses are potentially much more efficient than cars, if only they were full. But the way we do public transport at present, trains and buses are not that much more energy-efficient than cars. There remain many other good reasons for encouraging a switch to public transport (for example avoiding congestion and reducing accidents), but don't expect to reduce energy consumption enormously by a switch to public transport.

Short-range high-speed trains

See chapter K for theory of train power consumption

Energy cost per passenger-km

In Canada, Road, air and rail all deliver passenger transport at similar energy-per-distance costs – all about 50 kWh per 100 passenger-km.



[2yyb7q] (GPI Atlantic)

(Precise figures for 2002: Rail: 46; Air: 51; Road: 66.)

Subdivision by vehicle type (2002): Bus: 32; Motorcycle: 37; Small car: 56; Large car: 71; Light truck: 85.

[22187s] Amtrak, USA, 2002: 88 kWh per 100 passenger-km.

'I'm changing the climate; ask me how'.

Freight movement: in MJ per tonne-km. Air: 5.88; Road: 3.30; Marine: 0.54; Rail: 0.23. In kWh: 1.63 0.92 0.15 0.064.

Energy intensity of road freight by vehicle type in MJ per tonne-km.

Light truck: 10.34. Medium truck: 6.85. Heavy truck: 2.21.

See also stuff.tex

Car	68
Bus	19
Rail	6
Air	51
Sea	57

Table 20.19. Overall transport efficiencies of transport modes in Japan (1999) in kWh per 100 passenger-km.

Mode	g $CO_2^{(e)}$ per passenger-km
1990 average car	278
New catalyst car	197
Diesel car	161
Bus	69
Diesel train	79
Electric train	76
Local train	54
Aircraft	853

Table 20.20. Carbon dioxide emissions of passenger transport (grams of CO_2 equivalent), assuming 80% occupancies for aircraft and 40% for all other modes.

Energy total for transport

UK: 52 Mtoe (2002) of which road 39, air 11, rail 1.

Better trains

From Hitachi's research report Kaneko et al. [2004]: high-efficiency power generation and regenerative braking are 'expected to give fuel savings of approximately 20% compared with conventional diesel-powered trains'.

It's great stuff, but don't be duped into thinking that this system delivers the 60% or 90% saving that we would really like.

132 *High-speed train.*

Intercity trains

A diesel-powered intercity 125 train weighs 410 tons, and uses a power of 3.4 MW when travelling at 125 mph. (The power delivered 'at the rail' is 2.6 MW.) Each second-class carriage can carry about 74 passengers. (It used to be 64 seats to a carriage, but they have squashed us up.) First-class carriages can carry about 48 passengers. So the number of passengers in a full train is about 500 per train; and the power per person is about 7 kW. The transport efficiency is about 3.3 kWh per 100 seat-km.

Further evidence for a figure of 3 kWh per 100 seat-km: The government document http://www.cfit.gov.uk/docs/2001/racomp/racomp/pdf/racomp.pdf says that east-coast mainline and west-coast mainline trains both consume about 15 kWh per km (whole train). The number of seats in each train is 526 or 470 respectively. So that's 2.9–3.2 kWh per 100 seat-km.

> *We stand now at the transition point from hydrocarbon dependence to the start of the 'New Energy Era', in which no fossil fuels will be used.*
>
> Sir Peter Masefield, speaking in 1975.

Bombardier Voyager vital statistics

High speed diesel train. Super Voyager has 5 cars per trainset. Each coach has a 560 kW engine. 250 passengers. Weight 280 t.

Pendolino vital statistics

Electric train. 9 cars of length 24.1 m, width 2.9 m, height 2.73 m, weigh 466 t. Seat capacity: 439 passengers. Power output 5.1 MW. (These are heavy trains. Note the mass is more than 1 t per passenger.) Max speed 250 km/h.

Notes

Magnetic levitation

> 'driving without wheels; flying without wings'

The German company, Transrapid, which made the major maglev trains for Germany and China, says this:

> The Transrapid Superspeed Maglev System is unrivaled when it comes to noise emission, energy consumption, and land use. The innovative non-contact transportation system provides mobility without the environment falling by the wayside.

top speed is 431 km/h for the shanghai line
(30 km long)

In energy-consumption terms, the comparison with other fast trains is actually not as flattering as the hype suggests. From the Transrapid site,

Fast trains compared at 200 km/h (125mph)	
ICE	2.9 kWh per 100 seat-km
Transrapid	2.2 kWh per 100 seat-km

[The InterCityExpress or ICE compared here is a high-speed electric train in Europe.]

The main reasons why maglev is slightly better than the ICE are: the magnetic propulsion motor has high efficiency; the train itself has low mass, because most of the motor is in the track, rather than the train; and more passengers are inside the train because space is not needed

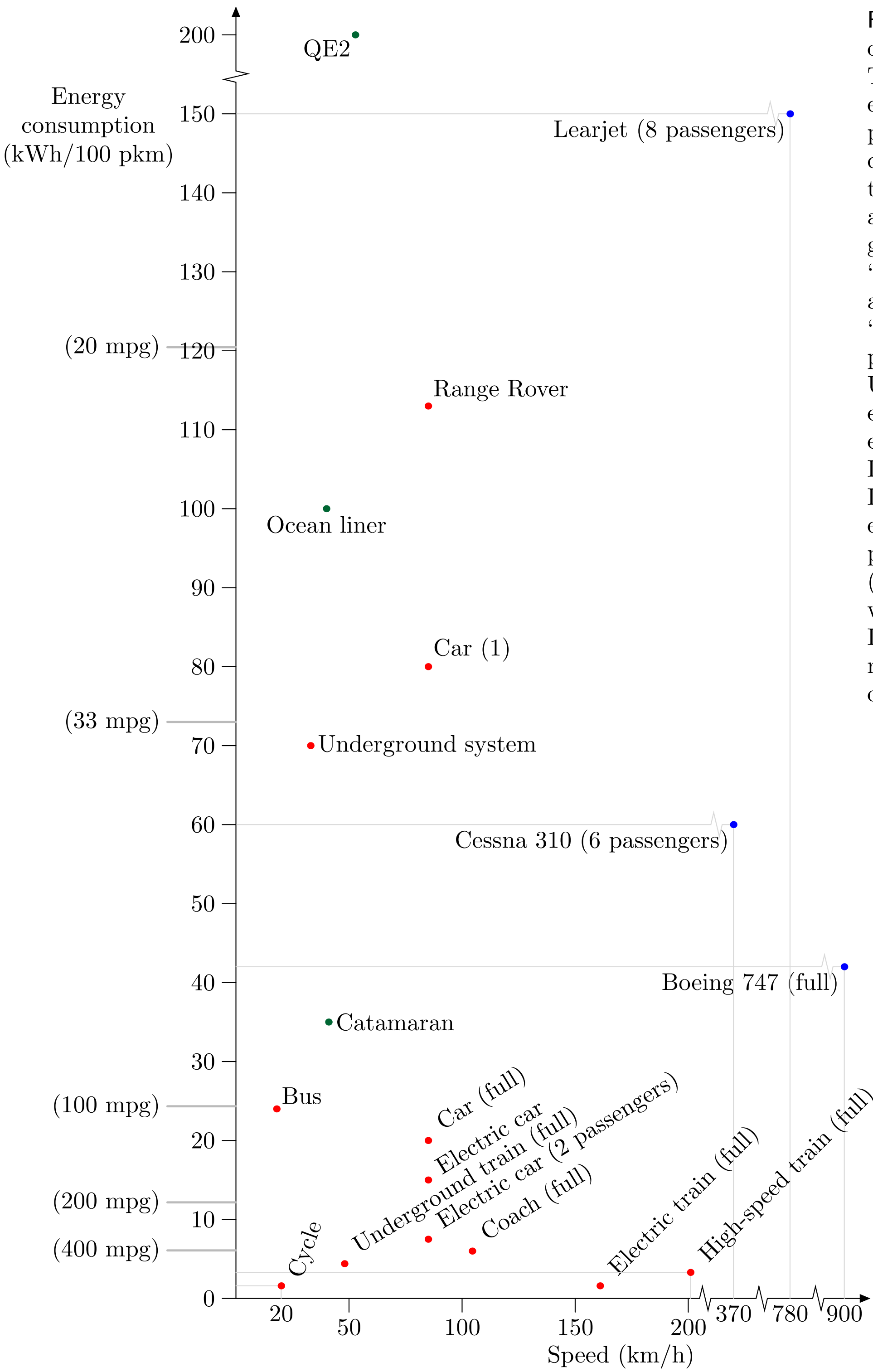


Figure 20.21. Energy requirements of different forms of transport. The vertical coordinate shows the energy consumed in kWh per 100 passenger-km. The horizontal coordinate indicates the speed of the transport. The 'Car (1)' is an average UK car doing 33 miles per gallon with a single occupant. The 'Bus' is the average performance of all London buses. The 'Underground system' shows the performance of the whole London Underground system, including the energy cost of its lighting, escalators, and depots.
In response to popular demand, I've indicated on the left-hand side equivalent fuel efficiencies in passenger-miles per imperial gallon (mpg). When comparing electric with chemical-powered vehicles, I've expressed both energy requirements in kWh with a one-for-one exchange rate.

for motors. The propulsion system is in the ground instead of in the vehicle.

Total vehicle weight: 110 metric tonnes (2 cars). 55 tons per car. (Weight per seat = 600 kg.) In china it is 5 cars I think

The train could also carry cargo, up to 15 tons per car.

See also `http://www.maglev2000.com/`

Bicycles

More on Human powered vehicles

Cycling costs about 1.6 kWh per 100 km, assuming a speed of 20 km/h. For theory, see chapter K.

Figure 20.22. Some bikes, yesterday.

Electric scooter

The Vectrix can be driven for up to 68 miles on a two-hour charge from a standard electrical socket.

At 25 miles/h (40 km/h).

That's 110 km for 3 kWh, or 2.75 kWh per 100 km. (see below)

"your carbon footprint will still be there, just from a power station rather than direct emissions, but so long as you sign up to a green energy tariff first you needn't worry about that." [See the chapter on myths for my views on this quote.]

Maximum speed 62 mph (100 km/h).

Battery capacity 30 Ah, 3.7 kWh. (2 hours delivers 80% charge.) Battery voltage 125 V. Charger is 1.5 kW. Battery life: 1700 cycles, 10 years, 50 000 miles (80 000 km).

Peak power of motor: 20 kW.

Weight: 210 kg.

Figure 20.23. 'Babies on board'. I estimate this mode of transportation has an energy cost of 1 kWh per 100 person-km.

Bicycle hire

In the French city of Lyon, a privately-run public bicycle network, Vélo'v, was introduced in 2005 and has proved popular. Lyon's population of 470 000 inhabitants is served by 2000 bikes distributed around 175 cycle-stations in an area of 50 km^2. In the city centre, you're usually within 400 m of a cycle-station. Users join the scheme by paying a subscription fee of €10 per year and may then hire bicycles free for all trips lasting less than 30 minutes. For longer hire periods, users pay up to €1 per hour. Short-term visitors to Lyon can buy one-week subscriptions for €1.

Figure 20.24. A Vélo'v station in Lyon.

Notes

126 *A widely quoted statistic says "Only 1 percent of fuel energy in a car goes into moving the driver."* In fact this statistic varies in size as it commutes around the urban community. Some people say "5% of the energy goes into moving the driver." Some say "A mere *three tenths of 1 percent* of fuel energy goes into moving the driver." [4qgg8q]

Stephen Salter has invented a brilliant way of automating congestion-charging. A simple daily congestion charge, as levied in London, sends only a crude signal to drivers; once a car-owner has decided to pay the day's charge and drive into a congestion zone, he has no incentive to drive *little* in the zone. Nor is he rewarded with any rebate if he carefully chooses routes in the zone that are not congested.

Instead of having a centralised authority that decides in advance when and where the congestion-charge zones are, with expensive monitoring and recording of vehicle movements into and within all those zones, Salter has a simpler, decentralized, anonymous method of charging drivers for driving in heavy, slow traffic, wherever and whenever it actually exists. The system would work nationwide. Here's how it works. We want a device which answers the question 'how congested is the traffic I am driving in?' A good measure of congestion is 'how many other active vehicles are close to mine?' In fast-moving traffic, the spacing between vehicles is larger than slow-moving traffic. Traffic that's trundling in tedious queues is the most densely packed. The number of nearby vehicles can be sensed by fitting in every vehicle a radio transmitter/receiver (like a very cheap mobile phone) that transmits little radio-bleeps at a steady rate whenever the engine is running, and which counts the number of bleeps it hears from other vehicles. The congestion charge would be proportional to the number of bleeps received; this charge could be paid at refuelling stations whenever the vehicle is refuelled. The radio transmitter/receiver would replace the current UK road tax disc.

21

Smarter heating

Summary: To reduce energy for heating, we have lifestyle options and technology options. On the lifestyle end of the spectrum, turn down the thermostat (get some material from the appendix to show halving of heat loss when turn down from 20 to 15); and read meters.

Technology: insulation, double glazing, and the heating devices themselves: especially heat pumps.

We start with the easiest and cheapest technologies for buildings.

Insulation and behaviour change

Effect of building modifications

Addition of loft and cavity insulation reduces heat loss in a typical old house by about a quarter Eden and Bending [1985]. Figure 21.1 shows Eden and Bending's estimates of the space heating required in a range of houses.

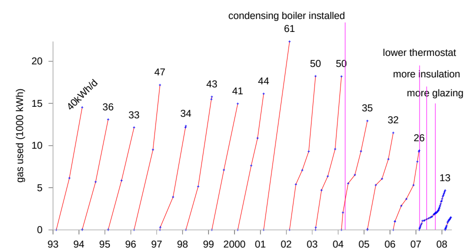


Figure 21.2. My domestic cumulative gas consumption, in kWh, each year from 1993 to 2007. The number at the top of each year's line is the average rate of energy consumption, in kWh per day.

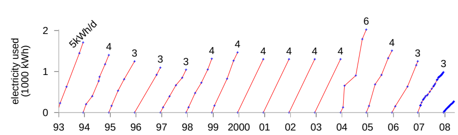


Figure 21.3. My domestic cumulative electricity consumption, in kWh, each year from 1993 to 2007. The number at the top of each year's line is the average rate of consumption, in kWh per day.

Case study

My three-bedroom house. In 2004 I had a condensing boiler installed, replacing the old gas back-boiler. At the same time I removed the house's hot water tank (so hot water is now made only on demand), and I put thermostats on all the bedroom radiators. Along with the new condensing boiler came a new heating controller allowing me to set different target temperatures for different times of day.

With these changes, my consumption decreased from an average of 50 kWh/d to about 30 kWh/d.

I think the main reason for the improvement was the removal of the hot water tank. It was pretty well insulated, but nevertheless made the room it was in noticeably warmer, all year round.

This reduction from 50 to 30 kWh/d is quite satisfying, but it's not enough. It's less than a 50% reduction, and 30 kWh/d of gas corresponds to over 2 tonnes CO_2 per year.

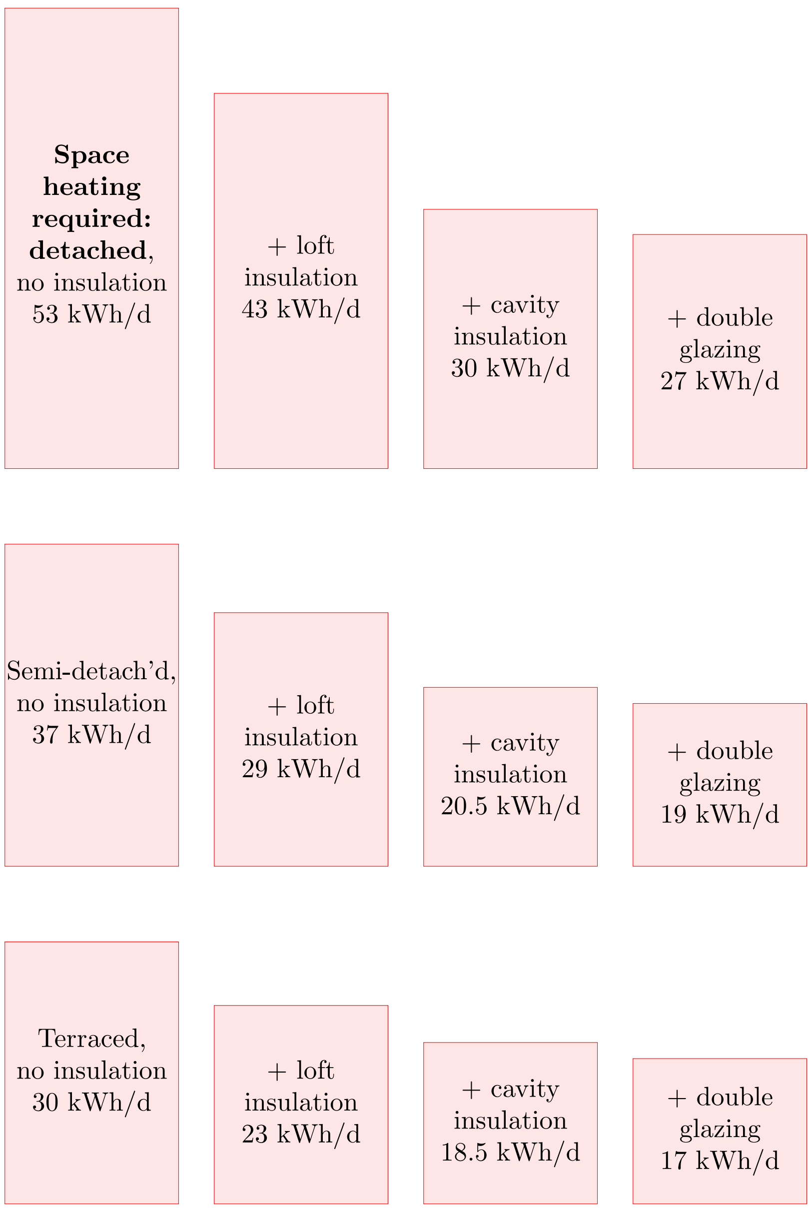


Figure 21.1. Estimates of the space heating required in a range of UK houses. From Eden and Bending [1985].

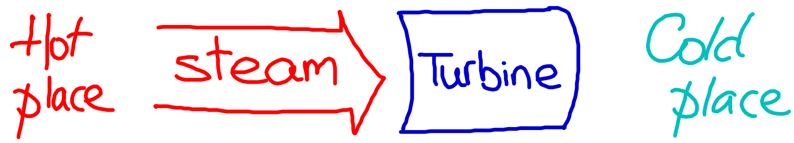


Figure 21.6. How a power station works.

In 2007, I started paying more careful attention to my energy meters. I had cavity wall insulation installed and improved my loft insulation. Most important of all, I paid more attention to my thermostat settings. This attentiveness seems to have led to a halving in gas consumption in 2007 compared with 2006. The end result: the latest year's consumption was 13 kWh/d!

Figure 21.4. Cavity wall insulation.

Combined heat and power

The standard view of conventional big centralised power stations is that they are terribly inefficient, chucking heat willy-nilly up chimneys and cooling towers. A slightly more sophisticated view recognises that to turn thermal energy into electricity, we inevitably have to dump heat in a cold place. But surely, it's argued, we could use buildings as the dumping place for this 'waste' heat instead of cooling towers or sea water? This idea is called 'combined heat and power' (CHP) or cogeneration, and it's been widely used in Europe for decades.

There's certainly some truth in the view that Britain is rather backward when it comes to district heating and combined heat and power, but discussion is hampered by a general lack of numbers, and by two particular errors. First, when comparing different ways of using fuel, the wrong measure of 'efficiency' is used, namely one that weights electricity as having exactly equal value to heat. Second, it's widely assumed that the 'waste' heat in a traditional power station could be captured without impairing the power station's electricity production. This sadly is not true, as the numbers will show. Delivering useful heat to a customer always reduces the electricity produced to some degree. And given that electricity actually has a higher value than heat, the true gains from combined heat and power are often much smaller than the hype would lead you to believe. (Just 10% or so.)

A final impediment to rational discussion of combined heat and power is an unfounded assumption that has grown up recently, that decentralizing a technology somehow makes it greener. So whereas big centralized fossil fuel power stations are viewed as clearly 'bad', flocks of local micro-power stations are imbued with goodness. Small may be beautiful, but if decentralization is actually a good idea then this fact should be evident in the numbers. Decentralization should be able to stand on its own two feet without religious belief in the need to decentralize. And what the numbers actually show is that centralized electricity generation has many benefits in both economic and energy

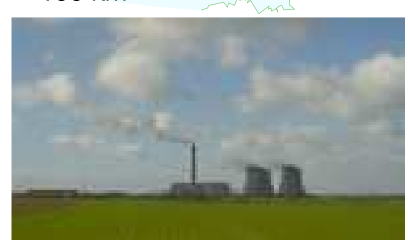


Figure 21.5. Eggborough. Not a power station participating in smart heating.

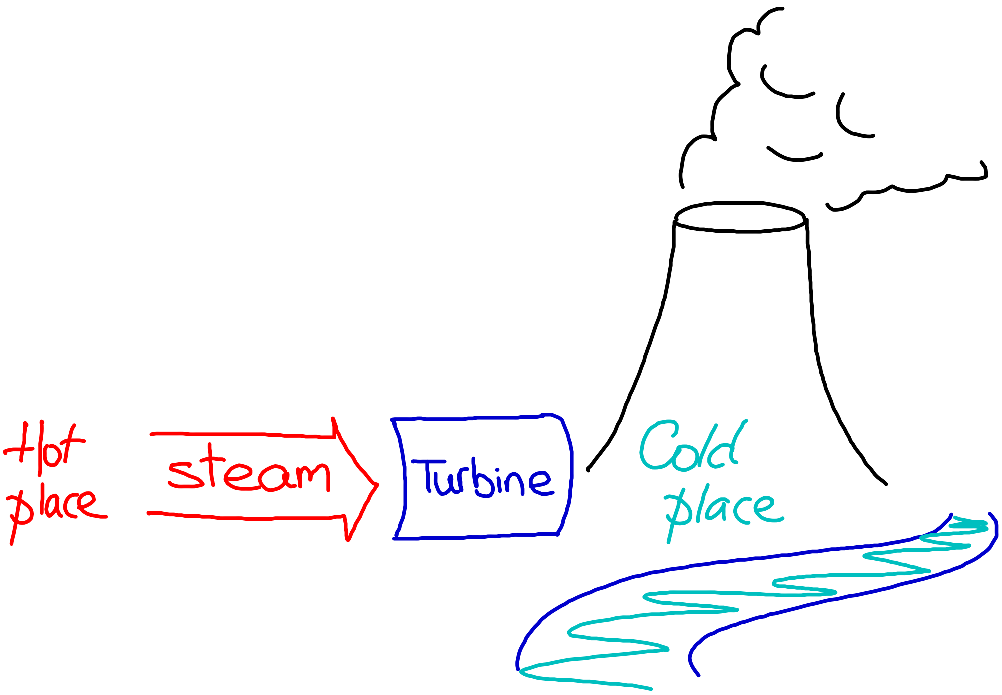


Figure 21.7. How a power station works. Cooling tower or river.

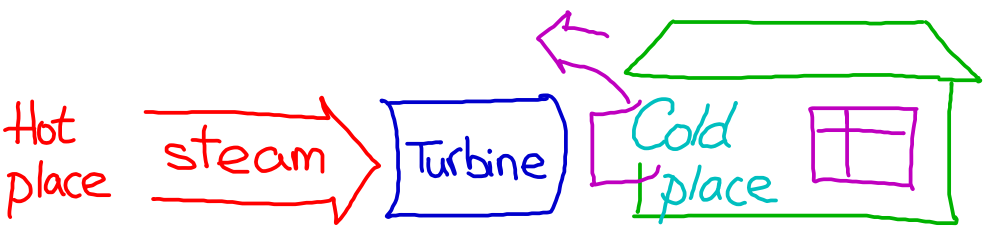


Figure 21.8. Combined heat and power. District heating.

terms. Only in large buildings is there any benefit to local generation, and usually that benefit is only of order 10% or 20%. And what this chapter will show is that there is another technology that is superior to combined heat and power: this technology is called 'heat pumps'. Like district heating and combined heat and power, heat pumps are already widely used in continental Europe. In contrast to most combined heat and power systems, heat pumps are not locked in to a fossil fuel such as gas.

The government has a target for growth of combined heat and power to 10 GW(e) by 2010, but I think that growth of gas-powered combined heat and power would be a mistake. Such combined heat and power is not green: it uses fossil fuel, and it locks us into continued use of fossil fuel. Given that there is a better technology – heat pumps, to be described here – I believe we should leapfrog over gas-powered combined heat and power.

The rejected heat from UK power stations could meet the heating needs of the entire country Wood [1985]. In Denmark (in 1985 at least), district heating systems supply 42% of space heating, with heat being transmitted to 20 km or more by hot pressurized water.

In West Germany in 1985, four million dwellings received 7 kW per dwelling from district heating. (I think that's capacity.) Total heat supplied averages 42 GJ/y. Two thirds of that heat was from power stations. Profitability of German district heating schemes: sale:purchase ratio of 3.5:1.

In Vasteras, Sweden, 98% of the city's heat was supplied from power stations.

Heat pumps

Explain how heat pumps work. They're back-to-front refrigerators.

According to the UK Ground Source Heat Pump Association, a ground-source heat pump will deliver three or four times as much heat as is used in electrical energy to drive the system. 275 000 systems have been installed in Sweden, many with vertical boreholes, and some with horizontal loops. About one fifth of Swedish heating and cooling is delivered by ground-source heat pumps. A typical ground source temperature is 7°C. The borehole length is 150 m. In Autumn and Winter in Sweden, the gain is a factor of 3: 1 kW of electricity creates 3 kW of heat output. In early Summer, 1 kW of electricity can deliver 30–50 kW of cooling. Ground can be used as a store for excess solar heat.

People sometimes say that ground-source heat pumps are using 'geothermal energy', but I think that's not the right name. As we saw in chapter 15, geothermal energy offers only a tiny trickle of power per unit area (about $50\,\mathrm{mW/m^2}$), in most parts of the world; but heat pumps can be used everywhere, and they can be used both for heating and for cooling. It would sound odd to say 'I'm using geothermal energy to cool my building'. Heat pumps simply use the ground as a place to suck heat from, or to dump heat into. It's just like a refrigerator. Feel the back of your refrigerator: it's *warm*. A refrigerator moves heat from one place (its inside) to another (its back panel). So one way to heat a building is to turn a refrigerator inside-out – put the *inside* of the refrigerator in the garden, thus cooling the garden down; and leave the outside of the refrigerator in your kitchen, thus warming the house up. That's what heat pumps do, if they are used for heating. To obtain cooling instead, just turn it round again, with the cool side in the house, and the warm bit facing outdoors.

The ground is not a limitless source of heat. The heat has to come from somewhere, and ground is not a very good conductor of heat. If we suck heat too hard from the ground, the ground will become as cold as ice, and the advantage of the ground-source heat pump will be diminished.

Let's put some numbers into this discussion. In Britain, the main purpose of heat pumps would be to get heat into buildings in the winter.

The ultimate source of this heat is the sun, which replenishes heat in the ground by direct radiation and by conduction through the air. The rate at which heat is sucked from the ground must satisfy two constraints: it must not cause the ground's temperature to drop too low during the winter; and the heat sucked in the winter must be replenished during the summer.

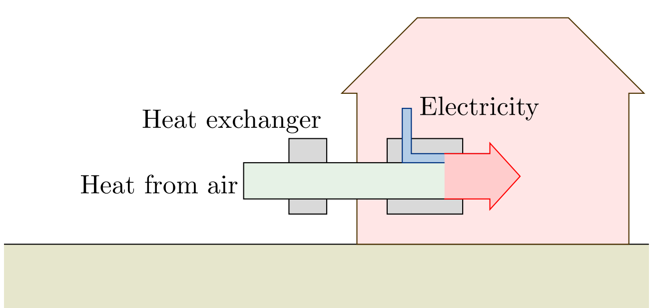
How big a piece of ground does a heat pump need? And is it feasible to store up a load of heat over the summer and suck it back again in the winter?

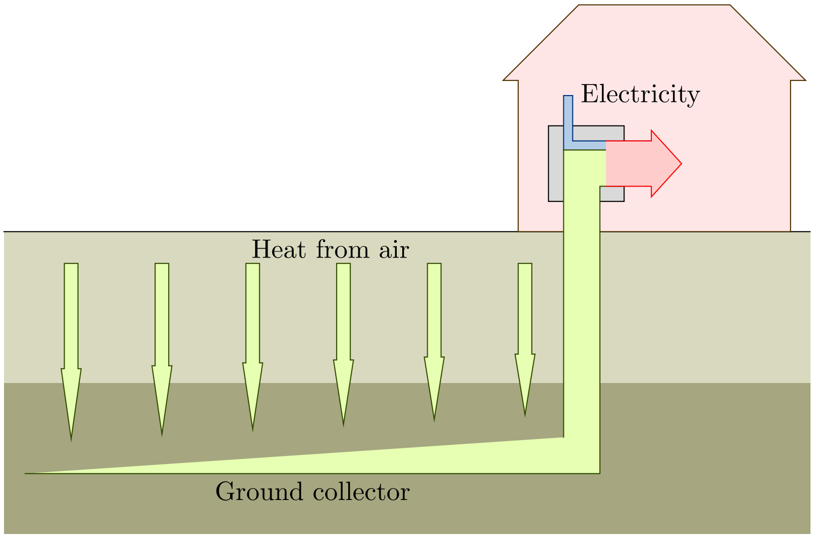
Here's an interesting calculation to do. Imagine having solar heating panels on your roof, and, whenever the water in the panels gets above 50°C, pumping the water through a large rock under your house. When a dreary grey cold month comes along, you could then use the heat in the rock to warm your house. Heat pumps are different from this scheme in two ways: they don't usually bother with the solar heating panels and they use a cunning electrical pump to boost the heat flow from the rock into the building. But before we discuss them, let's do this simple calculation for the solar scheme: roughly how big a 50°C rock would you need to hold enough energy to heat a house for a whole month? Let's assume we're after 24 kWh per day for 30 days and that the house is at 16°C. The heat capacity of granite is $0.195 \times 4200\,\mathrm{J/kg/K} = 820\,\mathrm{J/kg/K}$. The mass of granite required is:

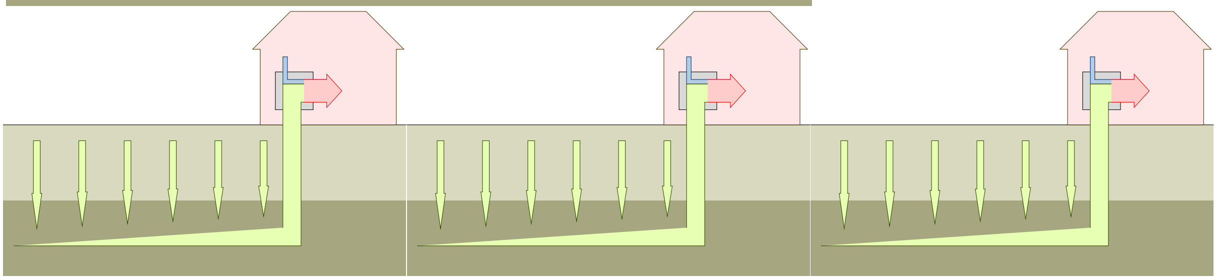
$$\begin{aligned}\text{mass} &= \frac{\text{energy}}{\text{heat capacity} \times \text{temperature difference}} \\ &= \frac{24 \times 30 \times 3.6\,\mathrm{MJ}}{(820\,\mathrm{J/kg/C})(34^\circ\mathrm{C})} \\ &= 100\,000\,\mathrm{kg},\end{aligned}$$

one hundred tonnes, which corresponds to a cuboid of rock of size $6\,\mathrm{m} \times 6\,\mathrm{m} \times 1\,\mathrm{m}$.

What *area* of interface is needed in order to dump or extract energy? Just to get a rough estimate, let's assume we need to dump 24 kWh into rock during one hour, and that the temperature difference is 10 C – over what lengthscale? Conductivity of granite: 2.1 W/m/K.







RESTART. Let's do this another way. Assume that we have a neighbourhood with quite a high population density. Can *everyone* use ground-source heat pumps, without using the Summer replenishment trick? For this calculation, I'll assume the ground just below the surface is held at a steady temperature by the combined influence of sun, air, cloud, and night sky. I'll assume that we put the ground loops in a layer $h = 5\,\text{m}$ deep – much shallower, and the ground temperature would fluctuate more during the year, reducing the pump's efficiency; much deeper, and the resulting temperature drop induced by our heat pump would reduce efficiency too. (Redo this, showing what the optimal depth actually is?) I'll assume that we'll allow ourselves to suck the ground temperature down to $\Delta T = 5°\text{C}$ below the average ground temperature at the surface. We can then use the assumed conductivity to deduce the heat flux from the surface.

$$\text{Flux} = \text{Conductivity} \times \frac{\Delta T}{h} = 2\,\text{W/m}^2.$$

Let's pick $6200/\text{km}^2$ as our representative density of a residential area; that's $160\,\text{m}^2$ per person. This is the population density of a typical English suburb: rows of semi-detached houses with about $400\,\text{m}^2$ per house (including pavements and streets). Then the maximum power per person deliverable by ground source heat pumps, if everyone in a neighbourhood has them, is 320 W, which is 8 kWh/d per person. Add in the electrical contribution, assuming a COP of 3: 12 kWh/d per person.

So the answer is a tentative *no*: If we were aiming for everyone

	People per km^2
Bangalore	26 719
Manhattan	25 849
Paris	24 775
Chelsea	15 177
Tokyo	13 800
Moscow	10 275
Taipei	9626
The Hague	6600
San Francisco	6423
Singapore	6411
Cambridge MA	6086
Sydney	5736
Portsmouth	4689

Table 21.9. Some urban population densities.

in the neighbourhood to be able to pull from the ground a heat flow of about 48 kWh/d (my estimate of our typical winter heat demand), this figure of 12 kWh/d comes up short. But not by a big factor. My conclusion is that when we switch to heat pumps, we should plan to include Summer heat-dumping in the design, to refill the ground with heat for use in the Winter. This Summer heat-dumping could use heat from air-conditioning, or heat from roof-mounted solar water-heating panels. Alternatively, we should expect to need to use some air-source heat pumps too, and then we'll be able to get all the heat we want – as long as we have the electricity to pump it. In the UK, air temperatures don't go very far below freezing, so concerns about poor winter-time coefficient of performance of air-source pumps, which might apply in North America and Scandanavia, probably do not apply in Britain.

Ground storage of heat

Idea: put solar panels on the roof of a building, and in summer take the excess heat and pump it down a hole in the ground. Then in the winter, pump the heat back out of the ground and warm buildings with it.

This system relies on the conductivity of the ground being so low that the heat will stay there for 6 months.

In the summer cooled liquid coming out of the ground can be used to help provide air-conditioning.

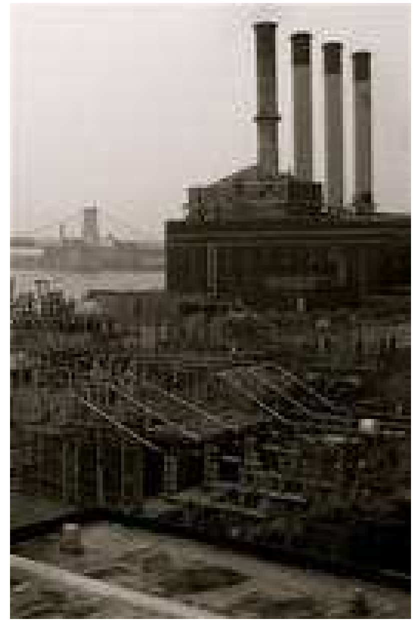
See technical chapter E (p. 289) for more.

Thermal mass

Does increasing the thermal mass of a building help reduce its heating and cooling bills? It depends. The outdoor temperature can vary during the day by about 10°C. A building with large thermal mass – thick stone walls, for example – will naturally ride out those variations in temperature, and, without heating or cooling, will have a temperature close to the average outdoor temperature. Such buildings, in the UK, need neither heating nor cooling for many months of the year. In contrast, a poorly-insulated building with low thermal mass might be found too hot during the day and too cool at night, leading to greater expenditure on heating and cooling.

However, large thermal mass is not always a boon. If a room is occupied in winter for just a couple of hours a day (think of a lecture room for example), the energy cost of warming the room up to a comfortable temperature will be greater, the greater the room's thermal mass. This extra invested heat will linger for longer in a thermally massive room, but if nobody is there to enjoy it, it's wasted heat. So in the case of infrequently used rooms it makes sense to aim for a structure with low thermal mass, and to rapidly warm that small mass when required.

Example data



4-bedroom house. [2va3tp] House heating costs (central heating and domestic hot water) are assumed to be 45 W/m^2. Or 32 400 kWh/y for a big house of 230 m^2. (This seems to include a factor of 1/3 presumably for winter/summer.)

They claim they deliver this 32 400 kWh/y (90 kWh/d) with an electricity cost of 7 500 kWh/y of heat pump plus 620 kWh/y of additional heating (22 kWh/d electricity total).

Residential ground-source heatpumps are available with a coefficient of performance of 5.7 for cooling and 4.3 for heating. Commercial ground-source heatpumps are available with a coefficient of performance of 5.4 for cooling and 4.9 for heating. [2fd8ar]

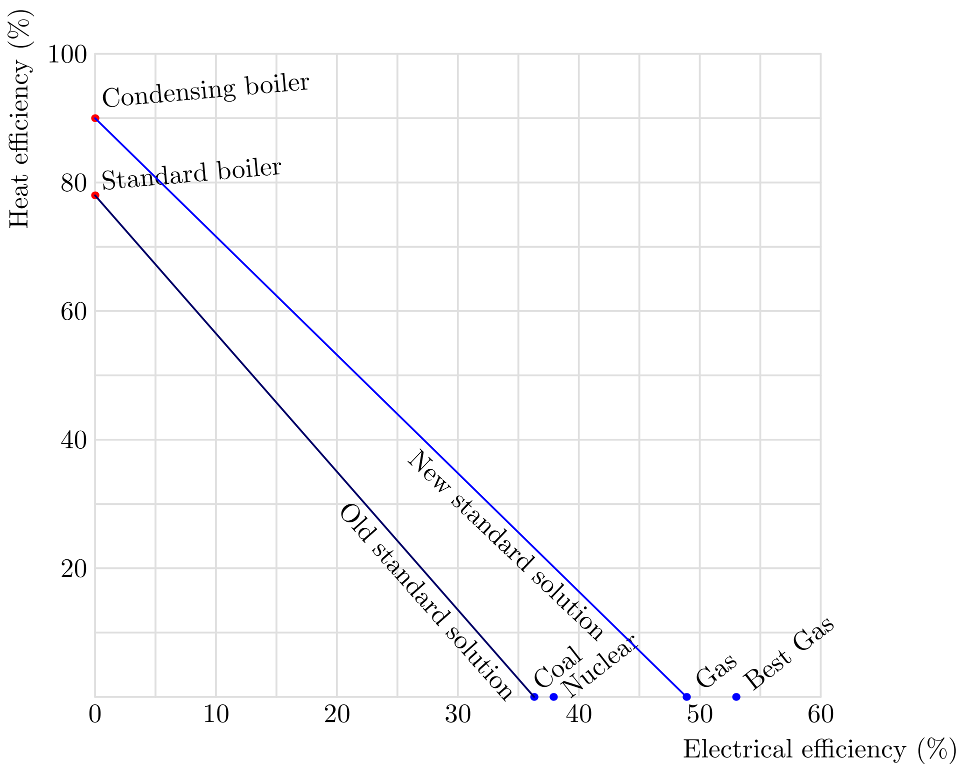
Combined heat and power, compared with the other modern options

I used to think that combined heat and power was a no-brainer. "Obviously, we should use the discarded heat from power stations to heat buildings rather than just chucking it up a cooling tower!" However, looking carefully at the numbers describing the performance of real CHP systems, I've come to the conclusion that there may be better ways of providing electricity and building-heating.

I'm going to build up a diagram in three steps. The diagram shows what electrical energy or heat energy can be delivered from chemical energy.

The standard solution with no CHP

In the first step, we show simple power stations and heating systems that deliver pure electricity or pure heat.

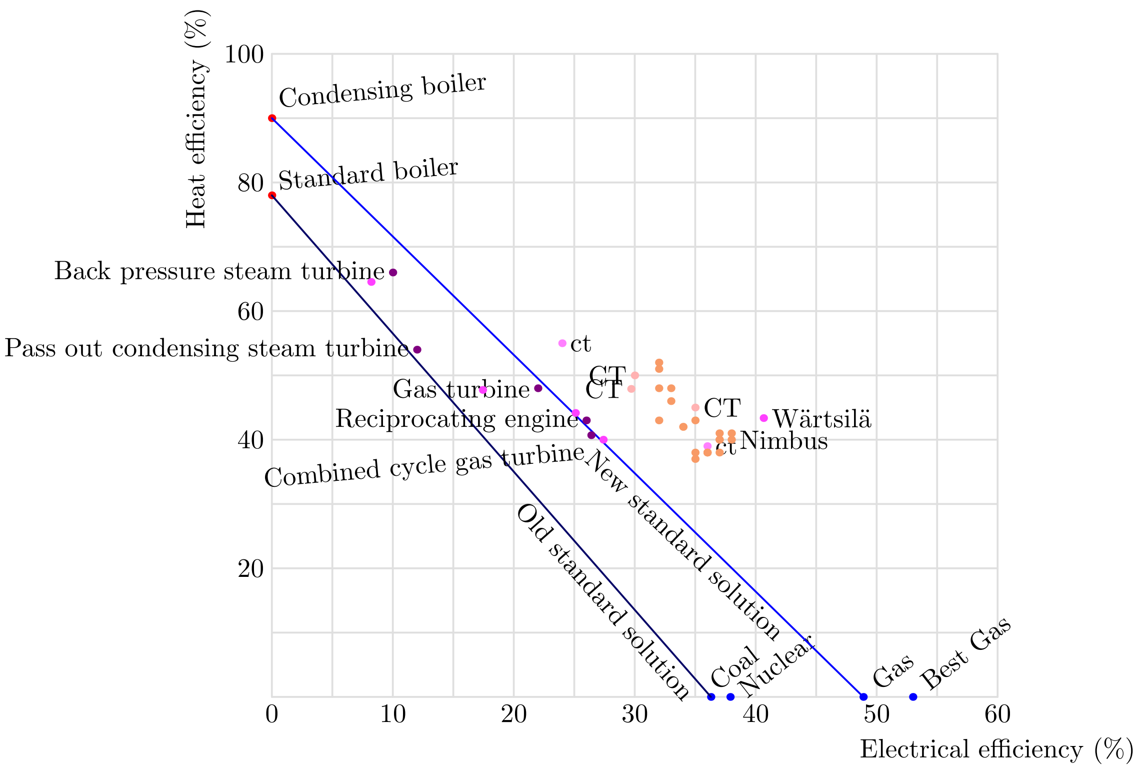


Condensing boilers (the top-left dot) are 90% efficient because 10% of the heat goes up the chimney. Britain's gas power stations (the bottom-right dot) are currently 49% efficient at turning the chemical energy of gas into electricity.

If you want any mix of electricity and heat, you can obtain it by burning appropriate quantities in the electricity power station and in the boiler.

Combined heat and power

Next we add combined heat and power systems. These simultaneously deliver, from chemical energy, some electricity and some heat.

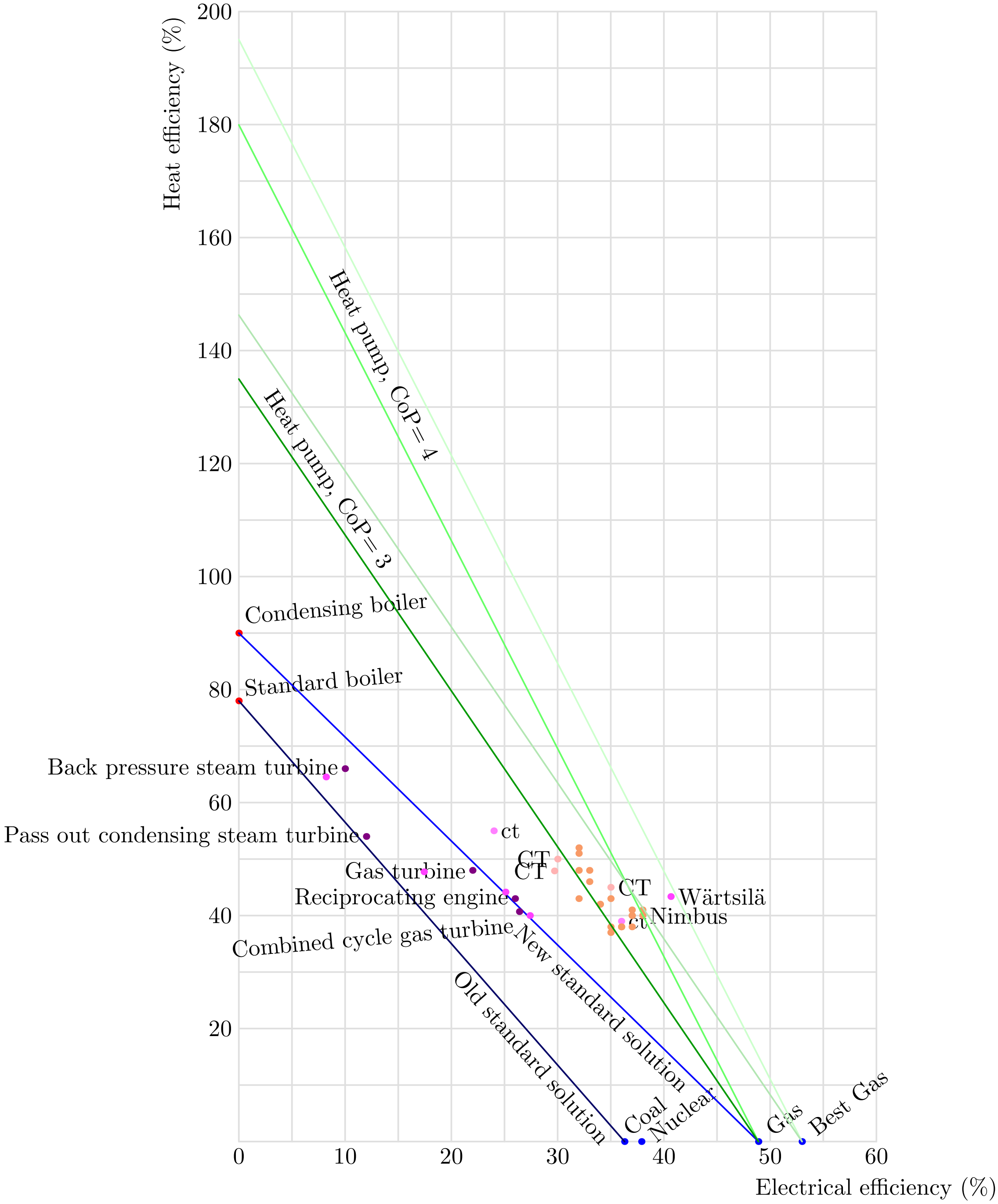


Each of the heavy dots shows actual average performances CHP systems in the UK, grouped by type. The lighter dots marked 'CT' show the performances of ideal CHP systems quoted by the Carbon Trust; the lighter dots marked 'Nimbus' are from a manufacturer. The dots marked 'ct' are the performances quoted by the Carbon Trust for two real systems (at Freeman hospital and Elizabeth house). It's common practice to lump together the two numbers (the efficiency of electricity production and heat production) into a single 'total efficiency' – for example, the back pressure steam turbines delivering 10% electric and 66% heat would be called '76% efficient', but I think this is a poor summary of performance. After all, by this measure, the condensing boiler is 'more efficient' than all the CHP systems! The fact is, electrical energy is more valuable than heat.

Many of the CHP points in this figure are superior to the 'old standard way of doing things' (getting electricity from coal and heat from standard boilers). And the ideal CHP systems are slightly superior to the 'new standard way of doing things' (getting electricity from gas and heat from condensing boilers). But we must bear in mind that this slight superiority comes with some drawbacks – a CHP system delivers heat only to the places it's connected to, whereas condensing boilers can be planted anywhere with a gas main; and compared to the standard way of doing things, CHP systems are not so flexible in the mix of electricity and heat they deliver; a system will work best when delivering a particular mix; this inflexibility leads to inefficiencies at times when, for example, excess heat is produced; a final problem with some micro-CHP systems is that when they have excess electricity to share, they may do a poor job of delivering power to the network.

One exceptional CHP system – the Wärtsilä 34SG – has specifications significantly better than all those described by the Carbon Trust. The spec sheets for a CHP engine for district heating claim an electrical efficiency of 41% and a heat efficiency of 43% with the heat load cooling 80°C water down to 35°C. (Technical detail: I express all efficiencies relative to the full energy content of the fuel, the 'higher heating value'.)

Finally we add in heat pumps.



The steep lines show the combinations of electricity and heat that you can obtain assuming that heat pumps have a coefficient of performance of 3 or 4, assuming the electricity is generated by an average gas power station or by a top-of-the-line gas power station, and allowing for 8% loss in the national electricity network between the power station and the building where the heat pumps pump heat. The top-of-the-line gas power station's efficiency is 53%, if it's running at its optimal setting. I imagine the carbon trust (CT) and Nimbus made a similar assumption when providing the numbers used in this diagram for CHP.

Notice that heat pumps offer a system that can be 'better than 100%-efficient'. For example the 'best gas' power station with heat pumps can deliver a combination of 30%-efficient electricity and 80%-efficient heat, a total efficiency of 110%. No plain CHP system could ever match this performance.

Heat pumps are superior in efficiency to condensing boilers. If you want to heat lots of buildings using natural gas, you could install condensing boilers, which are '90% efficient', or you could put up a new gas power station and install heat pumps in all the buildings; the second solution's efficiency would be somewhere between 140% and 190%. It's not necessary to dig big holes in the garden and install under-floor heating to get the benefits of heat pumps; the best air-source heat pumps (which require just a small external box, like an air-conditioner's) can deliver hot water to normal radiators with a coefficient of performance above 3.

I thus conclude that combined heat and power, even though it sounds a good idea, is probably not the best way to heat buildings and make electricity using natural gas, assuming that air-source or ground-source heat pumps can be installed in the buildings. The heat-pump solution has further advantages that should be emphasised: heat pumps can be located in any buildings where there is an electricity supply; they can be driven by any electricity source, so they keep on working when the gas runs out or the gas price goes through the roof; and heat pumps are flexible: they can be turned on and off to suit the demand of the building occupants.

I emphasize that this critical comparison does not mean that CHP is a bad idea in general. This is a comparison of methods for heating ordinary buildings. CHP can also be used to deliver higher grade heat to industrial users (at 200°C, for example). In such industrial settings, heat pumps are unlikely to compete well because their coefficient of performance would not be so big.

Do you worry that the figures for performance of heat pumps may be exaggerated? On p. 292 you mentioned a new office where the ground-source heat pump's actual coefficient of performance was only 2.5!

I'd love to have better data on the actual performance of modern heat pumps. But, taking the long view, it doesn't matter whether the coefficient of performance of heatpumps turns out to be 2.5 or 5.2. We have to plan to get off fossil fuels (because of climate change, natural gas running out, or security of supply). So using natural gas is not an option for any long-term plan. So that leaves. . . only heat pumps or other electrically powered heating. There is no alternative (for buildings that need heating). Biomass? No, we can't grow enough *Miscanthus* for all the buildings that need heating.

Notes

(from Mott MacDonald 2001). 80% of the CHP capacity in the UK (which totals 4.2 GW(e) and 15 GW(th)) is in large schemes (>10 MW). (81 installations)
(roughly 1200 other smaller installations exist)

Efficiency of the dominant technology: The biggest generator of CHP is combined cycle natural gas. In 2005, it generated 17 347 GWh(e) and 26 740 GWh(th), using fuel with an energy of 65 701 GWh. That's 26.4% efficient electricity, 40.7% efficient thermal, overall efficiency 67%.

143 [36w8o7].

Some heat pumps are said to have a COP bigger than 4.0 [yok2nw]. Indeed there is a government subsidy for water-source heat pumps that applies only to pumps with a COP better than 4.4 [2dtx8z].

To look into: In Switzerland, Heat Pumps, They have a field-study running called FAWA which has been looking at 221 Heat Pumps (Air, Water, Brine) over the past 15 years or so. The best HP (which are in the study, so not the best you can get on the market today!) operate with a performance of 5.59 (Brine) and 3.38 (Air).
Another site with information: http://www.kensaengineering.com/ Kensa heat pumps install GSHP in UK homes.
More Heat pump pictures and facts from http://www.iceenergy.co.uk/

mechanical ventilation with heat recovery

Passivhaus standard (15 kWh/m^2/y for heating, and 30 kWh/m^2/y for all energy use). "Carsten gave us another little trick used by PassivHaus designers. He said it was extremely difficult to get a really low theoretical heat demand from a detached two-storey structure as there is just too much external envelope in proportion to floor area. An easy way around this conundrum was to add a third storey, in his case a basement, and to include this in the heated envelope. The floor area goes up 50% whilst the space heating demand rises much less. As you are

> looking to meet a target expressed in kWh/m2/annum, the job of reaching PassivHaus standard becomes that much easier. "You could argue that this is daft and that the total energy load is actually increased in order to meet some notional standard. In fact, you'd be right but it's a criticism that can be levied at most of the other energy rating schemes as well, certainly all the ones that work on a floor area basis."

In the Netherlands, summer heat from roads stored in aquifers until the winter; and delivered to buildings via heat pumps: [2wmuw7].

Queries

How easy is it to save the heat of the hot water that we throw down the drain?

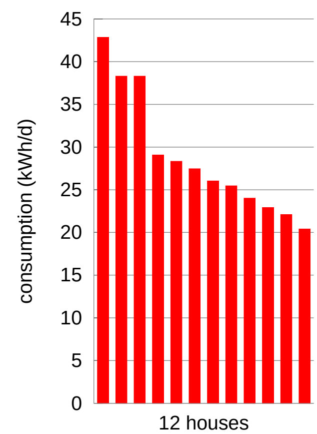


Figure 21.11. Actual heat consumption in 12 identical houses with identical heating systems. All houses were designed to have a heat loss coefficient of 2.7 kWh/d/°C (114 W/°C). From Carbon Trust.

State of the art

UEA campus, Elizabeth Fry Building, completed 1995: space heating 33 kWh/m^2/y. Water, 4 kWh/m2/y. Electricity 60 kWh/m2/y. (All rising with time.)

Criticism of micro CHP

`http://www.carboncommentary.com/2007/10/01/19#more-19`

Trigeneration example

Don't forget

The most important smart component in a building with smart heating is the occupant.

Some data for workplaces

(reproduced in heating2)

Needham Building, Cambridge. (A new building; holds computer science researchers and administrators.) 7216 m^2. Consumption 1923 MWh/y, or 266 kWh/y/m^2, or 0.73 kWh/d/m^2, or 30 W/m^2. Roughly 150 people work there on average.

William Gates building: (A new building; holds computer science researchers, administrators, and a small café.) Roughly 274 people work there. Gates: 11 110 m^2. 1982 MWh/y. 178 kWh/m^2/y, or 20 W/m^2.

Cavendish: Mott building 8249 m^2, 4580 MWh Rutherford bldg 4998 m^2, 1096 MWh

22

Nuclear fission?

We made the mistake of lumping nuclear energy in with nuclear weapons, as if all things nuclear were evil. I think that's as big a mistake as if you lumped nuclear medicine in with nuclear weapons.

Greenpeace co-founder Patrick Moore

We've estimated the power from all the traditional renewables in the UK. Now it's time to move on to non-renewable options.

Could nuclear energy be 'sustainable'? Leaving aside for a moment the usual questions about safety and waste-disposal, a key question is whether humanity could live for generations on fission. How great are the worldwide supplies of uranium, and of thorium? Do we have only a few decades' worth of uranium, or do we have enough for millennia?

To estimate a 'sustainable' power from uranium, I took the total recoverable uranium in the ground and in sea-water, divided it fairly between 6 billion humans, and asked 'how fast can we use this if it has to last 1000 years?' I'll be the first to admit this is an arbitrary definition of 'sustainable'! But I think the results are interesting anyway.

Almost all the recoverable uranium is in the oceans, not in the ground: seawater contains 3.3 mg of uranium per m^3 of water, which adds up to 4.5 billion tons worldwide. The extractable ore in the ground is about one thousandth of this. I called the uranium in the ocean 'recoverable' but this is a bit inaccurate – most ocean waters are quite inaccessible, and the ocean conveyor rolls round only once every thousand years or so; and no-one has yet demonstrated uranium-extraction from seawater on an industrial scale. So we'll make separate estimates for two cases: using ocean uranium, and using only mined uranium.

We'll also consider two ways to use uranium in a reactor: the widely-used *once-through method* gets energy only from the ^{235}U, which makes up just 0.7% of uranium, and discards the remaining ^{238}U; alternatively, *fast breeder reactors*, which are more expensive to build, convert the ^{238}U to fissionable plutonium-239 and obtain sixty times as much energy from the uranium. [Include reference.]

	thousand tonnes U	percentage of world total
Australia	1074	30%
Kazakhstan	622	17%
Canada	439	12%
South Africa	298	8%
Namibia	213	6%
Brazil	143	4%
Russian Federation	158	4%
USA	102	3%
Uzbekistan	93	3%
World total (in the ground)	3 537	
Seawater	4 500 000	

Table 22.1. Known recoverable resources of uranium.

Once-through, using uranium from the ground

A once-through **one-gigawatt** nuclear power station uses **162 tons per year of uranium**. So the known mineable resources of uranium correspond to

$$\frac{3.5\,\text{million tons per planet}}{162\text{ tons uranium per GW year}} = 20\text{ thousand GW years per planet.}$$

This would last for 1000 years if we produced nuclear power at a rate of

$$20\,\text{GW},$$

which, shared between 6 billion people, is just

$$0.1\,\text{kWh per day per person.}$$

It's possible this is an underestimate, since, as there is not yet a uranium shortage, there is little incentive for further exploration (little uranium exploration has been done since the 1980s.); so maybe more mineable uranium will be discovered; the estimated conventional uranium reserves worldwide (proven, 'additional', *and* 'speculative'), at a price up to $130/kg, are about 15 million tons, about 4 times the figure I used; but even if one hundred times more were discovered, this technology would still supply only 10 kWh per day per person of sustainable power.

I thus conclude that our current once-through use of uranium is not sustainable.

Fast breeder reactors, using uranium from the ground

If we switched to sixty-times-more-efficient fast breeder reactors, the power would be

$$5\,\text{kWh per day per person.}$$

Once-through, using uranium from the oceans

The oceans' uranium, if completely extracted, corresponds to

$$\frac{4.5\,\text{billion tons per planet}}{162\ \text{tons uranium per GW year}} = 28\ \text{million GW years per planet.}$$

How fast could uranium be extracted from the oceans? The oceans circulate slowly: half of the water is in the Pacific, and deep Pacific waters circulate to the surface on the great ocean conveyor only every 1600 years. Let's imagine that 10% of the uranium is extracted over such a 1600-year period. (That's an extraction rate of 280 000 tons per year.) In once-through reactors, this would deliver power at a rate of

$$2.8\ \text{million GW years} \ /\ 1.6\ \text{thousand years}\ = 1750\,\text{GW},$$

which, shared between 6 billion people, is

$$7\,\text{kWh per day per person.}$$

(There's currently 369 GW of nuclear reactors, so this figure corresponds to a four-fold increase in nuclear power.)

Fast breeder reactors, using uranium from the oceans

If fast reactors are sixty times more efficient, the same extraction of ocean uranium could deliver

$$420\,\text{kWh per day per person.}$$

At last, a sustainable figure that beats current consumption! – But only with the joint help of two technologies that are respectively scarcely-developed and unfashionable: ocean extraction of uranium, and fast breeder reactors.

Fast breeder reactors, using uranium from rivers

The uranium in the oceans is being topped up by rivers, which deliver uranium at a rate of 32 000 tons per year. If 10% of this influx were captured, it would provide enough fuel for 20 GW of once-through reactors, or 1200 GW of fast breeder reactors. The fast breeder reactors would deliver 5 kWh per day per person. All these numbers are summarised in figure 22.2.

What about costs?

As usual in this book, my main calculations have paid little attention to economics. However, since the potential contribution of ocean-uranium-based power is one of the biggest in our 'sustainable' production list, it seems appropriate to discuss whether this uranium-power figure is at all economically plausible.

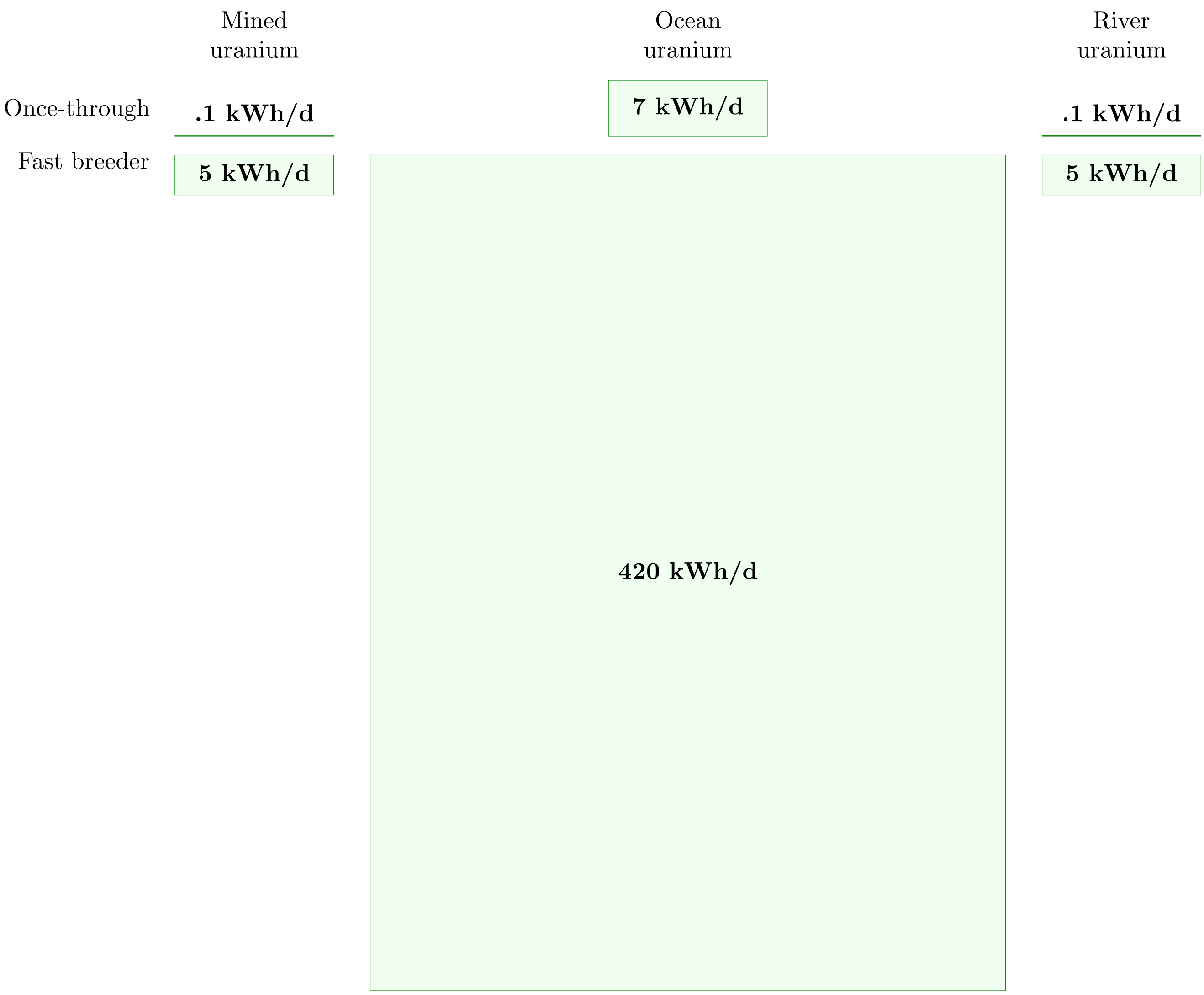


Figure 22.2. 'Sustainable' power from uranium.

Japanese researchers have found a technique for extracting uranium from seawater at a cost of \$100 per kilogram of uranium, in comparison with a current cost of about \$20/kg for uranium from ore. Because uranium contains so much more energy per ton than traditional fuels, this five-fold increase in the cost of uranium would have little effect on the cost of nuclear power: nuclear power's price is dominated by the cost of construction and decommissioning, not by the cost of the fuel. Even a price of \$200/kg would increase the cost of nuclear energy by only about 0.2 p per kWh.

The expense of uranium extraction could be reduced by combining it with another use of sea water – for example, cooling.

We're not home yet: does the Japanese technique scale up? What is the energy cost of processing all the seawater required for a single gigawatt reactor? In the Japanese experiment, three cages full of adsorbent material weighing 350 kg collected 'more than 1 kg of yellow cake in 240 days'; this figure corresponds to about 1.6 kg per year. The cages had a cross-sectional area of 48 m^2. To power a once-through 1 GW nuclear power station, we need 160 000 kg per year, which is 100 000 times more. If we simply scaled up the Japanese technique, which absorbed uranium passively from the sea, a power of 1 GW would thus need cages having a collecting area of 4.8 km^2 and containing a weight of 350 000 tons of adsorbent material – more than the weight of the steel in the reactor itself. To put these large numbers in human terms, if uranium were delivering, say, 22 kWh per day per person, each 1 GW reactor would be shared between one million people, each of whom needs 0.16 kg of uranium per year. So each person would require one tenth of the Japanese experimental facility, with a weight of 35 kg per person, and an area of 5 m^2 per person. The proposal that such uranium-extraction facilities should be created is thus similar in scale to proposals such as 'every person should have 10 m^2 of solar panels' and 'every person should have a one-ton car and a dedicated parking place for it'. A large investment, yes, but not absurdly off scale. And that was the calculation for once-through reactors. For fast breeder reactors, sixty times less uranium is required, so the mass per person of the uranium collector would be 1/2 kg.

Thorium

Thorium, an element similar to uranium, once used to make gas mantles, is about three times as abundant in the earth's crust as uranium. Soil commonly contains around 6 parts per million of thorium, and some minerals contain 12% thorium oxide. Sea water contains little thorium, because thorium oxide is insoluble. Thorium can be completely used up in simple reactors without fast neutrons (in contrast to standard uranium reactors which use only 0.7% of natural uranium). Thorium is used in nuclear reactors in India. If uranium ore runs low, thorium will probably become the dominant nuclear fuel.

Country	Reserves (thousand tons)
Turkey	380
Australia	300
India	290
Norway	170
USA	160
Canada	100
South Africa	35
Brazil	16
Other countries	95
World total	1 580

Table 22.3. World thorium resources in monazite (economically extractable).

Thorium reactors deliver 3.6×10^9 kWh of heat per ton of thorium, which implies a 1 GW reactor requires about 6 tons of thorium per year (assuming its generators are 40% efficient). Worldwide thorium resources are estimated to total about 6 million tons. (Table 22.3 shows the locations of 1.6 million tons of proven reserves.) If we assume, as with uranium, that these reserves are used up over 1000 years and shared equally among six billion people, we find that the 'sustainable' power thus generated is **4 kWh/d per person**.

An alternative nuclear reactor for Thorium, the 'energy amplifier' proposed by Nobel prizewinner Carlo Rubbia and his colleagues would, they estimated, convert 6 million tons of thorium to 15 000 TWy of energy, or **60 kWh/d/person** over 1000 years. And the waste from the energy amplifier would be much less radioactive too. They argue that, in due course, many times more thorium would be economically extractable than the current 6 million tons. If their suggestion – 300 times more – is correct, then thorium and the energy amplifier offer 300 kWh/d/person over 60 000 years.

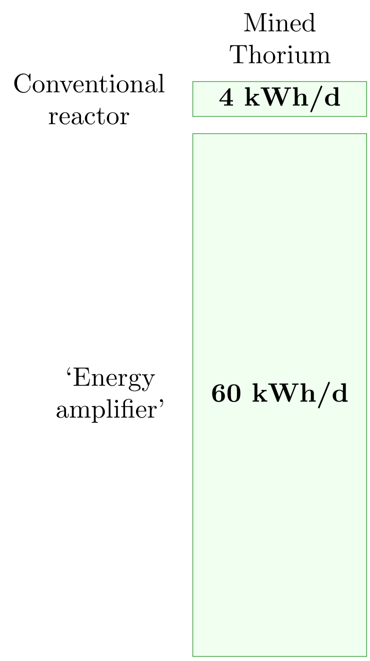
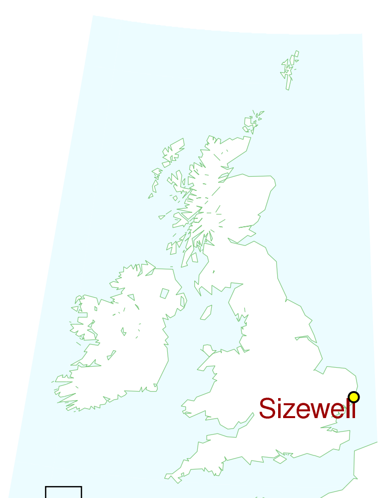


Figure 22.4. Thorium options

Land use

Let's imagine that Britain decides it is serious about getting off fossil fuels, and creates a lot of new nuclear reactors, even though this may not be 'sustainable'. If we build enough reactors to make possible a significant decarbonization of transport and heating, can we fit the required nuclear reactors into Britain? Let's discuss, for example, 22 kWh per day per person – equivalent to 55 GW (roughly the same as France's nuclear power), which could be delivered by 55 nuclear power stations, each occupying one square kilometre. That's about 0.02% of the area of the country. (Wind farms delivering the same average power would require 500 times as much land: 10% of the country.) If they were placed in pairs around the coast (length about 3000 km, at 5 km resolution), then there'd be two every 100 km. Thus while the area required is



modest, the fraction of coastline gobbled by these power stations would be about 2% (two kilometres in every hundred). (There's already 17 nuclear power station sites in the UK.)

Economics of cleanup

Reservations about nuclear power's association with military applications are well known. Hodgson Page 102 quotes 0.54p/kWh for decommissioning. The nuclear decommissioning authority has an annual budget of £2 *billion* for the next 25 years. If I estimate the nuclear industry has sold everyone in the UK 4 kWh/d for about 25 years, then the nuclear decommissioning authority's cost is 2.3 p/kWh. In fact the total generated to 2006 was about 2200 TWh. This agrees perfectly with my estimate.

So decommissioning past nuclear work is costly. But decommissioning in future should be cheaper as we get more experienced? Discuss Dan Kammen's paper on the unpredictability of nuclear costs.

Safety

The safety of nuclear operations in Britain remains a concern. The THORP reprocessing facility at Sellafield, built in 1994 at a cost of £1.8 billion, had a growing leak from a broken pipe from August 2004 to April 2005. Over eight months, the leak let 85 thousand litres of uranium-rich fluid flow into a sump which was equipped with safety systems that were designed to detect any leak of as little as 15 litres. But the leak went undetected because the operators hadn't completed the checks that ensured the safety systems were working; and the operators were in the habit of ignoring safety alarms anyway. The safety system came with belt and braces. Routine safety-measurements of fluids in the sump should have detected the abnormal presence of uranium there within one month of the start of the leak; but the operators often didn't bother taking these routine measurements, because they felt too busy; and when they *did* take measurements that detected the abnormal presence of uranium in the sump (on 28 August 2004, 26 November 2004, and 24 February 2005), no action was taken. By April 2005, 22 tons of uranium had leaked, but still none of the leak-detection systems detected the leak. The leak was finally detected by *accountancy*, when the bean-counters noticed that they were getting 10% less uranium out than their clients claimed they'd put in! Thank goodness this private company had a profit motive, hey? The criticism of the Chief Inspector of Nuclear Installations was withering: "The Plant was operated in a culture that seemed to allow instruments to operate in alarm mode rather than questioning the alarm and rectifying the relevant fault."

If we let private companies build new reactors, how can we ensure that higher safety standards are adhered to? I don't know.

At the same time, we must not let ourselves be swept off our feet in

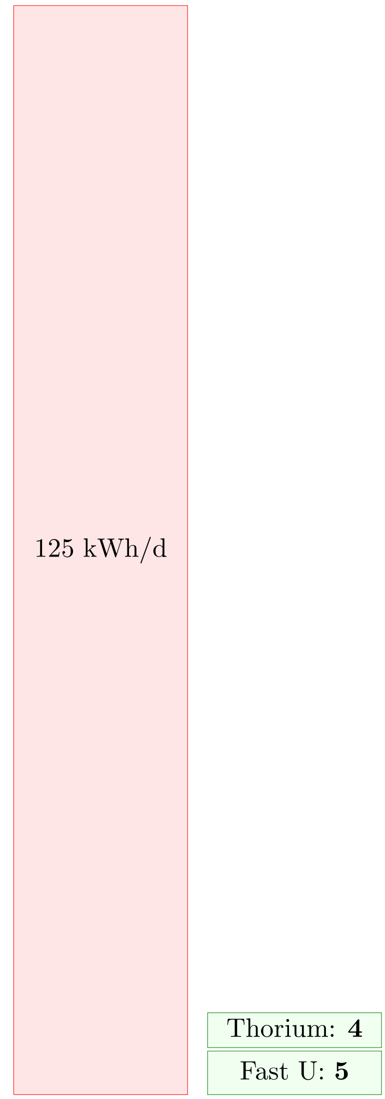


Figure 22.6. 'Sustainable nuclear energy' including thorium. These estimates are based on the assumption that all the accessible uranium on the planet is shared out fairly between 6 billion people, and used up at a steady rate over 1000 years. I've assumed that the uranium is burned up in fast breeder reactors, 60 times more efficient than current once-through reactors.

horror at the danger of nuclear power. Nuclear power is not infinitely dangerous. It's just dangerous, much as coal mines, petrol repositories, fossil-fuel burning and wind turbines are dangerous. Even if we have no guarantee against nuclear accidents in the future, I think the right way to assess nuclear is to compare it objectively with other sources of power. [Here I'd like to include a table of deaths per TWh or deaths per GWy.]

A first stab at deaths per GWy: nuclear in the UK: 200 GWy, zero direct public deaths from radiation, how many statistical deaths? One worker died at Chapelcross in 1978. wind in the UK: 3GWy; world wind, roughly 50GWy. coal: (Mining accidents) plus statistical deaths from dust and radiation exposure. oil: (Nigerian deaths, Piper Alpha)

Mythconceptions

Anti-nuclear people often point out the various 'huge' defects of nuclear power. Let's examine two of them.

Building a nuclear power station requires *huge* amounts of concrete and steel, materials whose creation involves *huge* CO_2 pollution.

How much concrete and steel in a 1 GW nuclear power station? The Nuclear Energy Institute say 520 000 cubic meters of concrete and 67 000 tons of steel. [2k8y7o]

How much CO_2 is produced when making 520 000 cubic meters of concrete? Take the density of concrete (2300 kg/m^3), the CO_2 to make cement (0.8 kg CO_2/kg cement), the cement in concrete (10% from cement.org). [A life-cycle analysis gives 43–240 kg CO_2 per ton of concrete, depending on the type of concrete, with 100 kg per ton of concrete as a median figure http://www.sustainableconcrete.org.uk/main.asp?page=210.] This makes a figure of around 100 000 tCO_2 for one nuclear plant.

How much CO_2 is produced in making 67 000 tons of steel?

Blue Scope Steel (http://csereport2005.bluescopesteel.com/) claim they put out 14.5 million tons of CO_2 equivalent gases in 2004/2005 to produce 5.72 million tons of steel product, which suggests around 2.5 kg CO_2 per kg of steel.

Azom.com materials suggests around 2 tons of CO_2 per ton of steel, and Tata Steel claim ([36y2e4]) between 1.2 and 1.9 tons of CO_2 per ton of steel, depending on the process.

Taking the largest figure, 3 tons of CO_2 for a tonne of steel, we have another 200 000 tons of CO_2 from the steel to make a 1 GW nuclear power station.

Summing the steel and concrete figures: 300 000 tCO_2 is associated with the construction of a 1 GW nuke.

Spreading this huge number over a 25-year reactor life we can express this contribution to the carbon intensity in the standard units (g CO_2

Figure 22.7. Steel plant in Tenaris Siderca, Argentina.

per kWh(e)),

$$\begin{array}{c}\text{carbon intensity}\\ \text{associated with construction}\end{array} = \frac{300 \times 10^9\,\text{g}}{10^6\text{kW(e)} \times 220\,000\,\text{h}} = 1.4\,\text{g/kWh(e)},$$

which is much smaller than the benchmark fossil-fuel figure of 400 g CO_2/kW

Please don't get me wrong: I'm not trying to be pro-nuclear. I'm just pro-arithmetic.

(Could compare with the steel and concrete requirements of offshore wind too.)

How does the volume of nuclear waste from a 1 GW power station compare with the volume of compressed CO_2 that a 'clean coal' power station would produce?

About one millionth?

Let's compare three things: the above two, and the volume of household waste for landfill that we currently produce, compared with the volume of nuclear waste if we got all our power from nuclear.

Waste from new nuclear.

"If the UK were to build a fleet of 10 modern reactors of around 1 GW each (such as the AP1000) and operate these for their full design lifetime of 60 years, the additional waste produced would occupy less than 10% of the volume occupied by wastes already in existence."

Source: BNFL's evidence to House of Commons Environmental Audit Committee.

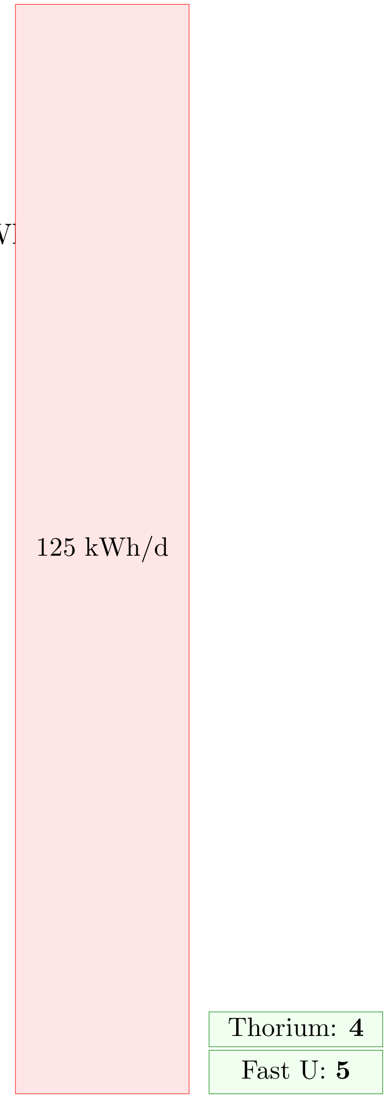


Figure 22.8. Chapter 22's conclusion: Even uranium-based nuclear power, if used fairly and 'sustainably', cannot match our current levels of consumption (unless we assume two developments: a switch to fast reactors, and the harvesting of uranium from sea-water).

Accidents

Chernobyl

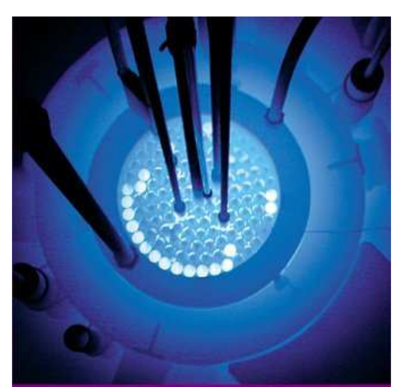
6.7 tons of radioactive junk released. 62 direct deaths. 4000 local cases of thyroid cancer of whom just 15 died. An estimate of 9000 total deaths worldwide. [Cancer already causes 25% of deaths in Europe, so an extra 9000 deaths is a small change in this percentage.]

What about nuclear fusion?

> *We say that we will put the sun into a box. The idea is pretty. The problem is, we don't know how to make the box.*
>
> Sébastien Balibar, director of research, CNRS

Fusion power is speculative and experimental. I think it is reckless to assume that the fusion problem *will* be cracked, but I'm happy to estimate how much power fusion could deliver, *if* the problems are cracked.

The two fusion reactions that are considered the most promising are:



The DT reaction, which fuses Deuterium with Tritium (obtained from lithium), making helium; and

The DD reaction, which fuses Deuterium with Deuterium.

The ITER project will use the DT reaction. DT is preferred over DD, because the DT reaction yields more energy and because it requires a temperature of 'only' one hundred million degrees to get it going (whereas the DD reaction requires three hundred million degrees). (The maximum temperature in the sun is 15 million degrees.)

Let's fantasize, and assume that the ITER project is successful. What sustainable power could fusion then deliver? Power stations using the DT reaction, fuelled by lithium, will run out of juice when the lithium runs out. Before that time, hopefully the second installment of the fantasy will have arrived: fusion reactors using deuterium alone.

I'll call these two fantasy energy sources 'lithium fusion' and 'deuterium fusion', naming them after the principal fuel we'd worry about in each case. Let's now estimate how much energy each of these sources could deliver.

Lithium fusion

World lithium reserves are estimated to be 9.5 million tons in ore deposits.

Taking all these reserves and devoting them to fusion over 1000 years, we find that the power delivered would be 10 kWh/d per person.

There's another source for lithium: seawater, where lithium has a concentration of 0.17 ppm. To produce lithium at a rate of 10^8 kg/y from seawater is estimated to have an energy requirement of 2.5 kWh(e) per gram of lithium. If the fusion reactors give back 2300 kWh(e)/g lithium, the power thus delivered would be 105 kWh/d per person (assuming 6 billion people). At this rate, the lithium in the oceans would last over a million years.

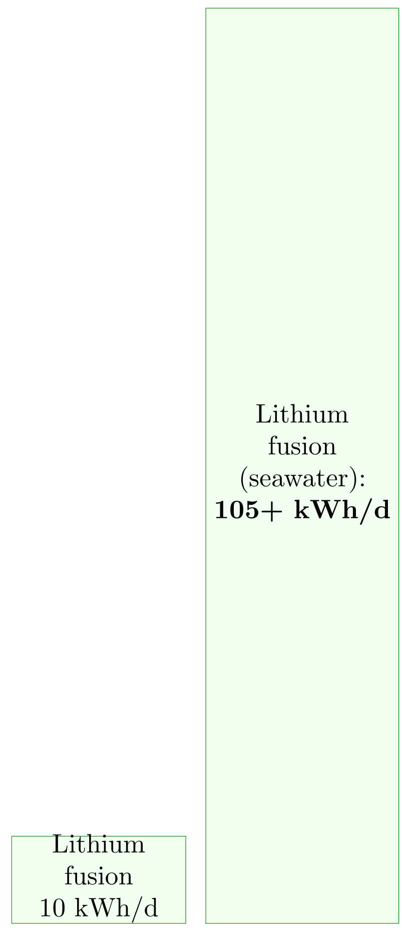


Figure 22.11. Lithium-based fusion, if used fairly and 'sustainably', could match our current levels of consumption. Mined lithium would deliver 10 kWh/d per person for 1000 years; lithium extracted from seawater could deliver 105 kWh/d per person for a million years.

Deuterium fusion

Using the D–D reaction (page 75 of Hodgson)

Deuterium is one part in 6000 in water. Deuterium represents approximately 0.015% of hydrogen in water.

From Ongena: 33 g of deuterium per ton of water. 4.6e13 tons of D in oceans. Energy density: 350e15J per ton of D. 100 000 kWh per g of D. 3200 kWh per litre of ordinary water.

Volume of oceans = 1.37 billion km^3, which is 0.23 km^3 each.

At 300 kWh per person per day, and 6 billion people, fusion would last 1 billion years.

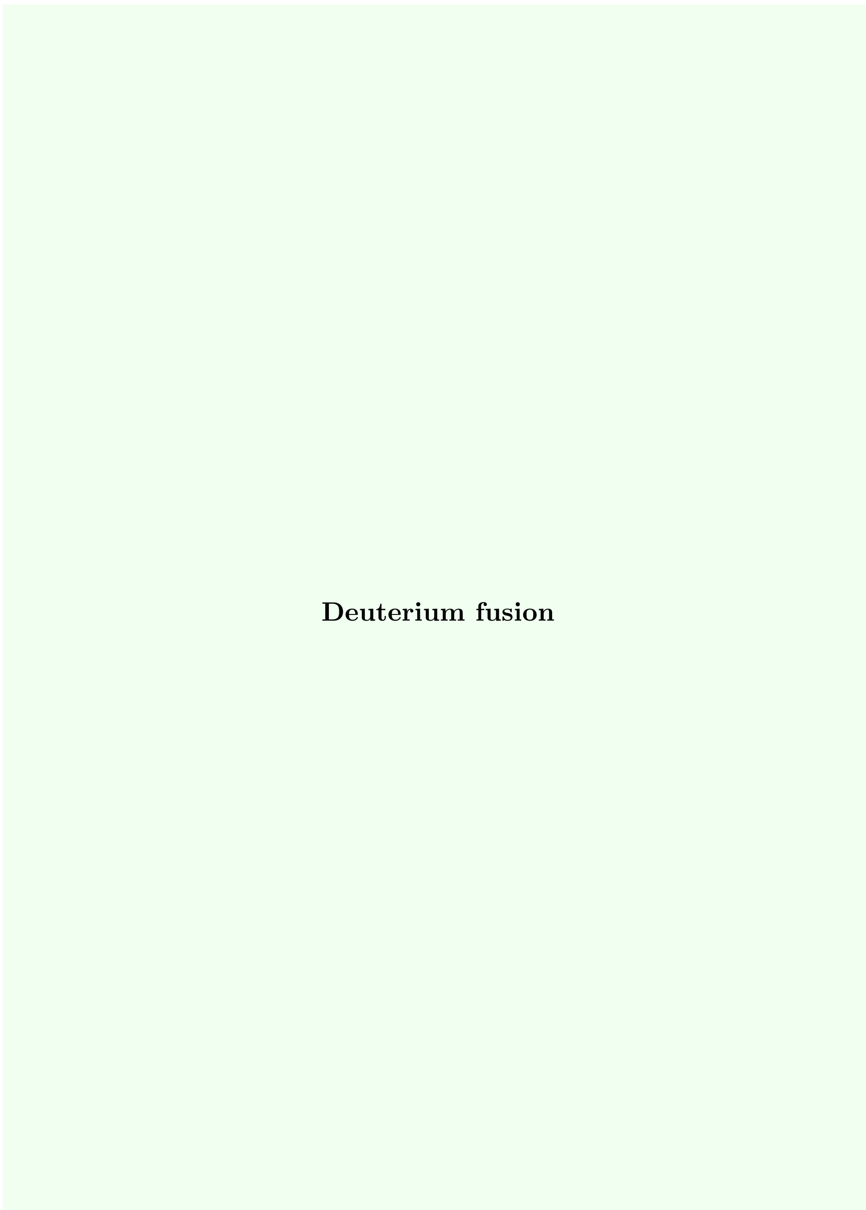


Figure 22.10. Deuterium-based fusion, if it is achievable, offers plentiful sustainable energy for millions of years.

Notes

Budget for fusion research and development in the UK: £65M per year. (Total UKAEA turnover: £378M/y.)

(cf. UK renewable R&D budget, £12M/y.)

(What is the UK's contribution to the ITER project? And to IFMIF? Perhaps these contributions are made via the EU?)

Euratom R&D. The total budget for Euratom FP7 in the period 2007-2011 is €2.75 billion and allocated as follows: Fusion energy research: €1,947 million. Nuclear fission and radiation protection: €287 million.

Nuclear activities at the JRC: €517 million.

What is UK share of FP7? Total EU budget is €129b. UK's contribution is 11%.

So of the current €2b European budget (over 5 years) for fusion energy research, Britain is effectively paying €0.22b over 5 years, or €44M per year.

Notes

155 A once-through **one-gigawatt** nuclear power station uses **162** tons **per year of uranium**. Source –
Alternative figure –

?? *The nuclear decommissioning authority has an annual budget of £2 billion.* In fact, just like the stock market, this cleanup budget seems to rise and rise. The latest figure for the total cost of decommissioning is £73 billion. `http://news.bbc.co.uk/1/hi/uk/7215688.stm`

160 *The criticism of the Chief Inspector of Nuclear Installations was withering. . .* Weightman [2007].

158 *The expense of uranium extraction could be reduced by combining it with another use of sea water – for example, cooling.* The idea of a nuclear-powered island producing hydrogen was floated by C. Marchetti. Breeder reactors would be cooled by sea water and would extract uranium from the cooling water at a rate of 600 t uranium per 500 000 Mt of sea water.

159 *An alternative nuclear reactor for Thorium, the 'energy amplifier'. . .* See Rubbia et al. [1995], `http://web.ift.uib.no/~lillestol/Energy_Web/EA.html`, [32t5zt].
See also [2qr3yr], [ynk54y].

Useful reading: Uranium Information Center – `http://www.uic.com.au/`.

158 Summary of Japanese research into extracting uranium from seawater – from [y3wnzr] The uranium extraction technique involves dunking tissue in the ocean for a couple of months; the tissue is made of polymer fibres that are made sticky by irradiating them before they are dunked; the sticky fibres collect uranium to the tune of 2**g** of uranium per kilogram of fibre. Even at $200/kg, uranium from seawater would be cheaper than reprocessing spent fuel and recycling plutonium and uranium. uranium at $200/kg would increase the cost of nuclear energy by about 0.4 ¢ per kWh.
[Seko et al., 2003]

159 *World thorium resources in monazite.* source: US Geological Survey, Mineral Commodity Summaries, January 1999. [yl7tkm] Quoted in UIC Nuclear Issues Briefing Paper # 67 November 2004.
'Other ore minerals with higher thorium contents, such as thorite, would be more likely sources if demand significantly increased'.
[yju4a4] omits the figure for Turkey, which is found here. [yeyr7z]

163 *There's another source for lithium: seawater...* Several extraction techniques have been investigated Steinberg and Dang [1975], Tsuruta [2005]. Chitrakar et al. [2001]. The extractable amount in seawater is roughly 10 000 times greater.

http://www.world-nuclear.org/co2&nfc.htm
Energy cost of full uranium cycle, broken down in detail here: [wnchw]

Enrichment accounts for almost half of the cost of nuclear fuel and about 5% of the total cost of the electricity generated. [t2948]

This page [ygwh8a] gives a life-cycle analysis for nuclear. This seems to be the source for the 'Ireland' document. For nuclear power, enrichment is clearly the key energy input where the older diffusion technology is used - it comprises more than half the lifetime total. However, with centrifuge technology it is far less significant than plant construction. Includes a range of mining costs for different ore concentrations.

Bottom line: 1 GW PWR power plant. where mine's ore is 0.234% U (energy cost of mining 165 GJ/t U_3O_8, or 195 GJ/t U, an output of 7 TWh/y (76 000 TJ) required mining and milling input of 39 TJ per y (for 230 t per yr of U_3O_8). Larger was the enrichment cost. Overall the energy ratio (assuming a 40-year life) is 58 if modern centrifuge enrichment used. (*i.e.*, 1.7% of the output is the input, respectively). Construction and decommissioning are about half of the energy cost. But if the ore were 0.01% U then the mining bill goes up to 924 TJ/y and the bottom line changes from 1.7% to 2.9%.

This same document also quotes other study (Forsmark 3 GW) giving nuclear an input/output of 1.35%, and CO_2 emissions of 3.1 g/kWh.

Nuclear CO_2: 40 kg/MWh in the USA. In France, where nuclear power is used for the electricity for diffusion enrichment, 20 kg/MWh.

	$g\,CO_2$/kWh		
	Japan	Sweden	Finland
coal	975	980	894
gas thermal	608	1170	–
gas combined cycle	519	450	472
solar photovoltaic	53	50	95
wind	29	5.5	14
nuclear	22	6	10–26
hydroelectric	11	3	–

Table 22.12. Source: Kivisto (2000) in http://www.world-nuclear.org/info/inf11.htm

The life cycle CO_2 emission coefficient for nuclear power, on the basis of centrifuge enrichment, is 2.7% of that for coal-fired generation.

British Energy's Torness nuclear power plant in 2002 was 5 g/kWh.

This same document also rebuts Storm van Leeuwen and Smith.

eg true modern Energy cost of mining: in-situ leaching (ISL) which can be more efficient than traditional mining methods in terms of both cost and energy use, eg about 19 kWh/kgU in Australia and 33 kWh/kgU in Kazakhstan.

Forsmark has three reactors totalling 3 GW(e). energy cost of construction and decom: The life cycle assessment for Vattenfall's Forsmark-3 nuclear plant showed that 4.1 PJ was required for construction and decommissioning, on basis of 40 year plant life.

(Which is about 950 MWh per MW if F-3 was 1.2GW)

Energy cost in Finland for making nuclear power: (construction only?) 650 MWh/MW capacity. Incidentally, this gives a useful money to energy ratio for construction project. The Finnish reactors cost Olkiluoto 3 project cost has been estimated by TVO at around €3 Billion. Zaleski [2005][32louu] – for a 1600 MW reactor *and* waste depository. [shrln]

Site for unbiased information on waste repositories.

162 *Chernobyl* Nature April 20 2006 page 984 Review articles
6.7 tons of radioactive junk released. 62 direct deaths. 4000 local cases of thyroid cancer of whom just 15 died. An estimate of 9000 total deaths worldwide. (4000 of whom are among a set of 600,000 people who were exposed to a significant amount of radiation, giving 4/600 chance of death; and the other 5000 are among a set of 6.8M others further away, exposed to 7 millisieverts, which is comparable to total natural yearly dose. Cancer already causes 25% of deaths in Europe.

163 *World lithium reserves are estimated as 9.5 million tons.* www.dnpm.gov.br The main lithium sources are found in Bolivia

(56.6%), Chile (31.4%) and the United States (4.3%). www.dnpm.gov.br

The energy density of natural lithium is about 7500 kWh per gram [Ongena and Van Oost, 2006]. There's considerable variation among the estimates of how efficiently fusion reactors would turn this into electricity, ranging from 310 kWh(e)/g [Eckhartt, 1995] to 3400 kWh(e)/g of natural lithium [Steinberg and Dang, 1975]. I've assumed 2300 kWh(e)/g, based on this widely quoted summary figure: "A 1 GW fusion plant will use about 100 kg of deuterium and 3 tonnes of natural lithium per year, generating about 7 billion kWh." http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=7200593 http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6773271&query_id=0 http://pubs.acs.org/cgi-bin/abstract.cgi/jacsat/2002/124/i18/abs/ja003472m.html

23

Sustainable fossil fuels?

Figure 23.1. Coal being delivered to Kingsnorth power station (capacity 1940 MW) in 2005. Photos by Ian Boyle www.simplonpc.co.uk.

> *It is an inescapable reality that fossil fuels will continue to be an important part of the energy mix for decades to come.*
>
> UK government spokesperson, April 2008

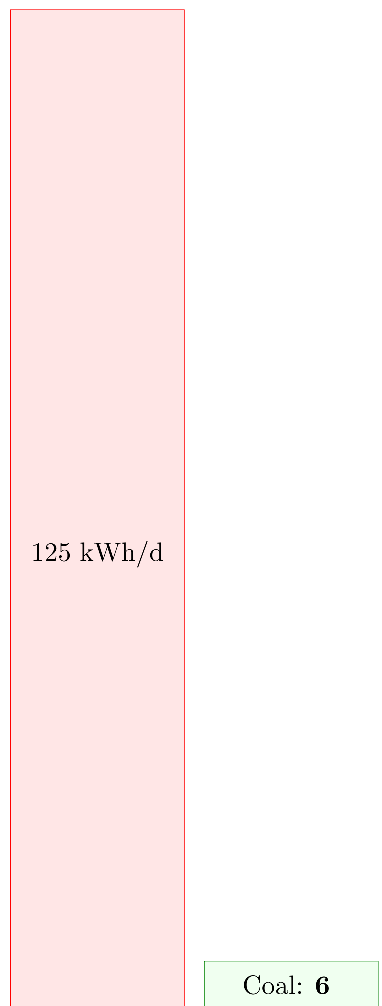
Take the known reserves of fossil fuels. Share them equally between six billion people, and burn them 'sustainably', such that they're all gone in 1000 years. [Could note that Hansen et al (2007) equate 'more than 500 years' with 'forever'.] 1600 Gt of coal shared between 6 billion people is 270 tons each; and a ton of coal delivers 8000 kWh of a chemical energy. So the power delivered would be **6 kWh per day per person**. A standard coal power station would turn this into electricity with an efficiency of about 37% – that means about 2.2 kWh(e) per day per person. If we care about the climate, however, then presumably we would not use a standard power station. Rather, we would go for 'clean coal', also known as 'coal with carbon capture and storage' – an as-yet unimplemented technology that sucks most of the carbon out of the chimney-flue gases. Cleaning up power station emissions in this way has a significant energy cost – it would reduce the delivered electricity by about 25%. So a 'sustainable' use of known coal reserves would deliver only about **1.6** kWh(e) **per day per person**.

We can compare this 'sustainable' coal-burning rate – 1.6 Gt per year – with the current rate of coal consumption: 6 Gt per year.

What about the UK alone? Britain used to have outstanding coal reserves. Now it's estimated to have 7 billion tons left. OK, if we share 7 Gt between 60 million people, we get 100 tons per person. If we want a 1000-year solution, that's 0.1 tonnes per year. Each tonne is 8000 kWh, so 800 kWh per year, which is about 2.5 kWh per day per person. In a power station performing carbon capture and storage, this sustainable approach to UK coal would yield 0.7 kWh(e) per day per person.

When's the end of business as usual?

The economist Jevons did a simple calculation in 1865. People were discussing how long British coal would last. They tended to calculate



answers to this question by dividing the estimated coal remaining by the current rate of coal consumption, and thus getting answers like '1000 years'. But, Jevons said, our rate of consumption is *not* constant. It's been doubling every 20 years, and 'progress' would have it continue to do so. So "reserves divided by consumption-rate" gives the wrong answer.

Instead, Jevons extrapolated the exponentially-growing consumption, calculating the time by which the total amount consumed would exceed the estimated reserves. This was a much shorter time. Jevons was not assuming that consumption would actually continue to grow at the same rate; rather he was making the point that growth was not sustainable. His calculation estimated for his British readership the inevitable limits to their growth, and the short time remaining before those limits would become evident. Jevons made the bold prediction that the end of British 'progress' would come within 100 years of 1865. Jevons was right. British coal production peaked in 1910, and by 1965 Britain was no longer a world superpower.

Let's repeat his calculation for the world as a whole. In 2006, the coal consumption rate was 6.3 Gt per year. Comparing this with reserves of 1600 Gt of coal, people often say "there's 250 years of coal left". But if we assume business as usual implies a growing consumption, we get a different answer. If the growth rate of coal consumption were to continue at 2% per year (which gives a reasonable fit to the data from 1930 to 2000), then all the coal would be gone in 2096. If the growth rate is 3.4% per year (the growth rate over the last decade), the end of business-as-usual is guaranteed to be before 2072. Not 250 years, but 60!

If Jevons were here today, I am sure he would firmly predict that unless we steer ourselves on a course different from business as usual, there will, by 2050 or 2060, be an end to our happy progressive condition.

> *The greatest shortcoming of the human race is our inability to understand the exponential function.*
>
> Albert Bartlett

Notes

World Energy Council [yhxf8b] survey of energy resources.

169 ton of coal equivalent = 29.3 GJ = 8000 kWh of chemical energy, not electricity. This figure also neglects energy costs of mining, transport, and carbon sequestration.

169 *UK coal.* In December 2005, the reserves and resources at *existing mines* were estimated to be 350 million tons. In November 2005, potential opencast reserves were estimated to be 620 million tons; and the underground coal gasification potential was estimated to be at least 7 billion tons. [yebuk8]
Further reading about underground coal gasification potential: [e2m9n]

24

Living on other countries' renewables?

In 2007, with the wars in Afghanistan and Iraq (and public opposition thereto) in full swing, BBC Radio 4's *Down the line* broadcast a public phone-in to discuss 'Who *should* we be at war with?' One elderly gentleman complains loudly about this topic: "It's outrageous! It's not, 'Who should we be at war with?' This is Radio 4! It should be 'With Whom Should We Be At War?'!"

And so now we carefully discuss: 'With whom should we be especially good friends?'

Land use	area per person (m^2)
domestic buildings	30
domestic gardens	114
other buildings	18
road	60
rail	4
path	3
greenspace	2335
water	69
other land uses	37
Total	2670

Table 24.1. Land uses in England.

Area and population

In our comparisons of consumption with conceivable sustainable production, we have discovered that land-based wind power can't match the energy consumption enjoyed by most Europeans. We would have come to a different conclusion, however, if the population density of the United Kingdom were smaller by a factor of 10.

When we think about living sustainably, we often find that the resources we depend on are related to land area: if you want to use solar panels, you need land to put them on; if you want to grow crops, you need land again. In Jared Diamond's book *Collapse* we learn that, while many factors contribute to the collapses of civilizations, one common feature of collapses is that the human population density became too great.

So let's settle on some units for measuring area in, and look at the current land area per person.

In this book, I use the square-kilometre and the square metre as my two units of area. The hectare (10 000 m^2, a football field) would actually be a good choice of unit in which to measure areas per person, but I feel it is not as well known a unit as the square-kilometre and the square metre.

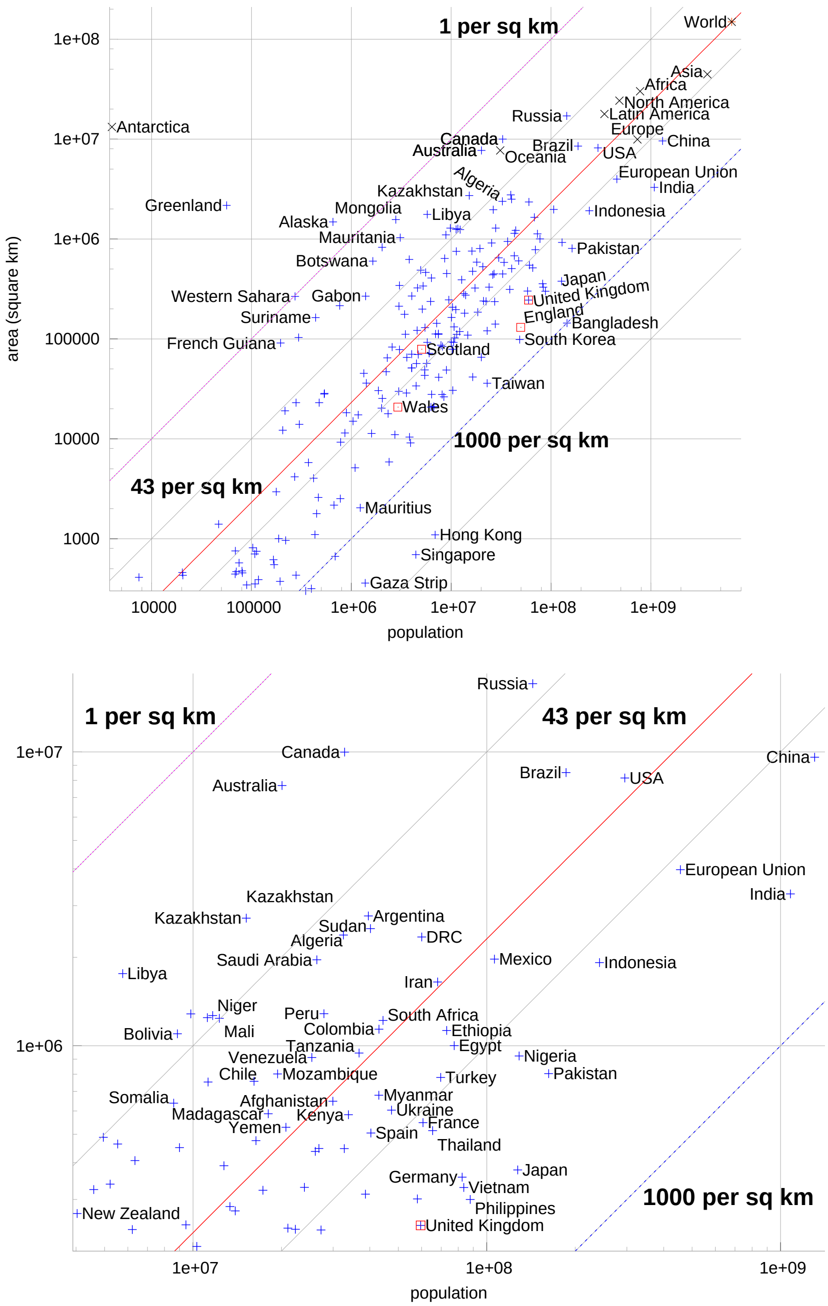


Figure 24.2. Populations and areas of countries and regions of the world.

Population densities

Figure 24.2 shows the areas in square kilometres of various regions versus their populations. Diagonal lines on this diagram are lines of constant population density. Bangladesh is on the rightmost diagonal line: it has a population density of 1000 per square kilometre; India, England, the Netherlands, and Japan have population densities one third that: about 350 per km^2. Many European countries have about 100 per km^2. At the other extreme, Canada, Australia, and Libya have population densities of about 3 people per km^2. The central diagonal line marks the population density of the world: 43 people per square kilometre. America is an average country from this point of view: the 48 contiguous states of the USA have the same population density as the world. Regions that are notably rich in area, and whose population density is below the average, include Russia, Canada, Latin America, Sudan, Algeria, and Saudi Arabia. These data are presented in tables on p. 326.

Of these large, area-rich countries, some that are close to Britain, and with whom Britain might therefore wish to be friendly, are Kazakhstan, Libya, Saudi Arabia, Algeria, and Sudan.

Figure 24.3. A '100 MW' solar power station under construction in Spain. Excess thermal energy produced during the day will be stored in liquid salt tanks for up to seven hours, allowing a continuous and stable supply of electric power to the grid. The power station is predicted to produce 350 GWh per year (40 MW). The parabolic troughs occupy 400 hectares, so the power per unit area will be 10 W/m^2.
Upper photo: ABB. Lower photo: IEA SolarPACES.

> Intensive international collaboration is a main requisite for success.

This chapter explores a presumptious idea, and I apologise for it.

We've found that it's hard to get off fossil fuels by living on our own renewables. Nuclear has its niggles too. So what else can we do? Well how about living on someone else's renewables?

"All the world's power could be provided by a square 100 km by 100 km in the Sahara." Is this true? Concentrating power in deserts delivers an average power per unit area of roughly 15 W/m^2. So, allowing no space for anything else in such a square, the power delivered would be 150 GW. This is *not* the same as current world power consumption. It's not even near current world *electricity* consumption, which is 2000 GW. World power consumption today is 15 000 GW. So the correct statement about power from the Sahara is that today's consumption could be provided by a 1000 km by 1000 km square in the desert, completely filled with concentrating solar power. That's four times the area of the United Kingdom. And if we are interested in living in an equitable world, we should presumably aim to supply more than *today's* consumption. To supply every person in the world with an average European's power consumption (125 kWh/d), the area required would be *two* 1000 km by 1000 km squares in the desert, or eight United Kingdoms.

Fortunately, the Sahara is not the only desert, so maybe a more relevant calculation is "what area is required in the North Sahara to supply *everyone in Europe and North Africa* with an average European's power consumption? Taking the population of Europe and North Africa to be one billion, the area required drops to 340 000 km^2, which corresponds to

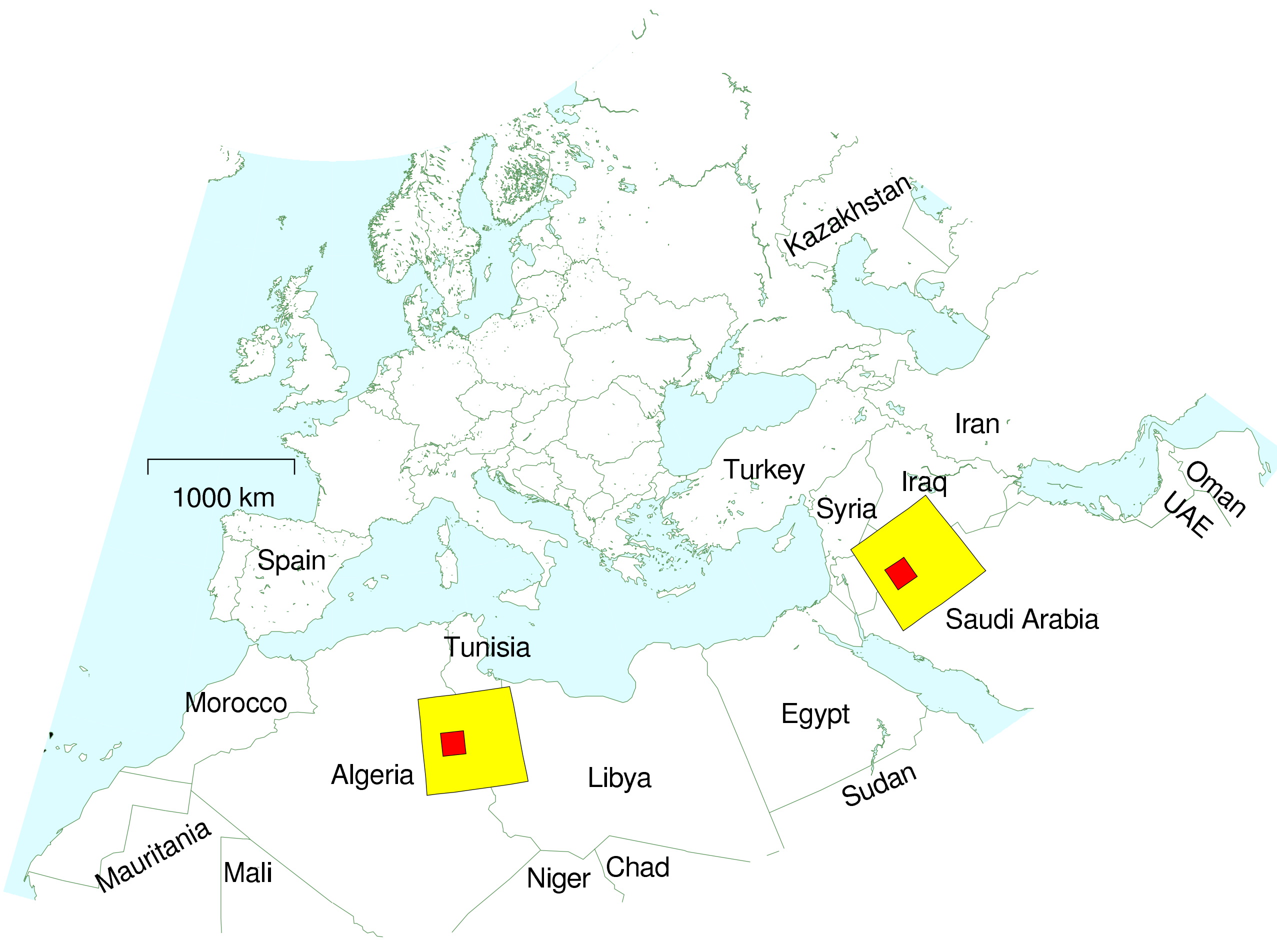


Figure 24.4. The celebrated little square. This map shows a square of size 600 km by 600 km in Africa, and another in Saudi Arabia, Jordan, and Iraq. Concentrating solar power facilities completely filling one such square would provide enough power to give one billion people the average European's consumption of 125 kWh/d. The area of one square is the same as the area of Germany, and 16 times the area of Wales. Within each big square is a smaller 145 km by 145 km square showing the area required in the Sahara – one Wales – to supply all British power consumption.

a square **600 km by 600 km**, to one Germany, to 1.4 United Kingdoms, or to **16 Waleses**.

The UK's share of this 16-Wales area would be one Wales: a 145 km by 145 km square in the Sahara would provide all the UK's current primary energy consumption.

The DESERTEC plan

The plan uses concentrating solar power and high-voltage direct-current (HVDC) transmission lines. This technology has been in use since 1954 to transmit power both through overhead lines and through submarine cables (such as the interconnector between France and England). HVDC is already used to transmit electricity over 1000-km distances in South Africa, China, America, Canada, Brazil, and Congo Asplund [2004]. A typical 500 kV line can transmit a power of 2 GW. One pair of HVDC lines in Brazil can transmit 6.3 GW.

The losses in the converter stations are about 0.6% of the transmitted power in each station.

Further reading: Carlsson [2002]. From Bahrman and Johnson [2007], savings in line construction: roughly 30%. Number of cables needed is roughly 40% of AC, and there are network stability benefits. Losses for different ac and dc transmission alternatives for a hypothetical 750-mile (1200 km), 3,000-MW transmission system: Best (lowest loss) DC option: 3.43% (103 MW). Cost: $2b. Best AC option: 4.62% (139 MW). $4.8b. Compare with coal taken 900 miles by rail to a 3GW power station. Rail: 500 ton-miles per gallon, so 20 million gallons of diesel per year.

The opposite of decentralization. Formerly known as TREC. Solar thermal in deserts.

Cost of Solar thermal: US$4/W installed, running costs US$0.11/kWh. Source: Solar UK Ltd, who recommend Solar One in Arizona.

Use sea-water as the cold sink? And obtain desalinated water as a by-product. (At 1 billion m^3 per year from 10 km $\times$ 10 km, 10% of which could provide 1 m per year of water for irrigating the land under the solar facility.

Algeria and Libya have about 2000 kWh/m^2/y of solar irradiance. Say 250 W/m^2.

The German TREC report projects about 2000 TWh/y electricity from CSP thermal. That's about 5.5 kWh/day per person if shared between 1 billion people; 11 kWh/day per person if shared between 0.5 billion people. EU is 0.5 billion.

The TREC plan requires investment of $75 billion.

Solar-to-electricity efficiency currently 10–15%, projected to be 18% for parabolic troughs.

Land use: 6 m^2/(MWh/y). Same as 20 W/m^2. (Is that including the 30% factor below? I guess not.)

Figure 24.5. A high-voltage DC power system in China. Photo: ABB.

Figure 24.6. Laying a high-voltage DC link between Finland and Estonia. A pair of these cables transmit a power of 350 MW. Photo: ABB.

They say that at $4\,\mathrm{m}^2/(\mathrm{MWh/y})$, solar can do 50 MWkk. But $4\,\mathrm{m}^2/(\mathrm{MW}$ is $28.5\,\mathrm{W/m}^2$! So they have exaggerated by nearly a factor of 2. (Or are assuming the 50 MW power station would not operate at full capacity!)

Figure 24.7. Stirling dish engine. Photo courtesy of Stirling Energy Systems. www.stirlingenergy.com

www.stirlingenergy.com say one of their dishes with a 25 kW Stirling engine at its focus can generate 60 000 kWh/y in a favourable desert location. They could be packed at a concentration of 8 per acre. That's an average power of $14\,\mathrm{W/m}^2$.

They say that solar dish stirling makes the best use of land area, in terms of energy delivered.

Other companies doing concentrating solar power for deserts: http://www.ausra.com/ use flat mirrors to heat water to 285°C and drive a steam turbine. The heated pressurized water can be stored in deep metal-lined caverns to allow power generation at night. Power density for a '240 MW(e)' plant proposed for Australia [Mills and Lièvre, 2004]: the designers claim that $3.5\,\mathrm{km}^2$ of mirrors would deliver 1.2 TWh(e); that's $38\,\mathrm{W/m}^2$ of mirror. Allowing for a bit of space for humans and other administrative hardware, that's a power density of perhaps $30\,\mathrm{W/m}^2$ of land.

Ausra say they need a 92 mile by 92 mile square in the desert to supply all US electric power. Total US electricity is 3600 TWh/y, so they are claiming a power density $19\,\mathrm{W/m}^2$.

Going back to TREC:

According to page 60, about half of the land area of Libya and Algeria and Saudi Arabia would be 'suitable'. What's the cooling method? Do they use sea water, or do they use cold air collected at night? They assumed they could use 30% of this suitable area and that the efficiency would be 15% (parabolic troughs).

When electricity is produced, the 'process heat' is also useable for cooling (how does that work? 'Vapour absorption chillers'), drying, or desalination.

Idea: Express the area required in terms of Londons. $6\,\mathrm{m}^2/(\mathrm{MWh/y})$. $6\,\mathrm{km}^2/(\mathrm{TWh/y})$. Same as $20\,\mathrm{W/m}^2$. $50\,\mathrm{km}^2/\mathrm{GW}$.

I guess a London is about $1500\,\mathrm{km}^2$. So each London is 30 GW. But if we assume a density of 30% land use, each London delivers 10 GW. The required 650 GW (to deliver 16 kWh/d per person to one billion people) would need 65 Londons.

Figure 24.9 tries to convey the scale of these Londons relative to the local hot spots. Each circular blob represents an area of $1500\,\mathrm{km}^2$. Figure 24.10 shows detail from figure 24.9.

European countries by themselves have economic potential for 1730 TWh/y of solar energy. They reckon the total renewable energy potential of Europe is 40 000 PJ/y (62% of present primary energy consumption).

They could get 2900 TWh/y electricity (which is the same as the total energy consumption of the UK) and 160 billion m^3 of water per year using $120 \times 120\,\mathrm{km}^2$.

Country	Economic potential (TWh/y)	Coastal potential (TWh/y)
Morocco	20 000	300
Tunisia	9 200	350
Algeria	169 000	60
Libya	140 000	500
Egypt	74 000	500
Portugal	140	7
Spain	1 300	70
Turkey	130	12
Israel	3 100	1
Jordan	6 400	0
Syria	10 000	0
Iraq	29 000	60
Qatar	800	320
UAE	2 000	540
Kuwait	1 500	130
Oman	19 000	500
Saudi Arabia	125 000	2 000
Yemen	5 100	390
Total	620 000 (70 000 GW)	6 000 (650 GW)

Table 24.8. Solar power potential in countries around and near to Europe.
The 'economic potential' is the power available in suitable places where the direct normal irradiance is more than 2000 kWh/m^2/y.
The 'coastal potential' is the power available within 20 m (vertical) of sea level; such power is especially promising because of the potential combination with desalination.
For comparison, the total power required to give 120 kWh per day to 1 billion people is 44 000 TWh/y (5 000 GW).
6000 TWh/y (650 GW) is 16 kWh per day each for 1 billion people.

Figure 24.9. Each circular blob represents an area of $1500\,\text{km}^2$, which, if one-third-filled with solar power facilities, would generate 10 GW on average. 65 such blobs would provide one billion people with 16 kWh/d per person. To give a sense of the scale of these blobs I've dropped a few in Britain too.

Figure 24.10. Detail from figure 24.9.

Trans-Mediterranean Interconnection for Concentrating Solar Power

Figure 24.11. A 25 kWp concentrator photovoltaic collector produced by Californian company Amonix. Its $225\,m^2$ aperture contains 5760 Fresnel lenses with optical concentration $\times 260$, each of which illuminates a 25%-efficient silicon cell. One such collector, in an appropriate desert location, generates 140 kWh per day – enough to cover the energy consumption of half an American. Photograph by David Faiman.

by German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment

France to GB interconnector transmits 10 000 GWh/y.

High voltage losses are 15% per 1000 km for 380 kV lines and 8% per 1000 km for 750 kV. Each transformer station loses 0.25%. HVDC: High Voltage Direct Current transmission. 600 kV or 800 kV. To transfer 50 GW, need a tract of land 100–150 m wide for pylons. (Lower than HVAC (800 kV).) DC cables good for long distances: the loss in transport is only about 3% per 1000 kilometres.

Queries: energy cost of making mirrors? – any scarce resources required? Associated CO_2 emissions?

Key points: can design a CSP thermal reactor to be driven by other fuels *e.g.*, fossil fuels or biomass, so as to increase power availability.

Today, a thermal solar power station produces electricity at a cost between 0.14 and 0.18 € per kilowatt-hour (kWh). If a capacity of 100 GW were created, the cost would fall to 0.04–0.06 € per kWh, according to Franz Trieb.

Concentrating photovoltaics

An alternative to concentrating thermal solar power in deserts is large-scale concentrator photovoltaics. This means plopping a high-quality electricity-producing solar cell at the focus of cheap lenses or mirrors. Faiman et al. [2007] say that "solar, in its concentrator photovoltaics variety, can be completely cost-competitive with fossil fuel [in desert states such as California, Arizona, New Mexico, and Texas] without the need for any kind of subsidy."

Manufactured by `http://www.amonix.com/`

Assumptions: 32% cell efficiency; 25% collector efficiency; 10% further loss due to shading. Aperture/land ratio of 1/3. Normal direct irradiance $2222\,kWh/m^2$/year. Expect each kWp to deliver 2000 kWh/kWp/y. (So average production 23% of nameplate peak power.) A VLSPV plant of 1 GWp capacity would occupy 12 km^2 of land and deliver 2000 GWh per year. That's $18\,W/m^2$.

Another way to get a feel for required hardware is to personalize. One of the 25 kWp collectors shown in the photograph generates on average about 138 kWh per day; the American lifestyle currently uses 300 kWh per day per person. So to get America off fossil fuels using solar power, we need one or two of these $15\,m\times15\,m$ collectors per person.

Notes

Weimers [2005]: High voltage conductors: current limit $1.5\,A/mm^2$ (because of heat generation). AC lines have significant corona losses – in rain or frost these may be as high as 200 kW per km. Corona losses increase at altitude. HVDC lines have corona losses too but in rain and frost they are roughly thirty times smaller than those of an AC line.

Numbers for a 10 GW line. Loss of an 800 kV AC line is about 8% per 1000 km; of a 750 kV DC line, about 4% per 1000 km.

For transmission of 10 GW, if the distance is larger than 600 km, HVDC is the cheapest choice of transmission line.

European Commission [2007]. Solar dish with Stirling currently cost 11 000€ per kW(e).
German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment [2006].
According to http://www.solarmillennium.de/ "The cost for generating electric power is 3 to 5 times lower with solar thermia than with photovoltaics."
There are three European demonstration plants for concentrating solar power. PS10, a tower near Seville; Andasol – using parabolic troughs; and Solartres, a tower using molten salt for heat storage. Solartres will occupy 142 ha and is expected to produce 96.4 GWh per year; that's a power density of 8 W/m^2. Andasol and Solartres will both use some natural gas in normal operation.

Solúcar: This '11 MW' solar tower has 624 mirrors, each 121 m^2. The mirrors concentrate sunlight to a radiation density of up to 650 kW/m^2. The receiver receives a peak power of 55 MW. The power station can store 20 MWh of thermal energy, allowing it to keep going for 50 minutes of cloudiness. It was expected to generate 24.2 GWh of electricity per year, and it occupies 55 hectares. That's an average power density of 5 W/m^2.

181 *For high voltage DC, the loss in transport is only about 3% per 1000 kilometres.* I got this from DESERTEC. I'd like another source, as the ABB website didn't confirm this clearly.

25

Fluctuations and storage

The wind, as a direct motive power, is wholly inapplicable to a system of machine labour, for during a calm season the whole business of the country would be thrown out of gear. Before the era of steam-engines, windmills were tried for draining mines; but though they were powerful machines, they were very irregular, so that in a long tract of calm weather the mines were drowned, and all the workmen thrown idle.

William Stanley Jevons, 1865

If we kick fossil fuels and go all-out for renewables, *or* all-out for nuclear, *or* a mixture of the two, we have a problem. Most of the big renewables are not turn-off-and-onable. When the wind blows and the sun comes out, power is there for the taking; two hours later, and it's not available any more. Nuclear power stations are not usually designed to be turn-off-and-onable either. They are usually on all the time, and their delivered power can be turned down and up only on a timescale of hours. To have an energy plan that adds up, we need *something easily turn-off-and-onable*.

This easily turn-off-and-onable something needs to be a *big* something because electricity demand varies a lot (figure 25.1). The demand

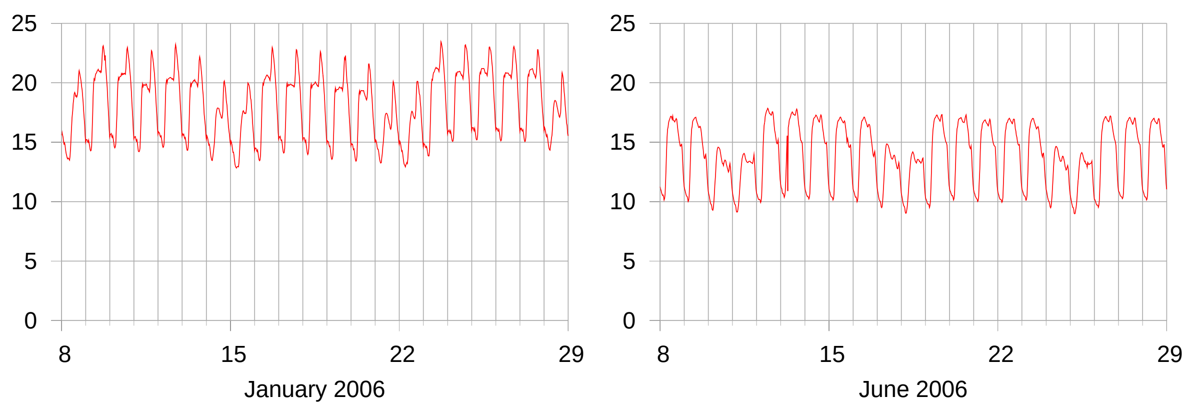


Figure 25.1. Electricity demand in Great Britain (in kWh/d per person) during two winter weeks

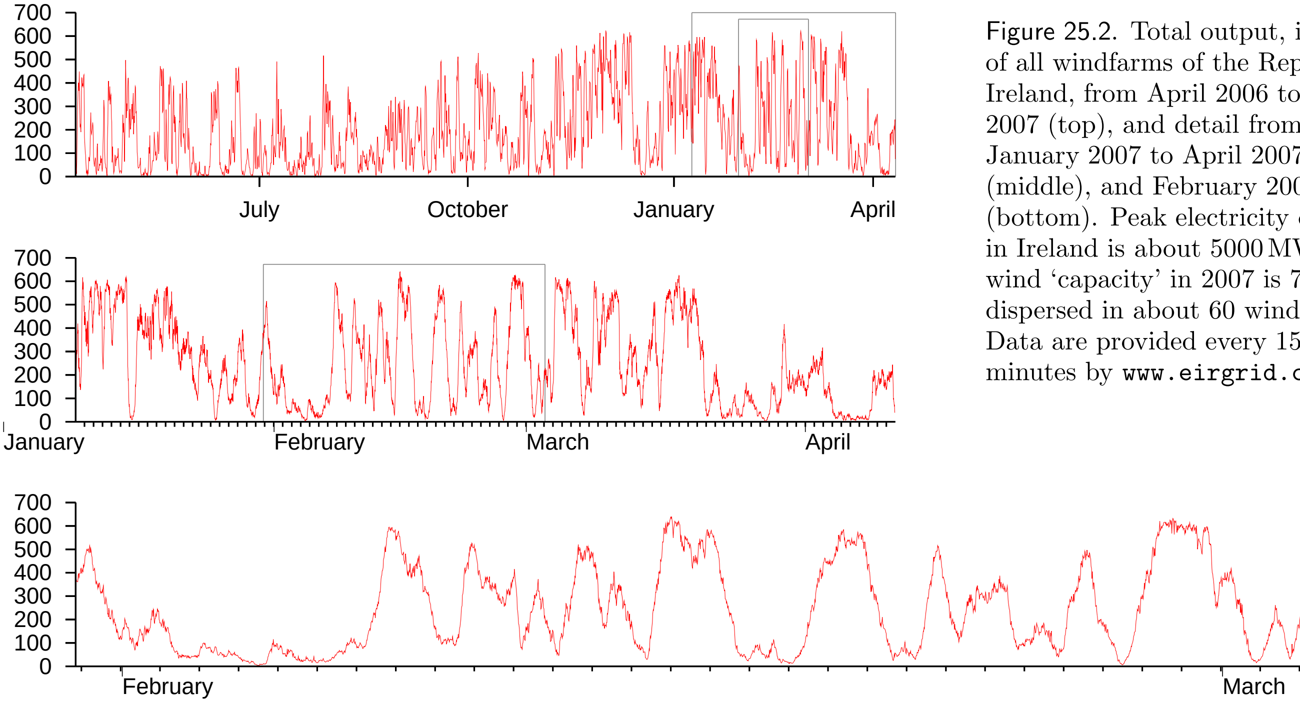


Figure 25.2. Total output, in MW, of all windfarms of the Republic of Ireland, from April 2006 to April 2007 (top), and detail from January 2007 to April 2007 (middle), and February 2007 (bottom). Peak electricity demand in Ireland is about 5000 MW. Its wind 'capacity' in 2007 is 745 MW, dispersed in about 60 wind farms. Data are provided every 15 minutes by `www.eirgrid.com`.

sometimes changes significantly on a timescale of a few minutes.

However much we love renewables, we must not kid ourselves about the fact that wind fluctuates.

The anti-wind lobby attack wind, saying: "Wind power is intermittent and unpredictable, so it can make no contribution to security of supply; if we create lots of wind power, we'll have to maintain lots of fossil-fuel power plant to replace the wind when it drops." Headlines such as "Loss of wind causes Texas power grid emergency" reinforce this view. Supporters of wind energy play down this problem: "Don't worry – individual wind farms may be intermittent, but taken together, the sum of all wind farms is much less intermittent."

Let's look at real data and try to figure out a balanced viewpoint.

Figure 25.2 shows the total output of the wind fleet of the Republic of Ireland from April 2006 to April 2007.

Wind *is* intermittent, even if we add up lots of turbines covering a whole country. The UK is a bit larger than Eire, but the same problem holds there too. Between October 2006 and February 2007 there were 17 days when output from the existing 1632 windmills was less than ten per cent of 'capacity'. During that period there were five days when output was less than 5% and one day when it was only 2%. Some of these periods of low wind coincide with periods of peak demand.

Let's quantify the fluctuations in country-wide wind power. The two issues are short-term changes, and long-term lulls. Let's find the fastest short-term change in a month of data. On 11th February 2007, the Irish wind power fell steadily from 415 MW at midnight to 79 MW at 4am. That's a slew rate of 84 MW per hour for a country-wide fleet of capacity 745 MW. (A slew rate is the rate at which the delivered power

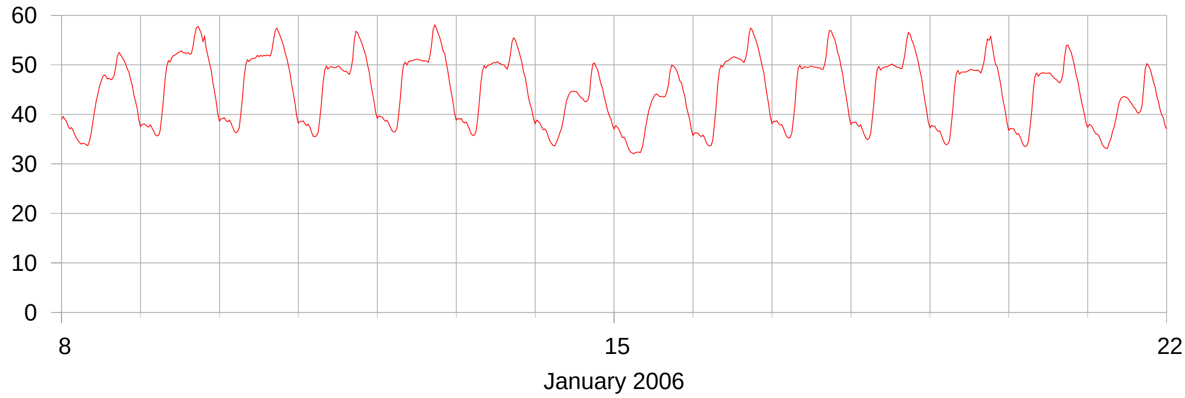


Figure 25.3. Electricity demand in Great Britain (in GW) during two winter weeks of 2006. This is exactly the same data as in the left half of figure 25.1, but in the national unit (GW), instead of the personal unit (kWh/d/person).

fell – the slope of the graph on 11th February.) OK: if we scale British wind power up to a capacity of 33 GW (so that it delivers 10 GW on average), we can expect to have occasional slew rates of

$$84\,\text{MW/h} \times \frac{33\,000\,\text{MW}}{745\,\text{MW}} = 3700\,\text{MW/h}$$

(assuming Britain is like Ireland). So we need to be able to either power *up* replacements for wind at a rate of 3.7 GW per hour – that's 4 nuclear power stations going from no power to full power every hour, say – *or* we need to be able to suddenly turn *down* our *demand* at a rate of 3.7 GW per hour.

Rather than laughing at this countercultural notion and crucifying the naive wind huggers, let's have a rummage outside the box and see if these windy demands could in fact be met.

This country-scale rummaging will require us to talk about 'gigawatts'. Gigawatts are big country-sized units of power. They are to a country what a kilowatt-hour-per-day is to a person: a nice convenient unit. The UK's average electricity consumption is about 40 GW. We can relate this national number to personal consumption: one kWh per day per person is equivalent to 2.5 GW. So if every person uses 16 kWh per day of electricity, then national consumption is 40 GW.

Is a national slew-rate of 4 GW per hour completely outside human experience? No. Every morning, as figure 25.3 shows, British demand climbs by about 13 GW between 6.30am and 8.30am. That's a slew rate of 6.5 GW per hour. So our power engineers already cope, every day, with slew rates bigger than 4 GW per hour on the national grid. An extra occasional slew of 4 GW per hour induced by sudden wind variations is no just cause for ditching the idea of country-sized wind farms. It's a problem just like problems that engineers have already solved. We simply need to figure out how to match ever-changing supply and demand in a grid with no fossil fuels.

OK, before we start looking for solutions, we need to quantify wind's other problem: lulls. At the start of February 2007, Ireland had a country-wide lull that lasted five days. This was not an unusual event, as you can see in figure 25.2. Lulls lasting two or three days happen several times a year.

There are two ways to get through lulls. Either we can store up energy somewhere before the lull. Or we need to have a way of reducing demand during the lull. If we have 33 GW of wind turbines delivering an average power of 10 GW then the amount of energy we need to either store up in advance or do without during a five-day lull is

$$10\,\text{GW} \times (5 \times 24\,\text{h}) = 1200\,\text{GWh}.$$

(The gigawatt-hour (GWh) is the cuddly unit of energy for nations. Britain's electricity consumption is roughly 1000 GWh per day.)

To personalise this quantity, an energy store of 1200 GWh for the nation is equivalent to an energy store of 20 kWh per person.

For the nation to go without 10 GW of electricity for 5 days is the same as every individual going without 4 kWh per day of electricity for 5 days.

more to do here

Would be nice to solve both problems (lulls and short-term slews) with a single system. Can cope with both lulls and short-term slews by pumped storage. Can cope with both lulls and short-term slews by charging up a fleet of electric batteries – used by electric vehicles.

Coping with slew on the supply side

Some of the renewables are turn-off-and-onable. Waste incineration, biomass incineration. Extra cost: Having it be turn-off-and-onable means that its generators will sometimes be idle and sometimes work twice as hard, so maybe we'll have to pay for extra generators. Plausible biomass and waste power in the UK: 3 GW – if all municipal waste incinerated, and an equal amount of agricultural waste. That's not enough slew.

Hydroelectricity has an average load factor of 20% so it has the potential to be turned on and off. Plus hydro can be turned on and off really quickly. Glendoe, with a capacity of 100 MW, will be able to switch from off to on in 30 seconds, for example. That's a slew rate of 12 GW per hour in just one power station! So a sufficiently large fleet of hydro power stations should be able to cope with the slew introduced by enormous windfarms. However, is that the capacity of the British hydro fleet is not currently big enough to solve the slew problem on its own (assuming we want to cope with the rapid loss of say 10 or 33 GW of wind power). The capacity is about 1.5 GW of traditional hydroelectricity, plus 2.8 GW of pumped storage, a total of 4.3 GW.

Storing 1000 GWh

If we use a significant amount of bursty wind power, then we need to have automated demand management, or backup powerplant that sits

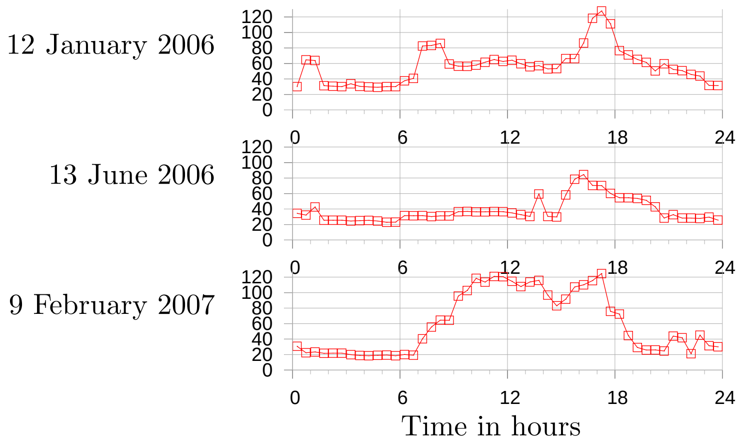


Figure 25.4. How Dinorwig pays for itself. Electricity prices, in £ per MWh, on three days in 2006 and 2007.

idle when the wind blows, or a significant storage system. Or all three.

Denmark

Here's how Denmark copes with the intermittency of its wind power. Almost all of Denmark's wind power is exported to its European neighbours, some of whom have hydroelectric power, which they can turn down to balance things out. The saved hydroelectric power is then sold back to the Danes (at a higher price) during the next period of low wind and high demand. Thus the other countries' hydroelectric facilities are effectively being used as a storage facility for Denmark. Overall, Danish wind is contributing useful energy, and the system as a whole has considerable security thanks to the capacity of the hydro system.

What lessons are there for the UK , an isolated island with little hydroelectric power? Well, we need to plan carefully. The Renewable Energy Foundation warns that "over-deployment of randomly intermittent renewables, such as wind power, to the exclusion of firm generating plant, such as tidal and biomass, may actually make the overall system more dependent, not less, on fossil systems." My guess is that the best thing to do is to increase the number of pumped storage systems as we increase the number of wind farms.

Demand management ideas

Use electric heat pumps for building heating and building cooling; include in many buildings large thermal reservoirs; pump heat into or out of those reservoirs from the ground at times of electricity abundance. Then have a second low-cost pump system to pump from the intermediate reservoir to the place where heating or cooling.

Indeed, put wind turbines and solar panels on-site and use their electricity directly to drive the buildings' own ground-source heat pumps; thus avoiding the cost of managing a connection to the grid.

Use electric cars, and charge the batteries when electricity is abundant, for example at night. Or hydrogen batteries, and hydrogen production at night. (Though as a battery, hydrogen is only about 25% efficient, round-trip from electricity to hydrogen and back.)

Controlling demand automatically would be easy. The simplest way of delivering dynamic demand control is to have devices such as fridges and freezers listen to the frequency of the mains. When there is a shortage of power on the grid, the frequency drops below its standard value of 50 Hz; when there is a power excess, the frequency rises above 50 Hz. Fridges can be modified to nudge their internal thermostats up and down just a little in response to the mains frequency, in such a way that, without ever jeopardising the temperature of your butter, they tend to take power at times that help the grid.

The introduction of such modified fridges could be driven by various incentives. Choosing a dynamic-demand branded fridge could be marketed as ‘good citizenship’, and given some sort of tax advantage. Electricity consumers could pay a variable rate for electricity that depends appropriately on the mains frequency at the instant of consumption; this dependence could reward the choice of smart demand-aware appliances, and it would promote other innovations too. For example, the internet could be used to send messages to wireless-connected devices, and contracts could be made on the fly, guaranteeing particular periods of demand and non-demand will be delivered by a fleet of electric-car-chargers and other appliances. In South Africa (where there are frequent electricity shortages), radio-controlled demand-management systems are being installed in hundreds of thousands of homes, to control electric water heaters and air-conditioning systems.

Can demand-management alone provide the virtual storage that's needed? How big a sink of power are the nation's fridges? On average, a typical fridge-freezer draws about 18 W, and the number of fridges is probably about 30 million. So the ability to switch off all the nation's fridges for a few minutes would be equivalent to 540 MW of automatic adjustable power. This is quite a lot of electrical power – more than one percent of the national total – but it's not as big as the sudden increases in demand produced when the people, united in an act of religious observance (such as watching Coronation Street, or watching England play footie against Sweden), simultaneously switch on half a million kettles. Such ‘’ can produce increases in demand of over 2000 MW. Popular soap operas such as Coronation Street and EastEnders typically generate TV pick-ups of 600–800 MW. So automatically switching off every fridge would *nearly* cover these daily blips of concerted kettle boiling.

Fluctuations in wind power will be a different matter.

Figure 25.5. Llyn Stwlan, the upper reservoir of the Ffestiniog pumped storage scheme in north Wales. Energy stored: 1.3 GWh. Photo by Adrian Pingstone.

Storage ideas

It's interesting to calculate the dimensions required for a useful storage system. Imagine that a huge expansion of wind power delivers a power averaging 10 GW – nearly one quarter of current UK electricity consumption. (This is 4 kWh per day per person, one quarter of the

Ways to store 100 GWh			
drop from upper lake	working volume required (million m^3)	example size of lake	
		Area	Depth
500 m	40	1 km × 2 km	×20 m
500 m	40	1 km × 4 km	×10 m
200 m	100	1 km × 5 km	×20 m
200 m	100	1 km × 10 km	×10 m
100 m	200	1 km × 10 km	×20 m
100 m	200	1 km × 20 km	×10 m

Table 25.6. Pumped storage. Ways to store 100 GWh.
For comparison with column 2, the working volume of Dinorwig is 7 million m^3, and the volume of Lake Windermere is 300 million m^3. For comparison with column 3, Rutland water has an area of $12.6\,km^2$; Grafham water $7.4\,km^2$. Carron valley reservoir is $3.9\,km^2$. Loch Lomond's area is $71\,km^2$ (it's the largest lake in Great Britain).

practical maximum for UK onshore wind estimated in chapter 3.)

Let's assume this power comes in bursts: in a three-day period, the windmills might deliver 30 GW for one day; then for the next two days, there might be no wind power at all. (Occasionally, as figure 25.2 showed, country-wide lulls in wind may last four days.) Can we imagine storage systems that could store the spare 20 GW during the day of plenty, then deliver 10 GW during the two still days?

Could pumped storage provide such a solution?

Pumped storage systems use spare electricity to shove water from a downhill lake to an uphill lake; then regenerate electricity when it's needed, just like hydroelectric power stations.

The Dinorwig power station, underneath the mountain Elidir Fawr in Snowdonia, can switch on, from 0 to 1.3 GW power, in 12 seconds. The total energy that can be stored is about 9 GWh. Its upper lake is about 500 m above the lower, and the working volume of 7 million m^3 flows at a maximum rate of $390\,m^3/s$, allowing power delivery at 1.7 GW for 5 hours.

The efficiency of this storage system is 75%.

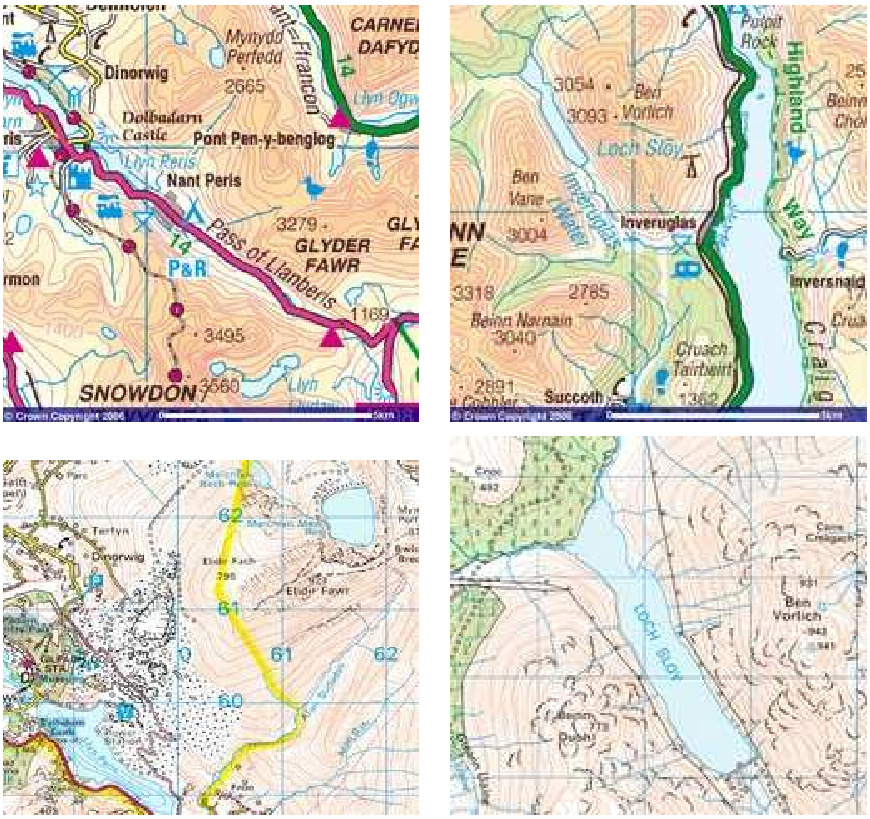
We are interested in making much bigger storage systems, storing a total of 480 GWh (that's 20 GW × 24 hours). Let's imagine sharing this between 10 new sites, each storing 50 GWh – a bit more than 5 times the energy of Dinorwig.

Assuming the generators have an efficiency of 90%, table 25 shows a few ways of storing 50 GWh, for a range of height drops. (For the physics behind this table, see the technical chapter, p.335.)

1 square mile $= 2.6 \times 10^6\,m^2 = 2.6\,km^2$

Is it at all plausible that ten such sites could be found? The most economical locations would be somewhere on the way from the windfarms (mainly in Scotland) to the consumers (mainly in England). The perfect spot for a new artifical lake would be a hanging valley (across the mouth of which a dam would be built) terminating above the sea, which would be used as the lower lake.

Scanning a map of Scotland, one candidate location would use Loch Sloy as its upper lake and Loch Lomond as its lower lake. There is already a small hydroelectric power station linking these lakes. Fig-



Dinorwig is the home of a 9 GWh storage system, using Marchlyn Mawr (615E, 620N) and Llyn Peris (590E, 598N) as its upper and lower reservoirs.

Loch Sloy illustrates the sort of location where a 40 GWh storage system could be created.

Figure 25.7. Dinorwig, in the Snowdonia National Park, compared with Loch Sloy and Loch Lomond. The upper maps show 10 km by 10 km areas. In the lower maps the blue grid is made of 1 km squares. Images produced from Ordnance Survey's Get-a-map service `www.ordnancesurvey.co.uk/getamap`. Images reproduced with permission of Ordnance Survey. © Crown Copyright 2006

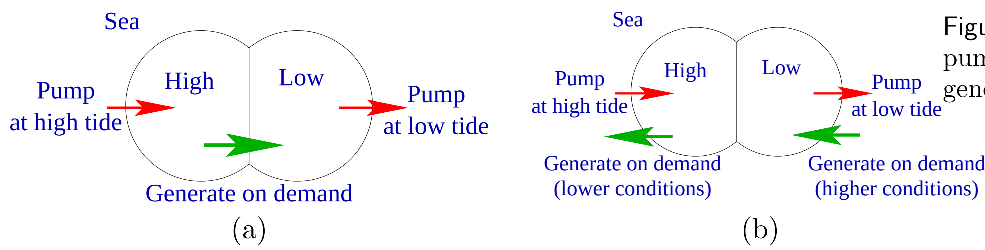


Figure 25.10. Two combined pumped-storage and tidal generators.

ure 25.7 shows these lakes and the Dinorwig lakes on the same scale. The height difference between Loch Sloy and Loch Lomond is about 270 m. Sloy's area is about 1.5 km^2. If Loch Sloy's height could be pumped up by about 40 m then the energy delivered on releasing that extra water would be about 40 GWh. If there were no compensating flows of water in and out of Loch Lomond, the water level in Loch Lomond would change by 80 cm during a full cycle. This is less than the normal range of annual water level variations of Loch Lomond, namely 2 m. This isn't a perfect location for a storage system, and 40 GWh isn't as much as we were hoping for; if you're keen on wind-power, perhaps you can scour the UK maps and find ten superior spots?

Other storage locations

Alternatively, thinking outside the box, one could get away from lakes and reservoirs, putting most of the facility underground or in the sea.

A possible advantage of using a tidal body of water as one of the reservoirs is the potential for a storage system to actually *generate* a little net power, by timing the pumping and generating to coincide – as near as possible – with low tide and high tide respectively. If the other reservoir is hundreds of metres from sea level, the advantage of this pumping truck is negligible; but in the case of a reservoir that's a few metres from sea-level, this trick could give a genuine energy benefit.

Figure 25.9. Okinawa seawater pumped-storage power plant, whose lower reservoir is the ocean. Energy stored: 0.2 GWh. Photo by courtesy of J-Power. `www.ieahydro.org`.

Two grids

Put wind power and other intermittent sources onto a second electricity grid, used to power systems that don't require reliable power, such as electric vehicle battery-charging. For over 25 years (since 1982), the Scottish island of Fair Isle (population 70, area 5.6 km^2) has had *two* electricity networks that distribute power from two wind turbines and, if necessary, a diesel-powered electricity generator. Standard electricity service is provided on one network, and electric heating is delivered by a second set of cables. The electric heating is mainly served by excess electricity from the turbines that would otherwise have had to be dumped. Remote frequency-sensitive programmable relays control individual water heaters and storage heaters in the individual buildings of the community. In fact there's up to six frequency channels per household, so the system emulates seven networks. Fair Isle also successfully

trialled a kinetic energy storage system (a flywheel) to store energy during fluctuations of wind strength on a time-scale of 20 seconds.

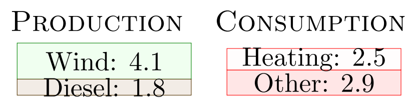


Figure 25.11. Electrical production and consumption on Fair Isle, 1995–96. All numbers are in kWh/d per person. Production exceeds consumption because 0.6 kWh/d per person were dumped.

Automated demand adjustment by industry

The idea of modifying the rate of production of stuff to match the power of a renewable source is not new. Many aluminium production plants are located close to hydroelectric power stations; the more it rains, the more aluminium is produced.

And to provide flexibility on a shorter timescale, many industrial users of electricity are on special contracts that allow the electricity grid managers to switch off those user's demand at very short notice.

Use wind power to power reverse-osmosis systems and other systems that produce a storable product.

In the future a new storable product we will perhaps start making is liquid carbon dioxide, created – at great expense – by sucking CO_2 out of the sky. I predict that some countries will start sucking CO_2 in another few decades, when it becomes obvious that the climate scientists' calls for cuts in carbon pollution should have been heeded in 2007. By that point it may be too late to turn the clock back, but one way of reducing CO_2 levels a little will be to create giant vacuum cleaners for sucking CO_2. To make a measurable difference to climate, these vacuum cleaners would have to consume a power similar to the current world energy consumption. These energy-guzzling suckers could be switched on most of the time, but switched off whenever dictated by fluctuations in supply and demand.

Other ideas

Another way to handle storage is to have a bigger grid.

To make a Europe-wide electricity grid, capable of sending spare power from England to or from Norway, we would use High-voltage DC transmission lines (HVDC). With this technology, transmission losses are about 4% per 1000 km. A Supergrid of this type has also been proposed by Airtricity `http://www.airtricity.com/england/` as a means of reducing the effects of intermittency in wind power across Europe and to facilitate the trading of electricity. (from `http://www.trec-uk.org.uk/index.htm`).

Trans-Mediterranean Renewable Energy Cooperation (Trec).

Electrical vehicles for grid stability

Vehicle-to-grid power. What would the storage capacity be, in GWh, if all vehicles were electric with the same storage capacity as the GWiz (9 kWh)? Let's assume 30 million. Then we'd have 270 GWh of storage available. The car users wouldn't be very happy if their cars were emptied when they went to be filled, though! But that could be fixed by an appropriate user interface. Definitely a useful contribution – even if only half were available, and you could only at most half-discharge them, that'd still be more than 7 Dinorwigs.

Notes

184 *"Loss of wind causes Texas power grid emergency".* [2l99ht] Actually, my reading of this news article is that this event, albeit unusual, was an example of normal power grid operation. The grid has industrial customers whose supply is interruptible, in the event of a mismatch between supply and demand. Wind output dropped by 1.4 GW at the same time that Texans' demand increased by 4.4 GW, causing exactly such a mismatch between supply and demand. The interruptible supplies were interrupted. Everything worked as intended.
Another example, where better power-system planning would have helped: "Spain wind power hits record, cut ordered". [3x2kvv] Spain's average electricity consumption is 31 GW. On Tuesday March 4th 2008, its wind generators were delivering 10 GW. "Spain's power market has become particularly sensitive to fluctuations in wind."

184 *Supporters of wind energy play down this problem: "Don't worry – individual wind farms may be intermittent, but taken together, the sum of all wind farms is much less intermittent."* For an example, see the website yes2wind.com, which, on its page 'debunking the myth that wind power isn't reliable' asserts that 'the variation in output from wind farms distributed around the country is scarcely noticeable'. http://www.yes2wind.com/intermittency_debunk.html

188 *In South Africa ... demand-management systems are being installed.* [2k8h4o]

191 *For over 25 years (since 1982), Fair Isle has had* two *electricity networks.* http://www.fairisle.org.uk/FIECo/
Wind speeds are between 3m/s and 16m/s most of the time with 7m/s the most probable speed.
Energy totals 1995–96 (MWh): In: Diesel = 47. Wind = 106. Out: Dump = 16, Demand = 74, Heating = 63.

More notes...

Dicussing electric vehicles They assume 3.4 miles per kWh, which is 18 kWh per 100 km, and 85% charging efficiency.

Additional economic benefit if the vehicles deliver power to the grid when attached if required.

Their model assumes the cars have batteries storing either 5.9 kWh (20 mile range before using fossil fuel?) or 17.7 kWh (60 mile range?)

Station	Power (MW)	Head (m)	Volume (million m^3)	Energy stored (GWh)
Ffestiniog	360	320/295	1.7	1.3
Cruachan	400	365/334	11.3	10
Foyers	300	178/172	13.6	6.3
Dinorwig	1800	542/494	6.7	9.1

Table 25.12. Pumped storage facilities in Britain

Proposed location	Power (MW)	Head (m)	Volume (million m^3)	Energy stored (GWh)
Bowydd	2400	250	17.7	12.0
Croesor	1350	310	8.0	6.7

Table 25.13. Alternative sites for pumped storage facilities in Snowdonia. At both these sites the lower lake would have been a new artificial reservoir.

Dinorwig notes

Baines et al. [1983, 1986]

Preliminary studies by the CEGB identified 3 possible sites all close to Ffestiniog. Bowydd, Croesor, and Dinorwig. Requirement: 1320 MW in under 10 s. Pumping daily, restricted to a 6 h period at night.

The alternative plans were at nearby sites in Snowdonia, as shown in table 25.13.

Figure 25.14. A possible site for another 7 GWh pumped storage facility. Croesor valley is in the centre-left, between the sharp peak (Cnicht) on the left and the broader peaks (the Moelwyns) on the right.

Storage criteria

Energy efficiency.

Lifetime (Number of cycles).

Storable energy per unit mass. (Including container / tank.) Mass per unit energy.

Storable energy per unit land area.

Maximum deliverable power per unit mass.

Maximum charging rate (power per unit mass).

Safety.

Cost of manufacture.

Cost of use.

Cost of making big.

How long one charge energy can be left stored.

Battery efficiencies

Battery efficiency.

Lithium-Ion Batteries: Linear Technology `http://www.national.com/appinfo/power/files/swcap_eet.pdf` Paper says 88% efficient (over the usable charge-discharge range)

Lead-Acid Batteries: Arizona Wind and Sun `http://www.windsun.com/Batteries/Battery_FAQ.htm` 'Typical efficiency in a lead-acid battery

Battery type	Energy density Wh/kg	Cycles
Nickel-cadmium	45–80	1500
NiMH	60–120	300–500
Lead-acid	30–50	200–300
Lithium-ion	110–160	300–500
Lithium-ion-polymer	100–130	300–500
Reusable alkaline	80	50

Table 25.15. Energy density of some batteries. Taken from Battery University, What is the best battery?

is 85–95%.'

How long they last: My pack of 16 lead-acid batteries costs about \$800, and can last me up to 8 years, if I take good care of it. (by an electric car owner, doing a daily commute less than 50 miles). Presumably this means about 3000 cycles.

Battery energy density

Compressed air and flywheels can also be used for energy storage Xtronics gives the figures below:

Energy source	Energy density Wh/kg
Compressed air	34
Flywheel	120

cf Energy content of some fuels

Fuel	Wh/kg	MJ/l
Propane	13 800	25.4
Petrol (auotomotive gasoline)	12 900	34.2
Kerosene	12 800	37
Heating oil	12 800	37.3
Ethanol	8200	23.4
Methanol	5500	15.6
Coal	8000	
Firewood	4400	
Hydrogen	39 000	

flamable fuels typically provide around 10 MJ/kg while batteries yield less than 0.5 MJ/kg.

Supercapacitors

Supercapacitors are used for storage of small amounts of electrical energy (up to 1 kWh) where many cycles of operation are required, and charging must be completed quickly. For example, supercapacitors are favoured over batteries for regenerative braking in vehicles that do many stops and starts. You can buy supercapacitors with an energy density of 6 Wh/kg.

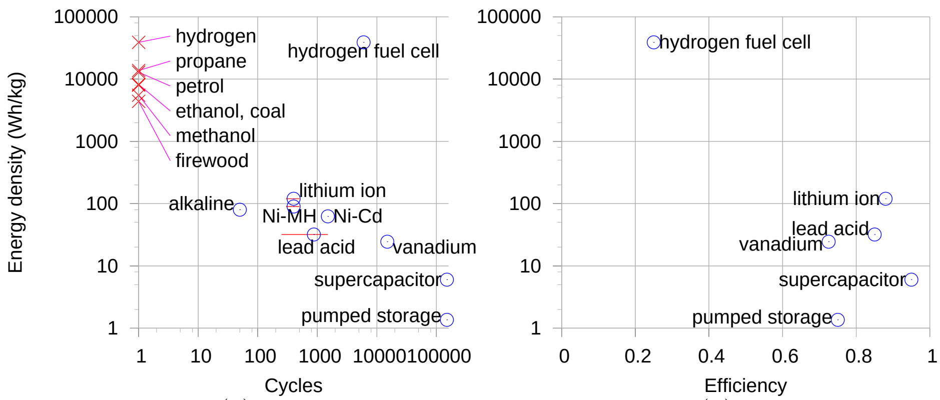


Figure 25.16. Some properties of storage systems and fuels. (a) Energy density versus lifetime (number of cycles). (b) Energy density versus efficiency. The energy densities don't include the masses of the energy systems' containers. The lifetimes for vanadium flow batteries and pumped storage are only indicative.

An American company, EEStor, claims to be able to make much better supercapacitors, using barium titanate, with an energy density of 280 Wh/kg.

Economics

In the present world which doesn't put any cost on carbon pollution, the financial bar that a storage system must beat is an ugly alternative: storage can be emulated by simply putting up an extra gas-fired power station to meet extra demand, and shedding excess electrical power by throwing it away in heaters. Gas stations cost £475 per kW to build, or £475 million per GW. Dinorwig spends much of the day running two of its six generators, that is, it delivers 600 MW; this power-delivery could be emulated by £285-million-worth of gas power station.

Notes

184 *The total output of the wind fleet of the Republic of Ireland* is available at [2hxf6c].

194 Table 25.13, *Alternative sites for pumped storage facilities.* The proposed upper reservoir for Bowydd was Llyn Newydd, grid reference SH 722 470; for Croesor: Llyn Cwm-y-Foel, SH 653 466.

Numbers In 2006, pumped storage bought 4918 GWh of electricity and supplied 3853 GWh – an efficiency of 78%. (Source: DUKES 07.) The amount supplied is 10.6 GWh per day.

188 *Fridges can be modified to nudge their internal thermostats up and down ... in response to the mains frequency.* [2n3pmb] Further links: `http://www.dynamicdemand.co.uk/` 'Dynamic Demand, a non-profit organization, promotes the introduction of dynamic demand control technologies on the UK power grid

by advocating institutional change and stimulating research and discussion. See also `http://www.responsiveload.com/` and `http://www.rltec.com/`.

26

Five energy plans for Britain

If we are to get off our current fossil fuel addiction we need a plan for radical action. And the plan needs to add up. The plan also needs a political and financial roadmap. Politics and economics are not part of this book's brief. So here I will simply discuss what the technical side of a plan that adds up might look like.

There may be many plans that add up. Please don't take any of the plans I present as 'the author's recommended solution'. My sole recommendation is this:

> Make sure your policies include a plan that adds up!

Each plan has a consumption-side and a production-side: we have to specify how much power our country will be consuming, and how that power is being produced. To avoid the plan's taking many pages, I propose to make a cartoon of our country, in which we consume power in just three forms: transport, heating, and electricity. This is a drastic simplification, omitting industry, farming, food, imports, and so forth. But I hope it's a helpful simplification, allowing us to compare and contrast alternative plans in one minute. Eventually we'll need more detailed plans, but today, we are so far away from our destination, I think that a simple cartoon is the best way to capture the issues.

I'll present a few plans which I believe are technically feasible plans for the UK in 2050. All will share the same consumption side. I emphasize again, this doesn't mean that I think this is the correct plan for consumption, or the only plan. I just wanted to avoid overwhelming you with a proliferation of plans. On the production side, I will describe a range of plans using different mixes of renewables, 'clean coal', and nuclear power.

The current situation

The current situation in our cartoon world is this: Transport uses 40 kWh/d per person. (That's transporting both humans and stuff.) Most of that energy is currently consumed as petrol, diesel, or kerosene. Heating of air and water uses 40 kWh/d per person. Much of that is provided by

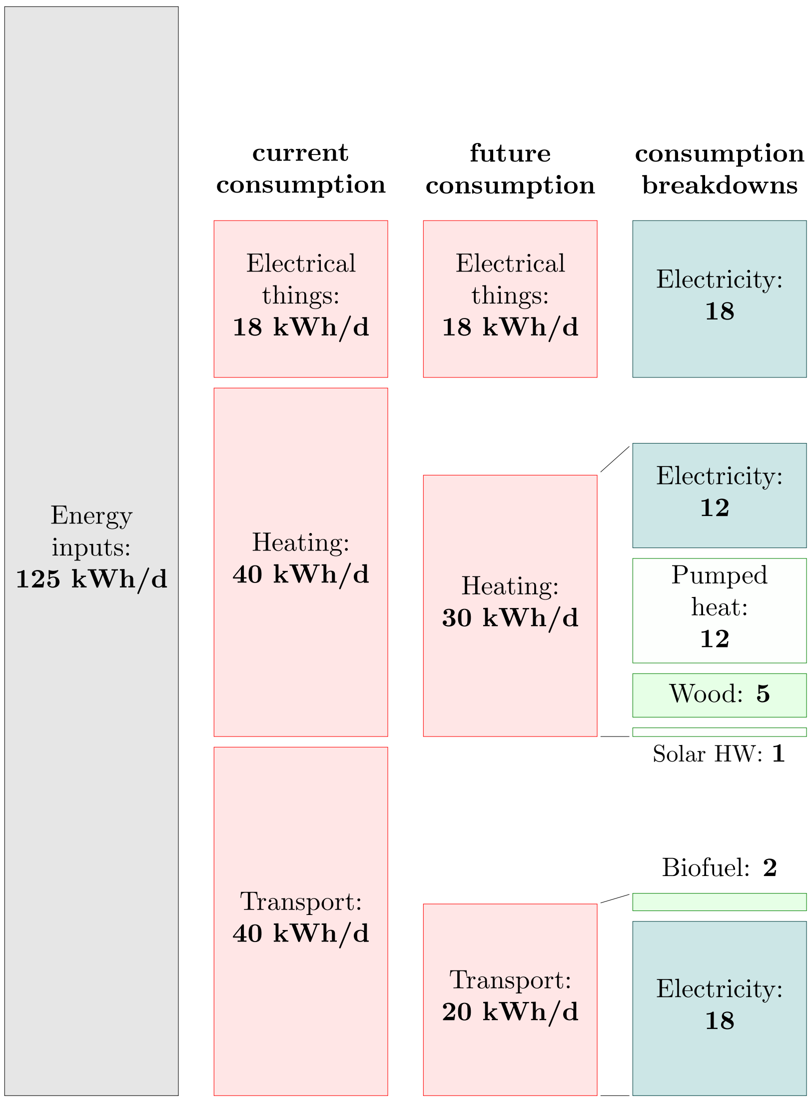


Figure 26.1. Current consumption in 'cartoon Britain 2008' (left two columns), and a future consumption plan, along with a possible breakdown of fuels (right two columns). This plan requires that electricity supply be increased from 18 to 50 kWh/d/p of electricity.

natural gas. Delivered electricity amounts to 18 kWh/d/p and uses fuel (mainly coal, gas, and nuclear) with an energy content of 45 kWh/d per person. The remaining 27 kWh/d/p is going up cooling towers (25 kWh/d/p) and lost in the wires and transformers of the distribution network (2 kWh/d/p). The total energy input to this cartoon country is 125 kWh/d per person.

Common features of all five plans

In these plans, **transport** is largely electrified. Electric engines are more efficient than petrol engines, so the energy required for transport is reduced. Public transport (also largely electrified) will be better integrated, better personalized, and better patronized. The energy for transport is 18 kWh/d/p of electricity and 2 kWh/d/p of liquid fuels (for example biodiesel or biomethanol or cellulosic bioethanol). The biomass might also be converted to liquid fuels for use in aeroplanes. The electric vehicles' batteries will serve as a helpful energy storage facility, to help cope with fluctuations in any renewables in our production plan. The area required for the biofuel production would be about 12% of the UK (500 m^2 per person), assuming that biofuel production comes from 1% efficient plants and that conversion of plant to fuel is 33% efficient. Alternatively, the biofuels could be imported if we could persuade another country to devote the required area of agricultural land to biofuels for us.

The energy consumption of **heating** is reduced by improving the insulation of all buildings, and improving the control of temperature (through thermostats, education, and the promotion of sweater-wearing by sexy personalities). New buildings (all those built from 2010 onwards) are really well insulated and require almost no space heating. Old buildings (which will still dominate in 2050) are mainly heated by air-source heat pumps and ground-source heat pumps. Some water heating is delivered by solar panels (2.5 square metres on every house), some by heat pumps, and some by electricity. Some buildings located near to managed forests and energy-crop plantations are heated by biomass. The power required for heating is thus reduced from 40 kWh/d/p to 12 kWh/d/p of electricity, 2 kWh/d/p of solar hot water, and 5 kWh/d/p of wood.

The wood for making heat (or possibly combined heat and power) comes from nearby forests and energy crops (perhaps miscanthus grass, willow, or poplar) covering a land area of 6 million hectares, or 1000 m^2 per person; this would correspond to 35% of the agricultural land of the UK, which has an area of 2800 m^2 per person. The energy crops would be grown mainly on the lower-grade land, leaving the higher-grade land for food-farming. 1000 m^2 of energy crops will yield 1 oven dry ton per year, which has an energy content of about 10 GJ; of this energy, about 33% is lost in the heat delivery process or required for production and transport. The final heat delivered is 5 kWh/d per person.

In these plans, I assume the current demand for **electricity** for gadgets, light, and so forth is maintained. So we still require 18 kWh(e)/d/p of electricity. Yes, lighting efficiency will be improved by a switch to LEDs for most lighting, but we'll have increased the number of gadgets in our lives, for example video-conferencing systems to help us travel less.

So the total consumption of electricity under this plan goes up (because of the 20 kWh/d/p for electric transport and the 12 kWh/d/p for heat pumps) to 50 kWh/d/p (or 125 GW per UK). This is nearly a tripling of UK electricity consumption. Where's that energy to come from?

Let's describe some alternatives. Not all of these alternatives are 'sustainable' as defined in this book; but they are all low-carbon plans.

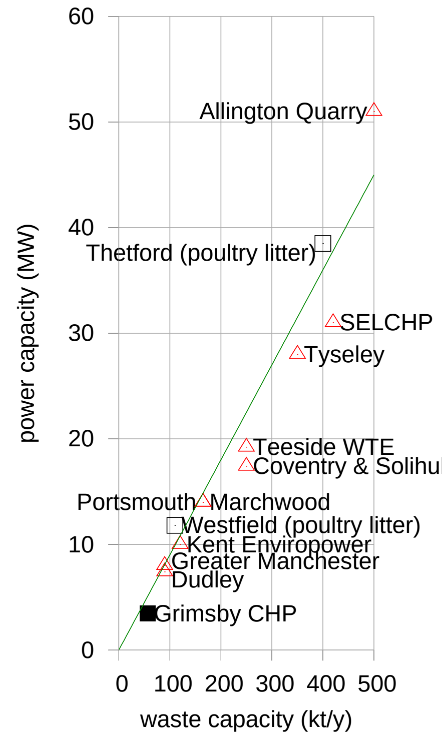


Figure 26.2. Waste-to-energy facilities in Britain. The line shows a summary exchange rate: 100 000 tons of waste per year → 9 MW; or to put it into individual terms, 1 kg of waste → 0.8 kWh of electricity. (Check this against the actual stats from SELCHP.)

Producing lots of electricity – the components

To make lots of electricity, our plan will use some amount of onshore and offshore wind; some solar photovoltaics; possibly some solar power bought from countries with deserts; waste incineration (including refuse and agricultural waste); hydroelectricity (the same amount as we get today); perhaps wave power; tidal barrages, tidal lagoons, and tidal stream power; perhaps nuclear power; and perhaps some 'clean fossil fuel', that is, coal burnt in power stations that do carbon capture and storage.

Some of the plans that follow will import power from other countries. For comparison, it may be helpful to know how much of our current power is imported today. The answer is that, in 2006, the UK imported 28 kWh/d/p of fuel, – 23% of its primary consumption. These imports are dominated by coal (18 kWh/d/p), crude oil (5 kWh/d/p), and natural gas (6 kWh/d/p). Nuclear fuel (uranium) is not usually counted as an import since it's easily stored.

In all five plans I will assume that we scale up municipal waste incineration so that almost all waste is incinerated or recycled rather than landfilled. UK waste production is roughly 1 kg per day per person. If we assume one third of this is recycled then the remainder yields roughly 0.5 kWh/d (figure 26.2). I'll assume that a similar amount of agricultural waste is also incinerated, yielding 0.6 kWh/d. Incinerating this waste would require roughly 3 GW of waste-to-energy capacity, a ten-fold increase over the incinerating power stations of 2008. London (7 million people) would have twelve 30 MW waste-to-energy plants like SELCHP in South London. Birmingham (1 million people) would have two of them. Every town of 200 000 people would have a 10 MW waste-to-energy plant. One good side-effect of this waste incineration plan is that it eliminates future methane emissions from landfill sites. SELCHP cost £85 million so the cost of the nation's 100 new 30 MW incinerators might be £8.5 billion (£140 per person).

In all five plans, hydroelectricity contributes 0.2 kWh/d, the same amount as we get from hydro today.

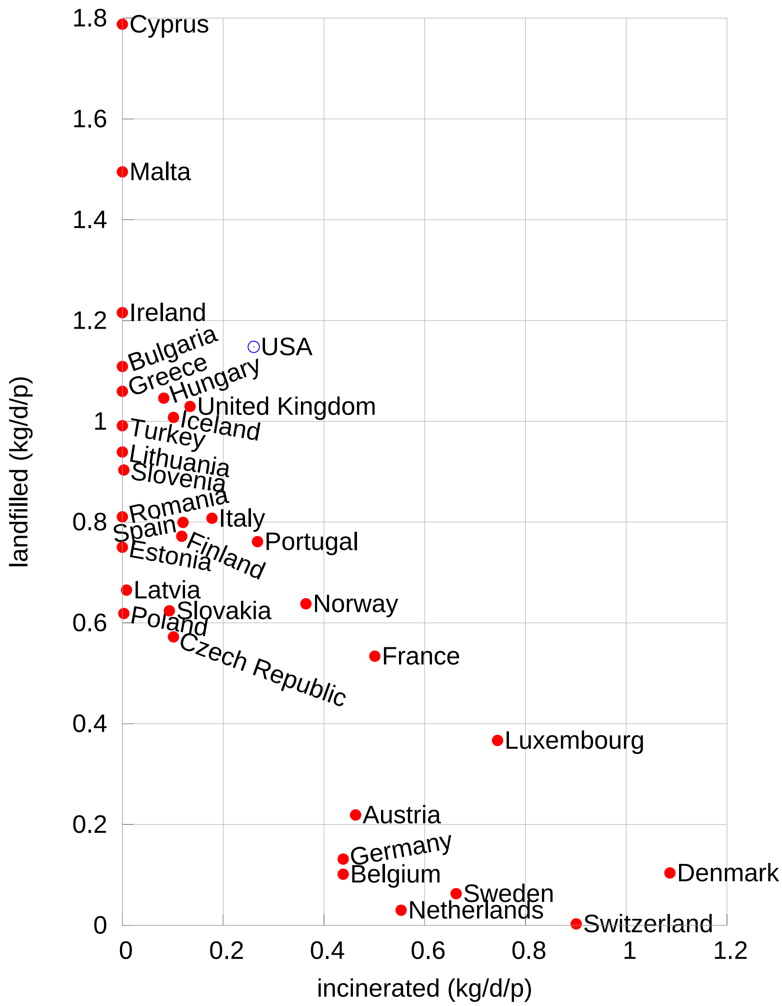
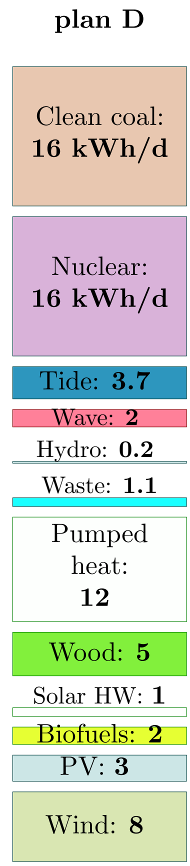


Figure 26.3. Municipal solid waste put into landfill, versus amount incinerated, in kg per day per person, by country. Data from Eurostat and `www.epa.gov`.

Electric vehicles are used as a dynamically-adjustable load on the electricity network. The average power required to charge the electric vehicles is 50 GW (20 kWh/d/p). So fluctuations in renewables such as solar and wind can be balanced this load, as long as the fluctuations are not too big.

Daily swings in electricity demand are going to be bigger because of the replacement of gas for cooking and heating by electricity. To ensure that sudden surges in consumer demand of 50 GW lasting up to 2 hours can be covered, all the plans would build new pumped storage facilities like Dinorwig. 100 GWh of storage is equal to ten Dinorwigs.



Producing lots of electricity – plan D

Plan D is the 'domestic diversity' plan, in which we use a lot of every possible source of electricity, and depend relatively little on energy supply from other countries.

Wind: 8 kWh/d/p (20 GW average; 66 GW peak) (plus about 1000 GWh of associated pumped storage facilities). Solar PV: 3 kWh/d/p. Hydro, waste incineration: 1.3 kWh/d/p. Wave: 2 kWh/d/p. Tide: 3.7 kWh/d/p. Nuclear: 16 kWh/d/p (40 GW). Clean coal: 16 kWh/d/p (40 GW).

Total: 50 kWh/d/p.

The figure for wind corresponds to a 30-fold increase in wind power over the 2007 installed power. Britain would have nearly three times as much wind hardware as Germany has now. Installing this windpower over a period of 10 years would require [how many?] jack-up barges.

The waste incineration corresponds to 1 kg per day per person of domestic waste (yielding 0.5 kWh/d) and a similar amount of agricultural waste yielding 0.6 kWh/d; the hydroelectricity is 0.2 kWh/d, the same amount as we get from hydro today.

The wave power requires 7500 Pelamis deep-sea wave devices occupying 500 km of Atlantic coastline.

The tide power comes from 5 GW of tidal stream installations, a 2 GW Severn barrage, and 2.5 GW of tidal lagoons, which can serve as pumped storage systems too.

The nuclear power (40 GW) is a roughly four-fold increase of the 2007 nuclear fleet.

The clean coal (40 GW) corresponds to taking the current fleet of coal stations, which deliver about 30 GW, retrofitting carbon capture systems to them, which would reduce their output to 22 GW, then building another 18 GW of new clean coal stations. This level of coal power requires an energy input of about 53 kWh/d/p of coal, which is a little bigger than our current rate of burning of fossil fuels, and well above the level we estimated as being 'sustainable' in chapter ??. This rate of consumption of coal is roughly three times the current rate of coal imports (18 kWh/d/p). If we didn't reopen UK coal mines, this plan would have 32% of UK electricity depending on imported coal. Reopened UK coal mines could deliver an energy input of about 8 kWh/d/p, so either way, the UK would not be self-sufficient for coal.

Producing lots of electricity – plan N

Plan N is the 'NIMBY' plan, for people who don't like industrializing the British countryside with renewable energy facilities, and who don't want new nuclear power stations either. Let's reveal the plan in stages.

First, we turn down all the renewable knobs from their very high settings in plan D:

Wind: 2 kWh/d/p (5 GW average). Solar PV: 0 kWh/d/p. Hydro, waste incineration: 1.3 kWh/d/p. Wave: 0 kWh/d/p. Tide: 1 kWh/d/p.

We've just lost ourselves 14 kWh/d/p (35 GW per UK) by turning down the renewables knob. (Don't misunderstand! Wind is still hugely increased over its 2007 levels – by a factor of 7.5, to be precise.)

Nuclear: 10 kWh/d/p (25 GW). Clean coal: 16 kWh/d/p (40 GW).

I've reduced nuclear by 15 GW compared to plan D. 25 GW of nuclear power could, I think, be squeezed onto the existing nuclear sites. I left the clean coal contribution unchanged.

Where are we going to get an extra 50 GW from? The NIMBY says, 'not in my back yard, but in someone else's'.

Solar power in deserts: 20 kWh/d/p (50 GW).

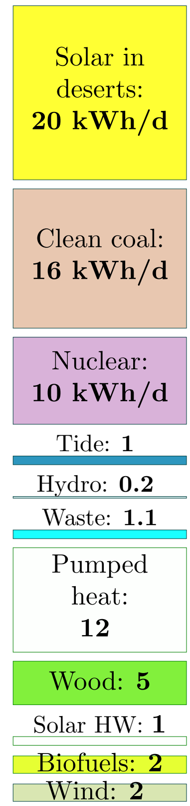
Total: 50 kWh/d/p.

This plan requires the creation of five blobs each the size of London (44 km in diameter) in the transmediterranean desert, filled with solar power stations. It also requires power transmission systems to get the power up to the UK, and storage systems to store energy from the fluctuating sun. Once we've decided to import solar power from other countries, there's little point having solar PV on our roofs at home – the same panels could always generate more in a sunnier country.

(neglected losses)

This plan gets 32%+40%=72% of the UK's electricity from other countries.

plan N



Producing lots of electricity – plan L

Some people say 'we don't want nuclear power!' How can we satisfy them? I think it should be the job of this anti-nuclear bunch to persuade the NIMBY bunch that they do want renewable energy in our back yard after all.

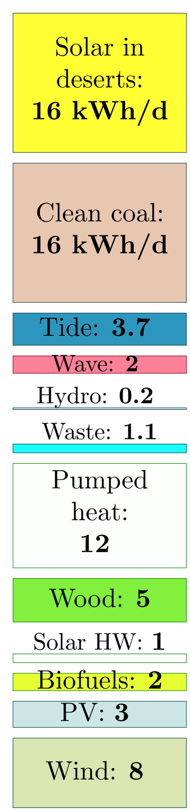
We can create a nuclear-free plan by taking plan D, keeping the renewables, and doing a straight swap of nuclear for desert power.

Wind: 8 kWh/d/p (20 GW average) (plus about 1000 GWh of associated pumped storage facilities). Solar PV: 3 kWh/d/p. Hydro, waste incineration: 1.3 kWh/d/p. Wave: 2 kWh/d/p. Tide: 3.7 kWh/d/p. Clean coal: 16 kWh/d/p (40 GW).

Solar power in deserts: 16 kWh/d/p (40 GW).

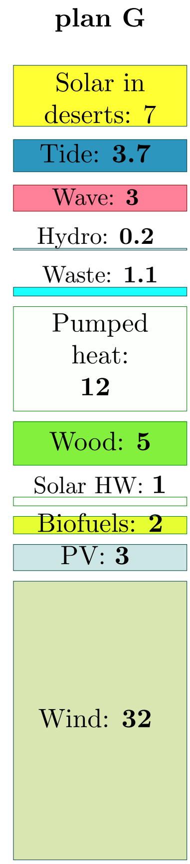
Total: 50 kWh/d/p.

plan L



This plan imports 64% of UK electricity from other countries.

I call this 'plan L' because I think it aligns fairly well with the current policies of the Liberal Democrats.



Producing lots of electricity – plan G

Some people say 'we don't want nuclear power, and we don't want coal!' It sounds a reasonable goal, but we need a plan to deliver it.

I call this plan 'plan G', because I guess the Green Party don't want nuclear or coal, though I think not all Greens would like the rest of the plan. Greenpeace, I know, *love* wind, so plan G is dedicated to them too, because it has *lots* of wind.

I make plan G by starting again from plan D, nudging up the wave contribution by 1 kWh/d and bumping up wind power by a whopping 24 kWh/d/p to 32 kWh/d/p, so that wind delivers 64% of all the electricity. Under this plan, world wind power in 2007 is multiplied by four, with all of the increase being placed on or around the British Isles. Roughly one hundred of Britain's major lakes and lochs would be required for the associated pumped storage systems.

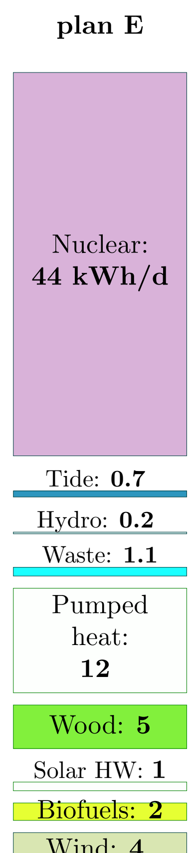
Wind: 32 kWh/d/p (80 GW average) (plus about 4000 GWh of associated pumped storage facilities). Solar PV: 3 kWh/d/p. Hydro, waste incineration: 1.3 kWh/d/p. Wave: 3 kWh/d/p. Tide: 3.7 kWh/d/p.

Solar power in deserts: 7 kWh/d/p (17 GW).

Total: 50 kWh/d/p.

This plan gets 14% of its electricity from other countries.

The immense dependence of plan G on renewables, especially wind, creates difficulties for our main method of balancing supply and demand, namely adjusting the charging rate of millions of rechargeable batteries for transport. So in plan G we have to include substantial additional pumped storage facilities, capable of balancing out the fluctuations in wind on a timescale of days. Pumped storage facilities equal to four hundred Dinorwigs can completely replace wind for a national lull lasting 2 days. Most major lochs in Scotland would be part of pumped storage systems.



Producing lots of electricity – plan E

E stands for 'economics'. On a level economic playing field with a strong price signal preventing the emission of CO_2, we don't get a diverse solution, we get an economically optimal solution that delivers the required power at the lowest cost. And when 'clean coal' and nuclear go head to head on price, it's nuclear that wins. (The capital cost of regular *dirty* coal power stations is £1 billion per GW, about the same as nuclear; but the capital cost of clean coal power, including carbon capture and storage, is roughly £2 billion per GW.) Offshore wind also loses to nuclear, but I've assumed that onshore wind costs about the same. My final plan

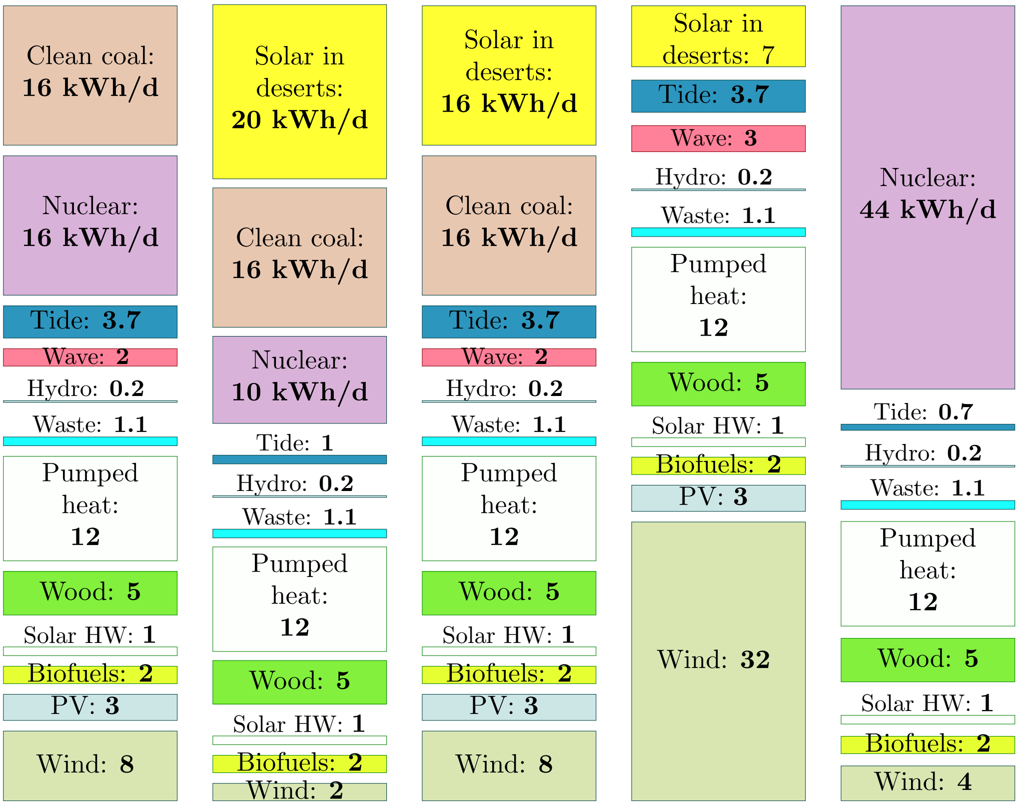


Figure 26.4. All five plans.

is a rough guess for what would happen in a liberated energy market with a strong carbon price.

Wind: 4 kWh/d/p (10 GW average) (plus about 500 GWh of associated pumped storage facilities). Solar PV: 0 kWh/d/p. Hydro, waste incineration: 1.3 kWh/d/p. Wave: 0 kWh/d/p. Tide: 0.7 kWh/d/p. Nuclear: 44 kWh/d/p (110 GW).

Total: 50 kWh/d/p.

This plan has a ten-fold increase in our nuclear power over 2007 levels. 110 GW is roughly double France's nuclear fleet. I included a little tide because I believe a well-designed tidal lagoon facility can compete with nuclear power.

In this plan, Britain has no energy imports (except for the uranium, which, as we said before, doesn't count).

How these plans relate to carbon-sucking and air travel

In a future world where carbon pollution is priced appropriately, we are interested in any power scheme that can at low-cost put extra carbon down a hole in the ground. Such schemes might permit us to continue flying at 2004 levels (while oil lasts). In 2004, average emissions of CO_2 from flying were about 0.5t per year per person. Accounting for the full greenhouse impact of flying, perhaps the effective emissions were about 1t per year per person $CO_2^{(e)}$. In all five of these plans I assumed that

25% of the UK was devoted to the production of energy crops which were then used for heating or for combined heat and power. If instead we directed all these crops to power plants with carbon capture and storage, the 'clean coal' plants that featured in three of the plans, then the amount of extra CO_2 captured would be about 1t of CO_2 per year. If the municipal and agricultural waste incinerators were located at clean coal plants too so that they could share the same chimney, perhaps the total captured could be increased to 2tCO_2 per year per person. This arrangement would have additional costs: the biomass and waste might have to be transported further; the carbon capture process would require a significant fraction of the energy from the crops; and the lost building-heating would have to be replaced by more air-source heat pumps. But I think it would be worth planning ahead by seeking to locate new clean coal plants with waste incinerators in regions close to potential biomass plantations.

'All these plans are absurd!'

If you don't like these plans, I'm not surprised. I agree that there is something unpalatable about every one of them. Feel free to make another plan that is more to your liking. But make sure it adds up!

Perhaps you will conclude that a viable plan has to involve less power consumption per capita. I might agree with that, but it's a difficult policy to sell – recall Tony Blair's response when someone suggested he should fly overseas for holidays less!

Alternatively, you may conclude that we have too high a population density, and that a viable plan requires fewer people. Again, a difficult policy to sell.

What about shipping?

International shipping is a surprisingly efficient user of fossil fuels; so decarbonising road transport is a higher priority than decarbonising ships. But fossil fuels are a finite resource, and eventually ships must be powered by something else. One option will be nuclear power. There are already many nuclear-powered ships, both military and civilian. Russia has ten nuclear-powered ice-breakers, for example, of which seven are still active. The first nuclear-powered ship for carrying cargo and passengers was the NS Savannah, launched in 1962 as part of President Dwight Eisenhower's Atoms for Peace initiative. Powered by one 74 MW nuclear reactor, the Savannah had a service speed of 21 knots (39 km/h) and could carry 60 passengers and 14 000 t of cargo. (That's a cargo transport cost of 0.14 kWh per ton-km.) She could travel 300 000 miles without refuelling.

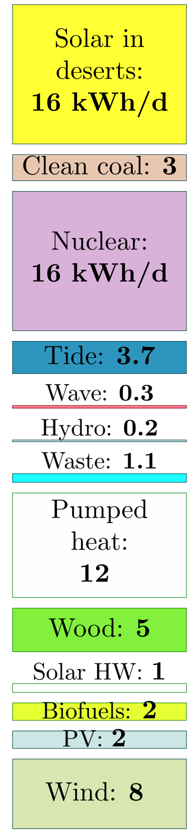
Figure 26.5. NS Savannah, the first commercial nuclear power cargo vessel, passing under the Golden Gate Bridge in 1962.

Notes

203 Current UK natural gas demand varies throughout the year, from typical average of 90 GW in July and August to average of 180 GW in December to February, with extremes of 75–200 GW. (Based on figures for 2002–3 from `http://www.simmonsco-intl.com/files/031104.pdf`.) There is a good correlation with temperature: 90 GW is always used no matter how high the temperature. From temperature 20 downwards demand increases linearly from 90 GW at 20°Cto 200 GW at 0°C.

27

Putting costs in perspective



A plan on a map

Let me try to make clear the scale of the previous chapter's plans by showing you a map of Britain bearing a sixth plan. This sixth plan lies roughly in the middle of the first five.

More explanatory notes to come here.

Blue dots: solar panels for hot water on all roofs. Green squares: wind-farms. Each is 100 km^2 in size and is shown to scale. Red lines in the sea: wave-farms. Light blue lightning polygons: solar photovoltaic panels (to be shown to scale in next draft). Total average production shown is 5 GW, which requires roughly 50 GW of peak capacity (cf in 2006 Germany's PV peak capacity was 3 GW). Blue polygons in the sea: tide-farms. Not all of the areas shown would be required. Blue blobs in the sea (Blackpool and the Wash): tidal lagoons. Light green land areas: woods and short-rotation coppices. Yellow areas: biofuel. Small Brown dots: waste incineration plants (not to scale). Big brown dots: clean coal power stations, with cofiring of biomass, and carbon capture an storage. Yellow dots: nuclear power stations (not to scale) – 3.3 GW at each of 12 sites. Yellow hexagons across the channel: concentrating solar power facilities in remote deserts. (To be shown to scale in the next draft.) Pink wiggly line in France: the new HVDC line conveying 40 GW from remote deserts to the UK. (Not to scale.) Red dots: existing pumped storage facilities.

Yellow dots in Scotland: new pumped storage facilities.

Let's look at this plan in a bit more detail to assess its costs: its land area costs, and its financial costs.

For simplicity, the financial costs are estimated using today's prices for comparable facilities, many of which are early prototypes. We can expect many of the prices to drop significantly.

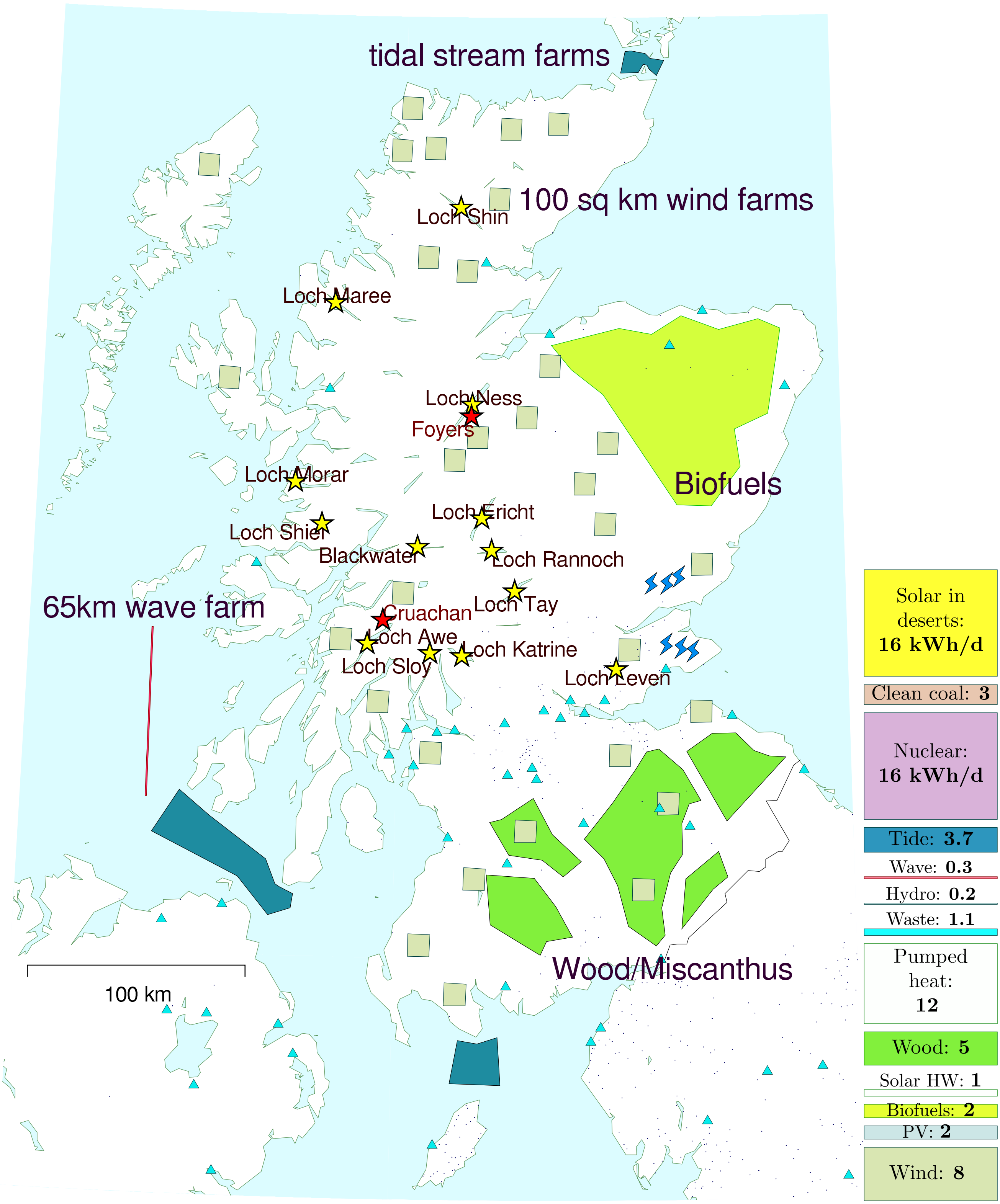


Figure 27.1. A plan that adds up, for Scotland.

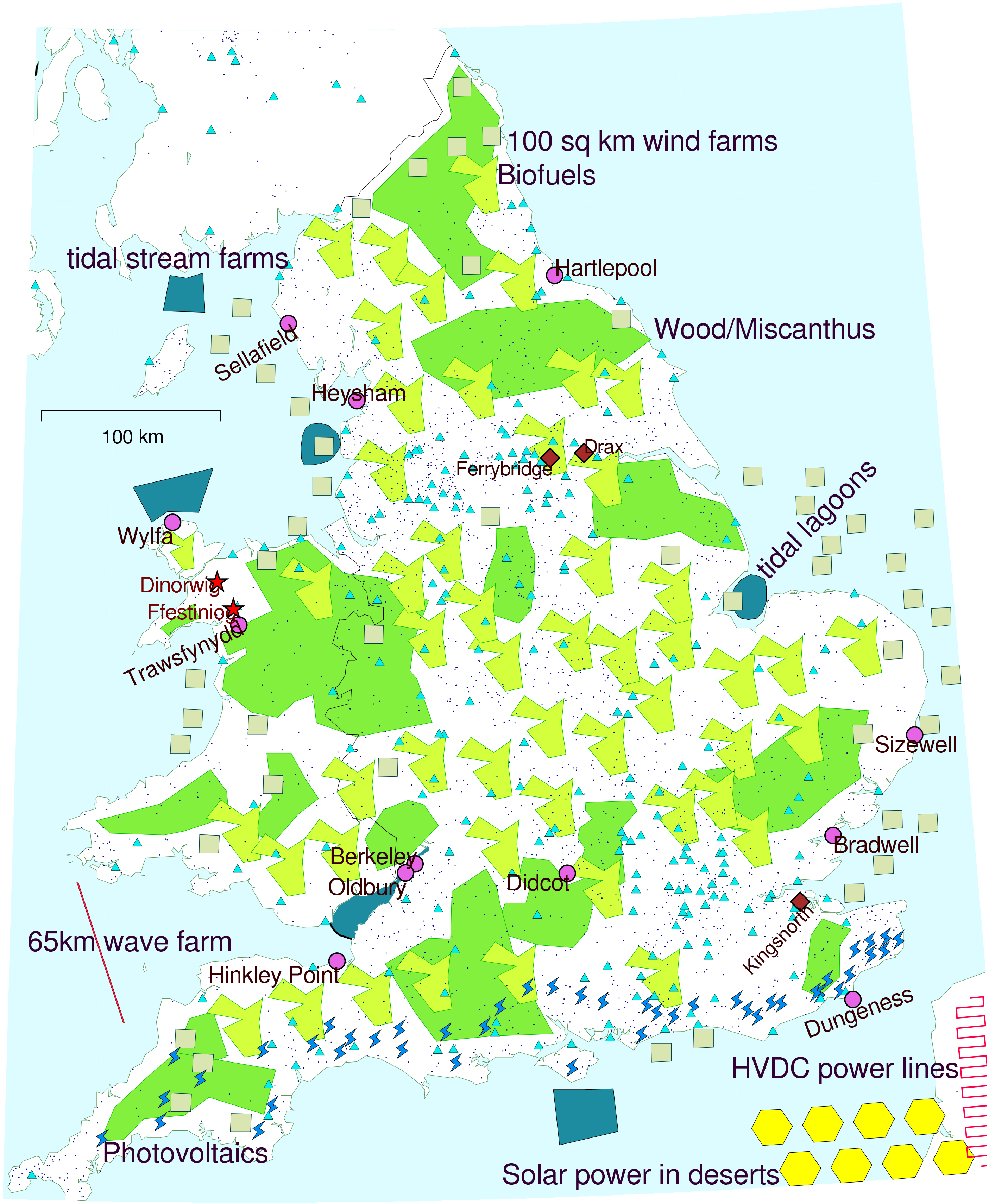


Figure 27.2. A plan that adds up, for England and Wales.

52 onshore windfarms, each 100 square km in size.	Capacity: 0.67 GW per windfarm. Total capacity 35 GW.	Rough cost: £27b. (Based on the projected cost of Lewis windfarm, £500 million for 650 MW.)	£450 per person.	Average power delivered: 4.2 kWh/d/p.
29 offshore windfarms, each 100 square km in size.	Capacity: 1 GW per windfarm. Total capacity 29 GW.	Rough cost: £33b, plus £6b capital investment in jack-up barges. (Based on the cost of Kentish Flats.)	£650 per person.	Average power delivered: 3.5 kWh/d/p.
1000 km^2 of photovoltaic farms	Capacity: 48 GW	Rough cost: £190b (Based on Solarpark in Mühlhausen, Bavaria)	£3200 per person.	2 kWh/d/p
Solar hot water panels: 1 m^2 of roof per person. (60 km^2 total)	£1200 per person	1 kWh/d/p		
Concentrating solar power in deserts: 2700 km^2. Average power output: 40 GW.	Rough cost: £500b	£8300 per person	16 kWh/d/p	
Land in Europe for 1600 km of HVDC power lines with 50 GW capacity: 1200 km^2	Rough cost: £1b (assuming land costs £7500 per ha in Europe)	£15 per person		
2000 km of HVDC power lines with 50 GW capacity:	£1b (based on German Aerospace Center estimates)	£15 per person		
Biofuels: 30 000 km^2			2 kWh/d/p	
Wood/Miscanthus: 31 000 km^2			5 kWh/d/p	

I'd like to emphasize that I am not advocating this particular plan – it includes several features that I, as dictator of Britain, would not select. I've deliberately included all the technologies, so that you can visualize other plans with other mixes.

For example, if you say 'photovoltaics are going to be too expensive, I'd like a plan with more wave power instead', you can see how to do it:

you need to increase the wave-farms eight-fold.

If you don't like the wind-farms' locations, feel free to say whither you'd move them. Bear in mind that putting more of them offshore will increase costs.

If you'd like fewer windfarms, no problem – just specify which of the other technologies you'd like instead.

Perhaps you think that this plan (and all five plans in the previous chapter) devotes unreasonably large areas to biofuels. Fine: you may therefore conclude that the demand for liquid fuels for transport must be reduced below the 2 kWh per day per person that this plan assumed; or that liquid fuels must be created in some other way.

Cost of switching from fossil fuels to renewables

Every wind farm costs a few millions and delivers a few megawatts. I'm talking here about the cost of installing the power generators (per unit power), not the cost of the delivered energy (per unit energy). As a very rough ballpark figure in 2007, installing one watt of power costs one pound; one kilowatt costs one thousand pounds; a megawatt of wind costs a million; a gigawatt of nuclear costs a billion or perhaps two. Other renewables are more expensive. We (Britain) currently consume a primary power of roughly 300 GW, most of which is fossil fuel. So we can anticipate that a major switching from fossil fuel to renewables is going to have a cost measured in hundreds of billions. A government report leaked by the Guardian in August 2007 agrees: it's estimated that achieving '20% by 2020' (that is, 20% of all energy from renewables, which would require an increase in renewable power of 60 Mtoe per year, or 80 GW) could cost 'up to £22 billion' (which would average out to £1.7 billion per year). The authors of the leaked report seem to view this as an 'unreasonable' cost, preferring a target of 9% renewables, which would cost approximately £4 billion (£0.3 billion per year). (Another reason they give for disliking the '20% by 2020' target is that the resulting greenhouse gas savings 'risk making the EU emissions trading scheme redundant'. Terrifying thought!)

Billions are big numbers and hard to get a feel for. To try to help put the cost of kicking fossil fuels in perspective, this chapter discusses other things that also come in billions of pounds, or in billions per year.

Perhaps the most relevant quantity to compare with is the money we *already* spend on energy every year. In the UK, the money spent on energy by final users is £75 billion per year. So the idea of spending £1.7 billion per year on investment in future energy infrastructure isn't at all unreasonable – it is less than 3% of our current expenditure on energy!

Another good comparison to make is with our annual expenditure on insurance: some of the investments we need to make offer an uncertain return – just like insurance. UK individuals and businesses spend £90b per year on insurance.

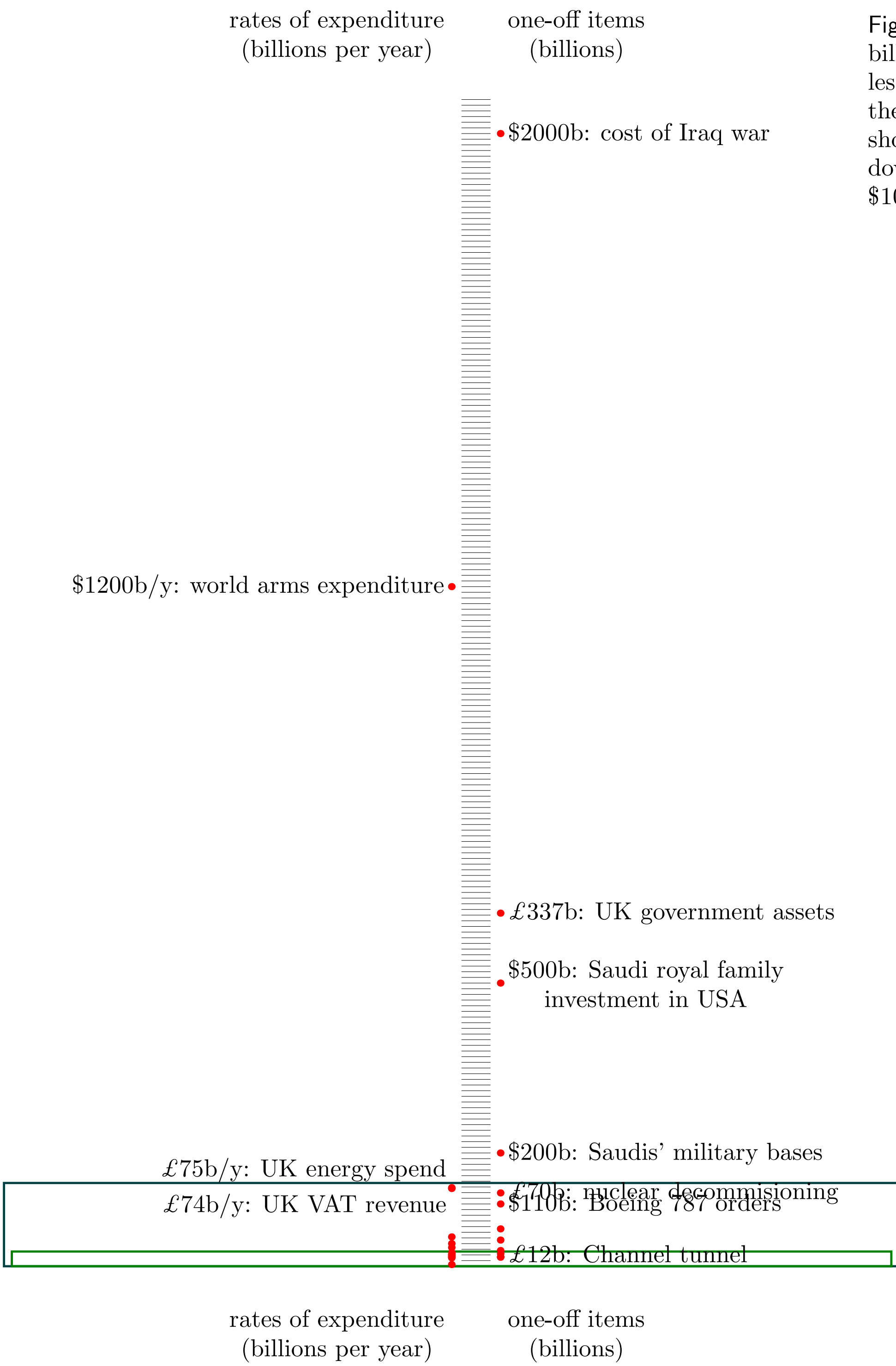


Figure 27.3. Things that run into billions. All the things that cost less than £70b, in the rectangle at the bottom of the diagram, are shown in the next figure. The scale down the centre has large tics at $10 billion intervals.

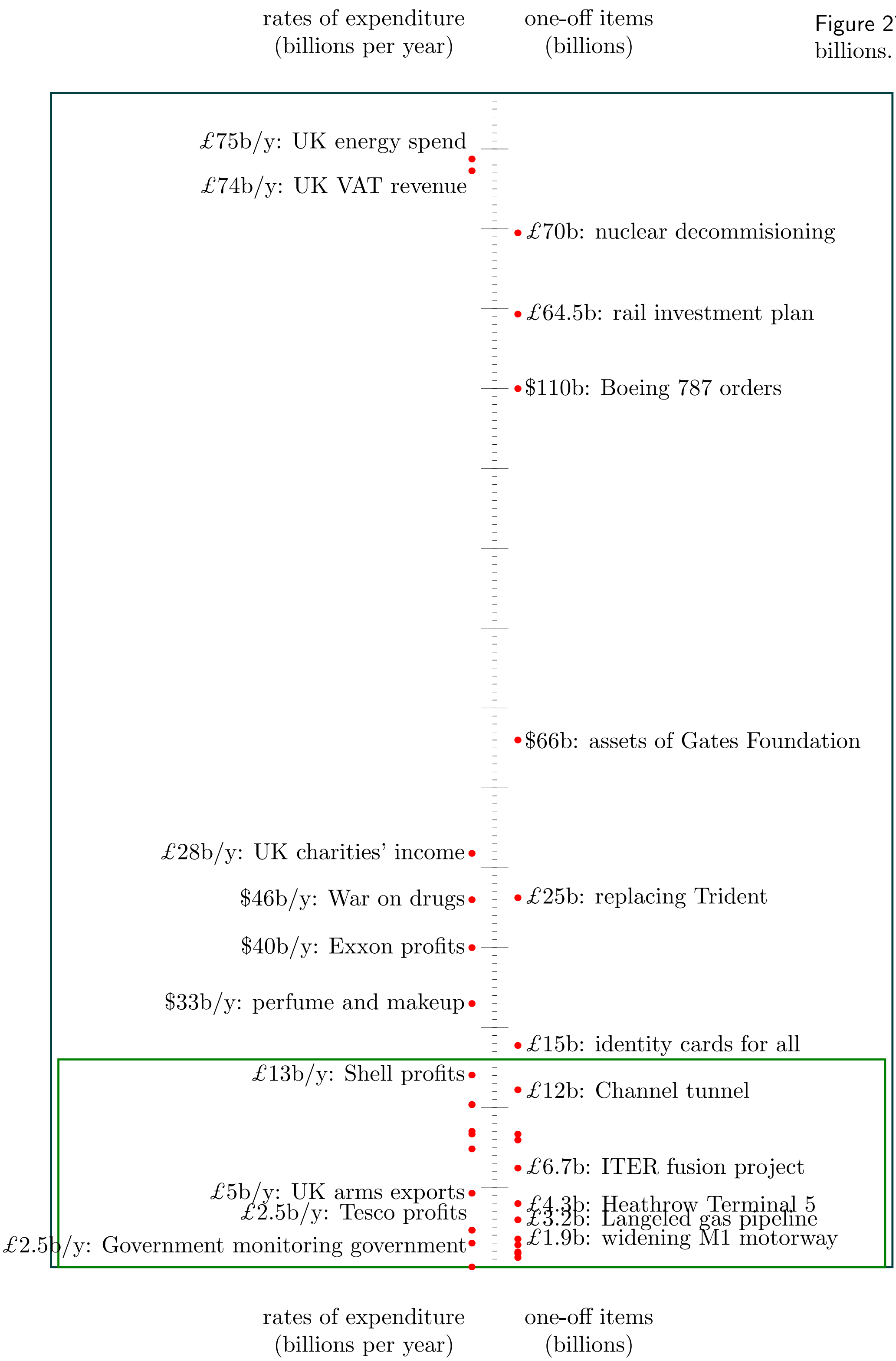


Figure 27.4. Things that run into billions. (Detail.)

Other things that cost a billion

Subsidies

US subsidy for corn-based ethanol: $2 billion per year [2kz3hk].

£1 billion: amount 'earned' in windfall profits by the UK's most-polluting industries from the first year of the European carbon trading scheme [37l7fr].

£56 billion over 25 years: cost of decommissioning the UK's nuclear power stations. (That's the 2004 figure; in 2008 it was up to £73 billion. http://news.bbc.co.uk/1/hi/uk/7215688.stm

Transport

$1.2 billion: President Bush's Hydrogen Fuel Initiative announced in the 2003 State of the Union Address.

£1.4 billion: The UK government gave Virgin trains a £1.4 billion subsidy over five years to run the London-to-Glasgow service and help offset high track charges

£4.3 billion: cost of London Heathrow Airport's Terminal 5.

£8.6 billion: cost of upgrading the west coast mainline [2qtr7l].

£64.5 billion – UK government's rail investment plan announced January 2002. (Half from the public purse, half from private investors.) [2lq4j8].

£15–20b/y: estimated cost to UK industry of traffic congestion.

$3b/y: annual spending by the eleven teams participating in Formula One racing.

$110b: as of 7/7/7, 47 customers worldwide have ordered 677 Boeing 787 airplanes worth more than $110 billion.

Subsidies and tax-breaks

The UK air transport industry receives over £9 billion per year in tax breaks because of tax-free fuel, VAT-free tickets, and profits from duty-free sales [2uraxb].

Tax cut for drivers: At the 2002 Budget, the Chancellor cut road fuel duty by around £1 billion a year.

Road-building

£1.9 billion: The cost of widening the M1 through the East Midlands (from junction 21 to 30), estimated at £700 million in the multi modal study Final Report (December 2001), has risen to £1.9 billion upon entry into the Targeted Programme of Improvements (April 2004) [yu8em5].

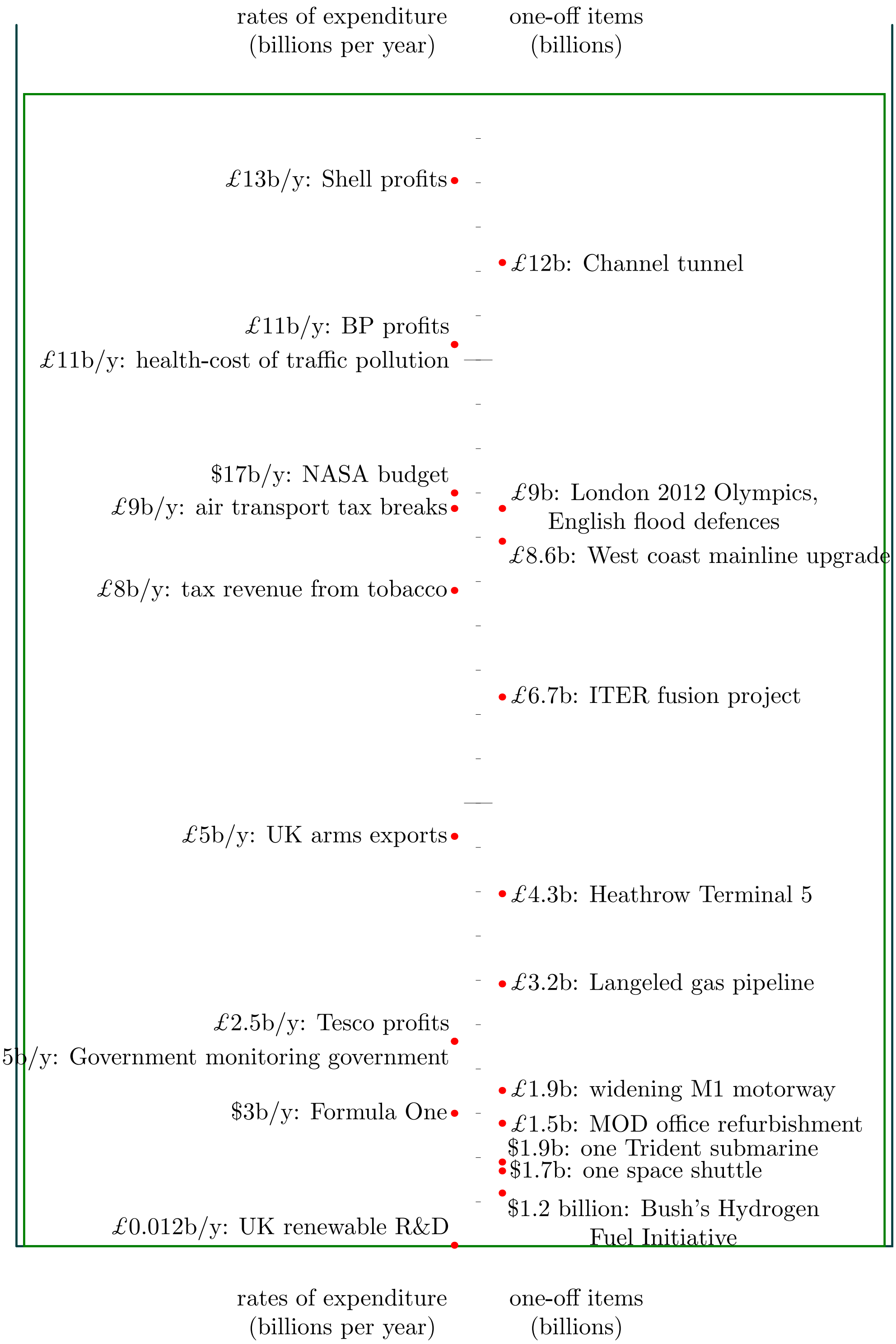


Figure 27.5. Things that run into billions. (Detail of detail.) The smallest item displayed (£0.012b/y) is the UK government's annual investment in renewable energy research and development. Comparably small is the government's allocation to the Low Carbon Buildings Programme, £0.018b/y shared between wind, biomass, solar hot water/PV, ground-source heat pumps, micro-hydro and micro CHP.

Government investment in renewable-energy-related research and development

In 2002–3, the UK Government's commitment to renewable-energy-related R&D was £12.2 million. (Source: House of Lords report.)

Global expenditure on climate research: $2 billion.

Energy

The money spent on energy by the final users in the UK in 2004 was £75 billion per year (£1250 per person), which is about 6% of the UK's gross domestic product (£1200 billion) (£20 000 per person). Dividing the money spent by the energy delivered, the average cost paid per kWh was 2.7p.

Individual philanthropy

The Gatsby Trust's Settlor (David Sainsbury) has declared his ambition to give away at least £1 billion in his lifetime. (The Gatsby Charitable Foundation. Annual Report and Accounts 2006, page 3.)

$66 billion – assets of the Gates Foundation [`ylx4xq`].

The endowment of the Mohammed Bin Rashid Al Maktoum foundation (`www.mbrfoundation.ae`) is $10 billion.

The annual income of UK charities is £28 billion.

Special occasions

Cost of Athens 2004 Olympics: €9 billion [`2nznsz`].

Cost of the London 2012 Olympics: £2.4 billion; no, I'm sorry, I meant to say £5 billion [`3x2cr4`]; or perhaps £9 billion [`2dd4mz`].

Easy money

£485 million and 100 avoided road-fatalities per year – predicted saving if the United Kingdom advanced its clocks by one hour [Hopkin, 2007].

Business as usual

£2.5b/y: Tesco's profits (announced 2007).

£10.2 b/y: spent by British people on food that they buy but do not eat.

£11b/y ($ 22b): BP's profits (2006).

£13b/y ($25b): Royal Dutch Shell's profits (2006). Most of Shell's profits come from finding and extracting oil, and then selling it on to the markets.

$40b/y. Exxon's profits (2006).

$33b/y. World expenditure on perfumes and makeup. Source: Worldwatch Institute `http://www.worldwatch.org/press/news/2004/01/07/`

Government business as usual

£2.5b/y: cost of central government's monitoring of local government.

£1.5b: cost of refurbishment of Ministry of Defence offices in Whitehall. (Private Eye No. 1176, 19th January 2007, page 5.)

£1.4b: cost of new headquarters for Home Office in Marsham Street. (Private Eye No. 1176, 19th January 2007, page 5.)

£8.5 billion: cost of Allenby/Connaught redevelopment of army barracks in Aldershot and Salisbury Plain.

£15 billion – cost of introducing new UK identity card scheme [7vlxp].

£1.8 billion. Central government departments spent almost £2 billion on consultants during 2006. [2qhyw2]

Government assets

The UK government owns assets worth £337 billion. [2hddq9]

Planning for the future

£9 billion – cost of flood defences required to protect England against 40 cm sea-level rises [324zyk].

£3.2 billion: cost of the Langeled pipeline, which ships gas from Norwegian producers to Britain. The pipeline's capacity is 20 billion m^3 per year, corresponding to a power of 25 GW(thermal). The pipeline is 1200 km long and used about one million tonnes of steel and one million tonnes of concrete [2nfp2d] [39g2wz] [3ac8sj].

Tobacco taxes and subsidies

£11b/y: annual cost of the impact of traffic pollution on health.

£1.5b/y: annual cost to National Health Service of treating smoking-related diseases.

£8b/y: annual revenue from tobacco taxes in the UK [y7kg26]. The European Union spends almost €1 billion a year subsidising tobacco farming. http://www.ash.org.uk/

International investments

$1.4 billion: money received in investments and contracts by the House of Bush from the House of Saud [8t7rd].

$500 billion: Saudi royal family's investment in USA [2f3nar].

Space

$1.7 billion: Cost of one space shuttle.

$17 billion: NASA's budget (2007) http://www.nasa.gov/about/budget/, [2gajp8].

Military

UK's arms exports are £5 billion per year, of which £2.5 billion go to the Middle East, and £1 billion go to Saudi Arabia. Source – Observer, 3 December 2006.

£1 billion: payments by British arms manufacturer BAE Systems to Saudi arms-deal-arranger Prince Bandar bin Sultan (relating to the Al Yamamah warplane deal in 1985, worth £43 billion.) Source: BBC News Thu 7/6/07.

Two new aircraft carriers will cost £3.8 billion. `http://news.bbc.co.uk/1/low/scotland/6914788.stm`

The Trident submarine costs about $1.9 billion apiece (not including warheads) `http://www.brook.edu/fp/projects/nucwcost/trident.htm`. Replacing Trident would cost £10–25 billion [`ysncks`].

$46 b/y: Annual cost of the USA's 'War on drugs'. [`r9fcf`]

$63 billion: American donation of 'military aid' (*i.e.*, weapons) to the Middle East over the next 10 years – roughly half to Israel, and half to Arab states. [`2vq59t`]

$200 billion: Saudi expenditure on new military bases from 1979 to 1989. [`2f3nar`].

World expenditure on arms: $1.2 trillion per year (2005 estimate) [`ym46a9`].

[`99bpt`] Iraq war could cost US over $2 trillion, says Nobel prize-winning economist Joseph Stiglitz.

UK spending on wars in Iraq and Afghanistan: £8 billion.

According to the Stern review, the global cost of averting dangerous climate change (if we act now) is $440 billion per year ($440 per year per person, if shared equally between the 1 billion richest people). In 2005, the US government alone spent $480 billion on wars and preparation for wars. The total military expenditure of the fifteen biggest military-spending countries was $840 billion.

Channel tunnel. £12 billion. (50 km long) The average depth is 150 feet (45 m) underneath the seabed.

ITER project (fusion) £6.7 billion.

Notes

105 A GOVERNMENT REPORT LEAKED BY THE GUARDIAN... The Guardian report, 13th August 2007, said [`do me`] 'Government officials have secretly briefed ministers that Britain has no hope of getting remotely near the new European Union renewable energy target that Tony Blair signed up to in the spring - and have suggested that they find ways of wriggling out of it.'
The leaked document is at [`do me`]

UK R+D spend on renewables (2004–5): 39 million pounds via the research councils and 26 million from the DTI capital grant fund and $20 million (for renewables) plus $3.4 million for clean coal. Grant program for offshore wind (2005–2010): £107 million to support the creation of 1 GW of installed capacity.

28

What to do now

What we should do depends in part on our motivation. Recall that on p. 4 we discussed three motivations for getting off fossil fuels. Let's assume that we have the climate-change motivation.

We are not on track to a zero-carbon future. Long-term investment is not happening. Carbon sequestration companies are not thriving, even though the advice from climate experts and economic experts alike is that sucking carbon dioxide from thin air will very likely be necessary to avoid dangerous climate change. Carbon is not even being captured at any coal power stations.

Why not?

The principal problem is that carbon pollution is not priced correctly. And there is no confidence that it's going to be priced correctly in the future. When I say correctly, I mean that the price of carbon dioxide should be big enough such that every running coal power station has got carbon capture technology fitted to it.

Solving climate change is a complex topic, but in a single crude brush-stroke, this is the solution: the price of carbon dioxide must be such that people *stop burning coal without capture.* Most of the solution is captured in this one brush-stroke because, in the long term, coal is the big fossil fuel. Trying to reduce emissions from oil and gas is of secondary importance because supplies of both oil and gas are expected to decline over the next 50 years.

So what do politicians need to do? They need to ensure that all coal power stations have carbon capture fitted. I think the simplest way to achieve this goal is to pass a law that says that – from 2020, say – all coal power stations must use carbon capture. However, most democratic politicians seem to think that the way to close a stable door is to create a market in permits to leave doors open. So, if we conform to the dogma that climate change should be solved through markets, what's the market-based way to ensure achievement of our simple goal (all coal power stations to have carbon capture)? Well, we can faff around with carbon trading, but the coal station owners will only act if they are convinced that the price of carbon is going to be high enough for long enough that their carbon-capturing facility will pay for itself. Experts

Figure 28.1. A fat lot of good that did! The price, in euro, of one ton of CO_2 under the first period of the European emissions trading scheme. Source: www.eex.com.

say that a long-term guaranteed carbon price of something like $100 per ton of CO_2 will do the trick.

So politicians need to modify the market so that investors have complete confidence that the price of carbon will always be at least $100 per ton of CO_2. One way to do this would be to issue carbon pollution permits in an auction with a fixed minimum price. Another way would be for governments to underwrite investment in carbon capture by guaranteeing that they will redeem captured-carbon certificates for $100 per ton of CO_2, whatever happens to the market.

I still think it would be wisest directly to close the stable door, rather than fiddling with an international market that is intended to encourage stable door-closing.

Greening the tax system

> "We need to profoundly revise all of our taxes and charges. The aim is to tax pollution - notably fossil fuels - more, and tax work less."
>
> Nicolas Sarkozy

`http://www.greenfiscalcommission.org.uk/`

Green Fiscal Commission. "The Commission was publicly launched on 14 November 2007 and over the next year and half we will be looking in detail at the whole range of issues surrounding green taxes and environmental tax reform (ETR). The Commission's work will cover four broad areas:

- How green taxes/ ETR works
- The environmental, economic and social implications of ETR
- Attitudes to green taxes and ETR
- Communication of our findings.

The focus of the Commission's work is greening the UK tax system - that is moving taxes from 'goods' like labour, to 'bads' like environmental damage. The key to a green tax shift is that it is revenue neutral – tax cuts on 'goods' must be balanced by equivalent tax increases on 'bads'.

The Commission does not have a view on what level of overall taxation is appropriate but considers that a significant shift from taxing 'goods' to 'bads' could make a important contribution to the cost-effective resolution of environmental problems.

Idea: instead of income tax, tax consumption – allows bigger multiplier on green taxes.

Even: just tax carbon, get rid of VAT and corporation taxes.

Environmental taxes are roughly 3% of GDP.

See UNITAX for example `http://www.rui.co.uk/indirect/page3.html` It's an Energy tax; accompanied by (to avoid regressive effects of energy taxes) a universal Basic Income. Similarly, he advocates ULAD (unified land area duty).

UNITAX applies a duty on all primary energy at the first point of use in any given national economy (or in any trading group of nations). All other taxes can be phased out. http://ourworld.compuserve.com/homepages/farel_bradbury/ UNITAX is based on Statutory Primary Energy Content (S.P.E.C) of cross-frontier billings for goods and services. All exports receive a rebate based on S.P.E.C. so that indigenous industry is at no disadvantage from high primary costs.

Policies

Need to make repair, refurbishment, and recycling tax-advantageous compared with simply buying new. For example: 'no VAT on repair work'.

http://news.bbc.co.uk/1/low/business/7151862.stm EU regulations: Carmakers would have to cut average emissions of CO2 from new passenger cars sold in the EU from about 160 grams per kilometre to an average 130 grams per kilometre in 2012.

Carbon trading and taxes

Grubb and Newbery [2008] discuss the merits of taxes versus tradable quotas, arguing in favour of a stable carbon price (which would be delivered by a carbon tax); and they discuss what needs to be done to the EU emissions trading scheme to fix it.

"current instruments will not deliver an adequate investment response"

What sort of carbon price is needed

Get content from carbon.tex

And put costs in perspective

Include 'the last thing we should talk about'?

Individual lifestyle change

"a bit impractical actually"

> "Unless we act now, not some time distant but now, these consequences, disastrous as they are, will be irreversible. So there is nothing more serious, more urgent or more demanding of leadership."
>
> *Tony Blair.*

"a bit impractical actually"

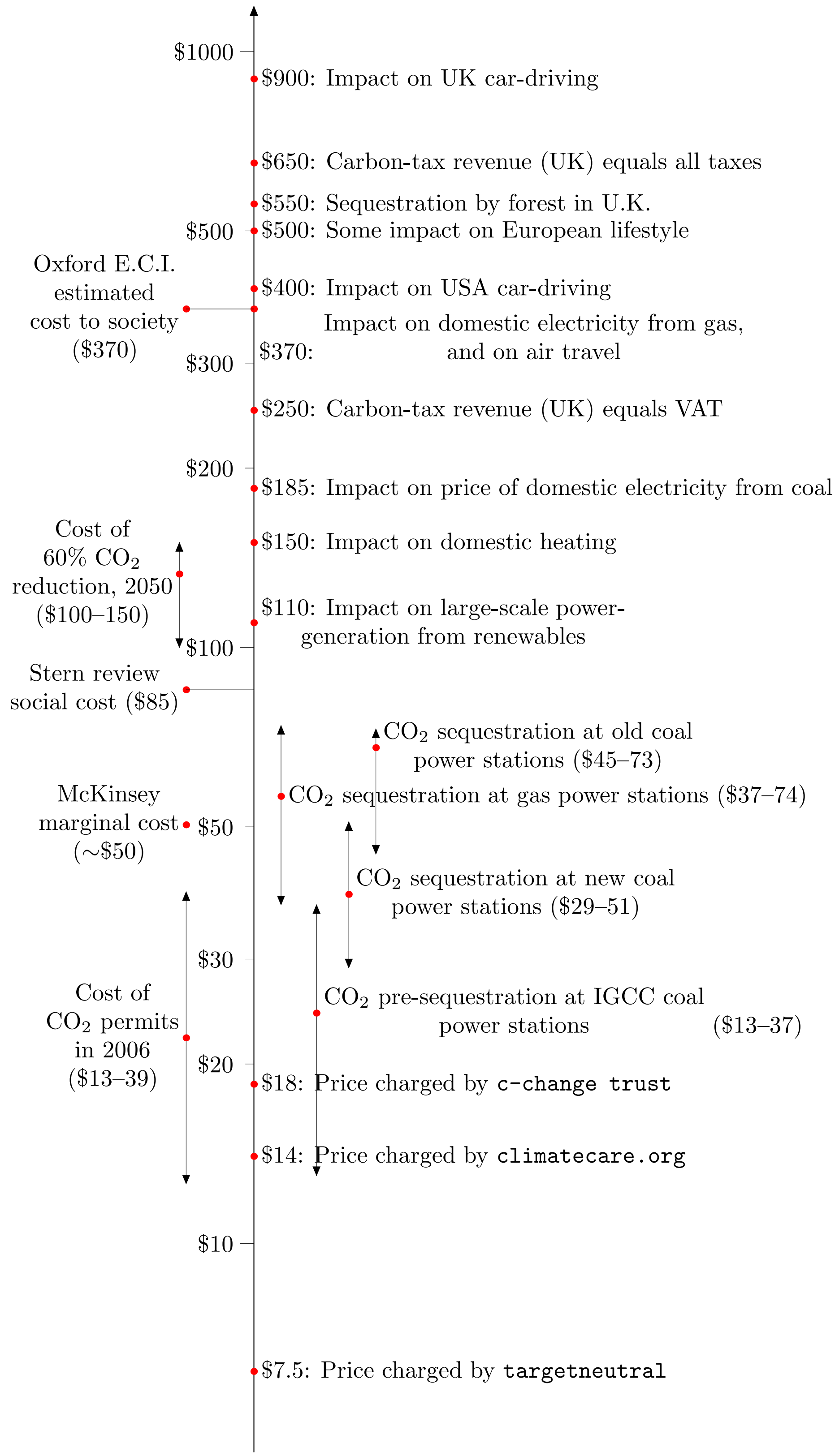


Figure 28.2. What would CO_2 prices need to be in order to drive society to make significant changes in CO_2 pollution?
Carbon dioxide costs (per tonne) at which particular actions will become economical, or particular behaviours will be economically impacted.
As the cost rises through \$20–70 per tonne, CO_2 would become sufficiently costly that it would be economical to add carbon sequestration to new and old power stations.
A price of \$110 per tonne would transform large-scale renewable electricity-generation projects that currently cost 3p per kWh more than gas from pipedreams into financially viable ventures. For example, the proposed Severn barrage would produce tidal power with a cost of £60 per MWh, which is £33 above a typical selling price of £27 per MWh; if each tidal MWh avoided one ton of CO_2 pollution at a value of £60 per ton, the Severn barrage would more than pay for itself.
At \$150 per tonne, domestic users of gas would notice the cost of carbon in their heating bills.
At \$370, carbon pollution would cost enough to reduce people's inclination to fly.
At \$500 per tonne, average Europeans who didn't change their lifestyle might spend 12% of income on the carbon costs of driving, flying, and heating their homes with gas.
And at \$900 per tonne, the carbon cost of driving would be noticeable.

Tony Blair, responding to the suggestion that he should show leadership by not flying to Barbados for holidays.

"Britain's energy policy just doesn't stack up. It won't deliver security. It won't deliver on our commitments on climate change. It falls short of what the world's poorest countries need."

Lord Patten of Barnes, Chair of Oxford University task force on energy and climate change, Monday 4th June 2007.

The best thing we can do with environmentalists is shoot them.

Michael O'Leary, CEO of Ryanair [3asmgy]

http://news.bbc.co.uk/1/low/sci/tech/6970730.stm "Brits 'addicted' to cheap flights."

It's like converting a peacetime economy to a wartime economy.

Efficiency

Action

People sometimes ask me 'What should *I* do? This table indicates eight simple personal actions I'd recommend, and a *very* rough indication of the savings associated with each action.

Simple action	Possible saving
Put on a wooly jumper and turn down your heating's thermostat (to 15 or 17°C, say). Put individual thermostats on all radiators. Make sure the heating's off when no-one's at home. Do the same at work.	20 kWh/d
Read all your meters (gas, electricity, water) every week, and identify easy changes to reduce consumption (e.g., switching things off). Compare competitively with a friend. Read the meters at your place of work too, creating a perpetual live energy audit.	4 kWh/d
Stop flying.	35 kWh/d
Drive less, drive slower, drive more gently, use an electric car, join a car club, cycle, walk, use trains and buses.	20 kWh/d
Keep using old gadgets (*e.g.* computers); don't replace them early.	4 kWh/d
Change lights to fluorescent or LED.	4 kWh/d
Don't buy clutter. Avoid packaging.	20 kWh/d
Eat vegetarian, six days out of seven	10 kWh/d

Whereas the above actions are easy to implement, these next ones take a bit of planning, determination, and money.

Major action	Possible saving
Eliminate draughts.	5 kWh/d
Double glazing.	10 kWh/d
Improve wall, roof, and floor insulation.	10 kWh/d
Solar hot water panels.	8 kWh/d
Photovoltaic panels.	5 kWh/d
Knock down old building and replace by new.	35 kWh/d
Replace fossil-fuel heating by ground-source or air-source heat pumps	10 kWh/d

Runners-up: simple actions with small savings.

Action	possible saving
Wash laundry at 30°C.	1.1 kWh/d
Stop using a tumble-dryer; use a clothes-line or airing cupboard.	0.5 kWh/d

Notes

226 *"a bit impractical actually"* The full transcript of the interview with Tony Blair (January 9 2007) is here [2ykfgw]. Here are some more quotes from it:
Interviewer: "have you thought of perhaps not flying to Barbados for a holiday and not using all those air miles?"
Tony Blair: "I would frankly, be reluctant to give up my holidays abroad."
Interviewer: "It would send out a clear message though wouldn't it, if we didn't see that great big air journey off to the sunshine? . . . – a holiday closer to home?"
Tony Blair: "Yeah – but I personally think these things are a bit impractical actually to expect people to do that. I think that what we need to do is to look at how you make air travel more energy efficient, how you develop the new fuels that will allow us to burn less energy and emit less. How – for example – in the new frames for the aircraft, they are far more energy efficient.
"I know everyone always – people probably think the Prime Minister shouldn't go on holiday at all, but I think if what we do in this area is set people unrealistic targets, you know if we say to people we're going to cancel all the cheap air travel . . . You know, I'm still waiting for the first politician who's actually running for office who's going to come out and say it – and they're not."

The other quote: "Unless we act now, not some time distant but now, these consequences, disastrous as they are, will be irreversible. So there is nothing more serious, more urgent or more demanding of leadership." is Tony Blair speaking at the launch of the Stern review, 30 October 2006 [2nsvx2]. See also [yxq5xk] for further comment.

EU Wed 23/1/08. Revenues resulting from the ETS will accrue to Member States and should be used to help the EU to adjust to an environment friendly economy by supporting innovation in areas such as renewables, carbon capture and storage and R&D. Part of the revenues should also go towards helping developing countries adapt to climate change. The Commission estimates that the revenues from the auctioning could amount to 50 billion annually by 2020.

What's needed

For long-term reduction of carbon emissions, the single most important global action is to introduce carbon capture technology everywhere where coal is used. This would happen if carbon pollution had an appropriate price.

radical fiscal reform

normative economics

political economics

get rid of taxes that penalise work and saving

get rid of deadweight costs of tax

demand-responsive road transport services are not permitted at present. Running a bus trip because it is needed is against the law.

Society lifestyle change

> Instead of planning wind farms all over Britain, would it not be better government policy to encourage people to use less electricity? Why don't they impose a massive levy on electric toothbrushes, razors, fan heaters, spin driers, and all the gadgets given out this Christmas?
>
> *Janet Street–Porter*

Ideas. 'Let the market handle it. Put a cap on global carbon emissions, and allow emissions credits to be traded.'

Are there actions that a market solution will not promote? A market approach may fail if consumers sometimes choose irrationally, or if the person choosing what to buy doesn't pay all the costs associated with their choice.

Here are some examples.

The admission barrier

Imagine that carbon taxes are sufficiently high that that a new super-duper low-carbon gizmo would cost 5% less than its long-standing high-carbon rival, the Dino-gizmo, *if* it were mass-produced in the same quantities. Thanks to clever technology, the Eco-gizmo's carbon emissions are a fantastic 90% lower than the Dino-gizmo's. It's clear that it would be good for society if everyone bought Eco-gizmos now. But at the moment, sales of the new Eco-gizmo are low, so the per-unit economic costs are higher than the Dino-gizmo's. Only a few tree-huggers and lab coats will buy the Eco-Gizmo, and Eco-Gizmo Inc. will quite likely go out of business.

Perhaps government interventions are necessary to oil the transition and give innovation a chance. Support for research and development? Tax-incentives favouring the new product (like the tax-incentives that oiled the transition from leaded to unleaded petrol)?

Small cost differences

Figure 28.3. Hard to believe... presumably ads like this influence people to buy planet-wreckers, believing that their choice of vehicle will do something for their hormone problem.

Imagine that Eco-Gizmo Inc. makes it from tadpole to frog, and that carbon taxes are sufficiently high that that a new super-duper low-carbon gizmo indeed costs 5% less than its long-standing high-carbon rival from Dino-appliances, Inc. Surely the carbon taxes will now do their job, and all consumers will buy the low-carbon gizmo? Ha. First, many consumers don't care too much about a 5% price differential. Second, if they feel at all threatened by the Eco-gizmo, Dino-appliances, Inc. will relaunch their Dino-gizmo, emphasizing that it's more patriotic, announcing that it's now available in green, and showing cool people sticking with the old faithful Dino-gizmo. "Real men buy Dino-gizmos."

If this doesn't work, Dino will issue press-releases saying scientists haven't ruled out the possibility that long-term use of the new low-carbon gizmo might cause cancer, highlighting the case of an old lady who was tripped up by an Eco-gizmo, or suggesting that Eco-gizmos harm the lesser spotted fruit bat. Fear, Uncertainty, Doubt. As a back-up plan, Dino-appliances could always buy up the Eco-gizmo company. The winning product will have nothing to do with energy saving if the economic incentive to the consumer is only 5%.

Government solutions? Perhaps *extra* carbon taxes and energy taxes should be applied to consumer goods? Critics might worry that such tinkering with the market might lead to sub-optimal products succeeding. Perhaps government should simply ban the sales of the Dino-gizmo (just as government banned sales of leaded-petrol cars)?

Larry and Tina

Imagine that Larry the landlord rents out a flat to Tina the tenant. Larry is responsible for maintaining the flat and providing the appliances in it, and Tina pays the monthly heating and electricity bills. Here's the problem: Larry feels no incentive to invest in modifications to the flat that would reduce Tina's bills. He could install more-efficient lightbulbs, and plug in a more economical fridge; these eco-friendly appliances would pay back their extra up-front cost over their long life; but it's Tina who would benefit, not Larry. Similarly, Larry feels little incentive to improve the flat's insulation or install double-glazing, especially when he takes into account the risk that Tina's boyfriend Wayne might smash one of the windows when drunk. In principle, in a perfect market, Larry and Tina would both make the 'right' decisions: Larry would install all the energy-saving features, and would charge Tina a slightly higher monthly rent; Tina would recognize that the modern and well-appointed flat would be cheaper to live in and thus be happy to pay; Larry would demand an increased deposit in case of breakage of the expensive new windows; and Tina would respond rationally and banish Wayne. However, I don't think that Larry and Tina can ever deliver a perfect market. Tina is poor, so has difficulty paying large deposits. Larry strongly wishes to rent out the flat, so Tina mistrusts his assurances about the property's low energy bills, suspecting Larry of exaggeration.

It seems to me that some sort of intervention is required, to get Larry and Tina to do the right thing – for example, government could legislate a huge tax on inefficient lightbulbs; they could ban from sale all fridges that do not meet economy benchmarks; they could require all flats to meet high standards of insulation; or they could introduce a system of mandatory independent flat assessment, so that Tina could read about the flat's energy profile before renting.

Acting as if the only cost of car-driving is the petrol. Not factoring in road tax, parking charges, insurance, maintenance, and depreciation of the car.

Buying a car in a way that ignores the lifetime emissions associated with the car.

Company car. Car provided by employer.

Other society resources that are not influenced by markets

The free market isn't responsible for building roads, dedicated bus lanes, car parks, or cycle paths. But road-building and the provision of car parks and cycle paths have a significant impact on people's transport choices. Local and national governments are responsible for the crucial decisions after which energy taxes will have an effect.

Similarly, planning laws, which determine *where* homes and workplaces may be created and *how densely* houses may be packed into land have an overwhelming influence on people's future travelling behaviour. If a new town is created that has no rail station, it is unlikely that the residents of that town will make long-distance journeys by rail. If housing and workplaces are more than a few miles apart, many people will insist that they have no choice but to drive to work.

Things that last 100 years

Most investors have a ten-year horizon: they want to get their money back in ten years, with interest. They thus feel little incentive to make things whose value persists for fifty or one hundred years.

Other topics

Waste incineration

Energy tax

Ensure energy use in production of goods is kept track of by some mechanism. Easiest to just use the financial market and tax energy at source.

Might be more educational to have energy consumption tracked (like sales tax, value-added-tax) and added on at the shop.

[Give energy credits to everyone on a per-capita basis, *i.e.* a universal wage.]

Recycled materials need to be promoted. Energy tax would help.

Carbon tax

The Economist recommends a carbon tax as the primary mechanism for government support of clean energy sources. 'Nuclear power's new age', The Economist, September 8th 2007.

The Conservative Party's Quality of Life Policy Group also recommends increasing environmental taxes and reducing other taxes. – "a shift from *pay as earn* to *pay as you burn*."

"Green taxes and emissions trading need not raise the overall tax burden. The principle of environmental tax reform (ETR) – whereby the revenue base is shifted away from taxes on work towards taxes on carbon and other pollutants – is a logical progression of fiscal policy. Like the market for individual products, the current tax system harks back to a time when environmental costs were not recognised. Attaching a price to environmental damage opens a door to reducing taxes on employment of capital."

"new green taxes should be replacement taxes," "shifting the tax base from 'goods' such as employment and capital, to 'bads' like pollution."

" We cannot delay while every country uses another as an excuse not to take action."

The Royal Commission also recommended that the UK should introduce a carbon tax. "It should apply upstream and cover all sectors."

Climate bonds: `http://www.igreens.org.uk/climate_stability_bonds.htm`

'Upstream cap and trade': `http://kyoto2.org`

Get rid of VAT

Either get rid of value-added tax altogether, or at least get rid of it for green services such as repair work. At present it's much cheaper to buy a new microwave, DVD player, or vacuum cleaner than to get a malfunctioning one fixed.

Committing to a low-carbon economy "will involve transcending party politics and building a cross-party consensus on a radical but realistic long-term framework for emissions reductions. In the UK, all three main political parties have already committed themselves to cutting emissions by at least 60 per cent by 2050, and a draft Climate Change Bill, the first of its kind in the world, has cross-party support."

"The scale and depth of the change which will be needed will not be easy to achieve. It will require true leadership from government."

Tax jet fuel like other fuel, or more

Building regulations

Figure 28.4. 'Green Dragon' – a human-powered roller coaster in North Wales. Riders walk up the hill twice and descend twice: the first descent is on a sedate inclined-plane railway which uses the riders' weight to bring the main roller coaster to the top; walking up again, they are rewarded with their second, high-speed, high-g ride.

Mandate energy-efficient construction; integrated solar panels in south-facing walls, roofs, and windows; solar electricity if economical; solar water heating otherwise; electricity-powered ground-source heat pumps instead of gas-powered central heating; thick massive walls to reduce the need for summer air-conditioning. Fit electric heat pumps to buildings. (Using air as the external heat source.)

Somehow, the consumer needs to perceive the energy content of their choices

For example, holiday-makers need to feel an incentive not to roar around on jet-skis – what horrible paradise-disturbing stink-tubs! – and instead get their thrills from, say, hang-gliding, mountain-climbing, cycling, or sailing.

(Need evidence that recreation consumes a lot of energy before this rant.)

Car production regulations

Once an inefficient thing is bought, it's too late. It's essential that inefficient things should not be manufactured in the first place; or, that the consumer, when buying, should feel influenced not to buy inefficient things.

Big up-front tax on cars whose efficiency is poor. (Better to have an up-front tax as well as big fuel tax because (a) a big fuel tax is only linear; we can get a bigger disincentive for gas-guzzlers by making the up-front tax steeper than linear. (b) People pay more attention to an up-front tax; it will influence their purchase decision much more.)

Road planning to help cycling

Figure 28.5 shows a roundabout in Enschede, Netherlands. There are two circles: the one for cars lies inside the one for bikes, with a comfortable car's length separating the two. The priority rules are the same as those of a British roundabout, except that cars exiting the central roundabout must give way to circulating cyclists (just as British cars give way to pedestrians on zebra crossings). Everyone drives calmly and there appear to be no problems.

UK street design guide: `http://www.manualforstreets.org.uk/` This guide encourages designing streets to make 20 miles/h the natural speed.

Packaging

Right to return packaging to vendor, who must then recycle it. – Not because the packaging itself has much embodied energy, but rather because of the extra transport costs for moving around lavishly packaged stuff.

Regulations making a difference

An airline has been flying an empty passenger plane in order to keep hold of its landing slots. "British Mediterranean Airways round-trip flights between London's Heathrow and Cardiff International have been taking off six days a week since October." The company wanted to keep the slot so that it could use them for profit in the Summer [25e5rv].

Information to the user

http://news.bbc.co.uk/1/hi/sci/tech/6550361.stm

Politics, legislation

Economic incentives are not enough to bring about lifestyle change. Consumers aren't aware of all the costs – and even if they were aware of the total cost, they wouldn't respond to it. Mr. Flaccid, who's suceptible to 'hard' advertisements like the the one on p. 230, doesn't choose a planet-wrecking car on economic grounds.

Indeed many brands names are *reassuringly expensive*, and some people (if they have the money) deliberately buy expensive. Consumer choice is not determined solely by price signals. Many consumers care more about image and perception.

Criticism of actions so far

From the House of Lords Science and Technology Committee "Renewable Energy: Practicalities" (4th report of session 2003–04).

"The Government are implementing their renewables programme by means of the Renewables Obligation (RO). This sets rising "targets" for the amount of renewable electricity to be generated each year (currently reaching as far ahead as 2015), and forms the basis for a complex and subtle market-driven set of incentives to generators. The incentive in any one year is high until around 70 percent of the Government's "target" for renewables generation in that year has been attained, and then declines rapidly. We believe that this mechanism will in fact ensure that the Government's targets are not attained, even though offshore wind enjoys additional capital grants.

The Renewables Obligation, although described as "technology-blind" discriminates strongly in favour of generation technologies that can be brought to market within the next year or so, because the uncertainty surrounding the future value of the RO incentives means that investors look for an early return on their investment. Only wind can produce this early return. If the Government wish to achieve their renewable target of 10 percent by 2010, or to diversify the national renewable portfolio, and there are good reasons to do so, the RO will need modification in the near future.

We found almost no one outside Government who believed that the White Paper targets were likely to be achieved. This was partly for practical reasons – planning consents, availability of labour and equipment and so on – and partly as a direct consequence of the RO method of support. We judge that by 2010 the United Kingdom may have achieved 6-7 percent renewable generation.

We deplore the minimal amounts that the Government have committed to renewable-energy-related R&D (£12.2 million in 2002-03). ... If resources other than wind are to be exploited in the United Kingdom this has to change.

We could not avoid the conclusion that the Government are not taking energy problems sufficiently seriously."

Ensuring continuity of supply: "We were told simply that market forces would solve the problem. We are not convinced and urge the Government to give these matters further consideration."

> *The absence of scientific understanding often leads to superficial decision-making. The 2003 energy white paper was a good example of that. I would not like publicly to call it amateurish but it did not tackle the problem in a realistic way.*
>
> Sir David King, former Chief Scientist

> *Our windswept island has more than enough wind, wave and tidal power potential to meet all of our energy needs many times over.*
>
> greenpeace

> *serving on the government's Renewables Advisory Board ... felt like watching several dozen episodes of Yes Minister in slow motion. I do not think this government has ever been serious about renewables*
>
> Jeremy Leggett, founder of Solarcentury

From OFGEM

In "Cutting the green customer confusion – next steps" (Appendices) from `www.ofgem.gov.uk`.

"There is mounting evidence that while the RO has been effective at *reducing carbon emissions* that other schemes or policies could have delivered the same (or greater) emissions reductions at lower costs. In

2006/07, the cost of carbon abatement through the RO was in the range £65-140/tCO2 depending on the fuel that is assumed to be displaced. In contrast the cost of abatement in the UK Emissions Trading Scheme is around £18/tCO2.

"There is also increasing evidence that there are more efficient and effective policy tools which can be used to encourage the *deployment of new renewables*. The European Commission compared the costs and associated effectiveness of "feed-in tariffs" to support renewables implemented in Europe with corresponding quota schemes, such as the RO. The analysis showed that the RO was the most expensive and least efficient method of support. However, it is also clear that the RO scheme's effectiveness has been hampered by the delays in planning for wind farms and transmission lines."

Incentives that are not working

Imagine that someone has got a lot of vegetable oil and wants to make it into fuel for vehicles. They can send it to a special biofuel refinery. They could also simply feed the vegetable oil straight into standard oil refineries. Under current British regulations, they'll get green credits only if the fuel is processed in the special biofuel refinery, not in a standard oil refinery. If both methods lead to the same reduction in fossil-fuel burning, it seems perverse to have unequal incentives.

"We should invest in artificial intelligence and nanotechnology; come 2080, nanorobots will be able to solve the CO_2 problem by sucking CO_2 out of thin air."

False. This is a really bad idea because, as explained in chapter **??** (p.**??**), sucking CO_2 out of thin air has an inescapable energy cost. The energy cost of capturing CO_2 and concentrating it for storage somewhere is in fact similar to the energy released by burning the fossil fuel in the first place.

Chargers

In 2005, the BBC news 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.' The last of these actions would save you £25, they advised.

At 10p per unit, that's 250 units per year. Or 0.7 units per day. Or 30W. That's almost the same as leaving a 40W lightbulb on? Clearly not true? My charger doesn't emit the same heat as a bulb!

[Actual mobile phone chargers are mostly less than 1 W.]

Same message in 2006:

`http://news.bbc.co.uk/1/low/uk/6075794.stm`

Britain tops energy waste league Standby button (BBC) British people are Europe's worst energy wasters, with bad habits such as leaving appliances on stand-by likely to waste £11bn by 2010, a study claims.

WASTEFUL HABITS

- Leaving devices on standby
- Leaving chargers plugged in
- Forgetting to turn off lights

The myth that won't die

The BBC is still banging the phone-charger drum in 2007: "turn off your TV, unplug your mobile charger and switch off lights when you leave a room" (Monday, 14 May 2007, `http://news.bbc.co.uk/1/hi/uk/6653687.stm`).

And on 6th June 2007, the Mayor of London launched 'DIY planet repairs', a public information campaign calling on citizens to 'unplug, switch off and turn down'. Under the heading 'Unplug', we are advised

> 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.

Let's think about these numbers. London's population is about 7 million. So what this poster is really saying is that if you unplug your charger, you're saving

$$\frac{31\,000}{7\,\text{million}} = 0.004\,\text{tonnes CO}_2\text{ per year per person.}$$

We should compare this quantity with the typical CO_2 pollution per person, which is about 10 tonnes per year. So what the Mayor is recommending is:

> 'Do your bit! Make a difference! Unplug the evil phone chargers, and reduce your CO_2 pollution by less than one twentieth of one per cent!'

The total of all the Mayor's recommendations, incidentally, comes to 1.6 million tonnes of CO_2 per year. [(Wash Low) 98,000 tonnes of CO_2 per year. (Standby Switch Off) 465,000 tonnes. (Switch Off Your Lights) 93,000 tonnes. (Unplug) 31,000 tonnes. (Turn down thermostat one degree) 837,000 tonnes. (Only Boil What You Need when making tea) 62,000 tonnes.] Which is 0.23 tonnes per year per Londoner. A 2% reduction. Go for it, London!

On 4th July 2007, the BBC continued to promote the 'phone chargers are huge' myth: their article reports that the newest mobile phone chargers waste much less energy than their older cousins, but nevertheless, according to an expert 'a huge amount of energy was still being

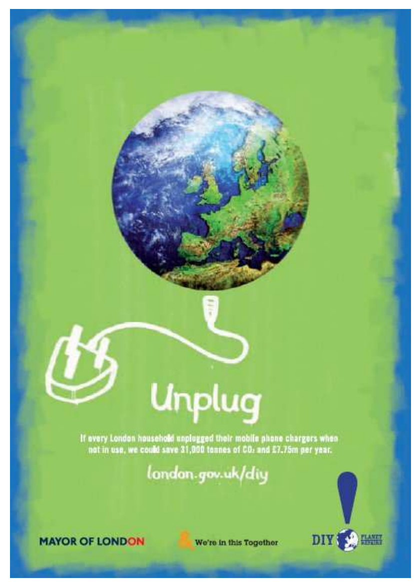


Figure 28.6. Advertisement from the 'DIY planet repairs' campaign. The text reads '**Unplug**. If every London household unplugged their mobile phone chargers when not in use, we could save 31,000 tonnes of CO_2 and £7.75m per year'. `london.gov.uk/diy/`

wasted if people were not unplugging their chargers when they were not being used'.[2wegkm]

This is a terrible abuse of the word 'huge'!

Quotes and links

Green with energy

There are many easy ways to reduce the amount of energy you use and cut fuel consumption, writes Hilary Osborne

Monday August 21, 2006

Turn off the lights

And the TV. And your mobile phone charger. These are all quick and easy ways to save energy. According to the Energy Saving Trust, if all UK households turned appliances off rather than putting them on standby it would save the energy produced by two-and-a-half 700 megawatt power stations each year.

Unplugging mobile phone chargers could save consumers £60m a year and cut CO_2 emissions by 250 000 tonnes, the Energy Saving Trust says.

60m pounds per UK is 0.03 kWh per day each. Which is 2 hundredths of 1 percent.

Leaving the phone and charger plugged in

"If 10 percent of the world's cell phone owners [unplugged their phones from their chargers once they were charged] , it would reduce energy consumption by an amount equivalent to that used by 60,000 European homes per year."

"Who knew such a little thing could make such a difference? Looks like I'm going to stop leaving my phone plugged in all night." – Gina Trapani

More quotes

"**Unplug your phone charger when not in use**

"In the UK, 95% of the energy used by mobile phone chargers is wasted. Only 5% is actually used to charge the phone and the rest is wasted by leaving the charger plugged in. Remember to unplug your charger when it's not in use. It takes a forest with an area equivalent to 500 football pitches to absorb all the CO2 produced by chargers that are left plugged in."

ECO-TIP: Unplug your cell phone charger

Bartlett Energy Heroes' Energy Saving Tips Remember to unplug your charger and you'll help make the earth greener.

Hahahahahahaha

'Simple steps to greener lifestyles Day-to-day habits damage the Earth – but small changes could go far to help heal it

flicking off that light, unplugging the cell phone charger and using fewer grocery bags.

Your cell phone is charged. You unplug your phone. But why do you leave the charger plugged into the wall?

That convenience is costing you money in energy and may be taking inches off the world's ice caps. Environmental studies estimate that only 5 percent of the power provided by the world's cell phone chargers actually go to charge the batteries. The wasted energy would equal what's needed to power about 60,000 homes in Europe.

Mrs Villiers on phone chargers

From the House of Commons Environmental Audit Committee. 'Keeping the lights on: Nuclear, Renewables and Climate Change' (2006).

Mrs. Theresa Villiers: "It strikes me that we could make a big impact on energy efficiency if we made people's energy consumption much more visible. I wondered whether you had any ideas about how one could change the current structure of metering so, say, when a consumer plugs his mobile phone charger into the wall something pops up visibly and tells him he is spending another five pence for every minute the charger is plugged in."

An excellent idea, making people aware of the energy they are using and the money they are spending! – But Mrs. Villiers's guess of what the displayed expenditure for a phone charger might be is comically far from the truth. A device that costs five pence per minute would have a power consumption of roughly 0.5 kWh per minute, which is 30 000 W – one hundred thousand times greater than the true power of a Nokia phone charger (0.3 W).

I have an urge to include a chapter lampooning suggestions for solving the energy crisis.

Perhaps I can include a few genuine suggestions along with Craig Brown's parody ('Way of the World', Daily Telegraph, Saturday April 8, 2006).

Replace lightbulbs with parsnips

If everyone replaced their lightbulbs with parsnips, the world would see a 67 per cent drop in energy wastage. Ordinary incandescent bulbs waste 90 per cent of their energy as heat, whereas parsnips waste none at all.

Conservative opponents of the scheme, and pressure groups financed by the multinationals, object that parsnips provide little or no light and are hard to screw into the existing sockets, but Deborah Barking from the Campaign for Better Parsnip Bulbs, maintains that this is pure myth.

"My family and I have replaced all our lightbulbs with parsnips," she says. "It couldn't have been easier and we're delighted with the result." She also has a handy tip for those who wish to pursue night-time reading when the moon is low. "We sometimes find it useful to supplement our parsnips with braille," she enthuses.

Turn over pages two at a time.

If you just read every other page of a 600-page novel, you can easily keep up with the plot while saving enough energy to light a small larder for anything up to half an hour.

Ideas that I should find people advocating: magnetic levitation railways – stupid because at high speed most energy is going into creating swirling turbulent air in the wake of the train.

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Summary of options

[Draft.]

Are we about to run out of fossil fuels? No. There are plenty of fossil fuels – especially coal – for the next generation or two. Enough to do serious damage to the climate.

Getting off fossil fuels, quick, is essential to reduce the risk of catastrophic damage. And with coal being so cheap and plentiful, getting off fossil fuels is going to be politically difficult.

One way to carry on living on coal is to burn it in power stations that do carbon capture and storage.

But don't forget that more than half of our fossil fuels are currently used in individual buildings and cars, where carbon capture doesn't seem to be an option.

Current nuclear technology and coal are not 'sustainable' for thousands of years; they are only stop-gaps with a life of at best one or two hundred years. For a thousand-year sustainable solution we would need to develop new nuclear technologies, such as more-efficient thorium reactors, or uranium extraction from sea water – as sketched in chapter 22.

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The last thing we should talk about

Part III

Technical chapters

A

Cars II

We estimated that a car driver who drives 100 km uses about 80 kWh of energy.

Where does this energy go? How does it scale with properties of the car? Could we make cars that are 100 times more efficient?

Let's make a simple cartoon of car-driving. Assume the driver accelerates rapidly up to a cruising speed v, and maintains that speed for a distance d, the distance between traffic lights or stop signs or congestion events. At this point, he slams on the brakes and turns all his kinetic energy into heat in the brakes (his vehicle doesn't have regenerative braking). Once he's able to move again, he accelerates back up to his cruising speed, v. This acceleration gives the car kinetic energy; braking throws that kinetic energy away.

Energy goes not only into the brakes. While the car is moving, it makes air swirl around. A car leaves behind it a tube of swirling air, moving at characteristic speed similar to v. Which of these two forms of energy is the bigger: kinetic energy of swirling air, or heat in the brakes? Let's work it out.

- The car speeds up and slows down once in each duration d/v. The rate at which energy pours into the brakes is

$$\frac{\text{kinetic energy}}{\text{time between braking events}} = \frac{\frac{1}{2}m_c v^2}{d/v} = \frac{\frac{1}{2}m_c v^3}{d}, \tag{A.1}$$

  where m_c is the mass of the car.

- The tube of air created in a time t has a volume Avt, where A is the cross-sectional area of the tube, which is the similar to the area of the front view of the car. [For a streamlined car, A is

Figure A.1. A Peugot 206 has a drag coefficient of 0.33. Photo by Christopher Batt.

The key formula for most of the calculations in this book is:

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

For example, a car of mass $m = 1000\,\text{kg}$ moving at 100 km per hour or $v = 28\,\text{m/s}$ has an energy of

$$\frac{1}{2}mv^2 = 390\,000\,\text{J} \simeq 0.1\,\text{kWh}.$$

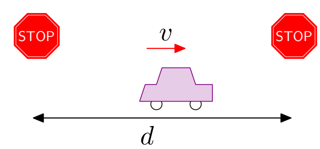


Figure A.3. Our cartoon: a car moves at speed v between stops separated by a distance d.

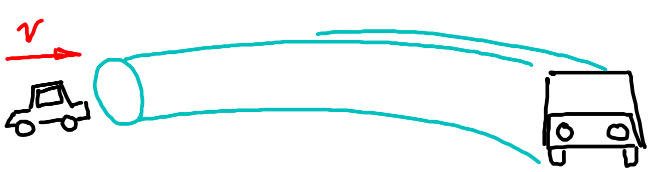


Figure A.4. A car moving at speed v creates behind it a tube of swirling air; the area of the tube is similar to the frontal area of the car, and the speed at which air in the tube swirls is roughly v.

usually a little smaller than the frontal area A_{car}, and the ratio c_{d} of the tube's effective cross sectional area to the car area is called the drag coefficient c_{d}. Throughout the following equations, A means the effective area of the car, $c_{\text{d}}A_{\text{car}}$.] The tube has mass $m_{\text{air}} = \rho A v t$ and swirls at speed v, so its kinetic energy is

$$\frac{1}{2}m_{\text{air}}v^2 = \frac{1}{2}\rho A v t\, v^2,$$

and the rate of generation of kinetic energy in swirling air is

$$\frac{\frac{1}{2}\rho A v t v^2}{t} = \frac{1}{2}\rho A v^3.$$

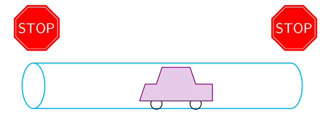


Figure A.5. To know whether energy consumption is braking-dominated or air-swirling-dominated, we compare the mass of the car with the mass of the tube of air between stop-signs.

Figure A.6. Power consumed by a car is proportional to its cross-sectional area, during motorway driving, and to its mass, during town driving. Guess which gets better mileage – the VW on the left, or the spaceship?

So the total rate of energy production by the car is

$$\begin{array}{rccc} & \text{power going into brakes} & + & \text{power going into swirling air} \\ = & \frac{1}{2}m_{\text{c}}v^3/d & + & \frac{1}{2}\rho A v^3. \end{array}$$

Both forms of energy dissipation scale as v^3. So this cartoon predicts that a driver who halves his speed v reduces his power consumption by a factor of 8. If he ends up driving the same total distance, his journey will take twice as long, and the total energy consumed by his journey will have dropped by a factor of four.

Which of the two forms of energy dissipation – brakes or air-swirling – is the bigger? It depends on the ratio of

$$(m_{\text{c}}/d)\,/(\rho A)\ .$$

If this ratio is much bigger than 1, then more power is going into brakes; if it is smaller, more power is going into swirling air. Rearranging this ratio, it is bigger than 1 if

$$m_{\text{c}} > \rho A d.$$

Now, Ad is the volume of the tube of air swept out from one stop sign to the next. And ρAd is the mass of that tube of air. So we have a very simple situation: energy dissipation is dominated by kinetic-energy-being-dumped-into-the-brakes if the mass of the car is *bigger* than the mass of the tube of air from one stop sign to the next; and energy dissipation is dominated by making-air-swirl if the mass of the car is *smaller*.

Let's work out the special distance d^* between stop signs, below which the dissipation is braking-dominated and above which it is air-swirling dominated (also known as drag-dominated). If the area of the car is

$$A_{\text{car}} = 2\,\text{m} \times 1.5\,\text{m} = 3\,\text{m}^2$$

and the drag coefficient is $c_{\rm d} = 1/3$ and its mass is $m_{\rm c} = 10^3\,{\rm kg}$ then the special distance is

$$d^* = \frac{m_{\rm c}}{\rho c_{\rm d} A_{\rm car}} = \frac{10^3\,{\rm kg}}{1.3\,{\rm kg/m^3} \times \frac{1}{3} \times 3\,{\rm m^2}} = 750\,{\rm m}.$$

So 'city-driving' is dominated by kinetic energy and braking if the distance between stops is less than 750 m. Under these conditions, it's a good idea, if you want to save energy,

1. to reduce the mass of your car, and
2. to get a car with regenerative brakes. (Regenerative brakes roughly halve the energy lost in braking.)

[It's also a good idea to drive more slowly.]

When the stops are significantly more than 750 m apart, energy dissipation is drag-dominated. Under these conditions, it doesn't much matter what your car weighs. Energy dissipation will be much the same whether the car contains one person or six. Energy dissipation can be reduced

1. by reducing the car's drag coefficient, or
2. by reducing its cross-sectional area.

[It's also a good idea to drive more slowly.]

The actual energy consumption of the car will be the energy dissipation estimated above, cranked up by a factor related to the inefficiency of the engine and the transmission. Typical petrol engines are about 25% efficient, so of the chemical energy that a car guzzles, three quarters is wasted in making the car's engine and radiator hot, and just one quarter goes into 'useful' energy:

$$\text{total power of car} \simeq 4\left[\frac{1}{2} m_{\rm c} v^3/d + \frac{1}{2}\rho A v^3\right].$$

Let's check this theory of cars by plugging in plausible numbers for motorway driving. Let $v = 70\,\text{miles per hour} = 110\,{\rm km/h} = 31\,{\rm m/s}$ and $A = 1\,{\rm m^2}$. The power is estimated to be roughly

$$4 \times \frac{1}{2}\rho A v^3 = 2 \times 1.3\,{\rm kg/m^3} \times 1\,{\rm m^2} \times (31\,{\rm m/s})^3 = 80\,{\rm kW}.$$

If you drive the car at this speed for one hour every day, then you travel 110 km and use 80 kWh of energy per day. If you drove at half this speed for two hours per day instead, you would travel the same distance and use up 20 kWh of energy. This simple theory seems consistent with the mileage figures for cars quoted in chapter 2. Moreover, the theory gives insight into how the energy consumed by your car could be reduced. The theory has a couple of flaws which we'll explore in a moment.

Energy-per-distance	
Car at 110 km/h	↔ 80 kWh/(100 km)
Bicycle at 21 km/h	↔ 2.4 kWh/(100 km)

Fast trains compared at 200 km/h (125mph)	
ICE	2.9 kWh/100 seat-km
Transrapid	2.2 kWh/100 seat-km

Planes at 900 km/h	
A380	27 kWh/100 seat-km

Table A.7. Facts worth remembering: car energy consumption.

Could we make a new car that consumes 100 times less energy and still goes at 70 mph? **No**. Not if the car has the same shape. The energy is going mainly into making air swirl. Changing the materials the car is made from makes no difference to that. A miraculous improvement to the engine could perhaps boost its efficiency from 25% to 50%. But the energy consumption of a car is still going to be roughly 40 kWh per 100 km.

Electric vehicles have some wins: while the weight of the energy store, per kWh stored, is bigger than that of petrol, the weight of an electric engine is smaller. **Storage:** Energy content of petrol: 12.5 kWh/kg of which roughly 30% can be turned into useful work, so the useful energy density is 3.7 kWh/kg. Lithium-ion polymer rechargeable cells: LiPo cell storage capacity is 0.15 kWh/kg (1/25 of net petrol) and these cells can deliver their energy at a maximum rate of 1000 W per kg.

Engine power: A 4-stroke petrol aero-engine power rating delivers roughly 0.75 kW/kg. The best electric motors have an efficiency of 90% and a power rating of 6 kW/kg. A 75 kW electric motor saves 85 kg in weight.

Drag coefficients	
Cars	
Honda Insight	0.25
Prius	0.26
Renault 25	0.28
Honda Civic (2006)	0.31
VW Polo GTi	0.32
Peugeot 206	0.33
Ford Sierra	0.34
Audi TT	0.35
Honda Civic (2001)	0.36
Citroën 2CV	0.51
Cyclist	0.9
Long-distance coach	0.425
Planes	
Cessna	0.027
Learjet	0.022
Boeing 747	0.031

Drag-areas (m^2)	
Land Rover Discovery	1.6
Volvo 740	0.81
Typical car	**0.8**
Honda Civic	0.68
VW Polo GTi	0.65
Honda Insight	0.47

Table A.8. Drag coefficients and drag areas.

Bicycles and the scaling trick

Here's a fun question: What's the energy consumption of a bicycle, in kWh per 100 kilometre? Pushing yourself along on a bicycle requires energy for the same reason as a car: you're making air swirl around. Now, we could do all the calculations from scratch, replacing car-numbers by bike-numbers. But there's a simple trick we can use to get the answer for the bike from the answer for the car. The energy consumed by a car, per distance travelled, is the power-consumption associated with air-swirling,

$$4 \times \frac{1}{2}\rho A v^3,$$

divided by the speed, v; that is,

$$\text{energy per distance } = 4 \times \frac{1}{2}\rho A v^2.$$

The factor of 4 came from engine inefficiency; ρ is the density of air; the area A is the effective frontal area of a car; and v is its speed.

Now, we can compare a bicycle with a car by dividing $4 \times \frac{1}{2}\rho A v^2$ for the bicycle by $4 \times \frac{1}{2}\rho A v^2$ for the car. All the fractions and ρs cancel, if we're happy assuming that the efficiency of the carbon-powered bicyclist's engine is similar to the efficiency of the carbon-powered car engine. The ratio is:

$$\frac{\text{energy per distance of bike}}{\text{energy per distance of car}} = \frac{c_{\rm d}^{\rm bike} A_{\rm bike} v_{\rm bike}^2}{c_{\rm d}^{\rm car} A_{\rm car} v_{\rm car}^2}.$$

The trick we are using is called 'scaling'. If we know how energy consumption scales with speed and area, then we can predict energy consumption of objects with completely different speeds and areas. Specifically, let's assume that the area ratio is

$$\frac{A_{\text{bike}}}{A_{\text{car}}} = \frac{1}{4}.$$

(Four cyclists can sit shoulder to shoulder in the width of one car.) I'll assume the bike is not very well stream-lined:

$$\frac{c_{\text{d}}^{\text{bike}}}{c_{\text{d}}^{\text{car}}} = \frac{1}{1/3}$$

And let's assume the speed of the bike is 21 km/h (13 miles per hour), so

$$\frac{v_{\text{bike}}}{v_{\text{car}}} = \frac{1}{5}.$$

Then

$$\begin{aligned}\frac{\text{energy-per-distance of bike}}{\text{energy-per-distance of car}} &= \left(\frac{c_{\text{d}}^{\text{bike}}}{c_{\text{d}}^{\text{car}}}\frac{A_{\text{bike}}}{A_{\text{car}}}\right)\left(\frac{v_{\text{bike}}}{v_{\text{car}}}\right)^2 \\ &= \left(\frac{3}{4}\right) \times \left(\frac{1}{5}\right)^2 \\ &= \frac{3}{100}\end{aligned}$$

So a cyclist at 21 km/h consumes about 30 times less energy per kilometre than a lone car-driver on the motorway: about **2.4 kWh per 100 km**.

If you would like a vehicle whose fuel efficiency is 100 times better than a car's, it's simple: ride a well-streamlined bike.

Queries

What about rolling resistance?

Some things we've completely ignored so far are the energy consumed in the tyres and bearings of the car, the energy that goes into the noise of wheels against asphalt, the energy that goes into grinding rubber off the tyres, and the energy that vehicles put into shaking the ground. Collectively, these forms of energy consumption are called *rolling resistance*. The standard model asserts that the force of rolling resistance is simply proportional to the weight of the vehicle, independent of the speed. The constant of proportionality is called the coefficient of rolling resistance, C_{rr}. Table A.9 gives some typical values.

The coefficient of rolling resistance for a car is about 0.01. The effect of rolling resistance is just like perpetually driving up a hill with a slope of one in a hundred. If set moving, a car will roll at steady speed down a hill with a slope of one in a hundred. So rolling friction is about 100 newtons per ton, independent of speed. You can confirm this by pushing a typical one-ton car along a flat road. Once you've got it

wheel	C_{rr}
train (steel on steel)	0.002
bicycle tire	0.005
truck rubber tyres	0.007
car rubber tyres	0.010

Table A.9. Rolling resistance – The rolling resistance is equal to the weight multiplied by the coefficient of rolling resistance, C_{rr}. The rolling resistance includes the force due to wheel flex, friction losses in the wheel bearings, shaking and vibration of both the roadbed and the vehicle (including energy absorbed by the vehicle's shock absorbers), and sliding of the wheels on the road or rail. The coefficient varies with the quality of the road, with the material the wheel is made from, and with temperature. The numbers given here assume smooth roads. [2bhu35]

moving, you'll find you can keep it moving with one hand. So at a speed of 31 m/s (70 mph), the power required to overcome rolling resistance, for a one-ton vehicle, is

$$(100\,\text{newtons}) \times (31\,\text{m/s}) = 3100\,\text{W};$$

which, allowing a factor of four for engine inefficiency, requires 12 kW of engine power; whereas the power required to overcome drag was estimated on p.246 to be 80 kW. So, at high speed, about 15% of the power is required for rolling resistance.

Figure A.10 shows the theory of fuel consumption (energy per unit distance) as a function of steady speed, when we add together the formulae for air resistance and rolling resistance.

The speed at which a car's rolling resistance is equal to air resistance is given by

$$C_{rr} m_c g = \frac{1}{2} \rho c_d A v^2,$$

that is,

$$v = \sqrt{2 \frac{C_{rr} m_c g}{\rho c_d A}} = 7\,\text{m/s} = 16\,\text{miles per hour}$$

At 32 mph, one fifth of the power is required for rolling resistance. At 48 mph, one tenth.

For an eight-carriage high-speed train ($m = 400\,000$ kg, $A = 11\,\text{m}^2$), the speed above which rolling resistance is less than air resistance is

$$v = 33\,\text{m/s} = 74\,\text{miles per hour}.$$

For a single-carriage train ($m = 50\,000$ kg, $A = 11\,\text{m}^2$) , the speed above which rolling resistance is less than air resistance is

$$v = 12\,\text{m/s} = 26\,\text{miles per hour}.$$

For a bike, *...move bike here?*

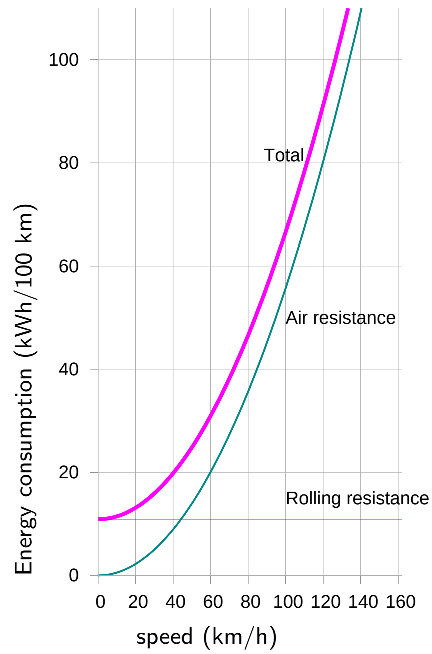
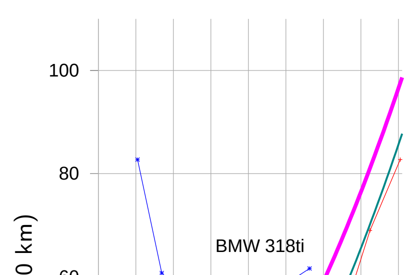


Figure A.10. Simple theory of car fuel consumption (energy per distance). Horizontal axis is speed in km/h. Vertical axis is fuel consumption in kWh per 100 km. Assuming that the car's engine uses energy with an efficiency of 0.25, whatever the speed; that the drag-area of the car is $1\,\text{m}^2$; that the car's mass is 1000 kg, and that $C_{rr} = 0.01$, the air resistance has an energy demand that grows as the square of the speed, and the rolling resistance makes a constant energy demand, whatever the speed.

Dependence of power on speed

When I say that halving your driving speed should reduce fuel consumption (in miles per gallon) by a factor of *four*, some people feel sceptical. They have a point: most cars' engines have an optimum revolution rate, and the choice of gears of the car determines a range of speeds at which the optimum engine efficiency can be delivered. My tacit assumption



that the engine's efficiency is the same at all speeds and all loads led to the conclusion that it's always good (in terms of miles per gallon) to travel slower; but if the engine's efficiency drops off at low speeds, then the most fuel-efficient speed might be large. For a BMW 318ti, for example, the optimum speed is about 60 km/h (figure A.11). If my suggested experiment of halving the car's speed takes the car out of this designed range of speeds, the consumption might not fall by as much as four. But if society were to decide that car speeds should be reduced, there is nothing to stop engines and gears being redesigned so that the peak engine efficiency was found at the right speed. As further evidence for the assertion that the power a car requires really does go as the cube of speed, figure A.12 shows the engine power versus the top speeds of a range of cars. The line shows the relationship 'power proportional to v^3'.

What about the energy-cost of making the car?

Good question! The creation of steel uses about 6000 kWh per tonne of steel. The energy cost of making the raw materials for a one tonne car is thus equivalent to about 3000 km of driving; an appreciable cost, but probably only 1% of the lifetime energy-cost of the car's fuel.

Electric cars: is range a problem?

People often say that the range of electric cars is not big enough. Electric car advocates say 'no problem, we can just put in more batteries' – and that's true, but we need to work out what effect the extra batteries have on the energy consumption. The answer depends sensitively on what energy density we assume the batteries deliver: for an energy density of 40 Wh/kg (typical of lead-acid batteries), we'll see that it's hard to push the range beyond 200 or 300 km; but for an energy density of 120 Wh/kg (typical of various lithium-based batteries), a range of 500 km is easily achievable.

So, let's work out what our cartoon says about the range of an electric car. Let's assume that the mass of the car and occupants is 740 kg, *without* any batteries. In due course we'll add in 100 kg, 200 kg, 500 kg, or perhaps 1000 kg of batteries. Let's assume a typical speed of 50 km/h (30 mph); a drag-area of 0.8 m^2; a rolling resistance of 0.01; a distance between stops of 500 m; an engine efficiency of 85%; and that during stops and starts, regenerative braking recovers half of the kinetic energy of the car. Charging up the car from the mains is assumed to be 85% efficient. Figure A.13 shows the transport cost of the car versus its range, as we vary the amount of battery on board. The upper curve shows the result for an energy density of 40 Wh/kg. The range is limited by a wall at about 500 km. To get close to this maximum range, we have to take along comically large batteries: for a range of 400 km, for example, 2000 kg of batteries are required, and the transport cost is above 25 kWh

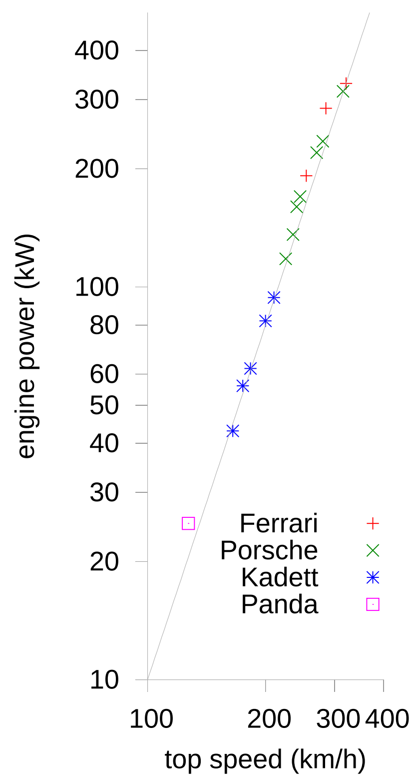


Figure A.12. Powers of cars (kW) versus their top speeds (km/h). The power increases as the third power of the speed. To go twice as fast requires eight times as much engine power. From Tennekes [1997].

per 100 km. If we are content with a range of 180 km, however, we can get by with 500 kg of batteries. Things get much better when we switch to lithium-ion batteries. At an energy density of 120 Wh/kg, electric cars with 500 kg of batteries can easily deliver a range of 500 km. The transport cost is predicted to be about 13 kWh per 100 km.

It thus seems to me that the range problem has been solved by the advent of modern batteries. It would be nice to have even better batteries, but an energy density of 120 Wh per kg is already good enough, as long as we're happy for the batteries to weigh up to 500 kg. In practice I imagine most people would be content to have a range of 300 km, which can be delivered by 250 kg of batteries. If these batteries were divided into ten 25 kg chunks, separately unpluggable, then a car user could keep just four of the ten chunks on board when he's doing regular commuting (100 kg gives a range of 140 km); and collect an extra six chunks from a battery-recharging station when he wants to make longer-range trips. During long-range trips, he would exchange his batteries for a fresh set at a BP battery-exchange station every 300 km or so.

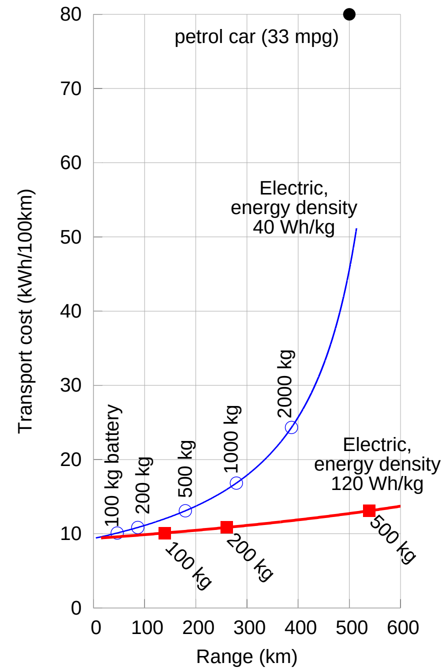


Figure A.13. Theory of electric car range (horizontal axis) and transport cost (vertical axis) as a function of battery mass, for two battery technologies. A car with 500 kg of old batteries, with an energy density of 40 Wh per kg, has a range of 180 km. With the same weight of modern batteries, delivering 120 Wh per kg, an electric car can have a range of more than 500 km. Both cars would have an energy cost of about 13 kWh per 100 km. These numbers allow for a battery charging efficiency of 85%.

Notes

246 *Typical petrol engines are about 25% efficient.* Encarta [6by8x] says "The efficiencies of good modern Otto-cycle engines range between 20 and 25 percent". The petrol engine of a Toyota Prius, famously one of the most efficient car engines, uses the Atkinson cycle instead of the Otto cycle; it has a peak power output of 52 kW and has an efficiency of 34% when delivering 10 kW [348whs]. The most efficient diesel engine in the world is 52%-efficient, but it's not suitable for cars as it weighs 2300 tons. The Wartsila–Sulzer RTA96-C turbocharged two-stroke diesel engine is intended for container ships and has an power output of 80 MW.

249 Figure A.11 Prius data from B.Z. Wilson `http://home.hiwaay.net/~bzwilson/prius/`. BMW data from Phil C. Stuart. `http://www.randomuseless.info/318ti/economy.html`.

246 *Regenerative brakes roughly halve the energy lost in braking.* Source: E4tech [2007].

Figure A.14. The Wartsila-Sulzer RTA96-C 14-cylinder engine. 27 m

B

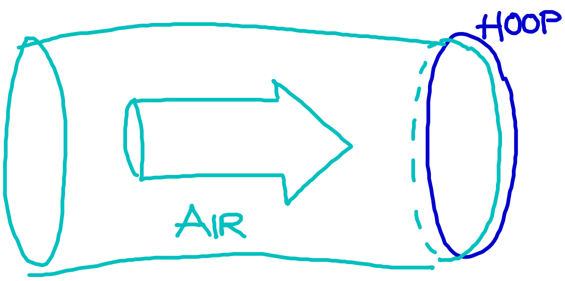
Wind II

The physics of wind power

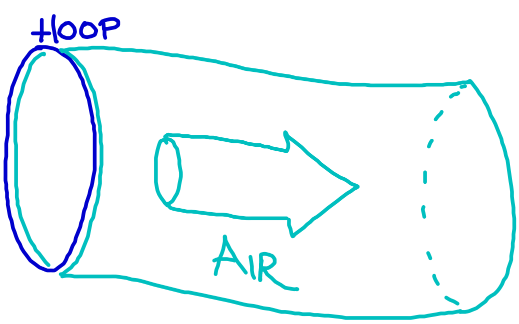
To estimate the energy available from wind, we'll again need one formula: if an object with mass m moves at speed v then its kinetic energy is

$$\frac{1}{2}mv^2.$$

To estimate the energy in wind, let's imagine holding up a hoop with an area of one square metre, facing the wind, whose speed is v. Consider the mass of air that passes through that hoop in one second. Here's a picture of that mass of air just before it passes through the hoop:



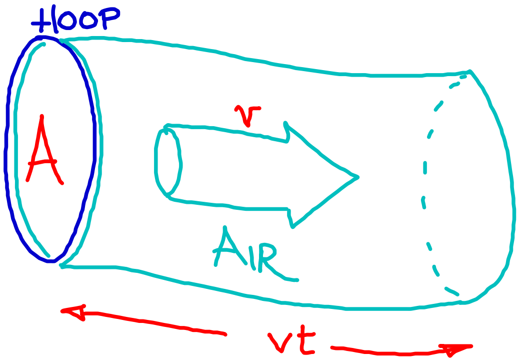
And here's a picture of the same mass of air one second later:



The mass of this piece of air is the product of its density ρ, its area A, and its length, which is v times t, where t is one second.

I'm using this formula:

mass = density × volume



The kinetic energy of this piece of air is

$$\frac{1}{2}mv^2 = \frac{1}{2}\rho Avt\,v^2 = \frac{1}{2}\rho Atv^3. \tag{B.1}$$

So the power of the wind, for an area A – that is, the kinetic energy passing across that area per unit time – is

$$\frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}\rho Av^3. \tag{B.2}$$

This formula may look familiar – we derived an identical expression on p.245 when we were discussing the power requirement of a moving car.

What's a typical wind speed? On a windy day, a cyclist really notices the wind direction; if the wind is behind you, you can go much faster than normal; the speed of such a wind is comparable to the typical speed of the cyclist, which is, let's say, 21 km per hour (13 miles per hour, or 6 metres per second). In Cambridge, the wind is only occasionally this big. Nevertheless, let's use this as a typical British figure (and bear in mind that we may need to revise our estimates).

The density of air is about 1.3 kg per m^3. [I usually round this to 1 kg per m^3, which is easier to remember.] Then the typical power of the wind per square metre of hoop is

$$\frac{1}{2}\rho v^3 = \frac{1}{2}1.3\,\mathrm{kg/m^3} \times (6\,\mathrm{m/s})^3 = 140\,\mathrm{W/m^2}. \tag{B.3}$$

Not all of this energy can be extracted by a windmill. The windmill slows the air down quite a lot, but it has to leave the air with *some* kinetic energy, otherwise that slowed-down air would get in the way. Figure B.3 is a cartoon of the actual flow past a windmill. The maximum fraction of the incoming energy that can be extracted by a disc-like windmill was worked out by a German Physicist called Albert Betz in 1919. If the departing wind speed is one third of the arriving wind speed, the power extracted is 16/27 of the total power in the wind. 16/27 is 0.59. In practice let's guess that a windmill might be 50% efficient. In fact, real windmills are designed with particular wind speeds in mind; if the wind speed is significantly greater than the turbine's ideal speed, it has to be switched off.

As an example, let's assume a diameter of $d = 25$ m, and a hub height of 32 m, which is roughly the size of the lone windmill above the city of

miles per hour	km/h	m/s	Beaufort scale
2.2	3.6	1	force 1
7	11	3	force 2
11	18	5	force 3
13	21	6	force 4
16	25	7	
22	36	10	force 5
29	47	13	force 6
36	31	16	force 7
42	68	19	force 8

Figure B.2. Speeds.

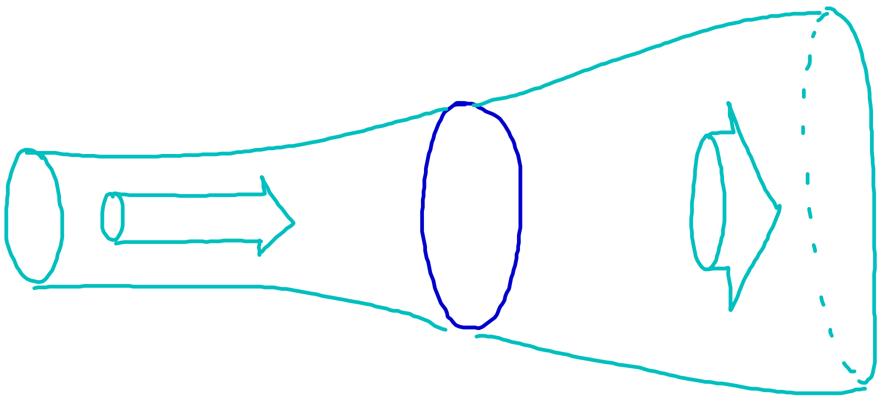


Figure B.3. Flow of air past a windmill. The air is slowed down and splayed out by the windmill.

Wellington, New Zealand (figure B.4). The power of a single windmill is

$$
\begin{aligned}
& \text{efficiency factor} \times \text{power per unit area} \times \text{area} \\
= \; & \frac{1}{2} \times \frac{1}{2}\rho v^3 \times \frac{\pi}{4} d^2 && \text{(B.4)} \\
= \; & \frac{1}{2} \times 140\,\mathrm{W/m^2} \times \frac{\pi}{4}(25\,\mathrm{m})^2 && \text{(B.5)} \\
= \; & 34\,\mathrm{kW}. && \text{(B.6)}
\end{aligned}
$$

Figure B.4. The Brooklyn windmill above Wellington, New Zealand, with people providing a scale at the base. On a breezy day, this windmill was producing 60 kW, or 1400 kWh per day. Photo by Philip Banks.

Indeed, when I visited this windmill on a good breezy day, its meter showed it was generating 60 kW.

To estimate how much power we can get from wind, we need to decide how big our windmills are going to be, and how close together we can pack them.

How densely could such windmills be packed? Too close and the upwind ones will cast wind-shadows on the downwind ones. Experts say that windmills can't be spaced closer than 5 times their diameter without losing significant power. At this spacing, the power that windmills can generate per unit land area is

$$
\begin{aligned}
\frac{\text{power per windmill}}{\text{land area per windmill}} & = \frac{\frac{1}{2}\rho v^3 \frac{\pi}{8} d^2}{(5d)^2} && \text{(B.7)} \\
& = \frac{\pi}{200}\frac{1}{2}\rho v^3 && \text{(B.8)} \\
& = 0.016 \times 140\,\mathrm{W/m^2} && \text{(B.9)} \\
& = 2.2\,\mathrm{W/m^2}. && \text{(B.10)}
\end{aligned}
$$

This number is worth remembering: a wind farm with a wind speed of 6 m/s produces a power of 2 W per m^2 of land area. Notice that our answer does not depend on the diameter of the windmill. The ds cancelled because bigger windmills have to be spaced further apart. Bigger windmills might be a good idea in order to catch bigger windspeeds that exist higher up (the taller a windmill is, the bigger the wind speed it encounters), or because of economies of scale, but those are the only reasons for preferring big windmills.

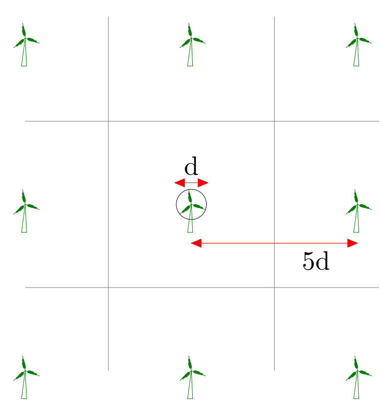


Figure B.5. Wind farm layout.

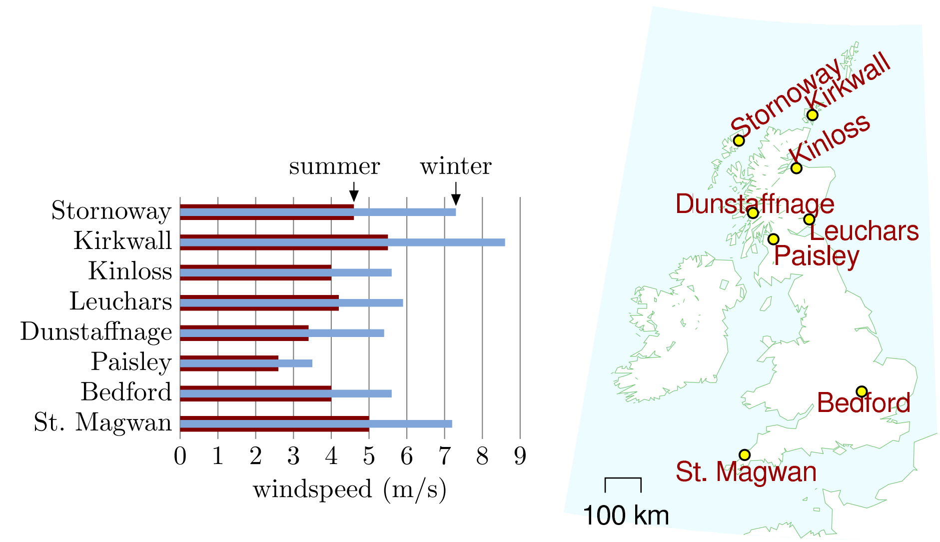


Figure B.7. Average summer windspeed (dark bar) and average winter windspeed (light bar) in eight locations around Britain.

This calculation depended sensitively on our estimate of the windspeed. Is 6 m/s plausible as a long-term typical windspeed in windy parts of Britain? Figures 3.2 and 3.3 showed windspeeds in Cambridge and Cairngorm. Figure B.7 shows the mean winter and summer windspeeds in eight more locations around Britain. The mean windspeed in St. Magwan, on the coast of South-west England, the windiest part of England, ranges from 10 knots (5 m/s) to 14 knots (7.2 m/s). In Bedford, a typical town in the middle of England, the mean windspeed ranges from 8 knots (4 m/s) to 11 knots (5.6 m/s) [`ykhss6`]. At Dunstaffnage, on the West coast of Scotland, the mean windspeed ranges from 6.7 knots to 10.6 knots (3.4–5.4 m/s). At Paisley, near Glasgow, the mean windspeed is 5.1 knots in August and 6.9 knots in Winter (2.6–3.5 m/s). At Leuchars, near St. Andrews on the East coast, 8.1 knots in August; 11.4 knots in winter (4.2–5.9 m/s). At Kinloss, in the north-east of Scotland, the mean speed ranges from 7.8 knots to 10.8 knots (4–5.6 m/s). In Stornoway, on the Isle of Lewis, where nothing stops the Atlantic winds, the mean windspeed ranges from 9.0 knots to 14.2 knots (4.6–7.3 m/s). Kirkwall on Orkney has higher average speeds, ranging from 10.7 knots in Summer to 16.8 knots in Winter (5.5–8.6 m/s). (These are the figures at the standard weather-man's height of 10 m; averages are over the period 1971–2000.)

I fear 6 m/s was an overestimate of the typical speed in most of Britain! If we replace 6 m/s by Bedford's 4 m/s as our estimated windspeed, we must revise our estimate down by a factor of $(4/6)^3 \simeq 0.3$. [Remember, wind power scales as wind-speed cubed.]

On the other hand, to estimate the typical power, we shouldn't take the mean wind speed and cube it; rather, we should find the mean cube of the windspeed. The average of the cube is bigger than the cube of the average. But if we start getting into these details, things get even more complicated, because real wind turbines don't actually deliver a power proportional to wind-speed cubed. Rather, they typically have just a range of wind-speeds within which the ideal behaviour holds. At higher or lower speeds real wind turbines deliver less than the ideal power.

Queries

What about micro-generation?

If you plop one of those mini-turbines on your own roof, what energy can you expect it to deliver? Assuming a windspeed of 6 m/s, which, as I said before, is above average for most parts of Britain; and assuming a diameter of 1 m, the power delivered would be 50 W. That's 1.3 kWh per day.

This estimate agrees with the figures for the D400 StealthGen, famously purchased by David Cameron, which has a diameter of 1.1 m (and should thus deliver about 1.6 kWh/d at a windspeed of 6 m/s). The website `http://www.d400.co.uk/`, says that at windspeeds of 5.1 m/s and 7.7 m/s, this microturbine delivers 40 W and 120 W, respectively. Eclectic Energy encourage the buyer to expect the power produced to be 660 kWh per year (1.8 kWh/d).

Standard windmill properties

The standard windmill of today is typically a machine with a rotor diameter of around 54 metres centred at a height of 80 metres; such a machine has a 'capacity' of 1 MW. The capacity is the *maximum* power the windmill can generate in optimal conditions. Usually, wind turbines are designed to start running at wind speeds somewhere around 3 to 5 m/s and to stop if the wind speed reaches gale speeds of 25 m/s [`ymfbsn`]. The actual average power delivered is the 'capacity' multiplied by a factor that describes the fraction of the time that wind conditions are near optimal. This factor, sometimes called the 'load factor' or 'capacity factor', depends on the site; a typical load factor for a *good* site in the UK is 1/3.

Other people's estimates of wind farm power densities

In `http://www.world-nuclear.org/policy/DTI-PIU.pdf` the UK onshore wind resource is estimated using an assumed wind farm power density of at most 9 W/m^2 (capacity, not average production). If the capacity factor is 33% then the average power production would be 3 W/m^2.

The Whitelee windfarm being built near Glasgow in Scotland has 140 turbines with a combined peak capacity of 322 MW in an area of 55 km^2. That's 5.85 W/m^2, *peak*. If we assume a capacity factor of 33% then the average power production is 2 W/m^2.

The London Array is an offshore wind farm planned for the outer Thames Estuary. With its 1 GW capacity, it is expected to become the world's largest offshore wind farm. The completed wind farm will consist of 271 wind turbines in $245\,km^2$ `http://www.londonarray.com/london-array-project-introduction/offshore/` and will deliver an average power of 3 100 GWh per year (350 MW). (Cost £1.5bn.) That's a power density of $350\,MW/245\,km^2 = 1.4\,W/m^2$. Lower than other offshore farms because, I guess, the site includes a big channel (Knock Deep) that's too deep (about 20 m) for economical planting of turbines.

> *I'm more worried about what these plans [for the proposed London Array wind farm] will do to this landscape and our way of life than I ever was about a Nazi invasion on the beach.*
>
> Bill Boggia, whose family owns and runs several caravan parks around Graveney, where the undersea cables of the windfarm will come ashore.

Figure B.8. The qr5.

Other shapes

Helical wind turbines – they look nice, and they work whatever the wind direction: especially useful in gusty urban environments. The qr5 from `quietrevolution.co.uk` is 5 m high × 3.1 m in diameter, mounted at the top of a 9 m pole. It costs about £33 000 including installation. The turbine weighs approximately 250 kg. Its start-up speed is 4.5 m/s. If the average wind speed is 5.9 m/s, it generates 10 000 kWh per year (27 kWh/d or 1.1 kW, on average). That's $70\,W/m^2$ of vertical area – about the same as a horizontal-axis turbine. And it has a capital cost of £30 000 per kW average power.

See ocean.tex for power density table.

See Faber [1995], p. 63.

Globally, 20 GW of wind capacity was added last year, costing about $36 billion, according to the Global Wind Energy Council.

Variation of wind speed with height

Taller windmills see higher wind speeds. The way that wind speed increases with height is complicated, depending on the roughness of the surrounding terrain. As a ballpark figure, doubling the height typically increases wind-speed by 10% and thus increases the power of the wind by 30%.

Some standard formulae for modelling speed v as a function of height z are:

1. According to the wind shear formula from NREL [ydt7uk], the speed is modelled as a power of height:

$$v(z) = v_{10}\left(\frac{z}{10\,\mathrm{m}}\right)^{\alpha}$$

where v_{10} is the speed at 10 m, and a typical value of the exponent α is 0.143 or 1/7. Thus

$$v(z) \propto z^{1/7}.$$

This one-seventh law is used by Elliott et al. [1991], for example.

2. The wind shear formula from the Danish Wind Industry Association [yaoonz] is

$$v(z) = v_{\mathrm{ref}}\frac{\log(z/z_0)}{\log(z_{\mathrm{ref}}/z_0)},$$

where z_0 is a parameter called the roughness length, and v_{ref} is the speed at a reference height z_{ref} such as 10 m. The roughness length for typical countryside (agricultural land with some houses and sheltering hedgerows with some 500 m intervals – 'roughness class 2') is $z_0 = 0.1$ m.

In practice, these two wind shear formulae give similar numerical answers. That's not to say that they are accurate at all times however. van den Berg [2004] suggests that different wind profiles often hold at night.

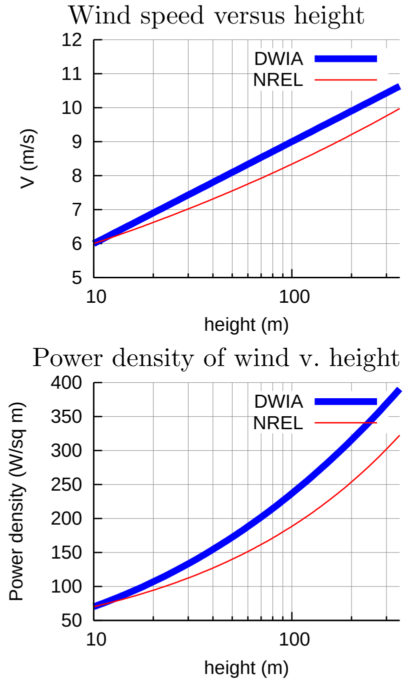


Figure B.9. Two models of wind speed and wind power as a function of height. DWIA = Danish Wind Industry Association; NREL = National Renewable Energy Laboratory. For each model the speed at 10 m has been fixed to 6 m/s. For the Danish Wind model, the roughness length is set to $z_0 = 0.1$ m.

Accidents

http://www.caithnesswindfarms.co.uk/ has data on wind fatalities and accidents. 45 fatalities since the 1970s, 17 in 2000–2006.

102 blade failure incidents. Pieces of blade travel 400 m.

Structural failures: 40 during 1998–2006.

Compare with nuclear, per GWy.

http://www.timesonline.co.uk/tol/news/world/asia/article687157.ece A set of wind turbines in Tsukuba City, Japan, so bad that they were actually importing more than they were exporting. Their installers were so embarrassed by the stationary turbines that they imported power to make them spin so that they looked like they were working!

Netherlands wind capacity factor: 22%; Germany: 19%.

253 MAXIMUM FRACTION OF THE INCOMING ENERGY THAT CAN BE EXTRACTED BY A DISC-LIKE WINDMILL WAS WORKED OUT BY A GERMAN PHYSICIST CALLED ALBERT BETZ There is a nice explanation on the Danish Wind Industry Association's website. [yekdaa].

Watson et al. [2002] say a minimum annual mean wind speed of 7.0 m/s is currently thought to be necessary for commercial viability of wind power. About 33% of UK land area has such speeds.

C

Planes II

What we need to do is to look at how you make air travel more energy efficient, how you develop the new fuels that will allow us to burn less energy and emit less.

Tony Blair

Hoping for the best is not a policy, it is a delusion.

Emily Armistead, Greenpeace

Figure C.1. Birds: two Arctic terns, a bar-tailed godwit, and a Boeing 747.

What are the fundamental limits of travel by flying? Does the physics of flight require an unavoidable use of a certain amount of energy, per tonne, per kilometre flown? What's the maximum distance a 300-tonne Boeing 747 can fly? What about a 1-kg bar-tailed godwit or a 100-gram Arctic tern?

Just as chapter 2, in which we estimated consumption by cars, was followed by chapter A, offering a model of where the energy goes in cars, this chapter fills out chapter 4, discussing where the energy goes in planes. The only physics required is Newton's laws of motion, which I'll describe when they're needed.

This discussion will allow us to answer questions such as 'would air travel consume much less energy if we travelled in slower propellor-driven planes?' There's a lot of equations ahead. I hope you enjoy them!

How to fly

Planes (and birds) move through air, so, just like cars and trains, they experience a drag force, and much of the energy guzzled by a plane goes into pushing the plane along against this force. Additionally, unlike cars and trains, planes have to expend energy *in order to stay up.*

Planes stay up by throwing air down. When the plane pushes down on air, the air pushes up on the plane (because Newton's third law tells it to). If this upward push (which is called lift) is big enough to balance the downward weight of the plane, the plane avoids plummeting downwards.

When the plane throws air down, it gives that air kinetic energy. So creating lift requires energy. The total power required by the plane is

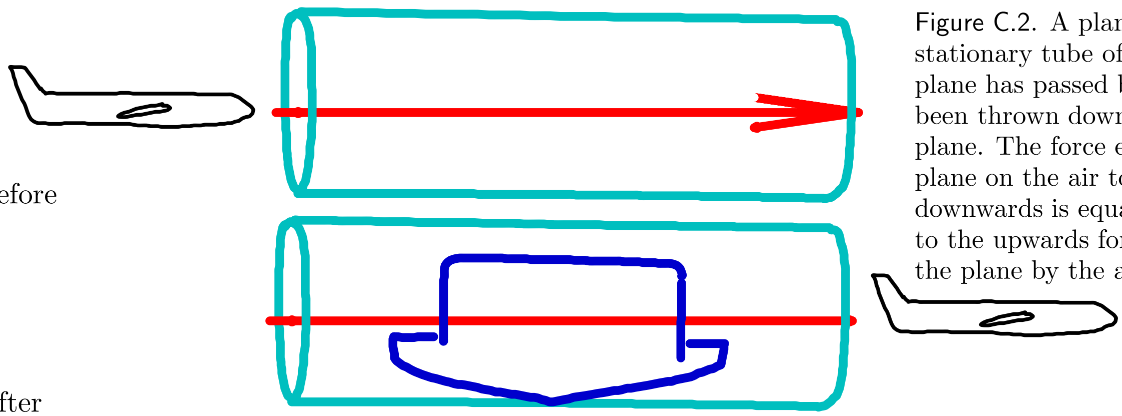


Figure C.2. A plane encounters a stationary tube of air. Once the plane has passed by, the air has been thrown downwards by the plane. The force exerted by the plane on the air to accelerate it downwards is equal and opposite to the upwards force exerted on the plane by the air.

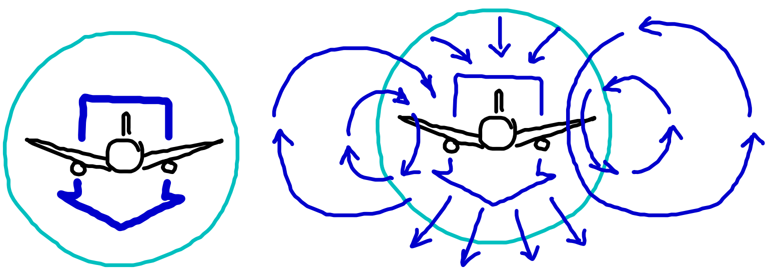


Figure C.3. Our cartoon assumes that the plane leaves a sausage of air moving down in its wake. A realistic picture involves a more complex swirling flow.

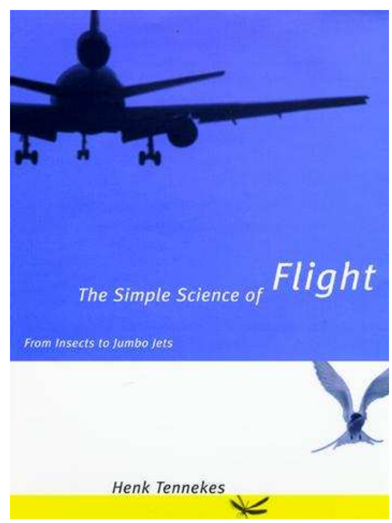


Figure C.4. A beautiful book: *The Simple Science of Flight* by Henk Tennekes (MIT Press, 1997).

the sum of the power required to create lift and the power required to overcome ordinary drag. (The power required to create lift is usually called 'induced drag', by the way. But I'll call it the lift power, $P_{\rm lift}$.)

The two equations we'll need, in order to work out a theory of flight, are Newton's second law:

$$\text{force} = \text{rate of change of momentum}, \tag{C.1}$$

and Newton's third law, which I just mentioned:

$$\text{force exerted on A by B} = -\,\text{force exerted on B by A}. \tag{C.2}$$

If you don't like equations, I can tell you the punchline now: we'll find that the power required to create lift turns out to be *equal* to the power required to overcome drag. So the requirement to 'stay up' *doubles* the power required.

Let's make a cartoon of the lift force on a plane moving at speed v. In a time t the plane moves a distance vt and leaves behind it a sausage of downward-moving air (figure C.2). We'll call the cross-sectional area of this sausage $A_{\rm s}$. This sausage's diameter is roughly equal to the wingspan w of the plane. (Within this large sausage is a smaller sausage of swirling turbulent air with cross-sectional area similar to the frontal area of the plane's body.) Actually, the details of the air flow are much more interesting than this sausage picture: each wing tip leaves behind it a vortex, with the air between the wingtips moving down fast, and the air beyond (outside) the wingtips moving up (figure C.3). This upward-moving air is exploited by birds flying in formation: just behind the tip of a bird's wing is a sweet little updraft. Anyway, let's get back to our sausage.

The sausage's mass is

$$m_{\text{sausage}} = \text{density} \times \text{volume} = \rho v t A_{\text{s}}.$$

Let's say the whole sausage is moving down with speed u, and figure out what u needs to be in order for the plane to experience a lift force equal to its weight mg. The downward momentum of the sausage created in time t is

$$m_{\text{sausage}} u = \rho v t A_{\text{s}} u.$$

And by Newton's laws this must equal the momentum delivered by the plane's weight in time t, namely,

$$mgt.$$

Rearranging this equation,

$$\rho v t A_{\text{s}} u = mgt$$

we can solve for the required sausage speed,

$$u = \frac{mg}{\rho v A_{\text{s}}}.$$

Interesting! The sausage speed is *inversely* related to the plane's speed. A slow-moving plane has to throw down air harder than a fast-moving plane, because it encounters less air per unit time. That's why landing planes, travelling slowly, have to extend their flaps: so as to create a larger and steeper wing that deflects air more.

What's the energetic cost of pushing the sausage down at the required speed u? The power required is

$$\begin{aligned} P_{\text{lift}} &= \frac{\text{kinetic energy of sausage}}{\text{time}} && \text{(C.3)} \\ &= \frac{1}{t}\frac{1}{2} m_{\text{sausage}} u^2 && \text{(C.4)} \\ &= \frac{1}{2t} \rho v t A_{\text{s}} \left(\frac{mg}{\rho v A_{\text{s}}}\right)^2 && \text{(C.5)} \\ &= \frac{1}{2}\frac{(mg)^2}{\rho v A_{\text{s}}}. && \text{(C.6)} \end{aligned}$$

The total power required to keep the plane going is the sum of the lift power and the power required to overcome drag.

$$\begin{aligned} P_{\text{total}} &= P_{\text{drag}} + P_{\text{lift}} && \text{(C.7)} \\ &= \frac{1}{2} c_{\text{d}} \rho A_{\text{p}} v^3 + \frac{1}{2}\frac{(mg)^2}{\rho v A_{\text{s}}}, && \text{(C.8)} \end{aligned}$$

Figure C.5. Air flow behind a plane. Photo by NASA Langley Research Center.

where A_p is the frontal area of the plane and c_d is its drag coefficient.

The fuel-efficiency of the plane, in the sense of energy per distance travelled, would be

$$\left.\frac{\text{energy}}{\text{distance}}\right|_{\text{ideal}} = \frac{P_{\text{total}}}{v} = \frac{1}{2}c_\mathrm{d}\rho A_\mathrm{p}v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_\mathrm{s}}, \qquad \text{(C.9)}$$

if the plane turned its fuel energy into drag power and lift power perfectly efficiently. [Incidentally, another name for 'energy per distance travelled' is 'force', and we can recognise the two terms above as the drag force $\frac{1}{2}c_\mathrm{d}\rho A_\mathrm{p}v^2$ and the lift-related force $\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_\mathrm{s}}$. The sum is the force that specifies exactly how hard the engines have to push.]

Real jet engines have an efficiency of about $\epsilon = 1/3$, so the energy-per-distance of a plane travelling at speed v is

$$\frac{\text{energy}}{\text{distance}} = \frac{1}{\epsilon}\left(\frac{1}{2}c_\mathrm{d}\rho A_\mathrm{p}v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_\mathrm{s}}\right). \qquad \text{(C.10)}$$

This fuel-efficiency is fairly complicated; but it simplifies greatly if we assume that the plane is *designed* to fly at the speed that *minimizes* the energy-per-distance. The energy-per-distance, you see, has got a sweet-spot as a function of v (figure C.6). The sum of the two quantities $\frac{1}{2}c_\mathrm{d}\rho A_\mathrm{p}v^2$ and $\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_\mathrm{s}}$ is smallest when the two quantities are equal. This phenomenon is very common in physics and engineering: two things that don't obviously *have* to be equal *are* actually equal, or equal within a factor of 2.

So, this equality principle tells us that the optimum speed for the plane is such that

$$c_\mathrm{d}\rho A_\mathrm{p}v^2 = \frac{(mg)^2}{\rho v^2 A_\mathrm{s}}, \qquad \text{(C.11)}$$

i.e.,

$$\rho v_{\text{opt}}^2 = \frac{mg}{\sqrt{c_\mathrm{d}A_\mathrm{p}A_\mathrm{s}}}, \qquad \text{(C.12)}$$

This defines the optimum speed if our cartoon of flight is accurate; the cartoon breaks down if the engine efficiency ϵ depends significantly on speed, or if the speed of the plane exceeds the speed of sound – above the speed of sound, we would need a different model of drag and lift.

Let's check our model by seeing what it predicts is the optimum speed for two planes: a 747 and an albatross. We must take care to use the correct air-density: if we want to estimate the optimum cruising speed for a 747 at 30 000 feet, we must remember that air density drops with increasing altitude z as $\exp(-mgz/kT)$, where m is the mass of nitrogen or oxygen molecules, and kT is the thermal energy (Boltzmann's constant times absolute temperature) – the density is about 3 times smaller at that altitude.

The predicted optimal speeds (table C.7) are more accurate than we have a right to expect! The 747's optimal speed is predicted to

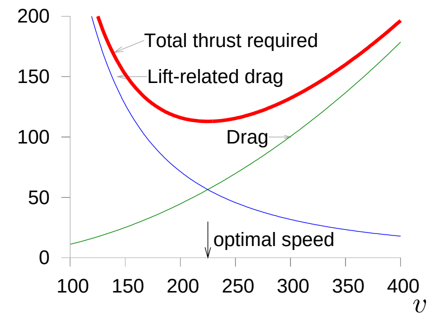


Figure C.6. The force required to keep a plane moving, as a function of its speed v, is the sum of an ordinary drag force $\frac{1}{2}c_\mathrm{d}\rho A_\mathrm{p}v^2$ – which increases with speed – and the lift-related force (also known as the induced drag) $\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_\mathrm{s}}$ – which decreases with speed. There is an ideal speed, v_{optimal}, at which the force required is minimized. The force is an energy per distance, so minimizing the force also minimizes the fuel per distance. To optimize the fuel efficiency, fly at v_{optimal}. This graph shows our cartoon's estimate of the thrust required, in Newtons, for a Boeing 747 of mass 319 tonnes, wingspan 64.4 m, drag coefficient 0.03, and frontal area 180 m^2, travelling in air of density $\rho = 0.41\,\mathrm{kg/m^3}$ (the density at a height of 10 km), as a function of its speed v in m/s. Our model has an optimal speed $v_{\text{optimal}} = 220$ m/s (540 mph). For a cartoon based on sausages, this is a good match to real life!

Bird		747	Albatross
Designer		Boeing	natural selection
Mass (fully-laden)	m	363 000 kg	8 kg
Wingspan	w	64.4 m	3.3 m
Area*	A_p	$180\,\mathrm{m}^2$	$0.09\,\mathrm{m}^2$
Density	ρ	$0.4\,\mathrm{kg/m}^3$	$1.2\,\mathrm{kg/m}^3$
Drag coefficient	c_d	0.03	0.1
Optimum speed	v_{opt}	220 m/s = 540 mph	14 m/s = 32 mph

Table C.7. Estimating the optimal speeds for a jumbo jet and an albatross.
⋆ Frontal area estimated for 747 by taking cabin width (6.1 m) times estimated height of body (10 m) and adding double to allow for the frontal area of engines, wings, and tail; for albatross, frontal area of 1 square foot estimated from a photograph.

be 540 mph, and the albatross's, 32 mph – both very close to the true cruising speeds of the two birds (560 mph and 30–55 mph respectively).

Let's explore a few more predictions of our cartoon. We can check whether the force (C.9) is compatible with the known thrust of the 747. Remembering that at the optimal speed, the two forces are equal, we just need to pick one of them and double it:

$$\begin{aligned} \text{force} &= \left.\frac{\text{energy}}{\text{distance}}\right|_{\text{ideal}} = \frac{1}{2}c_d\rho A_p v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s} && \text{(C.13)} \\ &= c_d\rho A_p v^2 && \text{(C.14)} \\ &= c_d\rho A_p \frac{mg}{\rho(c_d A_p A_s)^{1/2}} && \text{(C.15)} \\ &= \left(\frac{c_d A_p}{A_s}\right)^{1/2} mg. && \text{(C.16)} \end{aligned}$$

Let's define the filling factor f_A to be the area ratio:

$$f_A = \frac{A_p}{A_s} \quad \text{(C.17)}$$

(Think of f_A as the fraction of the square occupied by the plane in figure C.8.) Then

$$\text{force} = (c_d f_A)^{1/2}(mg) \quad \text{(C.18)}$$

Interesting! Independent of the density of the fluid through which the plane flies, the required thrust (for a plane travelling at the optimal speed) is just a dimensionless constant $(c_d f_A)^{1/2}$ times the weight of the plane. This constant, by the way, is known as the drag-to-lift ratio of the plane. (The lift-to-drag ratio has a few other names: the glide number, glide ratio, aerodynamic efficiency, or finesse.)

Taking the jumbo jet's figures, $c_d \simeq 0.03$ and $f_A \simeq 0.04$, we find the required thrust is

$$(c_d f_A)^{1/2} mg = 0.036\, mg = 130\,\mathrm{kN}$$

How does this agree with the 747's spec sheets? In fact each of the 4 engines has a maximum thrust of about 250 kN, but this maximum

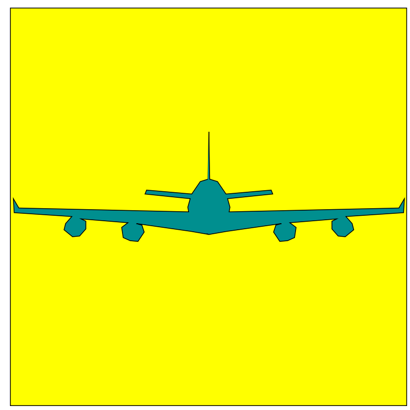


Figure C.8. Frontal view of a Boeing 747, used to estimate the frontal area A_p of the plane. The square has area A_s (the square of the wingspan).

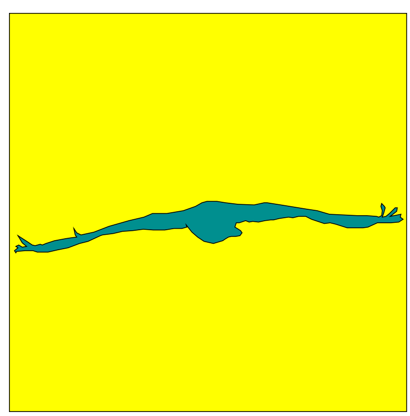


Figure C.9. Frontal view of a swan.

Airbus A320	17
Boeing 767-200	19
Boeing 747-100	18

thrust is used only during take-off. During cruise, the thrust is much smaller: the thrust of a cruising 747 is 200 kN, just 50% more than our cartoon suggested.

This thrust can be used directly to deduce the transport efficiency (in kWh per tonne-kilometre or kWh per 100 passenger-kilometres) achieved by any plane. Thrust is a force, and a force is an energy per unit distance. The total energy used per unit distance is bigger by a factor $(1/\epsilon)$, where ϵ is the efficiency of the engine, which we'll take to be 1/3.

Figure C.11. Cessna 310N: **60 kWh per 100 passenger-km**. A Cessna 310 Turbo carries 6 passengers (including 1 pilot) at a speed of 370 km/h. Photograph by Adrian Pingstone.

Efficiency in weight terms

Here's the transport efficiency, defined to be the energy per unit weight (of the entire craft) per unit distance:

$$\text{transport efficiency} = \frac{1}{\epsilon}\frac{\text{thrust}}{\text{mass}} \tag{C.19}$$

$$= \frac{1}{\epsilon}\frac{(c_{\rm d} f_A)^{1/2} mg}{m} \tag{C.20}$$

$$= \frac{(c_{\rm d} f_A)^{1/2}}{\epsilon} g \tag{C.21}$$

So the transport efficiency is just a dimensionless quantity (related to a plane's shape and its engine's efficiency), multiplied by g, the acceleration due to gravity. If we plug in $\epsilon = 1/3$, $c_{\rm d} = 0.03$, and $f_A \simeq 0.04$, we find the transport efficiency, according to our cartoon, is

$$0.1\, g$$

or

$$0.3\,\text{kWh/ton-km}.$$

Can planes be improved

If engine efficiency can be boosted only a tiny bit by technological progress, and if the shape of the plane has already been essentially perfected, then there is little that can be done about the dimensionless quantity. The transport efficiency is close to its physical limit. Experts in aerodynamics say that the shape of planes could be improved a little by a switch to blended-wing bodies, and that the drag coefficient could be reduced a little by laminar flow control, a technology that reduces the growth of turbulence over a wing by sucking a little air through small perforations in the surface [Braslow, 1999]. The addition of laminar flow control to existing planes would deliver a 15% improvement in drag coefficient, and the change of shape to blended-wing bodies is predicted to improve the drag coefficient by about 18% [Green, 2006].

Figure C.12. 'Fasten your cufflinks'. A Bombardier Learjet 60XR carrying 8 passengers at 780 km/h has a transport cost of **150 kWh per 100 passenger-km**. Photograph by Adrian Pingstone.

This transport efficiency is the efficiency of moving weight around, *including the weight of the plane itself.* To estimate the energy required to move freight by plane, per unit weight of freight, then we need to divide by the fraction that is cargo. For example, if a full 747 freighter is about 1/3 cargo, then its transport efficiency is

$$0.3g,$$

or roughly 1 kWh/ton-km. This is the same as the transport efficiency of a truck.

Transport efficiency in terms of bodies

Similarly, we can estimate a passenger transport-efficiency.

$$\begin{aligned}
&\text{transport efficiency (passenger–km per litre)} \\
&= \text{number of passengers} \times \frac{\text{energy per litre}}{\frac{\text{thrust}}{\epsilon}} && \text{(C.22)} \\
&= \text{number of passengers} \times \frac{\epsilon\text{energy per litre}}{\text{thrust}} && \text{(C.23)} \\
&= 400 \times \frac{1}{3}\frac{38\,\text{MJ/litre}}{200\,000\,\text{N}} && \text{(C.24)} \\
&= 25\,\text{passenger–km per litre} && \text{(C.25)}
\end{aligned}$$

which is a bit more efficient than a typical single-occupant car (12 km per litre). We can find the actual efficiency of a 747 by looking up its specifications: it is indeed 25 passenger-km per litre. So travelling by plane is more energy-efficient than car if there are only one or two people in the car; and cars are more efficient if there are three or more passengers in the vehicle.

Let's re-express these results in kWh per 100 kilometres travelled. Each litre of jet fuel delivers 10 kWh of energy, so the 747's energy efficiency is

$$42\,\text{kWh per } 100\,\text{seat-km}.$$

Key points

We've covered quite a lot of ground! Let's recap the key ideas. Half of the work done by a plane goes into *staying up*; the other half goes into *keeping going*. The fuel efficiency at the optimal speed, expressed as an energy-per-distance-travelled, was found in the force (C.18), and it was simply proportional to the weight of the plane; the constant of proportionality is the drag-to-lift ratio, which is determined by the shape of the plane. So whereas lowering speed-limits for cars would reduce the energy consumed per distance travelled, there is no point in considering speed-limits for planes. Planes that are up in the air have optimal speeds, different for each plane, depending on its weight, and they already go at their optimal speeds. The only way to make a plane consume less fuel is to put it on the ground and stop it. Planes have been fantastically optimized, and there is no prospect of significant improvements in plane efficiency.

Figure C.13. Boeing 737-700: **30 kWh per 100 passenger-km**. Photograph © Tom Collins.

Range

Another prediction we can make is, what's the range of a plane or bird? You might think that bigger planes have a bigger range, but the prediction of our model is startlingly simple. The range of the plane, the maximum distance it can go before refuelling, is proportional to its velocity and to the total energy of the fuel, and inversely proportional to the rate at which it guzzles fuel:

$$\text{range} = v_{\text{opt}} \frac{\text{energy}}{\text{power}} = \frac{\text{energy}\,\epsilon}{\text{force}} \tag{C.26}$$

Now, the total energy of fuel is the calorific value of the fuel, C (in joules per kilogram), times its mass; and the mass of fuel is some fraction f_{fuel} of the total mass of the plane. So

$$\text{range} = \frac{\text{energy}\,\epsilon}{\text{force}} = \frac{Cm\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}(mg)} = \frac{C\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2} g} = \frac{\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}} \frac{C}{g}. \tag{C.27}$$

It's hard to imagine a simpler prediction: the range of any bird or plane is the product of a dimensionless factor $\left(\frac{\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}}\right)$ which takes into account the engine efficiency, the drag coefficient, and the bird's geometry, with a fundamental distance,

$$\frac{C}{g},$$

which is a property of the fuel and gravity, and nothing else. No bird size, no bird mass, no bird length, no bird width; no dependence on the fluid density.

So what is this magic length? It's the same distance whether the fuel is albatross fat or jet fuel: both these fuels are essentially hydrocarbons $(CH_2)_n$. Jet fuel has a calorific value of $C = 40 \times 10^6$ J per kg. The distance associated with jet fuel is

$$d_{\text{Fuel}} = \frac{C}{g} = 4000\,\text{km}.$$

You can think of this as the distance that the fuel could throw itself if it suddenly converted all its chemical energy to kinetic energy and launched itself on a parabolic trajectory with no air resistance. [To be precise, the distance achieved by the optimal parabola is twice C/g.] Or, this distance is the vertical height to which the fuel could throw itself if there were no air resistance. Another amusing thing to notice is that the calorific value of a fuel C, which I gave in joules per kilogram, is also a squared-velocity (just as the energy-to-mass ratio E/m in Einstein's $E = mc^2$ is a squared-velocity, c^2): 40×10^6 J per kg is $(6000\,\text{m/s})^2$. So one way to think about fat is "fat is 6000 metres per second". If you want to lose weight by going jogging, 6000 m/s (12 000 mph) is the speed you should aim for in order to lose it all in one giant leap.

Back to the birds. The range is the intrinsic range of the fuel, 4000 km, times a factor $\left(\frac{\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}}\right)$. If our bird has engine efficiency

$\epsilon = 1/3$, and $(c_{\rm d} f_A)^{1/2} \simeq 0.03$, and if nearly half of the bird is fuel (a fully-laden 747 is 46% fuel), we find that all birds and planes, of whatever size, have the same range: about five times the fuel's distance, roughly 20 000 km.

This figure is again close to the true answer: the nonstop flight record for a 747 (set March 23–24, 1989) was a distance of 16 560 km.

And the claim that the range is independent of bird size is supported by the observation that birds of all sizes, from great geese down to dainty swallows and arctic tern migrate intercontinental distances.

The longest non-stop flight by a bird was a distance of 11 000 km, by a bar-tailed godwit.

How far did Fossett go in the specially-designed Scaled Composites Model 311 Virgin Atlantic GlobalFlyer? 41 467 km. `http://www.stevefossett.com/html/main_pages/records.html` An unusual plane: 83% of its take-off weight was fuel; the flight made careful use of the jet-stream to boost its distance. Fragile, the plane had several failures along the way.

One interesting point brought out by this cartoon is: if we ask 'what's the optimum air-density to fly in?' we find that the thrust required at the optimum speed is independent of the density. So our cartoon plane would be equally happy to fly at any height; it could achieve the same miles-per-gallon whatever the density; but the optimum speed does depend on the density ($v^2 \sim 1/\rho$). So all else being equal, our cartoon plane would have the shortest journey time if it flew in the lowest-density air possible. Now real engines' efficiencies aren't independent of speed and air density. As a plane gets lighter by burning fuel, our cartoon says its optimal speed at a given density would reduce ($v^2 \sim mg/(\rho w (c_{\rm d} f_A)^{1/2})$). But a plane can both keep going at a *constant speed* and continue flying at its *optimal* speed if it increases its altitude so as to reduce the air density. Next time you're on a long-distance flight, you could check whether the pilot increases the cruising height from, say, 31 000 feet to 39 000 feet by the end of the flight.

The A380: The future of flying

Figure C.14. Airbus A380.

The superjumbo A380 is said by Airbus to be 'a highly fuel-efficient aircraft'.

– in fact, as they then say, it burns 12 percent less fuel per passenger than a 747.

Boeing have announced similar breakthroughs: their new 747–8 Intercontinental, trumpeted for its planet-saving properties, is (according to Boeing's advertisements) 15% more fuel-efficient than a 747–400.

What would a Hydrogen plane do?

We've already argued that the efficiency of flight, in terms of energy per tonne-km, is just a simple dimensionless number times g. Changing the fuel isn't going to change this fundamental argument. Hydrogen-powered planes are worth discussing if we're hoping to reduce climate-changing emissions. They might also have better range. But don't expect them to be radically more energy-efficient.

We can estimate the range of a hydrogen-powered plane using the idea that the range is proportional to C, the energy content of the fuel. Hydrogen has the highest energy content of any common fuel by weight (about three times more than gasoline), but the lowest energy content by volume (about four times less than gasoline, if liquified). So the range of a hydrogen-fuelled plane could be three times bigger than that of a hydrocarbon-fuelled plane, if the storage tanks's weight was not significant. But if it were to have any space for passengers inside, the plane's shape would have to be altered. The big problem is storage. Real hydrogen storage containers weigh far more than the hydrogen they contain.

Engine efficiency

('specific fuel consumption') Typical engine efficiencies are in the range 0.23–0.36. For typical aircraft, overall engine efficiency ranges between 20% and 40%, with the best bypass engines delivering 30–37% when cruising. You can't simply pick the most efficient engine however, since it may be bigger and heavier, thus reducing overall plane efficiency.

Overall efficiency: 'The last piston-powered aircraft were as fuel-efficient as the current average jet.' `http://www.transportenvironment.org/Downloads-index-req-getit-lid-398.html`

Possible areas for improvement of plane efficiency

'Laminar flow control' (cunning trick for reducing drag a little). Flying wings: said to be 25% more fuel efficient. Propfans instead of turbofans? Said to be 12% more efficient for short journeys (less than 3000 km), but not for long journeys. They're more efficient because the engine efficiency is greater.

Formation flying in the style of geese could give a 10% improvement in fuel efficiency (because the lift-to-drag ratio of the formation is higher than that of a single aircraft), but this trick relies, of course, on the geese wanting to migrate to the same destination at the same time.

Optimizing the hop lengths: long-range planes (designed for a range of say 15 000 km) are not quite as fuel-efficient as shorter-range planes, because they have to carry extra fuel, which makes less space for cargo and passengers. It would be more energy efficient to fly shorter hops in shorter-range planes. The sweet spot is when the hops are about 5000 km long, so typical long-distance journeys would have one or two refuelling stops. Multi-stage long distance flying might be about 15% more fuel efficient; but of course it would introduce other costs.

Assumptions in my cartoon

I made these assumptions:

Long distance flights use fuel uniformly enough to not bother about the weight of the fuel changing the weight of the plane. In fact when landing the mass of a long-distance 747 is roughly half its take-off weight, because of the lost fuel.

When we think about the cost of lugging fuel around, we find a way of improving the transport efficiency of long-distance travel by 10% or so. If we want to maximize the transport efficiency of the cartoon plane, we should aim for shorter flights, and have long-distance planes refuel once or twice along the way. Carrying less fuel would allow more passengers and cargo to be transported, or reduce the weight required for the engines. Such stops along the way would obviously increase other costs associated with travel.

Eco-friendly aeroplanes

Occasionally you may hear about people making eco-friendly aeroplanes. `http://www.theaustralian.news.com.au/story/0,25197,23003236-23349,00.html` Earlier in this chapter, however, our cartoon made the assertion that the transport efficiency of *any* plane is about

$$0.3\,\text{kWh/tonne-km}.$$

According to the cartoon, the only ways in which a plane could significantly improve on this figure are to reduce air resistance (perhaps by some newfangled vacuum-cleaners-in-the-wings trick) or to change the geometry of the plane (making it look more like a glider, with immensely wide wings compared to the fuselage, or getting rid of the fuselage altogether).

So, let's look at the latest news story about 'eco-friendly aviation' and see whether one of these planes can beat the 0.3 kWh per tonne-km benchmark. If so, we might conclude that the cartoon is defective.

The Electra, a wood-and-fabric single-seater, flew for 48 minutes for 50km around the southern Alps. The Electra has a 9 m wingspan and a 18 kW electric motor powered by 48 kg of lithium-polymer batteries. The aircraft's take-off weight is 265 kg (134 kg of aircraft, 47 kg of batteries, and 84 kg of human cargo). On December 23rd, 2007 it flew a distance of 50 km. If we assume that the battery's energy density was 130 Wh/kg, and that the flight used 90% of a full charge (5.5 kWh), the transport efficiency of the plane was roughly

$$0.4\,\text{kWh/ton-km},$$

which is more energy than our cartoon's ideal. So the cartoon still stands. This electrical plane is not a lower-energy plane than a normal fossil-sucker.

Of course, this doesn't mean that electric planes are not interesting. (Incidentally, as a person-transporter, it delivers a respectable 11 kWh

The Electra F-WMDJ. Photo by Jean–Bernard Gache. `http://www.apame.eu/`

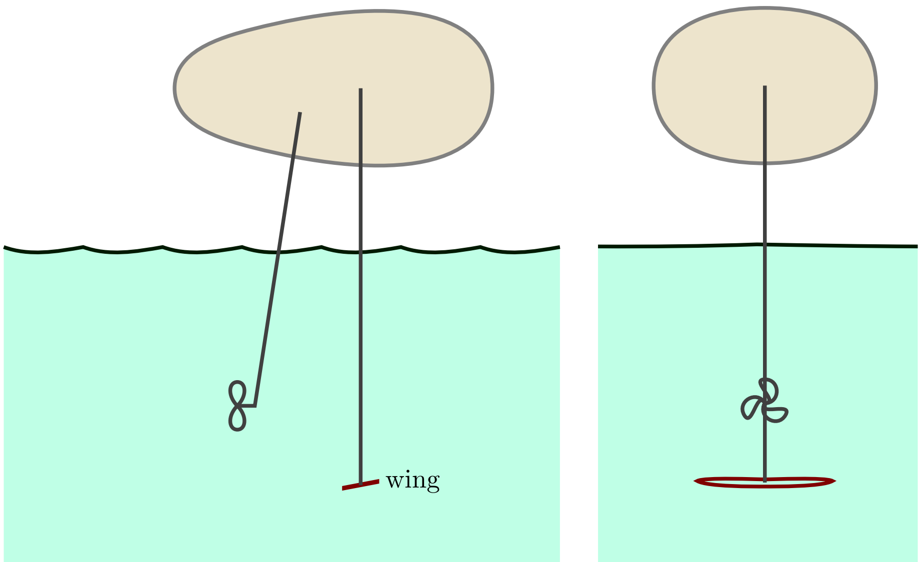


Figure C.16. Hydrofoil.

per 100 p-km, identical to the electric car in our transport diagram.) If one could replace traditional planes by alternatives with equal energy consumption but no carbon emissions, that would certainly be a useful technology. But for me the bottom line is always: "where is the energy to come from?"

Many boats are birds too

Some time after writing this cartoon of flight, I realised that it applies to more than just the birds of the air – it applies to hydrofoils, and to other high-speed watercraft too – all those that ride higher in the water when moving.

Figure C.16 shows the principle of the hydrofoil. The weight of the craft is supported by an underwater wing, which may be quite tiny compared with the craft. The wing generates lift by throwing fluid down, just like the plane of figure C.2. If we assume that the drag is dominated by the drag on the wing, and that the wing dimensions and vessel speed have been optimized to minimize the energy expended per unit distance, then the transport efficiency, in the sense of energy per tonne-kilometre, will be just the same as in equation (C.21):

$$\frac{(c_{\rm d} f_A)^{1/2}}{\epsilon} g$$

where $c_{\rm d}$ is the drag coefficient of the underwater wing, f_A is the dimensionless area ratio defined before, ϵ is the engine efficiency, and g is the acceleration due to gravity.

Perhaps $c_{\rm d}$ and f_A are not quite the same as those of an optimized plane. But the remarkable thing about this theory is that it has no dependence on the density of the fluid that the wing is flying through.

So our ballpark prediction is that the transport efficiency (energy-per-distance-per-weight, including the vehicle weight) of a hydrofoil is *the same* as the transport efficiency of an aeroplane! Namely, roughly 0.3 kWh per ton-km.

For vessels that skim the water surface, such as high-speed catamarans and water-skiers, an accurate cartoon should also include the energy going into making waves, but I'm tempted to guess that this hydrofoil theory is still roughly right.

I've not yet found data on the transport-efficiency of a hydrofoil, but some data for a passenger-carrying catamaran travelling at 41 km/h seem to agree pretty well: it consumes roughly 1 kWh per tonne-km.

It's quite a surprise to me to learn that an island hopper who goes from island to island by plane not only gets there faster than someone who hops by boat – he quite likely uses less energy too.

Mythconceptions

'The plane was going anyway, so my flying was energy-neutral'.

This is false for two reasons. First, your extra weight on the plane requires extra energy to be consumed in keeping you up. Second, airlines respond to demand by flying more planes.

Planes could be more efficient if they went slower.

False. Here's the rough idea, which this chapter covered in detail: yes, reducing the speed of a plane would reduce its turbulent drag, just like a car. But planes have to expend energy on another activity, namely throwing air down. Planes have to throw air down in order to stay up, whereas cars get pushed up for free by the road. The plane defies gravity at a cost. It costs energy to throw air down. And it's not obvious, but this throwing-down actually costs more energy, the slower the plane goes. This means that any plane has a sweet spot, an optimal speed that it should go at in order to deliver the most miles per gallon.

Notes

Load factor of Easyjet up to 90%. BBC News, Monday, 7 August 2006. [2oatgv]

Drag coefficient for 747 from www.aerospaceweb.org. Other 747 data from [2af5gw]. Albatross facts from [32judd]. Albatross estimated drag coefficient (0.1) based on C M Bishop paper – says cd=0.1 is conceivable.

New Scientist. 'Bar-tailed godwit is king of the skies' 26 March 2005. Magazine issue 2492.

Tuesday, 11 September 2007: Godwit flies 11 500 km non-stop from Alaska to New Zealand. [2qbquv]

272 *Data for a passenger-carrying catamaran.* From `http://www.goldcoastyachts.com/fastcat.htm`: Displacement (full load) 26.3 tons. On a 1050 nautical mile voyage she consumed just 4780 litres of fuel. I reckon that's a weight-transport-efficiency of 0.93 kWh per tonne-km. I'm counting the total weight of the vessel here, by the way. The same vessel's passenger-transport-efficiency is roughly 35 kWh per 100 pkm.

"Look – it's Low Carbon Emission Man"

Figure C.17. Private Eye No 1176. 19 January 2007.

D

Solar II

Solar biomass II

On p.40 we listed four solar biomass options.

1. 'coal substitution'
2. 'petroleum substitution'
3. food for humans or other animals
4. incineration of agricultural by-products

We'll estimate the maximum contribution of each of these processes in turn. In practice, many of these methods require so much energy be put *in* along the way that they are scarcely net contributors. But in what follows, I'll ignore such embodied-energy costs.

Solar biomass: energy crops as a coal substitute

Productivity of Britain's main biodiesel crop, rape

Typically, rape is sown in September and harvested the following August. Currently 450 000 ha of oilseed rape is grown in the UK each year. (That's 2% of the UK.) Fields of rape produce 1200 litres of biodiesel

Figure D.2. Oil-seed rape. If used to create biodiesel, the power density of rape is 0.13 W/m^2. Photo by Tim Dunne.

Power densities of power stations		
Wind farm: $v = 6$ m/s		2 W/m^2 flat ground
Solar		
Photovoltaic	20%	16 W/m^2 South-facing roof
	20%	10 W/m^2 flat ground
Biomass for chemicals	1%	0.5 W/m^2 flat ground
Biomass as coal-substitute	0.4%	0.2 W/m^2 flat ground
Nuclear fission		1000 W/m^2

Table D.1. Power densities

(net) per hectare per year; biodiesel has 9.8 kWh/l; that's $0.13\,\mathrm{W/m^2}$. Source: Bayer Crop Science.

I think this net figure allows for energy inputs. But does it include all of them? The processing of vegetable oil uses methanol derived from natural gas. 1 tonne of oilseed rape yields 409 l, which turns into 473 l of biodiesel but only with the help of 80 l of methanol. Evans [2007]

Mabee et al. Where sugar cane can be produced (eg Brazil) production is 80 t/ha, which yields about 17 600 l of ethanol. Cellulosic ethanol yield is expected to be in the range 0.12-0.32 l per kg of undried feedstock.

Jatropha is no exception to the rule: biosolar has low power density

Jatropha: 175 US gal biodiesel per acre per year (164 cubic m per square km) is $0.18\,\mathrm{W/m^2}$. Grows best in dry tropical regions (300–1000 mm rain per year). Likes temperatures 20–28°C. 583 l per ha of wasteland per year. Source: Francis et al 2005: That's $0.065\,\mathrm{W/m^2}$. They also project CO_2 sequestration of 2.29 t per ha.

Source: Francis et al. [2005] Asselbergs et al. [2006]; sounds like there are many niggles.

If the niggles are sorted out and 10% of Africa generates $0.065\,\mathrm{W/m^2}$, and we share this power between six billion people, what do we get? 0.8 kWh/d/p.

Corn-growing in the USA for bioethanol

1 acre ($4050\,\mathrm{m^2}$) produces 122 bushels (per year?), which makes 122×2.6 US gallons of ethanol, which at 84 000 BTU per gallon means 780 kWh per acre per year, which is **0.02** $\mathrm{W/m^2}$ – not taking into account any of the energy losses in processing.

The main research result for bioethanol is that for ethanol to break even, it is essential to make use of coproducts [Shapouri et al., 1995].

Solar biomass: farming byproducts as a coal substitute

We found a moment ago that the power per unit area of a biomass power station burning the best energy crops is $0.2\,\mathrm{W/m^2}$. If instead we grow crops for food, and put the left-overs that we don't eat into a power station – or if we feed the food to chickens and put the left-overs that come out of the chickens' back-ends into a power station – what power could be delivered per unit area of farmland? Let's make a rough guess, then take a look at some real data. For a wild guess, let's imagine that by-products are harvested from half of the area of Britain and trucked to power stations., and that general agriculture by-products deliver 10% as much power per unit area as the best energy crops: $0.02\,\mathrm{W/m^2}$. Multiplying this by $2000\,\mathrm{m^2}$ (half the area per person) we get 1 kWh per day per person.

Have I been unfair on agricultural garbage in making this wild guess? We can re-estimate the plausible production from agricultural left-overs by scaling up the prototype straw-burning power station at Elean in East Anglia. Elean's power output is 36 MW, and it uses 200 000 tonnes per year from land located within a 50-mile radius. If we assume this density can be replicated across the whole country, the Elean model offers 0.002 W/m^2. At 4000 m^2 per person, that's 8 W each, or 0.2 kWh/day per person. If power stations like Elean could be packed five times more densely our calculation would have recovered the 1 kWh per day of my wild guess.

Landfill methane gas

At present, much of the methane gas leaking out of rubbish tips comes from biological materials, especially waste food. So, as long as we keep throwing away things like food and newspapers, landfill gas is a sustainable energy source – plus, burning that methane might be a good idea from a climate-change perspective, since methane is a stronger greenhouse-gas than CO_2. A landfill site receiving 7.5 million tonnes of household waste per year can generate 50 000 m^3 per hour of methane. Source: Matthew Chester, City University, London.

Gas has a calorific value of 38 MJ/m^3, so this means that with methane capture at all landfill sites, total waste of 0.4 tonnes per year per person could generate 0.16 m^3 per day per person of methane, which is 1.7 kWh/d per person (of chemical energy). Or 0.7 kWh(e)/d per person, assuming conversion to electricity at 40% efficiency.

Burning household waste

Some numbers:

SELCHP ('South East London Combined Heat and Power') `http://www.selchp.com/` is a 35 MW(e) power station which receives 420 kt per year of black bag waste from the London area. They are *paid* £160 per ton of waste. They burn the waste (as a whole, without sorting) and are paid for the electricity (roughly £32 per MWh(e)). Ferrous metals are removed for recycling, hazardous wastes are filtered out and sent to a special landfill site, and the remaining ash is sent for reprocessing into recycled material for road building or construction use.

The calorific value of the waste is 9000 kJ/kg (2.5 kWh/kg), and the thermal efficiency of the power station is about 21%, so each 1 kg of waste gets turned into 0.5 kWh(e). The carbon emissions are about 1000 g CO_2 per kWh(e).

I don't think they deliver any heat to anyone, so it's not actually a CHP facility, in spite of its name.

Of the 35 MW(e) generated, about 4 MW(e) is immediately used by the plant itself to run its machinery and filtering processes.

Scaling all this per person: if every borough had one of these, and if everyone sent 1 kg per day of waste, then we'd get 0.5 kWh(e) per day per person from waste incineration.

Check this agrees with '5 plans'.

This is similar to the figure estimated above for methane capture at landfill sites. And remember, you can't have both. More waste incineration means less methane gas leaking out of landfill site.

Forest productivity

Other sources for productivity of forest.

Writing about willow, miscanthus, poplar, etc, not traditional wood: Select Committee on Science and Technology Minutes of Evidence – Memorandum from the Biotechnology & Biological Sciences Research Council. "Typically a sustainable crop of 10 dry t/ha/y of woody biomass can be produced in Northern Europe" "Thus an area of 1 sq km will produce 1000 dry t/y – enough for a power output 150 kWe at low conversion efficiencies or 300 kWe at high conversion efficiencies." (Which means 0.15–0.3 W(e)/m^2.)

Layzell et al. [2006] [`3ap7lc`]

Grain crops contain 13.9 GJ/t (Wet). (wheat, oats, barley, corn)

switch grass: 12 GJ/t(wet). willow: 9.3 GJ/t(wet). agri residues: 12 GJ/t(wet). municipal solid waste: 9.5 GJ/t(wet). wood: 9.3 GJ/t(wet).

Wheat yields in the UK

In the UK, 7.7 tons per hectare per year. Wheat to bioethanol: 1 t wheat makes 336 l. That's 0.17 W/m^2, not accounting for energy inputs required.

Sugar beet: 53 t/ha/y. 1 t sugar beet makes 108 l bioethanol. That's 0.4 W/m^2, not accounting for energy inputs required.

SDC exaggeration – is the word 'radical' appropriate?

[Move to 'presentation' chapter?] "Wood fuel heating could radically cut climate changing emissions." "On the basis of available evidence, it has been estimated that the wood fuel resource of 700 000 to 1 M odt per year would be able to support between 1.5 and 3.4 TWh per year of delivered energy consumption [my units: 0.8–1.8 kWh/day per person in Scotland; about 2% at most.] – enough to account for between 5% and 11% of domestic space and water heating requirements in Scotland. This would result in carbon savings of from 0.16 to 0.4 million tonnes of carbon (MtC), or 0.6 to 1.4 million tonnes of CO_2 ($MtCO_2$). [0.12–0.28 tonnes CO_2 per person per year. About 3% at most of average emissions (10 tonnes).] Such savings equate to between 7% and 23% of CO_2 emissions from domestic space and water heating in Scotland."

Incidentally, note the conversion rate for thermal heat from wood from these numbers: about 3 MWh/odt, or 3 kWh/kg. (Including wood stove's efficiency.)

Wood type		energy density (kWh/kg)
softwood	– air dried	4.4
	– oven dried	5.5
hardwood	– air dried	3.75
	– oven dried	5.0
white office paper		4.0
glossy paper		4.1
newspaper		4.9
cardboard		4.5
municipal solid waste		2.6

Table D.3. Calorific value of wood. Sources: Yaros [1997], Ucuncu [1993].

See also Laurie Michaelis, "The Real Cost of Liquid Biofuels," The OECD Observer, October/November 1994. [2mxsj9] Laurie Michaelis works in the Energy and Environment Division of the International Energy Agency at the OECD.

Oxen power

In 'coal substitution', we imagined growing plants and feeding them to a power station, which set fire to them and generated electricity and heat.

Another way of using plants to make electricity is to feed the plants to oxen and have the oxen drive an electricity mill. The power of an ox is 300 W, and it can work for 8 hours per day, so its average delivered power is 100 W (2.5 kWh/d). To supply 15 kWh/d per person, each person needs a team of six oxen.

What's the land area required to feed an oxen-powered power station? Oxen are about 10% efficient at turning chemical energy into work. A life-cycle analysis of oxen takes account the upstream requirements: each ox must first gestate inside an energy-consuming mother, then grow up for three energy-consuming years, before it can take up employment, which might last ten years. This bumps the net efficiency down to 7%. If we could feed oxen on plants with a power density of 0.5 W/m^2(an optimistic figure) then the net power density of the oxen-powered power station would be 0.035 W/m^2. This means that to deliver 15 kWh/d per person, an area of roughly 2 hectares per person would be required. If we assume plants with a more realistic power density of 0.1 W/m^{2}the area required rises to roughly 10 hectares per person.

"A thousand hours of work per year (6 hours per day for about 175 days) and 250 watts of average output, is about the maximum that a South Asian bullock will provide in energy output per year. (But surely it *could* provide more.) Under these assumptions, the annual output of energy amounts to 250 kilowatt hours or 0.9 gigajoules. This is a practical upper limit for the annual energy output of an average bullock." "we take the input to be 20 gigajoules per animal per year, the lower limit of our estimates for energy intake (which went from 20 to 40). About 25% of the input energy can be collected as dung and used as fuel, so that the net energy input is about 15 gigajoules.

For an output of 0.9 gigajoules, we get an estimate of the efficiency of draft animals of 6%. If we ignore dung recovery, then the efficiency would be 4.5%. This is about the upper limit of a range of efficiencies which one might calculate for draft animal use in agriculture.

[On a daily basis Rao estimates the efficiency of an adequately fed bullock as 8.6% (Rao; p. 542). Lawrence and Smith estimated the efficiency of draft animals on a daily basis as 10%, which gives an annual efficiency estimate of about 5%.]

This annual output corresponds to average power of 30 W. The input, in chemical energy in food, is 600 W (some of which can be recovered by using dung as fuel). But a more accurate accounting takes account of the upstream costs: A 3-year old bullock will have consumed 54,666 MJ of feed and its caretaker 1788 MJ of food for a total input of 56,454 MJ before it can begin to provide work output. It might have a ten-year working life. Spreading this embodied energy of 50 GJ over 10 years means the average total energy input per year of work is 25–45 GJ.

Feed's calorific value is 13 GJ per ton.

If the feed is produced from land at a rate of 2 ton/ha/y then a single bullock consuming 25–45 GJ requires 1–1.7 ha. Delivering 30 W from this area, we deduce the power density achieved by the plant–bullock–electric generator chain is 0.0016–0.003 W/m^2.

Energy input

South Asian Rice Production, 1988

Country	Cultivated Area (10^6 ha)	Yield (kg/ha)	Production (10^6 tons)
Bangladesh	10	2190	21.9
India	41	2487	102
Nepal	0.63	2649	1.7
Pakistan	1.4	1991	2.8

Wheat: yield is 1750 kg/ha.

Coarse grain: 1000 kg/ha.

Slash and burn agriculture with a 20-year cycle required 2 ha per person.

E

Heating II

A perfectly sealed and insulated building would hold heat for ever and thus would need no heating. The two dominant reasons why buildings lose heat are:

1. **conduction** – heat flowing directly through walls, windows and doors;

2. **ventilation** – hot air trickling out through cracks, gaps, or deliberate ventilation ducts.

In the standard model for heat loss, both these heat flows are proportional to the temperature difference between the air inside and outside. For a typical British house, conduction is the bigger of the two losses.

Conduction loss

The rate of conduction of heat through a wall, ceiling, floor, or window is the product of the temperature difference, the area of the wall, and a measure of conductivity of the wall known in the trade as the 'U-value' or thermal transmittance.

$$\text{power loss} = \text{temperature difference} \times \text{area} \times U$$

The U-value is usually measured in $\text{W/m}^2\text{/K}$. (One kelvin (1 K) is the same as one degree Celsius (1 °C).) Bigger U-values mean bigger losses of power. The thicker a wall is, the smaller its U-value. Double-glazing is about as good as a solid brick wall.

The U-values of objects that are 'in series', such as a wall and its inner lining, can be combined in the same way that electrical conductances combine:

$$u_{\text{series combination}} = 1 \bigg/ \left(\frac{1}{u_1} + \frac{1}{u_2} \right).$$

kitchen	2
bathroom	2
lounge	1
bedroom	0.5

Table E.3. Air changes per hour: typical values of N for draught-proofed rooms. The worst draughty rooms might have $N = 3$ air changes per hour.

Ventilation loss

To work out the heat required to warm up incoming cold air, we need the heat capacity of air. The heat capacity of air per unit volume is

Table E.2. U-values of other walls and windows.

	U-values (W/m²/K)		
	old buildings	modern standards	best methods
Walls		0.45–0.6	0.12
solid masonry wall	2.4		
outer wall: 9 inch solid brick	2.2		
11 inch brick-block cavity wall, unfilled	1.0		
11 inch brick-block cavity wall, insulated	0.6		
floors		0.45	0.14
suspended timber floor	0.7		
solid concrete floor	0.8		
Roofs		0.25	0.12
flat roof with 25 mm insulation	0.9		
pitched roof with 100mm insulation	0.3		
Windows			1.5
single-glazed	5.0		
double-glazed	2.9		
double-glazed, 20 mm gap	1.7		

1.2 kJ/m³/°C.

In the building trade, it's conventional to describe the power-losses caused by ventilation of a space as the product of the number of changes of the air per hour N, the volume V of the space in cubic metres, the heat capacity C, and the temperature difference δT.

$$\begin{aligned} \text{power (watts)} &= C\frac{N}{1\,\text{h}}V(\text{m}^3)\delta T(^\circ\text{C}) && \text{(E.1)} \\ &= (1.2\,\text{kJ/m}^3/^\circ\text{C})\frac{N}{3600\,\text{s}}V(\text{m}^3)\delta T(^\circ\text{C}) && \text{(E.2)} \\ &= \frac{1}{3}NV\delta T. && \text{(E.3)} \end{aligned}$$

Energy loss and temperature demand (degree-days)

Since energy is power times time, you can write the energy lost by conduction through an area in a short duration as

$$\text{energy loss} = \delta T \times \text{duration} \times \text{area} \times U,$$

and the energy lost by ventilation as

$$\delta T \times \text{duration} \times \frac{1}{3}NV.$$

Both these energy losses have the form

$$(\delta T \times \text{duration}) \times \text{Something},$$

where the 'Something' is measured in watts per °C. As day turns to night, and seasons pass, the temperature difference δT changes; we can think of a long period as being chopped into lots of small durations, during each of which the temperature difference is roughly constant. From duration to duration, the temperature difference changes, but the Somethings don't change. When predicting a space's total energy loss due to conduction and ventilation over a long period we thus need to multiply two things: the sum of all the Somethings (summing Area$\times U$ over walls, roofs, floors, doors, and windows, and $\frac{1}{3}NV$ for the volume), and the sum of all the Temperature difference $\times$ Duration factors (summing over all the durations). The first factor is a property of the building measured in watts per °C. I'll call this the *leakiness* of the building. The second factor is a property of the weather. This second factor is often expressed as a number of 'degree-days', since temperature difference is measured in degrees, and days are a convenient unit for thinking about durations. For example, if your house interior is at 18°C, and the outside temperature is 8°C for a week, then we say that that week contributed $10 \times 7 = 70$ degree-days to the ($\delta T \times$ Duration) sum. I'll call the sum of all the ($\delta T \times$ Duration) factors the 'temperature demand' of a period.

We can reduce our energy consumption for heating by reducing the leakiness of the building, and by reducing our temperature demand. The next two sections look more closely at these two factors, using a house in Cambridge as a case-study.

Temperature demand

We can visualize the temperature demand nicely on a graph of external temperature versus time. For a building held at a temperature of 20°C, the total temperature demand is the *area* between the straight line at 20°C and the external temperature. In figure E.4a, we see that, for one year in Cambridge, holding the temperature at 20°C year-round had a temperature demand of 3188 degree-days of heating and 91 degree-days of cooling. These pictures allow us easily to assess the effect of turning down the thermostat and living without airconditioning. Turning the winter thermostat down to 17°C, the temperature demand for heating drops from 3188 degree-days to 2265 degree-days (figure E.4b), which corresponds to a 30% reduction in heating demand. Turning the thermostat down to 15°C reduces the temperature demand from 3188 to 1748 degree days, a 45% reduction.

These calculations give us a ballpark indication of the benefit of turning down thermostats, but will only give an exact prediction if we take into account two details: buildings naturally absorb energy from the sun, boosting the inside above the outside temperature, even without any heating; and the occupants and their gadget companions emit heat, so further cutting down the artificial heating requirements. The temperature demand of a location, as conventionally expressed in degree-days, is a bit of an unwieldy thing. I find it hard to remember numbers like

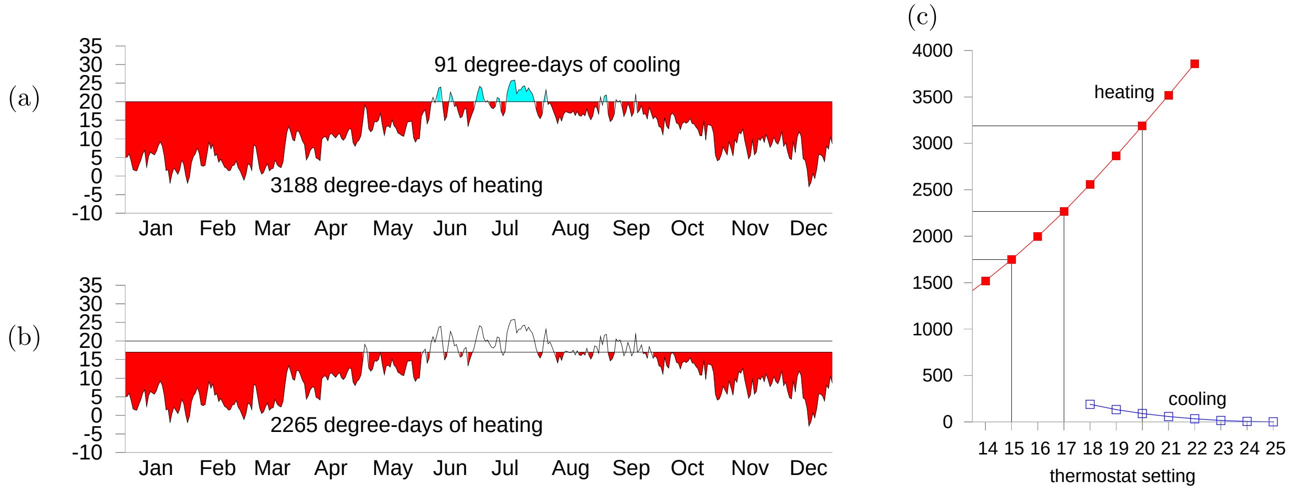


Figure E.4. The temperature demand in Cambridge, 2006, visualized as an area on a graph of daily average temperatures. (a) Thermostat set to 20°C, including cooling in Summer; (b) Winter thermostat set to 17°C. (c) Temperature demand, in degree-days, as a function of thermostat setting (°C). Reducing the winter thermostat from 20°C to 17°C reduces the temperature demand of heating by 30%, from 3188 to 2265 degree-days. Raising the Summer thermostat from 20°C to 23°C reduces the temperature demand of cooling by 82%, from 91 to 16 degree-days.

'3500 degree-days'. And academics may find the degree-day a distressing unit, since they already have another meaning for degree days (one involving dressing up in gowns and mortar boards). We can make this quantity more meaningful and perhaps easier to work with by dividing by 365, the number of days in the year, obtaining the temperature demand in 'degree-days per day', or, if you prefer, in plain 'degrees'. Figure E.7 shows this replotted temperature demand. Expressed this way, the temperature demand is simply the *average* of the temperature difference between inside and outside. The highlighted temperature demands are: for a thermostat setting of 20°C: 8.7°C; for 17°C: 6.2°C; and for 15°C: 4.8°C.

Leakiness – example: my house

My house is a three-bedroom semidetached house built about 1940. By 2006, its kitchen had been slightly extended, and most of the windows were double-glazed. The front door and back door were both still single-glazed.

My estimate of the leakiness is built up as follows:

Surfaces	Area (m^2)	U-value ($W/m^2/°C$)	leakiness ($W/°C$)
Horizontals			
Pitched roof	48	**0.6**	28.8
Flat roof	1.6	3	4.8
Floor	50	0.8	40
Verticals			
Extension walls	24.1	0.6	14.5
Main walls	50	**1**	50
Thin wall (5in)	2	3	6
Single-glazed doors and windows	7.35	**5**	36.7
Double-glazed windows	17.8	2.9	51.6
Total thermal leakiness			232.4

I've treated the central wall of the semi-detached house as a perfect insulating wall, but this may be wrong if there's actually a well-ventilated air gap in there.

Spaces	Volume (m^3)	N (airchanges per hour)	leakiness ($W/°C$)
Bedrooms	80	0.5	13.3
Kitchen	36	2	24
Hall	27	**3**	27
Other rooms	77	1	25.7
Total ventilation leakiness			90

The total leakiness of the house is 322 W/°C, with conductive leakiness accounting for 72% and ventilation leakiness for 28%. The conductive leakiness is roughly equally divided into three parts: windows; walls; and floor and ceiling.

We can also express the leakiness as 7.7 kWh/d/°C.

One way of presenting the leakiness that allows one dwelling to be compared with another is to divide the leakiness by the floor area; this gives the *heat loss parameter* of the dwelling, which is measured in $W/°C/m^2$. The heat loss parameter of this house (total floor area 88 m^2) is

$$3.7\,W/°C/m^2.$$

Let's use these figures to estimate the house's daily energy consumption on a cold winter's day, and year-round.

Assuming an external temperature of $-1°C$ and an internal temperature of 19°C, the temperature difference is $\Delta T = 20°C$. If this difference is maintained for 6 hours per day then the energy lost per day is

$$322\,W/°C \times 120\,\text{degree-hours} \simeq 39\,kWh.$$

If the temperature is maintained at 19°C for 24 hours per day, the energy lost per day is

$$155\,kWh/d.$$

To get a year-round heat-loss figure, we can take the temperature demand of Cambridge from figure E.4(c). With the thermostat at 19°C, the temperature demand in 2006 was 2866 degree-days. The average rate of heat loss, if the house is always held at or above 19°C, is therefore:

$$7.7\,\mathrm{kWh/d/°C} \times 2866\,\text{degree-days/y}/(365\,\text{days/y}) = 61\,\mathrm{kWh/d}.$$

Turning the thermostat down to 17°C, the average rate of heat loss drops to 48 kWh/d. Turning it up to a tropical 21°C, the average rate of heat loss is 75 kWh/d.

What's a reasonable thermostat setting to aim for? Nowadays many people seem to think that 17°C is unbearably cold. However, the average internal temperature in British houses in 1970 was 13°C! A human's perception of whether they feel warm enough depends on what they are doing, and what they've been doing for the last hour or so. My suggestion is, rather than fixing the thermostat to a single value, to try setting it to a low value most of the time (say 13 or 15°C), and turn it up for a few hours whenever you feel cold.

Figure E.5. My house.

Effects of extra insulation

During 2007, I made the following modifications to the house.

1. added cavity wall insulation (which was missing in the main walls of the house)
2. increased the insulation in the roof.
3. added a new front door outside the old one.
4. replaced the back door with double-glazed one.
5. double-glazed the one window that was still single-glazed.

What's the predicted change in heat loss?

The total leakiness was 322 W/°C.

Adding cavity-wall insulation (new U-value 0.6) to the main walls reduces the house's leakiness by 20 W/°C. The improved loft insulation (new U-value 0.3) should reduce the leakiness by 14 W/°C. The glazing modifications (new U-value 1.6–1.8) should reduce the conductive leakiness by 23 W/°C, and the ventilation leakiness by something like 24 W/°C. That's a total reduction in leakiness of 25%, from roughly 320 to 240 W/°C (7.7 to 6 kWh/d/°C).

The heat loss parameter of this house (total floor area 88 m^2) is thus hopefully reduced from 3.7 to 2.7 $\mathrm{W/°C/m}^2$ – a long way from the 1.1 $\mathrm{W/°C/m}^2$ required of a 'sustainable' house in the new building codes.

It's frustratingly hard to make a really big dent in the leakiness of an already-built house! As we saw a moment ago, a much easier way of achieving a big dent in heat loss is to turn the thermostat down. Turning down from 20 to 17°C gave a reduction in heat loss of 30%.

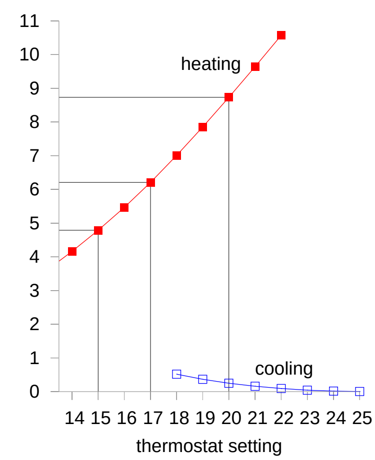


Figure E.7. The temperature demand in Cambridge, 2006, replotted in units of degree-days per day, also know as degrees. In these units, the temperature demand is just the average of the temperature difference between inside and outside.

The predicted reductions break down as follows (on a cold winter day):

– Ventilation reductions in hall and kitchen from improvements to doors and windows	2.9 kWh/d
– Reduction in conduction from double-glazing two doors and one window	1.9 kWh/d
– Cavity wall insulation (applicable to two thirds of the wall area)	4.8 kWh/d
– Improve roof insulation	3.5 kWh/d

Combining these two actions – the physical modifications and the turning-down of the thermostat – this model predicts that heat loss should be reduced by nearly 50%. Since some heat is generated in a house by sunshine, gadgets, and humans, the reduction in the heating bill should be more than 50%.

I made all these changes to my house and monitored my meters every week. I can confirm that my heating bill indeed went down by more than 50%. My gas consumption has gone down from 40 kWh/d to 13 kWh/d – a reduction of 67%.

Estimated loss, when temperature difference is 20°C:

Leakiness reduction by internal wall-coverings

Can you reduce your walls' leakiness by covering the *inside* of the wall with insulation? The answer is yes, but there may be two complications. First, the thickness of internal covering is bigger than you might expect. To transform an existing nine-inch solid brick wall (U-value 2.2 W/m^2/K) into a decent 0.30 W/m^2/K wall, roughly 6 cm of insulated lining board is required. `http://www.dorset-technical-committee.org.uk/reports/U-values-of-elements-Sept-2006.pdf` Second, condensation may form on the outside surface of such internal insulation layers, leading to damp problems.

If you're not looking for such a big reduction in wall leakiness, you can get by with a thinner internal covering. For example, you can buy 18-mm-thick insulated wallboards with a U-value of 1.7 W/m^2/K. With these over the existing wall, the U-value would be reduced from 2.2 to:

$$1 \Big/ \left(\frac{1}{2.2} + \frac{1}{1.7} \right) \simeq 1\,\mathrm{W/m^2/K}.$$

Definitely a worthwhile reduction.

Other heating topics

While we are on the topic of heating, we should discuss the ultimate energy cost of two alternative styles of heating: electricity, or direct combustion. Also other options including heat pumps and combined heat and power.

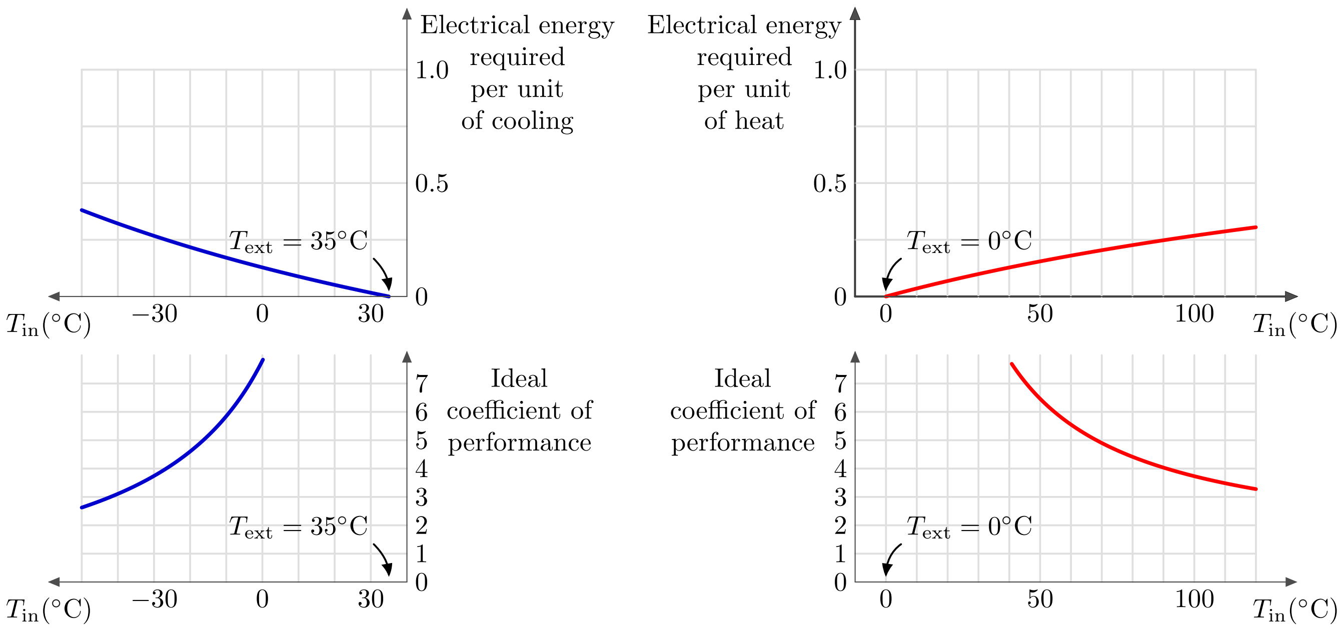


Figure E.8. Ideal heat pump efficiencies. Top left: Ideal electrical energy required, according to the limits of thermodynamics, to pump heat *out* of a place at temperature T_{in} when the heat is being pumped to a place at temperature $T_{\text{out}} = 35°\text{C}$. Right: ideal electrical energy required to pump heat *into* a place at temperature T_{in} when the heat is being pumped from a place at temperature $T_{\text{out}} = 0°\text{C}$. Bottom row: the efficiency is conventionally expressed as a 'coefficient of performance', which is simply the heat pumped per unit electrical energy. In practice, ground source heat pumps have a coefficient of performance of 3 to 4.

Theory of heat pumps

This is where a full explanation would require a discussion of entropy. For the time being, I'll just give the formulae for the ideal efficiency, that is, the electrical energy required per unit of heat pumped. If we are pumping heat from an outside place at temperature T_1 into a place at higher temperature T_2, both temperatures being expressed relative to absolute zero (that is, T_2, in kelvin, is given in terms of the Celsius temperature T_{in}, by $273.15 + T_{\text{in}}$).

$$\text{efficiency} = 1 - \frac{T_1}{T_2}$$

If we are pumping heat out from a place at temperature T_2 to a warmer exterior at temperature T_1, the ideal efficiency is

$$\text{efficiency} = \frac{T_1}{T_2} - 1.$$

Ground source heat pumps are discussed more in chapter 21.

Performance figures in the UK

'The largest drop in the the estimated coefficient of performance occurs when ideal heat exchangers are replaced by practical heat exchangers – ones both small enough to get through the door of a house and cheap enough to cost less than the house.' Wheatley et al. [1986]

An office heating/cooling unit, using external air as the heat source or sink, says in its blurb that it uses up to 0.83 kW(e) when heating and delivers 3.6 kW. Or when cooling, it uses 0.62 kW(e) and delivers 2.6 kW. The ratio of heat pumped in or out to power required is called the coefficient of performance. Both ratios are a bit more than a factor of 4. According to Wheatley et al. [1986] however, we should expect any air-source heat pump based on the standard Rankine cycle working between temperatures of 5 and 20°C (and thus having its cold and hot sides at −5 and 45°C) to have a coefficient of performance of 3 or at most 4.

A domestic ground source heat pump with an output temperature of 45°C and output power of 4 kW, collecting heat from a 200 m ground loop buried just 1 m deep, had a coefficient of performance of 3.16. This domestic system included a 90-watt distribution pump which ran non-stop all year round. Performance would have been better (a coefficient of performance of 3.43) if the pump had switched off when not needed. The ground collector collects heat a rate of about 20 or 30 W per metre of collector length. `http://www.heatpumpnet.org.uk/files/gir72.pdf`

Figure E.9. Great Oak Cohousing project, Ann Arbor, Michigan

Heating for cooling

How can heat (from say a solar collector) be used to supply cooling?

'The absorption refrigerator is a refrigerator that utilizes a heat source to provide the energy needed to drive the cooling system rather than being dependent on electricity to run a compressor. These refrigerators are popular where electricity is unreliable, costly, or unavailable, or where surplus heat is available, e.g., from turbine exhausts or industrial processes.'

'The classic absorptive home refrigerator cools by evaporating liquid ammonia in a hydrogen environment. The now-gaseous ammonia is then absorbed (dissolved) into water, and then later separated (boiled off from the water) by a small source of heat. This drives off the dissolved ammonia gas which is then condensed into a liquid. The liquid ammonia then enters the hydrogen-charged evaporator to repeat the cycle.'

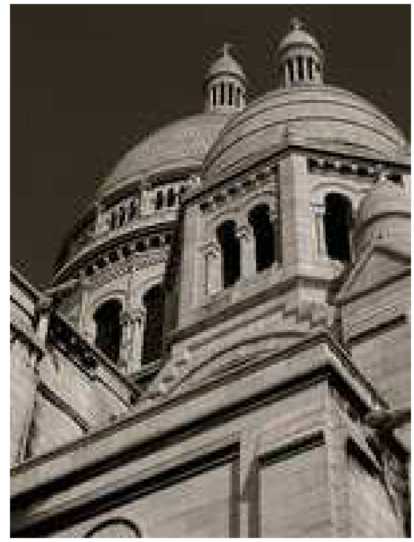
Notes

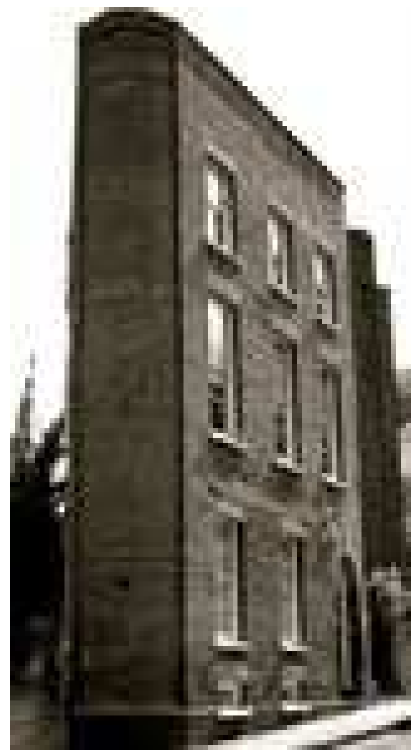
[K-value is conductivity, usually measured in W/m/K, for example 0.023 W/m/K. Sometimes called λ-value? R-value is thermal resistance (the inverse of U-value), usually measured in m^2K/W.]

285 *The average internal temperature in British houses in 1970 was 13°C!* [Department of Trade and Industry, 2002a, para 3.11]

What about the other things in the house that are involved in heating up and cooling down?

Heat capacity of asphalt, brick, concrete, glass, granite, marble, sand, soil: all around 0.85 J/g/K. Very close to air's 1 kJ/kg/K. Wood: 0.4 J/g/K. Iron: 0.45 J/g/K.





Chairs: 10 at 5 kg. Sofa: 60 kg. Tables: 30 kg. Cabinets: 50 kg. China: 50 kg. Everything: maybe a tonne of stuff, similar to wood? So warming a tonne of stuff has an energy cost of $1000\text{kg} \times 20°\text{C} \times 0.4\,\text{kJ/m}^3/°C = 8000\text{kJ} = 3\,\text{kWh}$. So the stuff dominates the air.

Air-exchange

Once a building is really well insulated, the principal loss of heat will be through ventilation (air changes) rather than through conduction. The heat loss through ventilation can be reduced by transferring the heat from the outgoing air to the incoming air. Remarkably, a great deal of this heat can indeed be transferred without any additional energy being required. The trick is to use a nose, as discovered by natural selection.

The longer your nose, the better it works as a counter-current heat exchanger. Noses also use the same principle to reduce water-loss.

Ground storage from summer to winter

Thermal conductivities: Water: 0.6 watts per metre-kelvin, (W m^{-1} K^{-1}). Quartz: 8. Conductivity of granite: 2.1 W/m/K. Earth's crust: 1.7. Dry soil: 0.14.

A spike of heat put down a hole in the ground will spread as

$$\frac{1}{\sqrt{4\pi\kappa t}} \exp\left(-x^2/(4(\kappa/(C\rho))t)\right)$$

where κ is the conductivity, C is the heat capacity, and ρ is the density. This describes a bell-shaped curve with width

$$\sqrt{2\frac{\kappa}{C\rho}t};$$

for example, after a time $t = 1.6 \times 10^7$ s (six months), using the figures for granite ($C = 820$ J/kg/K, $\rho = 2500\,\text{kg/m}^3$, $\kappa = 2.1\,\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$), the width is: 6 m.

Using the figures for water ($C = 4200$ J/kg/K, $\rho = 1000\,\text{kg/m}^3$, $\kappa = 0.6$ W/m/K), the width is: 2 m.

So if the storage region is bigger than $20\,\text{m} \times 20\,\text{m} \times 20\,\text{m}$ then most of the heat stored will still be there in six months time.

Two other constraints force the dimensions of the storage region: it must be big enough to hold all the energy that we want to leave there, and it must have enough surface area exposed to our pipes for us to be able to get the heat in.

Code for sustainable housing

To get credit towards a code rating the 'heat loss parameter' must be $\leq$ 1.1. What does that mean? Is it the U-value of the wall? $1.1\,\text{W/m}^2/\text{K}$.

Or is it the total leakiness (both thermal and ventilation) in W/K divided by total floor area in m^2? – which gives it the same units as a U-value.

The older 'EcoHome' standard measures CO_2 emissions relative to a baseline of 40 kg/m^2/y.

The German Passivhaus standard aims for total energy consumption of 15 kWh/m^2/y. One way to achieve this target is to take a house that comes close, then add some extra floor area to it, by adding a basement.

The building standards' standard set-point temperatures are Living area: 21 C; Rest of dwelling: 18C.

Typical heat capacity of a dwelling on a 3-hour time scale (for heating system calculations): 10 MJ/K. On a 24-hour time scale (for gains calculations): 25 MJ/K.

Maximum permitted U values in the 1985 building regulations: walls and floors: 0.45 W/m^2/K. Roofs: 0.25 W/m^2/K.

Maximum permitted U values in the 1991 building regulations: Exposed walls: 0.45 W/m^2/K. Roofs: 0.2 W/m^2/K. Exposed floors: 0.35 W/m^2 Windows, doors and rooflights: 3.0 W/m^2/K.

Maximum permitted U values in the 2000 building regulations: Roof: 0.16–0.25 W/m^2/K. (Different for different types.) Walls: 0.35 W/m^2/K. Floors: 0.25 W/m^2/K. Windows, doors and rooflights: 2.0 W/m^2/K.

The recommended rate of air exchange is between 0.5 and 1.0 air changes per hour, providing adequate fresh air for human health, for safe combustion of fuels and to prevent damage to the building fabric from excess moisture in the air (EST 2003).

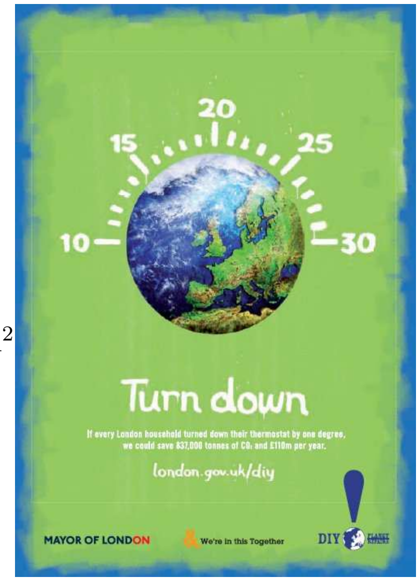


Figure E.11. Advertisement from the 'DIY planet repairs' campaign. The text reads "**Turn down**. If every London household turned down their thermostat by one degree, we could save 837 000 tonnes of CO_2 and £110m per year." `london.gov.uk/diy/` Expressed in savings per person, that's 0.12 t CO_2 per year per person. That's about 1% of our total, so this is good public advice. Well done, Ken!

An energy-efficient house

In 1984 an energy consultant, Alan Foster, built an energy-efficient house near Cambridge; he kindly gave me his thorough measurements. It is a timber-framed bungalow based on a Scandinavian 'Heatkeeper Serrekunda' design, with a floor area of 140 m^2, composed of 3 bedrooms, study, two bathrooms, living room, kitchen, and lobby. The wooden outside walls were supplied in kit form by a Scottish company, and the main parts of the house took only a few days to build.

The walls are 30 cm thick and have a U-value of 0.28. From the inside out, they consist of 13 mm of plasterboard, 27 mm airspace, a vapour barrier, 8 mm of plywood, 90 mm of rockwool, 12 mm of bitumen-impregnated fibreboard, 50 mm cavity, and 103 mm of brick. The external bricks are not load-bearing. The ceiling construction is similar with 100–200 mm of rockwool insulation. The ceiling has a U-value of 0.27 W/m^2/°C, and the floor, 0.22 W/m^2/°C. The windows are double-glazed (U-value 2 W/m^2/°C), with the inner panes's outer surfaces specially coated to reduce radiation. The windows are arranged to give substantial solar gain, contributing about 30% of the house's space-heating.

The house is well sealed, every door and window lined with neoprene gaskets. The house is heated by warm air pumped through floor grilles;

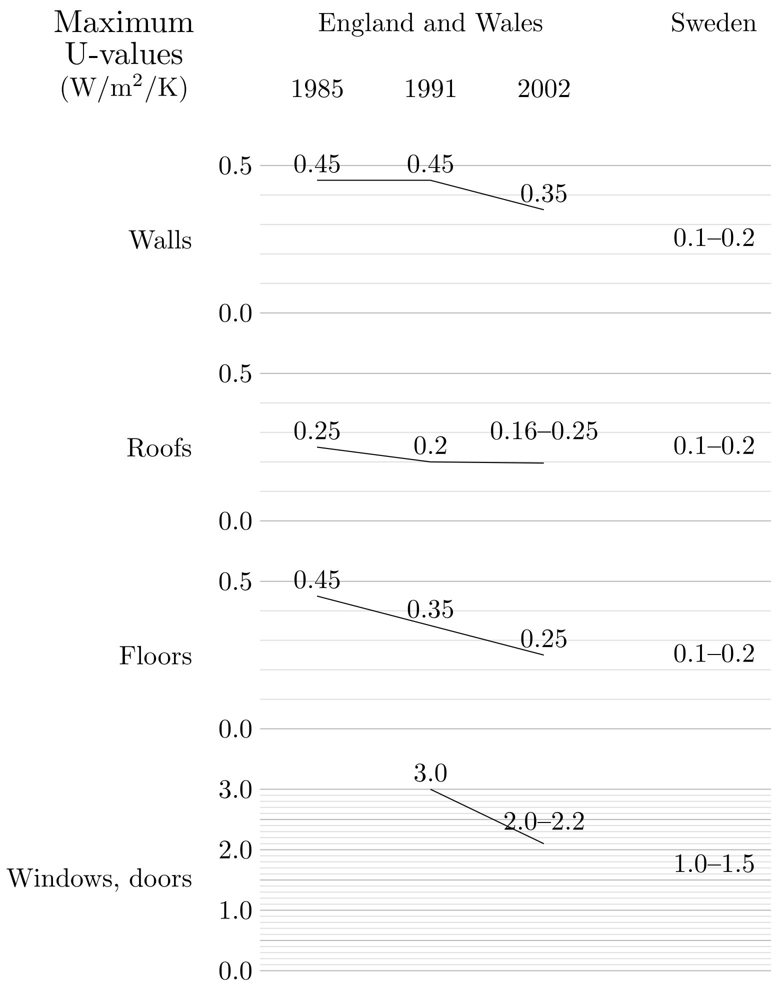


Figure E.10. U-values required by British and Swedish building regulations.

pumps extract air from several rooms and take in air from the loft space in winter, using a heat exchanger to save 60% of the heat in the extracted air. On a cold winter's day, the outside air temperature was −8°C, the temperature in the loft's air intake was 0°C, and the air coming out of the heat exchanger was at +8°C.

For the first decade, the heat was supplied entirely by electric heaters, heating a 150-gallon heat store during the overnight economy period. More recently a gas supply was brought to the house, and the space heating was obtained from a condensing boiler.

The heat loss through conduction and ventilation is 4.2 kWh/d/°C. The heat loss parameter (the leakiness per square metre of floor area) is 1.25 W/m^2/°C(*cf.* my house's 2.7 W/°C/m^2).

With the house occupied by two people, the average space-heating consumption, with the thermostat set at 19 or 20°C during the day, was 8100 kWh per year, or 22 kWh/d; the total energy consumption for all purposes was about 15000 kWh per year, or 40 kWh/d. Expressed as an average power per unit area, that's 6.6 W/m^2.

Benchmarks for offices

The average energy consumption of the UK service sector, per unit floor area, is 30 W/m^2.

An energy-efficient office

The National Energy Foundation built themselves a low-cost low-energy building. It has solar panels for hot water, solar photovoltaic panels generating up to 6.5 kW of electricity, and is heated by a 14 kW ground-source heat pump and occasionally by a wood stove. The floor area is 400 m^2 and the number of occupants is about 30. It is a single-storey building. The walls contain 300 mm of rockwool insulation. The heat-pump's coefficient of performance in winter was 2.5. The energy used is 65 kWh per year per square metre of floor area (7.4 W/m^2). The PV system delivers almost 20% of this energy.

Contemporary offices

Cambridge University built two new office buildings about the same time.

Roger Needham Building, Cambridge. (holds computer science researchers and administrators.) Area: 7216 m^2. Consumption 1923 MWh/y, or 266 kWh/y/m^2, or 0.73 kWh/d/m^2, or 30 W/m^2. Roughly 150 people work there on average. 35 kWh/d per person. "The Roger Needham building is designed for low energy consumption with a high degree of of spatial flexibility and comfort in order to adapt to future research trends and practices. The building has no conventional heating system, and cooling is achieved through chilled beams. The omission of heating system and choice of cooling system will minimise greenhouse gas emission and this building will set a new low energy standard for a computer building in the UK."

William Gates building: holds computer science researchers, administrators, and a small café. Roughly 274 people work there. 11 110 m^2. 1982 MWh/y. 178 $kWh/m^2/y$, or $20\,W/m^2$. And 20 kWh/d per person. This building won a RIBA award in 2001 for its predicted energy consumption. "The architects have incorporated many environmentally friendly features into the building."

But are these buildings impressive? Next door, the Rutherford building, designed in the 1970s without any fancy eco-claims – indeed without even double glazing – has a floor area of 4998 m^2 and consumes 1096 MWh per year; that's $0.6\,kWh/d/m^2$, or $25\,W/m^2$. Roughly 200? people work there. So that's 15 kWh/d per person.

F

Waves II

The physics of deep-water waves

Waves contain energy in two forms: potential energy, and kinetic energy. The potential energy is the energy required to move all the water from the troughs to the peaks.

People sometimes assume that when the crest of a wave moves across an ocean at 30 miles per hour, the water in that crest must also be moving at 30 miles per hour in the same direction. But this isn't so. It's just like a Mexican wave. When the wave rushes round the stadium, the humans who are making the wave aren't themselves moving round the stadium: they just bob up and down a little. The motion of a piece of water in the ocean is similar: if you focussed on a bit of seaweed floating in the water as waves go by, you'd see that the seaweed moves up and down; at the same time it moves a little to and fro in the direction of travel of the wave – the exact effect could be recreated in a Mexican wave if people moved like window-cleaners, polishing a big piece of glass in a circular motion. The wave has potential energy because of the elevation of the crests above the troughs. And it has kinetic energy because of the small circular bobbing motion of the water.

Our rough calculation of the power in ocean waves will require three ingredients: an estimate of the period T of the waves (the time between crests), an estimate of the height h of the waves, and a physics formula that tells us how to work out the speed v of the wave from its period.

The wavelength and period of the waves (the distance and time between two adjacent peaks) depend on the speed of the wind that creates the waves as shown in figure F. The height of the waves doesn't depend on the windspeed; rather, it depends on how long the wind has been caressing the water surface.

You can estimate the period of ocean waves by recalling the time between waves arriving on an ocean beach. Is 10 seconds reasonable? For the height of ocean waves, let's assume an amplitude of 1 m, which means 2 m from trough to peak. In waves this high, a man in a dinghy can't see beyond the nearest crest when he's in a trough; I think this height is bigger than average, but we can revisit this estimate if we

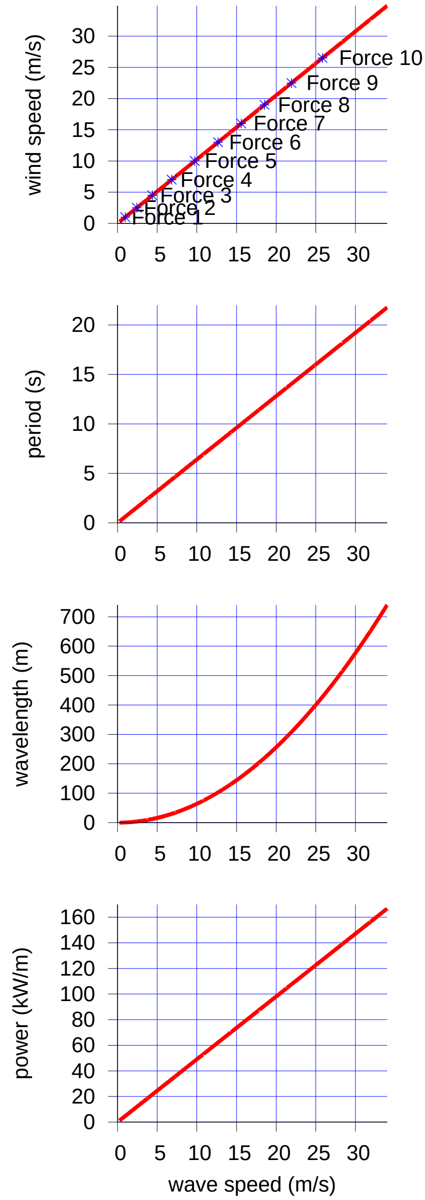


Figure F.2. Facts about deep-water waves. In all four figures the horizontal axis is the wave speed in m/s. From top to bottom the graphs show: wind speed (in m/s) required to make a wave with this wave speed; period (in seconds) of a wave; wavelength (in m) of a wave; and power density (in kW/m) of a wave with amplitude 1 m.

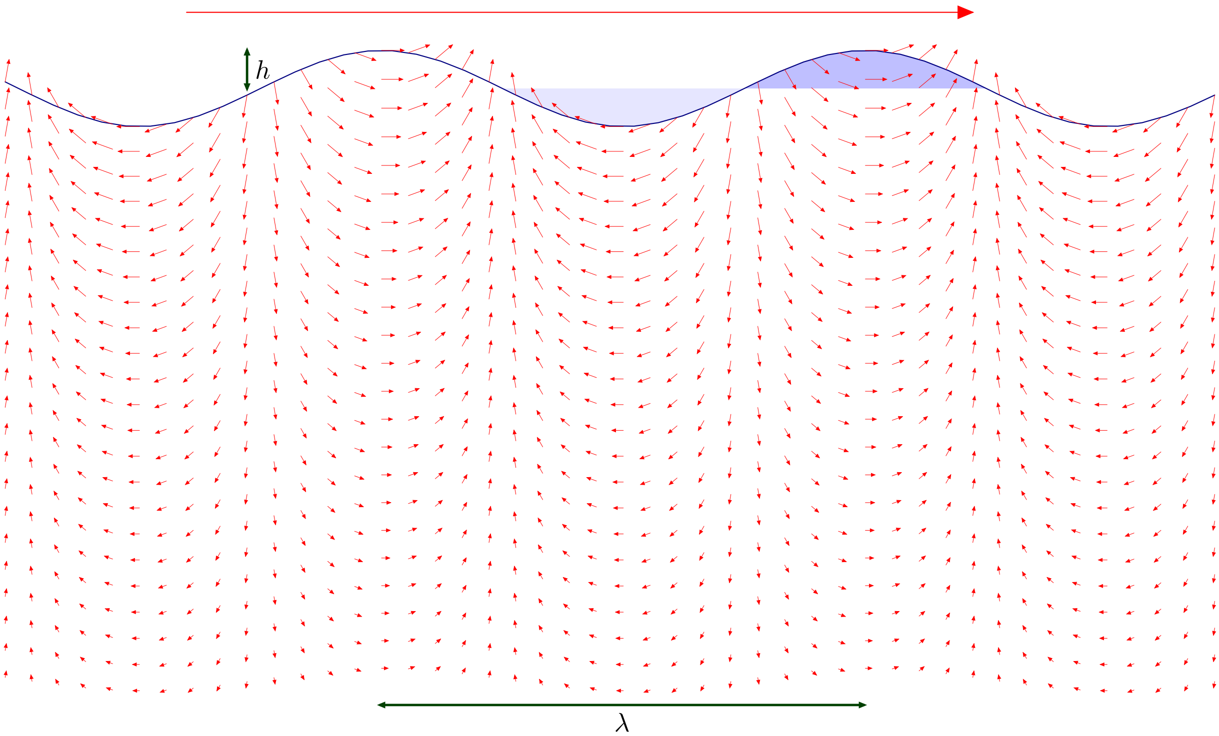


Figure F.1. A wave has energy in two forms: potential energy associated with raising water out of the light-shaded troughs into the heavy-shaded crests; and kinetic energy of all the water within a few wavelengths of the surface – the speed of the water is indicated by the small arrows. The speed of the wave, travelling from left to right, is indicated by the much bigger arrow at the top.

decide it's important. The speed of deep-water waves is related to the time T between peaks by

$$v = \frac{gT}{2\pi}.$$

(This formula is explained in this chapter's end-notes.) For example, if $T = 10$ seconds, then $v = 16\,\text{m/s}$. The wavelength λ of such a wave – the distance between crests – is $\lambda = vT = gT^2/2\pi = 160\,\text{m}$.

If a wave of wavelength λ passes by every $T = 10$ seconds, and if the height of each peak and depth of each trough is is $h = 1\,\text{m}$, then the potential energy passing per unit time, per unit length, is

$$P_{\text{potential}} \simeq m^* g\bar{h}/T, \tag{F.1}$$

where m^* is the mass per unit length, which is roughly $\frac{1}{2}\rho h(\lambda/2)$ (approximating the area of the shaded crest by the area of a triangle), and $\bar{h}$ is the change in height of the centre of mass of the chunk of elevated water, which is roughly h. So

$$P_{\text{potential}} \simeq \frac{1}{2}\rho h \frac{\lambda}{2} gh/T. \tag{F.2}$$

And λ/T is simply the speed at which the wave travels, v.

$$P_{\text{potential}} \simeq \frac{1}{4}\rho g h^2 v. \tag{F.3}$$

Now waves have kinetic energy as well as potential energy, and the total power of the waves is double the power calculated from potential energy.

$$P_{\text{total}} \simeq \frac{1}{2}\rho g h^2 v. \tag{F.4}$$

Plugging in $v = 16\,\text{m/s}$ and $h = 1\,\text{m}$, we find

$$P_{\text{total}} \simeq \frac{1}{2}\rho g h^2 v = 80\,\text{kW/m}. \tag{F.5}$$

Are ocean waves usually two metres high from peak to trough every day? As I said, that sounds quite big. We should certainly allow for some calmer days. Let's halve this estimate to obtain our average estimate of wave power:

$$\text{Wave power (average)} = 40\,\text{kW/m}.$$

This rough estimate agrees with real measurements in the Atlantic. Mollison [1986].

Real wave power systems

Deep-water devices

How effective are real systems at extracting power from waves? Salter's 'duck' has been well characterised: a row of 16 m diameter ducks sucks about 50% of the power out of incoming Atlantic waves, and the efficiency of the remaining steps (conversion to electricity, and transmission to a 'hydrodynamically underprivileged area' such as London is about 60%. So if we completely fill half of the 1000 km exposed Atlantic deep-sea-coastline with 50% efficient ducks, followed by 60% conversion and transmission efficiency, we get $40\,\text{kW/m} \times (1/2) \times 0.5 \times 0.6 \times 10^6\,\text{m} = 6\,GW$ or 2.4 kWh/d each.

Memorable figures: deep water Salter Ducks, feeding off 45 MW/km, deliver 19 MW/km, including transmission to central Scotland Mollison [1986].

From Mollison [1986]: "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." Using a conservative mean output estimate of 15–20 MW/km, the potential power delivered is UK: 12 GW (100 TWh/y, or 5 kWh/d per person); Ireland: 12 GW; Faeroes, France, Spain, Portugal: 5–8 GW each.

The Pelamis device, created by Ocean Power Delivery, has taken over the Salter duck's mantle as the leading floating deep-water wave device. Each snake-like device is 130 m long and is made of a chain of four segments, each 3.5 m in diameter. It has a maximum power output of 750 kW. The Pelamises are designed to be moored in depth about 50 m. In a wavefarm, 39 devices in three rows would face the principal wave direction, occupying a square km of ocean, about 400 m deep and 2.5 km wide. The effective cross section of a single Pelamis is 7 m (*i.e.*, for good waves, it extracts 100% of the energy that would cross 7 m). The company says that such a wave-farm would deliver about 10 kW/m (10 MW/km).

If 50% of the exposed Atlantic deep-sea-coastline (500 km) were occupied by Pelamis wave-farms (a total of 7500 devices in 200 wavefarms) then the power delivered would be 5 GW, or 2 kWh/d each.

What is the weight of each device? 700 tons, including 350 or 400 tons of ballast. Compare with the steel-requirements for offshore wind: An offshore wind-turbine with a maximum power of 3 MW weighs 500 tons, including its foundation. So the total weight per kW of a wave-machine, half a ton per kW, is not much bigger than that of a wind-turbine.

Shallow-water devices

Typically 70% of energy is lost through bottom-friction as the depth decreases from 100 m to 15 m. So the average wave-power per unit length of coastline in shallow waters is reduced to about 12 kW per metre. The Oyster, developed by Queen's University Belfast and Aquamarine Power Ltd., is a bottom-mounted flap, about 12 m high, that is intended to be deployed in waters about 12 m deep. A single device would produce about 270 kW in wave heights greater than 3.5 m. Assume its width is about 20 m? Then the ideal power for a device of cross section 20 m would be 240 kW. A rough average figure is about 100 kW. A smaller power than the Pelamis, but a bigger power per unit mass of hardware.

If 400 km of the shallow coastline were peppered with Oysters, three of them every hundred metres, then the power delivered would be 1.2 GW, or about 0.5 kWh/d each.

The total from deep- and shallow-water devices would be at most 5.2 GW (perhaps a little less, if they were installed in such a way that the one shadowed the other). (2.1 kWh/d each.)

Notes

The relationship between the frequency of a deep-water wave and its wavelength can be derived in a couple of ways. One neat trick is to ask what *possible* form the relationship could take. Relationships are *possible* if they don't involve adding apples to oranges (or equating them to each other). (Two examples of 'possible' relationships are 'area of triangle = half base times height' and 'area of triangle = base times base'; both are 'possible' because they equate an area to a product of two lengths. An illegal relationship, in contrast, is 'area of triangle = base + height'; this relationship can be ruled out instantly by 'dimensional analysis', because it equates an area to a length, and areas are not lengths, they are squared-lengths.)

If we find that only one form of relationship is possible, then, like Sherlock Holmes, we can deduce that that relationship must be true.

[More details of dimensional analysis here.]

ω	T^{-1}
λ	L
ρ	M/L^3
g	L/T^2

$$\Rightarrow \frac{\lambda\omega^2}{g} = \kappa \text{ (a dimensionless constant)}$$

$$v = \frac{gT}{2\pi}.$$

Or if you want speed in terms of wavelength,

$$v = \sqrt{\frac{g\lambda}{2\pi}}.$$

The group velocity is half of v.
See Faber [1995], p. 170.

CAT report

The CAT report (zerocarbonbritain) assumes that you could get 250 TWh/y out of a technical potential of 600–750 TWh. Where did they get this figure? Answer: BWEA. (2007) Marine Renewable Energy. British Wind Energy Association, www.bwea.com/marine/resource.html This gives a throw-away figure of 'as much as 700 TWh/y', but then says that ETSU reckoned 50 TWh/y.

Conventions

From Mollison [1986], we learn the following facts and conventions. A wave-train of amplitude a has root-mean-square wave-height H given by

$$H^2 = \frac{1}{2}a^2.$$

The power flux is

$$P = \frac{\rho g^2}{4\pi} H^2 T,$$

where T is the period. The phase velocity is $U = gT/(2\pi)$; the wavelength is $L = gT^2/(2\pi)$. The 'significant wave height' is

$$H_{\mathrm{S}} = 4H_{\mathrm{rms}}.$$

Wave growth

Wave energy density per unit area, $E = \rho g H^2$, grows roughly linearly with fetch x:

$$H_{\mathrm{rms}}^2 \simeq 1.6 \times 10^{-7} U_{10}^2 \frac{x}{g},$$

where U_{10} is the windspeed measured 10 m above the sea surface. The greater the fetch, the greater the mean period T_{e} of the waves created. Empirically $T_{\mathrm{e}} \sim x^{1/3}$. In fully developed seas, $H_{\mathrm{rms}} = 0.0053U_{19.5}^2$ (presumably SI units). And the mean period is $T_{\mathrm{e}} = 0.625U_{19.5}$ – again, presumably SI units. The associated phase velocity for this period of wave is $U_{\rm e} = gT_{\rm e}/(2\pi) = \frac{g}{2\pi}0.625U_{19.5} = 0.98U_{19.5}$. The power in such a fully developed sea is proportional to U^5 and the fetch required to generate it is proportional to U^2. This fetch is roughly 3000 wavelengths. (Using the wavelength associated with the mean period.) For example, if $U_{19.5} = 20\,\text{m/s}$, $H_{\rm rms} = 2.12\,\text{m}$, $T_{\rm e} = 12.5\,\text{s}$, and the required fetch is about 700 km. The power density attained is 440 kW/m, and the mean rate of energy transfer from wind to sea is 0.6 W/m^2.

Losses from viscosity are minimal: a wave of 9 seconds period would have to go three times round the world to lose 10% of its amplitude.

G

Tide II

Power density of tidal pools

Production on ebb and flow

To estimate the power of an artificial tide pool, imagine that it's filled rapidly at high tide, and emptied rapidly at low tide. Power is generated in both directions. The change in potential energy of the water, each six hours, is mgh, where h is the change in height of the centre of mass of the water, which is half the range (figure 13.3). The mass per unit land-area covered by tide-pool is $\rho \times (2h)$, where ρ is the density of water ($1000\,\mathrm{kg/m^3}$). So the power per unit area generated by a tide pool is

$$\frac{2\rho hgh}{6\,\mathrm{hours}},$$

assuming perfectly efficient generators. Plugging in $h = 2\,\mathrm{m}$ (*i.e.*, range 4 m), we find the power per unit area of tide-pool is $3.6\,\mathrm{W/m^2}$. Allowing for an efficiency of 90% for conversion of this power to electricity, we get

$$\text{power per unit area of tide-pool} \simeq 3\,\mathrm{W/m^2}.$$

So to generate 1 GW of power (on average), we need a tidepool with an area of about $300\,\mathrm{km^2}$. A circular pool with diameter 20 km would do the trick.

Tides as tidal waves

The tides around Britain are 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 Scillys to Portsmouth and on to Dover. Similarly, a high tide moves clockwise round Scotland, rolling down the North Sea from Wick to Berwick and on to Hull. These two high tides converge on the Thames Estuary. By coincidence, the Scottish wave arrives about 12 hours later than the one that came via Dover, so it arrives in synchrony with the

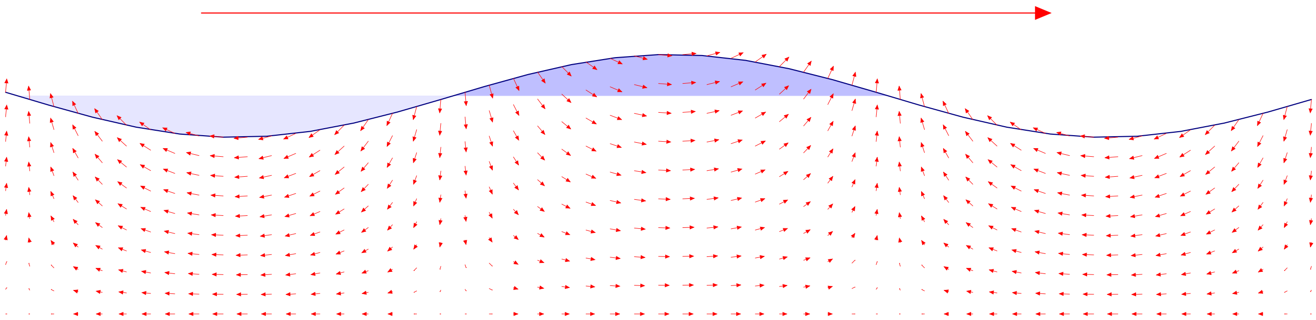


Figure G.1. A shallow-water wave. Just like a deep-water wave, the wave has energy in two forms: potential energy associated with raising water out of the light-shaded troughs into the heavy-shaded crests; and kinetic energy of all the water moving around as indicated by the small arrows. The speed of the wave, travelling from left to right, is indicated by the much bigger arrow at the top. For tidal waves, a typical depth might be 100 m, the crest velocity 30 m/s, the vertical amplitude at the surface 1 or 2 m, and the water velocity amplitude 0.3 or 0.6 m/s.

next high tide via Dover, and London receives the normal two high tides per day. The location of the high tide moves much faster than the tidal flow – one hundred miles per hour, say, while the water itself moves at just one mile per hour.

The energy we can extract from tides, using tidal pools or tide-farms, can never be more than the energy of these tidal waves from the Atlantic. We can estimate the total power of these great Atlantic tidal waves in the same was as we estimate the power of their smaller cousins, ordinary waves. The next section describes a standard model for the power arriving in travelling waves. The power per unit length of wavecrest of shallow-water tidal waves is $\rho g^{3/2}\sqrt{d}h^2$. At its west side, the continental shelf has a depth d of about 250 m and the mean spring tidal range is about $2h_{\text{Springs}} = 3$ m. So the power per unit length is 1100 kW/m. Multiplying by 800 km, the total incoming power at springs is 870 GW (350 kWh/d per person). The amplitude of neap tides is about half that of springs, so the power at neaps is 220 GW (90 kWh/d each). The average over a month is 520 GW (200 kWh/d each).

Chapter G estimates that the incoming power from the Atlantic is about 900–1500 kW per metre of wavecrest at spring tides, and 240–440 kW/m at neaps. Multiplying by 800 km of exposed Atlantic, the total incoming tidal power is about 1000 GW (or 400 kWh/d per person) at springs and 270 GW (100 kWh/d per person) at neaps. So, on average, perfect extraction of all tidal energy could deliver no more than 250 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 13 kWh per person per day. We can bear in mind this rough guess when we think about tide farms later.

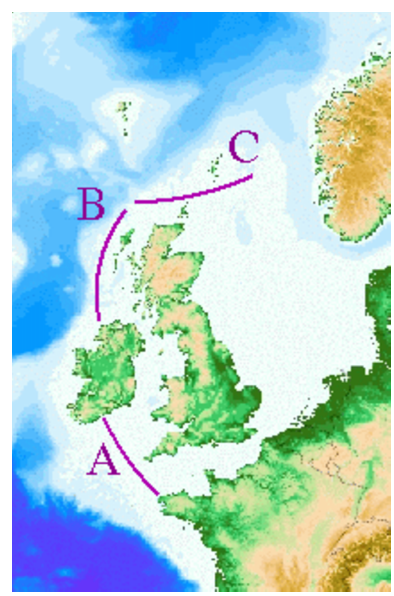


Figure G.2. Three lines near the edge of the continental shelf.

The power of tidal waves

I'm going to go into my model of tidal power in some detail because most of the official estimates of the UK tidal resource have been based on a model that I believe is incorrect.

Figure G.1 shows a model for a tidal wave travelling across relatively shallow water. This model is intended as a cartoon, for example, of tidal crests moving up the English channel or down the North Sea. It's important to distinguish the speed U at which the water itself moves (which might be about 1 mile per hour) from the speed v at which the high tide moves, which is typically one or two hundred miles per hour.

The water has depth d. Crests and troughs of water are injected from the left hand side by the 12-hourly ocean tides. The crests and troughs move with velocity

$$v = \sqrt{gd}. \tag{G.1}$$

We assume that the wavelength is much bigger than the depth, and we neglect details such as Coriolis forces and density variations in the water. Call the vertical amplitude of the tide h. For the standard assumption of nearly-vorticity-free flow, the horizontal velocity of the water is near-constant with depth. The velocity is proportional to the surface displacement and has amplitude U, which can be found by conservation of mass:

$$U = vh/d. \tag{G.2}$$

If the depth decreases gradually, the wave velocity v reduces. For the present discussion we'll assume the depth is constant. Energy flows from left to right at some rate. How should this total tidal power be estimated? And what's the maximum power that could be extracted?

One suggestion is to choose a cross-section and estimate the average *flux of kinetic energy* across that plane. This kinetic-energy-flux method was used by consultants Black and Veatch to estimate the UK resource. In this toy model, we can compute the total power by other means. We'll see that the kinetic-energy-flux answer is incorrect by a significant factor.

The peak kinetic-energy flux at any section is

$$K_{\mathrm{BV}} = \frac{1}{2}\rho A U^3, \tag{G.3}$$

where A is the cross-sectional area.

The true total incident power in a shallow-water wave is a standard textbook calculation; one way to get it is to find the total energy present in one wavelength and divide by the period.

The total energy per wavelength is the sum of the potential energy and the kinetic energy. The kinetic energy happens to be identical to the potential energy. (This is a standard feature of most all things that wobble, be they masses on springs or children on swings.) So to compute the total energy all we need to do is compute one of the two – the potential energy per wavelength, or the kinetic energy per wavelength – then double it. Let's go for the potential energy.

The potential energy of a wave (per wavelength and per unit width of wavefront) is

$$\frac{1}{2}\rho g h^2 \lambda. \tag{G.4}$$

So, doubling and dividing by the period, the true power of this model shallow-water tidal wave is

$$\text{power} = (\rho g h^2 \lambda) \times w/T = \rho g h^2 v \times w, \tag{G.5}$$

where w is the width of the wavefront. Substituting $v = \sqrt{gd}$,

$$\text{power} = \rho g h^2 \sqrt{gd} \times w = \rho g^{3/2} \sqrt{d} h^2 \times w. \tag{G.6}$$

Let's compare this power with the kinetic-energy flux $K_{\rm BV}$. Strikingly, the two expressions scale differently with amplitude. Using the amplitude conversion relation (G.2), the crest velocity (G.1), and $A = wd$, we can re-express the kinetic-energy flux as

$$K_{\rm BV} = \frac{1}{2}\rho A U^3 = \frac{1}{2}\rho w d (vh/d)^3 = \frac{1}{2}\rho \left(g^{3/2}/\sqrt{d}\right) h^3 \times w. \tag{G.7}$$

Thus the kinetic-energy-flux method suggests that the total power of a shallow-water wave scales as amplitude cubed; but the correct formula shows that the power scales as amplitude squared.

The ratio is

$$\frac{K_{\rm BV}}{\text{power}} = \frac{\rho w \left(g^{3/2}/\sqrt{d}\right) h^3}{\rho g^{3/2} h^2 \sqrt{d} w} = \frac{1}{2}\frac{h}{d}. \tag{G.8}$$

Thus estimates based on the kinetic-energy-flux method may be too small by a significant factor, at least in cases where this shallow-water cartoon of tidal waves is appropriate.

Moreover, estimates based on the kinetic-energy-flux method incorrectly assert that the total available power at springs is greater than at neaps by a factor of eight (assuming an amplitude ratio, springs to neaps, of two); but the correct answer is that the total available power of a travelling wave scales as its amplitude squared, so the springs-to-neaps ratio of total-incoming-power is four.

Shelving

If the depth d decreases gradually and the width remains constant such that there is minimal reflection or absorbtion of the incoming power, then the power of the wave will remain constant. This means $\sqrt{d}h^2$ is a constant, so we deduce that the height of the tide scales with depth as $h \sim 1/d^{1/4}$.

Application to the UK

Table G.3 shows the power per unit length of wave crest for some plausible figures. If $d = 100\,m$, and $h = 1$ or $2\,$m, the power per unit length of wave crest is 300 kW/m or 1200 kW/m respectively. These figures are impressive compared with the raw power per unit length of ordinary Atlantic deep-water waves, 40 kW/m. Since Atlantic waves and the Atlantic tide have similar vertical amplitudes (about 1 metre), the upper bound on tidal power is bigger by a factor of 20 or so than that for waves.

We can estimate the total incoming power from the Atlantic by multiplying appropriate lengths by powers per unit length. My lines A, B, and C (figure G.2) are all about 400 km long. The tidal range (at springs) on line A at depth $d = 100$ m is $2h = 4.5$ m. At neaps on line A, $2h = 2.4$ m seems a reasonable estimate. The tidal range (at springs) on line B at depth $d = 100$ m is $2h = 3.5$ m. For neaps, I'll assume a range of $2h = 1.8$ m. On line C, the tidal range at springs is between $2h = 2$ m and 3.5 m. I'll guess that the power coming over line C is half that of line B. Averaging the powers for springs and neaps, The incoming tidal resource over line A is 390 GW, over line B, 240 GW, and over line C, 120 GW, A total of

$$750\,\text{GW}, \tag{G.9}$$

or 300 kWh per day per person.

h (m)	$\rho g^{3/2}\sqrt{d}h^2$ (kW/m)
0.9	250
1.0	310
1.2	440
1.5	690
1.75	940
2.0	1200
2.25	1500

Table G.3. Power fluxes (power per unit length of wave crest) for depth $d = 100$ m.

[Compare with 215–250 GW estimated in the literature; of which 64 GW estimated to enter the Irish Sea. Blunden and Bahaj [2007]. Flather [1976] built a detailed numerical model of the lunar tide, chopping the continental shelf around the British Isles into roughly a thousand square cells. Their friction model has mean dissipation

$$\text{power} = k\rho v^3 \text{ (per unit area)},$$

with $k = 0.0025--0.003$. Flather estimates that the total average power entering this region is 215 GW. According to his model, 180 GW enters the gap between France and Ireland. From Northern Ireland round to Shetland, the incoming power is 49 GW. Between Shetland and Norway there is a net loss of 5 GW. Cartwright et al. [1980] found experimentally that the average power transmission was 60 GW between Malin Head (Eire) and Floro (Norway) and 190 GW between Valentia (Eire) and the Brittany coast near Ouessant. The power entering the Irish Sea was found to be 45 GW, and entering the North Sea via the Dover Straits, 16.7 GW. Near the Orkneys the incoming powers are 14 GW and 12 GW. They try to estimate the loss through bottom friction too (using $k = 0.0025$) and they estimate that there is less dissipation in the North Sea and Scottish waters (40 GW) than the incoming power (77 GW). They say they are not sure exactly where the correction to the loss arises. On a later page they mention finding that $k = 0.005$ is sometimes a better model.]

How much of this might conceivably be extracted? If we say 10%, and assume the conversion and transmission steps are 50% efficient, we arrive at

$$37\,\text{GW}, \tag{G.10}$$

or 15 kWh per person per day.

This estimate is based on a crude model. One neglected detail is the Coriolis effect. The Coriolis force causes tidal crests and troughs to tend to drive on the right – for example, going up the English Channel, the high tides are higher and the low tides are lower on the French side of the channel. By neglecting this effect I may have introduced some error into the estimates.

Power density of tidal stream farms

Imagine sticking underwater windmills on the sea-bed. The flow of water will turn the windmills. Because the density of water is roughly a thousand times that of air, the power of water flow is one thousand times greater than the power of wind at the same speed.

Polish me

It depends crucially on whether or not we can add up the power contributions of *adjacent* pieces of sea-floor. For wind, this additivity assumption is believed to work fine. As long as the wind turbines are spaced a standard distance apart from each other, the total power delivered by ten adjacent wind-farms is the sum of the powers that each would deliver if it were alone.

Does the same go for tide-farms? Or do underwater windmills interfere with each others' power extraction in a different way? I don't think the answer to this question is known. We can name two alternative assumptions, however, and identify cartoon situations in which each assumption seems valid. The 'tide is like wind' assumption says that you can put tide-turbines all over the sea-bed, spaced about 5 diameters apart from each other, and they won't interfere with each other, no matter how much of the sea-bed you cover with such tide-farms. This assumption seems to me to be valid if the heights of the turbines are small compared to the water depth. I think it might be valid even for tall turbines, but I'm not sure.

The 'you can have only one row' assumption, in contrast, asserts that the maximum power extractable in a region is the power that would be delivered by a *single* row of turbines facing the flow. A situation where this assumption is correct is the special case of a hydroelectric dam: if the water from the dam passes through a single well-designed turbine, there's no point putting any more turbines behind that one. You can't get one hundred times more power by putting ninety-nine more turbines downstream from the first. The oomph gets extracted by the first one, and there isn't any more oomph left for the others. I think the 'you can have only one row' assumption is the right assumption for estimating the extractable power in a place where water flows through a narrow channel from approximately stationary water at one height into another body of water at a lower height.

I'm now going to nail my colours to a mast. I think that in many places round the British Isles, the 'tide is like wind' assumption is a good approximation. Perhaps some spots have some of the character of a narrow channel. In those spots, my estimates may be over-estimates.

U / (m/s)	U / (knots)	Tide-farm power (W/m^2)
0.5	1	1
1	2	8
2	4	60
3	6	200
4	8	500
5	10	1000

Table G.4. Tide-farm power $R_1 \rho U^3$ (in watts per square metre of sea-floor) as a function of flow speed U. (1 knot = 1 nautical mile per hour = 0.514 m/s.)

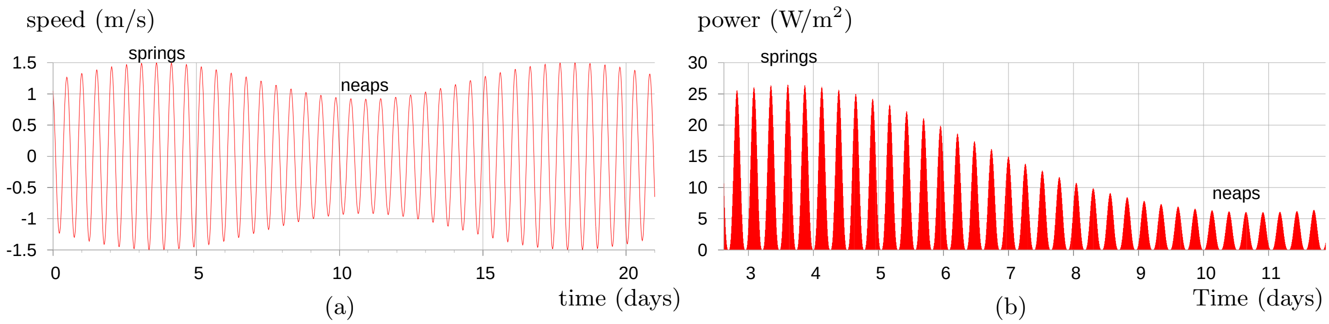


Figure G.5. (a) Tidal current over a 21-day period at a location where the maximum current at spring tide is 2.9 knots (1.5 m/s) and the maximum current at neap tide is 1.8 knots (0.9 m/s).
(b) The power per unit sea-floor area over a nine-day period extending from spring tides to neap tides. The power peaks four times per day, and has a maximum of about 27 W/m^2. The average power of the tide farm is 6.4 W/m^2.

Let's assume that the rules for laying out a sensible tide-farm will be similar to those for wind-farms, and that the efficiency of the tidemills will be like that of the best windmills, about 1/2. Given these assumptions, table G.4 shows this tide-farm power for a few tidal currents.

Now, what are plausible tidal currents? Tidal charts usually give the currents associated with the tides with the largest range (called spring tides) and the tides with the smallest range (called neap tides). Spring tides occur shortly after each full moon and each new moon. Neap tides occur shortly after the first and third quarters of the moon. The power of a tide farm would vary throughout the day in a completely predictable manner as illustrated in figure G.5.

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 density is similar to our estimates of the power densities of wind farms (2–3 W/m^2) and of photovoltaic solar farms (5 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?

We must be careful not to over-estimate the power. Tide is indeed like wind for a few small turbines placed in deep water – the air is many kilometres thick, and our wind turbines are just 100 m or so high; similar to a 2 m tide turbine in 50 m-deep water. But if we place many large tide turbines in shallow water, the analogy with wind farms may not be so good – there aren't vast layers of moving water above the turbines to steal energy from, so maybe neighbouring turbines interfere with each other more. I'm not certain how to make an accurate estimate. So we'll make two estimates now: we'll estimate the power of the tide, assuming

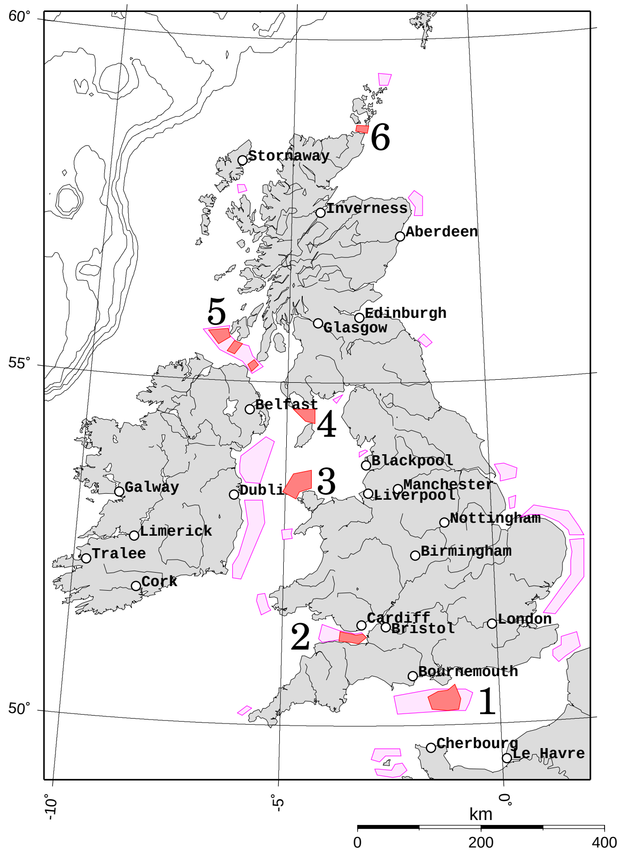


Figure G.6. Regions around the British Isles where peak tidal flows exceed 1 m/s. The six darkly-coloured regions are included in table G.8. Map created with the free software package GMT – thanks to Martin Weinelt and OMC. Tidal data from Reed's Nautical Almanac and DTI Atlas of UK Marine Renewable Energy Resources.

that 'tide farms are like wind farms'; and as a sanity check we'll also work out the total incoming power of the tide, using the 'power of tidal waves' theory, to check our tide-farm's estimated power isn't bigger than the total power available.

The main locations around the UK where tidal currents are large are: the English channel, especially around the Channel Islands; the Bristol channel; the North Sea, from the Thames (London) to the Wash (Kings Lynn); between Northern Ireland, the Mull of Kintyre, and Islay; Pentland Firth (between Orkney and mainland Scotland); and within the Orkneys.

I estimated the typical peak currents at six locations from low-resolution tidal charts in Reed's Nautical Almanac. (These estimates could easily be off by 30%.) Have I over-estimated or under-estimated the area of each region? I haven't surveyed the sea floor so I don't know if some regions might be unsuitable in some way – too deep, or too shallow, or too tricky to build on. I've included only six small regions with large currents. Perhaps I should also have included an estimate for the power from the much larger regions with small currents.

Admitting all these uncertainties, I arrive at an estimated total power of 15 kWh/d per person. *REVIEW THIS.*

	Region	peak current (knots) neaps	springs	power density (W/m^2)	area (km^2)	power (kWh/d/p)
1	English Channel (South of Isle of Wight)	1.7	3.1	7	1000	2.8
2	Bristol Channel	1.8	3.2	8	750	2.4
3	Irish Sea (near Anglesey)	1.3	2.3	2.9	1000	1.2
4	North of Isle of Man	1.7	3.4	9	400	1.4
5	Between Northern Ireland, Islay and Mull of Kintyre	1.7	3.1	7	1000	2.8
6	Pentland Firth	5.0	9.0	170	50	3.5
Total						**15**

Table G.7. Tidal power estimates assuming that tide farms are like wind farms. Power density is the average power density in W/m^2 of sea floor. The six regions are indicated in figure G.6.

	Region	depth (m)	width (km)	Maximum power (kWh/d/p) N	S	Tide-farm estimate
1	English Channel (South of Isle of Wight)	30	30	4.7	15.7	2.8
2	Bristol Channel	30	17	3.0	9.5	2.4
3	Irish Sea (near Anglesey)	50	30	5.9	18.6	1.2
4	North of Isle of Man	30	20	3.1	12.6	1.4
5	Between Northern Ireland, Islay and Mull of Kintyre	40	10	2.4	8.0	2.8
6	Pentland Firth	70	10	48	157	3.5
Total						**15**

Table G.8. Power density is the average power density in W/m^2 of sea floor. The six regions are indicated in figure G.6. N = Neaps. S = Springs.

v (m/s)	v (knots)	Friction power (W/m^2) $R_1 = 0.01$	$R_1 = 0.003$	Tide-farm power (W/m^2)
0.5	1	1.25	0.4	1
1	2	10	3	8
2	4	80	24	60
3	6	270	80	200
4	8	640	190	500
5	10	1250	375	1000

Table G.9. Friction power (in watts per square metre of sea-floor) as a function of flow speed, assuming $R_1 = 0.01$ or 0.003. Flather [1976] uses $R_1 = 0.0025 - -0.003$; Taylor [1920] uses 0.002. (I don't have a factor of 1/2 in the formula.) (1 knot = 1 nautical mile per hour = 0.514 m/s.)

Estimating the tidal resource via bottom friction

Another way to estimate the power available from tide is to compute how much power is already dissipated by friction on the sea floor. A coating of turbines placed just above the sea floor could act as a substitute bottom, exerting roughly the same drag on the passing water as the sea floor used to, and extracting roughly the same amount of power, without significantly altering the tidal flows.

So, what's the power dissipated by 'bottom friction'? Unfortunately, there isn't a straightforward model of bottom friction. It depends on the roughness of the sea bed and the material that the bed is made from – and even given this information, the correct formula to use is not settled. One widely used model says that the magnitude of the stress (force per unit area) is $R_1 \rho U^2$, where U is the average flow velocity and R_1 is a dimensionless quantity called the shear friction coefficient. We can estimate the power dissipated per unit area by multiplying the stress by the velocity. Table G.9 shows the power dissipated in friction, $R_1 \rho U^3$, assuming $R_1 = 0.01$ or $R_1 = 0.003$. (Add citations.) Kowalik [2004]

Tidal pools with pumping

The pumping trick artificially increases the amplitude of the tides in the tidal pool so as the amplify the power obtained. The energy cost of pumping in extra water at high tide is repaid with interest when the same water is let out at low tide; similarly, extra water can be pumped *out* at low tide, then let back in at high tide. Let's work out the theoretical limit for this technology.

I'll assume that generation has an efficiency of $\epsilon_{\rm g} = 0.9$ and that pumping has an efficiency of $\epsilon_{\rm p} = 0.85$ (these figures are based on the pumped storage system at Dinorwig, whose round-trip efficiency is about 75%).

Let the tidal range be $2h$. I'll assume that the prices of buying and selling electricity are the same at high tide and low tide, so that the optimal height boost b to which the pool is pumped above high water is given by (marginal cost of extra pumping = marginal return of extra water):

$$b/\epsilon_{\rm p} = \epsilon_{\rm g}(b + 2h)$$

Defining the round-trip efficiency $\epsilon = \epsilon_{\rm g}\epsilon_{\rm p}$, we have

$$b = 2h\frac{\epsilon}{1-\epsilon}$$

For example, with a tidal range of $2h = 4$ m, and a round-trip efficiency of $\epsilon = 76\%$, the optimal boost is $b = 13$ m. This is the maximum height to which pumping can be justified if the price of electricity is constant.

Let's assume the complementary trick is used at low tide. (This requires that the basin have a vertical range of 30 m!) The delivered power per unit area is then

$$\left(\frac{1}{2}\rho g \epsilon_{\rm g}(b+2h)^2 - \frac{1}{2}\rho g \frac{1}{\epsilon_{\rm p}} b^2\right) \Big/ T,$$

where T is the time from high tide to low tide. We can express this as the power density without pumping, $\epsilon_{\rm g} 2\rho g h^2/T$, scaled up by a boost factor

$$\left(\frac{1}{1-\epsilon}\right),$$

which is roughly a factor of 4.

tidal amplitude (half-range) h (m)	optimal boost height b (m)	power with pumping (W/m^2)	power without pumping (W/m^2)
0.5	3.3	0.9	0.2
1.0	6.5	3.5	0.8
2.0	13	14	3.3
3.0	20	31	7.4
4.0	26	56	13

Unfortunately, this pumping trick will rarely be exploited to the full because of the economics of basin construction: full exploitation of pumping requires the total height of the pool to be roughly 4 times the tidal range, and increases the delivered power by a factor of 4. But the material in a sea-wall of height H scales as H^2, so the cost of constructing a wall four times as high will be more than four times as big. Extra cash would probably be better spent on enlarging a tidal pool horizontally rather than vertically.

The pumping trick can nevertheless be used for free whenever the natural tides are smaller than the maximum tidal range. The next table gives the power delivered if the boost height is set to h, that is, the range in the pool is just double the external range.

tidal amplitude (half-range) h (m)	boost height b (m)	power with pumping (W/m^2)	power without pumping (W/m^2)
0.5	0.5	0.4	0.2
1.0	1.0	1.6	0.8
2.0	2.0	6.3	3.3
3.0	3.0	14	7.4
4.0	4.0	25	13

A doubling of vertical range is plausible at neap tides, since neap tides are typically about half as high as spring tides. Pumping the pool at neaps so that the full springs range is used thus allows neap tides to deliver roughly twice as much power as they would offer without pumping. So a system with pumping would show two-weekly variations in power of just a factor of 2 instead of 4.

Using multiple pools – for example, a high pool and a low pool – doesn't increase the deliverable power, but does increase the flexibility of when power can be delivered, thus enhancing the value of a facility. A two-pool facility is 'always on', and would be able to provide the same sort of valuable service as the Dinorwig pumped storage station. A two-pool facility can also do its own pumping. It's a delightful feature of a two-pool solution that the optimal time to pump water into the high pool is high tide, which is also the optimal time to generate power from the low pool. Similarly low tide is the perfect time to pump down the low pool, and it's the perfect time to generate power from the high pool.

Add graph here showing how a two-pool facility with pumping can generate steady power from the tides.

Haishan

There is a two-basin tidal power plant at Haishan, Maoyan Island, China. A single generator located between the two basins (as shown in figure **??**) delivers power continuously, and generates 39 kW on average.

Bristol barrage details

From Hammons Tidal Power paper Hammons [1993] and Taylor [2002]. 16 km barrage. The enclosed area of water would measure 520 km^2. 7 m mean tide range. Annual output of 17 TWh (2 GW average; peak capacity of 8.6 GW) would include a 10% boost from the pumping trick. Construction would take 9 years and cost £10 billion. (Note, £5 million per megawatt; similar to windmills, which seem to cost about £3 million per megawatt?) 370 km of new 400 kV transmission lines would be required.

Mersey barrage: 2 km long. 6.5 m mean tide range. 61 km^2 basin area. 1.5 TWh/y, or 170 MW average, again including the pumping trick. Peak capacity 700 MW. Estimated cost: about £1 billion.

	Barrage	Lagoons (largest scenario)
power generated	17–19 TWh/y	24 TWh/y
average output	1.95–2.17 GW	2.75 GW
capacity	8.64 GW	4.50 GW
impounded area	185 square miles	115 square miles
overall wall length	9.8 miles	95 miles (approx)
aggregates required	13 m tonnes	200 m tonnes (approx)

Swansea circular lagoon

Tidal Electric limited, backed by The Environment Trust, by AEA Technology, and by W.S. Atkins Engineering.

Area 5 km^2. Peak capacity of 60 MW. Annual output 187 GWh, *i.e.*, 21 MW average. (Which is 4 W/m^2.)

They say the potential capacity for the UK is 1500 MW in the Mersey, 4500 MW in the Severn Estuary, and 150 MW in the Thames Estuary. Dividing by 3 to get the average delivered, that's about 2 GW, or 1 kWh/d per person.

Friends of the Earth compare the Bristol barrage with the largest lagoon envisaged for the Severn Estuary. Friends of the Earth Cymru [2004] [`s8dry`] A good comparison they make is the tonnage of aggregates (200 Mt) compared with the tonnage of coal to produce the same power – 5 Mt tonnes coal per year, for 22 TWh/y. So 40 years' worth of coal.

Mersey lagoon

Tidal Lagoon without pumping. 7 km in diameter 350 MW 'capacity'; average power 650 GWh/y = 74 MW. (2 W/m^2).

For comparison, their Tidal Barrage plan 700 MW 'capacity'; average power 1200 GWh/y = 137 MW.

(They call this 'a sizeable proportion of the energy needs of Merseyside'). Fact: the population of Merseyside in the 2001 census was 1 362 034. How do the energy needs of Merseyside actually compare with the tidal energy figure, assuming, like the rest of the UK, that Merseysiders use 120 kWh/d per person? Well, 1200 GWh per year shared between 1.3 million works out to 2.4 kWh/d per person. Worth doing? I think so. But 'a sizeable proportion' of 120 kWh/d? Well, only if you call 2% a sizeable proportion!

The two-basin scheme: an 'always-on' tidal power scheme

A neat idea: have two basins, one of which is the 'full' basin and one the 'empty' basin; every high tide, the full basin is topped up; every low tide, the empty basin is emptied. These toppings-up and emptyings could be done either passively through sluices, or even actively by pumps (using the trick mentioned elsewhere). Whenever power is required, water is allowed to flow from the full basin to the empty basin, or (better in power terms) between one of the basins and the sea. The power per unit area is the same as that of the single-basin tidal barrage; the capital cost may be bigger because of the need for extra barriers; the big win is that power is available all the time, so the facility can follow demand.

We can even use power generated from the empty basin to pump extra water into the full basin at high tide, and similarly use power from the full basin to pump down the empty basin at low tide. This self-pumping would boost the total power delivered by the facility without ever needing to buy energy from the grid.

A two-basin system could also function as a pumped-storage facility. I'll come back to this in chapter 25.

Notes

306 *Table G.4.* To work out the power of a tide-farm (per unit sea-floor), we steal the formula for the power of a wind-farm (per unit land area) from p. 254. The power per unit sea-floor area is

$$\frac{\text{power per tidemill}}{\text{area per tidemill}} = \frac{\pi}{200}\frac{1}{2}\rho v^3$$

307 *The main locations around the UK where tidal currents are large...* I identified the regions with biggest flows using the DTI Atlas of UK Marine Renewable Energy Resources (2004).

311 *There is a two-basin tidal power plant at Haishan* [2bqapk].

Area behind the Bristol barrage is 480 km^2. So with average output of 2 GW, it would indeed deliver 4 W/m^2.

Estimates of possible tidal lagoon / barrage projects in the UK from [2bqapk]

site	mean tidal range (m)	basin area (km^2)	capacity (MW)	annual output (TWh/year)	load factor
Severn	7.0	520	8 640	17.0	23%
Mersey	6.5	61	700	1.4	23%
Duddon	5.6	20	100	0.212	22%
Wyre	6.0	5.8	64	0.131	24%
Conwy	5.2	5.5	33	0.060	21%

Other places in the world on the same scale as the Severn: Argentina: San José and Golfo Nuevo (two sites). Australia: Walcott Inlet. Cobequid, Canada. India: Gulf of Khambat. USA: Turnagain Arm and Knik Arm. Russia: Tugur.

Ten times as big as the Severn: Russia: Penzhinsk (190 TWh/y, 22 GW!).

Assumptions

In this chapter, we assumed that power would be produced with equal efficiency at all flow speeds. If tidemills are similar to windmills, this assumption won't be true; there will be only a range of speeds at which power is produced efficiently.

We also assumed that the flow rate at depth is the same as the flow rate at the surface, quoted in the Nautical Almanac. Again, this assumption is inaccurate. It's an object of ongoing research to measure the actual variations of current with depth. Figure G.11 shows the sort of variation of speed with depth that we expect in inviscid fluids: the flow is almost constant with depth, except in a thin layer near the sea floor.

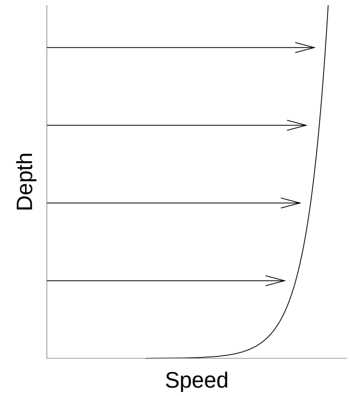


Figure G.11. Tidal flows at depth are usually similar to the surface flow. This figure is just a cartoon, indicating the expected shape of the speed-versus-depth curve. Real flows are always turbulent, with speeds fluctuating around a mean curve like this one. The numerical details depend on the roughness of the sea floor.

Notes

Pentland Firth

H

Stuff II

Imported energy

Dieter Helm and his colleagues estimated the footprint of each pound's worth of imports from country X using the average carbon intensity of country X's economy (that is, the ratio of their carbon emissions to their gross domestic product). They concluded that the embodied carbon in imports to Britain (which should be added to Britain's official carbon footprint of 11 tons $CO_2^{(e)}$ per person) is roughly 16 tons $CO_2^{(e)}$ per person.

Here, let's see if we can reproduce their conclusion in a different way, using the weight of the imports.

Figure H.1 shows Britain's imports in the year 2006 in three ways: on the left, the total value of the imports is broken down by the country of origin. In the middle the same total financial value is broken down by the type of stuff imported, using the categories of HM Revenue and Customs. On the right, all maritime imports to Britain are shown by *weight* and broken down by the categories used by the Department for Transport, who don't care whether something is leather or tobacco – they keep track of how heavy stuff is, whether it is dry or liquid, and whether the stuff arrived in a container or a lorry.

The energy cost of the imported fuels (top right) *is* included in the standard accounts of British energy consumption; the energy costs of all the other imports are not. For most materials, the embodied energy per unit weight is greater than or equal to 10 kWh per kg – the same as the energy per unit weight of fossil fuels. This is true of all metals and alloys, all polymers and composites, most paper products, and many ceramics, for example. The exceptions are raw materials like ores; porous ceramics such as concrete, brick, and porcelain, whose energy cost is ten times lower; wood and some rubbers; and glasses, whose energy-cost is a whisker lower than 10 kWh per kg. [r22oz]

We can thus roughly estimate the energy footprint of our imports simply from their weight of their manufactured materials, if we exclude things like ores and wood. Given the crudity of the data with which we are working, we will surely slip up and inadvertently include some things

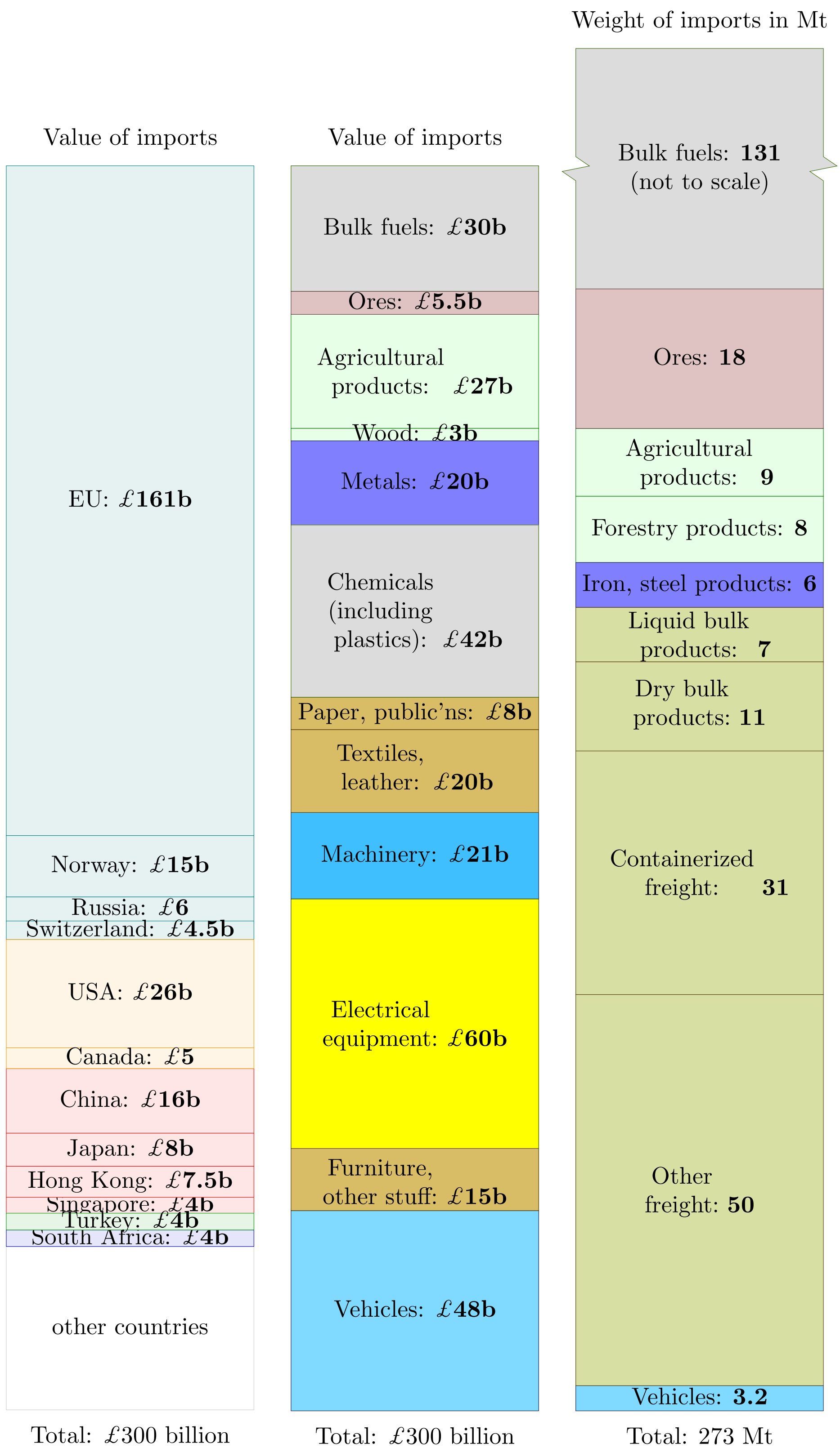


Figure H.1. Imports of stuff, 2006.

made of wood and glass, but hopefully such slips will be balanced by our underestimation of the energy content of most of the metals and plastics and more complex goods, many of which have an embodied energy of not 10 but 30 kWh per kg, or even more.

For this calculation I'll take from the right-hand column in figure H.1 the iron and steel products, the dry bulk products, the containerized freight and the 'other freight' which total 98 million tons per year in weight. I'm leaving the vehicles to one side for a moment. I subtract from this an estimated 25 million tonnes of food which is presumably lurking in the 'other freight' category (34 million tonnes of food were imported in 2006).

Converting 73 million tons to energy using the exchange rate suggested above, and sharing between 60 million people, we estimate that those imports have an embodied energy of 33 kWh/d per person.

For the cars, we can handwave a little less, because we know a little more: the number of imported vehicles in 2006 was 2.4 million. If we take the embodied energy per car to be 76 000 kWh (a number we picked up on p.92) then these imported cars have an embodied energy of 8 kWh/d per person.

We've arrived at a total estimate of 41 kWh/d per person for the embodied energy of imports – definitely in the same ballpark as the estimate of Dieter Helm and his colleagues.

I left the 'liquid bulk products' out of these estimates because I am not sure what sort of products they are. If they are actually liquid chemicals then their contribution might be significant. I suspect that 41 kWh/d per person may be an underestimate because the energy intensity we assumed (10 kWh/d/person) is too low for most forms of manufactured goods such as machinery or electrical equipment. However, without knowing the weights of all the import categories, this is the best estimate I can make for now.

Actual consumption of road transport in the UK

In 2005: heavy goods vehicles (diesel) 9.22 Mtons of petroleum; light goods diesel: 4.77 Mtons of petroleum; out of total 38.10Mtons. light goods vehicles motor spirit: 0.50 Mtons.

In 1997, 12.52 is goods vehicles, out of total of 37.04 for road transport.

2005, All petroleum for transport (air, water, road, rail) = 52.72.

HGV rigid vehicles do 8.3 mi/gal on average; articulated vehicles: 8.1 mi/gal. (Cars do 33 mi/gal.)

In 1997, amounts of goods moved: in billion tkm. 41 food, drink, tobacco 43 bulk products 15 chemicals, petrol, fertilizer 51 miscellaneous total 150 billion tonne km (1643 million tonnes lifted, taken 23111 million vehicle km. 1997.) That is 6.5 tons per vehicle on average.

So taking 12.52 M t fuel / 150 b tkm, and 45.9 GJ/tonne of petroleum, deduce that the transport efficiency of UK road freight is 45.9×12.52

MGJ / 150 G tkm = 3.8 MJ/tkm = 1.06 kWh/tkm. Based on megastatistics.

transwatch say Rail freight - 181 Tonne-miles per gallon. Road freight - 120 Tonne-miles per gallon. (assuming 8mpg and 30 tonne load, empty half the time) 2.35 l/100 tkm; which is 0.21 kWh/tkm.

Typical 38 ton lorry uses power of 400 kW at 105 km/h.

Freight movement in the UK: 163 billion tonne kilometres/y. Average haul: 87 kilometres. Food transport is quarter of HGV kilometres. UK international water-borne freight = 446 million tonnes/y.

Ship freight: 4948 TEU transported at 25 knots by Ever Uberty's 44 MW engine. Assume it is 50% efficient. 1 TEU is 13 tons. Gross tonnage 69 000 t. Actual tonnage transported $13 \times 4948 = 64324$ t. Energy per tkm: 0.015 kWh per tkm.

`http://www.greenhouse.gov.au/yourhome/technical/fs31.htm`

Building materials (assuming virgin product used, rather than recycled)

Material	Embodied energy (MJ/kg)	Embodied energy (kWh/kg)
kiln dried sawn softwood	3.4	0.94
kiln dried sawn hardwood	2.0	0.56
air dried sawn hardwood	0.5	0.14
hardboard	24.2	6.7
particleboard	8.0	2.2
MDF	11.3	3.1
plywood	10.4	2.9
glue-laminated timber	11	3.0
laminated veneer lumber	11	3.0
stabilised earth	0.7	0.19
imported dimension granite	13.9	3.9
local dimension granite	5.9	1.6
gypsum plaster	2.9	0.8
plasterboard	4.4	1.2
fibre cement	4.8	1.3
cement	5.6	1.6
in situ concrete	1.9	0.53
precast steam-cured concrete	2.0	0.56
precast tilt-up concrete	1.9	0.53
clay bricks	2.5	0.69
concrete blocks	1.5	0.42
autoclaved aerated concrete	3.6	1.0
plastics - general	90	25
PVC	80	22
synthetic rubber	110	30
acrylic paint	61.5	17
glass	12.7	3.5
aluminium	170	47
copper	100	28
galvanised steel	38	10.6

(Dimension stone is natural stone or rock that has been selected and trimmed to specific sizes or shapes.)

Here's the embodied energy in various constructions:

	Embodied energy (MJ/m^2)	(kWh/m^2)
Walls		
timber frame, timber weatherboard, plasterboard lining	188	52
timber frame, clay brick veneer, plasterboard lining	561	156
timber frame, aluminium weatherboard, plasterboard lining	403	112
steel frame, clay brick veneer, plasterboard lining	604	168
double clay brick, plasterboard lined	906	252
cement stabilised rammed earth	376	104
Floors		
elevated timber floor	293	81
110 mm concrete slab on ground	645	179
200 mm precast concrete T beam/infill	644	179
Roofs		
timber frame, concrete tile, plasterboard ceiling	251	70
timber frame, terracotta tile, plasterboard ceiling	271	75
timber frame, steel sheet, plasterboard ceiling	330	92

Source: Lawson 1996 Lawson, B 1996 Building materials, energy and the environment: Towards ecologically sustainable development RAIA, Canberra

'LCA examines the total environmental impact of a material or product through every step of its life - from obtaining raw materials (for example, through mining or logging) all the way through manufacture, transport to a store, using it in the home and disposal or recycling.' 'Process Energy Requirement (PER) is a measure of the energy directly related to the manufacture of the material. This is simpler to quantify. Consequently, most figures quoted for embodied energy are based on the PER. This would include the energy used in transporting the raw materials to the factory but not energy used to transport the final product to the building site.' That's what's quoted here. The gross energy requirement widens the boundary, including the embodied energy of urban infrastructure, the embodied energy of the machinery that makes the raw materials. A rough rule of thumb to get the gross energy requirement of a building is to double the process energy requirement.

Example: my house, approximate areas, process energy.

	Area × energy density	energy (GJ)	
Floors	100×293	$= 29$	
Roof	75×271	$= 20$	
External walls	75×906	$= 68$	
Internal walls	75×450	$= 34$	
Total		151 GJ	= 42 000 kWh

If we share 42 000 kWh over 100 years, and double it to allow for the gross energy cost, the embodied energy cost of a house comes to about 2.3 kWh/d. This is the energy cost of the *shell* of the house only – the bricks, tiles, roof beams.

All the stuff in China

As a double-check of the embedded energy of imported stuff, let's take China's energy consumption and attribute one quarter of it to 'us' (a billion people in the developed world). (Since China is the world's workshop.)

Source: Dr Tao Wang and Dr Jim Watson reckon that 25% of China's carbon emissions are associated with exports `http://www.greencarcongress.com/2007/10/manufacture-and.html`. China's primary energy consumption in 2004 was 17 500 TWh; if we share the blame for 25% of China's energy among one billion of 'us', that's 12 kWh/d per person.

UK imports of goods and services in 2006 had a value of £300 billion per year, a three-fold increase over 1990 levels. Helm et al. [2007] estimate that the embodied greenhouse gas emissions associated with British imports in 2006 were 950 $\mathrm{MtCO_2^{(e)}}$ (16 $\mathrm{tCO_2^{(e)}}$ per person), none of which is counted in standard accounts of the carbon footprint of Britain. These embodied emissions are greater than our own domestic emissions! (11 $\mathrm{tCO_2^{(e)}}$ per person in the year 2000.) Exports took away 325 $\mathrm{MtCO_2^{(e)}}$ from Britain, so we could judge *net* imports to be 10 $\mathrm{tCO_2^{(e)}}$ per person. Of these imports, they attribute 130 $\mathrm{MtCO_2^{(e)}}$ (2.2 $\mathrm{tCO_2^{(e)}}$) to imports from China. Converting back from $\mathrm{CO_2^{(e)}}$ to energy, these estimates imply an embodied-energy consumption, in imported stuff, of roughly 100 kWh per person in the UK.

Food-miles

From Resurgence. no. 208. Perspectives.

Britain imports 125,000 tonnes of lamb Britain exports 102,000 tonnes of lamb

Britain imports 61,000 tonnes of poultry FROM the Netherlands Britain exports 33,000 tonnes of poultry TO the Netherlands

Notes by SUSTAIN. In 1996 the UK imported 434 000 tonnes of apples, 202 000 tonnes of which came from outside the EU. Over 60 per cent of UK apple orchards have been lost since 1970. In 1997 the UK imported 105 000 tonnes of pears, 72 000 tonnes of which were from outside the EU. Nearly 50 per cent of UK pear orchards have been lost since 1970. In 1996 the UK imported 233,000 tonnes of beef, 80,000 tonnes of which were from outside the EU. The beef came from as far away as Namibia (9,500km) and Australia (21,000km) In 1997 we imported 126 million litres of liquid milk into the UK and exported 270 million litres of milk out of the UK. We imported 23,000 tonnes of milk powder in to the UK and exported 153,000 tonnes out of the UK, 135,000 tonnes of which went outside the EU. We imported 115,000 tonnes of butter, 51,000 tonnes of which was from outside the EU, and exported 67,000 tonnes of butter, 27,000 tonnes of which was exported outside the EU.

In 1998, 68% of UK food was home-produced.

Transport cost for 1kg of apples to a consumer = 4 kWh (including production costs as well a transport? not clear)

A tonne of food travels an average distance of 123 km. (I think this refers to transport on UK roads.)

Total food-miles for UK food, drink, and tobacco products (1998) 42.5 billion tonne-km. Food transport dominates freight.

346 million tonnes, avg distance 123 km.

Energy costs of raw materials for stuff

The energy requirements for virgin production of steel are 26–35 MJ/kg; 8–11 times higher for nickel; 1.2–1.6 times higher for lead; 1.5–2 times higher for zinc; and 2–4 times higher for plastics. [Rydh and Karlström, 2002].

Plastic bags

Tesco, Asda, Sainsburys, Morrisons, and Waitrose hand out 9 billion plastic bags per year. That's 150 bags per person per year.

Phones and computers

Some helpful cautions about life-cycle analysis: `http://www.gdrc.org/uem/lca/life-cycle.html`

more links: `http://www.epa.gov/ord/NRMRL/lcaccess/resources.htm`

Key facts

Transport uses 38% of all energy used by final users.

Figure H.2. Millau Viaduct in France, the highest bridge in the world. Steel and concrete, 2.5 km long and 353 m high.

Transport figures

Masefield [1975] overall energy cost of world transport: 1600 kJ to move 1 t of payload one mile at an average speed of 45 km/h (28 mile/h).

Of all transport, 62% of the load-t-km are sea; and 42% is bulk transport of oil in tankers. But the energy consumption of sea is about 4.5% of all transport-related energy. Inland water transport consumes 2% of the transport energy and produces 5.8% of the transport.

Industry

This section's not written.

Key headings for energy consumption and pollution are:

oil and gas extraction, refining, and processing

manufacture of chemicals

iron and steel

aluminium and other metals

cement

Steel and cement are both CO_2-producers.

Typically one tonne of CO_2 is released for the production of each tonne of Portland cement. (from Nuclear-paper2 footnote 23)

Would like to know the energy cost of making bricks too.

I

Freight

Shipping – further notes

Freight transport in USA:

(in kWh per ton km) Heavy trucks 0.61 Rail 0.062 Air freight 1.75 Inland water 0.093

I wonder what power is used to trundle the ship around. Sounds like 2 MW is plausible for a modest transport ship. Container ships have 6 MW engines (and I imagine they have more than one of these).

A tanker of 260 000 dwt might require 42 500 hp.

115 000 dwt oil tanker. Main engine power: 3 600 Hp. 58 000 dwt: 13 000 hp 81 000 dwt: 2000 hp (1.5 MW). 4000 dwt: 3600 hp cargo ship 3.8 MW. 8700 dwt: 3.3 MW.

One modern oil tanker: cargo weight 40 000 t. Capacity: 47 000 m^3 Main engine: 11.2 MW. Speed at 8.2 MW: 15.5 kn (29 km/h). Length 188 m, width 32 m. Draught: 10 m.

What's its transport efficiency? Crude oil is 1192 litres per tonne, so yes, it takes 40 000 tonnes at 29 km/h, using 8.2 MW. Express that as a loss per 1000 km: the energy of the fuel required to transport 40 000 tonnes a distance of 1000 km is $2.4 \times \frac{1000\text{km}}{29\text{km/h}} \times 8200\,\text{kW} = 680\,000\,\text{kWh}$. (The factor of 2.4 accounts for engine efficiency.) (This is 0.017 kWh/tkm.) The energy of the cargo is $13\,\text{kWh/kg} \times 40 \times 10^6\,\text{kg} = 520 \times 10^6\,\text{kWh}$. So that's a loss of

$$\frac{680\,000}{520 \times 10^6} = 0.0013\,\text{per }1000\,\text{km}.$$

Roughly one thousandth per 1000 km means that roughly 1% of the energy is lost is transporting it one-quarter of the way round the earth (10 000 km).

Dry cargo vessel, optimized for fuel consumption: 3360 dwt. Length: 91 m, breadth 14 m, draught: 5 m, gross tonnage 2460 t. Speed 13 kn (24 km/h), engine power 2 MW. Just one engine. Grain capacity: 5200 m^3. Engine's fuel oil consumption is 186 g/kWh. Onboard power supply: 300 kW. Emergency power: 70 kW diesel.

Oil is about 46 GJ/tonne, which is 13 kWh/kg. So 186 g/kWh is 2.4 kWh per kWh (or 42% efficiency).

Figure I.1. Water transport requires energy because boats make waves.

OK, this can go in my freight chapter: Energy per cargo-distance (counting the power of the main engine alone) is $2.4 \times 2000\,\mathrm{kWh}/2460\,\mathrm{t}/24\,\mathrm{km} = 0.08\,\mathrm{kWh/tkm}$.

The ships of WW (shipping company, especially roll-on, roll-off carriers) use 150 g/kWh (fuel), and emit 468 g/kWh (CO_2). Their CO_2 emissions per tkm range from 10 g/tkm to 5.5 g/tkm.

J

Area II

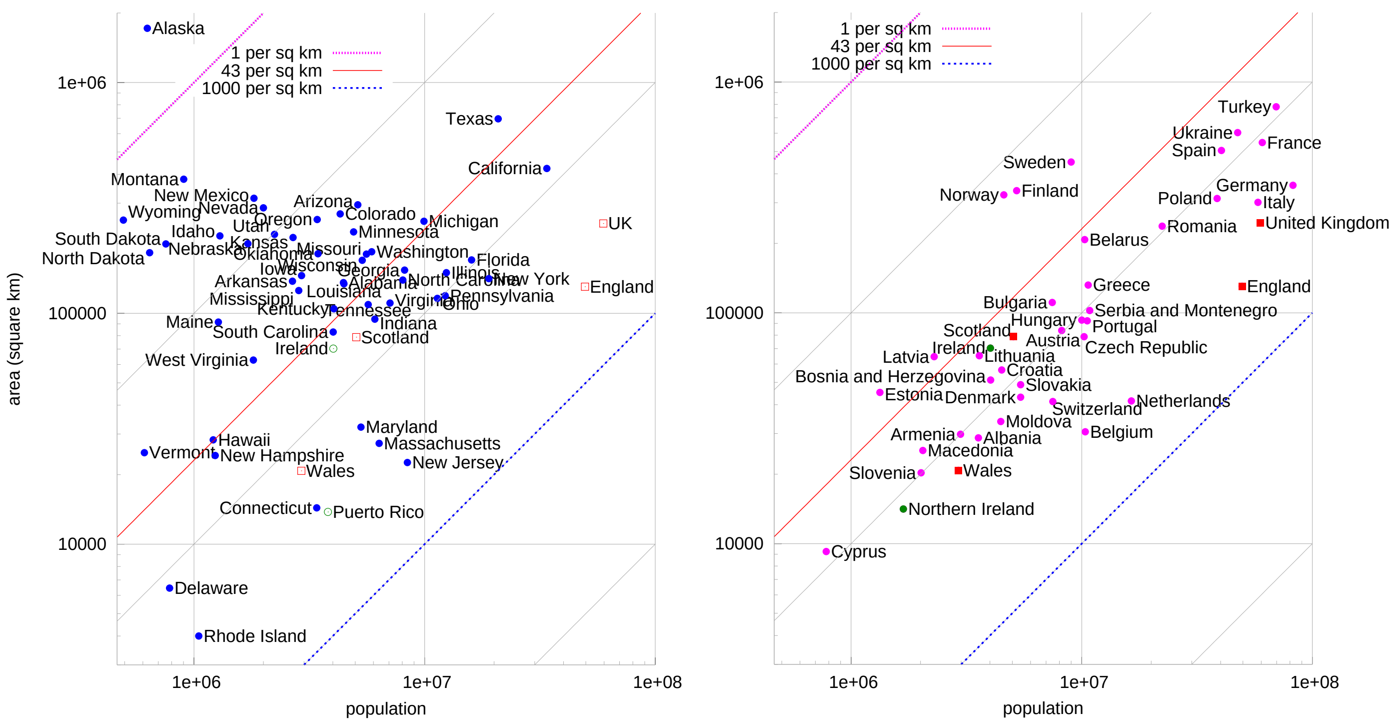


Figure J.1. Populations and areas of the States of America and regions around Europe.

Region	Population	Area (km^2)	People per km^2	Area each (m^2)
Antarctica	4 000	**13 200 000**		
Greenland	56 300	2 160 000	0.026	38 400 000
Alaska	655 000	1 480 000	0.44	2 260 000
Western Sahara	273 000	266 000	1	974 000
Mongolia	2 790 000	1 560 000	1.8	560 000
Namibia	2 030 000	825 000	2.5	406 000
Australia	20 000 000	**7 680 000**	2.6	382 000
Suriname	438 000	163 000	2.7	372 000
Botswana	1 640 000	600 000	2.7	366 000
Mauritania	3 080 000	1 030 000	3	333 000
Libya	5 760 000	1 750 000	3.3	305 000
Canada	32 800 000	**9 980 000**	3.3	304 000
Kazakhstan	15 100 000	2 710 000	6	178 000
CAR	3 790 000	622 000	6	163 000
Chad	9 820 000	1 280 000	8	130 000
Bolivia	8 850 000	1 090 000	8	124 000
Russia	**143 000 000**	**17 000 000**	8	119 000
Angola	11 100 000	1 240 000	9	111 000
Niger	11 600 000	1 260 000	9	108 000
Mali	12 200 000	1 240 000	10	100 000
Somalia	8 590 000	637 000	13	74 200
Saudi Arabia	26 400 000	1 960 000	13	74 200
Algeria	32 500 000	2 380 000	14	73 200
Argentina	39 500 000	2 760 000	14	69 900
Zambia	11 200 000	752 000	15	66 800
New Zealand	4 030 000	268 000	15	66 500
Sudan	40 100 000	2 500 000	16	62 300
Chile	16 100 000	756 000	21	46 900
Peru	27 900 000	1 280 000	22	46 000
Brazil	**186 000 000**	**8 510 000**	22	45 700
Mozambique	19 400 000	801 000	24	41 300
DRC	**60 000 000**	2 340 000	26	39 000
Venezuela	25 300 000	912 000	28	35 900
Madagascar	18 000 000	587 000	31	32 500
USA (ex. Alaska)	**295 000 000**	**8 150 000**	36	27 600
South Africa	44 300 000	1 210 000	36	27 500
Colombia	42 900 000	1 130 000	38	26 500
Tanzania	36 700 000	945 000	39	25 700
Yemen	20 700 000	527 000	39	25 400
Iran	**68 000 000**	1 640 000	41	24 200
World	**6 440 000 000**	**148 000 000**	43	23 100

Table J.2. Some regions with population density less than or equal to the world average. Populations above 50 million and areas greater than 5 million km^2 are highlighted.

Region	Population	Area (km^2)	People per km^2	Area each (m^2)
World	**6 440 000 000**	**148 000 000**	43	23 100
Afghanistan	29 900 000	647 000	46	21 600
Mexico	**106 000 000**	1 970 000	54	18 500
Ireland	4 010 000	70 200	57	17 500
Kenya	33 800 000	582 000	58	17 200
Myanmar	42 900 000	678 000	63	15 800
Scotland	5 050 000	78 700	64	15 500
Ethiopia	**73 000 000**	1 120 000	65	15 400
Egypt	**77 500 000**	1 000 000	77	12 900
Ukraine	47 400 000	603 000	78	12 700
Spain	40 300 000	504 000	80	12 500
Turkey	**69 600 000**	780 000	89	11 200
France	**60 600 000**	547 000	110	9 010
European Union	**496 000 000**	4 330 000	115	8 720
Poland	39 000 000	313 000	124	8 000
Indonesia	**241 000 000**	1 910 000	126	7 930
Thailand	**65 400 000**	514 000	127	7 850
China	**1 300 000 000**	**9 590 000**	136	7 340
Nigeria	**128 000 000**	923 000	139	7 170
Wales	2 910 000	20 700	140	7 110
Italy	**58 100 000**	301 000	192	5 180
Pakistan	**162 000 000**	803 000	202	4 940
Germany	**82 400 000**	357 000	230	4 330
United Kingdom	**59 500 000**	244 000	*243*	*4 110*
Vietnam	**83 500 000**	329 000	253	3 940
Philippines	**87 800 000**	300 000	292	3 410
India	**1 080 000 000**	3 280 000	328	3 040
Japan	**127 000 000**	377 000	337	2 960
England	49 600 000	130 000	380	2 630
South Korea	48 400 000	98 400	491	2 030
Taiwan	22 800 000	35 900	636	1 570
Bangladesh	**144 000 000**	144 000	1 000	997
Gaza Strip	1 370 000	360	3 820	261
Hong Kong	6 890 000	1 090	6 310	158
Singapore	4 420 000	693	6 380	156

Table J.3. Some regions with population density greater than or equal to the world average. Populations above 50 million and areas greater than 5 million km^2 are highlighted. [See p.326 for an alphabetical table.]

Region	Population	Land area (km^2)	People per km^2	Area each (m^2)
World	**6 440 000 000**	**148 000 000**	43	23 100
Asia	**3 670 000 000**	**44 500 000**	82	12 100
Africa	**778 000 000**	**30 000 000**	26	38 600
Europe	**732 000 000**	**9 930 000**	74	13 500
North America	**483 000 000**	**24 200 000**	20	50 200
Latin America	**342 000 000**	**17 800 000**	19	52 100
Oceania	31 000 000	**7 680 000**	4	247 000
Antarctica	4 000	**13 200 000**		

Table J.4. Population densities of the continents

Region	Population	Area (km^2)	People per km^2	Area each (m^2)
Iceland	296 000	103 000	2.9	347 000
Norway	4 593 000	324 000	14	71 000
Finland	5 220 000	338 000	15	64 700
Sweden	9 000 000	449 000	20	49 900
Estonia	1 330 000	45 200	29	33 900
Latvia	2 290 000	64 500	35	28 200
Belarus	10 300 000	207 000	50	20 100
Lithuania	3 590 000	65 200	55	18 100
Ireland	4 010 000	70 200	57	17 500
Scotland	5 050 000	78 700	64	15 500
Bulgaria	7 450 000	110 000	67	14 800
Ukraine	47 400 000	603 000	78	12 700
Spain	40 300 000	504 000	80	12 500
Croatia	4 490 000	56 500	80	12 500
Greece	10 600 000	131 000	81	12 300
Republic of Macedonia	2 040 000	25 300	81	12 300
Turkey	**69 600 000**	780 000	89	11 200
Bosnia and Herzegovina	4 020 000	51 100	79	12 700
Romania	22 300 000	237 000	94	10 600
Austria	8 180 000	83 800	98	10 200
Slovenia	2 010 000	20 200	99	10 000
Serbia and Montenegro	10 800 000	102 000	105	9 450
Hungary	10 000 000	93 000	107	9 290
France	**60 600 000**	547 000	110	9 010
Slovakia	5 430 000	48 800	111	8 990
Portugal	10 500 000	92 300	114	8 740
Albania	3 560 000	28 700	123	8 060
Poland	39 000 000	313 000	124	8 000
Denmark	5 430 000	43 000	126	7 930
Czech Republic	10 200 000	78 800	129	7 700
Moldova	4 450 000	33 800	131	7 590
Wales	2 910 000	20 700	140	7 110
Switzerland	7 480 000	41 200	181	5 510
Italy	**58 100 000**	301 000	192	5 180
Germany	**82 400 000**	357 000	230	4 330
United Kingdom	**59 500 000**	***244 000***	*243*	***4 110***
Belgium	10 000 000	31 000	340	2 945
England	49 600 000	130 000	380	2 630
Netherlands	16 400 000	41 500	395	2 530
Malta	398 000	316	1 260	792

Table J.5. Population densities of regions around Europe. [See p. 326 for an alphabetical table.]

Region	Population	Area (km^2)	People per km^2	Area each (m^2)
Afghanistan	29 900 000	647 000	46	21 600
Africa	**778 000 000**	**30 000 000**	26	38 600
Alaska	655 000	1 480 000	0.44	2 260 000
Albania	3 560 000	28 700	123	8 060
Algeria	32 500 000	2 380 000	14	73 200
Angola	11 100 000	1 240 000	9	111 000
Antarctica	4 000	**13 200 000**		
Argentina	39 500 000	2 760 000	14	69 900
Asia	**3 670 000 000**	**44 500 000**	82	12 100
Australia	20 000 000	**7 680 000**	2.6	382 000
Austria	8 180 000	83 800	98	10 200
Bangladesh	**144 000 000**	144 000	1 000	997
Belarus	10 300 000	207 000	50	20 100
Belgium	10 000 000	31 000	340	2 945
Bolivia	8 850 000	1 090 000	8	124 000
Bosnia and Herzegovina	4 020 000	51 100	79	12 700
Botswana	1 640 000	600 000	2.7	366 000
Brazil	**186 000 000**	**8 510 000**	22	45 700
Bulgaria	7 450 000	110 000	67	14 800
CAR	3 790 000	622 000	6	163 000
Canada	32 800 000	**9 980 000**	3.3	304 000
Chad	9 820 000	1 280 000	8	130 000
Chile	16 100 000	756 000	21	46 900
China	**1 300 000 000**	**9 590 000**	136	7 340
Colombia	42 900 000	1 130 000	38	26 500
Croatia	4 490 000	56 500	80	12 500
Czech Republic	10 200 000	78 800	129	7 700
DRC	**60 000 000**	2 340 000	26	39 000
Denmark	5 430 000	43 000	126	7 930
Egypt	**77 500 000**	1 000 000	77	12 900
England	49 600 000	130 000	380	2 630
Estonia	1 330 000	45 200	29	33 900
Ethiopia	**73 000 000**	1 120 000	65	15 400
Europe	**732 000 000**	**9 930 000**	74	13 500
European Union	**496 000 000**	4 330 000	115	8 720
Finland	5 220 000	338 000	15	64 700
France	**60 600 000**	547 000	110	9 010
Gaza Strip	1 370 000	360	3 820	261
Germany	**82 400 000**	357 000	230	4 330
Greece	10 600 000	131 000	81	12 300
Greenland	56 300	2 160 000	0.026	38 400 000
Hong Kong	6 890 000	1 090	6 310	158
Hungary	10 000 000	93 000	107	9 290
Iceland	296 000	103 000	2.9	347 000
India	**1 080 000 000**	3 280 000	328	3 040
Indonesia	**241 000 000**	1 910 000	126	7 930
Iran	**68 000 000**	1 640 000	41	24 200
Ireland	4 010 000	70 200	57	17 500
Italy	**58 100 000**	301 000	192	5 180

Table J.6. Regions and their population densities (alphabetical order). Populations above 50 million and areas greater than 5 million km^2 are highlighted.

Region	Population	Area (km^2)	People per km^2	Area each (m^2)
Japan	**127 000 000**	377 000	337	2 960
Kazakhstan	15 100 000	2 710 000	6	178 000
Kenya	33 800 000	582 000	58	17 200
Latin America	**342 000 000**	**17 800 000**	19	52 100
Latvia	2 290 000	64 500	35	28 200
Libya	5 760 000	1 750 000	3.3	305 000
Lithuania	3 590 000	65 200	55	18 100
Madagascar	18 000 000	587 000	31	32 500
Mali	12 200 000	1 240 000	10	100 000
Malta	398 000	316	1 260	792
Mauritania	3 080 000	1 030 000	3	333 000
Mexico	**106 000 000**	1 970 000	54	18 500
Moldova	4 450 000	33 800	131	7 590
Mongolia	2 790 000	1 560 000	1.8	560 000
Mozambique	19 400 000	801 000	24	41 300
Myanmar	42 900 000	678 000	63	15 800
Namibia	2 030 000	825 000	2.5	406 000
Netherlands	16 400 000	41 500	395	2 530
New Zealand	4 030 000	268 000	15	66 500
Niger	11 600 000	1 260 000	9	108 000
Nigeria	**128 000 000**	923 000	139	7 170
North America	**483 000 000**	**24 200 000**	20	50 200
Norway	4 593 000	324 000	14	71 000
Oceania	31 000 000	**7 680 000**	4	247 000
Pakistan	**162 000 000**	803 000	202	4 940
Peru	27 900 000	1 280 000	22	46 000
Philippines	**87 800 000**	300 000	292	3 410
Poland	39 000 000	313 000	124	8 000
Portugal	10 500 000	92 300	114	8 740
Republic of Macedonia	2 040 000	25 300	81	12 300
Romania	22 300 000	237 000	94	10 600
Russia	**143 000 000**	**17 000 000**	8	119 000
Saudi Arabia	26 400 000	1 960 000	13	74 200
Scotland	5 050 000	78 700	64	15 500
Serbia and Montenegro	10 800 000	102 000	105	9 450
Singapore	4 420 000	693	6 380	156
Slovakia	5 430 000	48 800	111	8 990
Slovenia	2 010 000	20 200	99	10 000
Somalia	8 590 000	637 000	13	74 200
South Africa	44 300 000	1 210 000	36	27 500
South Korea	48 400 000	98 400	491	2 030
Spain	40 300 000	504 000	80	12 500
Sudan	40 100 000	2 500 000	16	62 300
Suriname	438 000	163 000	2.7	372 000
Sweden	9 000 000	449 000	20	49 900
Switzerland	7 480 000	41 200	181	5 510

Table J.7. Regions and their population densities (alphabetical order). Populations above 50 million and areas greater than 5 million km^2 are highlighted.

Region	Population	Area (km^2)	People per km^2	Area each (m^2)
Taiwan	22 800 000	35 900	636	1 570
Tanzania	36 700 000	945 000	39	25 700
Thailand	**65 400 000**	514 000	127	7 850
Turkey	**69 600 000**	780 000	89	11 200
Ukraine	47 400 000	603 000	78	12 700
United Kingdom	**59 500 000**	***244 000***	*243*	***4 110***
USA (ex. Alaska)	**295 000 000**	**8 150 000**	36	27 600
Venezuela	25 300 000	912 000	28	35 900
Vietnam	**83 500 000**	329 000	253	3 940
Wales	2 910 000	20 700	140	7 110
Western Sahara	273 000	266 000	1	974 000
World	**6 440 000 000**	**148 000 000**	43	23 100
Yemen	20 700 000	527 000	39	25 400
Zambia	11 200 000	752 000	15	66 800

Table J.8. Regions and their population densities (alphabetical order). Populations above 50 million and areas greater than 5 million km^2 are highlighted.

K

Transport technology

Figure K.1. Multi-passenger vehicles.

Short-range high-speed trains

One carriage has weight 50 tonnes, length 20m, width 2.82 m, and contains 79 seats. (six windows and 2 doors, WAGN stock). Height is I think 4m.

What is the best that a high-speed train's energy-per-distance could possibly be? Just like a fast-moving car, a train needs energy because it makes air swirl. The energy-per-distance (or 'force') needed to make air swirl is

$$\frac{1}{2}c_d \rho A v^2,$$

where c_d is a drag coefficient, which I'll take to be 1, ρ is the density of air, A is the frontal area of the train, and v is its speed. This is the unavoidable energy that a train travelling at speed v must guzzle.

Let's plug in the figures for a 100 mph train from London to Cambridge ($v = 45\,\text{m/s}$). The train has width 2.8 m, height 4 m, weighs 400 tonnes, and seats 630 passengers (who themselves weigh an extra 50 tonnes). The energy per distance associated with air resistance comes out to

$$15\,000\,\text{J/m}$$

or

$$400\,\text{kWh per }100\,\text{km}$$

which, shared between 630 is

$$0.65\,\text{kWh per }100\,\text{seat-km}.$$

This is the smallest that the energy consumption could ever be. In practice, it's about five times bigger because of the inefficiency of energy conversion, and the other things that energy goes into.

Is the London-to-Cambridge train's energy consumption really drag-dominated? Let's check what the distance between stops needs to be for drag-power to exceed the starting-and-stopping power. The two powers are equal if $\rho A D = m_{\text{train}}$; which means $D \simeq 40\,\text{km}$. So if the train comes to a stop a couple of times between London and Cambridge (a distance of 100 km), the train would be putting equal energy into making its own kinetic energy as into air resistance. So to get an accurate estimate, I can't neglect the mass of the train.

What about rolling friction? If rolling friction is about 10 Newtons per tonne, the force for rolling friction is about 4500 Newtons. This is roughly one third of the force I estimated for air resistance.

Train mpg? Assume drag dominated;

energy per distance = force = $1/2 c_d rho A v^2$ Diesel or electric?

Diesel:

Scale compared to car (70mph). v = 100mph so v^2 is 4 times bigger;

A = 4 times bigger; (8m**2)

c_d much same as car; so energy per distance is 16 times bigger; but occupancy is 16*4 per carriage, times 8 carriages -¿ could be 500 per train.

So pmpg is up to 500/16 which is 31 times better.

Compute distance between stops for energy to indeed be drag dominated: $\rho A D = m_{\text{train}}$;

$m_{\text{train}} \simeq$ 50 tons per carriage, 8 carriages -¿ 400,000 kg D = 400,000/ 1 / 8 = 50,000 metres = 50km. (400 times bigger than car by weight; 4 times smaller by area).

Stopping train: kinetic energy dominated.

energy cost per distance is (1/2)mv**2 / D

where D is the dist between stops, say 3km (so always within a mile of a station, if you are adjacent to the line).

v = 30 mph = 15 m/s

m (single carriage) = 20,000 kg; actually 50,000. 64 people max.

-¿ energy cost per distance is 750 J per m (*5/2) or 750 kJ per km (for all 64 people) (*5/2) or 12 kJ per km per person; (*5/2) which is 0.3 units per 100 km; (300 km per unit) (*5/2) [what did I do here about internal combustion efficiency? Did I assume electric train?] or in mpg, 300km per (1/56 gall); /(5/2) which is 17000 km per gallon. /(5/2)

10 000 passenger miles per gallon /(5/2)

Don't use mpg, it doesn't translate to America or Europe. Let's use kWh per 100 seat-km instead.

Cost of new trains: 250 million pounds for 51 trains each 3 carriages and diesel powered.

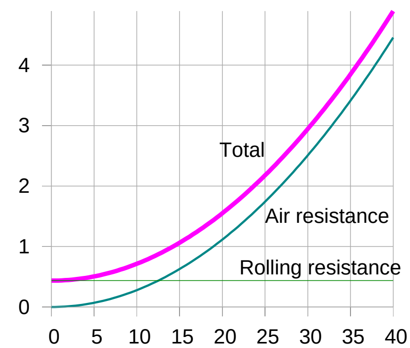


Figure K.2. Simple theory of bike fuel consumption (energy per distance). Horizontal axis is speed in km/h. Vertical axis is fuel consumption in kWh per 100 km. Assuming that the bike's engine (that's you!) uses energy with an efficiency of 0.25, whatever the speed; that the drag-area of the cyclist is 0.5 m^2; and that the cyclist+bike's mass is 80 kg, and that $C_{\text{rr}} = 0.005$: The transition from rolling-resistance-dominated cycling to air-resistance-dominated cycling takes place at a speed of about 12 km/h. At a speed of 20 km/h, cycling costs about 1.6 kWh per 100 km.

Bicycles

For a bicycle ($m = 90$ kg, $A = 0.75$ m^2) , the speed above which rolling resistance is less than air resistance is

$$v = 3\,\text{m/s}$$

or 7 mph.

Electric bicycle (according to a friendly user): 1 kWh(e) per 100 passenger-km. (I think he pedals too.)

L

Storage II

Pumped storage

The working volume required, V, depends on the height drop we assume. If ϵ is the efficiency of potential energy to electricity conversion,
$\epsilon \rho V g h = 50\,\mathrm{GWh}$

$$V = 50\,\mathrm{GWh}/(\rho g h \epsilon) \tag{L.1}$$

Assuming the generators have an efficiency of $\epsilon = 0.9$, table 25 (p. 189) shows a few ways of storing 50 GWh, for a range of height drops.

Tidal pumped storage

This calculation goes with the discussion on p. **??**.

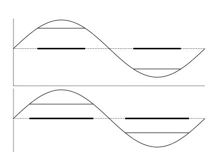
Let's denote the tidal range by $2h$ (for example 4 m) and the extra head by b. We start a daily cycle one evening, with high and low lagoons both at the mid-tide level. Overnight we pump the high lagoon up and the low lagoon down at the optimal times near to high and low tide. The total energy cost of the pumping, per unit area of facility, is

$$\frac{1}{2}\rho g b^2/\epsilon_{\mathrm{p}}$$

where ϵ_{p} is the pump's efficiency. In the design of figure 25.10(a), the energy returned at the time of peak demand, per unit area, is

$$\epsilon_{\mathrm{g}}\frac{1}{2}\rho g(h+b)^2.$$

The alternative design, figure 25.10(b), delivers slightly greater power by picking which pool to exploit depending on the sea level. At a randomly chosen time, there is a 50% chance that the tide is in quite an extreme state – more than 71% of the way to high tide or more than 71% of the way to low tide; and there is a 2/3 chance that the tide is either beyond half-full or beyond half-empty. So, as long as the profitable period lasts more than a couple of hours, both of the pools will have a good chance



of serving high-value electricity and the energy returned, per unit area, is about

$$\epsilon_{\rm g} \frac{1}{2} \rho g \left(\frac{3}{2} h + b \right)^2 .$$

Additionally,

$$\epsilon_{\rm g} \frac{1}{2} \rho g \left(\frac{3}{2} h + b \right)^2 .$$

Let's find the size required for a system with a stored energy of 10 GWh (about the same as Dinorwig), assuming $2h = 4$ m and $b = 10$ m. That's about 57 km^2, which would fit inside an 8 km square, and would need about 40 km of wall. Equipped with generators like Dinorwig's, it would deliver 2 GW of power during 5 hours of peak demand each day. And the energy cost of delivering that 10 GWh would be just 6.7 GWh. For comparison with other renewable sources, the power density of the useful power delivered at peak demand would be 10 W/m^2, averaged over 24 hours. The average net power delivered would be 3.3 W/m^2.

The economics for such a scheme especially favour large facilities: the cost of the lagoons' walls would be proportional to the walls' length, but the area enclosed, and thus the delivered power, would increase as the square of the length.

Loch Maree as a pumped storage facility

The following calculation may make me unpopular with conservationists. Loch Maree's surface area is 28.6 km^2, and it is less than 10 m above sea level. Tidal range in the Minch is near to 5 m at springs.

If we allowed ourselves to vary the water level in Loch Maree by one metre, the working volume would be about 300 million m^3. The energy delivered by dropping this water 12.5 m (at low tide) would be about 9.4 GWh (allowing for 90% efficient generators). The energy cost of pumping it up 7.5 m (at high tide) would be about 7.8 GWh (allowing for 80% efficient pumps). So Loch Maree could offer a Dinorwig's worth of storage, except, when the timing was right, it would be 120% efficient, in contrast to Dinorwig's 75%.

Major lochs near to the sea

Loch Katrine (area 13 km^2), a freshwater reservoir for Glasgow, is 100 m above Loch Lomond and about 6 km away. If Katrine's existing dam were increased in height by 5 m, and variations in height of 5 m were permitted, Katrine could be a 16-GWh storage system.

Blackwater Reservoir and Loch Leven (sea loch)

Water level: 320 m. Has a pipeline down to sea-level at Kinlochleven, with a hydro station built by the British Aluminium Company for a smelter, closed in 2000. The reservoir is roughly 1 km by 12 km. If it

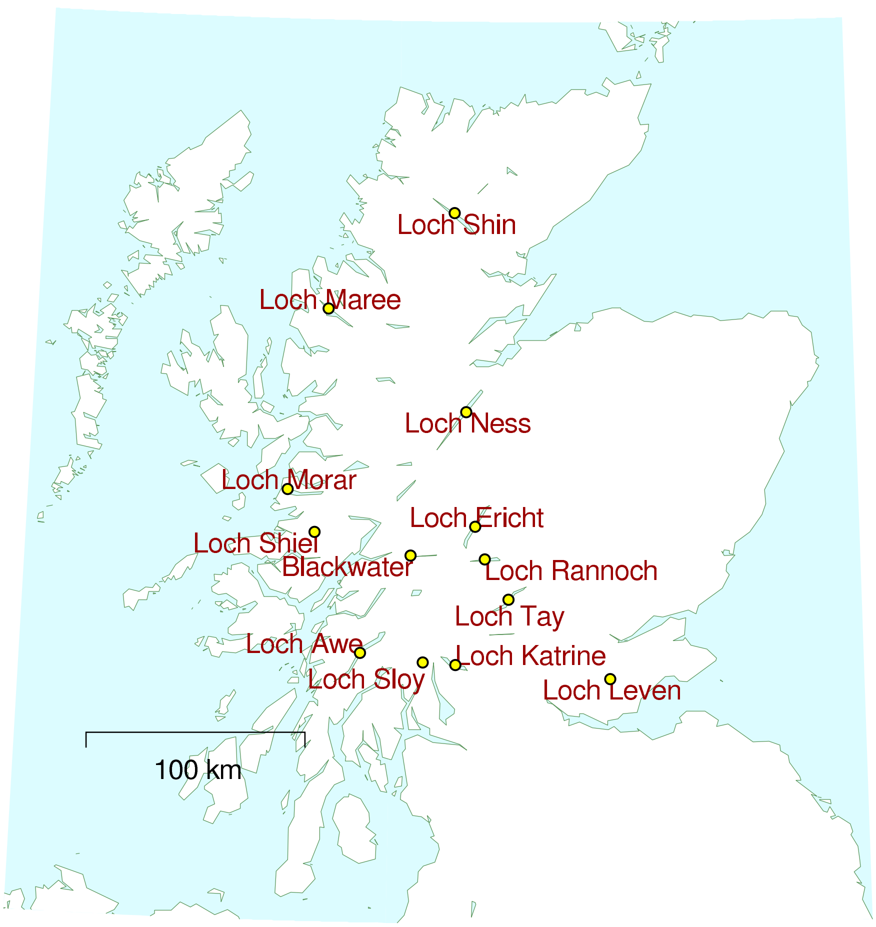


Figure L.2. Lochs in Scotland with potential for pumped storage.

were used for pumped storage with the sea as the lower reservoir, and if the range could be 20 m (perhaps with an enlarged dam), this reservoir could hold about 125 GWh.

Loch Morar

Very close to the sea. Surface area: 26.7 km^2. And very deep, so it could perhaps be pumped down instead of up. 10.1 m above sea level.

Loch Ness

Used for shipping. 15.8 m above sea level. Surface area: 56 km^2.

Look into Loch Lochy.

Dam Little Loch Broom?

Loch Damh, Upper Loch Torridon.

Loch Etive. Dam it? and Loch Awe? Lower Loch Etive, and raise Loch Awe? Loch Awe is a bit too high above sea-level to get the efficiency boost.

At Kylesku: Loch Glencoul and Loch Glendhu?

Owned/managed by property managers Grosvenor.

Raw tidal energy: (see data/tides) Loch Glendhu is 5km * 0.5km. Loch Glencoul is 4km * 1km. Total is about 6.5km^2. If 1 MW/km^2 (assuming 2 m range, optimistic!) then that's 6.5 MW.

See also proposed Reay Forest Hydroelectric Scheme, Kylesku, Sutherland. The proposal will consist of two linked schemes, one on the Maldie Burn and one in Gleann Dubh. Between them they will generate up to 35GWh of electricity per year, sufficient for the needs of approximately 8000 homes (8 MW).

Loch Awe

Surface area: 39 km^2. 36 m above sea-level. Natural fluctuations in water level: 2.7 m.

Loch Shiel

4.5 m above sea-level. Surface area: 20 km^2. Natural water level variations: 2 m.

Loch Shiel is close to three sea lochs: Loch Eil (Loch Linnhe) to its east, Loch Sunort to its south, and Loch Moidart to the northwest. It'd be interesting to explore whether the times of high and low tide in these lochs are different enough to motivate having pumping and generating turbines at both ends.

Loch Eil head High tides Sat 17 March 5.17 17.37 Thu 22 March 8.24 20.29

Loch Moidart Sat 17 March 4.55 17.14 4.6m 4.3m Thu 22 Mar 7.57 20.02 4.9m 4.6m

Salen Sat 17 Mar 4.51 17.10 4.2m 4.2m Springs = 21 March, 4.9m-0.2m = 4.7m range.

Major inland lochs

Loch Shin

With an area of 22.5 km^2, Loch Shin is already blessed with a hydroelectric dam. It's about 90 m above sealevel. No major body of water is nearby.

Loch Tay

28 km^2. Nearest loch is Loch Earn (about 10 km away).

Loch Ericht and Loch Rannoch

Loch Leven

56N, 3W. 107 m above sea-level. Surface area: 13.3 km^2. Normal variation in level: 0.3 m.

Chemical storage

This doc describes a storage system used to improve the reliability of a wind farm.

12 MWh of storage for a 32 MW windfarm with another 6.9 MW of turbines on the way. At the high efficiencies promised by VRB at full throughput, 10% of the output of the windfarm would fill up the storage in 4 hours. When the windfarm is becalmed, that storage would run down in under 20 minutes if they tried to use it to maintain the output from the site at the nominal capacity, or just over 3 hours if they set themselves the more modest target of exporting at least 10% of their capacity. This isn't a technology to turn intermittent wind into something predictable. It is a technology to make minor adustments to the profile of the variable output.

VRB Power Systems' sale of a storage system for Sorne Hill windfarm in Ireland This is a big battery, a vanadium-based redox regenerative fuel cell. It has a round-trip efficiency of 70–75%.

The space required for storage is about 1 m^3 for 20 kWh using 2-molar vanadium in sulphuric acid. reported by japanese paper. That's 0.02 kWh/kg or 72 kJ/kg.

So to store 10 GWh would require 500 000 m^3 – for example, tanks 2 m high covering a floor area of 500 m × 500 m.

More recently, VRB power systems have provided a 12 MWh energy storage system for the Sorne Hill windfarm in Ireland (currently '32 MW', increasing to '39 MW'). This storage system is a big battery, a vanadium-based redox regenerative fuel cell, with a couple of tanks full of vanadium in different chemical states. This storage system can smooth the output of its windfarm on a time-scale of minutes, but the longest time for which it could deliver one third of the 'capacity' (during a lull in the wind) is one hour. The same company installed a 1.1 MWh system on Tasmania. It can deliver 200 kW for four hours, 300 kW for 5 minutes and 400 kW for 10 seconds. VRB (vanadium redox battery) Comparison with lead-acid batteries: The flowbattery has a life of more than 10 000 cycles but a lead-acid has a life of only 1 500; it can be charged at the same rate that it is discharged (in contrast to lead-acid batteries which must be charged 5 times as slowly). Lead acids may be up to 3 times lighter in terms of power density (watts per kg). Lead acid battery (comparison authored by advocates of flow batteries): 11 000 Ah at 340 V (3.7 MWh) costs $780 000 and occupies 140 m^2 with a mass of 128 tonnes. Equivalent performance to vanadium system 1.5 MWh costing $480 000. Occupies 70 m^2 with a mass of 107 tonnes. Energy density in Wh/litre: Lead acid 12–18; VRB 16–33. Efficiency: lead acid 45%, VRB 70–75% (according to the company that sells them).

Scaling this up, a 10 GWh system using vanadium would cost $3.2 billion.

cf Dinorwig working volume is 6.7 million m^3 which is about ten times greater. Its cost was £0.4 billion in 1980.

M

Smart heating II

Ground source heat pumps

WARNING: This section is intended for an undergraduate science audience.

Let's work out a cartoon theory for below-ground temperatures, and for what happens when we lay down tubes and suck out heat.

I'm going to assume the ground is made of granite. Key quantities: Heat capacity: $C = 820\,\mathrm{J/kg/K}$. Conductivity: $\kappa = 2.1\,\mathrm{W/m/K}$. Density: $\rho = 2750\,\mathrm{kg/m^3}$. Heat capacity per unit volume: $C_\mathrm{V} = \rho C = 2.3\,\mathrm{MJ/m^3/K}$.

Response to external temperature

If we assume the ground is made of solid homogenous granite, then the temperature at depth z below the ground responds to the imposed temperature at the surface in accordance with the diffusion equation

$$\frac{\partial T}{\partial t} = \frac{\kappa}{C_\mathrm{V}} \frac{\partial^2 T}{\partial z^2}. \tag{M.1}$$

For a sinusoidal imposed temperature with frequency ω and amplitude A imposed at depth $z = 0$,

$$T_\mathrm{surface}(t) = T_\mathrm{average} + A\cos(\omega t), \tag{M.2}$$

the resulting temperature at depth z and time t is a decaying and oscillating function

$$T(z,t) = T_\mathrm{average} + Ae^{-z/z_0}\cos(\omega t - z/z_0), \tag{M.3}$$

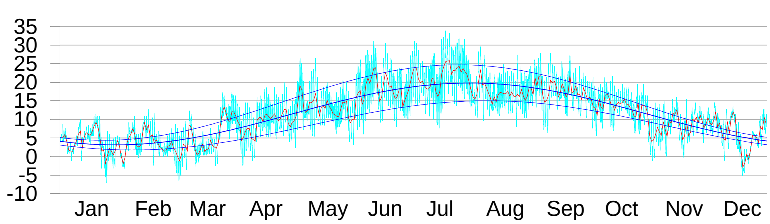


Figure M.1. The temperature in Cambridge, 2006, and a cartoon, which says the temperature is the sum of an annual sinusoidal variation between 3°C and 20°C, and a daily sinusoidal variation with range up to 10.3°C. The average temperature is 11.5°C.

where z_0 is the characteristic lengthscale of both the decay and the oscillation,

$$z_0 = \sqrt{\frac{2\kappa}{C_{\rm V}\omega}}. \tag{M.4}$$

For daily variations, this characteristic lengthscale is $z_0 = 0.16\,$m. (So 32 cm of rock is what you need to ride out external daily temperature fluctuations.) For yearly variations, the characteristic lengthscale is $z_0 = 3\,$m. At a depth of $2z_0$, the variations in temperature are one seventh of those at the surface, and lag them by about one third of a cycle. At a depth of $3z_0$, the variations in temperature are one twentieth of those at the surface, and lag them by half a cycle.

The flux of heat (the power per unit area) at depth z is

$$\kappa\frac{\partial T}{\partial z} = \kappa\frac{A}{z_0}\sqrt{2}e^{-z/z_0}\sin(\omega t - z/z_0 - \pi/4).$$

For example, at the surface, the peak flux is

$$\kappa\frac{A}{z_0}\sqrt{2} = A\sqrt{C_{\rm V}\kappa\omega},$$

which for the yearly driving signal of amplitude $A = 8.3°$C corresponds to $8\,{\rm W/m^2}$.

This flux is a useful benchmark, giving guidance about what sort of power we could expect to extract with a ground source heat pump. If we suck a flux significantly smaller than $8\,{\rm W/m^2}$, the perturbation we introduce to the natural flows will be small. If on the other hand we try to suck a flux bigger than $8\,{\rm W/m^2}$, we should expect that we'll be shifting the temperature of the ground significantly away from its natural value, and such fluxes may be impossible to demand.

If, as on p. 145, we pick $160\,{\rm m^2}$ per person as our representative density of a residential area, we deduce that a ballpark limit for heat pump power delivery is

$$8\,{\rm W/m^2} \times 160\,{\rm m^2} = 1300\,{\rm W} = 31\,{\rm kWh/d\ per\ person}.$$

This is uncomfortably close to the sort of power we would like to deliver in winter-time: it's plausible that our winter-time demand for hot air and hot water might be 48 kWh/d per person.

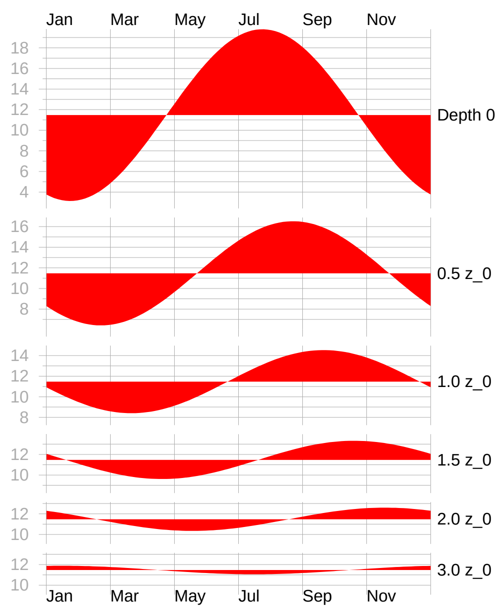


Figure M.2. Temperature versus depth in granite. The depths are given in units of the characteristic depth z_0, which for granite and annual variations is 3 m.

Depth 0	surface
Depth 1.0	3 m
Depth 2.0	6 m
Depth 3.0	9 m

N

Terminology

Words, words, words

Just so you know I've thought about some of the choices of words in this book, here's some responses to frequently asked questions and comments.

You refer to wind turbines as "windmills". They are not mills, of course, because a mill is something that grinds grain (or coffee), not which produces electricity.

Windmills – I agree, wrong noun. However, I like short words. (Wind turbine takes longer to say and write.) And I think the abuse of the word windmill, generalising it to have the wider meaning, 'any wind machine', has a long pedigree. Imagine you are in 1800s Holland, for example – what would you have called the things with 4 sails going round? Bear in mind that many of them were not grinding grain, but pumping water. Does anyone say 'I love the beautiful Dutch windpumps'? And what do people call the classic many-bladed wind machine of the American farmland? The Oxford English Dictionary defines a windmill to be 'a mill ... for grinding corn, pumping water ... or sawing.' The term 'windmill' has been used for general wind-powered machines since 1759. Finally, I like to use this word because it tweaks the noses of wind engineers who don't like their machines being confused with children's toys.

You refer to CO_2 "pollution". I think this term confuses the public. CO_2 is not a pollutant in the sense that the public understands the word (it has no discernable direct impact on humans until well above 1000 ppmv, and is directly beneficial to plants). Why not just say "CO_2 emissions"? The big concern is potentially catastrophic effects on climate, and the changes needed to avert this problem are far more fundamental than those needed to deal with any conventional pollution problem to date.

I have actually deliberately been through the book and changed almost all mentions of CO_2 "emission" *to* "pollution". I think unless we call it pollution, which is what it *is* when emitted on a 20 gigaton-per-year scale, we won't get action. I am perfectly happy for the definition of the word 'pollutant' to include "something that has potentially catastrophic effects on climate".

If we call them emissions, then people will talk about "emissions rights" and go on about useless trading systems. The terms "pollution rights" sticks in the throat more. Like "murder permit".

Give them an inch and they'll drive a mile.

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The errors that remain are my own.

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Thank you to Gilby Productions for providing the TinyURL service. TinyURL is a trademark of Gilby Productions. Thank you to Eric Johnston and Satellite Signals Limited for providing a nice interface for maps `http://www.satsig.net/`.

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The artwork on page **??** is 'Maid in London' by Banksy `http://www.banksy.co.uk/`; and on page 40, 'Sunflowers' also by Banksy. Thank you, Banksy!

I am grateful to the office of the Mayor of London for providing their advertisements.

This book is written in LaTeX on the ubuntu GNU/Linux operating system using free software. The figures were drawn with `gnuplot` and `metapost`. Many of the maps were created with Paul Wessel and Walter Smith's `gmt`. Thank you to Donald Knuth, Leslie Lamport, Richard Stallman, Linus Torvalds, and all those who contribute to free software.

Finally I owe the biggest debt of gratitude to the Gatsby Charitable Foundation, who supported me and my research group before, during, and after the writing of this book.

O

Quick reference

numbers

List of tables: Powers per unit area Transport efficiencies (kWh per 100 Passenger-km) Energy contents of fuels Carbon contents of fuels Things equivalent to one tonne of CO_2 per year Energy conversion Power conversion Population densities

Other useful numbers

Fraction of UK CO_2 emissions that come from industry: 40%.

13 nations – the G8 plus five big developing nations – account for 70% of greenhouse gas emissions.

Powers per unit area

Put my own figures here.

From Hodgson page 127, area per MW (m^2): Nuclear 630 Oil 870 Gas 1500 Coal 2400 Solar 1 000 000 Hydro 265 000 Wind 1 7000 000 (of which much of the land can be used for other purposes, eg agriculture)

Powers per unit length

Wave, tide.

Transport efficiencies (kWh per 100 Passenger-km)

Energy conversion

1 kWh = 3.6 MJ kJ/mol in eV: kT in eV and kJ/mol: 1 Food Calorie = 1000 calories = 4200 J.

Power conversion

$1\,\text{kWh/d} = \frac{1}{24}\,\text{kW}$ 1 TWh/y

Power from a petrol pump

Petrol comes out at about half a litre per second. So that's 10 kWh per 2 seconds, or 18 MW.

Power of a formula one racing car: 560 kW.

Energy contents of fuels

ton of coal equivalent = 29.3 GJ. = 8000 units of heat, Hydrocarbons: 30 000 kJ per kg

9 kWh per litre. The gross calorific value of DERV is 45.5 GJ/tonne; of aviation fuel, 46.2; of motor spirit, 47 GJ/tonne.

Interesting to express these per unit mass also. Petrol: 12 kWh/kg. Coal: 8 kWh/kg. Batteries: Car battery (lead-acid): 0.03 kWh/kg. Lithium-ion: 0.15–0.2 kWh/kg. Still about 50 times heavier than petrol.

Fusion energy of ordinary water: 1800 kWh per litre.

Gas is 40MJ per cubic metre.

Energy densities of fuels. Petrol 31.5 MJ/l; bioethanol 21.6 MJ/l; methanol 21.2 MJ/l. (too high?) Mabee et al. says methanol is 14.6 MJ/l. (too low?) Wikipedia says methanol's low heating value is 19.7 MJ/kg. Methanol lower value: 19.94 MJ/kg. Wikipedia. (15.8 MJ/l) Methanol HHV: 22.7 MJ/kg. Methanol density: 0.7918 g/cc; so HHV is 18.0 MJ/l. Ethanol density: 0.789. Ethanol Higher value: 29.8 MJ/kg. Wikipedia. Ethanol lower value: 28.87 MJ/kg. Wikipedia. That's HHV 23.512 MJ/l, LHV 22.778 MJ/l.

Carbon contents of fuels

Useful figure: Gas generation: 400 g CO_2/kWh(e).

(from page 127 in DTI-PIU.pdf)

Natural Gas raw energy: 15.5 tC/TJ (IPCC) is 15.5 kgC/GJ is 57 kg CO_2/GJ is 57 g CO_2/MJ is 200 g CO_2/kWh.

Raw heat:

1 kWh $\leftrightarrow$ 250 g of CO_2 (oil, petrol)

for gas, 1 kWh $\leftrightarrow$ 200 g CO_2.

1kWh(e) = 0.445 kg CO2 from Gas 1kWh = 0.955 kg CO2 from Coal (from Carbon trust talk)

Petrol: 1 kWh $\leftrightarrow$ 250 g of CO_2 (oil, petrol). 1 litre of fuel $\leftrightarrow$ 10 kWh $\leftrightarrow$ 2.2 kg of CO_2. (check) Each gallon of fuel contributes 10 kg of CO_2 pollution.

LCVs

I prefer to use HCVs, but here's a list of LCVs: Gas 50 MJ/kg; Oil 40 MJ/kg; Coal 30 MJ/kg.

1 ton of CO_2 per year	$\leftrightarrow$	3 kg CO_2 per day
1 kg of carbon per day	$\leftrightarrow$	4 kg CO_2 per day
1 ton of carbon per year	$\leftrightarrow$	10 kg CO_2 per day

Table O.1. Conversion rates for carbon emissions

Things equivalent to one tonne of CO_2 per year

Heat capacities

The heat capacity of water is $C = 4200\,\mathrm{J/litre/°C}$.

The heat capacity of air is 1000 J/kg/°C. 1 kJ/kg/°C. Or 29 J/mol/°C. The density of air is 1.2 kg/m^3.

So the heat capacity of air per unit volume is $1\,\mathrm{kJ/kg/°C} \times 1.2\,\mathrm{kg/m^3} = 1.2\,\mathrm{kJ/m^3/°C}$.

Latent heat of vaporization of water: 2257.92 kJ/kg. Water vapour's heat capacity: 1.87 kJ/kg/K. Water's heat capacity: 4.187 kJ/kg/K. Steam's density: 0.590 kg/m^3.

Money

Natural gas import price paid by the EU-15: 3.66 Euro per GJ (2003 price).

Liquified Natural gas import price paid by the EU-15: 3.38 Euro per GJ (2003 price).

Electricity price (industrial, UK): 11.14 € per GJ (2004).

Household natural gas price: 7.6 € per GJ (UK price 2004).

Household electricity price: 23.3 € per GJ. (UK price 2004)

Economic energy intensity

Energy intensity of EU-15 in 2002 was about 190 kg oil equivalent per 1000 €. Energy intensity of EU-25 in 2002 was about 210 kg oil equivalent per 1000 €.

Using Crude Oil 45.7 GJ/tonne, that's 12 700 kWh/tonne. So 200 kg oil is 2500 kWh.

(42 GJ is the standard figure, which gives 2300 kWh instead.)

SI prefixes

Throughout this book 'a billion' means an American billion, that is, 10^9, or a thousand million. A trillion is 10^{12}. The standard prefix meaning 'billion' (10^9) is 'giga'.

In continental Europe, the abbreviations Mio and Mrd are used to mean million and billion respectively. Mrd is short for milliard, which means 10^9.

The abbreviation m is often used to mean million, but this abbreviation is incompatible with the SI (think of mg (milligram) for example).

Name	exa	peta	tera	giga	mega	kilo	hecto
Symbol	E	P	T	G	M	k	h
Factor	10^{18}	10^{15}	10^{12}	10^{9}	10^{6}	10^{3}	10^{2}

Name	centi	milli	micro	nano	pico	femto	atto
Symbol	c	m	μ	n	p	f	a
Factor	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}

Table O.2. SI prefixes

So I don't use m to mean million. Where some people use m, I replace it by M. For example, I used Mtoe for million tonnes of oil equivalent, and Mt CO_2 for million tonnes of CO_2.

The abbreviation bn is often used to mean billion. I prefer b. But perhaps I should stick to bn.

Horses

Jevons: seven horses could do the work of 34 men.

Assorted crazy units

For flow of water: 1 Sv = 10^6 m^3/s

To sort

1 TOE = 10^7 kilocal = 397 therms = 41.9 GJ = 11 630kWh

1 toe/y = 1.33 kW

100 000Btu = 1 therm

Oil: 262 imperial gallons per tonne; 1192 litres per tonne.

Aviation gasoline 1397 litres per tonne

Motor spirit: 1357 litres per tonne

DERV fuel: 1203 litres per tonne

"toe" for comparing fuels

Net calorific value of fuel is calorific value minus the energy that gets wasted vaporizing the water in the fuel and the water generated by combustion. Which is 5 or 10 or 15 percent for oil and coal, gases, and straw/poultry litter. For wood IT DEPENDS A LOT. Dry wood has net calorific value of 19 GJ per tonne. Ordinary wood, 50% moisture content, is 10 GJ.

UK gallon = 1.2 US gall = 4.546 l The standard barrel for petroleum products = 42 US gallons and 1 barrel = 159 litres. (Seems to be an accepted definition.)

But beware! google says 1 barrel = 117.35 litres and 1 barrel is 31 US gallons. (This is the US beer barrel.)

In the UK a barrel is 36 imperial gallons, which is 163.7 litres.

So we can't trust the barrel.

Be aware, furthermore, that fluid ounces are not constants either: 1 Imperial fluid ounce = 0.961 US fluid ounces.

2 g CO_2 ↔ 1 litre

Table O.3. Volume-to-mass conversion: every 44 g of CO_2 occupies 22 litres.

Gross calorific values

Coal 26.7 GJ/tonne Wood 10 GJ per tonne Solid waste 9.5GJ/tonne Crude Oil 45.7 GJ/tonne Petroleum 45.9 GJ/tonne Petrol 47.1 Diesel 45.6 Natural gas 39.6 MJ/cubic metre or 1.1 MJ/cubic foot

Carbon

it takes 2.1 billion tons of carbon to raise the atmospheric CO2 concentration by one part per million." If all the CO2 we pumped into the atmosphere stayed there, the concentration would be rising by more than three ppm per year – but it is actually rising only one and a half ppm annually.

Carbon intensity of steel and concrete

Steel: roughly 2 tons of CO_2 per ton of steel.

Concrete: A life-cycle analysis gives 43–240 kg CO_2 per ton, depending on the type of concrete, with 100 kg per ton of concrete as a median figure `http://www.sustainableconcrete.org.uk/main.asp?page=210`.

Energy intensity of steel and concrete

Embodied energies: 32 MPa concrete: 5.85 GJ/m^3. 5 MPa concrete: 2.03 GJ/m^3. Steel (for use in road building): 68.6 GJ/t. Asphalt: 10.8 GJ/m^3. Treloar et al. [2004]

They suggest general emission factor for fossil fuels: 60 kg$CO_2^{(e)}$ per GJ. Which is 216 g per kWh. Which means 100 kWh per day is equivalent to 8 t $CO_2^{(e)}$ per year. They also assume a primary energy factor of 1.4 for all liquid fuels – *i.e.*, it takes 1.4 GJ of oil and other primary fuels to make 1 GJ of petrol.

Carbon intensity of electricity production

Depends on the country!

Source: PriceWaterHouse, EDF, www.manicore.com 2001 thanks to http://www.zerocarbonnow.org/

France	83
Sweden	87
Canada	220
Austria	250
Belgium	335
European Union	353
Finland	399
Spain	408
Japan	483
Portugal	525
UK	580
Luxembourg	590
Germany	601
USA	613
Netherlands	652
Italy	667
Ireland	784
Greece	864
Denmark	881

Table O.4. Carbon intensity of electricity production g CO_2 per kWh of Electricity

Home

The unit 'a home' is frequently used – for example, when there is talk of the UK having 2 GW of wind power capacity `http://www.bwea.com/ukwed/`, this gets converted to a 'homes equivalent', as if the phrase

'1137784 homes equivalent' is more comprehensible. I dislike the 'home' unit because it's unclear what aspects of home consumption are included – the full power consumption of a typical home, or just its electricity – and because I think it misleads people into overestimating the amount of power being discussed. For example, if I announced a new renewable source that would provide enough power for 'all the homes in Britain', I think many people would think we didn't need any more power than that. But using the standard exchange rates, the amount of power would be just 14 GW, which is only one third of current electricity consumption, and one twentieth of the total power consumption of the U.K..

The standard conversion rate seems to be that 1.787 kW of *peak* wind power is equivalent to one 'home'; and since peak wind power is usually bigger than average wind power by a factor of three, I think one that means a 'home' is about **0.6 kW**. In my calculation I assumed 24 million 'homes'.

The other quantity quoted is the number of tonnes of CO_2 saved per year. The official exchange rates appear to be 4 tonnes CO_2per home per year and 770 g CO_2per kWh.

Temperatures

Standard swimming pool temperature: 28°C, with the hall 1°C warmer.

Standard temperature for accommodation for elderly people: 20–21°C.

Average winter temperature of British houses in the 1970s: 12°C.

Areas

The area of the globe is $500 \times 10^6 \mathrm{km}^2$; the land area is $150 \times 10^6 \mathrm{km}^2$.

Volumes

A container is 2.4 by 2.6 by (6.1 or 12.2) metres.

One TEU is the size of a small 20-foot container – about $40\,\mathrm{m}^3$. 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.

DUKES standards

In DUKES the standard multiplier is 1 TWh of electricity = 0.086 Mtoe. This means 1 Mtoe = 11.6 TWhe.

UK electricity carbon emissions (DUKES 07): coal 239 tC per GWh; gas 101 tC per GWh; all fossil fuels 172 tC/GWh; average for all electricity 131 tC/GWh. Or in grams of CO_2 per kWh: coal 876; gas 370; all fossil fuels 630; average for all electricity 480.

A price of €30 per tonne of CO_2 implies €0.03 per kWh of electricity for coal generation.

Hmm, that figure for gas sounds smaller than normal?

House size

USA: In the last 25 years, the average size of a single-family house has increased from 1740 square feet (162 m^2) to 2330 square feet (216 m^2).

UK: My 3-bedroom house has a floor area of 88 m^2.

Greenhouse gas intensities of economies

The UK's GHG intensity in 2006 was 458t$CO_2^{(e)}$per $M (at year 2000 prices) Helm et al. [2007]. China's was 4,140 t$CO_2^{(e)}$/$M.

Energy intensities: The embodied energy intensity of of UK agriculture was 20 MJ of primary fossil energy use per US$ in 1985. Battjes et al. [1998] (Which is roughly four times the direct energy intensity.) For UK industry, 22 MJ per US$; UK transport, 24 MJ per $; UK services, 12 MJ per $. (All in 1985.)

Mode	g $CO_2^{(e)}$ per tonne-km
7.5-tonne truck	174
40-tonne truck	56
Fast rail	39
Slow rail	14
Aircraft	3 414

Table O.5. Carbon dioxide emissions by freight transport (CO_2 equivalent).

Greenhouse-gas intensities of transport

Fluxes

Incoming solar flux at ground level on a clear day: 240–250 W/m^2. Outgoing flux from black bodies at temperatures of

0 °C	4 °C	10 °C	20 °C
316 W/m^2	335 W/m^2	364 W/m^2	419 W/m^2

Nitrogen fertilizers: cost 80 GJ per ton to make.

Cattle feed: Feed's calorific value is 13 GJ per ton.

Quick reference – units, conversion factors

> **Watt**. This SI unit is named after James Watt. As for all SI units whose names are derived from the proper name of a person, the first letter of its symbol is uppercase (W). But when an SI unit is spelled out, it should always be written in lowercase (watt), unless it begins a sentence or is the name "degree Celsius".
>
> from wikipedia

SI stands for Système Internationale. SI units are the ones that all engineers should use, to avoid losing spacecraft.

SI units		
energy	one joule	1 J
power	one watt	1 W
force	one newton	1 N = 1 J/m
length	one metre	1 m
time	one second	1 s

	My preferred units, expressed in S.I.		
energy	one kilowatt-hour	1 kWh	3 600 000 J
power	one kilowatt-hour per day	1 kWh/d	(1000/24) W $\simeq$ 40 W
force	one kilowatt-hour per 100 km	1 kWh/100 km = 36 N	
time	one hour	1 h	3600 s
	one day	1 d	$24 \times 3600\,\mathrm{s} \simeq 10^5\,\mathrm{s}$
	one year	1 y	$365.25 \times 24 \times 3600\,\mathrm{s} \simeq \pi \times 10^7\,\mathrm{s}$

Additional units

In this book I use the following additional units:

Thing measured	unit name	symbol	value
humans	person	p	
mass	tonne or ton	t	1 t= 1000 kg
			$1\,\mathrm{Gt} = 10^9 \times 1000\,\mathrm{kg} = 1\,Pg$
transport	person-kilometre	p-km	
transport	tonne-kilometre	t-km	
volume	litre	l	$1\,\mathrm{l} = 1/1000\,\mathrm{m}^3$
area	square kilometre	sq km, km^2	$1\,\mathrm{sq\ km} = 10^6\,\mathrm{m}^2$
	hectare	ha	$1\,\mathrm{ha} = 10^4\,\mathrm{m}^2$
	Wales		$1\,\mathrm{Wales} = 21\,000\,\mathrm{km}^2$
	London		$1\,\mathrm{London} = 1500\,\mathrm{km}^2$
energy	Dinorwig		1 Dinorwig = 9 GWh

For example, a bus that travels 10 km with 20 people on board has delivered an amount of personal transportation equal to 200 p-km. A truck that shifts 10 tons of stuff a distance of 100 km provides 1000 t-km of transport.

Please note that when I write $1\,\mathrm{km}^2$ I mean $1\,(\mathrm{km})^2$, not $1000\,\mathrm{m}^2$.

When discussing millions, I use the prefix *M* (for example, one million tonnes of oil equivalent is written 1 Mtoe). When discussing money I use *b* for "billion".

Annoying units

homes

The 'home' is the one of the most common units used to describe the power of a new wind farm. For example, "The £300 million Whitelee project's 140 turbines will generate 322 MW – enough to power 200 000 homes." I think that a 'home' is about 0.6 kW, or 14 kWh per day. This guess is consistent with the above quote, assuming that the turbines will actually generate about 35% of 322 MW. The 'home' is defined by E-ON to be 4700 kWh/y, or 13 kWh/d.

The 'home' annoys me because I worry that people forget all their other methods of energy consumption. They think that the statement "these windmills will power one million homes" means that *all* energy used by the people living in those homes is covered by the windmills. But what about the energy cost of their workplaces, of the stuff they buy, and of their transport habits?

Hurray for the Danes/Swedes, they give an exchange rate. The annual production of 280 GWh corresponds to the consumption of 70 000 British households. (4000 kWh/y per household.) That means one 'home' uses 11 kWh/d. Or 0.46 kW.

However, the British Wind Energy Association says a home is 4700 kWh per year. That's 0.54 kW, or 13 kWh per day. `http://www.bwea.com/ukwed/operational.asp`

Here's another newspaper article using the 'home' to describe how big a tidal power scheme could be. 'Mersey could power all city homes' (June 14 2007, Liverpool Daily Post). A tidal barrage here could power 'up to 260 000 homes'. Using the Swedish exchange rate, that would mean they are anticipating getting up to 120 MW. The article mentions 700 MW. Presumably that's the peak capacity, not the average power. Yes, the annual power of the barrage would be 1200 GWh. Which is 140 MW. So we have a UK figure of 'one home = 0.52 kW'.

power stations

Energy saving ideas are sometimes described in terms of power stations. For example according to a BBC report on putting new everlasting LED lightbulbs in traffic lights, 'The power savings would be huge too – keeping the UK's traffic lights running requires the equivalent of two medium-sized power stations'. `http://news.bbc.co.uk/1/low/sci/tech/specials/sheffield_99/449368.stm`

What is a medium-sized power station? 10 MW? 50 MW? 100 MW? 500 MW? I don't have a clue. A google search indicates that some people think it's 30 MW, some 250 MW, some 500 MW (the most common choice), and some 800 MW. What a useless unit!

Nobody knows how many medium power stations our country's power consumption corresponds to. Surely it would be clearer for the article about traffic lights to express what it's saying as a percentage? "Keeping the UK's traffic lights running requires x MW of electricity, which is y percent of the UK's electricity." The only problem with expressing traffic lights in such precise terms instead of hiding them behind the fuzzy veil of 'medium-sized power stations' is that the resulting statement would not sound like 'huge' power savings any more!

Here is my rewrite with the correct value of the power inserted (obtained from [2tsyxe]):

> The power savings would be huge too – keeping the UK's traffic lights running requires 11 MW, which is about three ten-thousandths of the nation's electricity. I'm sorry, did I say 'huge'? I meant 'hugely easy to exaggerate'.

I think whoever came up with the original 'two power stations' line here made a plain mistake. There is no way that 5 MW could be considered a 'medium-sized power station' today! Figure O shows the powers

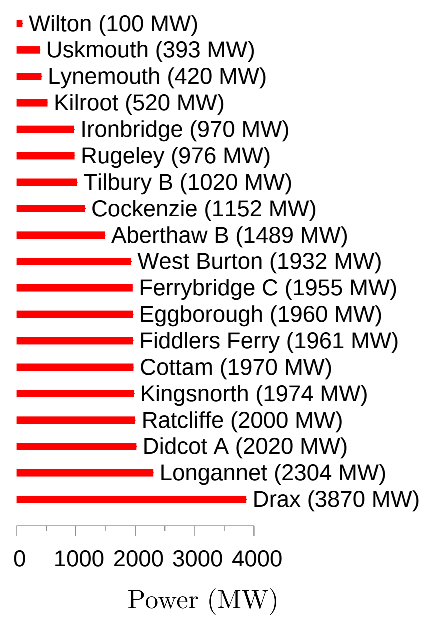

Figure O.6. Powers of Britain's coal power stations.

of the UK's nineteen coal power stations. http://www.ukqaa.org.uk/PowerStation.html

cars taken off the road

I've recently noticed advertisements describing wonderful reductions in CO_2 pollution in terms of the 'equivalent number of cars taken off the road'. For example, Richard Branson asserts that if Virgin Trains' Voyager fleet switched to 20% biodiesel – incidentally, don't you feel it's outrageous that people call a train a 'green' biodiesel-powered train when it runs on 80% fossil fuels and just 20% biodiesel?, Sorry, I got distracted. Richard Branson asserts that *if* Virgin Trains' Voyager fleet switched to 20% biodiesel – I emphasize the '*if*' because people like Beardie and BP are always getting media publicity for announcing that they are *thinking of* doing good things. Do they ever deliver? Sorry, I got distracted again. Richard Branson asserts that *if* Virgin Trains' Voyager fleet switched to 20% biodiesel, then there would be a reduction of 34 500 tonnes of CO_2 per year, which is equivalent to "23 000 cars taken off the road".

I'm grateful to Beardie for this statement because it reveals the exchange rate that I was trying to guess.

$$\text{'one car taken off the road'} \longleftrightarrow -1.5\,\text{tonnes per year of } CO_2$$

barrels

An annoying unit loved by the oil community. Why can't they just stick to one unit, such as the ton of oil? A barrel of oil is 6.1 GJ or 1700 kWh.

Barrels are doubly annoying because I think there are multiple definitions of barrels.

One barrel is 42 U.S. gallons; 159 litres; One barrel of oil is 0.1364 tonnes of oil; 1 barrel of crude oil is 5.75 GJ. The carbon-pollution rate of crude oil is 400 kg of CO_2 per barrel. http://www.chemlink.com.au/conversions.htm

This means that when the price of oil is \$90 per barrel, people are paying ¢5.4 per kWh, and they are paying \$225 per ton of CO_2 emitted.

1 tonne of crude oil is 7.33 barrels and 42.1 GJ.

gallons

Gallons would be a fine human-sized unit, except the Americans messed it up by defining the gallon differently from everyone else. They've similarly messed up the pint and the quart. The US volumes are all roughly five-sixths of the correct volumes.

1 US gal = 3.785 l = 0.83 imperial gal. 1 imperial gal = 4.545 l.

Tons

Tons are annoying because there are short tons, long tons and metric tons. They are close enough that I don't bother distinguishing between them. 1 short ton (2000 lb) = 907.2 kg; 1 long ton (2240 lb) = 1016 kg; 1 metric ton = 1000 kg.

BTU and quads

British thermal units are annoying because they are neither part of the *Système Internationale*, nor are they of a useful size. They are too small, so you have to roll out silly prefixes like 'quadrillion' (10^{15}) to make practical use of them.

1 kJ is 0.947 BTU. 1 kWh is 3409 BTU

A 'Quad' is 1 quadrillion BTU = 293 terawatt-hours.

Bushels

Bushels are what grains come in.

Before April 2007, wheat used to cost at most $5 per bushel. In August 2007, wheat prices rose above $7 per bushel.

Funny units

Cups of tea

Is this a way to make solar panels sound good? 'Once all the 7 000 photovoltaic panels are in place, it is expected that the solar panels will create 180 000 units of renewable electricity each year - enough energy to make **nine million cups of tea**.' This announcement thus equates 1 kWh to 50 cups of tea.

As a unit of volume, 1 US cup (half a US pint) is officially 0.24 l; but a cup of tea or coffee is usually about 0.18 l. I confirm that to raise 50 cups of water, at 0.18 l each, from 15°C to 100°C requires 1 kWh.

'Nine million cups of tea per year' is another way of saying '20 kW'.

The solar panels are outdone by Pendolino trains however: the regenerative braking systems of Virgin's Pendolinos deliver enough energy to brew 2.6 billion cuppas a year!

The personal computer

The same solar panel advertisement says 180 000 kWh per year is 'enough to power 1000 PCs for a year' `http://www.cis.co.uk/servlet/Satellite?cid=1116834043897&pagename=CoopBank/Page/tplBlank&c=Page` but that's not true. It would be true if a PC took only 20 W. But a typical PC takes 80 W or more.

Double-decker buses, Albert Halls and Wembley stadiums

"If everyone in the UK that could, installed cavity wall insulation, we could cut carbon dioxide emissions by a huge 7 million tonnes. That's enough carbon dioxide to fill nearly 40 million double-decker buses or fill the new Wembley stadium 900 times!"

From which we learn the helpful fact that one Wembley is 44 000 double decker buses.

1 unit	=	1 kWh	=	3.6 MJ
2500 kCal	=	3 kWh	=	10 000 kJ
1 MJ	=	0.3 kWh		
1000 BTU	=	0.3 kWh		
1000 BTU per hour	=	0.3 kW	=	7 kWh/d
1 horse power (1 hp or 1 cv)	=	0.75 kW	=	18 kWh/d
		1 kW	=	24 kWh/d

Box O.7. How other energy and power units relate to the kilowatt-hour and the kilowatt-hour per day.

Useful conversion rates	
Diesel	250 gCO_2/kWh
Biodiesel	320 gCO_2/kWh
Densities relative to water	
gasoline	0.74
diesel	0.820–0.950
Calorific value of fuel	10 kWh per litre

Table O.8. Carbon dioxide emissions per unit energy (gross calorific value) of various fuels.

"If every household installed just one energy saving light bulb, there would be enough carbon dioxide saved to fill the Royal Albert Hall 1,980 times!"

As I pointed out on p.??, expressing amounts of CO_2 by volume rather than mass is a great way to make them sound big. Should '1 kg of CO_2 per day' sound too small, just say 'Two hundred thousand litres of CO_2 per year'!

Wales

The Wales is a unit of area. One Wales is 20 000 km^2.

Carbon per energy

Coal-fired plants produced a kilogram of carbon dioxide for every unit (KWh) of energy produced. In contrast, gas produces only half a kilogram and nuclear just 30g.

Useful conversion factors

To change TWh per year to GW, divide by 9.

1 kWh/d per person is the same as 2.5 GW per UK, or 22 TWh/y per UK.

To change mpg (miles per UK gallon) to km per litre, divide by 3.

The most useful numbers of all

Consumption

UK energy consumption is 125 kWh per day per person, or 300 GW per UK.

UK CO_2 emissions are 10 tonnes of CO_2 per year each, or 600 Mt CO_2 per year per UK, or 160 Mt Carbon per year per UK. 'Safe' global emissions would be one eighth of this: $1\frac{1}{4}$ tonnes of CO_2 per year each.

UK electricity consumption is 18 kWh per day per person, or 45 GW per UK. UK electricity production emits 30% of UK CO_2.

Costs

Nuclear costs £30–37/MWh or 3–3.7 p/kWh.

Cars

1 kWh per km.

Air-conditioning

'One ton' of air-conditioning = 3.5 kW. According to three dudes on the internet, it's the heat removal-rate needed to freeze one ton of ice per day, and a standard average one ton A/C unit consumes 1.335 kW(e), and cools an area of 400 square feet.

Exchange rates

Coal: 1000 g of CO_2 per kWh electricity.

Gas: 445 g of CO_2 per kWh electricity.

Nuclear: 30 g.

More numbers

ton of coal equivalent = 29.3 GJ. = 8000 units

ton of oil equivalent = 41.8GJ = 10 tonnes of TNT. = 12,000 UNITS

1Megaton = 4.2e15 J. = 10^9 UNITS (actually 1.17e9)

USgal = 3.785l.

€= 1.26 ; £= 1.85 ; $1 = 1.12 Canadian dollars ;

gasoline = $3 per gallon to consumer in USA. Which is $0.79 per litre.

UK average income $34,000. (2004)

Cape Town / LHR return: your emissions are 2.82 tonnes of CO_2. The cost to offset this CO_2 will be £21.18.

Climatecare.org: £7.50 per tonne CO_2'offset'.

growaforest.com said 2.13 tonnes – 4 trees.

From co2Seq.tex 4 kWh of heat from fossil fuels is roughly 1 kg of CO_2

asserted that The Carbon impact of Gas was 0.5kg per unit (0.445 kg CO_2); and of coal, 1kg per unit (0.955 kg CO_2).]

k	kilo	1000^1	10^3	1 000
M	mega	1000^2	10^6	1 000 000
G	giga	1000^3	10^9	1 000 000 000
T	tera	1000^4	10^{12}	1 000 000 000 000
P	peta	1000^5	10^{15}	1 000 000 000 000 000
E	exa	1000^6	10^{18}	1 000 000 000 000 000 000

	CO_2	Carbon
Coal	1000 g CO_2/kWh(e)	250 tC/GWh(e)
Gas	400 g CO_2/kWh(e)	100 tC/GWh(e)
Nuclear	16 g CO_2/kWh(e)*	4.4 tC/GWh(e)*

Table O.9. Exchange rate between carbon emissions and electrical energy.
*) The figure for nuclear depends on the source of the energy for nuclear fuel creation. Currently, the UK is highly dependent on fossil-fired electricity generation, making indirect emissions the primary source of nuclear CO_2 output. If nuclear plants replaced fossil-fired plants as the primary electricity generators, the CO_2 emissions for nuclear power would fall. (from Nuclear-paper2, Sustainable Development Commission p23)

Power type		Power per unit area of flat ground
Wind farm: $v = 6$ m/s (force 4)		2 W/m^2
Solar	efficiency	
Photovoltaic	20%	16 W/m^2 South-facing roof
	20%	10 W/m^2 flat ground
Biomass	1%	0.5 W/m^2 flat ground
Ocean thermal		5 W/m^2 (upper bound in tropics)
Tide pool		4 W/m^2
Tide-farm (using currents)		
(spring 1.5 m/s : neap 0.9 m/s)		6 W/m^2
Geothermal		17 mW/m^2

Table O.10. Power densities of renewable sources (per unit land- or sea-area)

hectare	$= 10^4$ m^2	$= 10^{-2}$ km^2
acre	$= 4050$ m^2	$= 0.0040$ km^2
square mile	$= 2.6 \times 10^6$ m^2	$= 2.6$ km^2
square foot	$= 0.093$ m^2	$= 9.3 \times 10^{-8}$ km^2
square yard	$= 0.84$ m^2	$= 8.4 \times 10^{-7}$ km^2

Table O.11. Areas.

Carbon coefficients

from ORNL [2hcgdh].

	carbon coefficient kg CO_2 per kWh
coal	0.32
natural gas	0.18
jet fuel	0.24
motor gasoline	0.24

Heavy fuel oil – carbon emissions: 0.825 MtC/Mtoe.

Energy densities

coal: 20 GJ/ton. Crude oil: 37 MJ/l Natural gas: 38 MJ/m^3

20 GJ per tonne of dry wood.

Motor gasoline: 1 barrel = 0.1172 metric tons

Let's have a table converting between miles per gallon, miles per litre, miles per kilometre, and grammes CO_2 per kilometre

Lexus with a hybrid engine (emissions 184 g per km). Toyota Prius (104g). 65.7mpg

m/s	km/h	knot	mph	Beaufort scale
1	3.6	1.9	2.2	Force 1
2	7.2	3.9	4.5	Force 2
3	10.8	5.8	6.7	Force 2
4	14.4	7.8	8.9	Force 3
5	18.0	9.7	11.2	Force 3
6	21.6	11.7	13.4	Force 4
7	25.2	13.6	15.7	Force 4
8	28.8	15.6	17.9	Force 4
9	32.4	17.5	20.1	Force 5
10	36.0	19.4	22.4	Force 5
11	39.6	21.4	24.6	Force 5
12	43.2	23.3	26.8	Force 6
13	46.8	25.3	29.1	Force 6
14	50.4	27.2	31.3	Force 6
15	54.0	29.2	33.6	Force 7
16	57.6	31.1	35.8	Force 7
17	61.2	33.0	38.0	Force 7
18	64.8	35.0	40.3	Force 8
19	68.4	36.9	42.5	Force 8
20	72.0	38.9	44.7	Force 8
21	75.6	40.8	47.0	Force 9
22	79.2	42.8	49.2	Force 9
23	82.8	44.7	51.5	Force 9
24	86.4	46.7	53.7	Force 9
25	90.0	48.6	55.9	Force 10
26	93.6	50.5	58.2	Force 10
27	97.2	52.5	60.4	Force 10
28	100.8	54.4	62.6	Force 10
29	104.4	56.4	64.9	Force 11
30	108.0	58.3	67.1	Force 11
31	111.6	60.3	69.3	Force 11
32	115.2	62.2	71.6	Force 11
33	118.8	64.2	73.8	Force 12
34	122.4	66.1	76.1	Force 12
35	126.0	68.0	78.3	Force 12
36	129.6	70.0	80.5	Force 12
37	133.2	71.9	82.8	Force 12

m/s	km/h	knot	mph
38	136.8	73.9	85.0
39	140.4	75.8	87.2
40	144.0	77.8	89.5
41	147.6	79.7	91.7
42	151.2	81.6	94.0
43	154.8	83.6	96.2
44	158.4	85.5	98.4
45	162.0	87.5	100.7
46	165.6	89.4	102.9
47	169.2	91.4	105.1
48	172.8	93.3	107.4
49	176.4	95.3	109.6
50	180.0	97.2	111.9

Money

I assumed the following exchange rates when discussing money: €1 = $ 1.26; £1 = $ 1.85 ; $1 = $ 1.12 Canadian. These exchange rates were correct in mid-2006.

Official conversion factors

These emission figures are taken from DEFRA's Environmental Reporting Guidelines for Company Reporting on Greenhouse Gas Emissions.

Fuel Type	Emissions (kg CO_2 per kWh)
grid electricity	0.43
natural gas	0.19
gas/diesel oil	0.25
petrol	0.24
heavy fuel oil	0.26
coal	0.30
LPG	0.21
coking coal	0.30
jet kerosene	0.24
ethane	0.20
naptha	0.26
petroleum coke	0.34
refinery gas	0.20

By weight By volume Solid fuels kWh/tonne litres/tonne kWh/litre Coal (weighted average) 7,417 – – Coke 8,445 – – Liquid fuels kWh/tonne litres/tonne kWh/litre Crude oil (weighted average) 12,682 1,192 10.6 Petroleum products (weighted average) 12,751 – – Ethane 14,071 2,730 5.2 Liquefied petroleum gas 13,721 1,850 7.4 Aviation turbine fuel 12,845 1,251 10.3 Motor spirit 13,087 1,362 9.6 Gas/diesel oil 12,668 1,187 10.7 Fuel oil 12,087 1,031 11.7 Power station oil 12,087 1,142 10.6 Gaseous fuels kWh/tonne litres/tonne kWh/m^3 Natural gas – – 11.00 Coke oven gas – – 5.00 Blast furnace gas – – 0.83 Landfill gas – – 5.8-7.0* Sewage gas – – 5.8-7.0* Solid renewables kWh/tonne litres/tonne kWh/m^3 Domestic wood (2) 2,778 Industrial wood (3) 3,306 – – 4,167 Straw 2,445 – – Poultry litter General industrial waste 4,445 – – 3,889 Hospital waste Municipal solid waste 2,639 – – Refuse-derived waste 5,139 – – 8,890 – – Tyres Source: Annex A of the Digest of UK Energy Statistics 2005

$$
\begin{aligned}
1\,\text{therm} &= 29.31\,\text{kWh}\\
1\,\text{Btu} &= 0.2931\times10^{-3}\,\text{kWh}\\
1\,\text{MJ} &= 0.2778\,\text{kWh}\\
1\,\text{GJ} &= 277.8\,\text{kWh}\\
1\,\text{toe} &= 11\,630\,\text{kWh}\\
1\,\text{kcal} &= 1.163\times10^{-3}\,\text{kWh}
\end{aligned}
$$

In DUKES, Electricity generated from renewables is converted to equivalent Mtoe using (xTWh) 0.085985. Nuclear has thermal efficiency of 38%.

$$
1\,\text{kWh} = \begin{matrix} 0.03412 & 3412 & 3.6 & 86\times10^{-6} & 859.7 \\ \text{therms} & \text{Btu} & \text{MJ} & \text{toe} & \text{kcal} \end{matrix}
$$

Conversion of fossil fuel burning to CO_2 concentration changes: 1 ppm is roughly 7.5 $GtCO_2$/y.

standards.tex

Things I need on every page

Surface Area of the planet Surface Area of the land Population of earth 1kWh = 3600 kJ

Useful identities		
$1\,kT$ per molecule	=	$2.5\,\mathrm{kJ/mol}$
$1\,\mathrm{kWh}$	=	$3600\,\mathrm{kJ}$

Useful identities		
$1\,kT$	=	$\frac{1}{40}\mathrm{eV}$
Visible photon	=	$2\,\mathrm{eV}$

Useful relationships		
$10^4\,\mathrm{K}$	$\leftrightarrow$	$1\,\mathrm{eV}$
Visible photon	$\leftrightarrow$	$2\,\mathrm{eV}$

Conversion factors	
Burning fossil fuels:	$4\,\mathrm{kWh}$(enthalpy) $\leftrightarrow$ $1\,\mathrm{kg}$ of CO_2

World: 43 people per km^2. England population density: 380 per km^2, or 2 600 m^2 per person.

Energy density of petrol: 30 MJ/l or 40 MJ/kg.

European: 120 kWh/day.

THE BIG CONSUMPTION LIST

Food: Calories per day 2500 Cal = 10460 kJ = 10MJ = 2.9kWh = 3kWh Energy required to grow that food: solar energy making fertilizer and to transport it to your supermarket / kitchen. and cooking it.

Lighting Heating air Cooling air Heating water Making chlorine for water purification, etc Transport of humans Cars, planes, trains Transport of stuff road, planes, trains, boats Weapons Industry Waste during electricity transport

Production

Wind 60kW from the Wellington windmill which is 31m high (I think) Geothermal Ocean thermal? Nuclear – extraction from ocean? extraction from rivers?

From BP Statistical Review. One Million tonnes of oil produces about 4500 GWh of electricity in a modern power station. One tonne of oil equivalent equals 42GJ of heat or 12,000 kWh.

One tonne of oil per year is 32 kWh/day.

So 3.75 tonnes of oil per year is the same as 120 kWh/day; 9.8 toe per year is the same as 312 kWh/day (13kW).

A very very rough relationship is 1 toe per year = 1 kW.

1 British thermal unit (Btu) = 0.252 kcal = 1.055 kJ 1 kilowatt-hour (kWh) = 860 kcal = 3600 kJ = 3412 Btu ———————————— Calorific equivalents One tonne of oil equivalent equals

approximately: Heat units 10 million kilocalories 42 gigajoules 40 million Btu Solid fuels 1.5 tonnes of hard coal 3 tonnes of lignite Gaseous fuels see natural gas and LNG table Electricity 12 megawatt-hours ———————————————————— One million tonnes of oil produces about 4500 gigawatt-hours (= 4.5 terawatt-hours) of electricity in a modern power station.

List of web links

This section lists the full links corresponding to each of the tiny URLs mentioned in the text. Each item starts with the page number on which the tiny URL was mentioned. See also http://tinyurl.com/yh8xse (or http://www.inference.phy.cam.ac.uk/sustainable/book/tex/cft.url.html) for a clickable page with all URLs in this book.

iii f754 – tinyurl.com/f754
http://www.archive.org/web/web.php

8 2z2xg7 – tinyurl.com/2z2xg7
http://assets.panda.org/downloads/2_vs_3_degree_impacts_1oct06_1.pdf

15 ydoobr – tinyurl.com/ydoobr
http://www.bbc.co.uk/radio4/news/anyquestions_transcripts_20060127.shtml

15 2jhve6 – tinyurl.com/2jhve6
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15 2fztd3 – tinyurl.com/2fztd3
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php

15 26e8z – tinyurl.com/26e8z
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15 ykhayj – tinyurl.com/ykhayj
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16 yyxq2m – tinyurl.com/yyxq2m
http://www.bp.com/genericsection.do?categoryId=93&contentId=2014442

16 dzcqq – tinyurl.com/dzcqq
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16 y98ys5 – tinyurl.com/y98ys5
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27 27jdc5 – tinyurl.com/27jdc5
http://www.dft.gov.uk/pgr/statistics/datatablespublications/energyenvironment/tsgbchapter3energyan

27 28abpm – tinyurl.com/28abpm
http://corporate.honda.com/environmentology/

27 nmn4l – tinyurl.com/nmn4l
http://www.simetric.co.uk/si_liquids.htm

362 2hcgdh – tinyurl.com/2hcgdh
http://cta.ornl.gov/data/appendix_b.shtml

31 vxhhj – tinyurl.com/vxhhj
http://www.cl.cam.ac.uk/research/dtg/weather/

31 tdvml – tinyurl.com/tdvml
http://www.phy.hw.ac.uk/resrev/aws/awsarc.htm

256 ymfbsn – tinyurl.com/ymfbsn
http://www.windpower.org/en/tour/wres/powdensi.htm

32 ypvbvd – tinyurl.com/ypvbvd
http://www.ref.org.uk/images/pdfs/UK_Wind_Phase_1_web.pdf

64 wbd8o – tinyurl.com/wbd8o
http://www.ref.org.uk/energydata.php

34 3exmgv – tinyurl.com/3exmgv
http://www.ryanair.com/site/EN/about.php?page=About&sec=environment

34 9ehws – tinyurl.com/9ehws
http://www.boeing.com/commercial/747family/technical.html

34 yrnmum – tinyurl.com/yrnmum
http://www.grida.no/climate/ipcc/aviation/124.htm

35 36w5gz – tinyurl.com/36w5gz
http://www.rolls-royce.com/community/downloads/environment04/products/air.html

44 2rqloc – tinyurl.com/2rqloc
http://www.metoffice.gov.uk/climate/uk/location/scotland/index.html

44 2szckw – tinyurl.com/2szckw
http://www.metoffice.gov.uk/climate/uk/stationdata/cambridgedata.txt

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http://web.archive.org/web/20040401165322/http://members.cox.net/weller43/sunshine.htm

45 3b7zdf – tinyurl.com/3b7zdf
http://www.communities.gov.uk/publications/planningandbuilding/generalisedlanduse

44 39z5m5 – tinyurl.com/39z5m5
http://news.bbc.co.uk/1/hi/world/europe/6505221.stm

44 2uk8q8 – tinyurl.com/2uk8q8
http://www.powerlight.com/about/press2006_page.php?id=59

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http://www.reuk.co.uk/40-Percent-Efficiency-PV-Solar-Panels.htm

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http://www.aps.org/meetings/multimedia/upload/The_Status_and_Outlook_for_the_Photovoltaics_Industry_
David_E_Carlson.pdf

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64 wbd8o – tinyurl.com/wbd8o
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315 r22oz – tinyurl.com/r22oz
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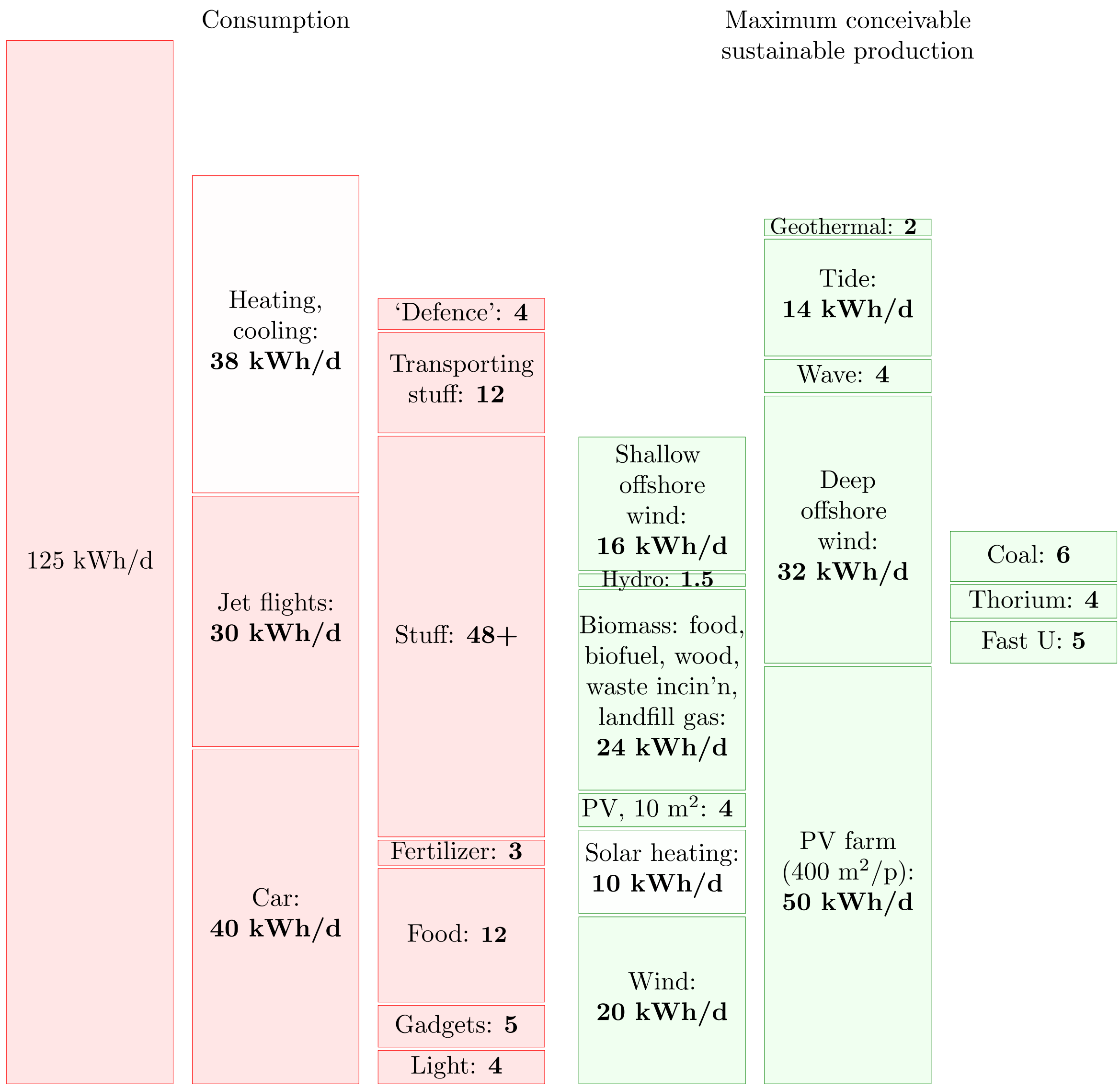
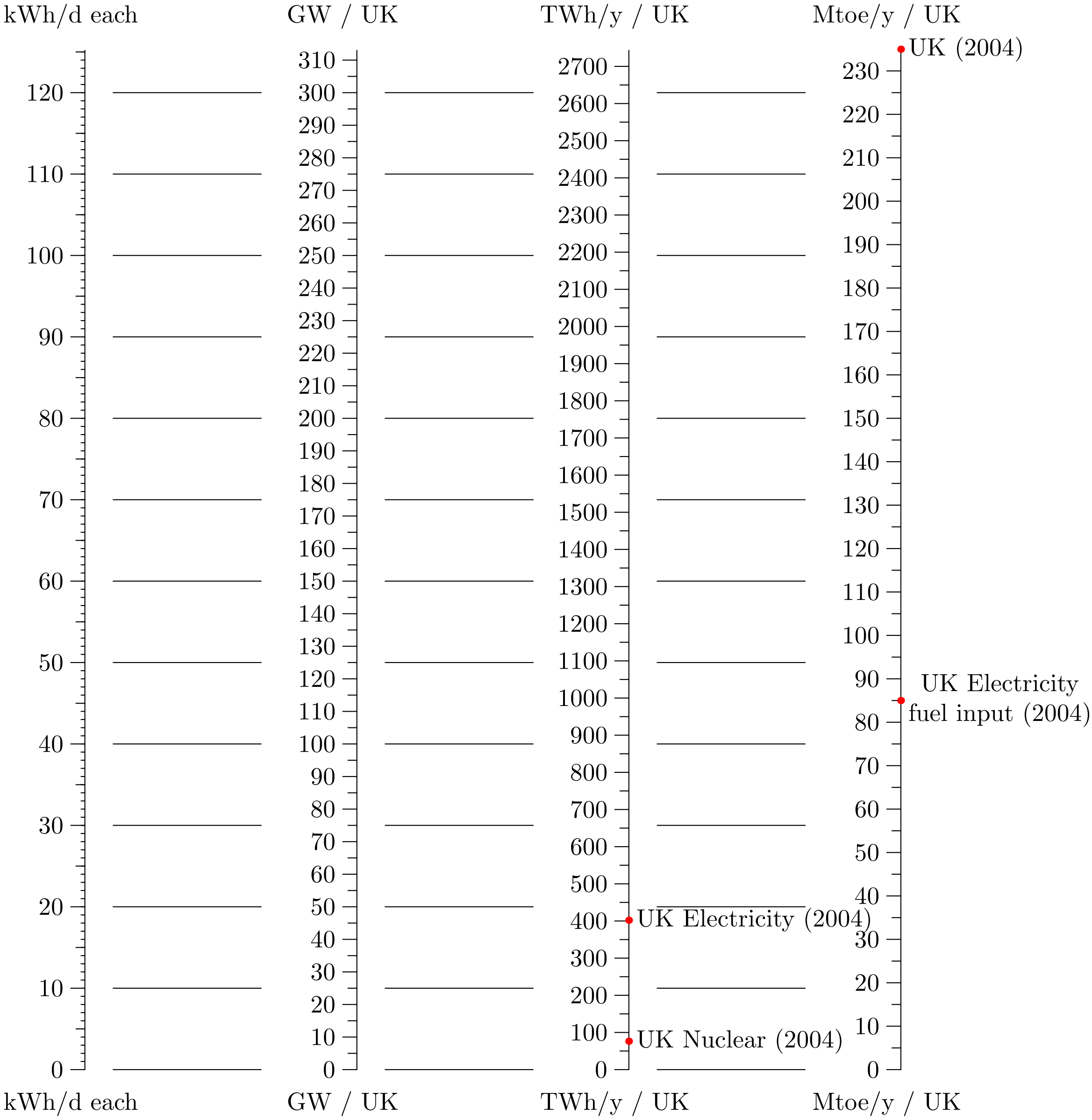
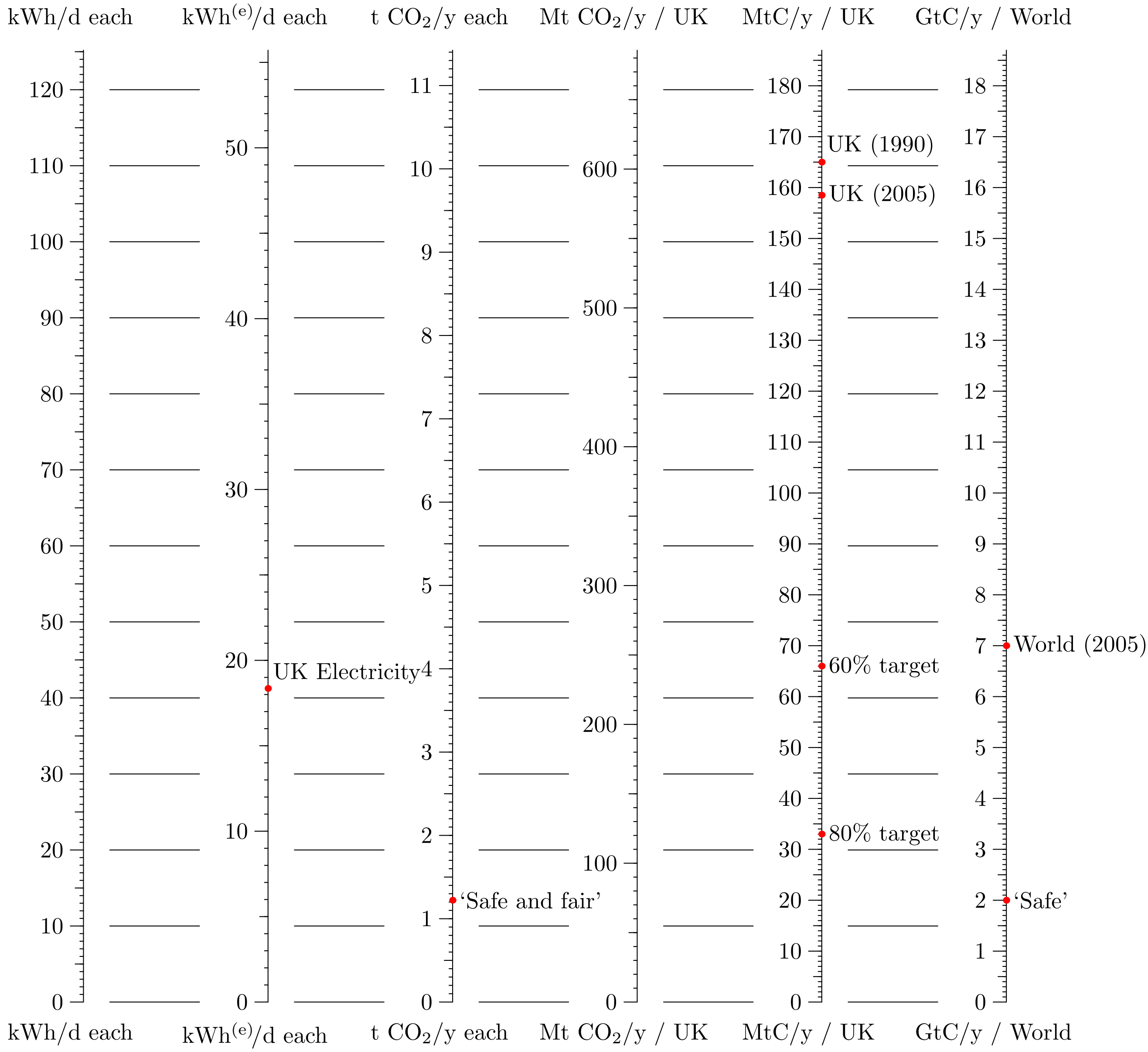

Consumption
Maximum conceivable sustainable production
125 kWh/d
Heating, cooling: 38 kWh/d
Jet flights: 30 kWh/d
Car: 40 kWh/d
'Defence': 4
Transporting stuff: 12
Stuff: 48+
Fertilizer: 3
Food: 12
Gadgets: 5
Light: 4
Shallow offshore wind: 16 kWh/d
Hydro: 1.5
Biomass: food, biofuel, wood, waste incin'n, landfill gas: 24 kWh/d
PV, 10 m²: 4
Solar heating: 10 kWh/d
Wind: 20 kWh/d
Geothermal: 2
Tide: 14 kWh/d
Wave: 4
Deep offshore wind: 32 kWh/d
PV farm (400 m²/p): 50 kWh/d
Coal: 6
Thorium: 4
Fast U: 5

Power translation chart



1 kWh/d	the same as 1/24 kW	'UK'	= 60 million people
GW	often used for '**capacity**' (peak output)		
TWh/y	often used for average output	USA:	300 kWh/d per person
1 Mtoe	'one million tonnes of oil equivalent'	Europe:	125 kWh/d per person

Carbon translation chart



kWh	*thermal* energy exchange rate: 1 kWh ↔ 250 g of CO_2 (oil, petrol) (for gas, 1 kWh ↔ 200 g)
kWh$^{(e)}$	*electrical* energy is more costly: 1 kWh$^{(e)}$ ↔ 445 g of CO_2 (gas) (Coal costs twice as much CO_2)
t CO_2	tonne of CO_2
Mt C	million tonnes of Carbon

'UK'	= 60 million people
'World'	= 6 billion people
UK:	160 Mt C per year (2005)
USA:	20 t CO_2/y each (1.5 GtC/y total)
World:	7 Gt C per year (2005)

To avoid 2 C global warming, need < 2 Gt C/y