25 Living on other countries' renewables?

Whether the Mediterranean becomes an area of cooperation or confrontation in the 21st century will be of strategic importance to our common security.

Joschka Fischer, German Foreign Minister, February 2004

We've found that it's hard to get off fossil fuels by living on our own renewables. Nuclear has its problems too. So what else can we do? Well, how about living on someone else's renewables? (Not that we have any entitlement to someone else's renewables, of course, but perhaps they might be interested in selling them to us.)

Most of the resources for living sustainably 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. Jared Diamond, in his book *Collapse*, observes that, while many factors contribute to the collapse of civilizations, a common feature of all collapses is that the human population density became too great.

Places like Britain and Europe are in a pickle because they have large population densities, and all the available renewables are diffuse – they have small power density (table 25.1). When looking for help, we should look to countries that have three things: *a*) low population density; *b*) large area; and *c*) a renewable power supply with high power density.

Power per unit land or water area	
Wind	2 W/m^2
Offshore wind	3 W/m^2
Tidal pools	3 W/m^2
Tidal stream	6 W/m^2
Solar PV panels	5–20 W/m^2
Plants	0.5 W/m^2
Rain-water (highlands)	0.24 W/m^2
Hydroelectric facility	11 W/m^2
Solar chimney	0.1 W/m^2
Concentrating solar power (desert)	**15** W/m^2

Table 25.1. Renewable facilities have to be country-sized because all renewables are so diffuse.

Region	Population	Area (km^2)	Density (persons per km^2)	Area per person (m^2)
Libya	5 760 000	1 750 000	3	305 000
Kazakhstan	15 100 000	2 710 000	6	178 000
Saudi Arabia	26 400 000	1 960 000	13	74 200
Algeria	32 500 000	2 380 000	14	73 200
Sudan	40 100 000	2 500 000	16	62 300
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 25.2. Some regions, ordered from small to large population density. See p338 for more population densities.

Table 25.2 highlights some countries that fit the bill. Libya's population density, for example, is 70 times smaller than Britain's, and its area is 7 times bigger. Other large, area-rich, countries are Kazakhstan, Saudi Arabia, Algeria, and Sudan.

In all these countries, I think the most promising renewable is solar power, *concentrating solar power* in particular, which uses mirrors or lenses to focus sunlight. Concentrating solar power stations come in several flavours, arranging their moving mirrors in various geometries, and putting various power conversion technologies at the focus – Stirling engines, pressurized water, or molten salt, for example – but they all deliver fairly similar average powers per unit area, in the ballpark of 15 W/m^2.

Figure 25.3. Stirling dish engine. These beautiful concentrators deliver a power per unit land area of 14 W/m^2. Photo courtesy of Stirling Energy Systems. `www.stirlingenergy.com`

A technology that adds up

"All the world's power could be provided by a square 100 km by 100 km in the Sahara." Is this true? Concentrating solar power in deserts delivers an average power per unit land 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 UK. 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.

Fortunately, the Sahara is not the only desert, so maybe it's more relevant to chop the world into smaller regions, and ask what area is needed in each region's local desert. So, focusing on Europe, "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 1 billion, the area required drops to 340 000 km^2, which corresponds to a square **600 km by 600 km**. This area is equal to one Germany, to 1.4 United Kingdoms, or to **16 Waleses**.

Figure 25.4. Andasol – a "100 MW" solar power station under construction in Spain. Excess thermal energy produced during the day will be stored in liquid salt tanks for up to seven hours, allowing a continuous and stable supply of electric power to the grid. The power station is predicted to produce 350 GWh per year (40 MW). The parabolic troughs occupy 400 hectares, so the power per unit land area will be 10 W/m^2. Upper photo: ABB. Lower photo: IEA SolarPACES.

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. These squares are shown in figure 25.5. Notice that while the yellow square may look "little" compared with Africa, it does have the same area as Germany.

The DESERTEC plan

An organization called DESERTEC [`www.desertec.org`] is promoting a plan to use concentrating solar power in sunny Mediterranean countries, and high-voltage direct-current (HVDC) transmission lines (figure 25.7) to deliver the power to cloudier northern parts. HVDC technology has been in use since 1954 to transmit power both through overhead lines and through

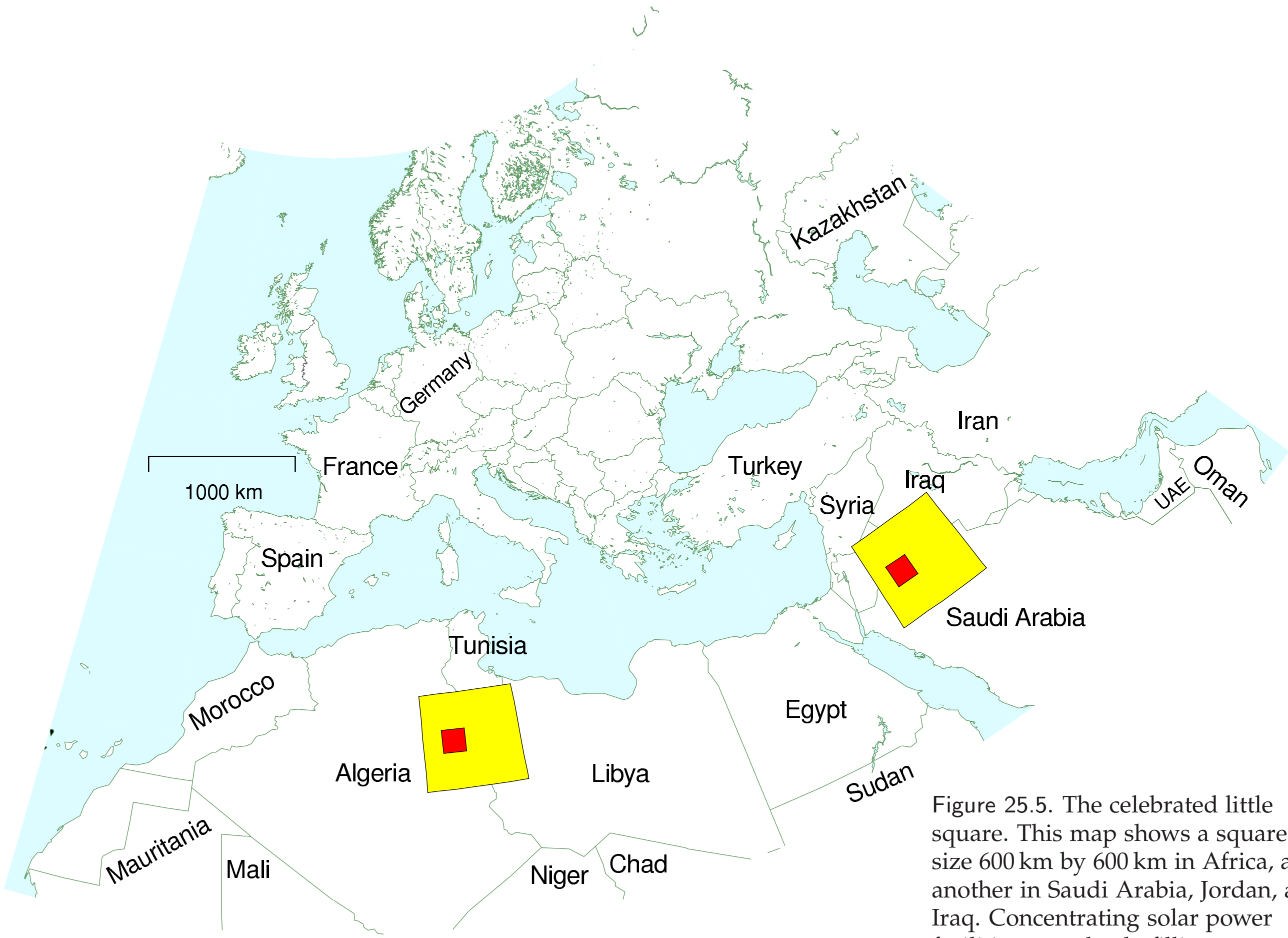


Figure 25.5. The celebrated little square. This map shows a square of size 600 km by 600 km in Africa, and another in Saudi Arabia, Jordan, and Iraq. Concentrating solar power facilities completely filling one such square would provide enough power to give 1 billion people the average European's consumption 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.

submarine cables (such as the interconnector between France and England). It is already used to transmit electricity over 1000-km distances in South Africa, China, America, Canada, Brazil, and Congo. A typical 500 kV line can transmit a power of 2 GW. A pair of HVDC lines in Brazil transmits 6.3 GW.

HVDC is preferred over traditional high-voltage AC lines because less physical hardware is needed, less land area is needed, and the power losses of HVDC are smaller. The power losses on a 3500 km-long HVDC line, including conversion from AC to DC and back, would be about 15%. A further advantage of HVDC systems is that they help stabilize the electricity networks to which they are connected.

In the DESERTEC plans, the prime areas to exploit are coastal areas, because concentrating solar power stations that are near to the sea can deliver desalinated water as a by-product – valuable for human use, and for agriculture.

Table 25.6 shows DESERTEC's estimates of the potential power that

Country	Economic potential (TWh/y)	Coastal potential (TWh/y)
Algeria	169 000	60
Libya	140 000	500
Saudi Arabia	125 000	2 000
Egypt	74 000	500
Iraq	29 000	60
Morocco	20 000	300
Oman	19 000	500
Syria	10 000	0
Tunisia	9 200	350
Jordan	6 400	0
Yemen	5 100	390
Israel	3 100	1
UAE	2 000	540
Kuwait	1 500	130
Spain	1 300	70
Qatar	800	320
Portugal	140	7
Turkey	130	12
Total	620 000 (70 000 GW)	6 000 (650 GW)

Table 25.6. Solar power potential in countries around and near to Europe. The "economic potential" is the power that could be generated in suitable places where the direct normal irradiance is more than 2000 kWh/m^2/y. The "coastal potential" is the power that could be generated 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 125 kWh per day to 1 billion people is 46 000 TWh/y (5 200 GW). 6000 TWh/y (650 GW) is 16 kWh per day per person for 1 billion people.

could be produced in countries in Europe and North Africa. The "economic potential" adds up to more than enough to supply 125 kWh per day to 1 billion people. The total "coastal potential" is enough to supply 16 kWh per day per person to 1 billion people.

Let's try to convey on a map what a realistic plan could look like. Imagine making solar facilities each having an area of 1500 km^2 – that's roughly the size of London. (Greater London has an area of 1580 km^2; the M25 orbital motorway around London encloses an area of 2300 km^2.) Let's call each facility a *blob*. Imagine that in each of these blobs, half the area is devoted to concentrating power stations with an average power density of 15 W/m^2, leaving space around for agriculture, buildings, railways, roads, pipelines, and cables. Allowing for 10% transmission loss between the blob and the consumer, each of these blobs generates an average power of 10 GW. Figure 25.8 shows some blobs to scale on a map. To give a sense of the scale of these blobs I've dropped a few in Britain too. *Four* of these blobs would have an output roughly equal to Britain's total electricity consumption (16 kWh/d per person for 60 million people). *Sixty-five* blobs would provide all one billion people in Europe and North Africa with 16 kWh/d per person. Figure 25.8 shows 68 blobs in the desert.

Figure 25.7. Laying a high-voltage DC link between Finland and Estonia. A pair of these cables transmit a power of 350 MW. Photo: ABB.

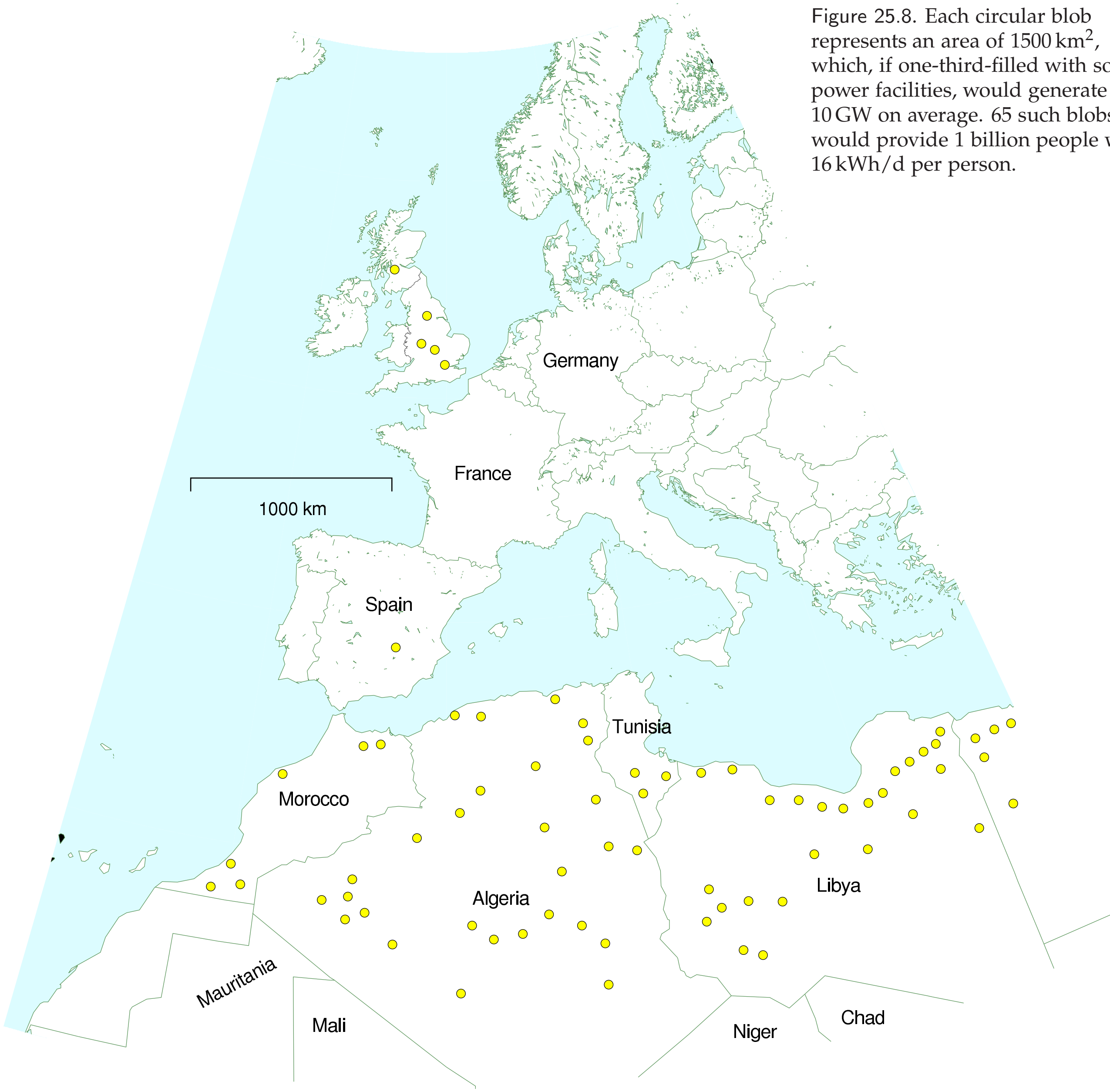


Figure 25.8. Each circular blob represents an area of 1500 km^2, which, if one-third-filled with solar power facilities, would generate 10 GW on average. 65 such blobs would provide 1 billion people with 16 kWh/d per person.

Concentrating photovoltaics

An alternative to concentrating thermal solar power in deserts is large-scale concentrating photovoltaic systems. To make these, we plop 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."

According to manufacturers Amonix, this form of concentrating solar power would have an average power per unit land area of 18 W/m^2.

Another way to get a feel for required hardware is to personalize. One of the "25 kW" (peak) collectors shown in figure 25.9 generates on average about 138 kWh per day; the American lifestyle currently uses 250 kWh per day per person. So to get the USA off fossil fuels using solar power, we need roughly two of these 15 m × 15 m collectors per person.

Figure 25.9. A 25 kW (peak) concentrator photovoltaic collector produced by Californian company Amonix. Its 225 m^2 aperture contains 5760 Fresnel lenses with optical concentration ×260, each of which illuminates a 25%-efficient silicon cell. One such collector, in an appropriate desert location, generates 138 kWh per day – enough to cover the energy consumption of half an American. Note the human providing a scale. Photo by David Faiman.

Queries

I'm confused! In Chapter 6, you said that the best photovoltaic panels deliver 20 W/m^2 on average, in a place with British sunniness. Presumably in the desert the same panels would deliver 40 W/m^2. So how come the concentrating solar power stations deliver only 15–20 W/m^2? Surely concentrating power should be even better than plain flat panels?

Good question. The short answer is no. Concentrating solar power does not achieve a better power per unit land area than flat panels. The concentrating contraption has to track the sun, otherwise the sunlight won't be focused right; once you start packing land with sun-tracking contraptions, you have to leave gaps between them; lots of sunlight falls through the gaps and is lost. The reason that people nevertheless make concentrating solar power systems is that, today, flat photovoltaic panels are very expensive, and concentrating systems are cheaper. The concentrating people's goal is not to make systems with big power per unit land area. Land area is cheap (they assume). The goal is to deliver big power per dollar.

But if flat panels have bigger power density, why don't you describe covering the Sahara desert with* them*?

Because I am trying to discuss practical options for large-scale sustainable power production for Europe and North Africa by 2050. My guess is that by 2050, mirrors will still be cheaper than photovoltaic panels, so concentrating solar power is the technology on which we should focus.

What about solar chimneys?

A solar chimney or solar updraft tower uses solar power in a very simple way. A huge chimney is built at the centre of an area covered by a transparent roof made of glass or plastic; because hot air rises, hot air created in this greenhouse-like heat-collector whooshes up the chimney, drawing in cooler air from the perimeter of the heat-collector. Power is extracted from the air-flow by turbines at the base of the chimney. Solar chimneys are fairly simple to build, but they don't deliver a very impressive power per unit area. A pilot plant in Manzanares, Spain operated for seven years between 1982 and 1989. The chimney had a height of 195 m and a diameter of 10 m; the collector had a diameter of 240 m, and its roof had 6000 m^2 of glass and 40 000 m^2 of transparent plastic. It generated 44 MWh per year, which corresponds to a power per unit area of 0.1 W/m^2. Theoretically, the bigger the collector and the taller the chimney, the bigger the power density of a solar chimney becomes. The engineers behind Manzanares reckon that, at a site with a solar radiation of 2300 kWh/m^2 per year (262 W/m^2), a 1000 m-high tower surrounded by a 7 km-diameter collector could generate 680 GWh per year, an average power of 78 MW. That's a power per unit area of about 1.6 W/m^2, which is similar to the power per unit area of windfarms in Britain, and one tenth of the power per unit area I said concentrating solar power stations would deliver. It's claimed that solar chimneys could generate electricity at a price similar to that of conventional power stations. I suggest that countries that have enough land and sunshine to spare should host a big bake-off contest between solar chimneys and concentrating solar power, to be funded by oil-producing and oil-consuming countries.

Figure 25.10. The Manzanares prototype solar chimney. Photos from `solarmillennium.de`.

What about getting power from Iceland, where geothermal power and hydroelectricity are so plentiful?

Indeed, Iceland already effectively exports energy by powering industries that make energy-intensive products. Iceland produces nearly one ton of aluminium per citizen per year, for example! So from Iceland's point of view, there are great profits to be made. But can Iceland save Europe? I would be surprised if Iceland's power production could be scaled up enough to make sizeable electricity exports even to Britain alone. As a benchmark, let's compare with the England–France Interconnector, which can deliver up to 2 GW across the English Channel. That maximum power is equivalent to 0.8 kWh per day per person in the UK, roughly 5% of British average electricity consumption. Iceland's average geothermal electricity generation is just 0.3 GW, which is less than 1% of Britain's average electricity consumption. Iceland's average electricity production is 1.1 GW. So to create a link sending power equal to the capacity of the French interconnector, Iceland would have to *triple* its electricity production. To provide us with 4 kWh per day per person (roughly what Britain gets from its own nuclear power stations), Iceland's electricity production would have to increase *ten-fold*. It is probably a good idea to build interconnectors to Iceland, but don't expect them to deliver more than a small contribution.

Figure 25.11. More geothermal power in Iceland. Photo by Rosie Ward.

Notes and further reading

page no.

178 *Concentrating solar power in deserts delivers an average power per unit area of roughly 15 W/m^2.* My sources for this number are two companies making concentrating solar power for deserts.

`www.stirlingenergy.com` says one of its 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 one dish per 500 m^2. That's an average power of 14 W/m^2. They say that solar dish Stirling makes the best use of land area, in terms of energy delivered.

`www.ausra.com` uses 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. Describing a "240 MW(e)" plant proposed for Australia (Mills and Lièvre, 2004), the designers claim that 3.5 km^2 of mirrors would deliver 1.2 TWh(e); that's 38 W/m^2 of mirror. To find the power per unit land area, we need to allow for the gaps between the mirrors. Ausra say they need a 153 km by 153 km square in the desert to supply all US electric power (Mills and Morgan, 2008). Total US electricity is 3600 TWh/y, so they are claiming a power per unit land area of 18 W/m^2. This technology goes by the name *compact linear fresnel reflector* (Mills and Morrison, 2000; Mills et al., 2004; Mills and Morgan, 2008). Incidentally, rather than "concentrating solar power," the company Ausra prefers to use the term *solar thermal electricity* (STE); they emphasize the benefits of thermal storage, in contrast to concentrating photovoltaics, which don't come with a natural storage option.

Trieb and Knies (2004), who are strong proponents of concentrating solar power, project that the alternative concentrating solar power technologies would have powers per unit land area in the following ranges: parabolic troughs, 14–19 W/m^2; linear fresnel collector, 19–28 W/m^2; tower with heliostats, 9–14 W/m^2; stirling dish, 9–14 W/m^2.

There are three European demonstration plants for concentrating solar power. Andasol – using parabolic troughs; Solúcar PS10, a tower near Seville; and Solartres, a tower using molten salt for heat storage. The Andasol parabolic-trough system shown in figure 25.4 is predicted to deliver 10 W/m^2. Solúcar's "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 during 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 per unit land area of 5 W/m^2. (Source: Abengoa Annual Report 2003.) Solartres will occupy 142 hectares 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.

179 *HVDC is already used to transmit electricity over 1000-km distances in South Africa, China, America, Canada, Brazil, and Congo.* Sources: Asplund (2004), Bahrman and Johnson (2007). Further reading on HVDC: Carlsson (2002).

Figure 25.12. Two engineers assembling an eSolar concentrating power station using heliostats (mirrors that rotate and tip to follow the sun). `esolar.com` make medium-scale power stations: a 33 MW (peak) power unit on a 64 hectare site. That's 51 W/m^2 peak, so I'd guess that in a typical desert location they would deliver about one quarter of that: 13 W/m^2.

Figure 25.13. A high-voltage DC power system in China. Photo: ABB.

179 *Losses on a 3500 km-long HVDC line, including conversion from AC to DC and back, would be about 15%.* Sources: Trieb and Knies (2004); van Voorthuysen (2008).

182 *According to Amonix, concentrating photovoltaics would have an average power per unit land area of 18 W/m^2.* The assumptions of www.amonix.com are: the lens transmits 85% of the light; 32% cell efficiency; 25% collector efficiency; and 10% further loss due to shading. Aperture/land ratio of 1/3. Normal direct irradiance: 2222 kWh/m^2/year. They expect each kW of peak capacity to deliver 2000 kWh/y (an average of 0.23 kW). A plant of 1 GW peak capacity would occupy 12 km^2 of land and deliver 2000 GWh per year. That's 18 W/m^2.

– *Solar chimneys.* Sources: Schlaich J (2001); Schlaich et al. (2005); Dennis (2006), www.enviromission.com.au, www.solarairpower.com.

183 *Iceland's average geothermal electricity generation is just 0.3 GW. Iceland's average electricity production is 1.1 GW.* These are the statistics for 2006: 7.3 TWh of hydroelectricity and 2.6 TWh of geothermal electricity, with capacities of 1.16 GW and 0.42 GW, respectively. Source: Orkustofnun National Energy Authority [www.os.is/page/energystatistics].

Further reading: European Commission (2007), German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment (2006), www.solarmillennium.de.

26 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

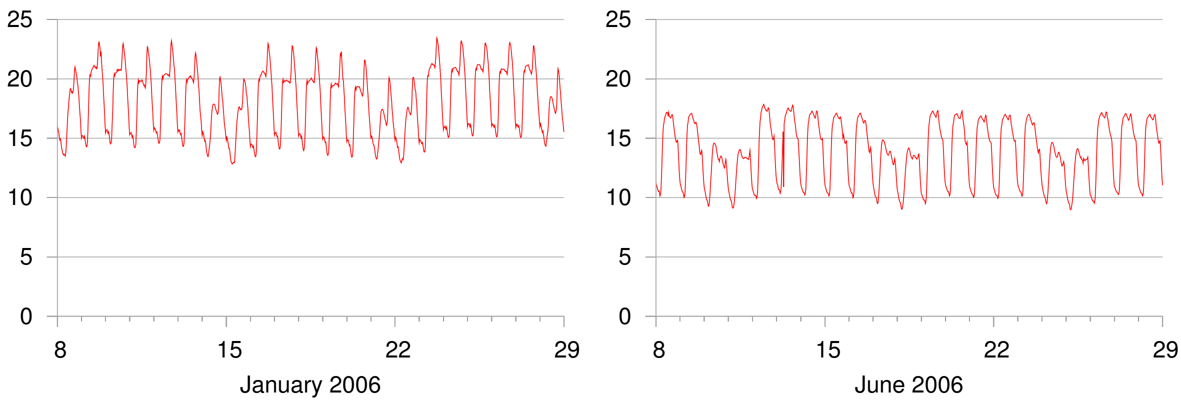


Figure 26.1. Electricity demand in Great Britain (in kWh/d per person) during two winter weeks and two summer weeks of 2006. The peaks in January are at 6pm each day. The five-day working week is evident in summer and winter. (If you'd like to obtain the national demand in GW, remember the top of the scale, 24 kWh/d per person, is the same as 60 GW per UK.)

If we kick fossil fuels and go all-out for renewables, *or* all-out for nuclear, *or* a mixture of the two, we may 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; but maybe two hours later, 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. This is a problem because, on an electricity network, consumption and production must be exactly equal all the time. The electricity grid can't *store* energy. To have an energy plan that adds up every minute of every day, we therefore need *something easily turn-off-and-onable*. It's commonly assumed that the easily turn-off-and-onable something should be a *source* of power that gets turned off and on to compensate for the fluctuations of supply relative to demand (for example, a fossil fuel power station!). But another equally effective way to match supply and demand would be to have an easily turn-off-and-onable *demand* for power – a sink of power that can be turned off and on at the drop of a hat.

Either way, the easily turn-off-and-onable something needs to be a *big* something because electricity demand varies a lot (figure 26.1). The de-

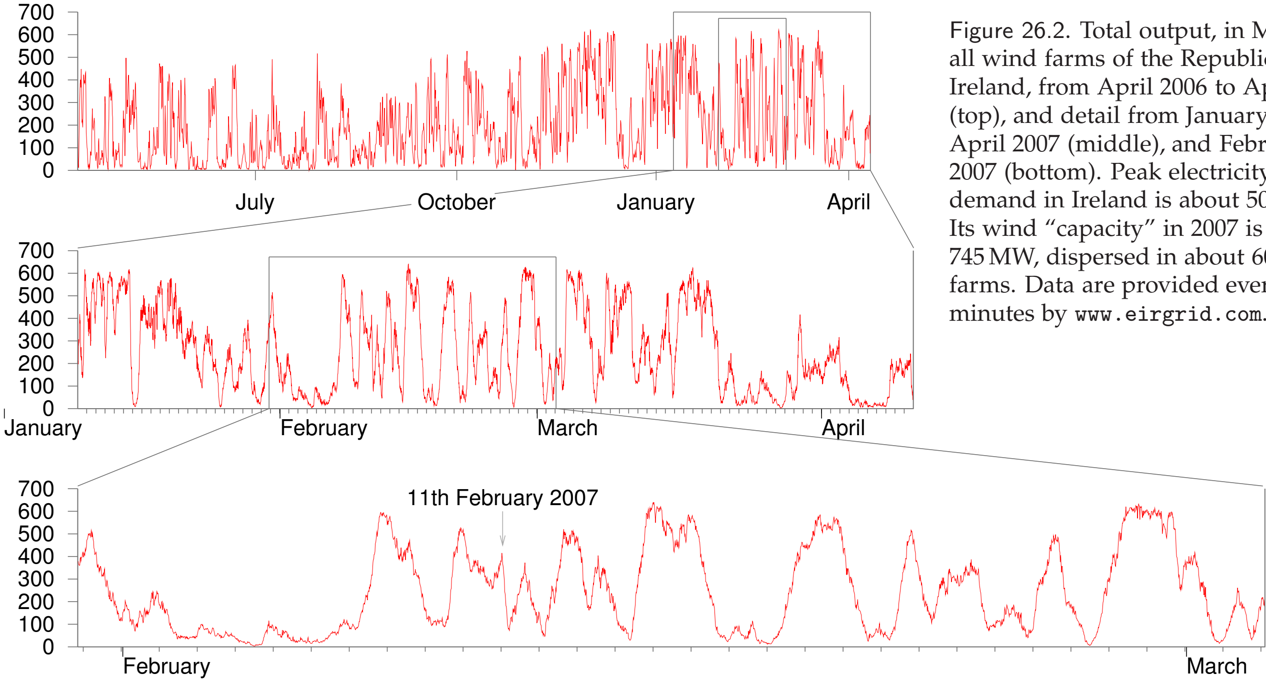


Figure 26.2. Total output, in MW, of all wind farms of the Republic of Ireland, from April 2006 to April 2007 (top), and detail from January 2007 to April 2007 (middle), and February 2007 (bottom). Peak electricity demand in Ireland is about 5000 MW. Its wind "capacity" in 2007 is 745 MW, dispersed in about 60 wind farms. Data are provided every 15 minutes by `www.eirgrid.com`.

mand sometimes changes significantly on a timescale of a few minutes. This chapter discusses how to cope with fluctuations in supply and demand, without using fossil fuels.

How much do renewables fluctuate?

However much we love renewables, we must not kid ourselves about the fact that wind does fluctuate.

Critics of wind power say: "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 in different locations is much less intermittent."

Let's look at real data and try to figure out a balanced viewpoint. Figure 26.2 shows the summed output of the wind fleet of the Republic of Ireland from April 2006 to April 2007. Clearly wind *is* intermittent, even if we add up lots of turbines covering a whole country. The UK is a bit larger than Ireland, but the same problem holds there too. Between October 2006 and February 2007 there were 17 days when the output from Britain's 1632 windmills was less than 10% of their capacity. During that period there were five days when output was less than 5% and one day when it was

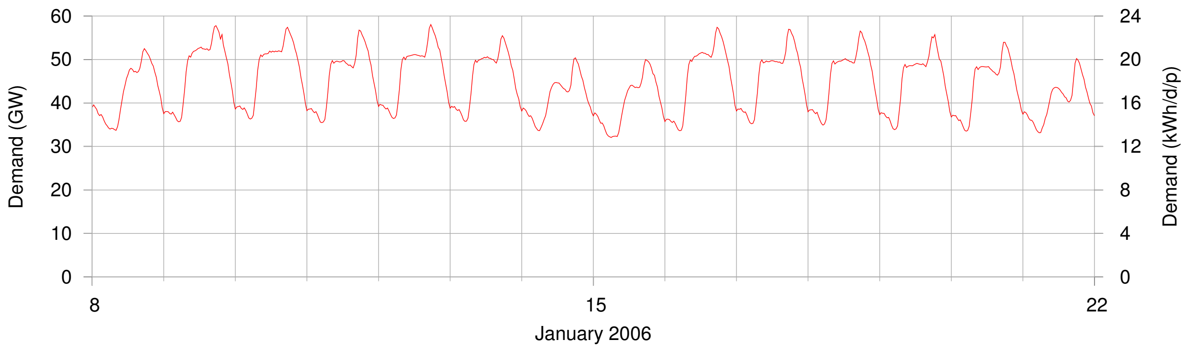


Figure 26.3. Electricity demand in Great Britain during two winter weeks of 2006. The left and right scales show the demand in national units (GW) and personal units (kWh/d per person) respectively. These are the same data as in figure 26.1.

only 2%.

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 Irish wind 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. (By slew rate I mean the rate at which the delivered power fell or rose – 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.

Could these windy demands be met? In answering this question we'll need to talk more 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: 1 kWh per day per person is equivalent to 2.5 GW nationally. 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 26.3 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 reasonable 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. I'm not saying that the wind-slew problem is *already* solved – just that it is a problem of the same size as other problems that have been solved.

OK, before we start looking for solutions, we need to quantify wind's other problem: long-term 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 26.2. 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 entire lull. (Or a mix of the two.) If we have 33 GW of wind turbines delivering an average power of 10 GW then the amount of energy we must 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 energy unit for nations. Britain's electricity consumption is roughly 1000 GWh per day.)

To personalize this quantity, an energy store of 1200 GWh for the nation is equivalent to an energy store of 20 kWh per person. Such an energy store would allow the nation to go without 10 GW of electricity for 5 days; or equivalently, every individual to go without 4 kWh per day of electricity for 5 days.

Coping with lulls and slews

We need to solve two problems – lulls (long periods with small renewable production), and slews (short-term changes in either supply or demand). We've quantified these problems, assuming that Britain had roughly 33 GW of wind power. To cope with lulls, we must effectively store up roughly 1200 GWh of energy (20 kWh per person). The slew rate we must cope with is 6.5 GW per hour (or 0.1 kW per hour per person).

There are two solutions, both of which could scale up to solve these problems. The first solution is a centralized solution, and the second is decentralized. The first solution stores up energy, then copes with fluctuations by turning on and off a *source* powered from the energy store. The second solution works by turning on and off a piece of *demand*.

The first solution is *pumped storage*. The second uses the batteries of the *electric vehicles* that we discussed in Chapter 20. Before I describe these solutions, let's discuss a few other ideas for coping with slew.

Other supply-side ways of coping with slew

Some of the renewables are turn-off-and-onable. If we had a lot of renewable power that was easily turn-off-and-onable, all the problems of this chapter would go away. Countries like Norway and Sweden have large and deep hydroelectric supplies which they can turn on and off. What might the options be in Britain?

First, Britain could have lots of waste incinerators and biomass incinerators – power stations playing the role that is today played by fossil power stations. If these stations were designed to be turn-off-and-onable, there would be cost implications, just as there are costs when we have extra fossil power stations that are only working part-time: their generators would sometimes be idle and sometimes work twice as hard; and most generators aren't as efficient if you keep turning them up and down, compared with running them at a steady speed. OK, leaving cost to one side, the crucial question is how big a turn-off-and-onable resource we might have. If all municipal waste were incinerated, and an equal amount of agricultural waste were incinerated, then the average power from these sources would be about 3 GW. If we built capacity equal to *twice* this power, making incinerators capable of delivering 6 GW, and thus planning to have them operate only half the time, these would be able to deliver 6 GW throughout periods of high demand, then zero in the wee hours. These power stations could be designed to switch on or off within an hour, thus coping with slew rates of 6 GW per hour – but only for a maximum slew range of 6 GW! That's a helpful contribution, but not enough slew range in itself, if we are to cope with the fluctuations of 33 GW of wind.

What about hydroelectricity? Britain's hydroelectric stations have an average load factor of 20% so they certainly have the potential to be turned on and off. Furthermore, hydro has the wonderful feature that it can be turned on and off very quickly. Glendoe, a new hydro station 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 wind farms. However, the capacity of the British hydro fleet is *not* currently big enough to make much contribution to our slew problem (assuming we want to cope with the rapid loss of say 10 or 33 GW of wind power). The total capacity of traditional hydroelectric stations in Britain is only about 1.5 GW.

So simply switching on and off other renewable power sources is not going to work in Britain. We need other solutions.

Pumped storage

Pumped storage systems use cheap electricity to shove water from a downhill lake to an uphill lake; then regenerate electricity when it's valuable,

station	power (GW)	head (m)	volume (million m^3)	energy stored (GWh)
Ffestiniog	0.36	320–295	1.7	1.3
Cruachan	0.40	365–334	11.3	10
Foyers	0.30	178–172	13.6	6.3
Dinorwig	1.80	542–494	6.7	9.1

Table 26.4. Pumped storage facilities in Britain. The maximum energy storable in today's pumped storage systems is about 30 GWh.

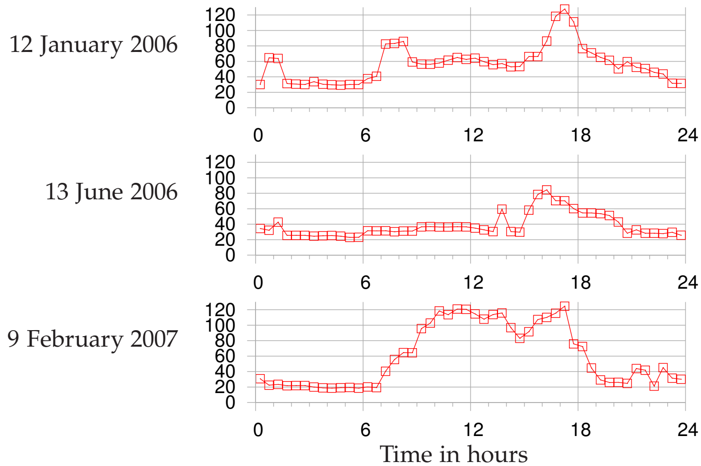


Figure 26.5. How pumped storage pays for itself. Electricity prices, in £ per MWh, on three days in 2006 and 2007.

using turbines just like the ones in hydroelectric power stations.

Britain has four pumped storage facilities, which can store 30 GWh between them (table 26.4, figure 26.6). They are typically used to store excess electricity at night, then return it during the day, especially at moments of peak demand – a profitable business, as figure 26.5 shows. The Dinorwig power station – an astonishing cathedral inside a mountain in Snowdonia – also plays an insurance role: it has enough oomph to restart the national grid in the event of a major failure. Dinorwig can switch on, from 0 to 1.3 GW power, in 12 seconds.

Dinorwig is the Queen of the four facilities. Let's review her vital statistics. The total energy that can be stored in Dinorwig 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%.

If all four pumped storage stations are switched on simultaneously, they can produce a power of 2.8 GW. They can switch on extremely fast, coping with any slew rate that demand-fluctuations or wind-fluctuations could come up with. However the capacity of 2.8 GW is not enough to replace 10 GW or 33 GW of wind power if it suddenly went missing. Nor is the total energy stored (30 GWh) anywhere near the 1200 GWh we are interested in storing in order to make it through a big lull. Could pumped

Figure 26.6. Llyn Stwlan, the upper reservoir of the Ffestiniog pumped storage scheme in north Wales. Energy stored: 1.3 GWh. Photo by Adrian Pingstone.

storage be ramped up? Can we imagine solving the entire lull problem using pumped storage alone?

Can we store 1200 GWh?

We are interested in making much bigger storage systems, storing a total of 1200 GWh (about 130 times what Dinorwig stores). And we'd like the capacity to be about 20 GW – about ten times bigger than Dinorwig's. So here is the pumped storage solution: we have to imagine creating roughly 12 new sites, each storing 100 GWh – roughly ten times the energy stored in Dinorwig. The pumping and generating hardware at each site would be the same as Dinorwig's.

Assuming the generators have an efficiency of 90%, table 26.7 shows a few ways of storing 100 GWh, for a range of height drops. (For the physics behind this table, see this chapter's endnotes.)

Ways to store 100 GWh		
drop from upper lake	working volume required (million m^3)	example size of lake area depth
500 m	40	$2\,km^2 \times 20\,m$
500 m	40	$4\,km^2 \times 10\,m$
200 m	100	$5\,km^2 \times 20\,m$
200 m	100	$10\,km^2 \times 10\,m$
100 m	200	$10\,km^2 \times 20\,m$
100 m	200	$20\,km^2 \times 10\,m$

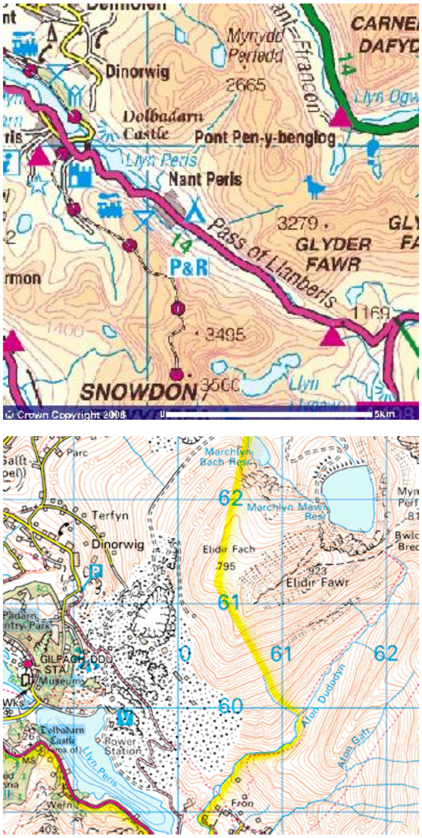
Table 26.7. Pumped storage. Ways to store 100 GWh. For comparison with column 2, the working volume of Dinorwig is 7 million m^3, and the volume of Lake Windermere is 300 million m^3. For comparison with column 3, Rutland water has an area of 12.6 km^2; Grafham water 7.4 km^2. Carron valley reservoir is 3.9 km^2. The largest lake in Great Britain is Loch Lomond, with an area of 71 km^2.

Is it plausible that twelve such sites could be found? Certainly, we could build several more sites like Dinorwig in Snowdonia alone. Table 26.8 shows two alternative sites near to Ffestiniog where two facilities equal to Dinorwig could have been built. These sites were considered alongside Dinorwig in the 1970s, and Dinorwig was chosen.

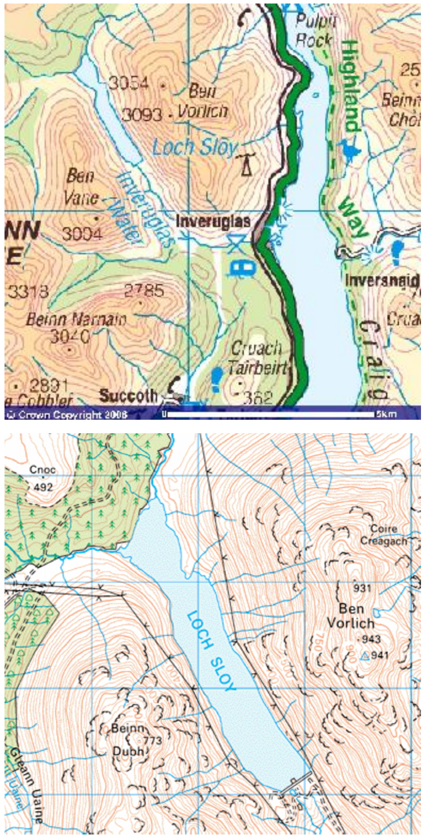
proposed location	power (GW)	head (m)	volume (million m^3)	energy stored (GWh)
Bowydd	2.40	250	17.7	12.0
Croesor	1.35	310	8.0	6.7

Table 26.8. Alternative sites for pumped storage facilities in Snowdonia. At both these sites the lower lake would have been a new artificial reservoir.

Pumped-storage facilities holding significantly more energy than Dinorwig could be built in Scotland by upgrading existing hydroelectric facilities. 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. Figure 26.9 shows these lakes and the Dinorwig lakes on the same scale. The height

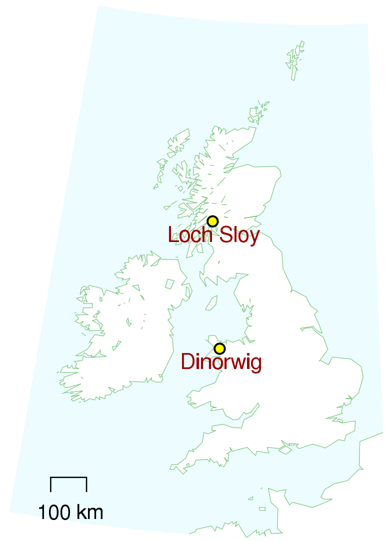


Dinorwig is the home of a 9 GWh storage system, using Marchlyn Mawr (615E, 620N) and Llyn Peris (590E, 598N) as its upper and lower reservoirs.



Loch Sloy illustrates the sort of location where a 40 GWh storage system could be created.

Figure 26.9. 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.



difference between Loch Sloy and Loch Lomond is about 270 m. Sloy's area is about 1.5 km^2, and it can already store an energy of 20 GWh. If Loch Sloy's dam were raised by another 40 m then the extra energy that could be stored would be about 40 GWh. The water level in Loch Lomond would change by at most 0.8 m during a cycle. This is less than the normal range of annual water level variations of Loch Lomond (2 m).

Figure 26.10 shows 13 locations in Scotland with potential for pumped storage. (Most of them already have a hydroelectric facility.) If ten of these had the same potential as I just estimated for Loch Sloy, then we could store 400 GWh – one third of the total of 1200 GWh that we were aiming for.

We could scour the map of Britain for other locations. The best locations would be near to big wind farms. One idea would be to make a new artificial lake in a hanging valley (across the mouth of which a dam would

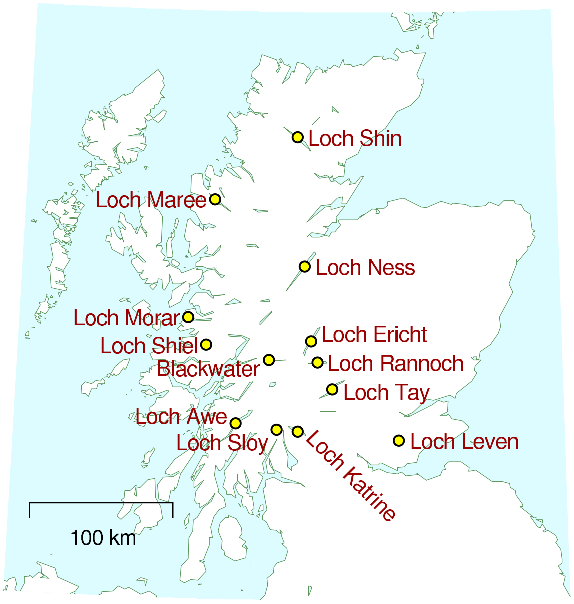


Figure 26.10. Lochs in Scotland with potential for pumped storage.

be built) terminating above the sea, with the sea being used as the lower lake.

Thinking further outside the box, one could imagine getting away from lakes and reservoirs, putting half of the facility in an underground chamber. A pumped-storage chamber one kilometre below London has been mooted.

By building more pumped storage systems, it looks as if we could increase our maximum energy store from 30 GWh to 100 GWh or perhaps 400 GWh. Achieving the full 1200 GWh that we were hoping for looks tough, however. Fortunately there is another solution.

Figure 26.11. Okinawa pumped-storage power plant, whose lower reservoir is the ocean. Energy stored: 0.2 GWh. Photo by courtesy of J-Power. www.ieahydro.org.

Demand management using electric vehicles

To recap our requirements: we'd like to be able to store or do without about 1200 GWh, which is 20 kWh per person; and to cope with swings in supply of up to 33 GW – that's 0.5 kW per person. These numbers are delightfully similar in size to the energy and power requirements of electric cars. The electric cars we saw in Chapter 20 had energy stores of between 9 kWh and 53 kWh. A national fleet of 30 million electric cars would store an energy similar to 20 kWh per person! Typical battery chargers draw a power of 2 or 3 kW. So simultaneously switching on 30 million battery chargers would create a change in demand of about 60 GW! The average power required to power all the nation's transport, if it were all electric, is roughly 40 or 50 GW. There's therefore a close match between the adoption of electric cars proposed in Chapter 20 and the creation of roughly 33 GW of wind capacity, delivering 10 GW of power on average.

Here's one way this match could be exploited: electric cars could be plugged in to smart chargers, at home or at work. These smart chargers would be aware both of the value of electricity, and of the car user's requirements (for example, "my car must be fully charged by 7am on Monday morning"). The charger would sensibly satisfy the user's requirements by guzzling electricity whenever the wind blows, and switching off when the wind drops, or when other forms of demand increase. These smart chargers would provide a useful service in balancing to the grid, a service which could be rewarded financially.

We could have an especially robust solution if the cars' batteries were exchangeable. Imagine popping in to a filling station and slotting in a set of fresh batteries in exchange for your exhausted batteries. The filling station would be responsible for recharging the batteries; they could do this at the perfect times, turning up and down their chargers so that total supply and demand were always kept in balance. Using exchangeable batteries is an especially robust solution because there could be millions of spare batteries in the filling stations' storerooms. These spare batteries would provide an extra buffer to help us get through wind lulls. Some people say, "Horrors! How could I trust the filling station to look after my batteries for me? What if they gave me a duff one?" Well, you could equally well ask today "What if the filling station gave me petrol laced with water?" Myself, I'd much rather use a vehicle maintained by a professional than by a muppet like me!

Let's recap our options. We can balance fluctuating demand and fluctuating supply by switching on and off power *generators* (waste incinerators and hydroelectric stations, for example); by *storing* energy somewhere and regenerating it when it's needed; or by switching *demand* off and on.

The most promising of these options, in terms of scale, is switching on and off the power demand of electric-vehicle charging. 30 million cars, with 40 kWh of associated batteries each (some of which might be exchangeable batteries sitting in filling stations) adds up to 1200 GWh. If freight delivery were electrified too then the total storage capacity would be bigger still.

There is thus a beautiful match between wind power and electric vehicles. If we ramp up electric vehicles at the same time as ramping up wind power, roughly 3000 new vehicles for every 3 MW wind turbine, and if we ensure that the charging systems for the vehicles are smart, this synergy would go a long way to solving the problem of wind fluctuations. If my prediction about hydrogen vehicles is wrong, and hydrogen vehicles turn out to be the low-energy vehicles of the future, then the wind-with-electric-vehicles match-up that I've just described could of course be replaced by a wind-with-hydrogen match-up. The wind turbines would make electricity; and whenever electricity was plentiful, hydrogen would be produced and stored in tanks, for subsequent use in vehicles or in other applications, such as glass production.

Other demand-management and storage ideas

There are a few other demand-management and energy-storage options, which we'll survey now.

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. Wherever power is used to create stuff that is storable, there's potential for switching that power-demand on and off in a smart way. For example, reverse-osmosis systems (which make pure water from sea-water – see p92) are major power consumers in many countries (though not Britain). Another storable product is heat. If, as suggested in Chapter 21, we electrify buildings' heating and cooling systems, especially water-heating and air-heating, then there's potential for lots of easily-turn-off-and-onable power demand to be attached to the grid. Well-insulated buildings hold their heat for many hours, so there's flexibility in the timing of their heating. Moreover, we could include large thermal reservoirs in buildings, and use heat-pumps to pump heat into or out of those reservoirs at times of electricity abundance; then use a second set of heat pumps to deliver heat or cold from the reservoirs to the places where heating or cooling are wanted.

Controlling electricity demand automatically would be easy. The simplest way to do this 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. (It's just like a dynamo on a bicycle: when you switch the lights on, you have to pedal harder to supply the extra power; if you don't then the bike goes a bit slower.) 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 jeopardizing the temperature of your butter, they tend to take power at times that help the grid.

Can demand-management provide a significant chunk of virtual storage? How big a sink of power are the nation's fridges? On average, a typical fridge-freezer draws about 18 W; let's guess that the number of fridges is about 30 million. So the ability to switch off all the nation's fridges for a few minutes would be equivalent to 0.54 GW of automatic adjustable power. This is quite a lot of electrical power – more than 1% of the national total – and it is similar in size to the sudden increases in demand produced when the people, united in an act of religious observance (such as watching EastEnders), simultaneously switch on their kettles. Such "TV pick-ups" typically produce increases of demand of 0.6–0.8 GW. Automatically switching off every fridge would *nearly* cover these daily blips of concerted kettle boiling. These smart fridges could also help iron out short-time-scale fluctuations in wind power. The TV pick-ups associated with the holiest acts of observance (for example, watching England play footie against Sweden) can produce sudden increases in demand of over 2 GW. On such occasions, electricity demand and supply are kept in balance by unleashing the full might of Dinorwig.

To provide flexibility to the electricity-grid's managers, who perpetually turn power stations up and down to match supply to demand, many industrial users of electricity are on special contracts that allow the managers to switch off those users' demand at very short notice. 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 air-conditioning systems and electric water heaters.

Denmark's solution

Here's how Denmark copes with the intermittency of its wind power. The Danes effectively pay to use other countries' hydroelectric facilities as storage facilities. 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. Overall, Danish wind is contributing useful energy, and the system as a whole has considerable security thanks to the capacity of the hydro system.

Could Britain adopt the Danish solution? We would need direct large-capacity connections to countries with lots of turn-off-and-on-able hydroelectric capacity; or a big connection to a Europe-wide electricity grid.

Norway has 27.5 GW of hydroelectric capacity. Sweden has roughly 16 GW. And Iceland has 1.8 GW. A 1.2 GW high-voltage DC interconnector to Norway was mooted in 2003, but not built. A connection to the Netherlands – the BritNed interconnector, with a capacity of 1 GW – will be built in 2010. Denmark's wind capacity is 3.1 GW, and it has a 1 GW connection to Norway, 0.6 GW to Sweden, and 1.2 GW to Germany, a total export capacity of 2.8 GW, very similar to its wind capacity. To be able to export all its excess wind power in the style of Denmark, Britain (assuming 33 GW of wind capacity) would need something like a 10 GW connection to Norway, 8 GW to Sweden, and 1 GW to Iceland.

A solution with two grids

A radical approach is to put wind power and other intermittent sources onto a separate *second* electricity grid, used to power systems that don't require reliable power, such as heating and electric vehicle battery-charging.

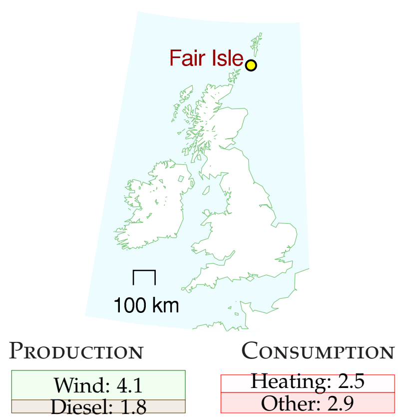


Figure 26.12. Electrical production and consumption on Fair Isle, 1995–96. All numbers are in kWh/d per person. Production exceeds consumption because 0.6 kWh/d per person were dumped.

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 wind-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. The mains frequency is used to inform heaters when they may switch on. In fact there are up to six frequency channels per household, so the system emulates seven grids. 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.

Electrical vehicles as generators

If 30 million electric vehicles were willing, in times of national electricity shortage, to run their chargers in reverse and put power back into the grid, then, at 2 kW per vehicle, we'd have a potential power source of 60 GW – similar to the capacity of all the power stations in the country. Even if only one third of the vehicles were connected and available at one time, they'd still amount to a potential source of 20 GW of power. If each of those vehicles made an emergency donation of 2 kWh of energy – corresponding to perhaps 20% of its battery's energy-storage capacity – then the total energy provided by the fleet would be 20 GWh – twice as much as the energy in the Dinorwig pumped storage facility.

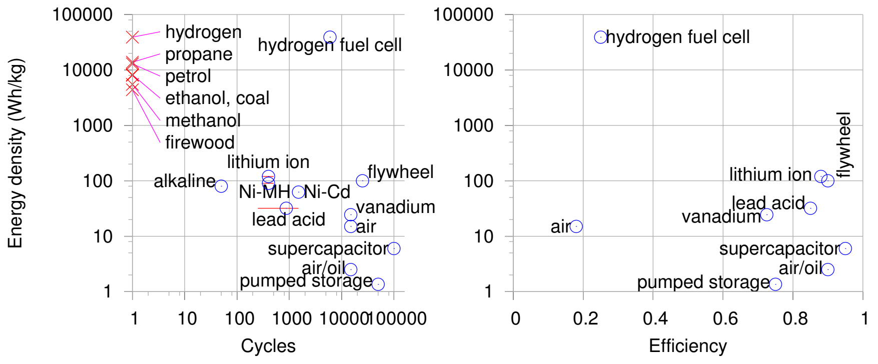
Other storage technologies

There are lots of ways to store energy, and lots of criteria by which storage solutions are judged. Figure 26.13 shows three of the most important criteria: energy density (how much energy is stored per kilogram of storage system); efficiency (how much energy you get back per unit energy put in); and lifetime (how many cycles of energy storage can be delivered before the system needs refurbishing). Other important criteria are: the maximum rate at which energy can be pumped into or out of the storage system, often expressed as a power per kg; the duration for which energy stays stored in the system; and of course the cost and safety of the system.

Flywheels

Figure 26.15 shows a monster flywheel used to supply brief bursts of power of up to 0.4 GW to power an experimental facility. It weighs 800 t. Spinning at 225 revolutions per minute, it can store 1000 kWh, and its energy density is about 1 Wh per kg.

Figure 26.15. One of the two flywheels at the fusion research facility in Culham, under construction. Photo: EFDA-JET. www.jet.efda.org.



(a) (b)

Figure 26.13. Some properties of storage systems and fuels. (a) Energy density (on a logarithmic scale) versus lifetime (number of cycles). (b) Energy density versus efficiency. The energy densities don't include the masses of the energy systems' containers, except in the case of "air" (compressed air storage). Taking into account the weight of a cryogenic tank for holding hydrogen, the energy density of hydrogen is reduced 39 000 Wh/kg to roughly 2400 Wh/kg.

fuel	calorific value	
	(kWh/kg)	(MJ/l)
propane	13.8	25.4
petrol	13.0	34.7
diesel oil (DERV)	12.7	37.9
kerosene	12.8	37
heating oil	12.8	37.3
ethanol	8.2	23.4
methanol	5.5	18.0
bioethanol		21.6
coal	8.0	
firewood	4.4	
hydrogen	39.0	
natural gas	14.85	0.04

(a)

battery type	energy density (Wh/kg)	lifetime (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

(b)

Table 26.14. (a) Calorific values (energy densities, per kg and per litre) of some fuels (in kWh per kg and MJ per litre).
(b) Energy density of some batteries (in Wh per kg). 1 kWh = 1000 Wh.

A flywheel system designed for energy storage in a racing car can store 400 kJ (0.1 kWh) of energy and weighs 24 kg (p126). That's an energy density of 4.6 Wh per kg.

High-speed flywheels made of composite materials have energy densities up to 100 Wh/kg.

Supercapacitors

Supercapacitors are used to store 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.

A US company, EEStor, claims to be able to make much better supercapacitors, using barium titanate, with an energy density of 280 Wh/kg.

Vanadium flow batteries

VRB power systems have provided a 12 MWh energy storage system for the Sorne Hill wind farm in Ireland, whose current capacity is "32 MW," increasing to "39 MW." (VRB stands for vanadium redox battery.) This storage system is a big "flow battery," a 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 wind farm 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.

A 1.5 MWh vanadium system costing $480 000 occupies 70 m^2 with a mass of 107 tons. The vanadium redox battery has a life of more than 10 000 cycles. 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). Its efficiency is 70–75%, round-trip. The volume required is about 1 m^3 of 2-molar vanadium in sulphuric acid to store 20 kWh. (That's 20 Wh/kg.)

So to store 10 GWh would require 500 000 m^3 (170 swimming pools) – for example, tanks 2 m high covering a floor area of 500 m × 500 m.

Scaling up the vanadium technology to match a big pumped-storage system – 10 GWh – might have a noticeable effect on the world vanadium market, but there is no long-term shortage of vanadium. Current world-wide production of vanadium is 40 000 tons per year. A 10 GWh system would contain 36 000 tons of vanadium – about one year's worth of current production. Vanadium is currently produced as a by-product of other processes, and the total world vanadium resource is estimated to be 63 million tons.

"Economical" solutions

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 any excess electrical power by throwing it away in heaters.

Seasonal fluctuations

The fluctuations of supply and demand that have the longest timescale are seasonal. The most important fluctuation is that of building-heating, which goes up every winter. Current UK natural gas demand varies throughout the year, from a typical average of 36 kWh/d per person in July and August to an average of 72 kWh/d per person in December to February, with extremes of 30–80 kWh/d/p (figure 26.16).

Some renewables also have yearly fluctuations – solar power is stronger in summer and wind power is weaker.

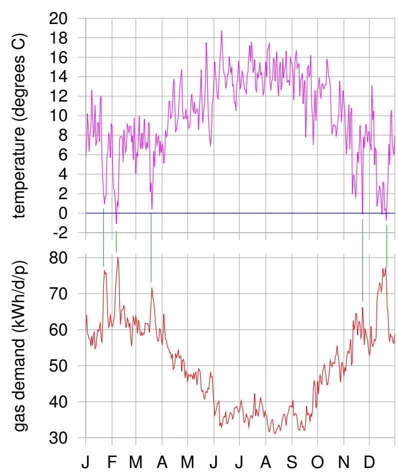


Figure 26.16. Gas demand (lower graph) and temperature (upper graph) in Britain during 2007.

How to ride through these very-long-timescale fluctuations? Electric vehicles and pumped storage are not going to help store the sort of quantities required. A useful technology will surely be long-term thermal storage. A big rock or a big vat of water can store a winter's worth of heat for a building – Chapter E discusses this idea in more detail. In the Netherlands, summer heat from roads is stored in aquifers until the winter; and delivered to buildings via heat pumps [2wmuw7].

Notes

page no.

187 *The total output of the wind fleet of the Republic of Ireland.* Data from `eirgrid.com` [2hxf6c].

– *"Loss of wind causes Texas power grid emergency".* [2199ht] 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.
Here is 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 4th March 2008, its wind generators were delivering 10 GW. "Spain's power market has become particularly sensitive to fluctuations in wind."

– *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." `www.yes2wind.com/intermittency_debunk.html`

– *... wind* **is** *intermittent, even if we add up lots of turbines covering a whole country. The UK is a bit larger than Ireland, but the same problem holds there too.* Source: Oswald et al. (2008).

191 *Dinorwig's pumped-storage efficiency is 75%.* Figure 26.17 shows data. Further information about Dinorwig and the alternate sites for pumped storage: Baines et al. (1983, 1986).

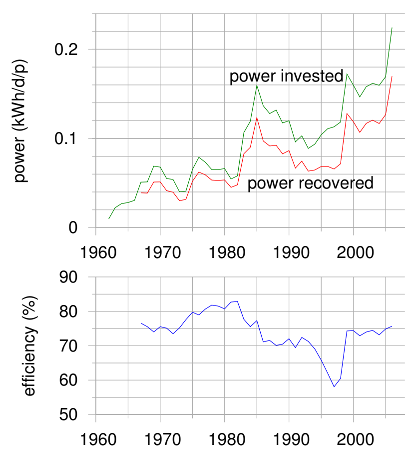


Figure 26.17. Efficiency of the four pumped storage systems of Britain.

192 *Table 26.7.* The working volume required, V, is computed from the height drop h as follows. If ϵ is the efficiency of potential energy to electricity conversion,

$$V = 100\,\text{GWh}/(\rho g h \epsilon),$$

where ρ is the density of water and g is the acceleration of gravity. I assumed the generators have an efficiency of $\epsilon = 0.9$.

192 *Table 26.8, 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.

193 *If ten Scottish pumped storage facilities had the same potential as Loch Sloy, then we could store 400 GWh.* This rough estimate is backed up by a study by Strathclyde University [5o2xgu] which lists 14 sites having an estimated storage capacity of 514 GWh.

196 *Fridges can be modified to nudge their internal thermostats up and down … in response to the mains frequency.* [2n3pmb] Further links: Dynamic Demand www.dynamicdemand.co.uk; www.rltec.com; www.responsiveload.com.

197 *In South Africa … demand-management systems are being installed.* Source: [2k8h4o]

– *Almost all of Denmark's wind power is exported to its European neighbours.* Source: Sharman (2005).

198 *For over 25 years (since 1982), Fair Isle has had two electricity networks.* www.fairisle.org.uk/FIECo/
Wind speeds are between 3 m/s and 16 m/s most of the time; 7 m/s is the most probable speed.

199 *Figure 26.13. Storage efficiencies.* Lithium-ion batteries: 88% efficient.
Source: www.national.com/appinfo/power/files/swcap_eet.pdf
Lead-acid batteries: 85–95%.
Source: www.windsun.com/Batteries/Battery_FAQ.htm
Compressed air storage: 18% efficient. Source: Lemofouet-Gatsi and Rufer (2005); Lemofouet-Gatsi (2006). See also Denholm et al. (2005).

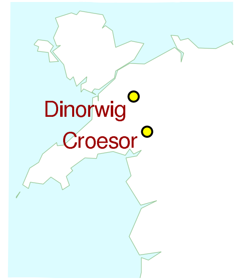


Figure 26.18. A possible site for another 7 GWh pumped storage facility. Croesor valley is in the centre-left, between the sharp peak (Cnicht) on the left and the broader peaks (the Moelwyns) on the right.

Air/oil: hydraulic accumulators, as used for regenerative braking in trucks, are compressed-air storage devices that can be 90%-efficient round-trip and allow 70% of kinetic energy to be captured. Sources: Lemofouet-Gatsi (2006), [5cp27j].

– *Table 26.14.* Sources: Xtronics xtronics.com/reference/energy_density.htm; Battery University [2sxlyj]; flywheel information from Ruddell (2003).
The latest batteries with highest energy density are lithium-sulphur and lithium-sulphide batteries, which have an energy density of 300 Wh/kg.
Some disillusioned hydrogen-enthusiasts seem to be making their way up the periodic table and becoming boron-enthusiasts. Boron (assuming you will burn it to B_2O_3) has an energy density of 15 000 Wh per kg, which is nice and high. But I imagine that my main concern about hydrogen will apply to boron too: that the production of the fuel (here, boron from boron oxide) will be inefficient in energy terms, and so will the combustion process.

200 *Vanadium flow batteries.* Sources: www.vrbpower.com; *Ireland wind farm* [ktd7a]; *charging rate* [627ced]; *worldwide production* [5fasl7].

201 *… summer heat from roads is stored in aquifers…* [2wmuw7].

27 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 are many plans that add up. In this chapter I will describe five. 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 to be produced. To avoid the plans' taking many pages, I deal with 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 from our destination that I think a simple cartoon is the best way to capture the issues.

I'll present a few plans that I believe are technically feasible for the UK by 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 want 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 country is as follows. Transport (of both humans and stuff) uses 40 kWh/d per person. 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 energy is currently provided by 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/p. The remaining 27 kWh/d/p goes up cooling towers (25 kWh/d/p) and is lost in the wires of the distribution network (2 kWh/d/p). The total energy input to this present-day cartoon country is 125 kWh/d per person.

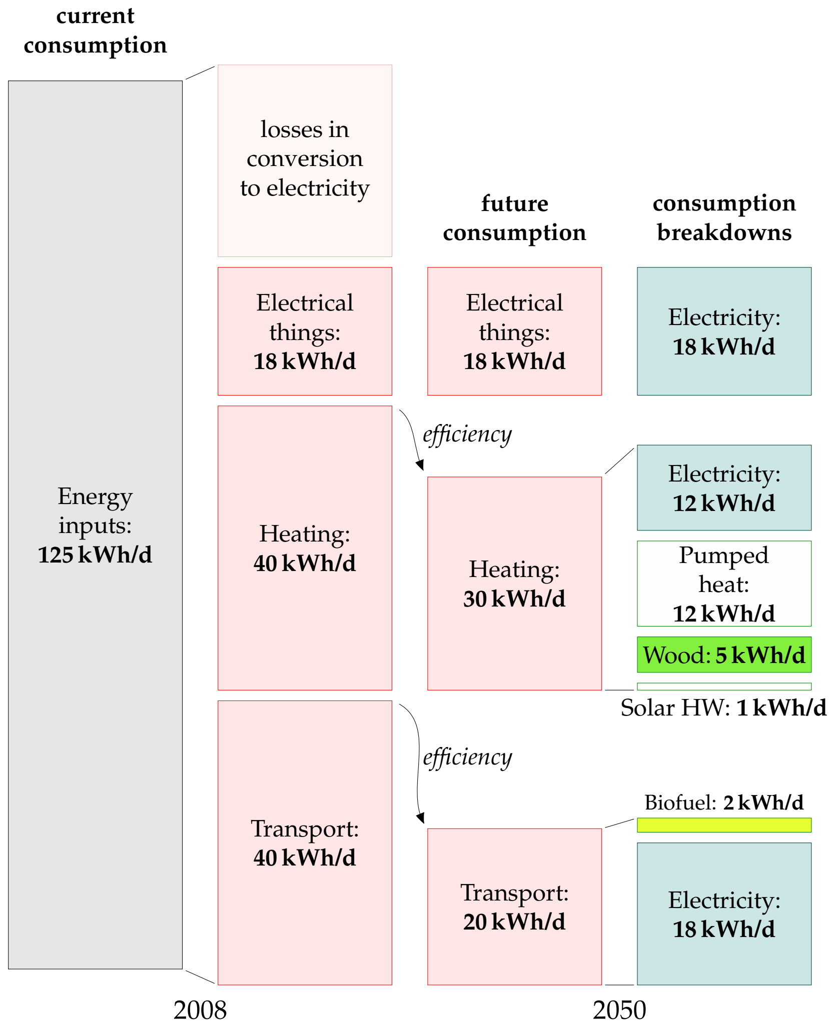


Figure 27.1. Current consumption per person in "cartoon Britain 2008" (left two columns), and a future consumption plan, along with a possible breakdown of fuels (right two columns). This plan requires that electricity supply be increased from 18 to 48 kWh/d per person of electricity.

Common features of all five plans

In my future cartoon country, the energy consumption is reduced by using more efficient technology for transport and heating.

In the five plans for the future, **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) is better integrated, better personalized, and better patronized. I've assumed that electrification makes transport about four times more efficient, and that economic growth cancels out some of these savings, so that the net effect is a halving of energy consumption for transport. There are a few essential vehicles that can't be easily electrified, and for those we make our own liquid fuels (for example biodiesel or biomethanol or cellulosic bioethanol). The energy for transport is 18 kWh/d/p of electricity and 2 kWh/d/p of liquid fuels. The electric vehicles' batteries serve as an energy storage facility, helping to cope with fluctuations of electricity supply and demand. The area required for the biofuel production is 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 other countries to devote the required (Wales-sized) area of agricultural land to biofuels for us.

In all five plans, 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 30 000 km^2, or 500 m^2 per person; this corresponds to 18% of the UK's agricultural land, which has an area of 2800 m^2 per person. The energy crops are grown mainly on the lower-grade land, leaving the higher-grade land for food-farming. Each 500 m^2 of energy crops yields 0.5 oven dry tons per year, which has an energy content of about 7 kWh/d; of this power, about 30% is lost in the process of heat production and delivery. 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 is improved by a switch to light-emitting diodes for most lighting, and many other gadgets will get more efficient; but thanks to the blessings of economic growth, we'll have increased the number of gadgets in our lives – for example video-conferencing systems to help us travel less.

The total consumption of electricity under this plan goes *up* (because of the 18 kWh/d/p for electric transport and the 12 kWh/d/p for heat pumps) to 48 kWh/d/p (or 120 GW nationally). 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.

Producing lots of electricity – the components

To make lots of electricity, each plan uses 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. Each plan aims for a total electricity production of 50 kWh/d/p on average – I got this figure by rounding up the 48 kWh/d/p of average demand, allowing for some loss in the distribution network.

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 that can't usefully be recycled is incinerated rather than landfilled. Incinerating 1 kg per day per person of waste yields roughly 0.5 kWh/d per person of electricity. I'll assume that a similar amount of agricultural waste is also incinerated, yielding 0.6 kWh/d/p. Incinerating this waste requires roughly 3 GW of waste-to-energy capacity, a ten-fold increase over the incinerating power stations of 2008 (figure 27.2). London (7 million people) would have twelve 30-MW waste-to-energy plants like the SELCHP plant in South London (see p287). Birmingham (1 million people) would have two of them. Every town of 200 000 people would have a 10 MW waste-to-energy plant. Any fears that waste incineration at this scale would be difficult, dirty, or dangerous should be allayed by figure 27.3, which shows that many countries in Europe incinerate *far* more waste per person than the UK; these incineration-loving countries include Germany, Sweden, Denmark, the Netherlands, and Switzerland – not usually nations associated with hygiene problems! One good side-effect of this waste incineration plan is that it eliminates future methane emissions from landfill sites.

In all five plans, hydroelectricity contributes 0.2 kWh/d/p, the same as today.

Electric vehicles are used as a dynamically-adjustable load on the electricity network. The average power required to charge the electric vehicles is 45 GW (18 kWh/d/p). So fluctuations in renewables such as solar and wind can be balanced by turning up and down this load, as long as the fluctuations are not too big or lengthy. Daily swings in electricity demand are going to be bigger than they are today because of the replacement of

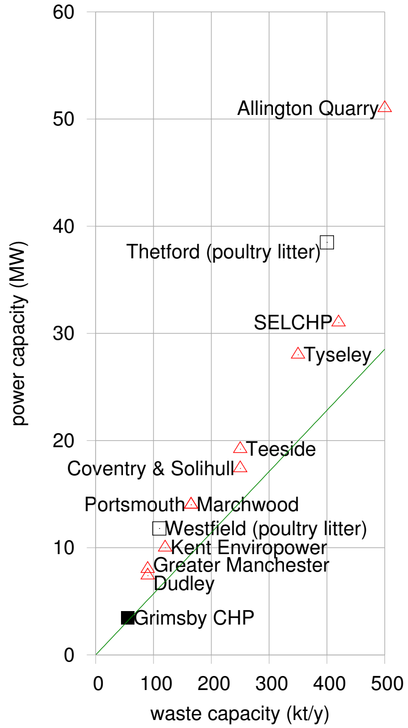


Figure 27.2. Waste-to-energy facilities in Britain. The line shows the average power production assuming 1 kg of waste → 0.5 kWh of electricity.

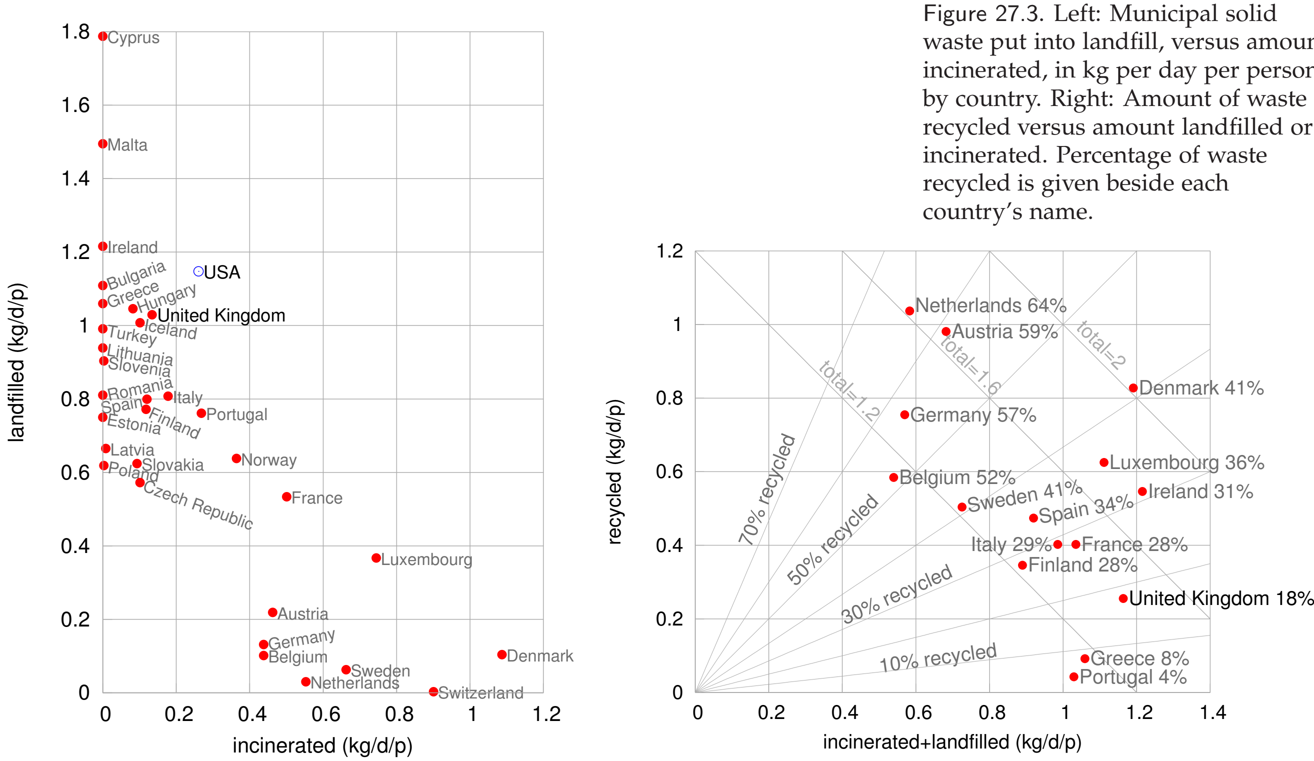


Figure 27.3. Left: Municipal solid waste put into landfill, versus amount incinerated, in kg per day per person, by country. Right: Amount of waste recycled versus amount landfilled or incinerated. Percentage of waste recycled is given beside each country's name.

gas for cooking and heating by electricity (see figure 26.16, p200). To ensure that surges in demand of 10 GW lasting up to 5 hours can be covered, all the plans would build five new pumped storage facilities like Dinorwig (or upgrade hydroelectric facilities to provide pumped storage). 50 GWh of storage is equal to five Dinorwigs, each with a capacity of 2 GW. Some of the plans that follow will require extra pumped storage beyond this. For additional insurance, all the plans would build an electricity interconnector to Norway, with a capacity of 2 GW.

Producing lots of electricity – plan D

Plan D ("D" stands for "domestic diversity") uses a lot of every possible domestic source of electricity, and depends relatively little on energy supply from other countries.

Here's where plan D gets its 50 kWh/d/p of electricity from. Wind: 8 kWh/d/p (20 GW average; 66 GW peak) (plus about 400 GWh of associated pumped storage facilities). Solar PV: 3 kWh/d/p. Waste incineration: 1.3 kWh/d/p. Hydroelectricity: 0.2 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).

To get 8 kWh/d/p of wind requires a 30-fold increase in wind power over the installed power in 2008. Britain would have nearly 3 times as much wind hardware as Germany has now. Installing this much wind-power offshore over a period of 10 years would require roughly 50 jack-up barges.

Getting 3 kWh/d/p from solar photovoltaics requires 6 m^2 of 20%-efficient panels per person. Most south-facing roofs would have to be completely covered with panels; alternatively, it might be more economical, and cause less distress to the League for the Preservation of Old Buildings, to plant many of these panels in the countryside in the traditional Bavarian manner (figure 6.7, p41).

The waste incineration corresponds to 1 kg per day per person of domestic waste (yielding 0.5 kWh/d/p) and a similar amount of agricultural waste yielding 0.6 kWh/d/p; the hydroelectricity is 0.2 kWh/d/p, the same amount as we get from hydro today.

The wave power requires 16 000 Pelamis deep-sea wave devices occupying 830 km of Atlantic coastline (see the map on p73).

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.

To get 16 kWh/d/p of nuclear power requires 40 GW of nukes, which is a roughly four-fold increase of the 2007 nuclear fleet. If we produced 16 kWh/d/p of nuclear power, we'd lie between Belgium, Finland, France and Sweden, in terms of per-capita production: Belgium and Finland each produce roughly 12 kWh/d/p; France and Sweden produce 19 kWh/d/p and 20 kWh/d/p respectively.

To get 16 kWh/d/p of "clean coal" (40 GW), we would have to take the current fleet of coal stations, which deliver about 30 GW, retrofit carbon-capture systems to them, which would reduce their output to 22 GW, then build 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 the total rate at which we currently burn *all* fossil fuels at power stations, and well above the level we estimated as being "sustainable" in Chapter 23. 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.

Do any features of this plan strike you as unreasonable or objectionable? If so, perhaps one of the next four plans is more to your liking.

Figure 27.4. Plan D

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 to: wind: 2 kWh/d/p (5 GW average); solar PV: 0; wave: 0; tide: 1 kWh/d/p.

We've just lost ourselves 14 kWh/d/p (35 GW nationally) by turning down the renewables. (Don't misunderstand! Wind is still eight-fold increased over its 2008 levels.)

In the NIMBY plan, we reduce the contribution of nuclear power to 10 kWh/d/p (25 GW) – a reduction by 15 GW compared to plan D, but still a substantial increase over today's levels. 25 GW of nuclear power could, I think, be squeezed onto the existing nuclear sites, so as to avoid imposing on any new back yards. I left the clean-coal contribution unchanged at 16 kWh/d/p (40 GW). The electricity contributions of hydroelectricity and waste incineration remain the same as in plan D.

Where are we going to get an extra 50 GW from? The NIMBY says, "not in my back yard, but in someone else's." Thus the NIMBY plan pays other countries for imports of solar power from their deserts to the tune of 20 kWh/d/p (50 GW).

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 50 GW of power up to the UK. Today's high voltage electricity connection from France can deliver only 2 GW of power. So this plan requires a 25-fold increase in the capacity of the electricity connection from the continent. (Or an equivalent power-transport solution – perhaps ships filled with methanol or boron plying their way from desert shores.)

Having less wind power, plan N doesn't need to build in Britain the extra pumped-storage facilities mentioned in plan D, but given its dependence on sunshine, it still requires storage systems to be built somewhere to store energy from the fluctuating sun. Molten salt storage systems at the solar power stations are one option. Tapping into pumped storage systems in the Alps might also be possible. Converting the electricity to a storable fuel such as methanol is another option, though conversions entail losses and thus require more solar power stations.

This plan gets 32% + 40% = 72% of the UK's electricity from other countries.

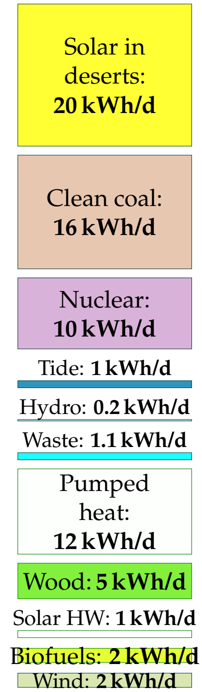


Figure 27.5. Plan N

Producing lots of electricity – plan L

Some people say "we don't want nuclear power!" How can we satisfy them? Perhaps 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 all those renewables in our back yard, and doing a straight swap of nuclear for

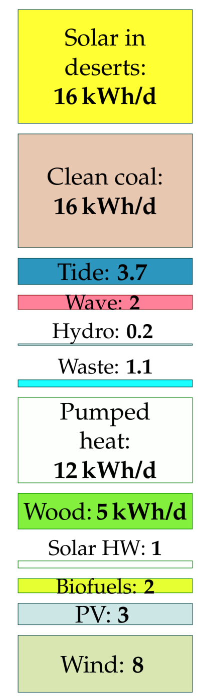


Figure 27.6. Plan L

desert power. As in plan N, the delivery of desert power requires a large increase in transmission systems between North Africa and Britain; the Europe–UK interconnectors would need to be increased from 2 GW to at least 40 GW.

Here's where plan L gets its 50 kWh/d/p of electricity from. Wind: 8 kWh/d/p (20 GW average) (plus about 400 GWh of associated pumped storage facilities). Solar PV: 3 kWh/d/p. Hydroelectricity and 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 average power).

This plan imports 64% of UK electricity from other countries.

I call this "plan L" because it aligns fairly well with the policies of the Liberal Democrats – at least it did when I first wrote this chapter in mid-2007; recently, they've been talking about "real energy independence for the UK," and have announced a zero-carbon policy, under which Britain would be a net energy *exporter*; their policy does not detail how these targets would be met.

Producing lots of electricity – plan G

Some people say "we don't want nuclear power, *and* we don't want coal!" It sounds a desirable goal, but we need a plan to deliver it. I call this "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/p (by pumping money into wave research and increasing the efficiency of the Pelamis converter) and bumping up wind power fourfold (relative to plan D) to 32 kWh/d/p, so that wind delivers 64% of all the electricity. This is a 120-fold increase of British wind power over today's levels. Under this plan, *world* wind power in 2008 is multiplied by 4, with all of the increase being placed on or around the British Isles.

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 400 Dinorwigs can completely replace wind for a national lull lasting 2 days. Roughly 100 of Britain's major lakes and lochs would be required for the associated pumped-storage systems.

Plan G's electricity breaks down as follows. Wind: 32 kWh/d/p (80 GW average) (plus about 4000 GWh of associated pumped-storage facilities). Solar photovoltaics: 3 kWh/d/p. Hydroelectricity and waste incineration:

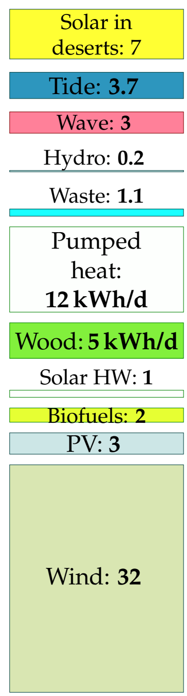


Figure 27.7. Plan G

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).

This plan gets 14% of its electricity from other countries.

Producing lots of electricity – plan E

E stands for "economics." This fifth plan is a rough guess for what might happen in a liberated energy market with a strong carbon price. On a level economic playing field with a strong price signal preventing the emission of CO_2, we don't expect a diverse solution with a wide range of power-costs; rather, we expect 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. (Engineers at a UK electricity generator told me that 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.) I've assumed that solar power in other people's deserts loses to nuclear power when we take into account the cost of the required 2000-km-long transmission lines (though van Voorthuysen (2008) reckons that with Nobel-prize-worthy developments in solar-powered production of chemical fuels, solar power in deserts would be the economic equal of nuclear power). Offshore wind also loses to nuclear, but I've assumed that onshore wind costs about the same as nuclear.

Here's where plan E gets its 50 kWh/d/p of electricity from. Wind: 4 kWh/d/p (10 GW average). Solar PV: 0. Hydroelectricity and waste incineration: 1.3 kWh/d/p. Wave: 0. Tide: 0.7 kWh/d/p. And nuclear: 44 kWh/d/p (110 GW).

This plan has a ten-fold increase in our nuclear power over 2007 levels. Britain would have 110 GW, which is roughly double France's nuclear fleet. I included a little tidal power 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, is not conventionally counted as an import).

Figure 27.9 shows all five plans.

Figure 27.8. Plan E

How these plans relate to carbon-sucking and air travel

In a future world where carbon pollution is priced appropriately to prevent catastrophic climate change, we will be interested in any power scheme that can at low cost put extra carbon down a hole in the ground. Such carbon-neutralization schemes might permit us to continue flying at 2004 levels (while oil lasts). In 2004, average UK emissions of CO_2 from flying were about 0.5 t CO_2 per year per person. Accounting for the full greenhouse impact of flying, perhaps the effective emissions were about 1 t CO_2e per year per person. Now, in all five of these plans I assumed that one

1 t CO_2e means greenhouse-gas emissions equivalent to one ton of CO_2.

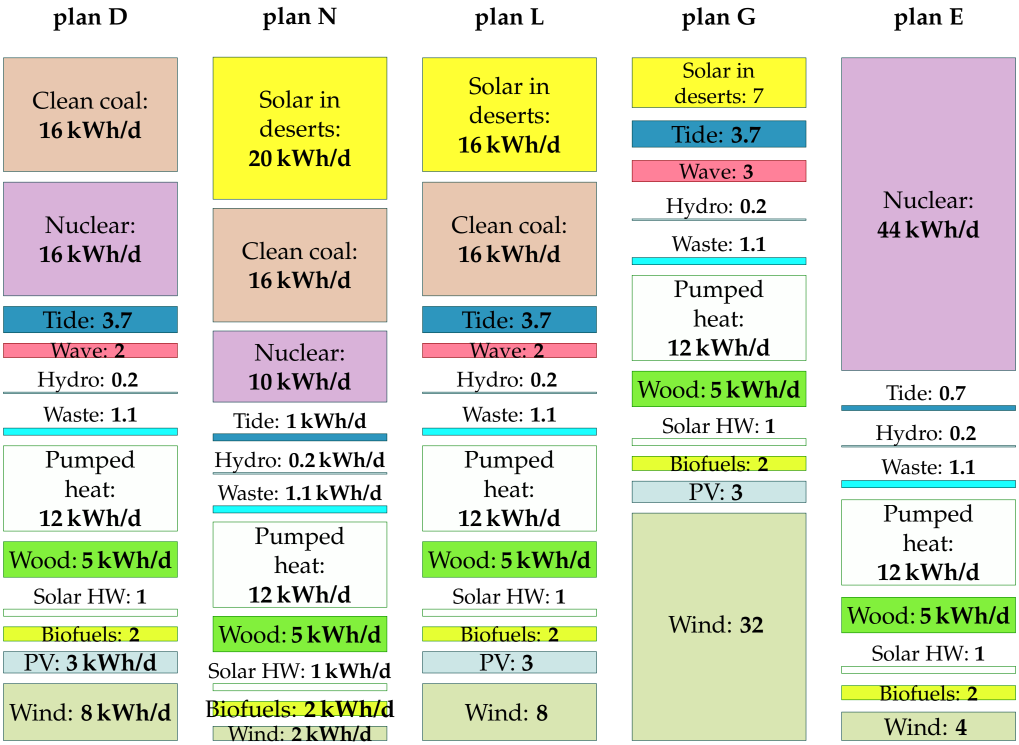


Figure 27.9. All five plans.

eighth 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 stations 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 1 t of CO_2 per year per person. 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 2 t CO_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, if carbon-neutrality is our aim, 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 (p222) when someone suggested he should fly overseas for holidays less frequently!

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.

Notes and further reading

page no.

206 *Incinerating 1 kg of waste yields roughly 0.5 kWh of electricity.* The calorific value of municipal solid waste is about 2.6 kWh per kg; power stations burning waste produce electricity with an efficiency of about 20%. Source: SELCHP tour guide.

207 *Figure 27.3.* Data from Eurostat, `www.epa.gov`, and `www.esrcsocietytoday.ac.uk/ESRCInfoCentre/`.

210 *The policies of the Liberal Democrats*. See `www.libdems.org.uk`: [5os7dy], [yrw2oo].

28 *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, so I call it plan M (figure 28.1).

The areas and rough costs of these facilities are shown in table 28.3. 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. The rough costs given here are the building costs, and don't include running costs or decommissioning costs. The "per person" costs are found by dividing the total cost by 60 million. Please remember, this is not a book about economics – that would require another 400 pages! I'm providing these cost estimates only to give a *rough* indication of the price tag we should expect to see on a plan that adds up.

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 available technologies, so that you can try out your own 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 move them (but where to?). Bear in mind that putting more of them offshore will increase costs. If you'd like fewer wind farms, no problem – just specify which of the other technologies you'd like instead. You can replace five of the 100 km^2 wind farms by adding one more 1 GW nuclear power station, for example.

Perhaps you think that this plan (like each of the 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.

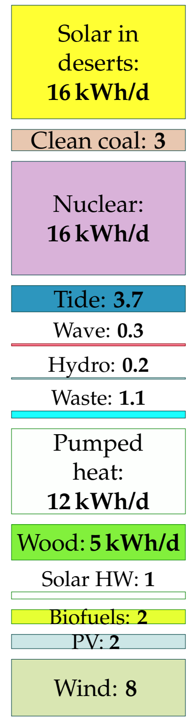


Figure 28.1. Plan M

Cost of switching from fossil fuels to renewables

Every wind farm costs a few million pounds to build and delivers a few megawatts. As a very rough ballpark figure in 2008, installing one watt of capacity costs one pound; one kilowatt costs 1000 pounds; a megawatt of wind costs a million; a gigawatt of nuclear costs a billion or perhaps two. Other renewables are more expensive. We (the UK) currently consume a total power of roughly 300 GW, most of which is fossil fuel. So we can anticipate that a major switching from fossil fuel to renewables and/or nuclear is going to require roughly 300 GW of renewables and/or nuclear and

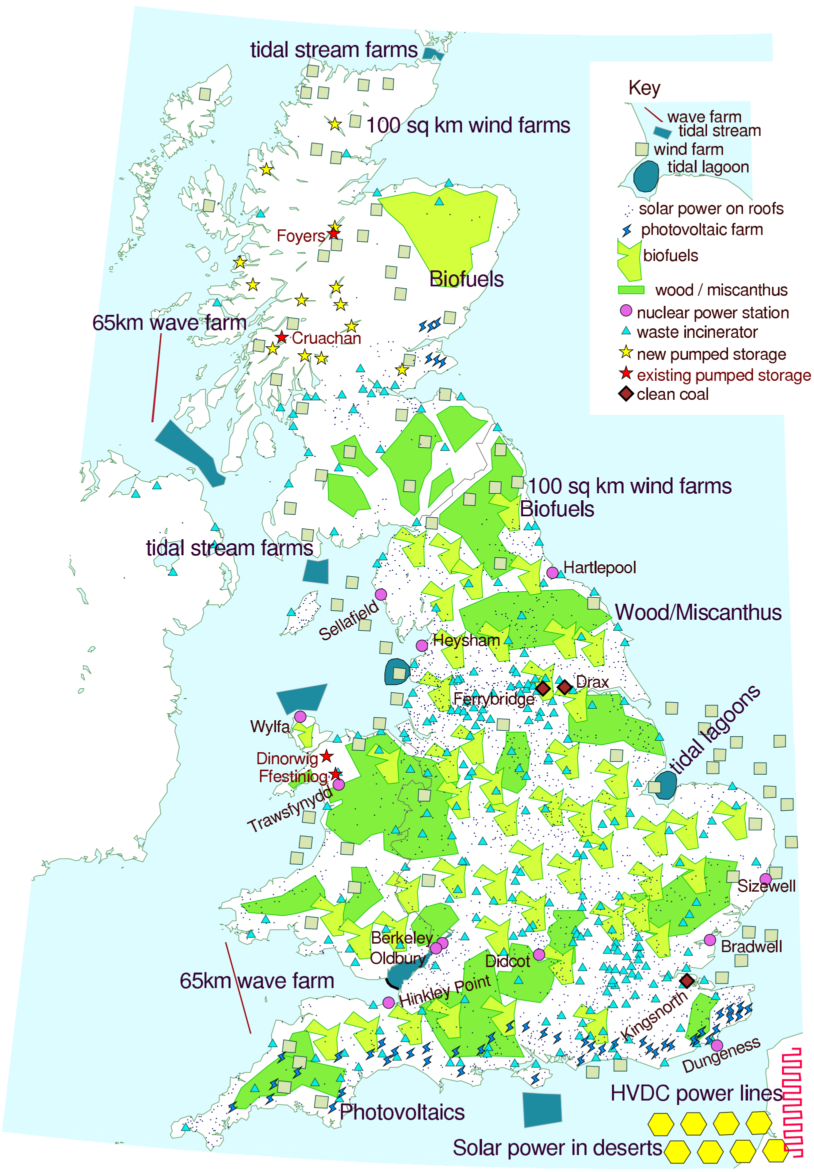


Figure 28.2. A plan that adds up, for Scotland, England, and Wales.
The grey-green squares are wind farms. Each is 100 km^2 in size and is shown to scale.
The red lines in the sea are wave farms, shown to scale.
Light-blue lightning-shaped polygons: solar photovoltaic farms – 20 km^2 each, shown to scale.
Blue sharp-cornered polygons in the sea: tide farms.
Blue blobs in the sea (Blackpool and the Wash): tidal lagoons.
Light-green land areas: woods and short-rotation coppices (to scale).
Yellow-green areas: biofuel (to scale).
Small blue triangles: waste incineration plants (not to scale).
Big brown diamonds: clean coal power stations, with cofiring of biomass, and carbon capture and storage (not to scale).
Purple dots: nuclear power stations (not to scale) – 3.3 GW average production at each of 12 sites.
Yellow hexagons across the channel: concentrating solar power facilities in remote deserts (to scale, 335 km^2 each). The pink wiggly line in France represents new HVDC lines, 2000 km long, conveying 40 GW from remote deserts to the UK.
Yellow stars in Scotland: new pumped storage facilities.
Red stars: existing pumped storage facilities.
Blue dots: solar panels for hot water on all roofs.

	Capacity	Rough cost total	per person	Average power delivered
52 onshore wind farms: 5200 km²	35 GW	£27bn – based on Lewis wind farm	£450	4.2 kWh/d/p
29 offshore wind farms: 2900 km²	29 GW	£36bn – based on Kentish Flats, & including £3bn investment in jack-up barges.	£650	3.5 kWh/d/p
Pumped storage: 15 facilities similar to Dinorwig	30 GW	£15bn	£250	
Photovoltaic farms: 1000 km²	48 GW	£190bn – based on Solarpark in Bavaria	£3200	2 kWh/d/p
Solar hot water panels: 1 m² of roof-mounted panel per person. (60 km² total)	2.5 GW(th) average	£72bn	£1200	1 kWh/d/p
Waste incinerators: 100 new 30 MW incinerators	3 GW	£8.5bn – based on SELCHP	£140	1.1 kWh/d/p
Heat pumps	210 GW(th)	£60bn	£1000	12 kWh/d/p
Wave farms – 2500 Pelamis, 130 km of sea	1.9 GW (0.76 GW average)	£6bn?	£100	0.3 kWh/d/p
Severn barrage: 550 km²	8 GW (2 GW average)	£15bn	£250	0.8 kWh/d/p
Tidal lagoons: 800 km²	1.75 GW average	£2.6bn?	£45	0.7 kWh/d/p
Tidal stream: 15 000 turbines – 2000 km²	18 GW (5.5 GW average)	£21bn?	£350	2.2 kWh/d/p
Nuclear power: 40 stations	45 GW	£60bn – based on Olkiluoto, Finland	£1000	16 kWh/d/p
Clean coal	8 GW	£16bn	£270	3 kWh/d/p
Concentrating solar power in deserts: 2700 km²	40 GW average	£340bn – based on Solúcar	£5700	16 kWh/d/p
Land in Europe for 1600 km of HVDC power lines: 1200 km²	50 GW	£1bn – assuming land costs £7500 per ha	£15	
2000 km of HVDC power lines	50 GW	£1bn – based on German Aerospace Center estimates	£15	
Biofuels: 30 000 km²		(cost not estimated)		2 kWh/d/p
Wood/Miscanthus: 31 000 km²		(cost not estimated)		5 kWh/d/p

Table 28.3. Areas of land and sea required by plan M, and rough costs. Costs with a question mark are for technologies where no accurate cost is yet available from prototypes. "1 GW(th)" denotes one GW of thermal power.

thus have a cost in the ballpark of £300 billion. The rough costs in table 28.3 add up to £870bn, with the solar power facilities dominating the total – the photovoltaics cost £190bn and the concentrating solar stations cost £340bn. Both these costs might well come down dramatically as we learn by doing. A government report leaked by the Guardian in August 2007 estimates that achieving "20% by 2020" (that is, 20% of all energy from renewables, which would require an increase in renewable power of 80 GW) could cost "up to £22 billion" (which would average out to £1.7 billion per year). Even though this estimate is smaller than the £80 billion that the rule of thumb I just mentioned would have suggested, the authors of the leaked report seem to view £22 billion as an "unreasonable" cost, preferring a target of just 9% renewables. (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!)

Other things that cost a billion

Billions are big numbers and hard to get a feel for. To try to help put the cost of kicking fossil fuels into perspective, let's now list some other things that also come in billions of pounds, or in billions per year. I'll also express many of these expenditures "per person," dividing the total by an appropriate population.

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, and the total market value of all energy consumed is £130 billion per year. So the idea of spending £1.7 billion per year on investment in future energy infrastructure seems not 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 £90bn per year on insurance.

Subsidies

£56 billion over 25 years: the cost of decommissioning the UK's nuclear power stations. That's the 2004 figure; in 2008 it was up to £73 billion (£1200 per person in the UK). [6eoyhg]

Transport

£4.3 billion: the cost of London Heathrow Airport's Terminal 5. (£72 per person in the UK.)
£1.9 billion: the cost of widening 91 km of the M1 (from junction 21 to 30, figure 28.4). [yu8em5]. (£32 per person in the UK.)

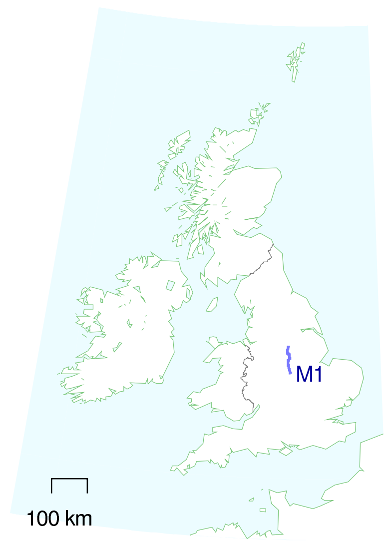


Figure 28.4. The M1, from junction 21 to 30.

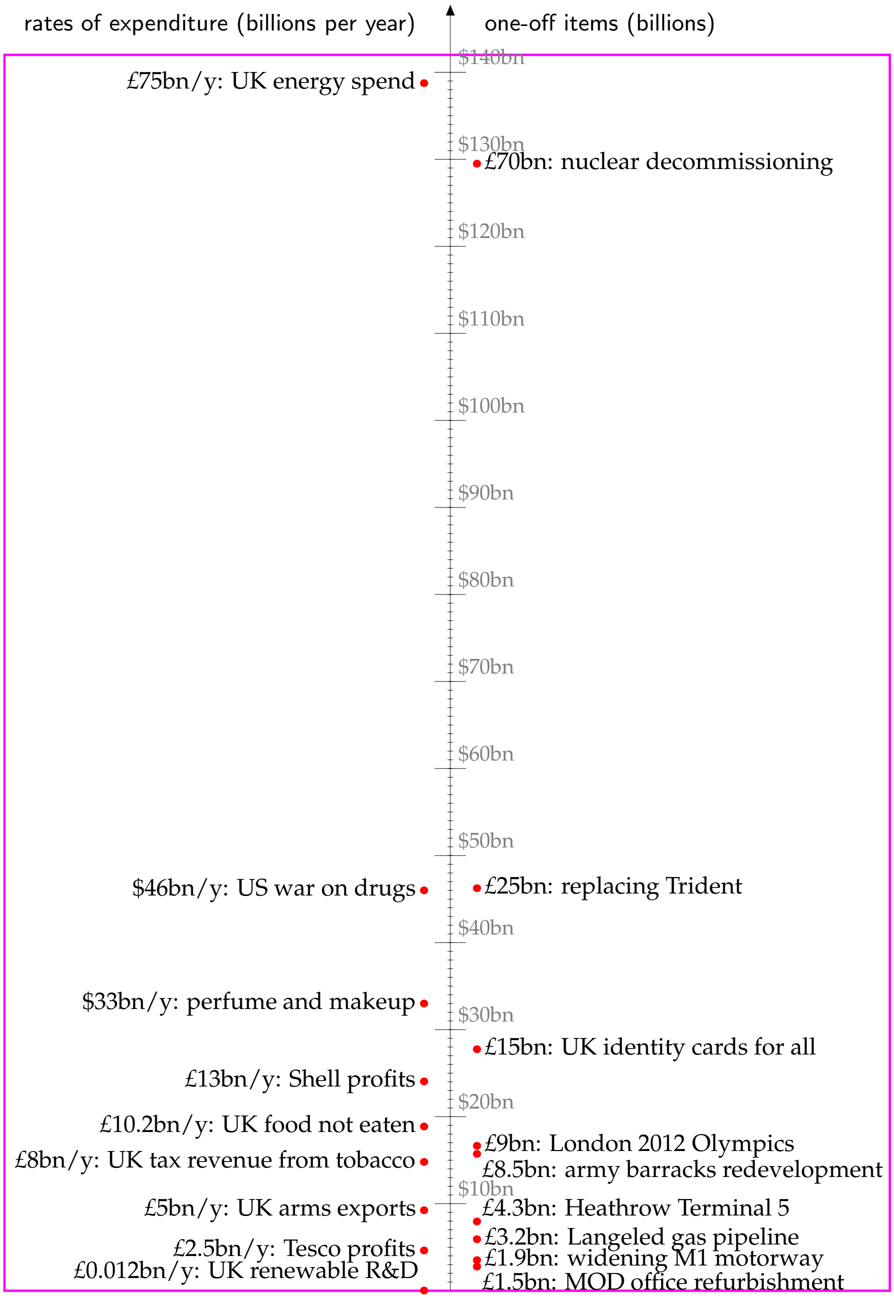


Figure 28.5. Things that run into billions. The scale down the centre has large ticks at $10 billion intervals and small ticks at $1 billion intervals.

Special occasions

Cost of the London 2012 Olympics: £2.4 billion; no, I'm sorry, £5 billion [3x2cr4]; or perhaps £9 billion [2dd4mz]. (£150 per person in the UK.)

Business as usual

£2.5 billion/y: Tesco's profits (announced 2007). (£42 per year per person in the UK.)
£10.2 billion/y: spent by British people on food that they buy but do not eat. (£170 per year per person in the UK.)
£11 billion/y: BP's profits (2006).
£13 billion/y: Royal Dutch Shell's profits (2006).
$40 billion/y. Exxon's profits (2006).
$33 billion/y. World expenditure on perfumes and make-up.
$700 billion per year: USA's expenditure on foreign oil (2008). ($2300 per year per person in the USA.)

Government business as usual

£1.5 billion: the cost of refurbishment of Ministry of Defence offices. (Private Eye No. 1176, 19th January 2007, page 5.) (£25 per person in the UK.)
£15 billion: the cost of introducing UK identity card scheme [7vlxp]. (£250 per person in the UK.)

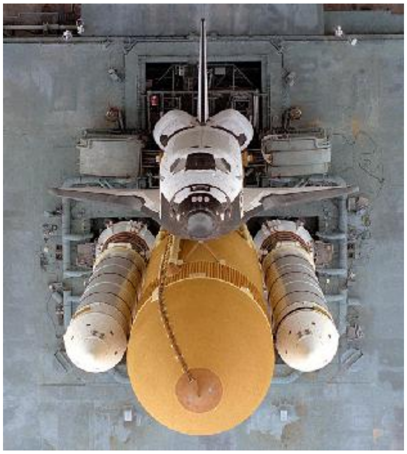
Planning for the future

£3.2 billion: the 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. [6x4nvu] [39g2wz] [3ac8sj]. (£53 per person in the UK.)

Tobacco taxes and related games

£8 billion/y: annual revenue from tobacco taxes in the UK [y7kg26]. (£130 per year per person in the UK.) The European Union spends almost €1 billion a year subsidising tobacco farming. www.ash.org.uk
$46 billion/y: Annual cost of the USA's "War on drugs." [r9fcf] ($150 per year per person in the USA.)

Space



$1.7 billion: the cost of one space shuttle. ($6 per person in the USA.)

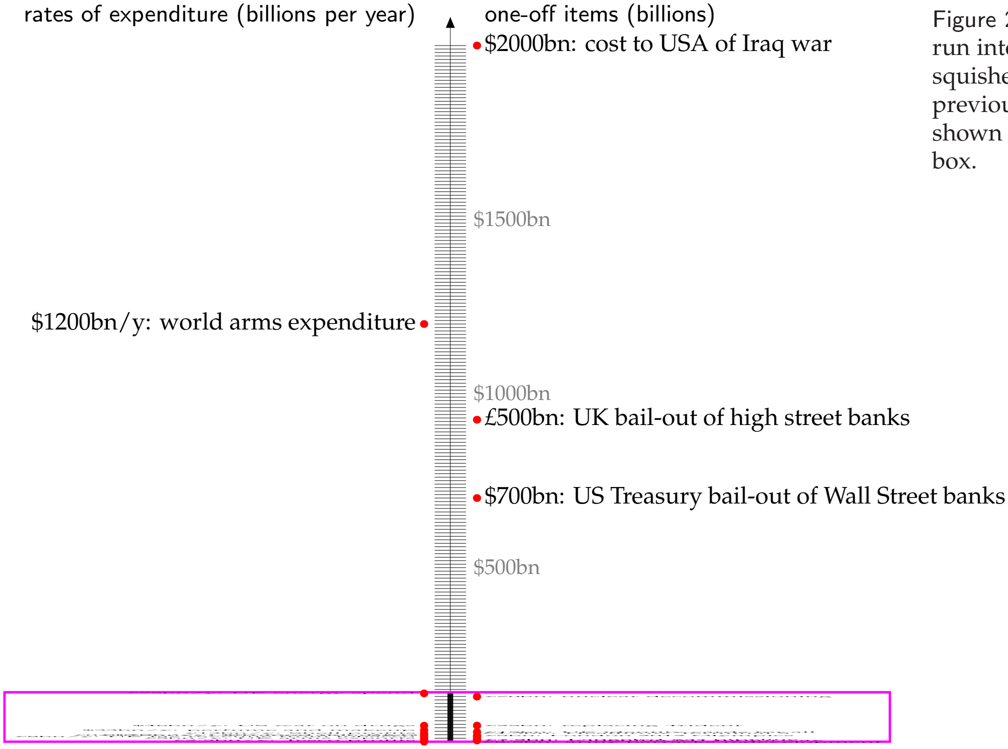


Figure 28.6. A few more things that run into billions. The vertical scale is squished 20-fold compared with the previous figure, figure 28.5, which is shown to scale inside the magenta box.

Banks

$700 billion: in October 2008, the US government committed $700 billion to bailing out Wall Street, and . . .
£500 billion: the UK government committed £500 billion to bailing out British banks.

Military

£5 billion per year: UK's arms exports (£83 per year per person in the UK), of which £2.5 billion go to the Middle East, and £1 billion go to Saudi Arabia. Source: Observer, 3 December 2006.
£8.5 billion: cost of redevelopment of army barracks in Aldershot and Salisbury Plain. (£140 per person in the UK.)
£3.8 billion: the cost of two new aircraft carriers (£63 per person in the UK). `news.bbc.co.uk/1/low/scotland/6914788.stm`
$4.5 billion per year: the cost of not making nuclear weapons – 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. ($15 per year per person in America.)

£10–25 billion: the cost of replacing Trident, the British nuclear weapon system. (£170–420 per person in the UK.) [ysncks].
$63 billion: American donation of "military aid" (i.e. weapons) to the Middle East over 10 years – roughly half to Israel, and half to Arab states. [2vq59t] ($210 per person in the USA.)
$1200 billion per year: world expenditure on arms [ym46a9]. ($200 per year per person in the world.)
$2000 billion or more: the cost, to the USA, of the [99bpt] Iraq war according to Nobel prize-winning economist Joseph Stiglitz. ($7000 per person in America.)

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 15 biggest military-spending countries was $840 billion.

*Expenditure that does **not** run into billions*

£0.012 billion per year: the smallest item displayed in figure 28.5 is the UK government's annual investment in renewable-energy research and development. (£0.20 per person in the UK, per year.)

Notes and further reading

215 *Figure 28.2.* I've assumed that the solar photovoltaic farms have a power per unit area of 5 W/m^2, the same as the Bavaria farm on p41, so each farm on the map delivers 100 MW on average. Their total average production would be 5 GW, which requires roughly 50 GW of peak capacity (that's 16 times Germany's PV capacity in 2006).
The yellow hexagons representing concentrating solar power have an average power of 5 GW each; it takes two of these hexagons to power one of the "blobs" of Chapter 25.

217 *A government report leaked by the Guardian...* The Guardian report, 13th August 2007, said [2bmuod] "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 [3g8nn8].

219 *...perfume...* Source: Worldwatch Institute
www.worldwatch.org/press/news/2004/01/07/

221 *...wars and preparation for wars ...* www.conscienceonline.org.uk

– *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 Science and Technology Committee, 4th Report of Session 2003–04. [3jo7q2]
Comparably small is the government's allocation to the Low Carbon Buildings Programme, £0.018bn/y shared between wind, biomass, solar hot water/PV, ground-source heat pumps, micro-hydro and micro CHP.

29 What to do now

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, 30 October 2006

a bit impractical actually…

Tony Blair, two months later, responding to the suggestion that he should *show* leadership by not flying to Barbados for holidays.

What we should do depends in part on our motivation. Recall that on page 5 we discussed three motivations for getting off fossil fuels: the end of cheap fossil fuels; security of supply; and climate change. Let's assume first that we have the climate-change motivation – that we want to reduce carbon emissions radically. (Anyone who doesn't believe in climate change can skip this section and rejoin the rest of us on page 223.)

What to do about carbon pollution

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 probably be necessary to avoid dangerous climate change. Carbon is not even being captured at any coal power stations (except for one tiny prototype in Germany).

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 emitting carbon dioxide should be big enough such that every running coal power station has carbon capture technology fitted to it.

Solving climate change is a complex topic, but in a single crude brush-stroke, here 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. The first step towards this goal is for government to finance a large-scale demonstration project to sort out the technology for carbon capture and storage; second, politicians need to change the long-term regulations for power stations so that the perfected technology is adopted everywhere. My simple-minded suggestion for this second step is to pass a law that says that – from some date – *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 we achieve our simple goal – all coal power stations to have carbon capture? Well, we can faff around with carbon trading – trading of permits to emit carbon and of certificates of carbon-capture, with one-tonne carbon-capture certificates being convertible into one-tonne carbon-emission permits. But coal station owners will invest in carbon capture and storage only if they are convinced that the price of carbon is going to be high enough for long enough that carbon-capturing facilities will pay for themselves. Experts 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 agree long-term reductions in CO_2 emissions that are sufficiently strong that investors have confidence that the price of carbon will rise permanently to at least \$100 per ton of CO_2. Alternatively they could 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 in carbon-emission permits.

I still wonder whether it would be wisest to close the stable door directly, rather than fiddling with an international market that is merely *intended* to encourage stable door-closing.

Figure 29.1. 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`.

> *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, 4 June 2007.

What to do about energy supply

Let's now expand our set of motivations, and assume that we want to get off fossil fuels in order to ensure security of energy supply.

What should we do to bring about the development of non-fossil energy supply, and of efficiency measures? One attitude is "Just let the market handle it. As fossil fuels become expensive, renewables and nuclear power will become relatively cheaper, and the rational consumer will prefer efficient technologies." I find it odd that people have such faith in markets, given how regularly markets give us things like booms and busts, credit crunches, and collapses of banks. Markets may be a good

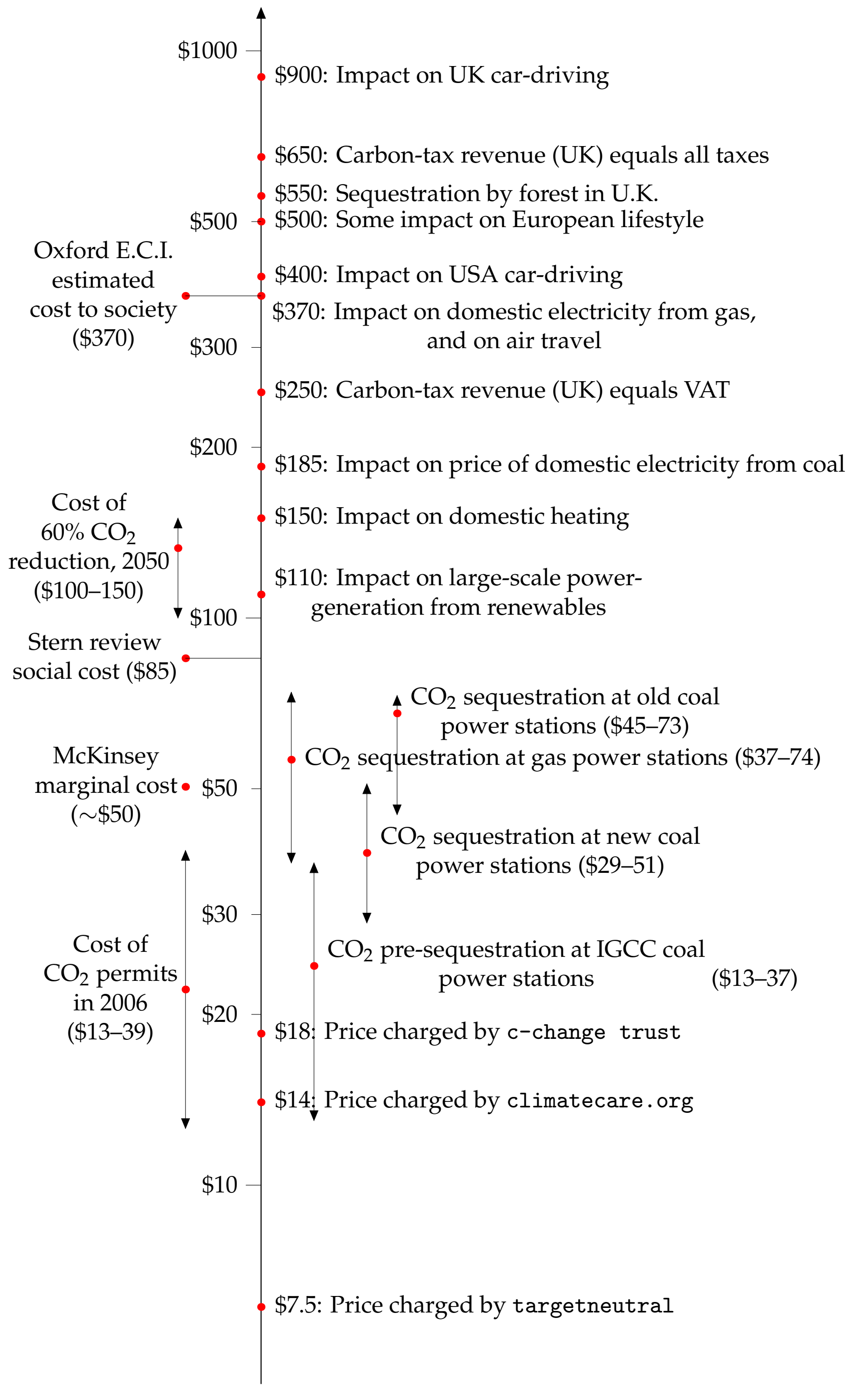


Figure 29.2. What price would CO_2 need to have in order to drive society to make significant changes in CO_2 pollution?
The diagram shows carbon dioxide costs (per tonne) at which particular investments will become economical, or particular behaviours will be significantly impacted, assuming that a major behavioural impact on activities like flying and driving results if the carbon cost doubles the cost of the activity.
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 6p per kWh, which is 3.3p above a typical selling price of 2.7p per kWh; if each 1000 kWh from the barrage 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.
A price of \$250 per tonne would increase the effective cost of a barrel of oil by \$100.
At \$370, carbon pollution would cost enough to significantly 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.

way of making some short-term decisions – about investments that will pay off within ten years or so – but can we expect markets to do a good job of making decisions about energy, decisions whose impacts last many decades or centuries?

If the free market is allowed to build houses, we end up with houses that are poorly insulated. Modern houses are only more energy-efficient thanks to legislation.

The free market isn't responsible for building roads, railways, 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. 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 feel that they have no choice but to drive to work.

One of the biggest energy-sinks is the manufacture of stuff; in a free market, many manufacturers supply us with stuff that has planned obsolescence, stuff that has to be thrown away and replaced, so as to make more business for the manufacturers.

So, while markets may play a role, it's silly to say "let the market handle it *all*." Surely we need to talk about legislation, regulations, and taxes.

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, President of France

At present it's much cheaper to buy a new microwave, DVD player, or vacuum cleaner than to get a malfunctioning one fixed. That's crazy.

This craziness is partly caused by our tax system, which taxes the labour of the microwave-repair man, and surrounds his business with time-consuming paperwork. He's doing a *good* thing, repairing my microwave! – yet the tax system makes it difficult for him to do business.

The idea of "greening the tax system" is to move taxes from "goods" like labour, to "bads" like environmental damage. Advocates of environmental tax reform suggest balancing tax cuts on "goods" by equivalent tax increases on "bads," so that the tax reforms are revenue-neutral.

Carbon tax

The most important tax to increase, if we want to promote fossil-fuel-free technologies, is a tax on carbon. The price of carbon needs to be high enough to promote investment in alternatives to fossil fuels, and investment in efficiency measures. Notice this is exactly the same policy as was suggested in the previous section. So, whether our motivation is fixing climate change, or ensuring security of supply, the policy outcome is the same: we need a carbon price that is stable and high. Figure 29.2 indicates very roughly the various carbon prices that are required to bring about various behaviour changes and investments; and the much lower prices charged by organizations that claim to "offset" greenhouse-gas emissions. How best to arrange a high carbon price? Is the European emissions trading scheme (figure 29.1) the way to go? This question lies in the domain of economists and international policy experts. The view of Cambridge economists Michael Grubb and David Newbery is that the European emissions trading scheme is not up to the job – "current instruments will not deliver an adequate investment response."

The Economist recommends a carbon tax as the primary mechanism for government support of clean energy sources. The Conservative Party's Quality of Life Policy Group also recommends increasing environmental taxes and reducing other taxes – "a shift from *pay as you earn* to *pay as you burn*." The Royal Commission on Environmental Pollution also says that the UK should introduce a carbon tax. "It should apply upstream and cover all sectors."

So, there's clear support for a big carbon tax, accompanied by reductions in employment taxes, corporation taxes, and value-added taxes. But taxes and markets alone are not going to bring about all the actions needed. The tax-and-market approach fails if consumers sometimes choose irrationally, if consumers value short-term cash more highly than long-term savings, or if the person choosing what to buy doesn't pay all the costs associated with their choice.

Indeed many brands are "*reassuringly expensive*." Consumer choice is not determined solely by price signals. Many consumers care more about image and perception, and some deliberately buy expensive.

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.

Here are some further examples of failures of the free market.

The admission barrier

Imagine that carbon taxes are sufficiently high 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 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)?

The problem of small cost differences

Imagine that Eco-Gizmo Inc. makes it from tadpole to frog, and that carbon taxes are sufficiently high that an Eco-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 difference. Image is everything. 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 Eco-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%.

How to fix this problem? Perhaps government should simply ban the sales of the Dino-gizmo (just as it banned sales of leaded-petrol cars)?

The problem of 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 easily 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 would thus be happy to pay the higher rent; 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.

So 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 appliances; ban from sale all fridges that do not meet economy benchmarks; require all flats to meet high standards of insulation; or introduce a system of mandatory independent flat assessment, so that Tina could read about the flat's energy profile before renting.

Investment in research and development

> *We deplore the minimal amounts that the Government have committed to renewable-energy-related research and development (£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.*
>
> House of Lords Science and Technology Committee

> *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

> *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

I think the numbers speak for themselves. Just look at figure 28.5 (p218) and compare the billions spent on office refurbishments and military toys with the hundred-fold smaller commitment to renewable-energy-related research and development. It takes decades to develop renewable technologies such as tidal stream power, concentrating solar power, and photovoltaics. Nuclear fusion takes decades too. All these technologies need up-front support if they are going to succeed.

Individual action

People sometimes ask me "What should *I* do?" Table 29.3 indicates eight simple personal actions I'd recommend, and a *very* rough indication of the savings associated with each action. Terms and conditions apply. Your savings will depend on your starting point. The numbers in table 29.3 assume the starting point of an above-average consumer.

Simple action	possible saving
Put on a woolly 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 more slowly, drive more gently, carpool, 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

Table 29.3. Eight simple personal actions.

Whereas the above actions are easy to implement, the ones in table 29.4 take a bit more 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

Table 29.4. Seven harder actions.

Finally, table 29.5 shows a few runners-up: some simple actions with small savings.

Action	possible saving
Wash laundry in cold water.	0.5 kWh/d
Stop using a tumble-dryer; use a clothes-line or airing cupboard.	0.5 kWh/d

Table 29.5. A few more simple actions with small savings.

Notes and further reading

page no.

222 *"a bit impractical actually"* The full transcript of the interview with Tony Blair (9 January 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.

225 *Environmental tax reform.* See the Green Fiscal Commission, www.greenfiscalcommission.org.uk.

226 The Economist *recommends a carbon tax.* "Nuclear power's new age," *The Economist*, September 8th 2007.

– *The Conservative Party's Quality of Life Policy Group* – Gummer et al. (2007).

30 Energy plans for Europe, America, and the World

Figure 30.1 shows the power consumptions of lots of countries or regions, versus their gross domestic products (GDPs). It is a widely held assumption that human development and growth are good things, so when sketching world plans for sustainable energy I am going to assume that all the countries with low GDP per capita are going to progress rightwards in figure 30.1. And as their GDPs increase, it's inevitable that their power consumptions will increase too. It's not clear what consumption we should plan for, but I think that the average European level (125 kWh per day per person) seems a reasonable assumption; alternatively, we could assume that efficiency measures, like those envisaged in Cartoon Britain in Chapters 19–28, allow all countries to attain a European standard of living with a lower power consumption. In the consumption plan on p204, Cartoon Britain's consumption fell to about 68 kWh/d/p. Bearing in mind that Cartoon Britain doesn't have much industrial activity, perhaps it would be sensible to assume a slightly higher target, such as Hong Kong's 80 kWh/d/p.

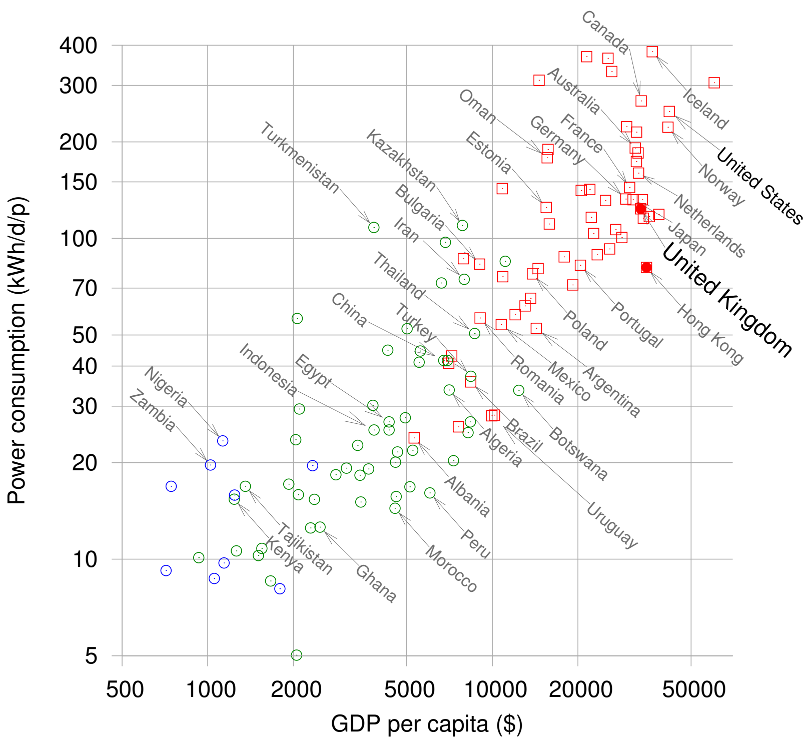


Figure 30.1. Power consumption per capita versus GDP per capita, in purchasing-power-parity US dollars. Data from UNDP Human Development Report, 2007. Squares show countries having "high human development;" circles, "medium" or "low." Both variables are on logarithmic scales. Figure 18.4 shows the same data on normal scales.

Redoing the calculations for Europe

Can Europe live on renewables?

Europe's average population density is roughly half of Britain's, so there is more land area in which to put enormous renewable facilities. The area of the European Union is roughly 9000 m^2 per person. However, many of the renewables have lower power density in Europe than in Britain: most of Europe has less wind, less wave, and less tide. Some parts do have more hydro (in Scandanavia and Central Europe); and some have more solar. Let's work out some rough numbers.

Wind

The heart of continental Europe has lower typical windspeeds than the British Isles – in much of Italy, for example, windspeeds are below 4 m/s. Let's guess that one fifth of Europe has big enough wind-speeds for economical wind-farms, having a power density of 2 W/m^2, and then assume that we give those regions the same treatment we gave Britain in Chapter 4, filling 10% of them with wind farms. The area of the European Union is roughly 9000 m^2 per person. So wind gives

$$\frac{1}{5} \times 10\% \times 9000\,\mathrm{m}^2 \times 2\,\mathrm{W/m}^2 = 360\,\mathrm{W}$$

which is 9 kWh/d per person.

Hydroelectricity

Hydroelectric production in Europe totals 590 TWh/y, or 67 GW; shared between 500 million, that's 3.2 kWh/d per person. This production is dominated by Norway, France, Sweden, Italy, Austria, and Switzerland. If every country doubled its hydroelectric facilities – which I think would be difficult – then hydro would give 6.4 kWh/d per person.

Wave

Taking the whole Atlantic coastline (about 4000 km) and multiplying by an assumed average production rate of 10 kW/m, we get 2 kWh/d per person. The Baltic and Mediterranean coastlines have no wave resource worth talking of.

Tide

Doubling the estimated total resource around the British Isles (11 kWh/d per person, from Chapter 14) to allow for French, Irish and Norwegian tidal resources, then sharing between a population of 500 million, we get

2.6 kWh/d per person. The Baltic and Mediterranean coastlines have no tidal resource worth talking of.

Figure 30.2. 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.

Solar photovoltaics and thermal panels on roofs

Most places are sunnier than the UK, so solar panels would deliver more power in continental Europe. 10 m^2 of roof-mounted photovoltaic panels would deliver about 7 kWh/d in all places south of the UK. Similarly, 2 m^2 of water-heating panels could deliver on average 3.6 kWh/d of low-grade thermal heat. (I don't see much point in suggesting having more than 2 m^2 per person of water-heating panels, since this capacity would already be enough to saturate typical demand for hot water.)

What else?

The total so far is $9 + 6.4 + 2 + 2.6 + 7 + 3.6 = 30.6$ kWh/d per person. The only resources not mentioned so far are geothermal power, and large-scale solar farming (with mirrors, panels, or biomass).

Geothermal power might work, but it's still in the research stages. I suggest treating it like fusion power: a good investment, but not to be relied on.

So what about solar farming? We could imagine using 5% of Europe (450 m^2 per person) for solar photovoltaic farms like the Bavarian one in figure 6.7 (which has a power density of 5 W/m^2). This would deliver an average power of

$$5\,\mathrm{W/m^2} \times 450\,\mathrm{m^2} = 54\,\mathrm{kWh/d\ per\ person}.$$

Solar PV farming would, therefore, add up to something substantial. The main problem with photovoltaic panels is their cost. Getting power during the winter is also a concern!

Energy crops? Plants capture only 0.5 W/m^2 (figure 6.11). Given that Europe needs to feed itself, the non-food energy contribution from plants in Europe can never be enormous. Yes, there will be some oil-seed rape here and some forestry there, but I don't imagine that the total non-food contribution of plants could be more than 12 kWh/d per person.

The bottom line

Let's be realistic. Just like Britain, *Europe can't live on its own renewables*. So if the aim is to get off fossil fuels, Europe needs nuclear power, or solar power in other people's deserts (as discussed on p179), or both.

Redoing the calculations for North America

The average American uses 250 kWh/d per day. Can we hit that target with renewables? What if we imagine imposing shocking efficiency measures (such as efficient cars and high-speed electric trains) such that Americans were reduced to the misery of living on the mere 125 kWh/d of an average European or Japanese citizen?

Wind

A study by Elliott et al. (1991) assessed the wind energy potential of the USA. The windiest spots are in North Dakota, Wyoming, and Montana. They reckoned that, over the whole country, 435 000 km^2 of windy land could be exploited without raising too many hackles, and that the electricity generated would be 4600 TWh per year, which is 42 kWh per day per person if shared between 300 million people. Their calculations assumed an average power density of 1.2 W/m^2, incidentally – smaller than the 2 W/m^2 we assumed in Chapter 4. The area of these wind farms, 435 000 km^2, is roughly the same as the area of California. The amount of wind hardware required (assuming a load factor of 20%) would be a capacity of about 2600 GW, which would be a 200-fold increase in wind hardware in the USA.

Offshore wind

If we assume that shallow offshore waters with an area equal to the sum of Delaware and Connecticut (20 000 km^2, a substantial chunk of all shallow waters on the east coast of the USA) are filled with offshore wind farms having a power density of 3 W/m^2, we obtain an average power of 60 GW. That's 4.8 kWh/d per person if shared between 300 million people. The wind hardware required would be 15 times the total wind hardware currently in the USA.

Geothermal

I mentioned the MIT geothermal energy study (Massachusetts Institute of Technology, 2006) in Chapter 16. The authors are upbeat about the potential of geothermal energy in North America, especially in the western states where there is more hotter rock. "With a reasonable investment in R&D, enhanced geothermal systems could provide 100 GW(e) or more of cost-competitive generating capacity in the next 50 years. Further, enhanced geothermal systems provide a secure source of power for the long term." Let's assume they are right. 100 GW of electricity is 8 kWh/d per person when shared between 300 million.

Hydro

The hydroelectric facilities of Canada, the USA, and Mexico generate about 660 TWh per year. Shared between 500 million people, that amounts to 3.6 kWh/d per person. Could the hydroelectric output of North America be doubled? If so, hydro would provide 7.2 kWh/d per person.

What else?

The total so far is $42 + 4.8 + 8 + 7.2 = 62$ kWh/d per person. Not enough for even a European existence! I could discuss various other options such as the sustainable burning of Canadian forests in power stations. But rather than prolong the agony, let's go immediately for a technology that adds up: concentrating solar power.

Figure 30.3 shows the area within North America that would provide everyone there (500 million people) with an average power of 250 kWh/d.

The bottom line

North America's *non-solar* renewables aren't enough for North America to live on. But when we include a massive expansion of solar power, there's enough. So North America needs solar in its own deserts, or nuclear power, or both.

Redoing the calculations for the world

How can 6 billion people obtain the power for a European standard of living – 80 kWh per day per person, say?

Wind

The exceptional spots in the world with strong steady winds are the central states of the USA (Kansas, Oklahoma); Saskatchewan, Canada; the southern extremities of Argentina and Chile; northeast Australia; northeast and northwest China; northwest Sudan; southwest South Africa; Somalia; Iran; and Afghanistan. And everywhere offshore except for a tropical strip 60 degrees wide centred on the equator.

For our global estimate, let's go with the numbers from Greenpeace and the European Wind Energy Association: "the total available wind resources worldwide are estimated at 53 000 TWh per year." That's 24 kWh/d per person.

Hydro

Worldwide, hydroelectricity currently contributes about 1.4 kWh/d per person.

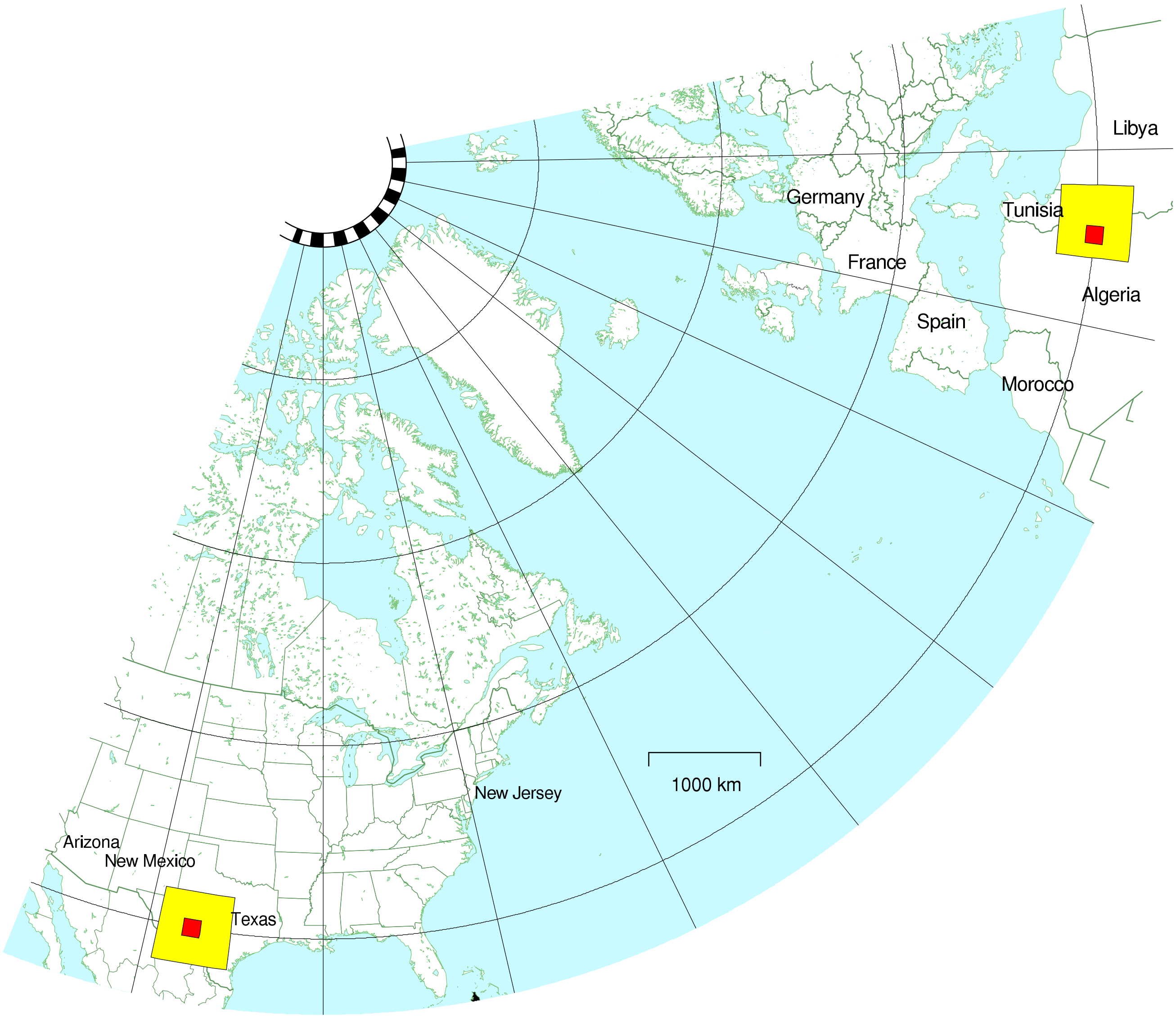


Figure 30.3. The little square strikes again. The 600 km by 600 km square in North America, completely filled with concentrating solar power, would provide enough power to give 500 million people the average American's consumption of 250 kWh/d.

This map also shows the square of size 600 km by 600 km in Africa, which we met earlier. I've assumed a power density of 15 W/m^2, as before.

The area of one yellow square is a little bigger than the area of Arizona, and 16 times the area of New Jersey. Within each big square is a smaller 145 km by 145 km square showing the area required in the desert – one New Jersey – to supply 30 million people with 250 kWh per day per person.

From the website `www.ieahydro.org`, "The International Hydropower Association and the International Energy Agency estimate the world's total technical feasible hydro potential at 14 000 TWh/year [6.4 kWh/d per person on the globe], of which about 8000 TWh/year [3.6 kWh/d per person] is currently considered economically feasible for development. Most of the potential for development is in Africa, Asia and Latin America."

Tide

There are several places in the world with tidal resources on the same scale as the Severn estuary (figure 14.8). In Argentina there are two sites: San José and Golfo Nuevo; Australia has the Walcott Inlet; the USA & Canada share the Bay of Fundy; Canada has Cobequid; India has the Gulf of Khambat; the USA has Turnagain Arm and Knik Arm; and Russia has Tugur.

And then there is the world's tidal whopper, a place called Penzhinsk in Russia with a resource of 22 GW – ten times as big as the Severn!

Kowalik (2004) estimates that worldwide, 40–80 GW of tidal power could be generated. Shared between 6 billion people, that comes to 0.16–0.32 kWh/d per person.

Wave

We can estimate the total extractable power from waves by multiplying the length of exposed coastlines (roughly 300 000 km) by the typical power per unit length of coastline (10 kW per metre): the raw power is thus about 3000 GW.

Assuming 10% of this raw power is intercepted by systems that are 50%-efficient at converting power to electricity, wave power could deliver 0.5 kWh/d per person.

Geothermal

According to D. H. Freeston of the Auckland Geothermal Institute, geothermal power amounted on average to about 4 GW, worldwide, in 1995 – which is 0.01 kWh/d per person.

If we assume that the MIT authors on p234 were right, and if we assume that the whole world is like America, then geothermal power offers 8 kWh/d per person.

Solar for energy crops

People get all excited about energy crops like jatropha, which, it's claimed, wouldn't need to compete with food for land, because it can be grown on wastelands. People need to look at the numbers before they get excited.

The numbers for jatropha are on p284. Even if *all* of Africa were completely covered with jatropha plantations, the power produced, shared between six billion people, would be 8 kWh/d per person (which is only one third of today's global oil consumption). You can't fix your oil addiction by switching to jatropha!

Let's estimate a bound on the power that energy crops could deliver for the whole world, using the same method we applied to Britain in Chapter 6: imagine taking all arable land and devoting it to energy crops. 18% of the world's land is currently arable or crop land – an area of 27 million km^2. That's 4500 m^2 per person, if shared between 6 billion. Assuming a power density of 0.5 W/m^2, and losses of 33% in processing and farming, we find that energy crops, fully taking over all agricultural land, would deliver 36 kWh/d per person. Now, maybe this is an underestimate since in figure 6.11 (p43) we saw that Brazilian sugarcane can deliver a power density of 1.6 W/m^2, three times bigger than I just assumed. OK, maybe energy crops from Brazil have some sort of future. But I'd like to move on to the last option.

Solar heaters, solar photovoltaics, and concentrating solar power

Solar thermal water heaters are a no-brainer. They will work almost everywhere in the world. China are world leaders in this technology. There's over 100 GW of solar water heating capacity worldwide, and more than half of it is in China.

Solar photovoltaics were technically feasible for Europe, but I judged them too expensive. I hope I'm wrong, obviously. It will be wonderful if the cost of photovoltaic power drops in the same way that the cost of computer power has dropped over the last forty years.

My guess is that in many regions, the best solar technology for electricity production will be the concentrating solar power that we discussed on pages 178 and 236. On those pages we already established that one billion people in Europe and North Africa could be sustained by country-sized solar power facilities in deserts near the Mediterranean; and that half a billion in North America could be sustained by Arizona-sized facilities in the deserts of the USA and Mexico. I'll leave it as an exercise for the reader to identify appropriate deserts to help out the other 4.5 billion people in the world.

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 2403	55%
Sydney 2446	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%
Upington, SA	91%
Yuma, AZ	93%
Sahara Desert	98%

Table 30.4. World sunniness figures. [3doaeg]

The bottom line

The non-solar numbers add up as follows. Wind: 24 kWh/d/p; hydro: 3.6 kWh/d/p; tide: 0.3 kWh/d/p; wave: 0.5 kWh/d/p; geothermal: 8 kWh/d/p – a total of 36 kWh/d/p. Our target was a post-European consumption of 80 kWh/d per person. We have a clear conclusion: the non-solar renewables may be "huge," but they are not huge enough. To complete a plan that adds up, we must rely on one or more forms of solar power. Or use nuclear power. Or both.

Notes and further reading

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234 *North American offshore wind resources.* www.ocean.udel.edu/windpower/ResourceMap/index-wn-dp.html

235 *North America needs solar in its own deserts, or nuclear power, or both.* To read Google's 2008 plan for a 40% defossilization of the USA, see Jeffery Greenblatt's article *Clean Energy 2030* [31cw9c]. The main features of this plan are efficiency measures, electrification of transport, and electricity production from renewables. Their electricity production plan includes

10.6 kWh/d/p	of wind power,
2.7 kWh/d/p	of solar photovoltaic,
1.9 kWh/d/p	of concentrating solar power,
1.7 kWh/d/p	of biomass,
and 5.8 kWh/d/p	of geothermal power

by 2030. That's a total of 23 kWh/d/p of new renewables. They also assume a small increase in nuclear power from 7.2 kWh/d/p to 8.3 kWh/d/p, and no change in hydroelectricity. Natural gas would continue to be used, contributing 4 kWh/d/p.

237 *The world's total hydro potential…* Source: www.ieahydro.org/faq.htm.

– *Global coastal wave power resource is estimated to be 3000 GW.* See Quayle and Changery (1981).

– *Geothermal power in 1995.* Freeston (1996).

238 *Energy crops.* See Rogner (2000) for estimates similar to mine.

Further reading: *Nature* magazine has an 8-page article discussing how to power the world (Schiermeier et al., 2008).

31 The last thing we should talk about

Capturing carbon dioxide from thin air is the last thing we should talk about.

When I say this, I am deliberately expressing a double meaning. First, the energy requirements for carbon capture from thin air are so enormous, it seems almost absurd to talk about it (and there's the worry that raising the possibility of fixing climate change by this sort of geoengineering might promote inaction today). But second, I do think we should talk about it, contemplate how best to do it, and fund research into how to do it better, because capturing carbon from thin air may turn out to be our last line of defense, if climate change is as bad as the climate scientists say, and if humanity fails to take the cheaper and more sensible options that may still be available today.

Before we discuss capturing carbon from thin air, we need to understand the global carbon picture better.

Understanding CO_2

When I first planned this book, my intention was to ignore climate change altogether. In some circles, "Is climate change happening?" was a controversial question. As were "Is it caused by humans?" and "Does it matter?" And, dangling at the end of a chain of controversies, "What should we do about it?" I felt that sustainable energy was a compelling issue by itself, and it was best to avoid controversy. My argument was to be: "Never mind when fossil fuels are going to run out; never mind whether climate change is happening; *burning fossil fuels is not sustainable anyway*; let's imagine living sustainably, and figure out how much sustainable energy is available."

However, climate change has risen into public consciousness, and it raises all sorts of interesting back-of-envelope questions. So I decided to discuss it a little in the preface and in this closing chapter. Not a complete discussion, just a few interesting numbers.

Units

Carbon pollution charges are usually measured in dollars or euros per ton of CO_2, so I'll use the *ton of CO_2* as the main unit when talking about per-capita carbon pollution, and the *ton of CO_2 per year* to measure rates of pollution. (The average European's greenhouse emissions are equivalent to 11 tons per year of CO_2; or 30 kg per day of CO_2.) But when talking about carbon in fossil fuels, vegetation, soil, and water, I'll talk about tons of carbon. One ton of CO_2 contains 12/44 tons of carbon, a bit more than a quarter of a ton. On a planetary scale, I'll talk about gigatons of carbon (Gt C). A gigaton of carbon is a billion tons. Gigatons are hard to imagine, but if you want to bring it down to a human scale, imagine burning one

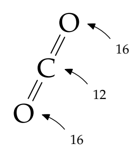

Figure 31.1. The weights of an atom of carbon and a molecule of CO_2 are in the ratio 12 to 44, because the carbon atom weighs 12 units and the two oxygen atoms weigh 16 each. $12 + 16 + 16 = 44$.

ton of coal (which is what you might use to heat a house over a year). Now imagine everyone on the planet burning one ton of coal per year: that's 6 Gt C per year, because the planet has 6 billion people.

Where is the carbon?

Where is all the carbon? We need to know how much is in the oceans, in the ground, and in vegetation, compared to the atmosphere, if we want to understand the consequences of CO_2 emissions.

Figure 31.2 shows where the carbon is. Most of it – 40 000 Gt – is in the ocean (in the form of dissolved CO_2 gas, carbonates, living plant and

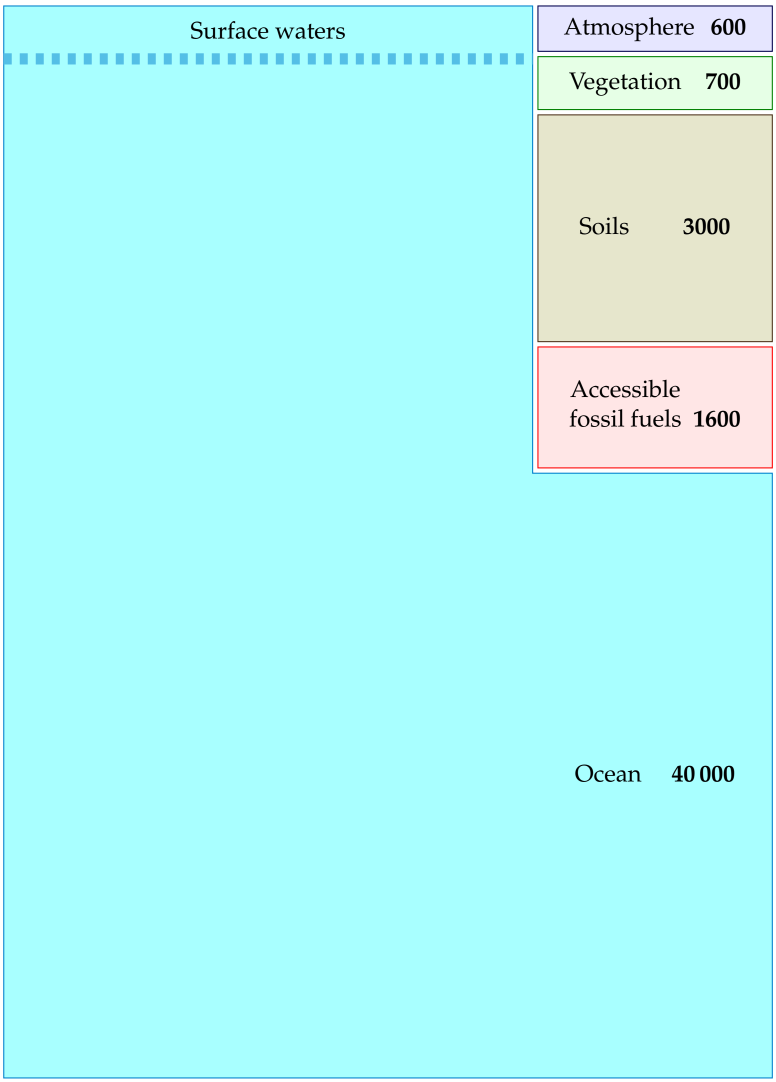

Figure 31.2. Estimated amounts of carbon, in gigatons, in accessible places on the earth. (There's a load more carbon in rocks too; this carbon moves round on a timescale of millions of years, with a long-term balance between carbon in sediment being subducted at tectonic plate boundaries, and carbon popping out of volcanoes from time to time. For simplicity I ignore this geological carbon.)

animal life, and decaying materials). Soils and vegetation together contain about 3700 Gt. Accessible fossil fuels – mainly coal – contain about 1600 Gt. Finally, the atmosphere contains about 600 Gt of carbon.

Until recently, all these pools of carbon were roughly in balance: all flows of carbon out of a pool (say, soils, vegetation, or atmosphere) were balanced by equal flows into that pool. The flows into and out of the fossil fuel pool were both negligible. Then humans started burning fossil fuels. This added two extra *unbalanced* flows, as shown in figure 31.3.

The rate of fossil fuel burning was roughly 1 Gt C/y in 1920, 2 Gt C/y in 1955, and 8.4 Gt C in 2006. (These figures include a small contribution from cement production, which releases CO_2 from limestone.)

How has this significant extra flow of carbon modified the picture shown in figure 31.2? Well, it's not exactly known. Figure 31.3 shows the key things that *are* known. Much of the extra 8.4 Gt C per year that we're putting into the atmosphere stays in the atmosphere, raising the atmospheric concentration of carbon-dioxide. The atmosphere equilibrates fairly rapidly with the surface waters of the oceans (this equilibration takes only five or ten years), and there is a net flow of CO_2 from the atmosphere into the surface waters of the oceans, amounting to 2 Gt C per year. (Recent research indicates this rate of carbon-uptake by the oceans may be reducing, however.) This unbalanced flow into the surface waters causes ocean acidification, which is bad news for coral. Some extra carbon is moving into vegetation and soil too, perhaps about 1.5 Gt C per year, but these flows are less well measured. Because roughly half of the carbon emissions are staying in the atmosphere, continued carbon pollution at a rate of 8.4 Gt C per year will continue to increase CO_2 levels in the atmosphere, and in the surface waters.

What is the long-term destination of the extra CO_2? Well, since the amount in fossil fuels is so much smaller than the total in the oceans, "in the long term" the extra carbon will make its way into the ocean, and the amounts of carbon in the atmosphere, vegetation, and soil will return to normal. However, "the long term" means thousands of years. Equilibration between atmosphere and the *surface* waters is rapid, as I said, but figures 31.2 and 31.3 show a dashed line separating the surface waters of the ocean from the rest of the ocean. On a time-scale of 50 years, this boundary is virtually a solid wall. Radioactive carbon dispersed across the globe by the atomic bomb tests of the 1960s and 70s has penetrated the oceans to a depth of only about 400 m. In contrast the average depth of the oceans is about 4000 m.

The oceans circulate slowly: a chunk of deep-ocean water takes about 1000 years to roll up to the surface and down again. The circulation of the deep waters is driven by a combination of temperature gradients and salinity gradients, so it's called the thermohaline circulation (in contrast to the circulations of the surface waters, which are wind-driven).

This slow turn-over of the oceans has a crucial consequence: we have

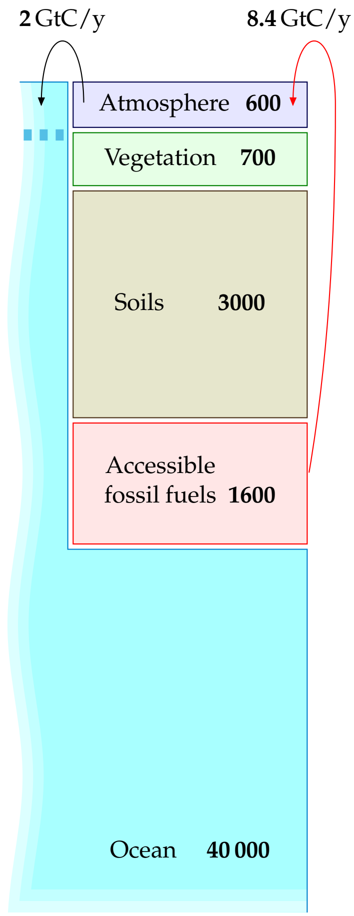

Figure 31.3. The arrows show two extra carbon flows produced by burning fossil fuels. There is an imbalance between the 8.4 Gt C/y emissions into the atmosphere from burning fossil fuels and the 2 Gt C/y take-up of CO_2 by the oceans. This cartoon omits the less-well quantified flows between atmosphere, soil, vegetation, and so forth.

enough fossil fuels to seriously influence the climate over the next 1000 years.

Where is the carbon going

Figure 31.3 is a gross simplification. For example, humans are causing additional flows not shown on this diagram: the burning of peat and forests in Borneo in 1997 alone released about 0.7 Gt C. Accidentally-started fires in coal seams release about 0.25 Gt C per year.

Nevertheless, this cartoon helps us understand roughly what will happen in the short term and the medium term under various policies. First, if carbon pollution follows a "business as usual" trajectory, burning another 500 Gt of carbon over the next 50 years, we can expect the carbon to continue to trickle gradually into the surface waters of the ocean at a rate of 2 Gt C per year. By 2055, at least 100 Gt of the 500 would have gone into the surface waters, and CO_2 concentrations in the atmosphere would be roughly double their pre-industrial levels.

If fossil-fuel burning were reduced to zero in the 2050s, the 2 Gt flow from atmosphere to ocean would also reduce significantly. (I used to imagine that this flow into the ocean would persist for decades, but that would be true only if the surface waters were out of equilibrium with the atmosphere; but, as I mentioned earlier, the surface waters and the atmosphere reach equilibrium within just a few years.) Much of the 500 Gt we put into the atmosphere would only gradually drift into the oceans over the next few thousand years, as the surface waters roll down and are replaced by new water from the deep.

Thus our perturbation of the carbon concentration might eventually be righted, but only after thousands of years. And that's assuming that this large perturbation of the atmosphere doesn't drastically alter the ecosystem. It's conceivable, for example, that the acidification of the surface waters of the ocean might cause a sufficient extinction of ocean plant-life that a new vicious cycle kicks in: acidification means extinguished plant-life, means plant-life absorbs less CO_2 from the ocean, means oceans become even more acidic. Such vicious cycles (which scientists call "positive feedbacks" or "runaway feedbacks") have happened on earth before: it's believed, for example, that ice ages ended relatively rapidly because of positive feedback cycles in which rising temperatures caused surface snow and ice to melt, which reduced the ground's reflection of sunlight, which meant the ground absorbed more heat, which led to increased temperatures. (Melted snow – water – is much darker than frozen snow.) Another positive feedback possibility to worry about involves methane hydrates, which are frozen in gigaton quantities in places like Arctic Siberia, and in 100-gigaton quantities on continental shelves. Global warming greater than 1 °C would possibly melt methane hydrates, which release methane into the atmosphere, and methane increases global warming more strongly

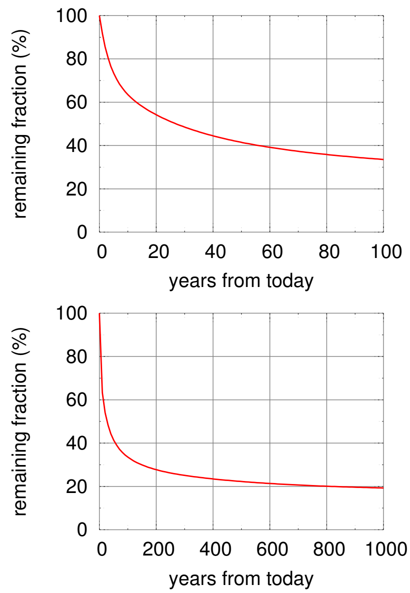

Figure 31.4. Decay of a small pulse of CO_2 added to today's atmosphere, according to the Bern model of the carbon cycle. Source: Hansen et al. (2007).

than CO_2 does.

This isn't the place to discuss the uncertainties of climate change in any more detail. I highly recommend the books *Avoiding Dangerous Climate Change* (Schellnhuber et al., 2006) and *Global Climate Change* (Dessler and Parson, 2006). Also the papers by Hansen et al. (2007) and Charney et al. (1979).

The purpose of this chapter is to discuss the idea of fixing climate change by sucking carbon dioxide from thin air; we discuss the energy cost of this sucking next.

The cost of sucking

Today, pumping carbon out of the ground is big bucks. In the future, perhaps pumping carbon *into* the ground is going to be big bucks. Assuming that inadequate action is taken now to halt global carbon pollution, perhaps a coalition of the willing will in a few decades pay to create a giant vacuum cleaner, and clean up everyone's mess.

Before we go into details of how to capture carbon from thin air, let's discuss the unavoidable energy cost of carbon capture. Whatever technologies we use, they have to respect the laws of physics, and unfortunately grabbing CO_2 from thin air and concentrating it requires energy. The laws of physics say that the energy required must be at least 0.2 kWh per kg of CO_2 (table 31.5). Given that real processes are typically 35% efficient at best, I'd be amazed if the energy cost of carbon capture is ever reduced below 0.55 kWh per kg.

Now, let's assume that we wish to neutralize a typical European's CO_2 output of 11 tons per year, which is 30 kg per day per person. The energy required, assuming a cost of 0.55 kWh per kg of CO_2, is 16.5 kWh per day per person. This is exactly the same as British electricity consumption. So powering the giant vacuum cleaner may require us to *double* our electricity production – or at least, to somehow obtain extra power equal to our current electricity production.

If the cost of running giant vacuum cleaners can be brought down, brilliant, let's make them. But no amount of research and development can get round the laws of physics, which say that grabbing CO_2 from thin air and concentrating it into liquid CO_2 requires at least 0.2 kWh per kg of CO_2.

Now, what's the best way to suck CO_2 from thin air? I'll discuss four technologies for building the giant vacuum cleaner:

A. chemical pumps;

B. trees;

C. accelerated weathering of rocks;

D. ocean nourishment.

A. Chemical technologies for carbon capture

The chemical technologies typically deal with carbon dioxide in two steps.

$$0.03\%\ CO_2 \xrightarrow{\text{concentrate}} \text{Pure } CO_2 \xrightarrow{\text{compress}} \text{Liquid } CO_2$$

First, they *concentrate* CO_2 from its low concentration in the atmosphere; then they *compress* it into a small volume ready for shoving somewhere (either down a hole in the ground or deep in the ocean). Each of these steps has an energy cost. The costs required by the laws of physics are shown in table 31.5.

	cost (kWh/kg)
concentrate	0.13
compress	0.07
total	0.20

Table 31.5. The inescapable energy-cost of concentrating and compressing CO_2 from thin air.

In 2005, the best published methods for CO_2 capture from thin air were quite inefficient: the energy cost was about 3.3 kWh per kg, with a financial cost of about $140 per ton of CO_2. At this energy cost, capturing a European's 30 kg per day would cost 100 kWh per day – almost the same as the European's energy consumption of 125 kWh per day. Can better vacuum cleaners be designed?

Recently, Wallace Broecker, climate scientist, "perhaps the world's foremost interpreter of the Earth's operation as a biological, chemical, and physical system," has been promoting an as yet unpublished technology developed by physicist Klaus Lackner for capturing CO_2 from thin air. Broecker imagines that the world could carry on burning fossil fuels at much the same rate as it does now, and 60 million CO_2-scrubbers (each the size of an up-ended shipping container) will vacuum up the CO_2. What energy does Lackner's process require? In June 2007 Lackner told me that his lab was achieving 1.3 kWh per kg, but since then they have developed a new process based on a resin that absorbs CO_2 when dry and releases CO_2 when moist. Lackner told me in June 2008 that, in a dry climate, the concentration cost has been reduced to about 0.18–0.37 kWh of low-grade heat per kg CO_2. The compression cost is 0.11 kWh per kg. Thus Lackner's total cost is 0.48 kWh or less per kg. For a European's emissions of 30 kg CO_2 per day, we are still talking about a cost of 14 kWh per day, of which 3.3 kWh per day would be electricity, and the rest heat.

Hurray for technical progress! But please don't think that this is a *small* cost. We would require roughly a 20% increase in world energy production, just to run the vacuum cleaners.

B. What about trees?

Trees are carbon-capturing systems; they suck CO_2 out of thin air, and they don't violate any laws of physics. They are two-in-one machines: they are carbon-capture facilities powered by built-in solar power stations. They capture carbon using energy obtained from sunlight. The fossil fuels that we burn were originally created by this process. So, the suggestion is, how about trying to do the opposite of fossil fuel burning? How about creating wood and burying it in a hole in the ground, while, next door, humanity continues digging up fossil wood and setting fire to it? It's daft to imagine creating buried wood at the same time as digging up buried wood. Even so, let's work out the land area required to solve the climate problem with trees.

The best plants in Europe capture carbon at a rate of roughly 10 tons of dry wood per hectare per year – equivalent to about 15 tons of CO_2 per hectare per year – so to fix a European's output of 11 tons of CO_2 per year we need 7500 square metres of forest per person. This required area of 7500 square metres per person is *twice the area of Britain* per person. And then you'd have to find somewhere to permanently store 7.5 tons of wood per person per year! At a density of 500 kg per m^3, each person's wood would occupy 15 m^3 per year. A lifetime's wood – which, remember, must be safely stored away and never burned – would occupy 1000 m^3. That's five times the entire volume of a typical house. If anyone proposes using trees to undo climate change, they need to realise that country-sized facilities are required. I don't see how it could ever work.

1 hectare = 10 000 m^2

C. Enhanced weathering of rocks

Is there a sneaky way to avoid the significant energy cost of the chemical approach to carbon-sucking? Here is an interesting idea: pulverize rocks that are capable of absorbing CO_2, and leave them in the open air. This idea can be pitched as the acceleration of a natural geological process. Let me explain.

Two flows of carbon that I omitted from figure 31.3 are the flow of carbon from rocks into oceans, associated with the natural weathering of rocks, and the natural precipitation of carbon into marine sediments, which eventually turn back into rocks. These flows are relatively small, involving about 0.2 Gt C per year (0.7 Gt CO_2 per year). So they are dwarfed by current human carbon emissions, which are about 40 times bigger. But the suggestion of enhanced-weathering advocates is that we could fix climate change by speeding up the rate at which rocks are broken down and absorb CO_2. The appropriate rocks to break down include olivines or magnesium silicate minerals, which are widespread. The idea would be to find mines in places surrounded by many square kilometres of land on which crushed rocks could be spread, or perhaps to spread the crushed rocks directly on the oceans. Either way, the rocks would absorb CO_2 and turn into carbonates and the resulting carbonates would end up being washed into the oceans. To pulverized the rocks into appropriately small grains for the reaction with CO_2 to take place requires only 0.04 kWh per kg of sucked CO_2. Hang on, isn't that smaller than the 0.20 kWh per kg required by the laws of physics? Yes, but nothing is wrong: the rocks themselves are the sources of the missing energy. Silicates have higher energy than carbonates, so the rocks pay the energy cost of sucking the CO_2 from thin air.

I like the small energy cost of this scheme but the difficult question is, who would like to volunteer to cover their country with pulverized rock?

D. Ocean nourishment

One problem with chemical methods, tree-growing methods, and rock-pulverizing methods for sucking CO_2 from thin air is that all would require a lot of work, and no-one has any incentive to do it – unless an international agreement pays for the cost of carbon capture. At the moment, carbon prices are too low.

A final idea for carbon sucking might sidestep this difficulty. The idea is to persuade the ocean to capture carbon a little faster than normal as a by-product of fish farming.

Some regions of the world have food shortages. There are fish shortages in many areas, because of over-fishing during the last 50 years. The idea of *ocean nourishment* is to fertilize the oceans, supporting the base of the food chain, enabling the oceans to support more plant life and more fish, and incidentally to fix more carbon. Led by Australian scientist Ian Jones, the ocean nourishment engineers would like to pump a nitrogen-containing fertilizer such as urea into appropriate fish-poor parts of the ocean. They claim that 900 km^2 of ocean can be nourished to take up about 5 Mt CO_2/y. Jones and his colleagues reckon that the ocean nourishment process is suitable for any areas of the ocean deficient in nitrogen. That includes most of the North Atlantic. Let's put this idea on a map. UK carbon emissions are about 600 Mt CO_2/y. So complete neutralization of UK carbon emissions would require 120 such areas in the ocean. The map

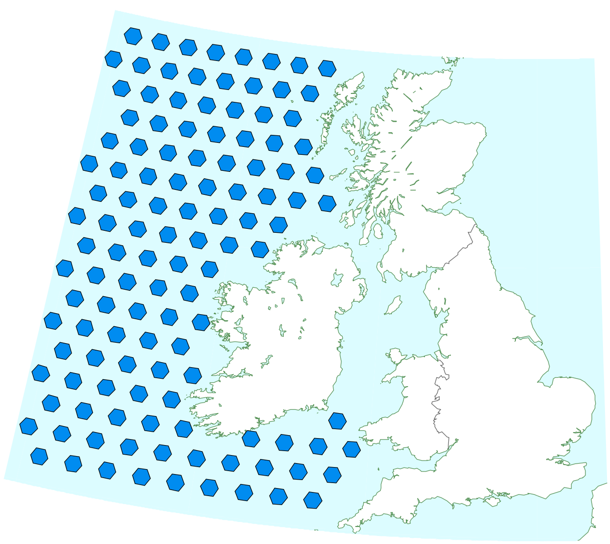

Figure 31.6. 120 areas in the Atlantic Ocean, each 900 km^2 in size. These make up the estimated area required in order to fix Britain's carbon emissions by ocean nourishment.

in figure 31.6 shows these areas to scale alongside the British Isles. As usual, a plan that actually adds up requires country-sized facilities! And we haven't touched on how we would make all the required urea.

While it's an untested idea, and currently illegal, I do find ocean nourishment interesting because, in contrast to geological carbon storage, it's a technology that might be implemented even if the international community doesn't agree on a high value for cleaning up carbon pollution; fishermen might nourish the oceans purely in order to catch more fish.

> *Commentators can be predicted to oppose manipulations of the ocean, focusing on the uncertainties rather than on the potential benefits. They will be playing to the public's fear of the unknown. People are ready to passively accept an escalation of an established practice (e.g., dumping CO_2 in the atmosphere) while being wary of innovations that might improve their future well being. They have an uneven aversion to risk.*
>
> Ian Jones

> *We, humanity, cannot release to the atmosphere all, or even most, fossil fuel CO_2. To do so would guarantee dramatic climate change, yielding a different planet...*
>
> J. Hansen et al (2007)

> *"Avoiding dangerous climate change" is impossible – dangerous climate change is already here. The question is, can we avoid* **catastrophic** *climate change?*
>
> David King, UK Chief Scientist, 2007

Notes

page no.

240 *climate change ... was a controversial question.* Indeed there still is a "yawning gap between mainstream opinion on climate change among the educated elites of Europe and America" [voxbz].

241 *Where is the carbon?* Sources: Schellnhuber et al. (2006), Davidson and Janssens (2006).

242 *The rate of fossil fuel burning...* Source: Marland et al. (2007).

– *Recent research indicates carbon-uptake by the oceans may be reducing.* www.timesonline.co.uk/tol/news/uk/science/article1805870.ece, www.sciencemag.org/cgi/content/abstract/1136188, [yofchc], Le Quéré et al. (2007).

– *roughly half of the carbon emissions are staying in the atmosphere.* It takes 2.1 billion tons of carbon in the atmosphere (7.5 Gt CO_2) to raise the atmospheric CO_2 concentration by one part per million (1 ppm). If all the CO_2 we pumped into the atmosphere stayed there, the concentration would be rising by more than 3 ppm per year – but it is actually rising at only 1.5 ppm per year.

– *Radioactive carbon ... has penetrated to a depth of only about 400 m.* The mean value of the penetration depth of bomb ^{14}C for all observational sites during the late 1970s is 390±39 m (Broecker et al., 1995). From [3e28ed].

244 *Global warming greater than 1 °C would possibly melt methane hydrates.* Source: Hansen et al. (2007, p1942).

245 *Table 31.5. Inescapable cost of concentrating and compressing CO_2 from thin air.* The unavoidable energy requirement to concentrate CO_2 from 0.03% to 100% at atmospheric pressure is $kT \ln 100/0.03$ per molecule, which is 0.13 kWh per kg. The ideal energy cost of compression of CO_2 to 110 bar (a pressure mentioned for geological storage) is 0.067 kWh/kg. So the total ideal cost of CO_2 capture and compression is 0.2 kWh/kg. According to the IPCC special report on carbon capture and storage, the practical cost of the second step, compression of CO_2 to 110 bar, is 0.11 kWh per kg. (0.4 GJ per t CO_2; 18 kJ per mole CO_2; 7 kT per molecule.)

245 *Shoving the CO_2 down a hole in the ground or deep in the ocean.* See Williams (2000) for discussion. "For a large fraction of injected CO_2 to remain in the ocean, injection must be at great depths. A consensus is developing that the best near-term strategy would be to discharge CO_2 at depths of 1000–1500 metres, which can be done with existing technology."
See also the Special Report by the IPCC: `www.ipcc.ch/ipccreports/srccs.htm`.

– *In 2005, the best methods for carbon capture were quite inefficient: the energy cost was about 3.3 kWh per kg, with a financial cost of about $140 per ton of CO_2.* Sources: Keith et al. (2005), Lackner et al. (2001), Herzog (2003), Herzog (2001), David and Herzog (2000).

– *Wallace Broecker, climate scientist...* `www.af-info.or.jp/eng/honor/hot/enrbro.html`. His book promoting artificial trees: Broecker and Kunzig (2008).

246 *The best plants in Europe capture carbon at a rate of roughly 10 tons of dry wood per hectare per year.* Source: Select Committee on Science and Technology.

– *Enhanced weathering of rocks.* See Schuiling and Krijgsman (2006).

247 *Ocean nourishment.* See Judd et al. (2008). See also Chisholm et al. (2001). The risks of ocean nourishment are discussed in Jones (2008).

32 Saying yes

Because Britain currently gets 90% of its energy from fossil fuels, it's no surprise that getting off fossil fuels requires big, big changes – a total change in the transport fleet; a complete change of most building heating systems; and a 10- or 20-fold increase in green power.

Given the general tendency of the public to say "no" to wind farms, "no" to nuclear power, "no" to tidal barrages – "no" to anything other than fossil fuel power systems – I am worried that we won't actually get off fossil fuels when we need to. Instead, we'll settle for half-measures: slightly-more-efficient fossil-fuel power stations, cars, and home heating systems; a fig-leaf of a carbon trading system; a sprinkling of wind turbines; an inadequate number of nuclear power stations.

We need to choose a plan that adds up. It *is* possible to make a plan that adds up, but it's not going to be easy.

We need to stop saying no and start saying yes. We need to stop the Punch and Judy show and get building.

If you would like an honest, realistic energy policy that adds up, please tell all your political representatives and prospective political candidates.

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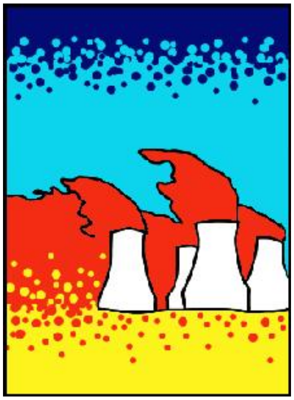
Part III

Technical chapters



A Cars II

We estimated that a car driven 100 km uses about 80 kWh of energy.

Where does this energy go? How does it depend on properties of the car? Could we make cars that are 100 times more efficient? Let's make a simple cartoon of car-driving, to describe where the energy goes. The energy in a typical fossil-fuel car goes to four main destinations, all of which we will explore:

1. speeding up then slowing down using the brakes;

2. air resistance;

3. rolling resistance;

4. heat – 75% of the energy is thrown away as heat, because the energy-conversion chain is inefficient.

Initially our cartoon will ignore rolling resistance; we'll add in this effect later in the chapter.

Assume the driver accelerates rapidly up to a cruising speed v, and maintains that speed for a distance d, which is the distance between traffic lights, stop signs, or congestion events. At this point, he slams on the brakes and turns all his kinetic energy into heat in the brakes. (This vehicle doesn't have fancy 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 a speed similar to v. Which of these two forms of energy is the bigger: kinetic energy of the 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:

$$\frac{\text{kinetic energy}}{\text{time between braking events}} = \frac{\frac{1}{2}m_c v^2}{d/v} = \frac{\frac{1}{2}m_c v^3}{d}, \qquad \text{(A.1)}$$

where m_c is the mass of the car.

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 $m = 1000$ kg moving at 100 km per hour or $v = 28$ m/s has an energy of

$$\frac{1}{2}mv^2 \simeq 390\,000\,\text{J} \simeq 0.1\,\text{kWh}.$$

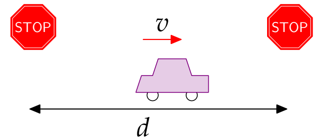


Figure A.2. Our cartoon: a car moves at speed v between stops separated by a distance d.

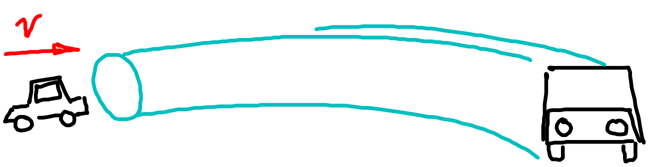


Figure A.3. A car moving at speed v creates behind it a tube of swirling air; the cross-sectional area of the tube is similar to the frontal area of the car, and the speed at which air in the tube swirls is roughly v.

- 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 similar to the area of the front view of the car. (For a streamlined car, A is usually a little smaller than the frontal area A_{car}, and the ratio 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, $c_d A_{car}$.) The tube has mass $m_{air} = \rho A v t$ (where ρ is the density of air) and swirls at speed v, so its kinetic energy is:

$$\frac{1}{2} m_{air} v^2 = \frac{1}{2} \rho A v t \, v^2,$$

and the rate of generation of kinetic energy in swirling air is:

$$\frac{\frac{1}{2}\rho A v t v^2}{t} = \frac{1}{2}\rho A v^3.$$

I'm using this formula:

mass = density × volume

The symbol ρ (Greek letter 'rho') denotes the density.

So the total rate of energy production by the car is:

$$\begin{aligned} &\text{power going into brakes} &+& \text{ power going into swirling air} \\ &= \tfrac{1}{2} m_c v^3 / d &+& \tfrac{1}{2}\rho A v^3. \end{aligned} \qquad \text{(A.2)}$$

Both forms of energy dissipation scale as v^3. So this cartoon predicts that a driver who halves his speed v makes his power consumption 8 times smaller. If he ends up driving the same total distance, his journey will take twice as long, but the total energy consumed by his journey will be four times smaller.

Which of the two forms of energy dissipation – brakes or air-swirling – is the bigger? It depends on the ratio of

$$(m_c/d) \, / (\rho A) \, .$$

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

$$m_c > \rho A d.$$

Now, Ad is the volume of the tube of air swept out from one stop sign to the next. And $\rho A d$ 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* (figure A.4).

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 frontal area of the car is:

$$A_{car} = 2\,\text{m wide} \times 1.5\,\text{m high} = 3\,\text{m}^2$$

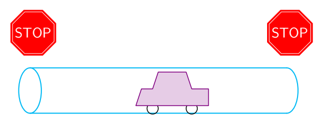


Figure A.4. To know whether energy consumption is braking-dominated or air-swirling-dominated, we compare the mass of the car with the mass of the tube of air between stop-signs.

Figure A.5. 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?

and the drag coefficient is $c_d = 1/3$ and the mass is $m_c = 1000$ kg then the special distance is:

$$d^* = \frac{m_c}{\rho c_d A_{car}} = \frac{1000\,\text{kg}}{1.3\,\text{kg/m}^3 \times \frac{1}{3} \times 3\,\text{m}^2} = 750\,\text{m}.$$

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;
2. to get a car with regenerative brakes (which roughly halve the energy lost in braking – see Chapter 20); and
3. 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;
2. by reducing its cross-sectional area; or
3. by driving more slowly.

The actual energy consumption of the car will be the energy dissipation in equation (A.2), 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:

$$\text{total power of car} \simeq 4\left[\frac{1}{2}m_c v^3/d + \frac{1}{2}\rho A v^3\right].$$

Let's check this theory of cars by plugging in plausible numbers for motorway driving. Let v = 70 miles per hour = 110 km/h = 31 m/s and $A = c_d A_{car} = 1\,\text{m}^2$. The power consumed by the engine is estimated to be roughly

$$4 \times \frac{1}{2}\rho A v^3 = 2 \times 1.3\,\text{kg/m}^3 \times 1\,\text{m}^2 \times (31\,\text{m/s})^3 = 80\,\text{kW}.$$

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

Energy-per-distance	
Car at 110 km/h	↔ 80 kWh/(100 km)
Bicycle at 21 km/h	↔ 2.4 kWh/(100 km)

Planes at 900 km/h	
A380	27 kWh/100 seat-km

Table A.6. Facts worth remembering: car energy consumption.

mileage figures for cars quoted in Chapter 3. 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.

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. On the motorway at 70 mph, 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 fossil-fuel engine could perhaps boost its efficiency from 25% to 50%, bringing the energy consumption of a fossil-fuelled car down to roughly 40 kWh per 100 km.

Electric vehicles have some wins: while the weight of the energy store, per useful kWh stored, is about 25 times bigger than that of petrol, the weight of an electric engine can be about 8 times smaller. And the energy-chain in an electric car is much more efficient: electric motors can be 90% efficient.

We'll come back to electric cars in more detail towards the end of this chapter.

Bicycles and the scaling trick

Here's a fun question: what's the energy consumption of a bicycle, in kWh per 100 km? 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 "4" came from engine inefficiency; ρ is the density of air; the area $A = c_d A_{car}$ 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 the efficiency of the carbon-powered bicyclist's engine is similar to the efficiency of the carbon-powered car engine (which it is). The ratio is:

$$\frac{\text{energy per distance of bike}}{\text{energy per distance of car}} = \frac{c_d^{bike} A_{bike} v_{bike}^2}{c_d^{car} A_{car} v_{car}^2}.$$

The trick we are using is called "scaling." If we know how energy consumption scales with speed and area, then we can predict energy con-

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.7. Drag coefficients and drag areas.

sumption 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.) Let's assume the bike is not very well streamlined:

$$\frac{c_{\text{d}}^{\text{bike}}}{c_{\text{d}}^{\text{car}}} = \frac{1}{1/3}$$

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 3% of the energy per kilometre of a lone car-driver on the motorway – about **2.4 kWh per 100 km**.

If you would like a vehicle whose fuel efficiency is 30 times better than a car's, it's simple: ride a bike.

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 of rolling resistance asserts that the force of rolling resistance is simply proportional to the weight of the vehicle, independent of

wheel	C_{rr}
train (steel on steel)	0.002
bicycle tyre	0.005
truck rubber tyres	0.007
car rubber tyres	0.010

Table A.8. 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]

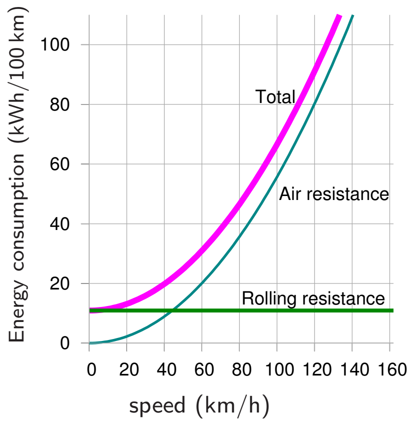


Figure A.9. Simple theory of car fuel consumption (energy per distance) when driving at steady speed. Assumptions: the car's engine uses energy with an efficiency of 0.25, whatever the speed; $c_d A_{car} = 1\,m^2$; $m_{car} = 1000\,kg$; and $C_{rr} = 0.01$.

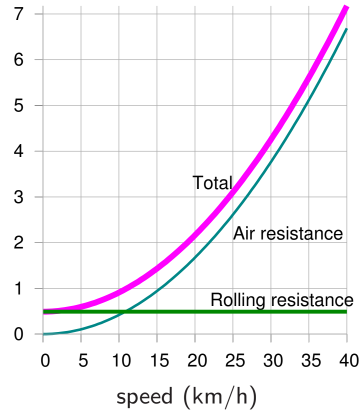


Figure A.10. Simple theory of bike fuel consumption (energy per distance). Vertical axis is energy consumption in kWh per 100 km. Assumptions: the bike's engine (that's you!) uses energy with an efficiency of 0.25,; the drag-area of the cyclist is $0.75\,m^2$; the cyclist+bike's mass is 90 kg; and $C_{rr} = 0.005$.

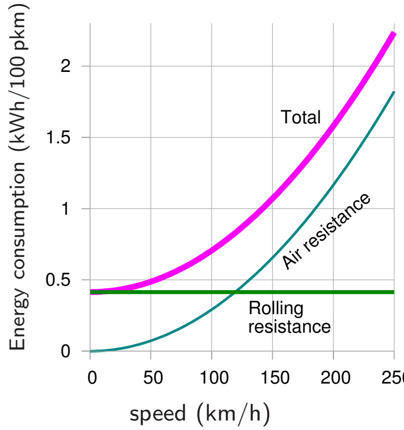


Figure A.11. Simple theory of train energy consumption, *per passenger*, for an eight-carriage train carrying 584 passengers. Vertical axis is energy consumption in kWh per 100 p-km. Assumptions: the train's engine uses energy with an efficiency of 0.90; $c_d A_{train} = 11\,m^2$; $m_{train} = 400\,000\,kg$; and $C_{rr} = 0.002$.

the speed. The constant of proportionality is called the coefficient of rolling resistance, C_{rr}. Table A.8 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. 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 moving, you'll find you can keep it moving with one hand. (100 newtons is the weight of 100 apples.) So at a speed of 31 m/s (70 mph), the power required to overcome rolling resistance, for a one-ton vehicle, is

$$\text{force} \times \text{velocity} \;=\; (100\text{ newtons}) \times (31\,\text{m/s}) \;=\; 3100\,\text{W};$$

which, allowing for an engine efficiency of 25%, requires 12 kW of power to go into the engine; whereas the power required to overcome drag was estimated on p256 to be 80 kW. So, at high speed, about 15% of the power is required for rolling resistance.

Figure A.9 shows the theory of fuel consumption (energy per unit distance) as a function of steady speed, when we add together the 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,

$$v = \sqrt{2 \frac{C_{rr} m_c g}{\rho c_d A}} = 7\,\text{m/s} = 16\,\text{miles per hour.}$$

Bicycles

For a bicycle ($m = 90$ kg, $A = 0.75\,\text{m}^2$), the transition from rolling-resistance-dominated cycling to air-resistance-dominated cycling takes place at a speed of about 12 km/h. At a steady speed of 20 km/h, cycling costs about 2.2 kWh per 100 km. By adopting an aerodynamic posture, you can reduce your drag area and cut the energy consumption down to about 1.6 kWh per 100 km.

Trains

For an eight-carriage train as depicted in figure 20.4 ($m = 400\,000$ kg, $A = 11\,\text{m}^2$), the speed above which air resistance is greater than rolling 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 air resistance is greater than rolling resistance is

$$v = 12\,\text{m/s} = 26\,\text{miles per hour.}$$

Dependence of power on speed

When I say that halving your driving speed should reduce fuel consumption (in miles per gallon) to *one quarter* of current levels, 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. 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-fold. 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 at an intermediate speed that makes a compromise between going slow and keeping the engine efficient. For the BMW 318ti in figure A.12, for example, the optimum speed is about 60 km/h. 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

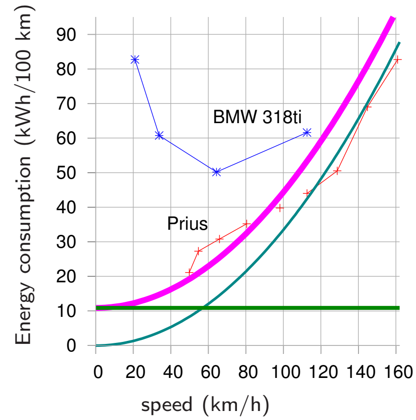


Figure A.12. Current cars' fuel consumptions do not vary as speed squared. Prius data from B.Z. Wilson; BMW data from Phil C. Stuart. The smooth curve shows what a speed-squared curve would look like, assuming a drag-area of $0.6\,\text{m}^2$.

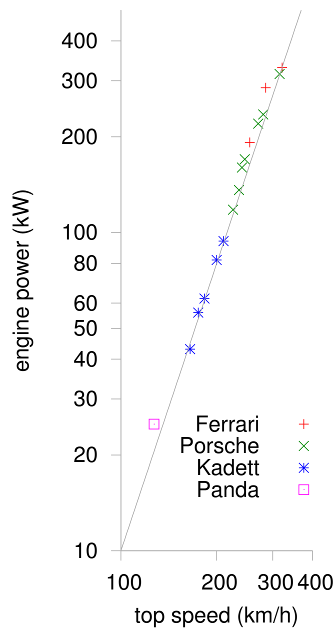


Figure A.13. Powers of cars (kW) versus their top speeds (km/h). Both scales are logarithmic. The power increases as the third power of the speed. To go twice as fast requires eight times as much engine power. From Tennekes (1997).

that the power a car requires really does increase as the cube of speed, figure A.13 shows the engine power versus the top speeds of a range of cars. The line shows the relationship "power proportional to v^3."

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.

Let's assume that the mass of the car and occupants is 740 kg, *without* any batteries. In due course we'll add 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.14 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 a battery whose energy density is 40 Wh/kg (old-style lead-acid batteries). 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 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 lighter 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 in a car 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 battery-exchange station every 300 km or so.

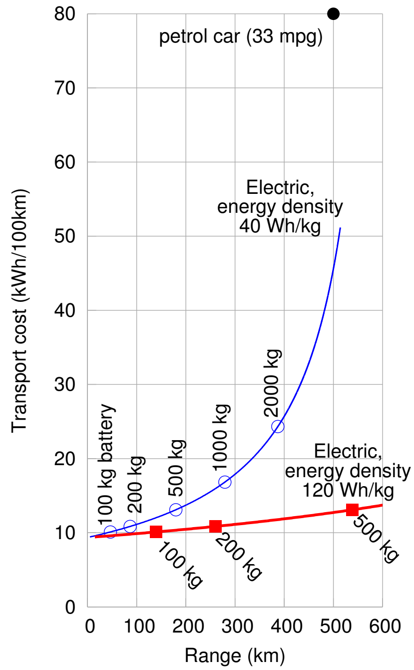


Figure A.14. Theory of electric car range (horizontal axis) and transport cost (vertical axis) as a function of battery mass, for two battery technologies. A car with 500 kg of old batteries, with an energy density of 40 Wh per kg, has a range of 180 km. With the same weight of modern batteries, delivering 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 and further reading

page no.

256 *Typical petrol engines are about 25% efficient.* Encarta [6by8x] says "The efficiencies of good modern Otto-cycle engines range between 20 and 25%." 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 diesel engine (figure A.15) is intended for container ships and has a power output of 80 MW.

– *Regenerative brakes roughly halve the energy lost in braking.* Source: E4tech (2007).

257 *Electric engines can be about 8 times lighter than petrol engines.* A 4-stroke petrol engine has a power-to-mass ratio of roughly 0.75 kW/kg. The best electric motors have an efficiency of 90% and a power-to-mass ratio of 6 kW/kg. So replacing a 75 kW petrol engine with a 75 kW electric motor saves 85 kg in weight. Sadly, the power to weight ratio of batteries is about 1 kW per kg, so what the electric vehicle gained on the motor, it loses on the batteries.

259 *The bike's engine uses energy with an efficiency of 0.25.* This and the other assumptions about cycling are confirmed by di Prampero et al. (1979). The drag-area of a cyclist in racing posture is $c_d A = 0.3\,\text{m}^2$. The rolling resistance of a cyclist on a high-quality racing cycle (total weight 73 kg) is 3.2 N.

260 *Figure A.12.* Prius data from B. Z. Wilson [home.hiwaay.net/~bzwilson/prius/]. BMW data from Phil C. Stuart [www.randomuseless.info/318ti/economy.html].

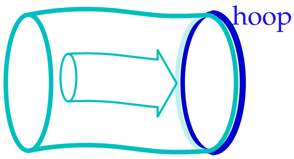
Further reading: Gabrielli and von Kármán (1950).

Figure A.15. The Wartsila-Sulzer RTA96-C 14-cylinder two-stroke diesel engine. 27 m long and 13.5 m high. www.wartsila.com

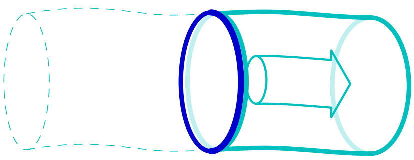
B Wind II

The physics of wind power

To estimate the energy in wind, let's imagine holding up a hoop with area A, 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:



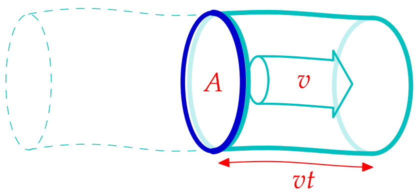
And here's a picture of the same mass of air one second later:



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 again:

mass = density × volume



The kinetic energy of this piece of air is

$$\frac{1}{2}mv^2 = \frac{1}{2}\rho A v t\, v^2 = \frac{1}{2}\rho A t v^3. \tag{B.1}$$

So the power of the wind, for an area A – that is, the kinetic energy passing across that area per unit time – is

$$\frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}\rho A v^3. \tag{B.2}$$

This formula may look familiar – we derived an identical expression on p255 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

miles/ 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
49	79	22	force 9
60	97	27	force 10
69	112	31	force 11
78	126	35	force 12

Figure B.1. Speeds.

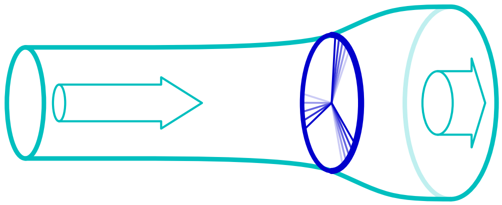


Figure B.2. Flow of air past a windmill. The air is slowed down and splayed out by the windmill.

normal; the speed of such a wind is therefore 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, although I haven't done so here.) Then the typical power of the wind per square metre of hoop is

$$\frac{1}{2}\rho v^3 = \frac{1}{2} 1.3\,\mathrm{kg/m^3} \times (6\,\mathrm{m/s})^3 = 140\,\mathrm{W/m^2}. \quad \text{(B.3)}$$

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.2 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 Wellington, New Zealand (figure B.3). The power of a single windmill is

$$\begin{aligned} & \text{efficiency factor} \times \text{power per unit area} \times \text{area} \\ = \;& 50\% \times \frac{1}{2}\rho v^3 \times \frac{\pi}{4} d^2 && \text{(B.4)} \\ = \;& 50\% \times 140\,\mathrm{W/m^2} \times \frac{\pi}{4}(25\,\mathrm{m})^2 && \text{(B.5)} \\ = \;& 34\,\mathrm{kW}. && \text{(B.6)} \end{aligned}$$

Indeed, when I visited this windmill on a very 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.

Figure B.3. 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, (1400 kWh per day). Photo by Philip Banks.

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

$$\frac{\text{power per windmill (B.4)}}{\text{land area per windmill}} = \frac{\frac{1}{2}\rho v^3 \frac{\pi}{8} d^2}{(5d)^2} \tag{B.7}$$

$$= \frac{\pi}{200}\frac{1}{2}\rho v^3 \tag{B.8}$$

$$= 0.016 \times 140\,\mathrm{W/m^2} \tag{B.9}$$

$$= 2.2\,\mathrm{W/m^2}. \tag{B.10}$$

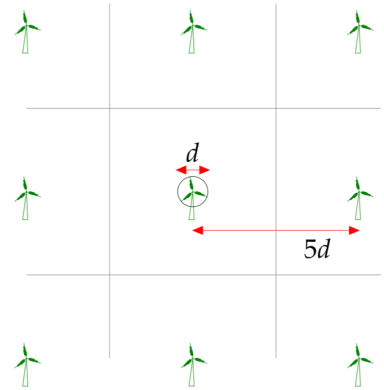


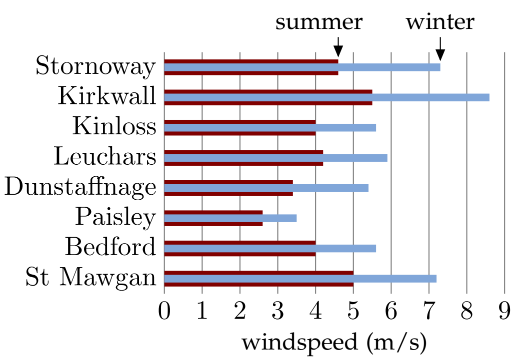
Figure B.4. Wind farm layout.

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

Table B.5. Facts worth remembering: wind farms.

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 *d*s 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.

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 4.1 and 4.2 showed windspeeds in Cambridge and Cairngorm. Figure B.6 shows the mean winter and summer windspeeds in eight more locations around Britain. 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



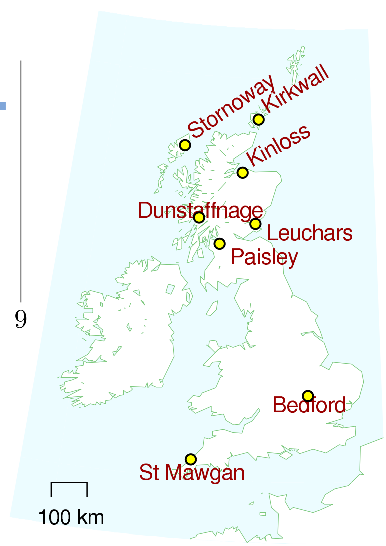


Figure B.6. Average summer windspeed (dark bar) and average winter windspeed (light bar) in eight locations around Britain. Speeds were measured at the standard weatherman's height of 10 metres. Averages are over the period 1971–2000.

4 m/s as our estimated windspeed, we must scale our estimate down, multiplying it by $(4/6)^3 \simeq 0.3$. (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 they deliver the ideal power; at higher or lower speeds real wind turbines deliver less than the ideal power.

Variation of wind speed with height

Taller windmills see higher wind speeds. The way that wind speed increases with height is complicated and depends on the roughness of the surrounding terrain and on the time of day. 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 speed v as a function of height z are:

1. According to the wind shear formula from NREL [ydt7uk], the speed varies as a power of the height:

$$v(z) = v_{10} \left(\frac{z}{10\,\text{m}} \right)^{\alpha},$$

where v_{10} is the speed at 10 m, and a typical value of the exponent α is 0.143 or 1/7. The one-seventh law ($v(z)$ is proportional to $z^{1/7}$) is used by Elliott et al. (1991), for example.

2. The wind shear formula from the Danish Wind Industry Association [yaoonz] is

$$v(z) = v_{\text{ref}} \frac{\log(z/z_0)}{\log(z_{\text{ref}}/z_0)},$$

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.

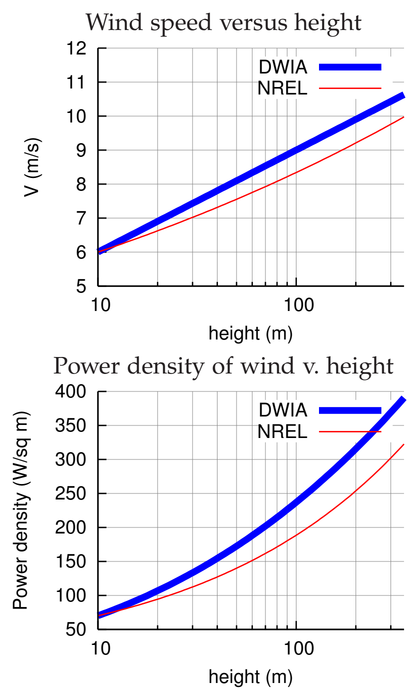


Figure B.7. Top: Two models of wind speed and wind power as a function of height. DWIA = Danish Wind Industry Association; NREL = National Renewable Energy Laboratory. For each model the speed at 10 m has been fixed to 6 m/s. For the Danish Wind model, the roughness length is set to $z_0 = 0.1$ m. Bottom: The power density (the power per unit of upright area) according to each of these models.

Figure B.8. The qr5 from quietrevolution.co.uk. Not a typical windmill.

Standard windmill properties

The typical windmill of today has 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 power" 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. 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 30%. In the Netherlands, the typical load factor is 22%; in Germany, it is 19%.

Other people's estimates of wind farm power per unit area

In the government's study [www.world-nuclear.org/policy/DTI-PIU.pdf] the UK onshore wind resource is estimated using an assumed wind farm power per unit area 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 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 [6o86ec] and will deliver an average power of 3100 GWh per year (350 MW). (Cost £1.5 bn.) That's a power per unit area of 350 MW/245 km^2 = 1.4 W/m^2. This is 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 of Graveney, where the undersea cables of the wind farm will come ashore.

Queries

What about micro-generation? If you plop one of those mini-turbines on your roof, what energy can you expect it to deliver?

Assuming a windspeed of 6 m/s, which, as I said before, is *above* the 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 – not very much. And in reality, in a typical urban location in England, a microturbine delivers just 0.2 kWh per day – see p66.

Perhaps the worst windmills in the world are a set in Tsukuba City, Japan, which actually consume more power than they generate. 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! [6bkvbn]

Figure B.9. An Ampair "600 W" micro-turbine. The average power generated by this micro-turbine in Leamington Spa is 0.037 kWh per day (1.5 W).

Notes and further reading

page no.

264 *The maximum fraction of the incoming energy that can be extracted by a disc-like windmill...* There is a nice explanation of this on the Danish Wind Industry Association's website. [yekdaa].

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

– *a typical load factor for a good site is 30%*. In 2005, the average load factor of all major UK wind farms was 28% [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 wind farms 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%. [wbd8o]

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.

Figure B.10. A 5.5-m diameter Iskra 5 kW turbine [www.iskrawind.com] having its annual check-up. This turbine, located in Hertfordshire (not the windiest of locations in Britain), mounted at a height of 12 m, has an average output of 11 kWh per day. A wind farm of machines with this performance, one per 30 m × 30 m square, would have a power per unit area of 0.5 W/m^2.

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

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 ton, per kilometre flown? What's the maximum distance a 300-ton Boeing 747 can fly? What about a 1-kg bar-tailed godwit or a 100-gram Arctic tern?

Just as Chapter 3, 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 5, 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!

Figure C.1. Birds: two Arctic terns, a bar-tailed godwit, and a Boeing 747.

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). As long as 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 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_{lift}.)

The two equations we'll need, in order to work out a theory of flight, are Newton's second law:

$$\text{force} = \text{rate of change of momentum}, \tag{C.1}$$

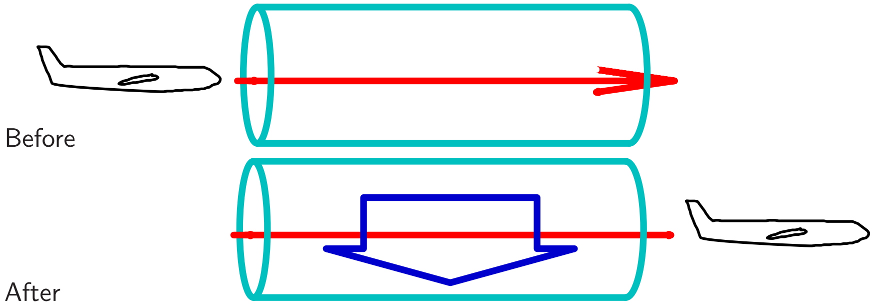


Figure C.2. A plane encounters a stationary tube of air. Once the plane has passed by, the air has been thrown downwards by the plane. The force exerted by the plane on the air to accelerate it downwards is equal and opposite to the upwards force exerted on the plane by the air.

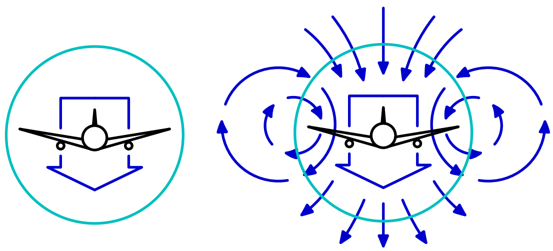


Figure C.3. Our cartoon assumes that the plane leaves a sausage of air moving down in its wake. A realistic picture involves a more complex swirling flow. For the real thing, see figure C.4.

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're going to 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_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 (figures C.3 & C.4). 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

$$m_{\text{sausage}} = \text{density} \times \text{volume} = \rho v t A_s. \tag{C.3}$$

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

Figure C.4. Air flow behind a plane. Photo by NASA Langley Research Center.

its weight mg. The downward momentum of the sausage created in time t is

$$\text{mass} \times \text{velocity} = m_{\text{sausage}} u = \rho v t A_s u. \tag{C.4}$$

And by Newton's laws this must equal the momentum delivered by the plane's weight in time t, namely,

$$mgt. \tag{C.5}$$

Rearranging this equation,

$$\rho v t A_s u = mgt, \tag{C.6}$$

we can solve for the required downward sausage speed,

$$u = \frac{mg}{\rho v A_s}.$$

Interesting! The sausage speed is *inversely* related to the plane's speed v. 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

$$\begin{aligned} P_{\text{lift}} &= \frac{\text{kinetic energy of sausage}}{\text{time}} && \text{(C.7)} \\ &= \frac{1}{t}\frac{1}{2} m_{\text{sausage}} u^2 && \text{(C.8)} \\ &= \frac{1}{2t} \rho v t A_s \left(\frac{mg}{\rho v A_s}\right)^2 && \text{(C.9)} \\ &= \frac{1}{2}\frac{(mg)^2}{\rho v A_s}. && \text{(C.10)} \end{aligned}$$

The total power required to keep the plane going is the sum of the drag power and the lift power:

$$\begin{aligned} P_{\text{total}} &= P_{\text{drag}} + P_{\text{lift}} && \text{(C.11)} \\ &= \frac{1}{2} c_d \rho A_p v^3 + \frac{1}{2}\frac{(mg)^2}{\rho v A_s}, && \text{(C.12)} \end{aligned}$$

where A_p is the frontal area of the plane and c_d is its drag coefficient (as in Chapter A).

The fuel-efficiency of the plane, expressed as the energy per distance travelled, would be

$$\left.\frac{\text{energy}}{\text{distance}}\right|_{\text{ideal}} = \frac{P_{\text{total}}}{v} = \frac{1}{2} c_d \rho A_p v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}, \tag{C.13}$$

if the plane turned its fuel's power into drag power and lift power perfectly efficiently. (Incidentally, another name for "energy per distance travelled" is "force," and we can recognize the two terms above as the drag force $\frac{1}{2}c_d\rho A_p v^2$ and the lift-related force $\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}$. The sum is the force, or "thrust," 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

$$\frac{\text{energy}}{\text{distance}} = \frac{1}{\epsilon}\left(\frac{1}{2}c_d\rho A_p v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}\right). \tag{C.14}$$

This energy-per-distance 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.5). The sum of the two quantities $\frac{1}{2}c_d\rho A_p v^2$ and $\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}$ is smallest when the two quantities are equal. This phenomenon is delightfully 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

$$c_d\rho A_p v^2 = \frac{(mg)^2}{\rho v^2 A_s}, \tag{C.15}$$

i.e.,

$$\rho v_{\text{opt}}^2 = \frac{mg}{\sqrt{c_d A_p A_s}}, \tag{C.16}$$

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 (330 m/s); 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 a 747 and for 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.6) are more accurate than we have a right to expect! The 747's optimal speed is predicted to 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.13) is compatible with the known thrust of the 747. Remembering that at the optimal speed, the two forces are equal, we just

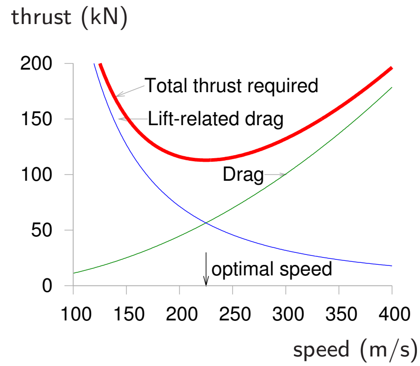


Figure C.5. The force required to keep a plane moving, as a function of its speed v, is the sum of an ordinary drag force $\frac{1}{2}c_d\rho A_p v^2$ – which increases with speed – and the lift-related force (also known as the induced drag) $\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}$ – which decreases 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 kilonewtons, for a Boeing 747 of mass 319 t, wingspan 64.4 m, drag coefficient 0.03, and frontal area 180 m^2, travelling in air of density $\rho = 0.41$ 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 m^2	0.09 m^2
Density	ρ	0.4 kg/m^3	1.2 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.6. 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.

need to pick one of them and double it:

$$\text{force} = \left.\frac{\text{energy}}{\text{distance}}\right|_{\text{ideal}} = \frac{1}{2}c_d\rho A_p v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s} \quad (C.17)$$

$$= c_d\rho A_p v_{opt}^2 \quad (C.18)$$

$$= c_d\rho A_p \frac{mg}{\rho(c_d A_p A_s)^{1/2}} \quad (C.19)$$

$$= \left(\frac{c_d A_p}{A_s}\right)^{1/2} mg. \quad (C.20)$$

Let's define the filling factor f_A to be the area ratio:

$$f_A = \frac{A_p}{A_s}. \quad (C.21)$$

(Think of f_A as the fraction of the square occupied by the plane in figure C.7.) Then

$$\text{force} = (c_d f_A)^{1/2}(mg). \quad (C.22)$$

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; typical values are shown in table C.8.)

Taking the jumbo jet's figures, $c_d \simeq 0.03$ and $f_A \simeq 0.04$, we find the required thrust is

$$(c_d f_A)^{1/2} mg = 0.036\, mg = 130\,\text{kN}. \quad (C.23)$$

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 thrust is used only during take-off. During cruise, the thrust is much smaller:

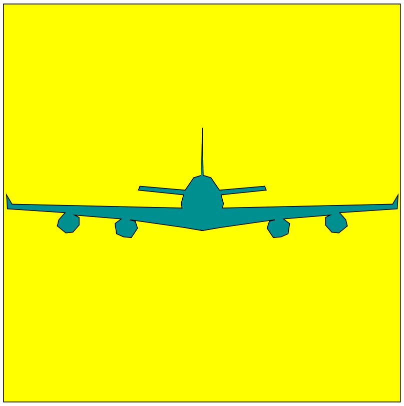


Figure C.7. Frontal view of a Boeing 747, used to estimate the frontal area A_p of the plane. The square has area A_s (the square of the wingspan).

Airbus A320	17
Boeing 767-200	19
Boeing 747-100	18
Common Tern	12
Albatross	20

Table C.8. Lift-to-drag ratios.

the thrust of a cruising 747 is 200 kN, just 50% more than our cartoon suggested. Our cartoon is a little bit off because our estimate of the drag-to-lift ratio was a little bit low.

This thrust can be used directly to deduce the transport efficiency achieved by any plane. We can work out two sorts of transport efficiency: the energy cost of moving *weight* around, measured in kWh per ton-kilometre; and the energy cost of moving people, measured in kWh per 100 passenger-kilometres.

Figure C.9. 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

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.

Here's the gross transport cost, defined to be the energy per unit weight (of the entire craft) per unit distance:

$$\text{transport cost} = \frac{1}{\epsilon}\frac{\text{force}}{\text{mass}} \tag{C.24}$$

$$= \frac{1}{\epsilon}\frac{(c_{\rm d} f_A)^{1/2} mg}{m} \tag{C.25}$$

$$= \frac{(c_{\rm d} f_A)^{1/2}}{\epsilon} g. \tag{C.26}$$

So the transport cost is just a dimensionless quantity (related to a plane's shape and its engine's efficiency), multiplied by g, the acceleration due to gravity. Notice that this gross transport cost applies to all planes, but depends only on three simple properties of the plane: its drag coefficient, the shape of the plane, and its engine efficiency. It doesn't depend on the size of the plane, nor on its weight, nor on the density of air. If we plug in $\epsilon = 1/3$ and assume a lift-to-drag ratio of 20 we find the gross transport cost of *any* plane, according to our cartoon, is

$$0.15\, g$$

or

$$0.4\,\text{kWh/ton-km}.$$

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. The aerodynamics community 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). Adding 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). And equation (C.26) says that the transport cost is proportional to the square root of the drag coefficient, so improvements of c_d by 15% or 18% would improve transport cost by 7.5% and 9% respectively.

This gross transport cost is the energy cost 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, 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 cost is

$$0.45\,g,$$

or roughly 1.2 kWh/ton-km. This is just a little bigger than the transport cost of a truck, which is 1 kWh/ton-km.

Figure C.10. "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.

Transport efficiency in terms of bodies

Similarly, we can estimate a passenger transport-efficiency for a 747.

$$\begin{aligned} &\text{transport efficiency (passenger–km per litre of fuel)} \\ &= \text{number of passengers} \times \frac{\text{energy per litre}}{\frac{\text{thrust}}{\epsilon}} && \text{(C.27)} \\ &= \text{number of passengers} \times \frac{\epsilon \times \text{energy per litre}}{\text{thrust}} && \text{(C.28)} \\ &= 400 \times \frac{1}{3}\frac{38\,\text{MJ/litre}}{200\,000\,\text{N}} && \text{(C.29)} \\ &= 25\,\text{passenger–km per litre} && \text{(C.30)} \end{aligned}$$

This is a bit more efficient than a typical single-occupant car (12 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.

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.22), 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. If you ordered a plane to go slower, its energy consumption would *increase*. The only way to make a plane consume fuel more efficiently 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. (See pages 37 and 132 for further discussion of the notion that new super-jumbos are "far more efficient" than old jumbos; and p35 for discussion of the notion that turboprops are "far more efficient" than jets.)

Figure C.11. 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 – the biggest distance it can go without refuelling? 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:

$$\text{range} = v_{\text{opt}} \frac{\text{energy}}{\text{power}} = \frac{\text{energy} \times \epsilon}{\text{force}}. \tag{C.31}$$

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

$$\text{range} = \frac{\text{energy}\,\epsilon}{\text{force}} = \frac{Cm\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}(mg)} = \frac{\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}} \frac{C}{g}. \tag{C.32}$$

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 goose fat or jet fuel: both these fuels are essentially hydrocarbons $(CH_2)_n$. Jet fuel has a calorific value of $C = 40\,\text{MJ}$ per kg. The distance associated with jet fuel is

$$d_{\text{Fuel}} = \frac{C}{g} = 4000\,\text{km}. \tag{C.33}$$

The range of the bird 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 drag-to-lift ratio $(c_{\text{d}} f_A)^{1/2} \simeq 1/20$, 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 three times the fuel's distance – roughly 13 000 km.

This figure is again close to the true answer: the nonstop flight record for a 747 (set on 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 recorded non-stop flight by a bird was a distance of 11 000 km, by a bar-tailed godwit.

How far did Steve Fossett go in the specially-designed Scaled Composites Model 311 Virgin Atlantic GlobalFlyer? 41 467 km. [33ptcg] 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: if we ask "what's the optimum air-density to fly in?", we find that the *thrust* required (C.20) at the optimum speed is independent of the density. So our cartoon plane would be equally happy to fly at any height; there isn't an optimum density; the plane could achieve the same miles-per-gallon in any density; but the optimum *speed* does depend on the density ($v^2 \sim 1/\rho$, equation (C.16)). 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 ($v^2 \sim mg/(\rho(c_{\text{d}} A_{\text{p}} A_{\text{s}})^{1/2})$). So a plane travelling in air of constant density should slow down a little as it gets lighter. 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.

You can think of d_{Fuel} 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.] This distance is also 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.

How would a hydrogen plane perform?

We've already argued that the efficiency of flight, in terms of energy per ton-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.

Possible areas for improvement of plane efficiency

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 (Green, 2006). Multi-stage long-distance flying might be about 15% more fuel-efficient; but of course it would introduce other costs.

Eco-friendly aeroplanes

Occasionally you may hear about people making eco-friendly aeroplanes. Earlier in this chapter, however, our cartoon made the assertion that the transport cost of *any* plane is about

$$0.4\,\text{kWh/ton-km}.$$

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 new-fangled 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 0.4 kWh per ton-km benchmark. If a plane uses less than 0.4 kWh per ton-km, we might conclude that the cartoon is defective.

Figure C.12. The Electra F-WMDJ: 11 kWh per 100 p-km. Photo by Jean–Bernard Gache. www.apame.eu

The Electra, a wood-and-fabric single-seater, flew for 48 minutes for 50 km around the southern Alps [6r32hf]. The Electra has a 9-m wingspan and an 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 23rd December, 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 cost was roughly

$$0.4\,\text{kWh/ton-km},$$

which exactly matches our cartoon. 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. If one could replace traditional planes by alternatives with equal energy

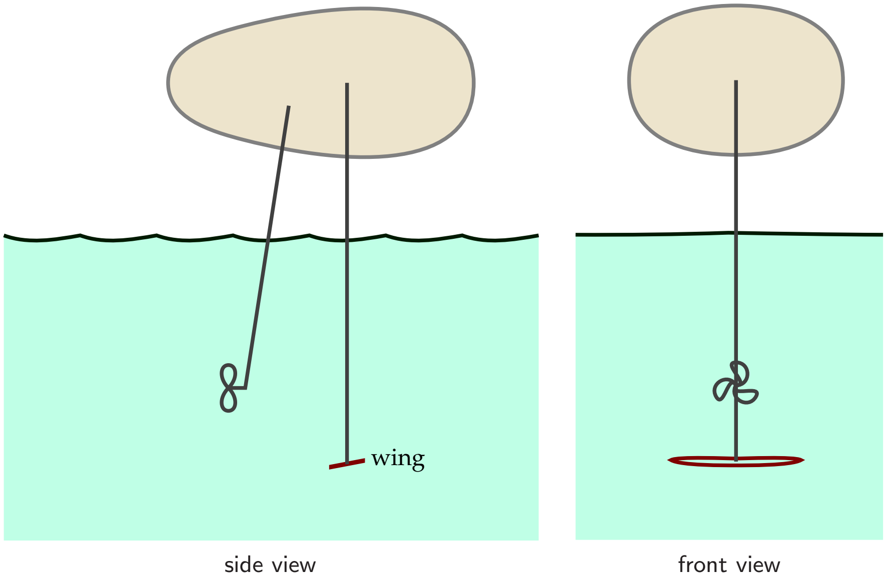


Figure C.13. Hydrofoil. Photograph by Georgios Pazios.

consumption but no carbon emissions, that would certainly be a useful technology. And, as a person-transporter, the Electra delivers a respectable 11 kWh per 100 p-km, similar to the electric car in our transport diagram on p128. But in this book 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 realized 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.13 shows the principle of the hydrofoil. The weight of the craft is supported by a tilted 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 best possible transport cost, in the sense of energy per ton-kilometre, will be just the same as in equation (C.26):

$$\frac{(c_{\rm d} f_A)^{1/2}}{\epsilon} g, \tag{C.34}$$

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_d and f_A are not quite the same as those of an optimized aeroplane. But the remarkable thing about this theory is that it has no dependence on the density of the fluid through which the wing is flying. So our ballpark prediction is that the transport cost (energy-per-distance-per-weight, including the vehicle weight) of a hydrofoil is *the same* as the transport cost of an aeroplane! Namely, roughly 0.4 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-cost 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 ton-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 probably uses less energy too.

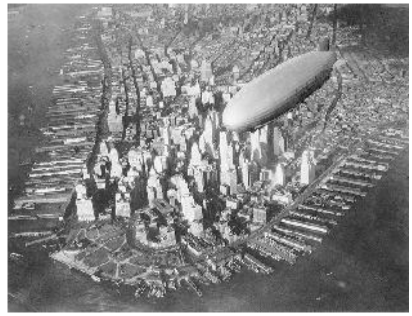


Figure C.14. The 239 m-long USS Akron (ZRS-4) flying over Manhattan. It weighed 100 t and could carry 83 t. Its engines had a total power of 3.4 MW, and it could transport 89 personnel and a stack of weapons at 93 km/h. It was also used as an aircraft carrier.

Other ways of staying up

Airships

This chapter has emphasized that planes can't be made more energy-efficient by slowing them down, because any benefit from reduced air-resistance is more than cancelled by having to chuck air down harder. Can this problem be solved by switching strategy: not throwing air down, but being as light as air instead? An airship, blimp, zeppelin, or dirigible uses an enormous helium-filled balloon, which is lighter than air, to counteract the weight of its little cabin. The disadvantage of this strategy is that the enormous balloon greatly increases the air resistance of the vehicle.

The way to keep the energy cost of an airship (per weight, per distance) low is to move slowly, to be fish-shaped, and to be very large and long. Let's work out a cartoon of the energy required by an idealized airship.

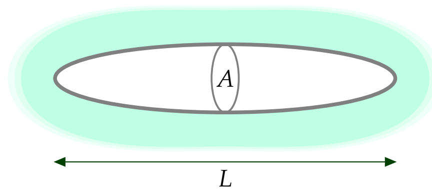


Figure C.15. An ellipsoidal airship.

I'll assume the balloon is ellipsoidal, with cross-sectional area A and length L. The volume is $V = \frac{2}{3}AL$. If the airship floats stably in air of density ρ, the total mass of the airship, including its cargo and its helium, must be $m_{\text{total}} = \rho V$. If it moves at speed v, the force of air resistance is

$$F = \frac{1}{2} c_d A \rho v^2, \tag{C.35}$$

where c_d is the drag coefficient, which, based on aeroplanes, we might expect to be about 0.03. The energy expended, per unit distance, is equal to F divided by the efficiency ϵ of the engines. So the gross transport cost – the energy used per unit distance per unit mass – is

$$\frac{F}{\epsilon m_{\text{total}}} = \frac{\frac{1}{2} c_d A \rho v^2}{\epsilon \rho \frac{2}{3} A L} \tag{C.36}$$

$$= \frac{3}{4\epsilon} c_{\rm d} \frac{v^2}{L} \tag{C.37}$$

That's a rather nice result! The gross transport cost of this idealized airship depends only its speed v and length L, not on the density ρ of the air, nor on the airship's frontal area A.

This cartoon also applies without modification to submarines. The gross transport cost (in kWh per ton-km) of an airship is just the same as the gross transport cost of a submarine of identical length and speed. The submarine will contain 1000 times more mass, since water is 1000 times denser than air; and it will cost 1000 times more to move it along. The only difference between the two will be the advertising revenue.

So, let's plug in some numbers. Let's assume we desire to travel at a speed of 80 km/h (so that crossing the Atlantic takes three days). In SI units, that's 22 m/s. Let's assume an efficiency ϵ of 1/4. To get the best possible transport cost, what is the longest blimp we can imagine? The Hindenburg was 245 m long. If we say $L = 400$ m, we find the transport cost is:

$$\frac{F}{\epsilon m_{\rm total}} = 3 \times 0.03 \frac{(22\,{\rm m/s})^2}{400\,{\rm m}} = 0.1\,{\rm m/s}^2 = 0.03\,{\rm kWh/t\text{-}km}.$$

If useful cargo made up half of the vessel's mass, the net transport cost of this monster airship would be 0.06 kWh/t-km – similar to rail.

Ekranoplans

The ekranoplan, or water-skimming wingship, is a ground-effect aircraft: an aircraft that flies very close to the surface of the water, obtaining its lift not from hurling air down like a plane, nor from hurling water down like a hydrofoil or speed boat, but by sitting on a cushion of compressed air sandwiched between its wings and the nearby surface. You can demonstrate the ground effect by flicking a piece of card across a flat table. Maintaining this air-cushion requires very little energy, so the ground-effect aircraft, in energy terms, is a lot like a surface vehicle with no rolling resistance. Its main energy expenditure is associated with air resistance. Remember that for a plane at its optimal speed, half of its energy expenditure is associated with air resistance, and half with throwing air down.

The Soviet Union developed the ekranoplan as a military transport vehicle and missile launcher in the Khrushchev era. The Lun ekranoplan could travel at 500 km/h, and the total thrust of its eight engines was 1000 kN, though this total was not required once the vessel had risen clear of the water. Assuming the cruising thrust was one quarter of the maximum; that the engines were 30% efficient; and that of its 400-ton weight, 100 tons were cargo, this vehicle had a net freight-transport cost of 2 kWh per ton-km. I imagine that, if perfected for non-military freight transport, the ekranoplan might have a freight-transport cost about half that of an ordinary aeroplane.

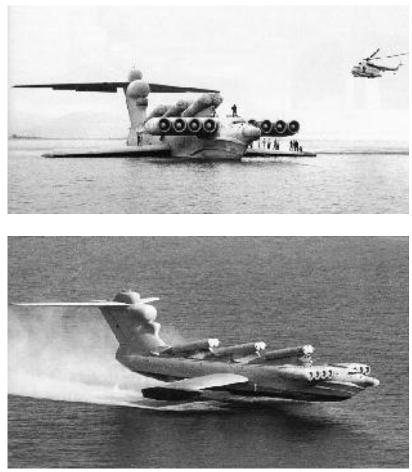


Figure C.16. The Lun ekranoplan – slightly longer and heavier than a Boeing 747. Photographs: A. Belyaev.

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.

Notes and further reading

page no.

272 *Boeing 747.* Drag coefficient for 747 from `www.aerospaceweb.org`. Other 747 data from [`2af5gw`]. Albatross facts from [`32judd`].

– *Real jet engines have an efficiency of about $\epsilon = 1/3$.* Typical engine efficiencies are in the range 23%–36% [`adg.stanford.edu/aa241/propulsion/sfc.html`]. For typical aircraft, overall engine efficiency ranges between 20% and 40%, with the best bypass engines delivering 30–37% when cruising [`www.grida.no/climate/ipcc/aviation/097.htm`]. You can't simply pick the most efficient engine however, since it may be heavier (I mean, it may have bigger mass per unit thrust), thus reducing overall plane efficiency.

277 *The longest recorded non-stop flight by a bird...*
New Scientist 2492. "Bar-tailed godwit is king of the skies." 26 March, 2005.
11 September, 2007: Godwit flies 11 500 km non-stop from Alaska to New Zealand. [`2qbquv`]

278 *Optimizing hop lengths: the sweet spot is when the hops are about 5000 km long.* Source: Green (2006).

280 *Data for a passenger-carrying catamaran.* From [`5h6xph`]: 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-cost of 0.93 kWh per ton-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 p-km.

281 *The Lun ekranoplan.* Sources: `www.fas.org` [`4p3yco`], (Taylor, 2002a).

Further reading: Tennekes (1997), Shyy et al. (1999).

D Solar II

Figure D.1. Two trees.

On p42 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 plausible contribution of each of these processes in turn. In practice, many of these methods require so much energy to be put *in* along the way that they are scarcely net contributors (figure 6.14). But in what follows, I'll ignore such embodied-energy costs.

Energy crops as a coal substitute

If we grow in Britain energy crops such as willow, miscanthus, or poplar (which have an average power of 0.5 W per square metre of land), then shove them in a 40%-efficient power station, the resulting power per unit area is 0.2 W/m^2. If one eighth of Britain (500 m^2 per person) were covered in these plantations, the resulting power would be 2.5 kWh/d per person.

Petroleum substitution

There are several ways to turn plants into liquid fuels. I'll express the potential of each method in terms of its power per unit area (as in figure 6.11).

Britain's main biodiesel crop, rape

Figure D.2. Oilseed rape. If used to create biodiesel, the power per unit area of rape is 0.13 W/m^2. Photo by Tim Dunne.

Typically, rape is sown in September and harvested the following August. Currently 450 000 hectares of oilseed rape are grown in the UK each year. (That's 2% of the UK.) Fields of rape produce 1200 litres of biodiesel per hectare per year; biodiesel has an energy of 9.8 kWh per litre; So that's a power per unit area of 0.13 W/m^2.

If we used 25% of Britain for oilseed rape, we'd obtain biodiesel with an energy content of 3.1 kWh/d per person.

Sugar beet to ethanol

Sugar beet, in the UK, delivers an impressive yield of 53 t per hectare per year. And 1 t of sugar beet makes 108 litres of bioethanol. Bioethanol has an energy density of 6 kWh per litre, so this process has a power per unit area of 0.4 W/m^2, not accounting for energy inputs required.

Bioethanol from sugar cane

Where sugar cane can be produced (e.g., Brazil) production is 80 tons per hectare per year, which yields about 17 600 l of ethanol. Bioethanol has an energy density of 6 kWh per litre, so this process has a power per unit area of 1.2 W/m^2.

Bioethanol from corn in the USA

The power per unit area of bioethanol from corn is astonishingly low. Just for fun, let's report the numbers first in archaic units. 1 acre produces 122 bushels of corn per year, which makes 122 × 2.6 US gallons of ethanol, which at 84 000 BTU per gallon means a power per unit area of just 0.02 W/m^2 – and we haven't taken into account any of the energy losses in processing!

Cellulosic ethanol from switchgrass

Cellulosic ethanol – the wonderful "next generation" biofuel? Schmer et al. (2008) found that the net energy yield of switchgrass grown over five years on marginal cropland on 10 farms in the midcontinental US was 60 GJ per hectare per year, which is 0.2 W/m^2. "This is a baseline study that represents the genetic material and agronomic technology available for switchgrass production in 2000 and 2001, when the fields were planted. Improved genetics and agronomics may further enhance energy sustainability and biofuel yield of switchgrass."

Jatropha also has low power per unit area

Jatropha is an oil-bearing crop that grows best in dry tropical regions (300–1000 mm rain per year). It likes temperatures 20–28 °C. The projected yield in hot countries on good land is 1600 litres of biodiesel per hectare per year. That's a power per unit area of 0.18 W/m^2. On wasteland, the yield is 583 litres per hectare per year. That's 0.065 W/m^2.

If people decided to use 10% of Africa to generate 0.065 W/m^2, and shared this power between six billion people, what would we all get? 0.8 kWh/d/p. For comparison, world oil consumption is 80 million barrels per day, which, shared between six billion people, is 23 kWh/d/p. So even if *all* of Africa were covered with jatropha plantations, the power produced would be only one third of world oil consumption.

What about algae?

Algae are just plants, so everything I've said so far applies to algae. Slimy underwater plants are no more efficient at photosynthesis than their terrestrial cousins. But there is one trick that I haven't discussed, which is

	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
coal	8
straw	4.2
poultry litter	2.4
general indust'l waste	4.4
hospital waste	3.9
municipal solid waste	2.6
refuse-derived waste	5.1
tyres	8.9

Table D.3. Calorific value of wood and similar things. Sources: Yaros (1997); Ucuncu (1993), Digest of UK Energy Statistics 2005.

standard practice in the algae-to-biodiesel community: they grow their algae in water heavily enriched with carbon dioxide, which might be collected from power stations or other industrial facilities. It takes much less effort for plants to photosynthesize if the carbon dioxide has already been concentrated for them. In a sunny spot in America, in ponds fed with concentrated CO_2 (concentrated to 10%), Ron Putt of Auburn University says that algae can grow at 30 g per square metre per day, producing 0.01 litres of biodiesel per square metre per day. This corresponds to a power per unit pond area of 4 W/m^2 – similar to the Bavaria photovoltaic farm. If you wanted to drive a typical car (doing 12 km per litre) a distance of 50 km per day, then you'd need 420 square metres of algae-ponds just to power your car; for comparison, the area of the UK per person is 4000 square metres, of which 69 m^2 is water (figure 6.8). Please don't forget that it's essential to feed these ponds with concentrated carbon dioxide. So this technology would be limited both by land area – how much of the UK we could turn into algal ponds – and by the availability of concentrated CO_2, the capture of which would have an energy cost (a topic discussed in Chapters 23 and 31). Let's check the limit imposed by the concentrated CO_2. To grow 30 g of algae per m^2 per day would require at least 60 g of CO_2 per m^2 per day (because the CO_2 molecule has more mass per carbon atom than the molecules in algae). If all the CO_2 from all UK power stations were captured (roughly $2^1/2$ tons per year per person), it could service 230 square metres per person of the algal ponds described above – roughly 6% of the country. This area would deliver biodiesel with a power of 24 kWh per day per person, assuming that the numbers for sunny America apply here. A plausible vision? Perhaps on one tenth of that scale? I'll leave it to you to decide.

What about algae in the sea?

Remember what I just said: the algae-to-biodiesel posse always feed their algae concentrated CO_2. If you're going out to sea, presumably pumping CO_2 into it won't be an option. And without the concentrated CO_2, the productivity of algae drops 100-fold. For algae in the sea to make a difference, a country-sized harvesting area in the sea would be required.

What about algae that produce hydrogen?

Trying to get slime to produce hydrogen in sunlight is a smart idea because it cuts out a load of chemical steps normally performed by carbohydrate-producing plants. Every chemical step reduces efficiency a little. Hydrogen can be produced directly by the photosynthetic system, right at step one. A research study from the National Renewable Energy Laboratory in Colorado predicted that a reactor filled with genetically-modified green algae, covering an area of 11 hectares in the Arizona desert, could produce 300 kg of hydrogen per day. Hydrogen contains 39 kWh per kg, so this algae-to-hydrogen facility would deliver a power per unit area of 4.4 W/m^2. Taking into account the estimated electricity required to run the facility, the net power delivered would be reduced to 3.6 W/m^2. That strikes me as still quite a promising number – compare it with the Bavarian solar photovoltaic farm, for example (5 W/m^2).

Food for humans or other animals

Grain crops such as wheat, oats, barley, and corn have an energy density of about 4 kWh per kg. In the UK, wheat yields of 7.7 tons per hectare per year are typical. If the wheat is eaten by an animal, the power per unit area of this process is 0.34 W/m^2. If 2800 m^2 of Britain (that's all agricultural land) were devoted to the growth of crops like these, the chemical energy generated would be about 24 kWh/d per person.

Incineration of agricultural by-products

We found a moment ago that the power per unit area of a biomass power station burning the best energy crops is 0.2 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 (2000 m^2 per person) and trucked to power stations, and that general agricultural by-products deliver 10% as much power per unit area as the best energy crops: 0.02 W/m^2. Multiplying this by 2000 m^2 we get 1 kWh per day per person.

Have I been unfair to 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 tons 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 per person, or 0.2 kWh/day per person.

Let's calculate this another way. UK straw production is 10 million tons per year, or 0.46 kg per day per person. At 4.2 kWh per kg, this straw has a chemical energy of 2 kWh per day per person. If all the straw were burned in 30%-efficient power stations – a proposal that wouldn't go down well with farm animals, who have other uses for straw – the electricity generated would be 0.6 kWh/d per person.

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 tons of household waste per year can generate 50 000 m^3 per hour of methane.

In 1994, landfill methane emissions were estimated to be 0.05 m^3 per person per day, which has a chemical energy of 0.5 kWh/d per person, and would generate 0.2 kWh(e)/d per person, if it were all converted to electricity with 40% efficiency. Landfill gas emissions are declining because of changes in legislation, and are now roughly 50% lower.

Burning household waste

SELCHP ("South East London Combined Heat and Power") [www.selchp.com] is a 35 MW power station that is paid to burn 420 kt per year of black-bag waste from the London area. They burn the waste as a whole, without sorting. After burning, 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 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 of electricity. The carbon emissions are about 1000 g CO_2 per kWh. Of the 35 MW generated, about 4 MW is used by the plant itself to run its machinery and filtering processes.

Scaling this idea up, 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.

This is similar to the figure estimated above for methane capture at landfill sites. And remember, we can't have both. More waste incineration means less methane gas leaking out of landfill sites. See figure 27.2, p206, and figure 27.3, p207, for further data on waste incineration.

Figure D.4. SELCHP – your trash is their business.

Notes and further reading

page no.

283 *The power per unit area of using willow, miscanthus, or poplar, for electricity is 0.2 W/m^2.* Source: Select Committee on Science and Technology Minutes of Evidence – Memorandum from the Biotechnology & Biological Sciences Research Council [www.publications.parliament.uk/pa/ld200304/ldselect/ldsctech/126/4032413.htm]. "Typically a sustainable crop of 10

dry t/ha/y of woody biomass can be produced in Northern Europe. ... Thus an area of 1 km^2 will produce 1000 dry t/y – enough for a power output 150 kWe at low conversion efficiencies or 300 kWe at high conversion efficiencies." This means 0.15–0.3 W(e)/m^2.
See also Layzell et al. (2006), [3ap7lc].

283 *Oilseed rape.* Sources: Bayer Crop Science (2003), Evans (2007), www.defra.gov.uk.

– *Sugar beet.* Source: statistics.defra.gov.uk/esg/default.asp

284 *Bioethanol from corn.* Source: Shapouri et al. (1995).

– *Bioethanol from cellulose.* See also Mabee et al. (2006).

– *Jatropha.* Sources: Francis et al. (2005), Asselbergs et al. (2006).

285 *In America, in ponds fed with concentrated CO_2, algae can grow at 30 grams per square metre per day, producing 0.01 litres of biodiesel per square metre per day.* Source: Putt (2007). This calculation has ignored the energy cost of running the algae ponds and processing the algae into biodiesel. Putt describes the energy balance of a proposed design for a 100-acre algae farm, powered by methane from an animal litter digester. The farm described would in fact produce less power than the methane power input. The 100-acre farm would use 2600 kW of methane, which corresponds to an input power density of 6.4 W/m^2. To recap, the power density of the output, in the form of biodiesel, would be just 4.2 W/m^2. All proposals to make biofuels should be approached with a critical eye!

286 *A research study from the National Renewable Energy Laboratory predicted that genetically-modified green algae, covering an area of 11 hectares, could produce 300 kg of hydrogen per day.* Source: Amos (2004).

– *Elean power station.* Source: Government White Paper (2003). Elean Power Station (36 MW) – the UK's first straw-fired power plant. *Straw production:* www.biomassenergycentre.org.uk.

287 *Landfill gas.* Sources: Matthew Chester, City University, London, personal communication; Meadows (1996), Aitchison (1996); Alan Rosevear, UK Representative on Methane to Markets Landfill Gas Sub-Committee, May 2005 [4hamks].

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, as we'll see.

Conduction loss

The rate of conduction of heat through a wall, ceiling, floor, or window is the product of three things: the area of the wall, a measure of conductivity of the wall known in the trade as the "U-value" or thermal transmittance, and the temperature difference –

$$\text{power loss} = \text{area} \times U \times \text{temperature difference}.$$

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. (See table E.2.)

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:

$$u_{\text{series combination}} = 1 \Big/ \left(\frac{1}{u_1} + \frac{1}{u_2} \right).$$

There's a worked example using this rule on page 296.

Ventilation loss

To work out the heat required to warm up incoming cold air, we need the heat capacity of air: $1.2\,\text{kJ/m}^3\text{/K}$.

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 N of the air per hour, the volume V of the space in cubic metres, the heat capacity C, and the temperature difference ΔT between the inside and

kitchen	2
bathroom	2
lounge	1
bedroom	0.5

Table E.1. Air changes per hour: typical values of N for draught-proofed rooms. The worst draughty rooms might have $N = 3$ air changes per hour. The recommended minimum 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).

	U-values (W/m^2/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 in brick-block cavity wall, unfilled	1.0		
11 in 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		
triple-glazed	0.7–0.9		

Table E.2. U-values of walls, floors, roofs, and windows.

outside of the building.

$$\begin{aligned}\text{power (watts)} &= C\frac{N}{1\,\text{h}}V(\text{m}^3)\Delta T(\text{K}) &\text{(E.1)}\\ &= (1.2\,\text{kJ/m}^3/\text{K})\frac{N}{3600\,\text{s}}V(\text{m}^3)\Delta T(\text{K}) &\text{(E.2)}\\ &= \frac{1}{3}NV\Delta T. &\text{(E.3)}\end{aligned}$$

Energy loss and temperature demand (degree-days)

Since energy is power × time, you can write the energy lost by *conduction* through an area in a short duration as

$$\text{energy loss} = \text{area} \times U \times (\Delta T \times \text{duration}),$$

and the energy lost by *ventilation* as

$$\frac{1}{3}NV \times (\Delta T \times \text{duration}).$$

Both these energy losses have the form

$$\text{Something} \times (\Delta T \times \text{duration}),$$

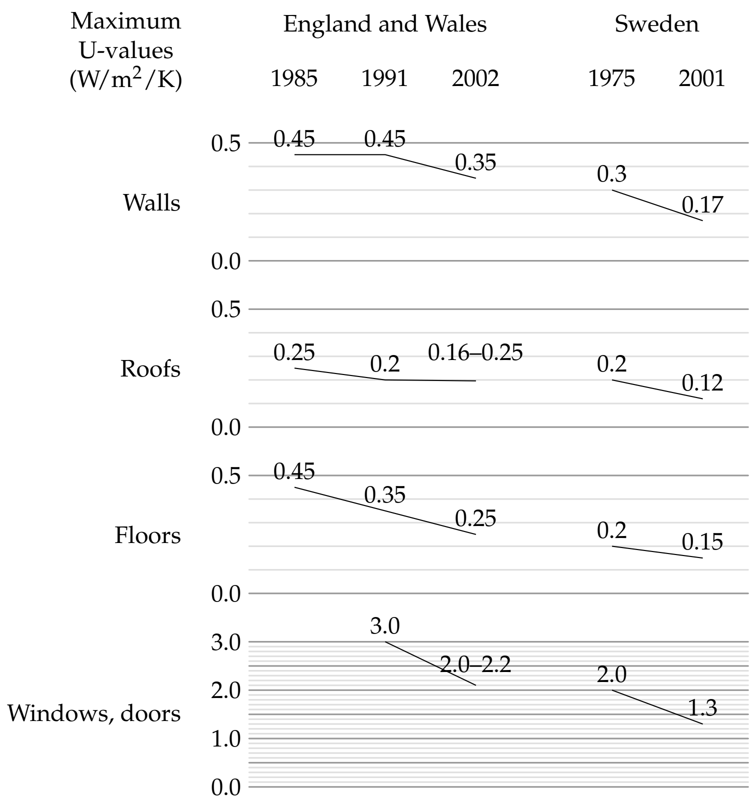


Figure E.3. U-values required by British and Swedish building regulations.

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:

1. the sum of all the Somethings (adding area $\times$ U for all walls, roofs, floors, doors, and windows, and $\frac{1}{3}NV$ for the volume); and

2. the sum of all the Temperature difference $\times$ duration factors (for 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. (This leakiness is sometimes called the building's *heat-loss coefficient*.) The second factor is a property of the weather; it's 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

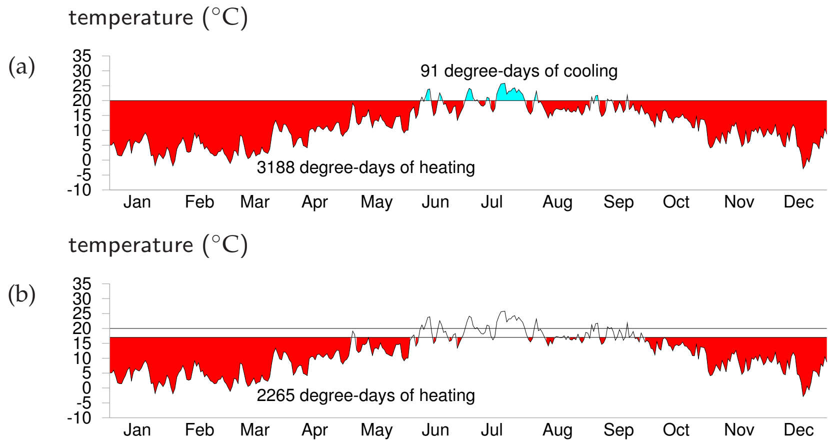


Figure E.4. The temperature demand in Cambridge, 2006, visualized as an area on a graph of daily average temperatures. (a) Thermostat set to 20 °C, including cooling in summer; (b) winter thermostat set to 17 °C.

week contributed $10 \times 7 = 70$ degree-days to the $(\Delta T \times \text{duration})$ sum. I'll call the sum of all the $(\Delta T \times \text{duration})$ factors the *temperature demand* of a period.

$$\text{energy lost} = \text{leakiness} \times \text{temperature demand}.$$

We can reduce our energy loss by reducing the leakiness of the building, or by reducing our temperature demand, or both. The next two sections look more closely at these two factors, using a house in Cambridge as a case-study.

There is a third factor we must also discuss. The lost energy is replenished by the building's heating system, and by other sources of energy such as the occupants, their gadgets, their cookers, and the sun. Focussing on the heating system, the energy *delivered* by the heating is not the same as the energy *consumed* by the heating. They are related by the *coefficient of performance* of the heating system.

$$\text{energy consumed} = \text{energy delivered}/\text{coefficient of performance}.$$

For a condensing boiler burning natural gas, for example, the coefficient of performance is 90%, because 10% of the energy is lost up the chimney.

To summarise, we can reduce the energy consumption of a building in three ways:

1. by reducing temperature demand;
2. by reducing leakiness; or
3. by increasing the coefficient of performance.

We now quantify the potential of these options. (A fourth option – increasing the building's incidental heat gains, especially from the sun – may also be useful, but I won't address it here.)

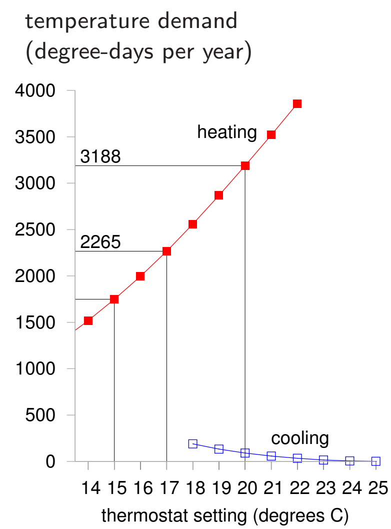


Figure E.5. Temperature demand in Cambridge, in degree-days per year, as a function of thermostat setting (°C). Reducing the winter thermostat from 20 °C to 17 °C reduces the temperature demand of heating by 30%, from 3188 to 2265 degree-days. Raising the summer thermostat from 20 °C to 23 °C reduces the temperature demand of cooling by 82%, from 91 to 16 degree-days.

Temperature demand

We can visualize the temperature demand nicely on a graph of external temperature versus time (figure E.4). For a building held at a temperature of 20 °C, the total temperature demand is the *area* between the horizontal 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 air-conditioning. 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 give an exact prediction only if we take into account two details: first, buildings naturally absorb energy from the sun, boosting the inside above the outside temperature, even without any heating; and second, 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 "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 it 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.6 shows this replotted temperature demand. Expressed this way, the temperature demand is simply the *average* temperature difference between inside and outside. The highlighted temperature demands are: 8.7 °C, for a thermostat setting of 20 °C; 6.2 °C, for a setting of 17 °C; and 4.8 °C, for a setting of 15 °C.

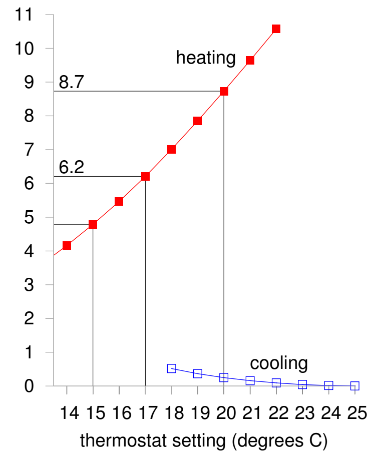


Figure E.6. The temperature demand in Cambridge, 2006, replotted in units of degree-days per day, also known as degrees. In these units, the temperature demand is just the average of the temperature difference between inside and outside.

Leakiness – example: my house

My house is a three-bedroom semi-detached house built about 1940 (figure E.7). 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 in 2006 is built up as shown in table E.8. The total leakiness of the house was 322 W/°C (or 7.7 kWh/d/°C), with conductive leakiness accounting for 72% and ventilation leakiness for 28% of the total. The conductive leakiness is roughly equally divided into three parts: windows; walls; and floor and ceiling.

Figure E.7. My house.

Conductive leakiness	area (m^2)	U-value ($W/m^2/°C$)	leakiness (W/°C)
Horizontal surfaces			
Pitched roof	48	0.6	28.8
Flat roof	1.6	3	4.8
Floor	50	0.8	40
Vertical surfaces			
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 conductive leakiness			232.4

Ventilation leakiness	volume (m^3)	N (air-changes 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

Table E.8. Breakdown of my house's conductive leakiness, and its ventilation leakiness, pre-2006. I've treated the central wall of the semi-detached house as a perfect insulating wall, but this may be wrong if the gap between the adjacent houses is actually well-ventilated.

I've highlighted the parameters that I altered after 2006, in modifications to be described shortly.

To compare the leakinesses of two buildings that have different floor areas, we can divide the leakiness by the floor area; this gives the *heat-loss parameter* of the building, 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.

On a cold day, 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.5. 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 19 °C, is therefore:

$$7.7\,\text{kWh/d/}^\circ\text{C} \times 2866\,\text{degree-days/y}/(365\,\text{days/y}) = 61\,\text{kWh/d}.$$

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.

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) – figure 21.5.
2. Increased the insulation in the roof.
3. Added a new front door outside the old – figure 21.6.
4. Replaced the back door with a 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 before the changes 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). Table E.9 shows the predicted savings from each of the modifications.

The heat-loss parameter of this house (total floor area 88 m^2) is thus hopefully reduced by about 25%, from 3.7 to 2.7 W/°C/m^2. (This is a long way from the 1.1 W/°C/m^2 required of a "sustainable" house in the new building codes.)

–	Cavity-wall insulation (applicable to two-thirds of the wall area)	4.8 kWh/d
–	Improved roof insulation	3.5 kWh/d
–	Reduction in conduction from double-glazing two doors and one window	1.9 kWh/d
–	Ventilation reductions in hall and kitchen from improvements to doors and windows	2.9 kWh/d

Table E.9. Break-down of the predicted reductions in heat loss from my house, on a cold winter day.

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%.

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 gas consumption 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%. As figure 21.4 showed, my gas consumption has gone down from 40 kWh/d to 13 kWh/d – a reduction of 67%.

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. [65h3cb] Second, condensation may form on the hidden 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 1.8-cm-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 $W/m^2/K$ to:

$$1 \Big/ \left(\frac{1}{2.2} + \frac{1}{1.7} \right) \simeq 1\,\mathrm{W/m^2/K}.$$

Definitely a worthwhile reduction.

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. A nose warms incoming air by cooling down outgoing air. There's a temperature gradient along the nose; the walls of a nose are coldest near the nostrils. The longer your nose, the better it works as a counter-current heat exchanger. In nature's noses, the direction of the air-flow usually alternates. Another way to organize a nose is to have two air-passages, one for in-flow and one for out-flow, separate from the point of view of air, but tightly coupled with each other so that heat can easily flow between the two passages. This is how the noses work in buildings. It's conventional to call these noses heat-exchangers.

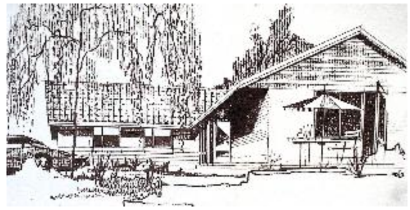


Figure E.10. The Heatkeeper Serrekunda.

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. The house is a timber-framed bungalow based on a Scandinavian "Heatkeeper Serrekunda" design (figure E.10), with a floor area of 140 m^2, composed of three bedrooms, a study, two bathrooms, a living room, a kitchen, and a 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 W/m^2/°C. 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 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' 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; in winter, pumps remove used air from several rooms, exhausting it to the outside, and they take in air from the loft space. The incoming air and outgoing air pass through a heat exchanger (figure E.11), which saves 60% of the heat in the extracted air. The heat exchanger is a passive device, using no energy: it's like a big metal nose, warming the incoming air with the outgoing 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.

Figure E.11. The Heatkeeper's heat-exchanger.

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 is now 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 15 000 kWh per year, or 40 kWh/d. Expressed as an average power per unit area, that's 6.6 W/m^2.

Figure E.12 compares the power consumption per unit area of this Heatkeeper house with my house (before and after my efficiency push) and with the European average. My house's post-efficiency-push consumption is close to that of the Heatkeeper, thanks to the adoption of lower thermostat settings.

Benchmarks for houses and offices

The German Passivhaus standard aims for power consumption for heating and cooling of 15 kWh/m^2/y, which is 1.7 W/m^2; and total power consumption of 120 kWh/m^2/y, which is 13.7 W/m^2.

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 (PV) 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

New office buildings are often hyped up as being amazingly environment-friendly. Let's look at some numbers.

The William Gates building at Cambridge University holds computer science researchers, administrators, and a small café. Its area is 11 110 m^2, and its energy consumption is 2392 MWh/y. That's a power per unit area of 215 kWh/m^2/y, or 25 W/m^2. This building won a RIBA award in 2001 for its predicted energy consumption. "The architects have incorporated many environmentally friendly features into the building." [5dhups]

But are these buildings impressive? Next door, the Rutherford building, built in the 1970s without any fancy eco-claims – indeed without even double glazing – has a floor area of 4998 m^2 and consumes 1557 MWh per year; that's 0.85 kWh/d/m^2, or 36 W/m^2. So the award-winning building is just 30% better, in terms of power per unit area, than its simple 1970s cousin. Figure E.12 compares these buildings and another new building, the Law Faculty, with the Old Schools, which are ancient offices built pre-

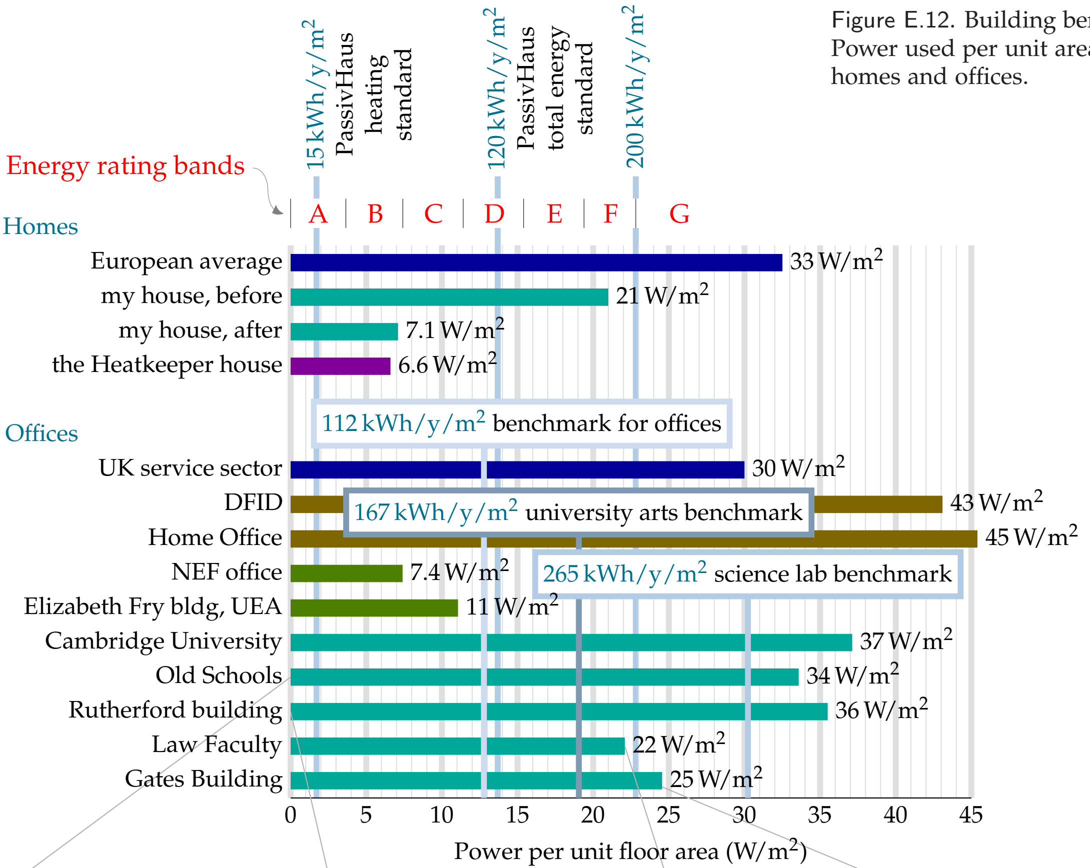


Figure E.12. Building benchmarks. Power used per unit area in various homes and offices.

Old Schools

Rutherford building

Law faculty

Gates building

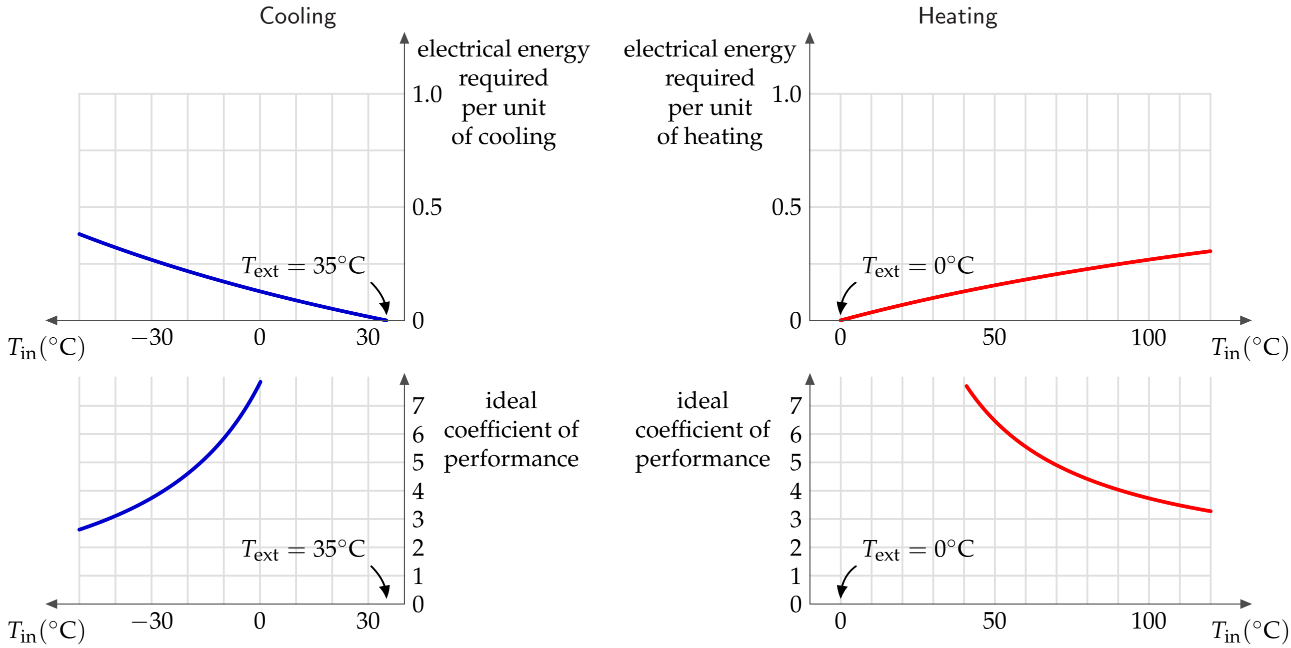


Figure E.13. Ideal heat pump efficiencies. Top left: ideal electrical energy required, according to the limits of thermodynamics, to pump heat *out* of a place at temperature T_{in} when the heat is being pumped to a place at temperature $T_{out} = 35\,°C$. Right: ideal electrical energy required to pump heat *into* a place at temperature T_{in} when the heat is being pumped from a place at temperature $T_{out} = 0\,°C$. Bottom row: the efficiency is conventionally expressed as a "coefficient of performance," which is the heat pumped per unit electrical energy. In practice, I understand that well-installed ground-source heat pumps and the best air-source heat pumps usually have a coefficient of performance of 3 or 4; however, government regulations in Japan have driven the coefficient of performance as high as 6.6.

1890. For all the fanfare, the difference between the new and the old is really quite disappointing!

Notice that the building power consumptions, per unit floor area, are in just the same units (W/m^2) as the renewable powers per unit area that we discussed on pages 43, 47, and 177. Comparing these consumption and production numbers helps us realize how difficult it is to power modern buildings entirely from on-site renewables. The power per unit area of biofuels (figure 6.11, p43) is $0.5\,W/m^2$; of wind farms, $2\,W/m^2$; of solar photovoltaics, $20\,W/m^2$ (figure 6.18, p47); only solar hot-water panels come in at the right sort of power per unit area, $53\,W/m^2$ (figure 6.3, p39).

Improving the coefficient of performance

You might think that the coefficient of performance of a condensing boiler, 90%, sounds pretty hard to beat. But it can be significantly improved upon, by heat pumps. Whereas the condensing boiler takes chemical energy and turns 90% of it into useful heat, the heat pump takes some electrical energy and uses it to *move* heat from one place to another (for example, from outside a building to inside). Usually the amount of useful heat delivered is much bigger than the amount of electricity used. A coefficient of performance of 3 or 4 is normal.

Theory of heat pumps

Here are the formulae for the ideal efficiency of a heat pump, 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 $T_{\rm in}$, by $273.15 + T_{\rm in}$), the ideal efficiency is:

$$\text{efficiency} = \frac{T_2}{T_2 - T_1}.$$

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:

$$\text{efficiency} = \frac{T_2}{T_1 - T_2}.$$

These theoretical limits could only be achieved by systems that pump heat infinitely slowly. Notice that the ideal efficiency is bigger, the closer the inside temperature T_2 is to the outside temperature T_1.

While in theory ground-source heat pumps might have better performance than air-source, because the ground temperature is usually closer than the air temperature to the indoor temperature, in practice an air-source heat pump might be the best and simplest choice. In cities, there may be uncertainty about the future effectiveness of ground-source heat pumps, because the more people use them in winter, the colder the ground gets; this thermal fly-tipping problem may also show up in the summer in cities where too many buildings use ground-source (or should I say "ground-sink"?) heat pumps for air-conditioning.

Heat capacity:	$C = 820\,\text{J/kg/K}$
Conductivity:	$\kappa = 2.1\,\text{W/m/K}$
Density:	$\rho = 2750\,\text{kg/m}^3$
Heat capacity per unit volume:	
	$C_V = 2.3\,\text{MJ/m}^3\text{/K}$

Table E.14. Vital statistics for granite. (I use granite as an example of a typical rock.)

Heating and the ground

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. 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 $0.195 \times 4200\,\text{J/kg/K} = 820\,\text{J/kg/K}$. The mass of granite required is:

$$\begin{aligned}\text{mass} &= \frac{\text{energy}}{\text{heat capacity} \times \text{temperature difference}} \\ &= \frac{24 \times 30 \times 3.6\,\text{MJ}}{(820\,\text{J/kg/°C})(50\,\text{°C} - 16\,\text{°C})} \\ &= 100\,000\,\text{kg},\end{aligned}$$

100 tonnes, which corresponds to a cuboid of rock of size $6\,\text{m} \times 6\,\text{m} \times 1\,\text{m}$.

Ground storage without walls

OK, we've established the size of a useful ground store. But is it difficult to keep the heat in? Would you need to surround your rock cuboid with lots of insulation? It turns out that the ground itself is a pretty good insulator. A spike of heat put down a hole in the ground will spread as

$$\frac{1}{\sqrt{4\pi\kappa t}} \exp\left(-\frac{x^2}{4(\kappa/(C\rho))t}\right)$$

where κ is the conductivity of the ground, C is its heat capacity, and ρ is its density. This describes a bell-shaped curve with width

$$\sqrt{2\frac{\kappa}{C\rho}t};$$

for example, after six months ($t = 1.6 \times 10^7$ s), using the figures for granite ($C = 0.82$ kJ/kg/K, $\rho = 2500$ kg/m^3, $\kappa = 2.1$ W/m/K), the width is 6 m.

Using the figures for water ($C = 4.2$ kJ/kg/K, $\rho = 1000$ kg/m^3, $\kappa = 0.6$ W/m/K), the width is 2 m.

So if the storage region is bigger than 20 m × 20 m × 20 m then most of the heat stored will still be there in six months time (because 20 m is significantly bigger than 6 m and 2 m).

	(W/m/K)
water	0.6
quartz	8
granite	2.1
earth's crust	1.7
dry soil	0.14

Table E.15. Thermal conductivities. For more data see table E.18, p304.

Limits of ground-source heat pumps

The low thermal conductivity of the ground is a double-edged sword. Thanks to low conductivity, the ground holds heat well for a long time. But on the other hand, low conductivity means that it's not easy to shove heat in and out of the ground rapidly. We now explore how the conductivity of the ground limits the use of ground-source heat pumps.

Consider a neighbourhood with quite a high population density. Can *everyone* use ground-source heat pumps, without using active summer replenishment (as discussed on p152)? The concern is that if we all sucked heat from the ground at the same time, we might freeze the ground solid. I'm going to address this question by two calculations. First, I'll work out the natural flux of energy in and out of the ground in summer and winter.

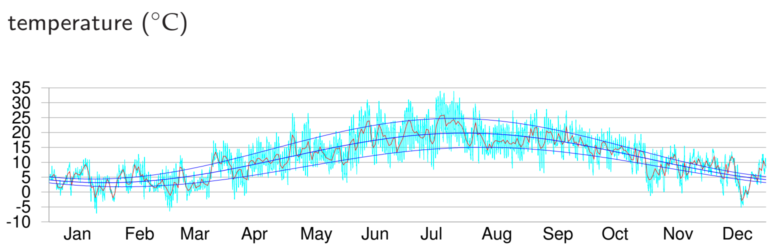


Figure E.16. The temperature in Cambridge, 2006, and a cartoon, which says the temperature is the sum of an annual sinusoidal variation between 3 °C and 20 °C, and a daily sinusoidal variation with range up to 10.3 °C. The average temperature is 11.5 °C.

If the flux we want to suck out of the ground in winter is much bigger than these natural fluxes then we know that our sucking is going to significantly alter ground temperatures, and may thus not be feasible. For this calculation, I'll assume the ground just below the surface is held, by the combined influence of sun, air, cloud, and night sky, at a temperature that varies slowly up and down during the year (figure E.16).

Response to external temperature variations

Working out how the temperature inside the ground responds, and what the flux in or out is, requires some advanced mathematics, which I've cordoned off in box E.19 (p306).

The payoff from this calculation is a rather beautiful diagram (figure E.17) that shows how the temperature varies in time at each depth. This diagram shows the answer for any material in terms of the *characteristic length-scale* z_0 (equation (E.7)), which depends on the conductivity κ and heat capacity C_V of the material, and on the frequency ω of the external temperature variations. (We can choose to look at either daily and yearly variations using the same theory.) 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 (figure E.17). 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.

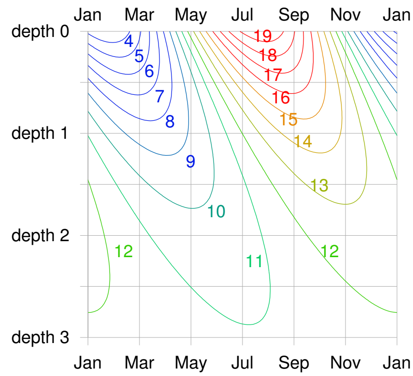


Figure E.17. Temperature (in °C) versus depth and time. The depths are given in units of the characteristic depth z_0, which for granite and annual variations is 3 m.

At "depth 2" (6 m), the temperature is always about 11 or 12 °C. At "depth 1" (3 m), it wobbles between 8 and 15 °C.

For the case of daily variations and solid granite, the characteristic length-scale is $z_0 = 0.16$ m. (So 32 cm of rock is the thickness you need to ride out external daily temperature oscillations.) For yearly variations and solid granite, the characteristic length-scale is $z_0 = 3$ m.

Let's focus on annual variations and discuss a few other materials. Characteristic length-scales for various materials are in the third column of table E.18. For damp sandy soils or concrete, the characteristic length-scale z_0 is similar to that of granite – about 2.6 m. In dry or peaty soils, the length-scale z_0 is shorter – about 1.3 m. That's perhaps good news because it means you don't have to dig so deep to find ground with a stable temperature. But it's also coupled with some bad news: the natural fluxes are smaller in dry soils.

The natural flux varies during the year and has a peak value (equation (E.9)) that is smaller, the smaller the conductivity.

For the case of solid granite, the peak flux is 8 W/m^2. For dry soils, the peak flux ranges from 0.7 W/m^2 to 2.3 W/m^2. For damp soils, the peak flux ranges from 3 W/m^2 to 8 W/m^2.

What does this mean? I suggest we take a flux in the middle of these numbers, 5 W/m^2, as a useful benchmark, giving guidance about what sort of power we could expect to extract, per unit area, with a ground-source heat pump. If we suck a flux significantly smaller than 5 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 5 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.

The population density of a typical English suburb corresponds to 160 m^2 per person (rows of semi-detached houses with about 400 m^2 per house, including pavements and streets). At this density of residential area, we can deduce that a ballpark limit for heat pump power delivery is

$$5\,\mathrm{W/m^2} \times 160\,\mathrm{m^2} = 800\,\mathrm{W} = 19\,\mathrm{kWh/d} \text{ per person.}$$

This is uncomfortably close to the sort of power we would like to deliver in winter-time: it's plausible that our peak winter-time demand for hot air and hot water, in an old house like mine, might be 40 kWh/d per person.

This calculation suggests that in a typical suburban area, *not everyone can use ground-source heat pumps*, unless they are careful to actively dump heat back into the ground during the summer.

Let's do a second calculation, working out how much power we could steadily suck from a ground loop at a depth of $h = 2$ m. Let's assume that we'll allow ourselves to suck the temperature at the ground loop down to $\Delta T = 5\,°$C below the average ground temperature at the surface, and let's assume that the surface temperature is constant. We can then deduce the heat flux from the surface. Assuming a conductivity of 1.2 W/m/K

	thermal conductivity κ (W/m/K)	heat capacity C_V (MJ/m^3/K)	length-scale z_0 (m)	flux $A\sqrt{C_V \kappa \omega}$ (W/m^2)
Air	0.02	0.0012		
Water	0.57	4.18	1.2	5.7
Solid granite	2.1	2.3	3.0	8.1
Concrete	1.28	1.94	2.6	5.8
Sandy soil				
dry	0.30	1.28	1.5	2.3
50% saturated	1.80	2.12	2.9	7.2
100% saturated	2.20	2.96	2.7	9.5
Clay soil				
dry	0.25	1.42	1.3	2.2
50% saturated	1.18	2.25	2.3	6.0
100% saturated	1.58	3.10	2.3	8.2
Peat soil				
dry	0.06	0.58	1.0	0.7
50% saturated	0.29	2.31	1.1	3.0
100% saturated	0.50	4.02	1.1	5.3

Table E.18. Thermal conductivity and heat capacity of various materials and soil types, and the deduced length-scale $z_0 = \sqrt{\frac{2\kappa}{C_V \omega}}$ and peak flux $A\sqrt{C_V \kappa \omega}$ associated with annual temperature variations with amplitude $A = 8.3\,°$C. The sandy and clay soils have porosity 0.4; the peat soil has porosity 0.8.

(typical of damp clay soil),

$$\text{Flux} = \kappa \times \frac{\Delta T}{h} = 3\,\text{W/m}^2.$$

If, as above, we assume a population density corresponding to $160\,\text{m}^2$ per person, then the maximum power per person deliverable by ground-source heat pumps, if everyone in a neighbourhood has them, is 480 W, which is 12 kWh/d per person.

So again we come to the conclusion that in a typical suburban area composed of poorly insulated houses like mine, *not everyone can use ground-source heat pumps*, unless they are careful to actively dump heat back into the ground during the summer. And in cities with higher population density, ground-source heat pumps are unlikely to be viable.

I therefore suggest air-source heat pumps are the best heating choice for most people.

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 judged too hot during the day and too cool at night, leading to greater expenditure on cooling and heating.

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 warm that small mass rapidly when required.

Notes and further reading

page no.

304 *Table E.18.* Sources: Bonan (2002), www.hukseflux.com/thermalScience/thermalConductivity.html

If we assume the ground is made of solid homogenous material with conductivity κ and heat capacity C_V, then the temperature at depth z below the ground and time t responds to the imposed temperature at the surface in accordance with the diffusion equation

$$\frac{\partial T(z,t)}{\partial t} = \frac{\kappa}{C_V}\frac{\partial^2 T(z,t)}{\partial z^2}. \tag{E.4}$$

For a sinusoidal imposed temperature with frequency ω and amplitude A at depth $z = 0$,

$$T(0,t) = T_{\text{surface}}(t) = T_{\text{average}} + A\cos(\omega t), \tag{E.5}$$

the resulting temperature at depth z and time t is a decaying and oscillating function

$$T(z,t) = T_{\text{average}} + A\, e^{-z/z_0}\cos(\omega t - z/z_0), \tag{E.6}$$

where z_0 is the characteristic length-scale of both the decay and the oscillation,

$$z_0 = \sqrt{\frac{2\kappa}{C_V\omega}}. \tag{E.7}$$

The flux of heat (the power per unit area) at depth z is

$$\kappa\frac{\partial T}{\partial z} = \kappa\frac{A}{z_0}\sqrt{2}e^{-z/z_0}\sin(\omega t - z/z_0 - \pi/4). \tag{E.8}$$

For example, at the surface, the peak flux is

$$\kappa\frac{A}{z_0}\sqrt{2} = A\sqrt{C_V\kappa\omega}. \tag{E.9}$$

Box E.19. Working out the natural flux caused by sinusoidal temperature variations.

F Waves II

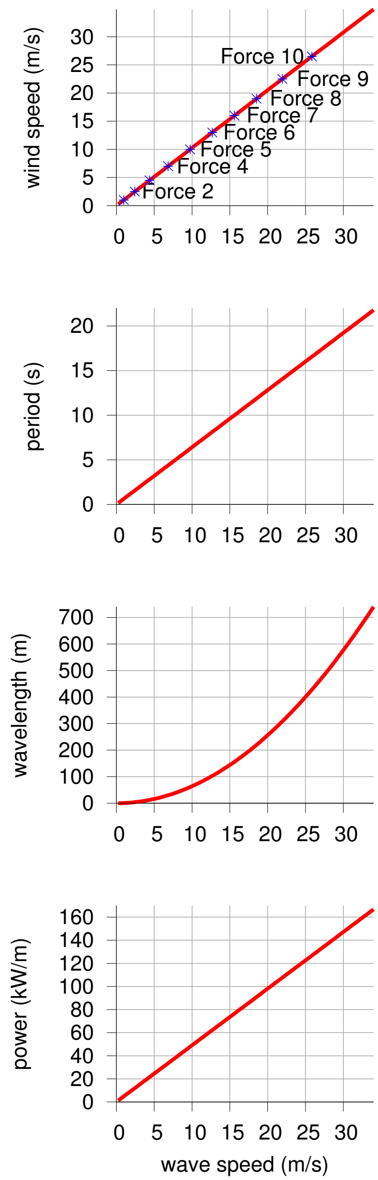


Figure F.1. Facts about deep-water waves. In all four figures the horizontal axis is the wave speed in m/s. From top to bottom the graphs show: wind speed (in m/s) required to make a wave with this wave speed; period (in seconds) of a wave; wavelength (in m) of a wave; and power density (in kW/m) of a wave with amplitude 1 m.

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 crests. The kinetic energy is associated with the water moving around.

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 focused on a bit of seaweed floating in the water as waves go by, you'd see that the seaweed moves up and down, and also 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 λ and period of the waves (the distance and time respectively between two adjacent crests) depend on the speed of the wind that creates the waves, as shown in figure F.1. 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 crest. 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 decide it's important. The speed of deep-water waves is related to the time T between crests by the physics formula (see Faber (1995), p170):

$$v = \frac{gT}{2\pi},$$

where g is the acceleration of gravity ($9.8\,\text{m/s}^2$). For example, if $T = 10$ seconds, then $v = 16\,\text{m/s}$. The wavelength of such a wave – the distance between crests – is $\lambda = vT = gT^2/2\pi = 160\,\text{m}$.

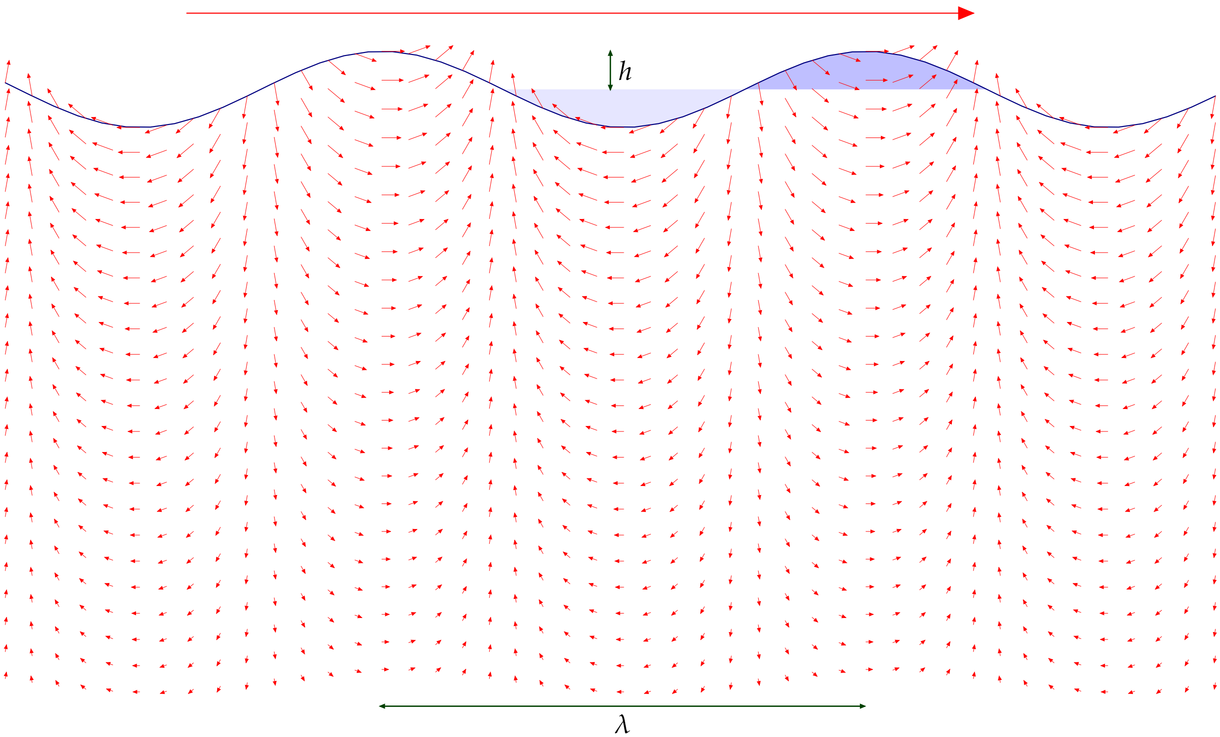


Figure F.2. A wave has energy in two forms: potential energy associated with raising water out of the light-shaded troughs into the heavy-shaded crests; and kinetic energy of all the water within a few wavelengths of the surface – the speed of the water is indicated by the small arrows. The speed of the wave, travelling from left to right, is indicated by the much bigger arrow at the top.

For a wave of wavelength λ and period T, if the height of each crest and depth of each trough is $h = 1\,\text{m}$, 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 in figure F.2 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

$$P_{\text{potential}} \simeq \frac{1}{2}\rho h\frac{\lambda}{2}gh/T. \tag{F.2}$$

(To find the potential energy properly, we should have done an integral here; it would have given the same answer.) Now λ/T is simply the speed at which the wave travels, v, so:

$$P_{\text{potential}} \simeq \frac{1}{4}\rho g h^2 v. \tag{F.3}$$

Waves have kinetic energy as well as potential energy, and, remarkably, these are exactly equal, although I don't show that calculation here; so the total power of the waves is double the power calculated from potential energy.

$$P_{\text{total}} \simeq \frac{1}{2}\rho g h^2 v. \tag{F.4}$$

There's only one thing wrong with this answer: it's too big, because we've neglected a strange property of dispersive waves: the energy in the wave doesn't actually travel at the same speed as the crests; it travels at a speed called the group velocity, which for deep-water waves is *half* of the speed v. You can see that the energy travels slower than the crests by chucking a pebble in a pond and watching the expanding waves carefully. What this means is that equation (F.4) is wrong: we need to halve it. The correct power per unit length of wave-front is

$$P_{\text{total}} = \frac{1}{4}\rho g h^2 v. \tag{F.5}$$

Plugging in $v = 16\,\text{m/s}$ and $h = 1\,\text{m}$, we find

$$P_{\text{total}} = \frac{1}{4}\rho g h^2 v = 40\,\text{kW/m}. \tag{F.6}$$

This rough estimate agrees with real measurements in the Atlantic (Mollison, 1986). (See p75.)

The 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.

Real wave power systems

Deep-water devices

How effective are real systems at extracting power from waves? Stephen Salter's "duck" has been well characterized: a row of 16-m diameter ducks, feeding off Atlantic waves with an average power of 45 kW/m, would deliver 19 kW/m, including transmission to central Scotland (Mollison, 1986).

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 a depth of about 50 m. In a wavefarm, 39 devices in three rows would face the principal wave direction, occupying an area of ocean, about 400 m long and 2.5 km wide (an area of 1 km^2). 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.

Shallow-water devices

Typically 70% of energy in ocean waves 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/m. The Oyster, developed by Queen's University Belfast and Aquamarine Power Ltd [www.aquamarinepower.com], is a bottom-mounted flap, about 12 m high, that is intended to be deployed in waters about 12 m deep, in areas where the average incident wave power is greater than 15 kW/m. Its peak power is 600 kW. A single device would produce about 270 kW in wave heights greater than 3.5 m. It's predicted that an Oyster would have a bigger power per unit mass of hardware than a Pelamis.

Oysters could also be used to directly drive reverse-osmosis desalination facilities. "The peak freshwater output of an Oyster desalinator is between 2000 and 6000 m^3/day." That production has a value, going by the Jersey facility (which uses 8 kWh per m^3), equivalent to 600–2000 kW of electricity.

G Tide II

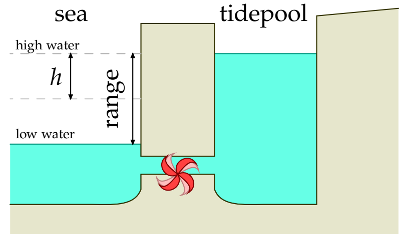


Figure G.1. A tide-pool in cross section. The pool was filled at high tide, and now it's low tide. We let the water out through the electricity generator to turn the water's potential energy into electricity.

Power density of tidal pools

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, on the ebb and on the flood. (This is called two-way generation or double-effect generation.) 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. (The range is the difference in height between low and high tide; figure G.1.) The mass per unit area covered by tide-pool is $\rho \times (2h)$, where ρ is the density of water (1000 kg/m^3). So the power per unit area generated by a tide-pool is

$$\frac{2\rho h g h}{6\,\text{hours}},$$

assuming perfectly efficient generators. Plugging in $h = 2$ m (i.e., range 4 m), we find the power per unit area of tide-pool is 3.6 W/m^2. Allowing for an efficiency of 90% for conversion of this power to electricity, we get

$$\text{power per unit area of tide-pool} \simeq 3\,\text{W/m}^2.$$

So to generate 1 GW of power (on average), we need a tide-pool with an area of about 300 km^2. A circular pool with diameter 20 km would do the trick. (For comparison, the area of the Severn estuary behind the proposed barrage is about 550 km^2, and the area of the Wash is more than 400 km^2.

If a tide-pool produces electricity in one direction only, the power per unit area is halved. The average power density of the tidal barrage at La Rance, where the mean tidal range is 10.9 m, has been 2.7 W/m^2 for decades (p87).

The raw tidal resource

The tides around Britain are genuine tidal waves. (Tsunamis, which are called "tidal waves," have nothing to do with tides: they are caused by underwater landslides and earthquakes.) The location of the high tide (the crest of the tidal wave) moves much faster than the tidal flow – 100 miles per hour, say, while the water itself moves at just 1 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 way that we estimate the power of ordinary wind-generated waves. The next section describes a standard model for the power arriving in

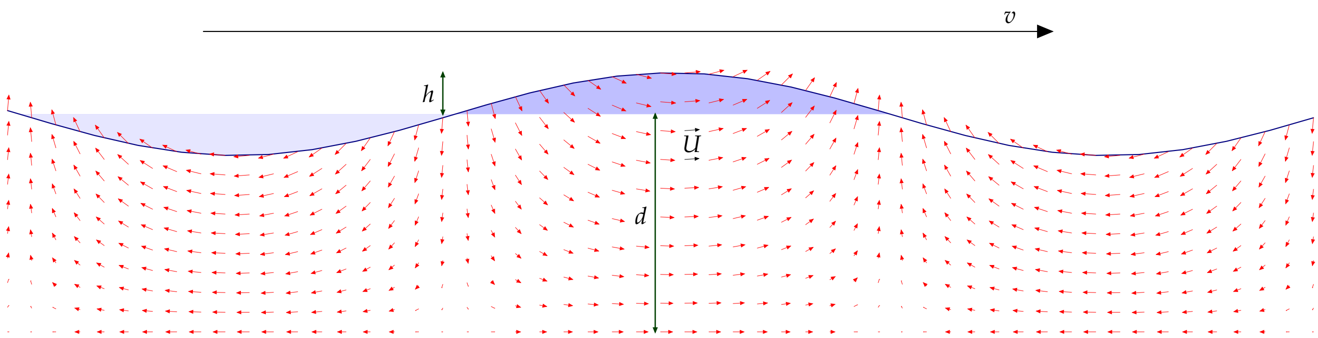


Figure G.2. A shallow-water wave. Just like a deep-water wave, the wave has energy in two forms: potential energy associated with raising water out of the light-shaded troughs into the heavy-shaded crests; and kinetic energy of all the water moving around as indicated by the small arrows. The speed of 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.

travelling waves in water of depth d that is shallow compared to the wavelength of the waves (figure G.2). The power per unit length of wavecrest of shallow-water tidal waves is

$$\rho g^{3/2}\sqrt{d}h^2/2. \tag{G.1}$$

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 150 kW/m or 600 kW/m respectively. These figures are impressive compared with the raw power per unit length of ordinary Atlantic deep-water waves, 40 kW/m (Chapter F). Atlantic waves and the Atlantic tide have similar vertical amplitudes (about 1 m), but the raw power in tides is roughly 10 times bigger than that of ordinary wind-driven waves.

Taylor (1920) worked out a more detailed model of tidal power that includes important details such as the Coriolis effect (the effect produced by the earth's daily rotation), the existence of tidal waves travelling in the opposite direction, and the direct effect of the moon on the energy flow in the Irish Sea. Since then, experimental measurements and computer models have verified and extended Taylor's analysis. Flather (1976) built a detailed numerical model of the lunar tide, chopping the continental shelf around the British Isles into roughly 1000 square cells. Flather estimated 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. As shown in figure G.4, Cartwright et al. (1980) found experimentally that the average power transmission was 60 GW between Malin Head (Ireland) and Florø (Norway) and 190 GW between Valentia (Ireland) 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.

h (m)	$\rho g^{3/2}\sqrt{d}h^2/2$ (kW/m)
0.9	125
1.0	155
1.2	220
1.5	345
1.75	470
2.0	600
2.25	780

Table G.3. Power fluxes (power per unit length of wave crest) for depth $d = 100$ m.

The power of tidal waves

This section, which can safely be skipped, provides more details behind the formula for tidal power used in the previous section. I'm going to go into this 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.2 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 100 or 200 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

$$v = \sqrt{gd}. \tag{G.2}$$

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 horizontal velocity U is proportional to the surface displacement and can be found by conservation of mass:

$$U = vh/d. \tag{G.3}$$

If the depth decreases, the wave velocity v reduces (equation (G.2)). 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, then assert that this quantity represents the power that could be extracted. This kinetic-energy-flux method was used by consultants Black and Veatch to estimate the UK resource. In our cartoon model, we can compute the total power by other means. We'll see that the kinetic-energy-flux answer is too small by a significant factor.

The peak kinetic-energy flux at any section is

$$K_{\rm BV} = \frac{1}{2}\rho A U^3, \tag{G.4}$$

where A is the cross-sectional area. (This is the formula for kinetic energy flux, which we encountered in Chapter B.)

The true total incident power is not equal to this kinetic-energy flux. 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 almost all things that wobble, be they masses on springs or children

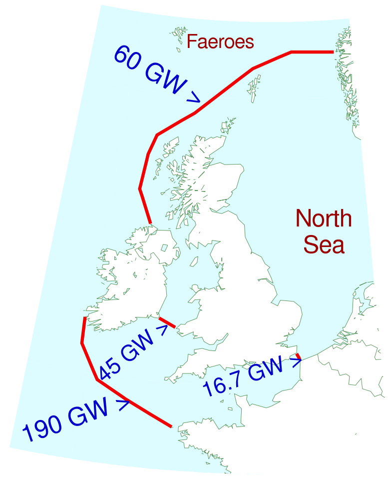


Figure G.4. Average tidal powers measured by Cartwright et al. (1980).

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. The potential energy of a wave (per wavelength and per unit width of wavefront) is found by integration to be

$$\frac{1}{4}\rho g h^2 \lambda. \tag{G.5}$$

So, doubling and dividing by the period, the true power of this model shallow-water tidal wave is

$$\text{power} = \frac{1}{2}(\rho g h^2 \lambda) \times w/T = \frac{1}{2}\rho g h^2 v \times w, \tag{G.6}$$

where w is the width of the wavefront. Substituting $v = \sqrt{gd}$,

$$\text{power} = \rho g h^2 \sqrt{gd} \times w/2 = \rho g^{3/2}\sqrt{d} h^2 \times w/2. \tag{G.7}$$

Let's compare this power with the kinetic-energy flux K_{BV}. Strikingly, the two expressions scale differently with the amplitude h. Using the amplitude conversion relation (G.3), the crest velocity (G.2), and $A = wd$, we can re-express the kinetic-energy flux as

$$K_{\text{BV}} = \frac{1}{2}\rho A U^3 = \frac{1}{2}\rho w d (vh/d)^3 = \rho\left(g^{3/2}/\sqrt{d}\right) h^3 \times w/2. \tag{G.8}$$

So the kinetic-energy-flux method suggests that the total power of a shallow-water wave scales as amplitude *cubed* (equation (G.8)); but the correct formula shows that the power scales as amplitude *squared* (equation (G.7)).

The ratio is

$$\frac{K_{\text{BV}}}{\text{power}} = \frac{\rho w \left(g^{3/2}/\sqrt{d}\right) h^3}{\rho g^{3/2} h^2 \sqrt{d} w} = \frac{h}{d}. \tag{G.9}$$

Because h is usually much smaller than d (h is about 1 m or 2 m, while d is 100 m or 10 m), estimates of tidal power resources that are based on the kinetic-energy-flux method may be *much too small*, 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 (the biggest tides) is eight times greater than at neaps (the smallest tides), assuming an amplitude ratio, springs to neaps, of two to one; 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 to one.

Effect of shelving of sea bed, and Coriolis force

If the depth d decreases gradually and the width remains constant such that there is minimal reflection or absorption of the incoming power, then

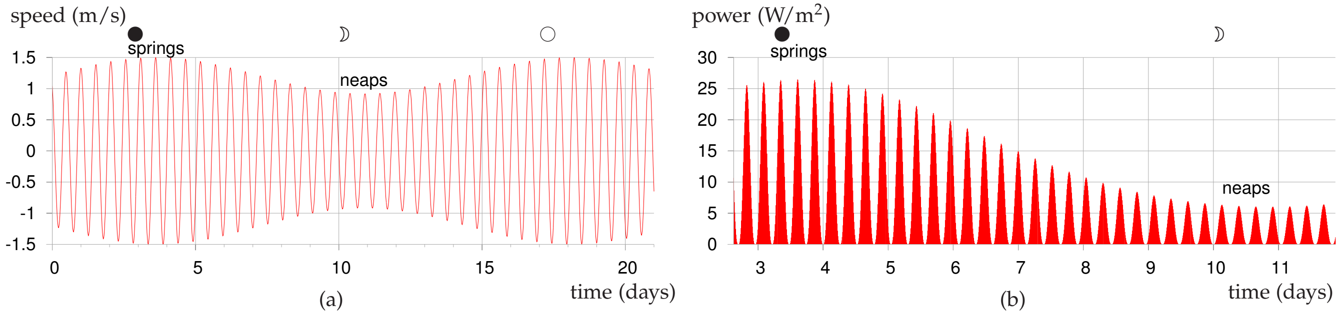


Figure G.5. (a) Tidal current over a 21-day period at a location where the maximum current at spring tide is 2.9 knots (1.5 m/s) and the maximum current at neap tide is 1.8 knots (0.9 m/s).
(b) The power per unit sea-floor area over a nine-day period extending from spring tides to neap tides. The power 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.

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 $h \sim 1/d^{1/4}$.

This is 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 1000 times that of air, the power of water flow is 1000 times greater than the power of wind at the same speed.

What power could tidal stream farms extract? It depends crucially on whether or not we can add up the power contributions of tidefarms on *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 10 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 other's power extraction in a different way? I don't think the answer to this question is known in general. 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.

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 100 times more power by putting 99 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. 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. (This case is analysed by Garrett and Cummins (2005, 2007).)

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.

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. We can then steal the formula for the power of a wind farm (per unit land area) from p265. The power per unit sea-floor area is

$$\frac{\text{power per tidemill}}{\text{area per tidemill}} = \frac{\pi}{200}\frac{1}{2}\rho U^3$$

Using this formula, table G.6 shows this tide farm power for a few tidal currents.

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.6. Tide farm power density (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.) The power density is computed using $\frac{\pi}{200}\frac{1}{2}\rho U^3$ (equation (G.10)).

Now, what are typical 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. Figure G.5 illustrates the variation of power density of a tide farm with a maximum current of 1.5 m/s. The average power density of this tide farm would be 6.4 W/m^2. 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 (5–10 W/m^2).

We'll now use this "tide farms are like wind farms" theory to estimate the extractable power from tidal streams in promising regions around the British Isles. As a sanity check, we'll also work out the total tidal power crossing each of these regions, 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 British Isles where tidal currents are large are shown in figure G.7.

I estimated the typical peak currents at six locations with large currents by looking at 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

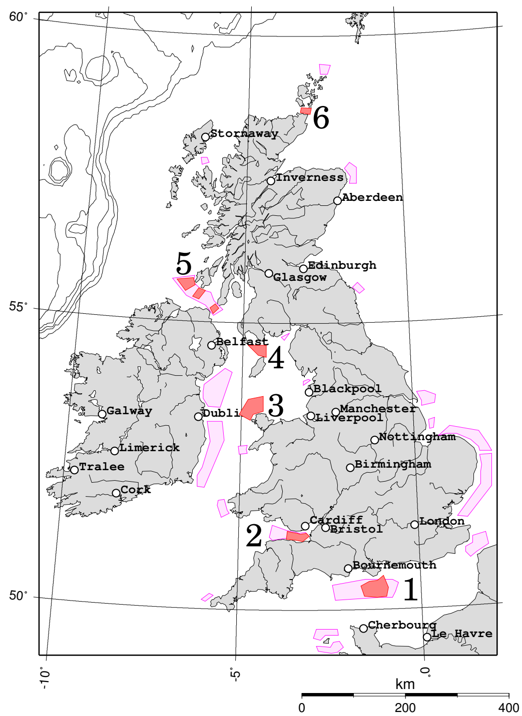


Figure G.7. Regions around the British Isles where peak tidal flows exceed 1 m/s. The six darkly-coloured regions are included in table G.8:

1. the English channel (south of the Isle of Wight);
2. the Bristol channel;
3. to the north of Anglesey;
4. to the north of the Isle of Man;
5. between Northern Ireland, the Mull of Kintyre, and Islay; and
6. the Pentland Firth (between Orkney and mainland Scotland), and within the Orkneys.

There are also enormous currents around the Channel Islands, but they are not governed by the UK. Runner-up regions include the North Sea, from the Thames (London) to the Wash (Kings Lynn). The contours show water depths greater than 100 m. Tidal data are from Reed's Nautical Almanac and DTI Atlas of UK Marine Renewable Energy Resources (2004).

tricky to build on.

Admitting all these uncertainties, I arrive at an estimated total power of 9 kWh/d per person from tidal stream-farms. This corresponds to 9% of the raw incoming power mentioned on p83, 100 kWh per day per person. (The extraction of 1.1 kWh/d/p in the Bristol channel, region 2, might conflict with power generation by the Severn barrage; it would depend on whether the tide farm significantly *adds* to the existing natural friction created by the channel, or *replaces* it.)

Region	U (knots) N	U (knots) S	power density (W/m^2)	area (km^2)	average power (kWh/d/p)	d (m)	w (km)	raw power N (kWh/d/p)	raw power S (kWh/d/p)
1	1.7	3.1	7	400	1.1	30	30	2.3	7.8
2	1.8	3.2	8	350	1.1	30	17	1.5	4.7
3	1.3	2.3	2.9	1000	1.2	50	30	3.0	9.3
4	1.7	3.4	9	400	1.4	30	20	1.5	6.3
5	1.7	3.1	7	300	0.8	40	10	1.2	4.0
6	5.0	9.0	170	50	3.5	70	10	24	78
Total					**9**				

(a) (b)

Table G.8. (a) Tidal power estimates assuming that stream farms are like wind farms. The power density is the average power per unit area of sea floor. The six regions are indicated in figure G.7. N = Neaps. S = Springs. (b) For comparison, this table shows the raw incoming power estimated using equation (G.1) (p312).

v (m/s)	v (knots)	Friction power density (W/m^2) $R_1 = 0.01$	$R_1 = 0.003$	tide farm power density (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 density $R_1 \rho U^3$ (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. (1 knot = 1 nautical mile per hour = 0.514 m/s.) The final column shows the tide farm power estimated in table G.6. For further reading see Kowalik (2004), Sleath (1984).

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 exert, and extracting roughly the same amount of power as friction used to dissipate, 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 $R_1 = 0.003$. For values of the shear friction coefficient in this range, the friction power is very similar to the estimated power that a tide farm would deliver. This is good news, because it suggests that planting a forest of underwater windmills on the sea-bottom, spaced five diameters apart, won't radically alter the flow. The natural friction already has an effect that is in the same ballpark.

Tidal pools with pumping

"The pumping trick" artificially increases the amplitude of the tides in a tidal pool so as to 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. The pumping trick is sometimes used at La Rance, boosting its net power generation by about 10% (Wilson and Balls, 1990). Let's work out the theoretical limit for this technology. I'll assume

tidal amplitude (half-range) h (m)	optimal boost height b (m)	power with pumping (W/m^2)	power without pumping (W/m^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

Table G.10. Theoretical power density from tidal power using the pumping trick, assuming no constraint on the height of the basin's walls.

that generation has an efficiency of $\epsilon_g = 0.9$ and that pumping has an efficiency of $\epsilon_p = 0.85$. Let the tidal range be $2h$. I'll assume for simplicity that the prices of buying and selling electricity are the same at all times, 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):

$$b/\epsilon_p = \epsilon_g(b + 2h).$$

Defining the round-trip efficiency $\epsilon = \epsilon_g\epsilon_p$, 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 the basin to have a vertical range of 30 m!) The delivered power per unit area is then

$$\left(\frac{1}{2}\rho g \epsilon_g (b+2h)^2 - \frac{1}{2}\rho g \frac{1}{\epsilon_p} b^2\right) \Big/ T,$$

where T is the time from high tide to low tide. We can express this as the maximum possible power density without pumping, $\epsilon_g 2\rho g h^2/T$, scaled up by a boost factor

$$\left(\frac{1}{1-\epsilon}\right),$$

which is roughly a factor of 4. Table G.10 shows the theoretical power density that pumping could deliver. 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 four-fold. But the amount of 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 on any day when the range of natural tides is smaller than the maximum range: the water

tidal amplitude (half-range) h (m)	boost height b (m)	power with pumping (W/m^2)	power without pumping (W/m^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

Table G.11. Power density offered by the pumping trick, assuming the boost height is constrained to be the same as the tidal amplitude. This assumption applies, for example, at neap tides, if the pumping pushes the tidal range up to the springs range.

level at high tide can be pumped up to the maximum. Table G.11 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. A doubling of vertical range is easy 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.

Getting "always-on" tidal power by using two basins

Here's 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 actively by pumps (using the trick mentioned above). 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 capital cost of a two-basin scheme may be bigger because of the need for extra walls; the big win is that power is available all the time, so the facility can follow demand.

We can 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. 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. In a simple simulation, I've found that a two-lagoon system in a location with a natural tidal range of 4 m can, with an appropriate pumping schedule, deliver a *steady* power of 4.5 W/m^2 (MacKay, 2007a). One lagoon's water level is always kept above mean sea-level; the other lagoon's level is always kept below mean sea-level. This power density of 4.5 W/m^2 is 50% bigger than the maximum possible average power density of an ordinary tide-pool in the same lo-

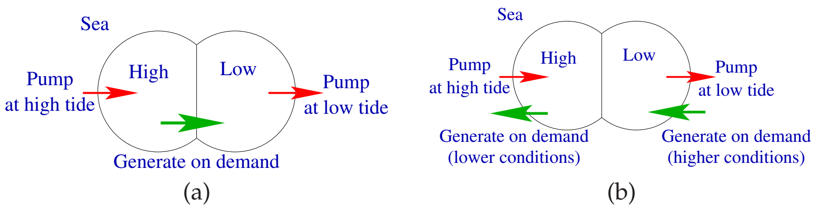


Figure G.12. Different ways to use the tidal pumping trick. Two lagoons are located at sea-level. (a) One simple way of using two lagoons is to label one the high pool and the other the low pool; when the surrounding sea level is near to high tide, let water into the high pool, or actively pump it in (using electricity from other sources); and similarly, when the sea level is near to low tide, empty the low pool, either passively or by active pumping; then whenever power is sufficiently valuable, generate power on demand by letting water from the high pool to the low pool. (b) Another arrangement that might deliver more power per unit area has no flow of water between the two lagoons. While one lagoon is being pumped full or pumped empty, the other lagoon can deliver steady, demand-following power to the grid. Pumping may be powered by bursty sources such as wind, by spare power from the grid (say, nuclear power stations), or by the other half of the facility, using one lagoon's power to pump the other lagoon up or down.

cation (3 W/m^2). The steady power of the lagoon system would be more valuable than the intermittent and less-flexible power from the ordinary tide-pool.

A two-basin system could also function as a pumped-storage facility.

Notes

page no.

311 *Efficiency of 90%...* Turbines are about 90% efficient for heads of 3.7 m or more. Baker et al. (2006).

320 *Getting "always-on" tidal power by using two basins.* 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 G.12(a), delivers power continuously, and generates 39 kW on average. [2bqapk].

Further reading: Shaw and Watson (2003b); Blunden and Bahaj (2007); Charlier (2003a,b).

For further reading on bottom friction and variation of flow with depth, see Sleath (1984).

For more on the estimation of the UK tidal resource, see MacKay (2007b).

For more on tidal lagoons, see MacKay (2007a).

H Stuff II

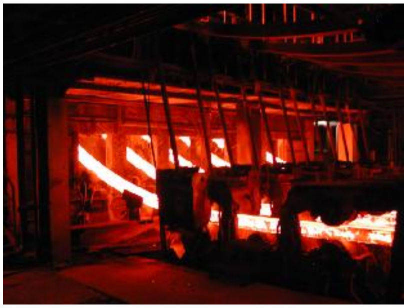


Figure H.1. Continuous casting of steel strands at Korea Iron and Steel Company.

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 arguably be added to Britain's official carbon footprint of 11 tons CO_2e per year per person) is roughly 16 tons CO_2e per year per person. A subsequent, more detailed study commissioned by DEFRA estimated that the embodied carbon in imports is smaller, but still very significant: about 6.2 tons CO_2e per year per person. In energy terms, 6 tons CO_2e per year is something like 60 kWh/d.

Here, let's see if we can reproduce these conclusions in a different way, using the weights of the imports.

Figure H.2 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, which doesn't care whether something is leather or tobacco – it keeps 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 10 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 the 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 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.2

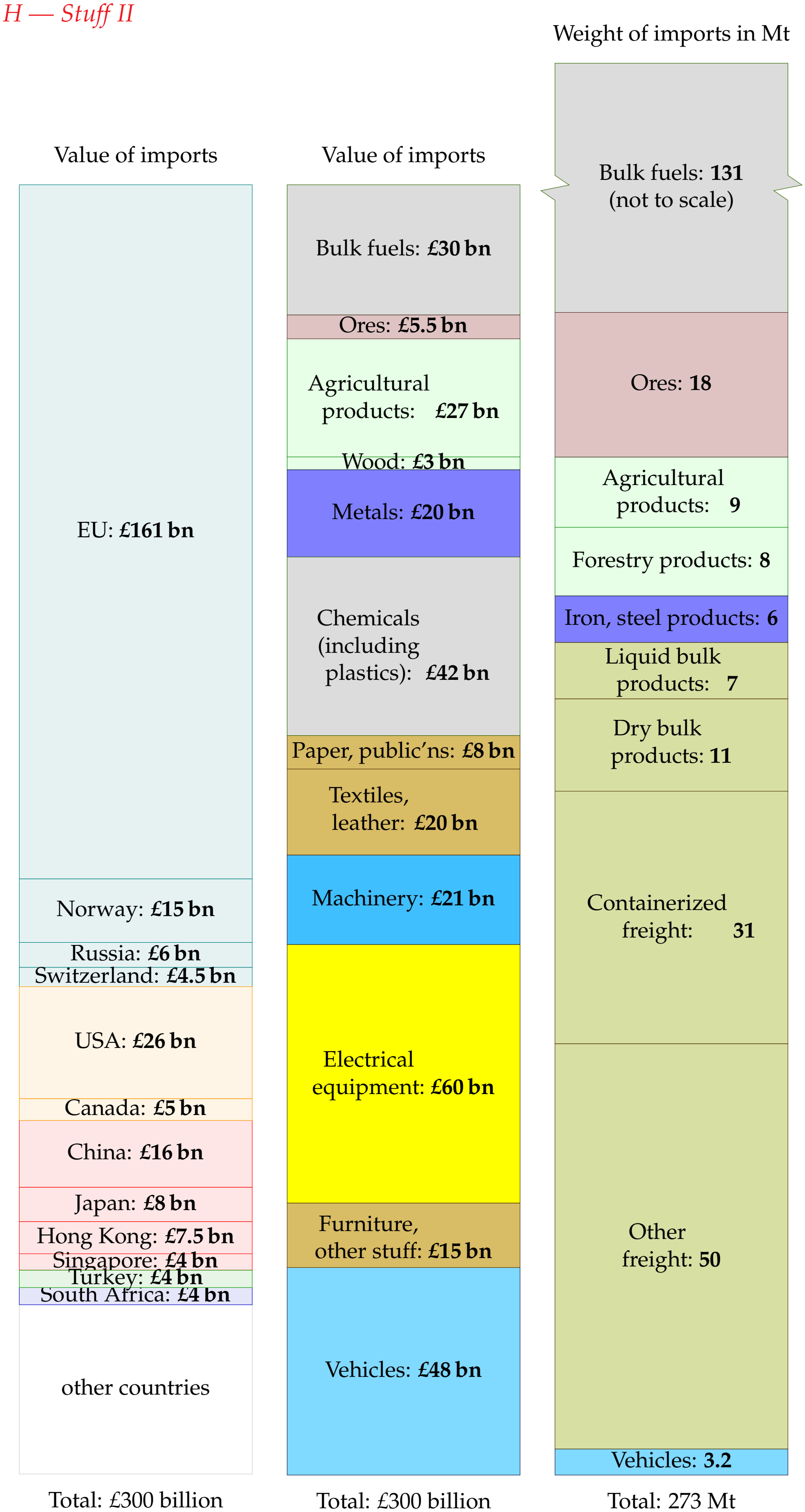


Figure H.2. Imports of stuff to the UK, 2006.

the iron and steel products, the dry bulk products, the containerized freight and the "other freight," which total 98 million tons per year. I'm leaving the vehicles to one side for a moment. I subtract from this an estimated 25 million tons of food which is presumably lurking in the "other freight" category (34 million tons of food were imported in 2006), leaving 73 million tons.

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 hand-wave 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 p90) then these imported cars have an embodied energy of 8 kWh/d per person.

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.

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 suspect that 41 kWh/d per person may be an underestimate because the energy intensity we assumed (10 kWh/d per 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.

Figure H.3. Niobium open cast mine, Brazil.

Lifecycle analysis for buildings

Tables H.4 and H.5 show estimates of the *Process Energy Requirement* of building materials and building constructions. This includes the energy used in transporting the raw materials to the factory but not energy used to transport the final product to the building site.

Table H.6 uses these numbers to estimate the process energy for making a three-bedroom house. The *gross energy requirement* widens the boundary, including the embodied energy of urban infrastructure, for example, 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 [3kmcks].

If we share 42 000 kWh over 100 years, and double it to estimate the gross energy cost, the total embodied energy 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.

Material	Embodied energy (MJ/kg)	(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
straw	0.24	0.07
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
fibreglass (glasswool)	28	7.8
aluminium	170	47
copper	100	28
galvanised steel	38	10.6
stainless steel	51.5	14.3

Table H.4. Embodied energy of building materials (assuming virgin rather than recycled product is used). (Dimension stone is natural stone or rock that has been selected and trimmed to specific sizes or shapes.) Sources: [3kmcks], Lawson (1996).

	Embodied energy (kWh/m^2)
Walls	
timber frame, timber weatherboard, plasterboard lining	52
timber frame, clay brick veneer, plasterboard lining	156
timber frame, aluminium weatherboard, plasterboard lining	112
steel frame, clay brick veneer, plasterboard lining	168
double clay brick, plasterboard lined	252
cement stabilised rammed earth	104
Floors	
elevated timber floor	81
110 mm concrete slab on ground	179
200 mm precast concrete T beam/infill	179
Roofs	
timber frame, concrete tile, plasterboard ceiling	70
timber frame, terracotta tile, plasterboard ceiling	75
timber frame, steel sheet, plasterboard ceiling	92

Table H.5. Embodied energy in various walls, floors, and roofs. Sources: [3kmcks], Lawson (1996).

	Area (m^2)	×	energy density (kWh/m^2)		energy (kWh)
Floors	100	×	81	=	8100
Roof	75	×	75	=	5600
External walls	75	×	252	=	19 000
Internal walls	75	×	125	=	9400
Total					42 000

Table H.6. Process energy for making a three-bedroom house.

Notes and further reading

page no.

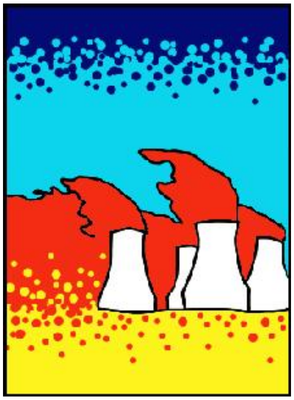
322 *A subsequent more-detailed study commissioned by DEFRA estimated that the embodied carbon in imports is about 6.2 tons CO_2e per person.* Wiedmann et al. (2008).

Further resources: `www.greenbooklive.com` has life cycle assessments of building products.
Some helpful cautions about life-cycle analysis: `www.gdrc.org/uem/lca/life-cycle.html`.
More links: `www.epa.gov/ord/NRMRL/lcaccess/resources.htm`.

Figure H.7. Millau Viaduct in France, the highest bridge in the world. Steel and concrete, 2.5 km long and 353 m high.

Part IV

Useful data



I Quick reference

SI Units

> **The 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), with the exception of the "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
length	one metre	1 m
time	one second	1 s
temperature	one kelvin	1 K

prefix	kilo	mega	giga	tera	peta	exa
symbol	k	M	G	T	P	E
factor	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}

prefix	centi	milli	micro	nano	pico	femto
symbol	c	m	μ	n	p	f
factor	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}

Table I.1. SI units and prefixes

My preferred units for energy, power, and transport efficiencies

My preferred units, expressed in SI			
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	$24 \times 3600\,\text{s} \simeq 10^5\,\text{s}$
	one year	1 y	$365.25 \times 24 \times 3600\,\text{s} \simeq \pi \times 10^7\,\text{s}$
force per mass	kilowatt-hour per ton-kilometre	1 kWh/t-km	$3.6\,\text{m/s}^2$ ($\simeq 0.37g$)

Additional units and symbols

Thing measured	unit name	symbol	value
humans	person	p	
mass	ton	t	1 t = 1000 kg
	gigaton	Gt	1 Gt = $10^9 \times 1000$ kg = 1 Pg
transport	person-kilometre	p-km	
transport	ton-kilometre	t-km	
volume	litre	l	1 l = 0.001 m^3
area	square kilometre	sq km, km^2	1 sq km = $10^6\ m^2$
	hectare	ha	1 ha = $10^4\ m^2$
	Wales		1 Wales = 21 000 km^2
	London (Greater London)		1 London = 1580 km^2
energy	Dinorwig		1 Dinorwig = 9 GWh

Billions, millions, and other people's prefixes

Throughout this book "a billion" (1 bn) means a standard 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 denote a 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. So I don't use m to mean million. Where some people use m, I replace it by M. For example, I use Mtoe for million tons of oil equivalent, and Mt CO_2 for million tons of CO_2.

Annoying units

There's a whole bunch of commonly used units that are annoying for various reasons. I've figured out what some of them mean. I list them here, to help you translate the media stories you read.

Homes

The "home" is commonly used when describing the power of renewable facilities. For example, "The £300 million Whitelee wind farm's 140 turbines will generate 322 MW – enough to power 200 000 homes." The "home" is defined by the British Wind Energy Association to be a power of 4700 kWh per year [`www.bwea.com/ukwed/operational.asp`]. That's 0.54 kW, or 13 kWh per day. (A few other organizations use 4000 kWh/y per household.)

The "home" annoys me because I worry that people confuse it with *the total power consumption of the occupants of a home* – but the latter is actually about 24 times bigger. The "home" covers the average domestic *electricity* consumption of a household, only. Not the household's home heating. Nor their workplace. Nor their transport. Nor all the energy-consuming things that society does for them.

Incidentally, when they talk of the CO_2 emissions of a "home," the official exchange rate appears to be 4 tons CO_2 per home per year.

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 – keeping the UK's traffic lights running requires the equivalent of two medium-sized power stations." 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!

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 11 MW of electricity, which is 0.03% of the UK's electricity." This would reveal how "huge" the power savings are.

Figure I.2 shows the powers of the UK's 19 coal power stations.

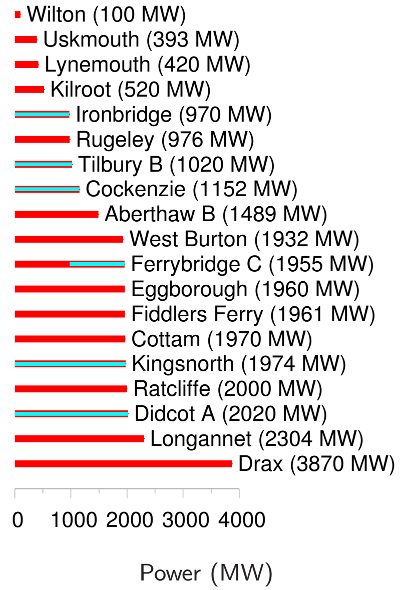


Figure I.2. Powers of Britain's coal power stations. I've highlighted in blue 8 GW of generating capacity that will close by 2015. 2500 MW, shared across Britain, is the same as 1 kWh per day per person.

Cars taken off the road

Some advertisements describe reductions in CO_2 pollution in terms of the "equivalent number of cars taken off the road." For example, Richard Branson says that if Virgin Trains' Voyager fleet switched to 20% biodiesel – incidentally, don't you feel it's outrageous to 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 says that *if* Virgin Trains' Voyager fleet switched to 20% biodiesel – I emphasize the "*if*" because people like Beardie are always getting media publicity for announcing that they are *thinking of* doing good things, but some of these fanfared initiatives are later quietly cancelled, such as the idea of towing aircraft around airports to make them greener – sorry, I got distracted again. Richard Branson says that *if* Virgin Trains' Voyager fleet switched to 20% biodiesel, then there would be a reduction of 34 500 tons of CO_2 per year, which is equivalent to "23 000 cars taken off the road." This statement reveals the exchange rate:

$$\text{"one car taken off the road"} \longleftrightarrow -1.5 \text{ tons per year of } CO_2.$$

Calories

The calorie is annoying because the diet community call a kilocalorie a Calorie. 1 such food Calorie = 1000 calories.

$$2500\,\text{kcal} = 3\,\text{kWh} = 10\,000\,\text{kJ} = 10\,\text{MJ}.$$

Barrels

An annoying unit loved by the oil community, along with the ton of oil. Why can't they stick to one unit? A barrel of oil is 6.1 GJ or 1700 kWh.

Barrels are doubly annoying because there are multiple definitions of barrels, all having different volumes.

Here's everything you need to know about barrels of oil. One barrel is 42 U.S. gallons, or 159 litres. One barrel of oil is 0.1364 tons of oil. One barrel of crude oil has an energy of 5.75 GJ. One barrel of oil weighs 136 kg. One ton of crude oil is 7.33 barrels and 42.1 GJ. The carbon-pollution rate of crude oil is 400 kg of CO_2 per barrel. `www.chemlink.com.au/conversions.htm` This means that when the price of oil is $100 per barrel, oil energy costs 6¢ per kWh. If there were a carbon tax of $250 per ton of CO_2 on fossil fuels, that tax would increase the price of a barrel of oil by $100.

Gallons

The gallon would be a fine human-friendly unit, except the Yanks messed it up by defining the gallon differently from everyone else, as they did 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 kg; 1 long ton (2240 lb) = 1016 kg; 1 metric ton (or tonne) = 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. Like the useless joule, 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 TWh.

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. To raise 50 cups of water, at 0.18 l per cup, from 15 °C to 100 °C requires 1 kWh.

So "nine million cups of tea per year" is another way of saying "20 kW."

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 tons. 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. Actually, Wembley's bowl has a volume of 1 140 000 m^3.

"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!" (An Albert Hall is 100 000 m^3.)

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 "200 000 litres of CO_2 per year"!

mass of CO_2	↔	volume
2 kg CO_2	↔	1 m^3
1 kg CO_2	↔	500 litres
44 g CO_2	↔	22 litres
2 g CO_2	↔	1 litre

Table I.3. Volume-to-mass conversion.

More volumes

A container is 2.4 m wide by 2.6 m high by (6.1 or 12.2) metres long (for the TEU and FEU respectively).

One TEU is the size of a small 20-foot container – an interior volume of about 33 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; its volume is 67.5 m^3.

A swimming pool has a volume of about 3000 m^3.

One double decker bus has a volume of 100 m^3.

One hot air balloon is 2500 m^3.

The great pyramid at Giza has a volume of 2 500 000 cubic metres.

Figure I.4. A twenty-foot container (1 TEU).

Areas

The area of the earth's surface is 500×10^6 km^2; the land area is 150×10^6 km^2.

My typical British 3-bedroom house has a floor area of 88 m^2. In the USA, the average size of a single-family house is 2330 square feet (216 m^2).

hectare	$= 10^4$ m^2
acre	= 4050 m^2
square mile	= 2.6 km^2
square foot	= 0.093 m^2
square yard	= 0.84 m^2

Table I.5. Areas.

Powers

If we add the suffix "e" to a power, this means that we're explicitly talking about electrical power. So, for example, a power station's output might be 1 GW(e), while it uses chemical power at a rate of 2.5 GW. Similarly the

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

Table I.6. Land areas, in England, devoted to different uses. Source: Generalized Land Use Database Statistics for England 2005. [3b7zdf]

1000 BTU per hour	=	0.3 kW	=	7 kWh/d
1 horse power (1 hp or 1 cv or 1 ps)	=	0.75 kW	=	18 kWh/d
		1 kW	=	24 kWh/d

1 therm	=	29.31 kWh
1000 Btu	=	0.2931 kWh
1 MJ	=	0.2778 kWh
1 GJ	=	277.8 kWh
1 toe (ton of oil equivalent)	=	11 630 kWh
1 kcal	=	1.163×10^{-3} kWh

1 kWh	=	0.03412 therms	3412 Btu	3.6 MJ	86×10^{-6} toe	859.7 kcal

Box I.7. How other energy and power units relate to the kilowatt-hour and the kilowatt-hour per day.

suffix "th" may be added to indicate that a quantity of energy is thermal energy. The same suffixes can be added to amounts of energy. "My house uses 2 kWh(e) of electricity per day."

If we add a suffix "p" to a power, this indicates that it's a "peak" power, or capacity. For example, 10 m^2 of panels might have a power of 1 kWp.

1 kWh/d = $\frac{1}{24}$ kW.

1 toe/y = 1.33 kW.

Petrol comes out of a petrol pump at about half a litre per second. So that's 5 kWh per second, or 18 MW.

The power of a Formula One racing car is 560 kW.

UK electricity consumption is 17 kWh per day per person, or 42.5 GW per UK.

"One ton" of air-conditioning = 3.5 kW.

World power consumption

World power consumption is 15 TW. World electricity consumption is 2 TW.

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.
At room temperature, $1\,kT = \frac{1}{40}\text{eV}$
At room temperature, $1\,kT$ per molecule = 2.5 kJ/mol.

Meter reading

How to convert your gas-meter reading into kilowatt-hours:

- If the meter reads **100s of cubic feet**, take the number of units used, and multiply by **32.32** to get the number of kWh.
- If the meter reads **cubic metres**, take the number of units used, and multiply by **11.42** to get the number of kWh.

	kWh/t-km
inland water	0.083
rail	0.083
truck	0.75
air	2.8
oil pipeline	0.056
gas pipeline	0.47
int'l water container	0.056
int'l water bulk	0.056
int'l water tanker	0.028

Table I.8. Energy intensity of transport modes in the USA. Source: Weber and Matthews (2008).

Calorific values of fuels

Crude oil: 37 MJ/l; 10.3 kWh/l.
Natural gas: 38 MJ/m^3. (Methane has a density of 1.819 kg/m^3.)
1 ton of coal: 29.3 GJ; 8000 kWh.
Fusion energy of ordinary water: 1800 kWh per litre.
See also table 26.14, p199, and table D.3, p284.

Heat capacities

The heat capacity of air is 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 1.2 kJ/m^3/°C.

Latent heat of vaporization of water: 2257.92 kJ/kg. Water vapour's heat capacity: 1.87 kJ/kg/°C. Water's heat capacity is 4.2 kJ/l/°C.

Steam's density is 0.590 kg/m^3.

Pressure

Atmospheric pressure: 1 bar $\simeq 10^5$ Pa (pascal). Pressure under 1000 m of water: 100 bar. Pressure under 3000 m of water: 300 bar.

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.

Greenhouse gas conversion factors

France	83
Sweden	87
Canada	220
Austria	250
Belgium	335
European Union	353
Finland	399
Spain	408
Japan	483
Portugal	525
United Kingdom	580
Luxembourg	590
Germany	601
USA	613
Netherlands	652
Italy	667
Ireland	784
Greece	864
Denmark	881

Figure I.9. Carbon intensity of electricity production (g CO_2 per kWh of electricity).

Fuel type	emissions (g CO_2 per kWh of chemical energy)
natural gas	190
refinery gas	200
ethane	200
LPG	210
jet kerosene	240
petrol	240
gas/diesel oil	250
heavy fuel oil	260
naptha	260
coking coal	300
coal	300
petroleum coke	340

Figure I.10. Emissions associated with fuel combustion. Source: DEFRA's Environmental Reporting Guidelines for Company Reporting on Greenhouse Gas Emissions.

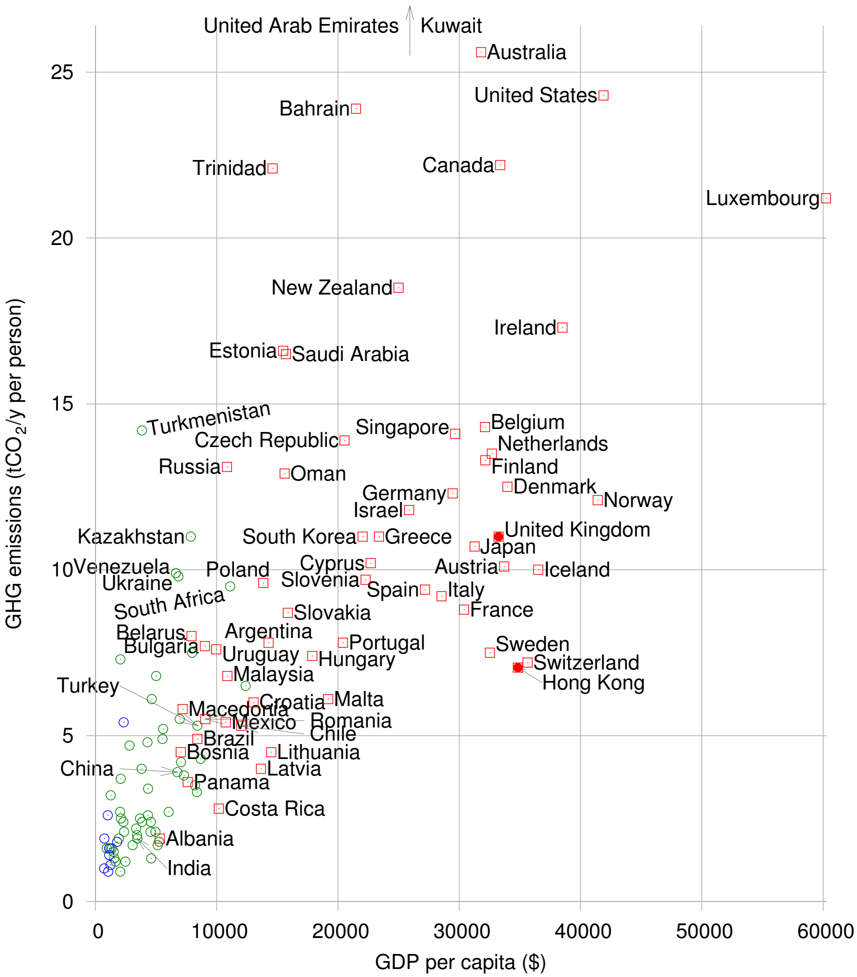


Figure I.11. Greenhouse-gas emissions per capita, versus GDP per capita, in purchasing-power-parity US dollars. Squares show countries having "high human development;" circles, "medium" or "low." See also figures 30.1 (p231) and 18.4 (p105). Source: UNDP Human Development Report, 2007. [3av4s9]

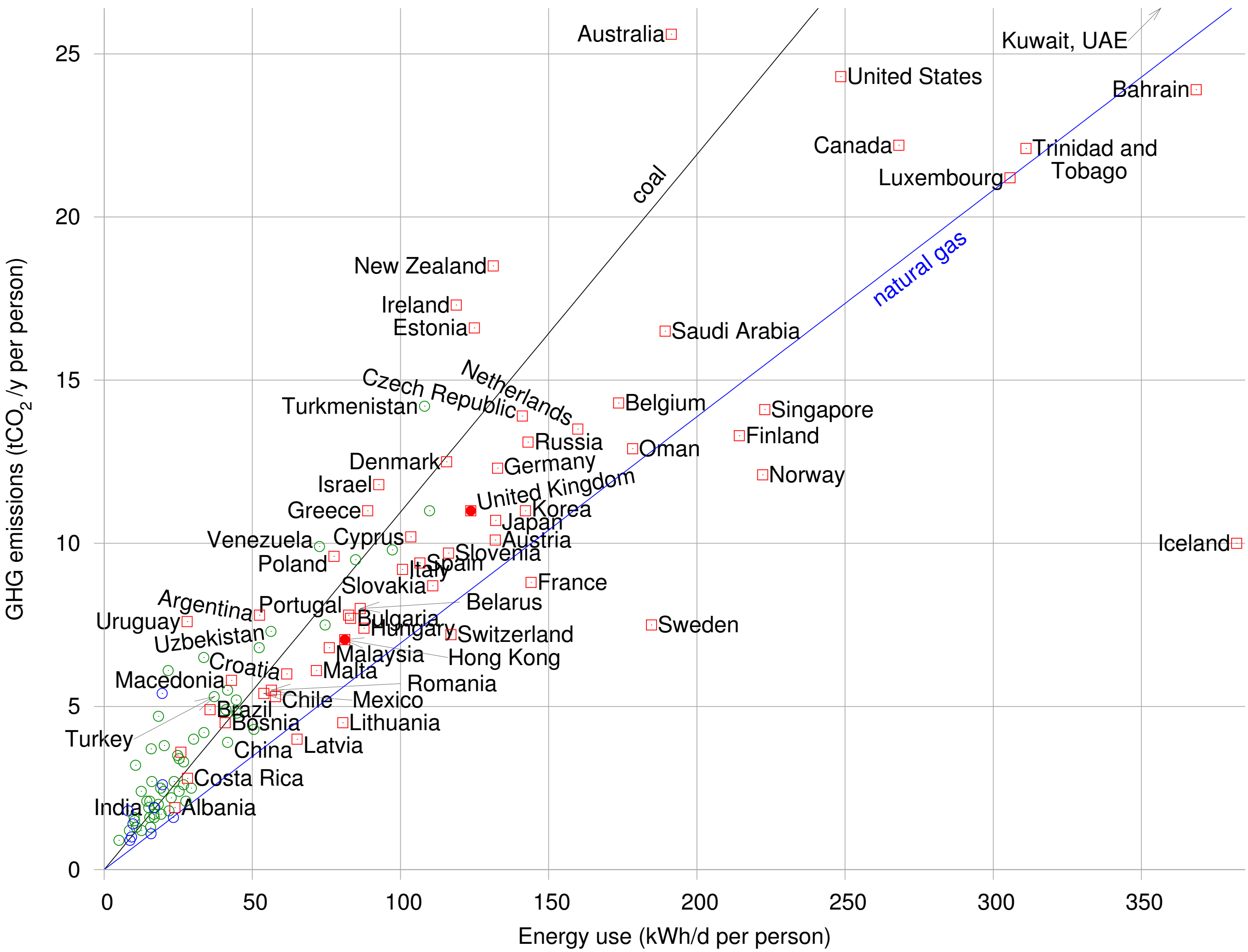


Figure I.12. Greenhouse-gas emissions per capita, versus power consumption per capita. The lines show the emission-intensities of coal and natural gas. Squares show countries having "high human development;" circles, "medium" or "low." See also figures 30.1 (p231) and 18.4 (p105). Source: UNDP Human Development Report, 2007.

J Populations and areas

Population densities

Figure J.1 shows the areas of various regions versus their populations. Diagonal lines on this diagram are lines of constant population density. Bangladesh, on the rightmost-but-one diagonal, 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.

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.

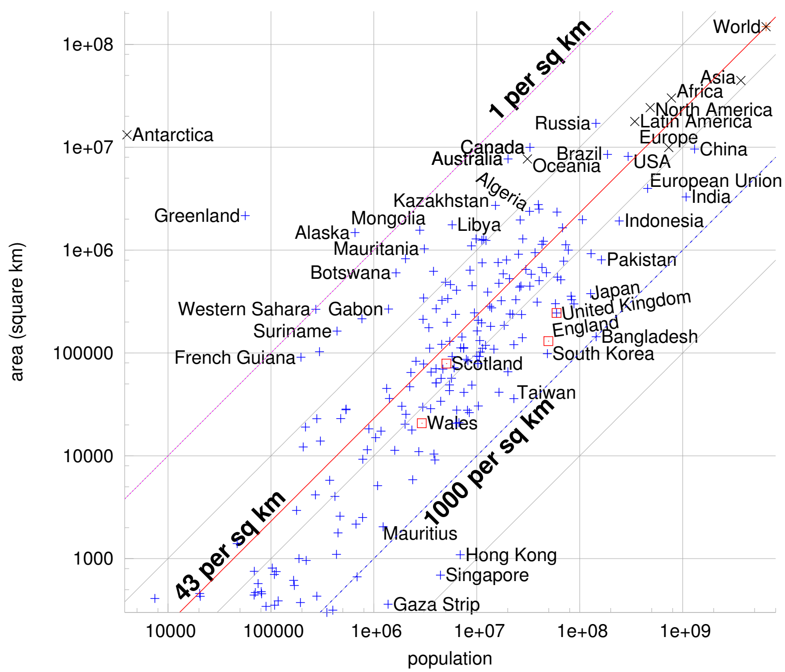


Figure J.1. Populations and areas of countries and regions of the world. Both scales are logarithmic. Each sloping line identifies a population density; countries with highest population density are towards the lower right, and lower population densities are towards the upper left. These data are provided in tabular form on p341.

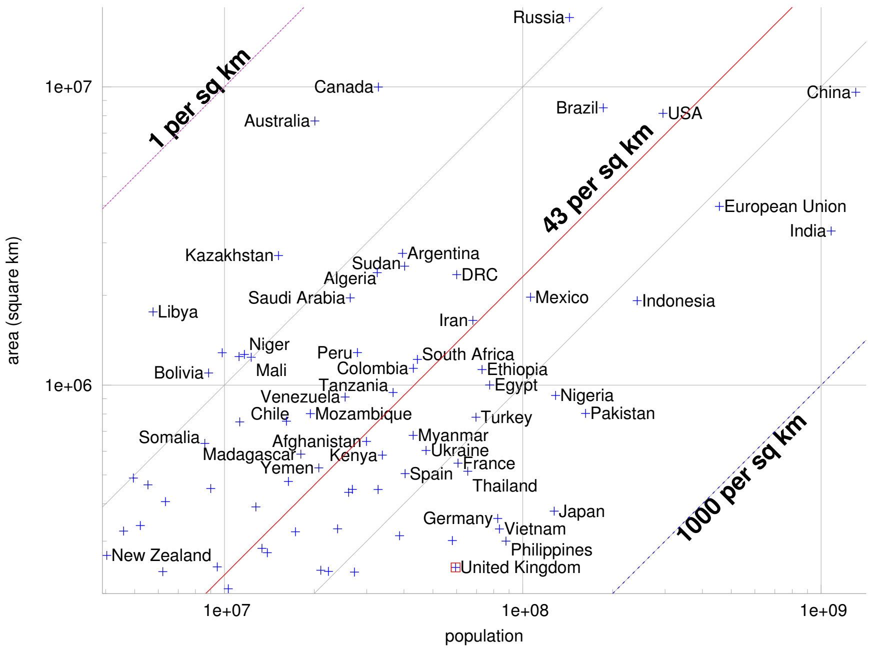


Figure J.2. Populations and areas of countries and regions of the world. Both scales are logarithmic. Sloping lines are lines of constant population density. This figure shows detail from figure J.1 (p338).
These data are provided in tabular form on p341.

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.3. Population densities of the continents. These data are displayed graphically in figures J.1 and J.2. Data are from 2005.

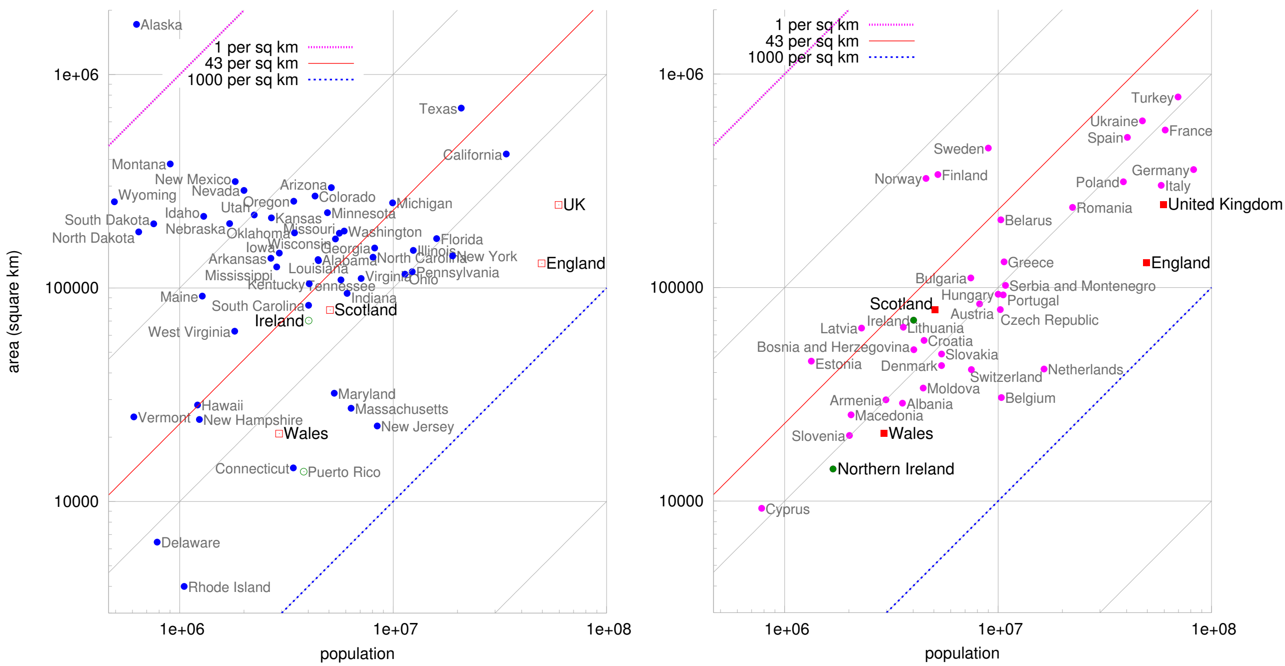


Figure J.4. Populations and areas of the States of America and regions around Europe.

Region	Population	Area (km^2)	People per km^2	Area per person (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 & 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
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 & 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
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.5. Regions and their population densities. Populations above 50 million and areas greater than 5 million km^2 are highlighted. These data are displayed graphically in figure J.1 (p338). Data are from 2005.

K UK energy history

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 K.1. Breakdown of primary energy sources in the UK (2004–2006).

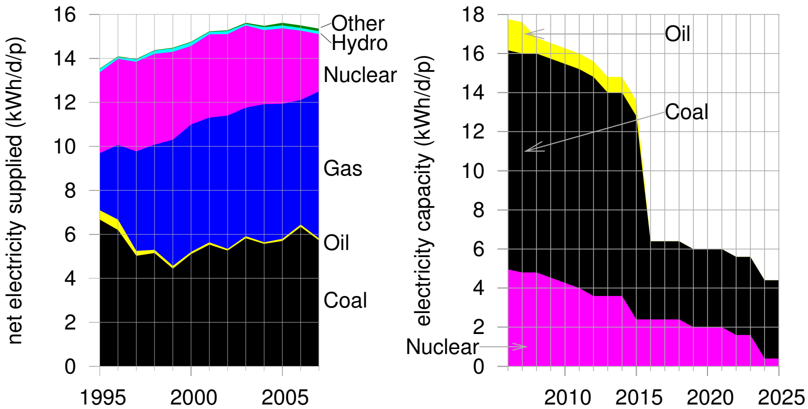


Figure K.2. Left: UK net electricity supplied, by source, in kWh per day per person. (Another 0.9 kWh/d/p is generated and used by the generators themselves.)
Right: the energy gap created by UK power station closures, as projected by energy company EdF. This graph shows the predicted *capacity* of nuclear, coal, and oil power stations, in kilowatt-hours per day per person. The capacity is the maximum deliverable power of a source.

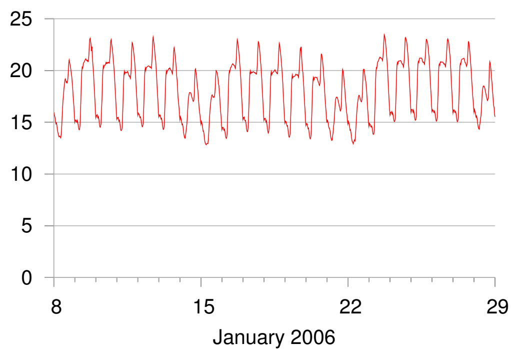


Figure K.3. Electricity demand in Great Britain (in kWh/d per person) during two winter weeks of 2006. The peaks in January are at 6pm each day. (If you'd like to obtain the national demand in GW, the top of the scale, 24 kWh/d per person, is the same as 60 GW per UK.)

	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 K.4. Domestic electricity charges (2006, 2007) for Powergen customers in Cambridge, including tax.

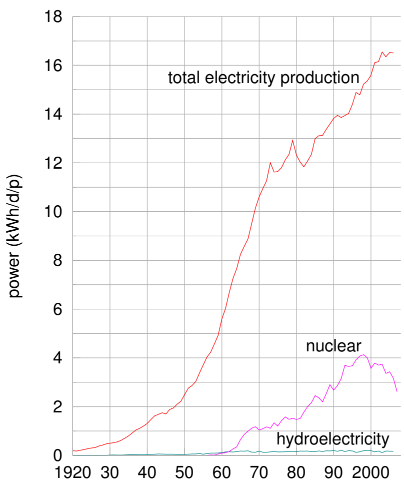


Figure K.5. History of UK production of electricity, hydroelectricity, and nuclear electricity.
Powers are expressed "per person" by dividing each power by 60 million.

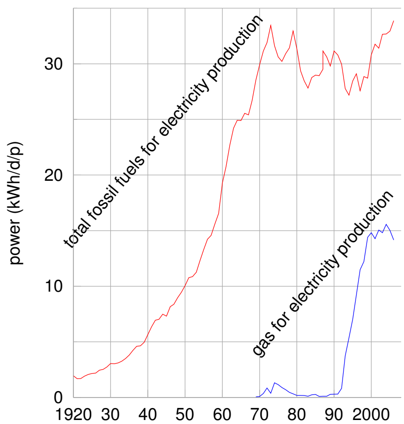


Figure K.6. History of UK use of fossil fuels for electricity production.
Powers are expressed "per person" by dividing each power by 60 million.

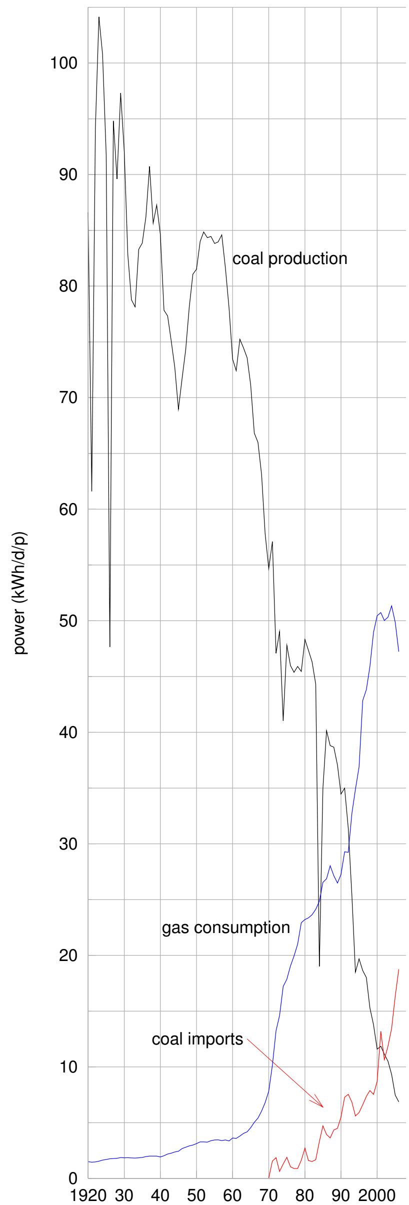


Figure K.7. UK production and imports of coal, and UK consumption of gas.
Powers are expressed "per person" by dividing each power by 60 million.

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 `www.inference.phy.cam.ac.uk/sustainable/book/tex/cft.url.html`) for a clickable page with all URLs in this book.

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].

p	tinyURL	Full web link.
18	ydoobr	www.bbc.co.uk/radio4/news/anyquestions_transcripts_20060127.shtml
18	2jhve6	www.ft.com/cms/s/0/48e334ce-f355-11db-9845-000b5df10621.html
19	25e59w	news.bbc.co.uk/1/low/uk_politics/7135299.stm
19	5o7mxk	www.guardian.co.uk/environment/2007/dec/10/politics
19	5c4olc	www.foe.co.uk/resource/press_releases/green_solutions_undermined_10012008.html
19	2fztd3	www.jalopnik.com/cars/alternative-energy/now-thats-some-high-quality-h20-car-runs-on-water-177788.php
19	26e8z	news.bbc.co.uk/1/hi/sci/tech/3381425.stm
19	ykhayj	politics.guardian.co.uk/terrorism/story/0,,1752937,00.html
20	l6y5g	www.grida.no/climate/ipcc_tar/wg1/fig3-1.htm
20	5qfkaw	www.nap.edu/catalog.php?record_id=12181
21	2z2xg7	assets.panda.org/downloads/2_vs_3_degree_impacts_1oct06_1.pdf
21	yyxq2m	www.bp.com/genericsection.do?categoryId=93&contentId=2014442
21	dzcqq	www.defra.gov.uk/environment/climatechange/internat/pdf/avoid-dangercc.pdf
21	y98ys5	news.bbc.co.uk/1/hi/business/4933190.stm
30	5647rh	www.dft.gov.uk/pgr/statistics/datatablespublications/tsgb/
31	27jdc5	www.dft.gov.uk/pgr/statistics/datatablespublications/energyenvironment/tsgb-chapter3energyandtheenvi1863
31	28abpm	corporate.honda.com/environmentology/
31	nmn4l	www.simetric.co.uk/si_liquids.htm
31	2hcgdh	cta.ornl.gov/data/appendix_b.shtml
34	vxhhj	www.cl.cam.ac.uk/research/dtg/weather/
34	tdvml	www.phy.hw.ac.uk/resrev/aws/awsarc.htm
36	3fbufz	www.ipcc.ch/ipccreports/sres/aviation/004.htm
36	3asmgy	news.independent.co.uk/uk/transport/article324294.ece
36	9ehws	www.boeing.com/commercial/747family/technical.html
36	3exmgv	www.ryanair.com/site/EN/about.php?page=About&sec=environment
36	yrnmum	www.grida.no/climate/ipcc/aviation/124.htm
37	36w5gz	www.rolls-royce.com/community/downloads/environment04/products/air.html
44	2rqloc	www.metoffice.gov.uk/climate/uk/location/scotland/index.html
44	2szckw	www.metoffice.gov.uk/climate/uk/stationdata/cambridgedata.txt
45	5hrxls	eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?+s01
45	6z9epq	www.solarcentury.com/knowledge_base/images/solar_pv_orientation_diagram
47	2tl7t6	www.reuk.co.uk/40-Percent-Efficiency-PV-Solar-Panels.htm
47	6hobq2	www.azonano.com/news.asp?newsID=4546
47	2lsx6t	www.udel.edu/PR/UDaily/2008/jul/solar072307.html
47	62ccou	www.nrel.gov/news/press/2008/625.html
48	5hzs5y	www.ens-newswire.com/ens/dec2007/2007-12-26-093.asp
48	39z5m5	news.bbc.co.uk/1/hi/world/europe/6505221.stm

48 2uk8q8 www.powerlight.com/about/press2006_page.php?id=59

48 2ahecp www.aps.org/meetings/multimedia/upload/The_Status_and_Outlook_for_the_Photovoltaics_Industry_David_E_Carlson.pdf

48 6kqq77 www.defra.gov.uk/erdp/pdfs/ecs/miscanthus-guide.pdf

58 ynjzej www.aceee.org/conf/06modeling/azevado.pdf

64 wbd8o www.ref.org.uk/energydata.php

66 25e59w news.bbc.co.uk/1/low/uk_politics/7135299.stm

66 2t2vjq www.guardian.co.uk/environment/2007/dec/11/windpower.renewableenergy

66 57984r www.businessgreen.com/business-green/news/2205496/critics-question-government

66 6oc3ja www.independent.co.uk/environment/green-living/donnachadh-mccarthy-my-carbonfree-year-767115.html

66 5soql2 www.housebuildersupdate.co.uk/2006/12/eco-bollocks-award-windsave-ws1000.html

66 6g2jm5 www.carbontrust.co.uk/technology/technologyaccelerator/small-wind

79 5h69fm www.thepoultrysite.com/articles/894/economic-approach-to-broiler-production

80 5pwojp www.fertilizer.org/ifa/statistics/STATSIND/pkann.asp

80 5bj8k3 www.walkerscarbonfootprint.co.uk/walkers_carbon_footprint.html

80 3s576h www.permatopia.com/transportation.html

87 6xrm5q www.edf.fr/html/en/decouvertes/voyage/usine/retour-usine.html

94 yx7zm4 www.cancentral.com/funFacts.cfm

94 r22oz www-materials.eng.cam.ac.uk/mpsite/interactive_charts/energy-cost/NS6Chart.html

94 yhrest www.transportation.anl.gov/pdfs/TA/106.pdf

94 y5as53 www.aluminum.org/Content/NavigationMenu/The_Industry/Government_Policy/Energy/Energy.htm

94 y2ktgg www.ssab.com/templates/Ordinary___573.aspx

95 6lbrab www.lindenau-shipyard.de/pages/newsb.html

95 5ctx4k www.wilhelmsen.com/SiteCollectionDocuments/WW_Miljorapport_engelsk.pdf

95 yqbzl3 www.normanbaker.org.uk/downloads/Supermarkets Report Final Version.doc

102 yttg7p budget2007.treasury.gov.uk/page_09.htm

102 fcqfw www.mod.uk/DefenceInternet/AboutDefence/Organisation/KeyFactsAboutDefence/DefenceSpending.htm

102 2e4fcs press.homeoffice.gov.uk/press-releases/security-prebudget-report

102 33x5kc www.mod.uk/NR/rdonlyres/95BBA015-22B9-43EF-B2DC-DFF14482A590/0/gep_200708.pdf

102 35ab2c www.dasa.mod.uk/natstats/ukds/2007/c1/table103.html

102 yg5fsj siteresources.worldbank.org/DATASTATISTICS/Resources/GDP.pdf

102 yfgjna www.sipri.org/contents/milap/milex/mex_major_spenders.pdf/download

102 slbae www.wisconsinproject.org/countries/israel/plut.html

102 yh45h8 www.usec.com/v2001_02/HTML/Aboutusec_swu.asp

102 t2948 www.world-nuclear.org/info/inf28.htm

102 2ywzee www.globalsecurity.org/wmd/intro/u-centrifuge.htm

112 uzek2 www.dti.gov.uk/energy/inform/dukes/

112 3av4s9 hdr.undp.org/en/statistics/

112 6frj55 news.independent.co.uk/environment/article2086678.ece

129 5qhvcb www.tramwayinfo.com/Tramframe.htm?www.tramwayinfo.com/tramways/Articles/Compair2.htm

134 4qgg8q www.newsweek.com/id/112733/output/print

135 5o5x5m www.cambridgeenergy.com/archive/2007-02-08/cef08feb2007kemp.pdf

135 5o5x5m www.cambridgeenergy.com/archive/2007-02-08/cef08feb2007kemp.pdf

135 5fbeg9 www.cfit.gov.uk/docs/2001/racomp/racomp/pdf/racomp.pdf

135 679rpc www.tfl.gov.uk/assets/downloads/environmental-report-2007.pdf

136 5cp27j www.eaton.com/EatonCom/ProductsServices/Hybrid/SystemsOverview/HydraulicHLA/index.htm

137 4wm2w4 www.citroenet.org.uk/passenger-cars/psa/berlingo/berlingo-electrique.html

137 658ode www.greencarcongress.com/2008/02/mitsubishi-moto.html

139 czjjo corporate.honda.com/environment/fuel_cells.aspx?id=fuel_cells_fcx

139 5a3ryx automobiles.honda.com/fcx-clarity/specifications.aspx

154 yok2nw www.eca.gov.uk/etl/find/_P_Heatpumps/detail.htm?ProductID=9868&FromTechnology=S_WaterSourcePackaged

154	2dtx8z	www.eca.gov.uk/NR/rdonlyres/6754FE19-C697-49DA-B482-DA9426611ACF/0/ETCL2007.pdf
154	2fd8ar	www.geothermalint.co.uk/commercial/hydronicheatpumpranges.html
159	5kpjk8	blogs.reuters.com/environment/2008/09/09/a-silver-bullet-or-just-greenwash/
159	yebuk8	www.dti.gov.uk/energy/sources/coal/index.html
160	yhxf8b	www.worldenergy.org/wec-geis/publications/reports/ser/coal/coal.asp
160	e2m9n	www.coal.gov.uk/resources/cleanercoaltechnologies/ucgoverview.cfm
173	5qntkb	www.world-nuclear.org/info/reactors.htm
174	y3wnzr	npc.sarov.ru/english/digest/132004/appendix8.html
174	32t5zt	web.ift.uib.no/~lillestol/Energy_Web/EA.html
174	2qr3yr	documents.cern.ch/cgi-bin/setlink?base=generic&categ=public&id=cer-0210391
174	ynk54y	doc.cern.ch//archive/electronic/other/generic/public/cer-0210391.pdf
174	yl7tkm	minerals.usgs.gov/minerals/pubs/mcs/1999/mcs99.pdf
174	yju4a4	www.uic.com.au/nip67.htm
175	yeyr7z	taylorandfrancis.metapress.com/index/W7241163J23386MG.pdf
175	4f2ekz	www.publications.parliament.uk/pa/cm199900/cmhansrd/vo000505/text/00505w05.htm
175	2k8y7o	www.nei.org/resourcesandstats/
175	3pvf4j	www.sustainableconcrete.org.uk/main.asp?page=210
175	4r7zpg	csereport2005.bluescopesteel.com/
175	49hcnw	www.ace.mmu.ac.uk/Resources/Fact_Sheets/Key_Stage_4/Waste/pdf/02.pdf
175	3kduo7	www.esrcsocietytoday.ac.uk/ESRCInfoCentre/facts/UK/index29.aspx?ComponentId=7104&SourcePageId=18130
176	69vt8r	www.osti.gov/energycitations/product.biblio.jsp?osti_id=7200593
176	6oby22	www.osti.gov/energycitations/product.biblio.jsp?osti_id=6773271&query_id=0
176	63l2lp	pubs.acs.org/cgi-bin/abstract.cgi/jacsat/2002/124/i18/abs/ja003472m.html
176	wnchw	www.feasta.org/documents/wells/contents.html?one/horelacy.html
176	shrln	www.enviros.com/vrepository/
201	2wmuw7	news.yahoo.com/s/ap/20071231/ap_on_hi_te/solar_roads;_ylt=AuEFouXxz16nP8MRlInTJMms0NUE
201	2hxf6c	www.eirgrid.com/EirGridPortal/DesktopDefault.aspx?tabid=WindGenerationCurve&TreeLinkModID=1451&TreeLinkItemID=247
201	2l99ht	www.reuters.com/article/domesticNews/idUSN2749522920080228
201	3x2kvv	www.reuters.com/article/rbssIndustryMaterialsUtilitiesNews/idUSL057816620080305
202	5o2xgu	www.esru.strath.ac.uk/EandE/Web_sites/03-04/wind/content/storageavailable.html
202	2n3pmb	www.dynamicdemand.co.uk/pdf_fridge_test.pdf
202	2k8h4o	www.int.iol.co.za/index.php?art_id=vn20080201045821205C890035
202	5cp27j	www.eaton.com/EatonCom/ProductsServices/Hybrid/SystemsOverview/HydraulicHLA/index.htm
202	2sxlyj	www.batteryuniversity.com/partone-3.htm
202	ktd7a	www.vrbpower.com/docs/news/2006/20060830-PR-TapburySale-IrelandWindfarm.pdf
202	627ced	www.vrbpower.com/docs/whitepapers/SEItechpaper1.pdf
202	5fasl7	www.indexmundi.com/en/commodities/minerals/vanadium/vanadium_t7.html
202	2wmuw7	news.yahoo.com/s/ap/20071231/ap_on_hi_te/solar_roads;_ylt=AuEFouXxz16nP8MRlInTJMms0NUE
213	5os7dy	tinyurl.com/5os7dy
213	yrw2oo	tinyurl.com/yrw2oo
217	6eoyhg	news.bbc.co.uk/1/hi/uk/7215688.stm
217	yu8em5	www.foe.co.uk/resource/reports/paying_for_better_transport.pdf
219	3x2cr4	news.bbc.co.uk/1/hi/england/london/6151176.stm
219	2dd4mz	news.bbc.co.uk/1/low/uk_politics/6391075.stm
219	7vlxp	www.lse.ac.uk/collections/pressAndInformationOffice/newsAndEvents/archives/2005/IDCard_FinalReport.htm
219	6x4nvu	www.statoil.com/statoilcom/svg00990.nsf?opendatabase&artid=F5255D55E1E78319C1256FEF0044704B
219	39g2wz	www.dillinger.de/dh/referenzen/linepipe/01617/index.shtml.en
219	3ac8sj	www.hydro.com/ormenlange/en/
219	y7kg26	www.politics.co.uk/issue-briefs/economy/taxation/tobacco-duty/tobacco-duty-$366602.htm
219	r9fcf	en.wikipedia.org/wiki/War_on_Drugs

221	ysncks	news.bbc.co.uk/1/low/uk_politics/6205174.stm
221	2vq59t	www.boston.com/news/globe/editorial_opinion/oped/articles/2007/08/01/the_63_billion_sham/
221	ym46a9	https://www.cia.gov/cia/publications/factbook/print/xx.html
221	99bpt	www.guardian.co.uk/Iraq/Story/0,2763,1681119,00.html
221	2bmuod	www.guardian.co.uk/environment/2007/aug/13/renewableenergy.energy
221	3g8nn8	image.guardian.co.uk/sys-files/Guardian/documents/2007/08/13/RenewablesTargetDocument.pdf
221	3jo7q2	www.viewsofscotland.org/library/docs/HoL_STC_RE_Practicalities_04.pdf
230	2ykfgw	www.guardian.co.uk/environment/2007/jan/09/travelsenvironmentalimpact.greenpolitics
230	2nsvx2	www.number-10.gov.uk/output/Page10300.asp
230	yxq5xk	commentisfree.guardian.co.uk/george_monbiot/2007/01/an_open_letter_to_the_prime_mi.html
238	3doaeg	web.archive.org/web/20040401165322/members.cox.net/weller43/sunshine.htm
239	3lcw9c	knol.google.com/k/-/-/15x31uzlqeo5n/1
248	voxbz	news.bbc.co.uk/1/low/business/6247371.stm
248	yofchc	news.bbc.co.uk/1/low/uk/7053903.stm
248	3e28ed	www.grida.no/climate/ipcc_tar/wg1/118.htm
258	2bhu35	www.lafn.org/~dave/trans/energy/rail_vs_auto_EE.html
262	6by8x	encarta.msn.com/encyclopedia_761553622/Internal-Combustion_Engine.html
262	348whs	www.cleangreencar.co.nz/page/prius-petrol-engine
266	ydt7uk	www.nrel.gov/business_opportunities/pdfs/31235sow.pdf
266	yaoonz	www.windpower.org/en/tour/wres/shear.htm
267	6o86ec	www.londonarray.com/london-array-project-introduction/offshore/
268	6bkvbn	www.timesonline.co.uk/tol/news/world/asia/article687157.ece
268	yekdaa	www.windpower.org/en/stat/betzpro.htm
268	ymfbsn	www.windpower.org/en/tour/wres/powdensi.htm
268	ypvbvd	www.ref.org.uk/images/pdfs/UK_Wind_Phase_1_web.pdf
268	wbd8o	www.ref.org.uk/energydata.php
277	33ptcg	www.stevefossett.com/html/main_pages/records.html
278	6r32hf	www.theaustralian.news.com.au/story/0,25197,23003236-23349,00.html
282	2af5gw	www.airliners.net/info/stats.main?id=100
282	32judd	www.wildanimalsonline.com/birds/wanderingalbatross.php
282	2qbquv	news.bbc.co.uk/1/low/sci/tech/6988720.stm
282	5h6xph	www.goldcoastyachts.com/fastcat.htm
282	4p3yco	www.fas.org/man/dod-101/sys/ship/row/rus/903.htm
288	3ap7lc	www.biocap.ca/files/Ont_bioenergy_OPA_Feb23_final.pdf
288	4hamks	www.methanetomarkets.org/resources/landfills/docs/uk_lf_profile.pdf
296	65h3cb	www.dorset-technical-committee.org.uk/reports/U-values-of-elements-Sept-2006.pdf
298	5dhups	www.arct.cam.ac.uk/UCPB/Place.aspx?rid=943658&p=6&ix=8&pid=1&prcid=27&ppid=201
321	2bqapk	wwwphys.murdoch.edu.au/rise/reslab/resfiles/tidal/text.html
322	r22oz	www-materials.eng.cam.ac.uk/mpsite/interactive_charts/energy-cost/NS6Chart.html
325	3kmcks	www.yourhome.gov.au/technical/index.html
324	3kmcks	www.yourhome.gov.au/technical/index.html
333	3b7zdf	www.communities.gov.uk/publications/planningandbuilding/generalizedlanduse
336	3av4s9	hdr.undp.org/en/statistics/
344	f754	www.archive.org/web/web.php

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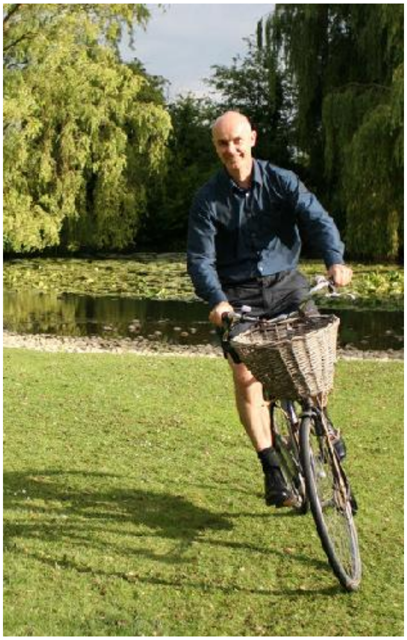
Index

Sustainable Energy – without the hot air

David JC MacKay

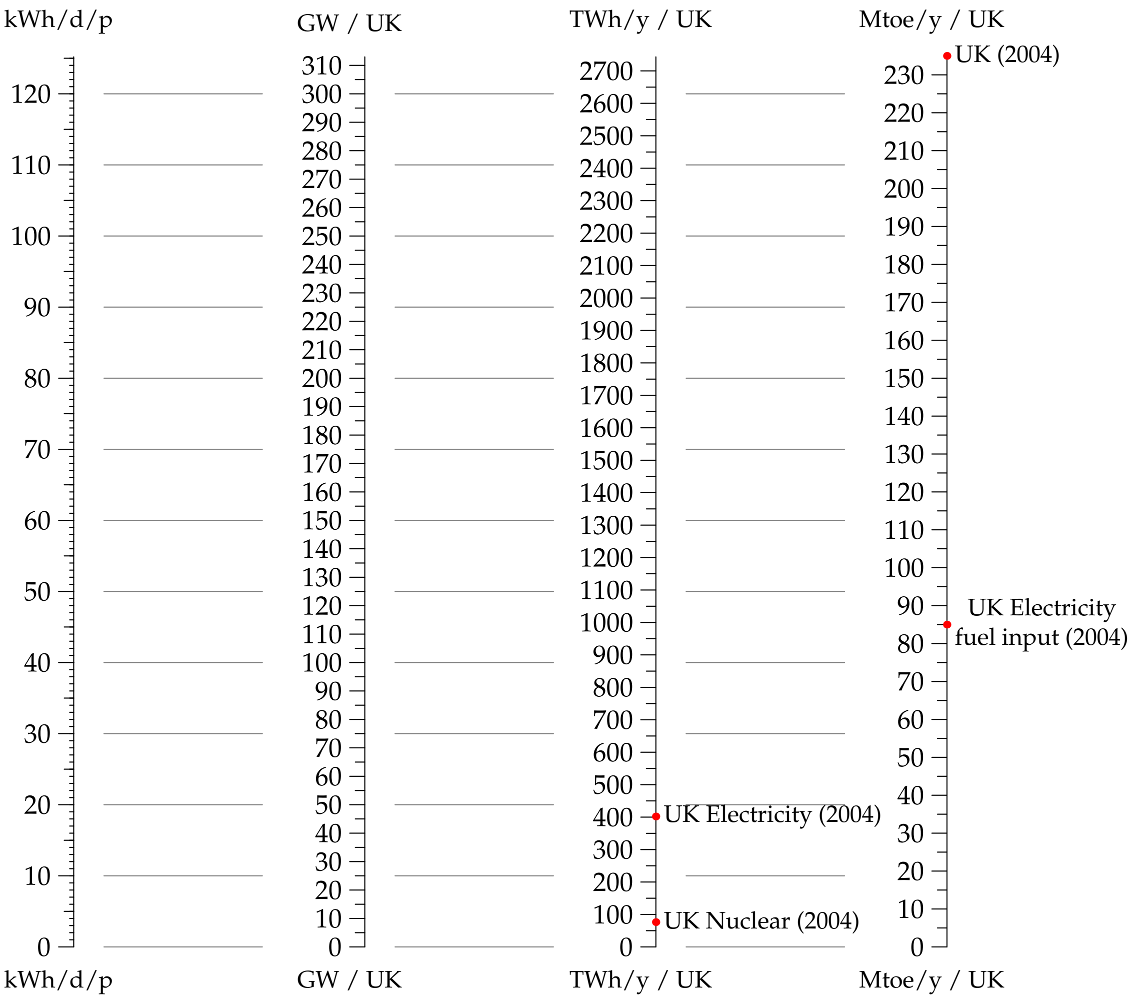
About the author

David MacKay is a Professor in the Department of Physics at the University of Cambridge. He studied Natural Sciences at Cambridge and then obtained his PhD in Computation and Neural Systems at the California Institute of Technology. He returned to Cambridge as a Royal Society research fellow at Darwin College. He is internationally known for his research in machine learning, information theory, and communication systems, including the invention of Dasher, a software interface that enables efficient communication in any language with any muscle. He has taught Physics in Cambridge since 1995. Since 2005, he has devoted much of his time to public teaching about energy. He is a member of the World Economic Forum Global Agenda Council on Climate Change.



The author, July 2008.
Photo by David Stern.

Power translation chart

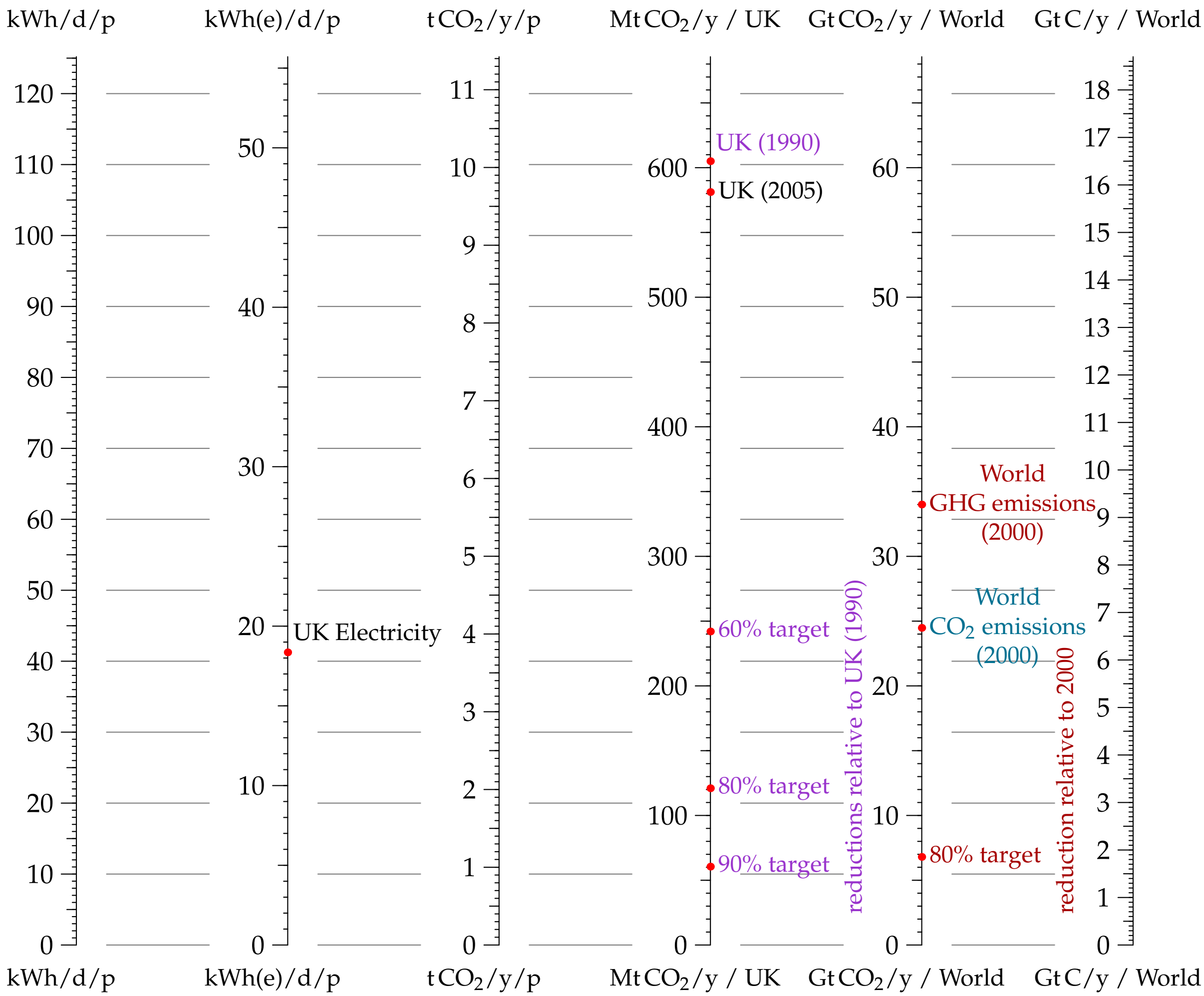


1 kWh/d	the same as 1/24 kW	"UK"	= 60 million people
GW	often used for '**capacity**' (peak output)		
TWh/y	often used for average output	USA energy consumption:	250 kWh/d per person
1 Mtoe	'one million tons of oil equivalent'	Europe energy consumption:	125 kWh/d per person

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

Carbon translation chart



kWh	*chemical* 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	ton of CO_2
Mt C	million tons of carbon

“UK” = 60 million people

“World” = 6 billion people

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