The unit of **energy** I have chosen is the kilowatt-hour (kWh).

This quantity is called “one unit” on electricity bills, and it costs a domestic user about 10p in the UK in 2008. As we’ll see, most individual daily choices involve amounts of energy equal to small numbers of kilowatt-hours.

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

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

energy = power ×time.

In some summaries of energy production and consumption, all the different forms of energy are put into the same units, but multipliers are introduced, rating electrical energy from hydroelectricity for example as being worth 2.5 times more than the chemical energy in oil. This bumping up of electricity’s effective energy value can be justified by saying, “well,

1 kWh of electricity is equivalent to 2.5 kWh of oil, because if we put that much oil into a standard power station it would deliver 40% of 2.5 kWh, which is 1 kWh of electricity.”

It is *not* the case that 2.5 kWh of oil is inescapably equivalent to 1 kWh of electricity; that just happens to be the perceived exchange rate in a worldview where oil is used to make electricity. Yes, conversion of chemical energy to electrical energy is done with this particular inefficient exchange rate.

But electrical energy can also be converted to chemical energy. In an alternative world (perhaps not far-off) with relatively plentiful electricity and little oil, we might use electricity to make liquid fuels; in that world we would surely not use the same exchange rate – each kWh of gasoline would then cost us something like 3 kWh of electricity! I think the timeless and scientific way to summarize and compare energies is to hold 1 kWh of chemical energy equivalent to 1 kWh of electricity

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

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

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

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

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

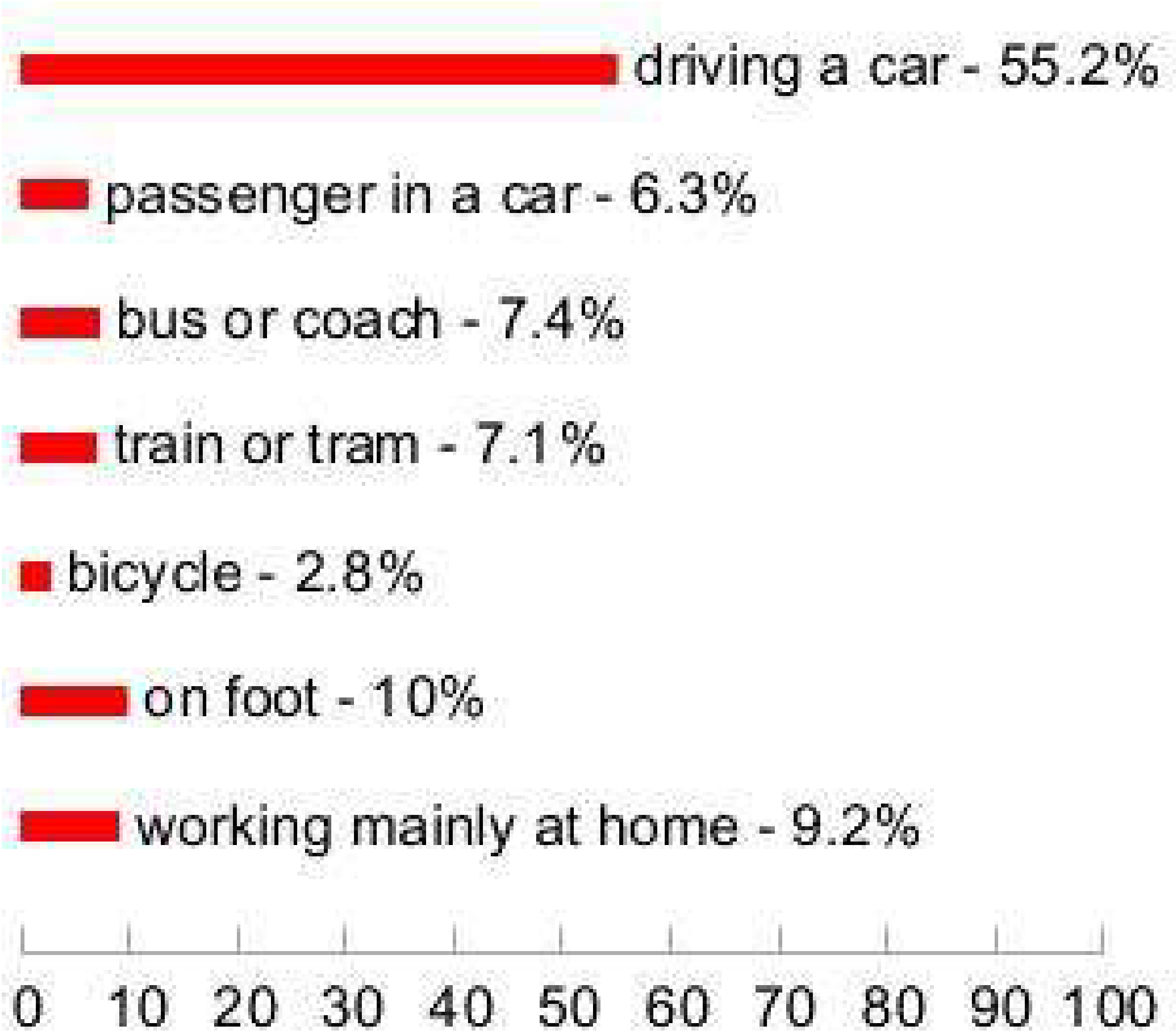
which is 1 kg per litre. If we guess a density of 0.8 kg per litre, we obtain a calorific value of:

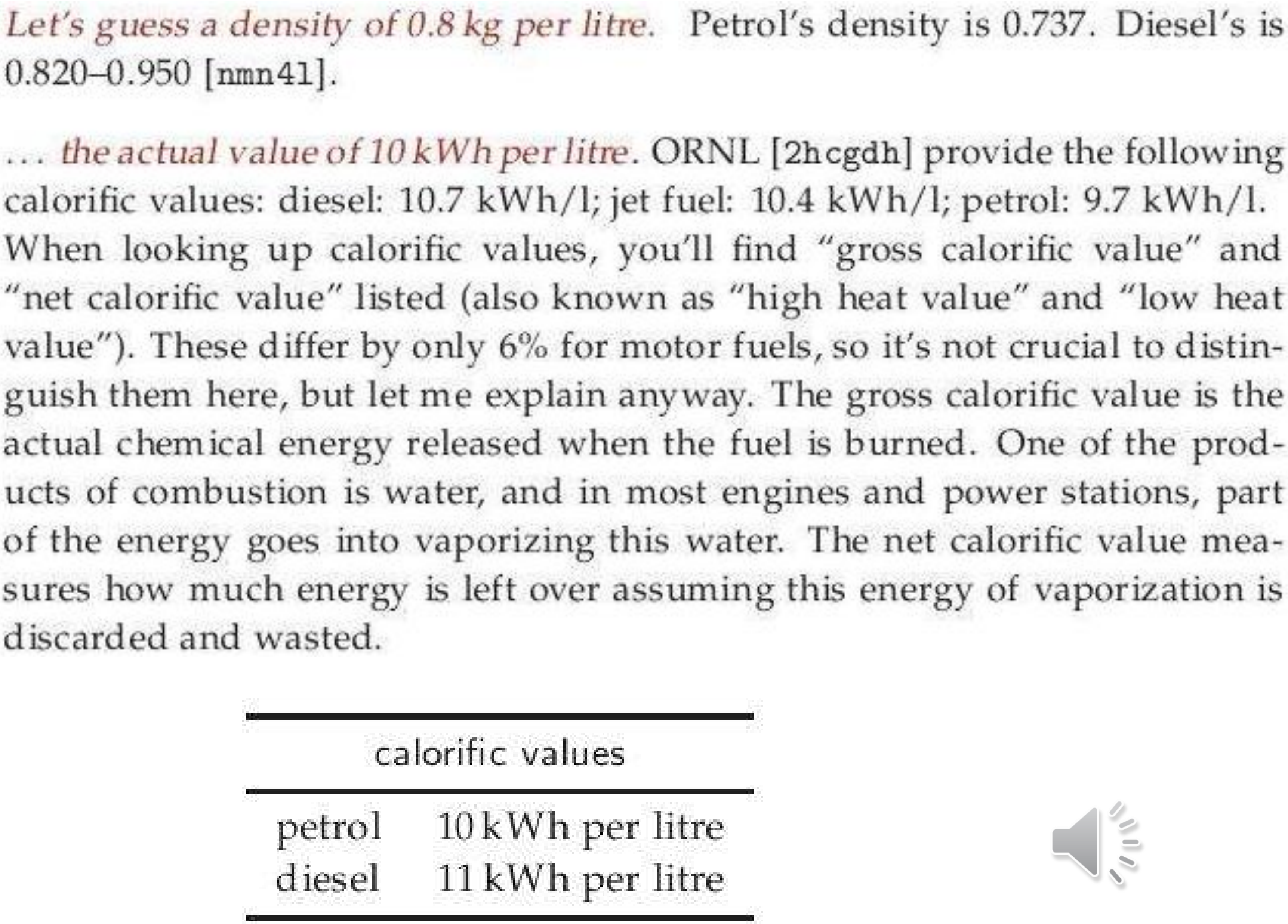
$$8\,\text{kWh per kg} \times 0.8\,\text{kg per litre} \simeq 7\,\text{kWh per litre.}$$

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

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

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

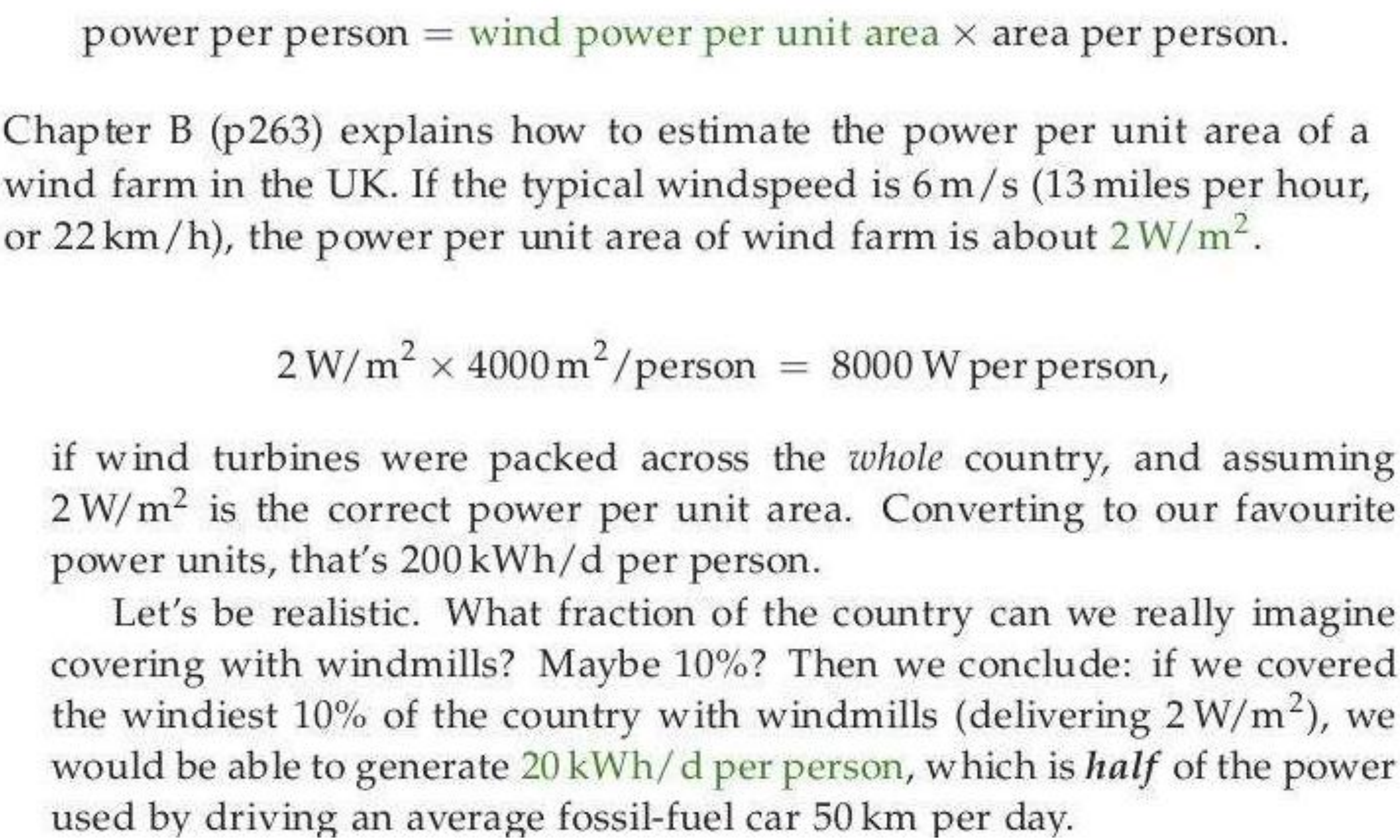

driving a car - 55.2%
passenger in a car - 6.3%
bus or coach - 7.4%
train or tram - 7.1%
bicycle - 2.8%
on foot - 10%
working mainly at home - 9.2%
0
10
20
30
40
50
60
70
80
90
100



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

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

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



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

Chapter B (p263) explains how to estimate the power per unit area of a wind farm in the UK. If the typical windspeed is 6 m/s (13 miles per hour, or 22 km/h), the power per unit area of wind farm is about 2 W/m².

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

if wind turbines were packed across the *whole* country, and assuming 2 W/m² is the correct power per unit area. Converting to our favourite power units, that's 200 kWh/d per person.

Let's be realistic. What fraction of the country can we really imagine covering with windmills? Maybe 10%? Then we conclude: if we covered the windiest 10% of the country with windmills (delivering 2 W/m²), we would be able to generate 20 kWh/d per person, which is ***half*** of the power used by driving an average fossil-fuel car 50 km per day.

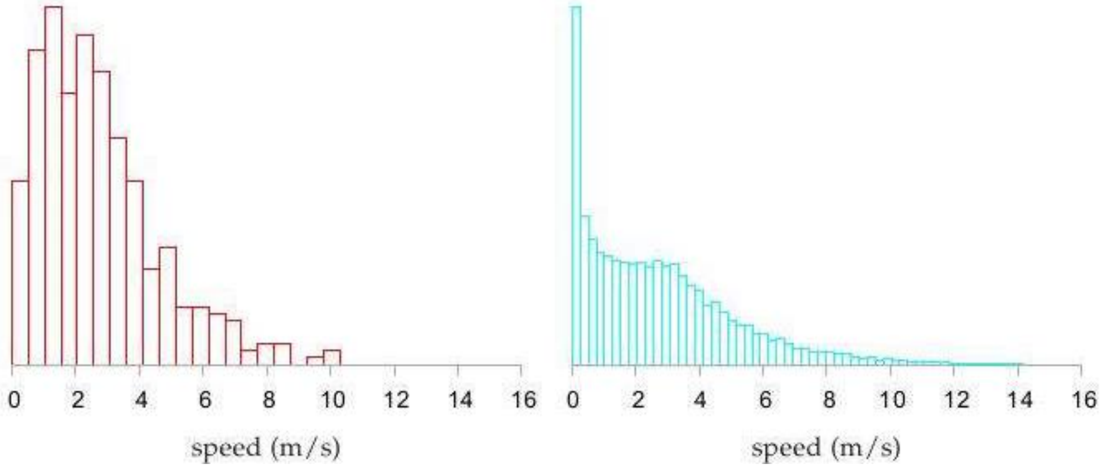
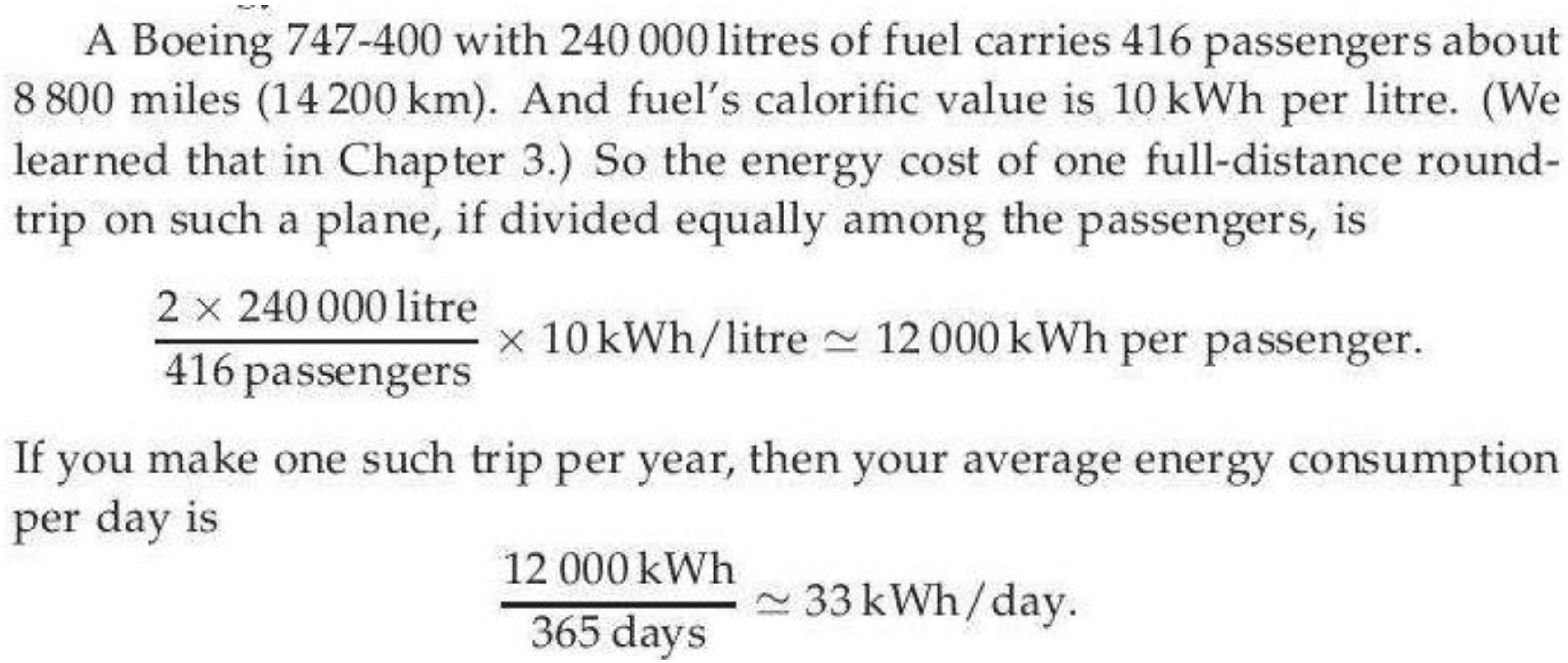


Figure 4.6. Histogram of Cambridge average wind speed in metres per second: daily averages (left), and half-hourly averages (right).



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

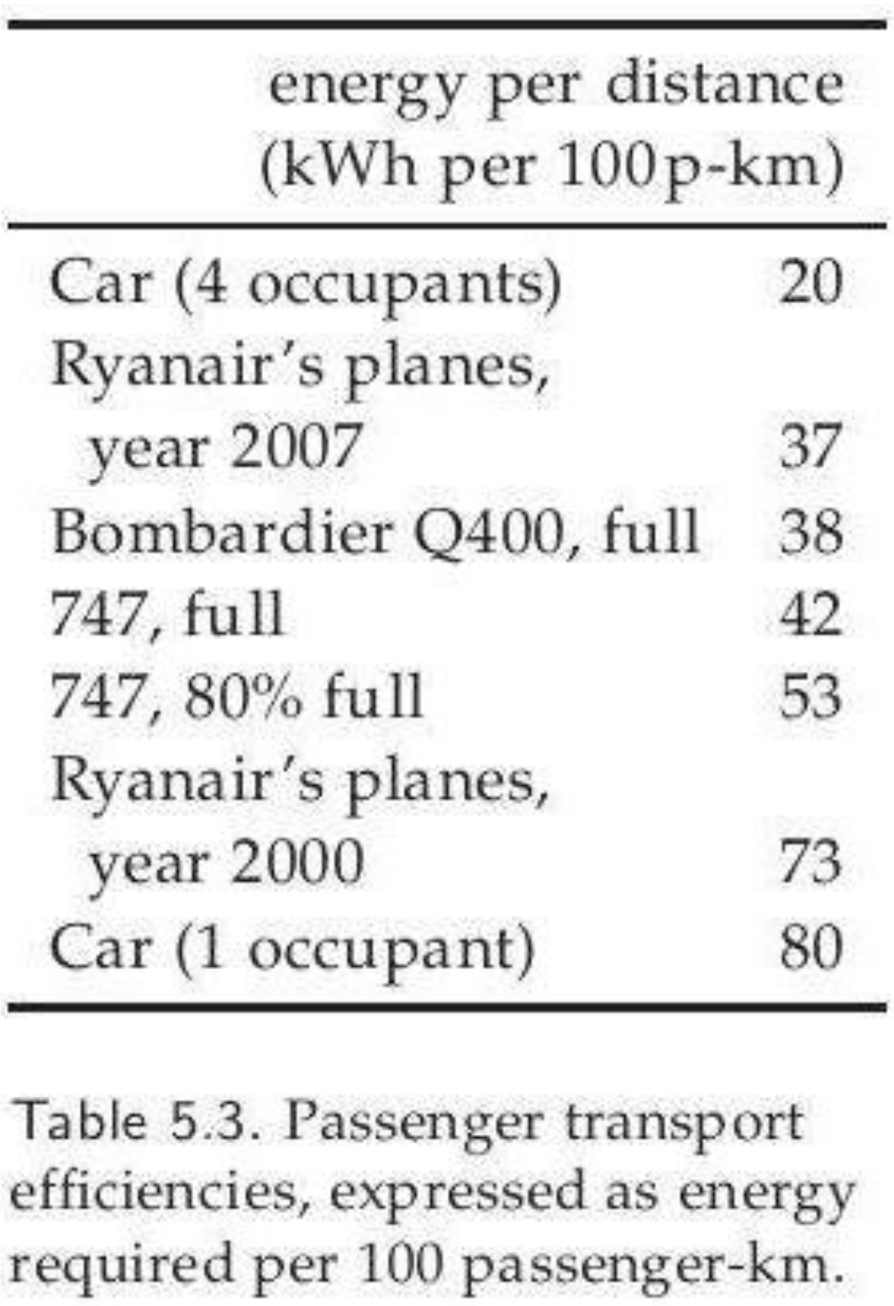
$$\frac{2 \times 240\,000\,\text{litre}}{416\,\text{passengers}} \times 10\,\text{kWh/litre} \simeq 12\,000\,\text{kWh per passenger.}$$

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

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

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

No. The "comfortably greener" Bombardier Q400 NextGen, "the most technologically advanced turboprop in the world," according to its manufacturers [`www.q400.com`], uses 3.81 litres per 100 passenger-km (at a cruise speed of 667 km/h), which is an energy cost of 38 kWh per 100 p-km. The full 747 has an energy cost of 42 kWh per 100 p-km. So both planes are twice as fuel-efficient as a single-occupancy car. (The car I'm assuming here is the average European car that we discussed in Chapter 3.)



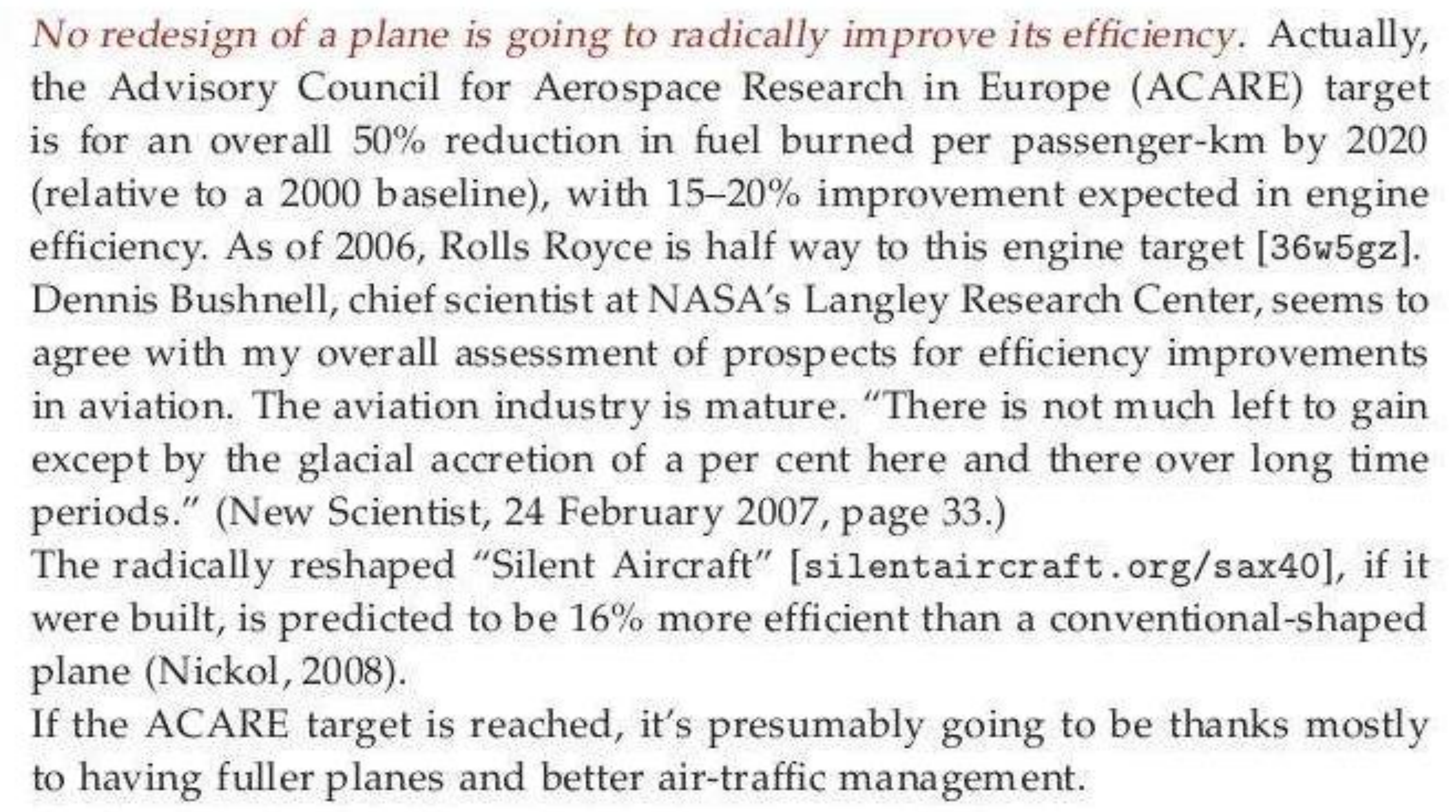
	energy per distance (kWh per 100p-km)
Car (4 occupants)	20
Ryanair's planes, year 2007	37
Bombardier Q400, full	38
747, full	42
747, 80% full	53
Ryanair's planes, year 2000	73
Car (1 occupant)	80

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

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

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

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

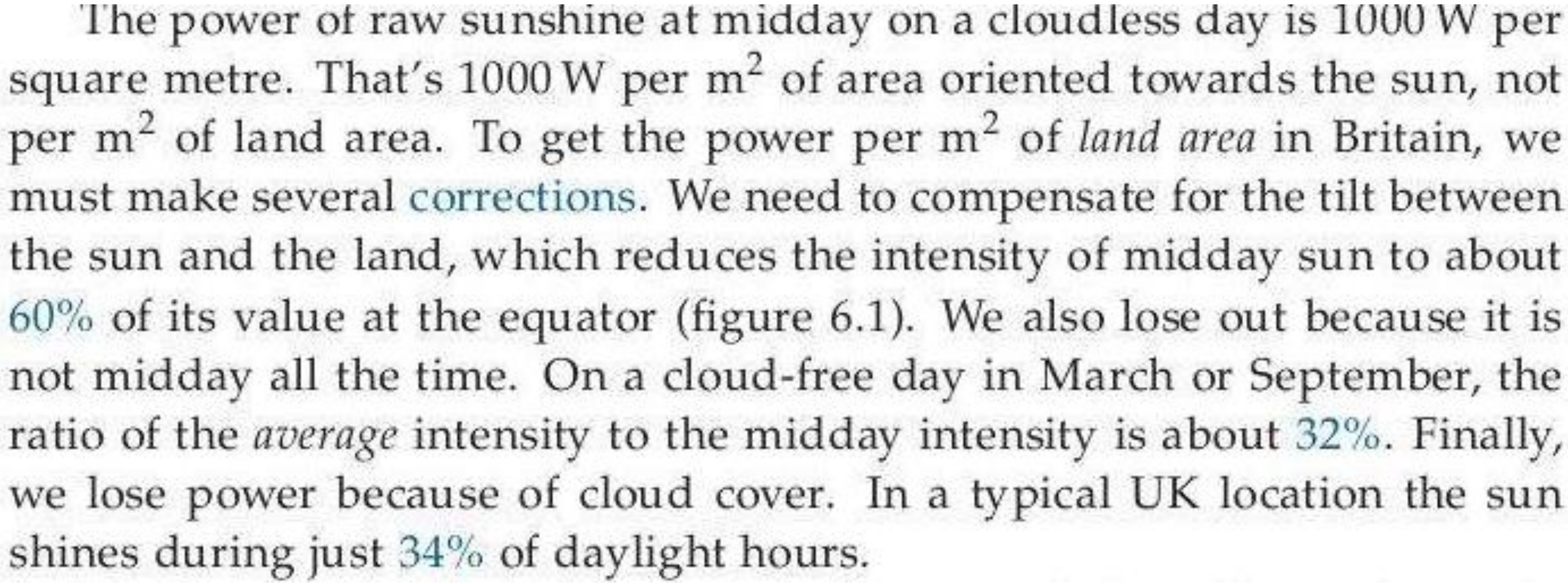


No redesign of a plane is going to radically improve its efficiency. Actually, the Advisory Council for Aerospace Research in Europe (ACARE) target is for an overall 50% reduction in fuel burned per passenger-km by 2020 (relative to a 2000 baseline), with 15–20% improvement expected in engine efficiency. As of 2006, Rolls Royce is half way to this engine target [`36w5gz`].

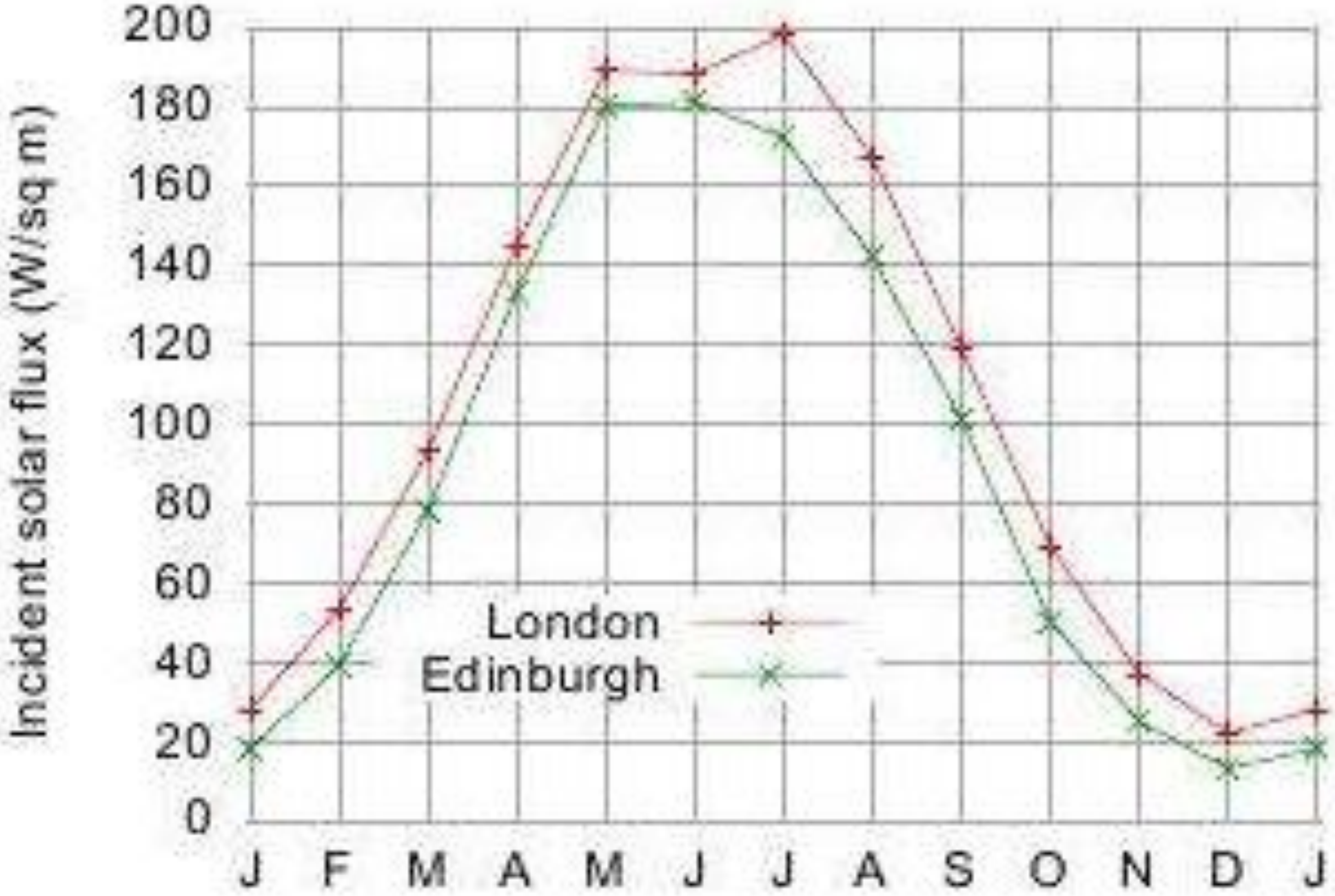
Dennis Bushnell, chief scientist at NASA's Langley Research Center, seems to agree with my overall assessment of prospects for efficiency improvements in aviation. The aviation industry is mature. "There is not much left to gain except by the glacial accretion of a per cent here and there over long time periods." (New Scientist, 24 February 2007, page 33.)

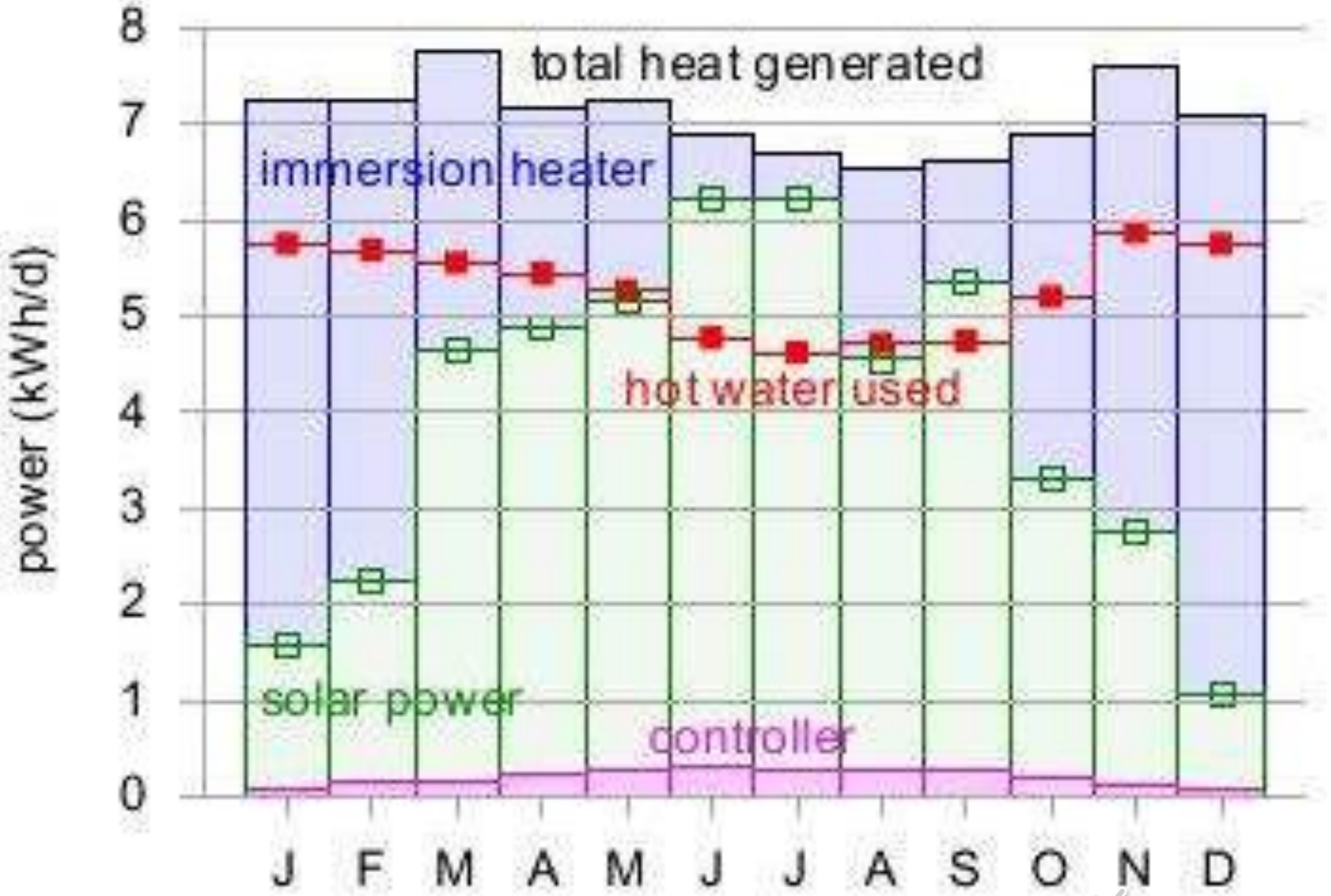
The radically reshaped "Silent Aircraft" [`silentaircraft.org/sax40`], if it were built, is predicted to be 16% more efficient than a conventional-shaped plane (Nickol, 2008).

If the ACARE target is reached, it's presumably going to be thanks mostly to having fuller planes and better air-traffic management.



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


Incident solar flux (W/sq m)
200
180
160
140
120
100
80
60
40
20
0
J
F
M
A
M
J
J
A
S
O
N
D
J
London
Edinburgh


total heat generated
immersion heater
hot water used
solar power
controller
power (kWh/d)
8
7
6
5
4
3
2
1
0
J
F
M
A
M
J
J
A
S
O
N
D

Solar thermal

The simplest solar power technology is a panel making hot water. Let's imagine we cover *all* south-facing roofs with solar thermal panels – that would be about $10\,\mathrm{m}^2$ of panels per person – and let's assume these are 50%-efficient at turning the sunlight's $110\,\mathrm{W/m}^2$ into hot water (figure 6.3). Multiplying

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

we find solar heating could deliver

13 kWh per day per person.

Solar photovoltaic

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

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

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

5 kWh per day per person.

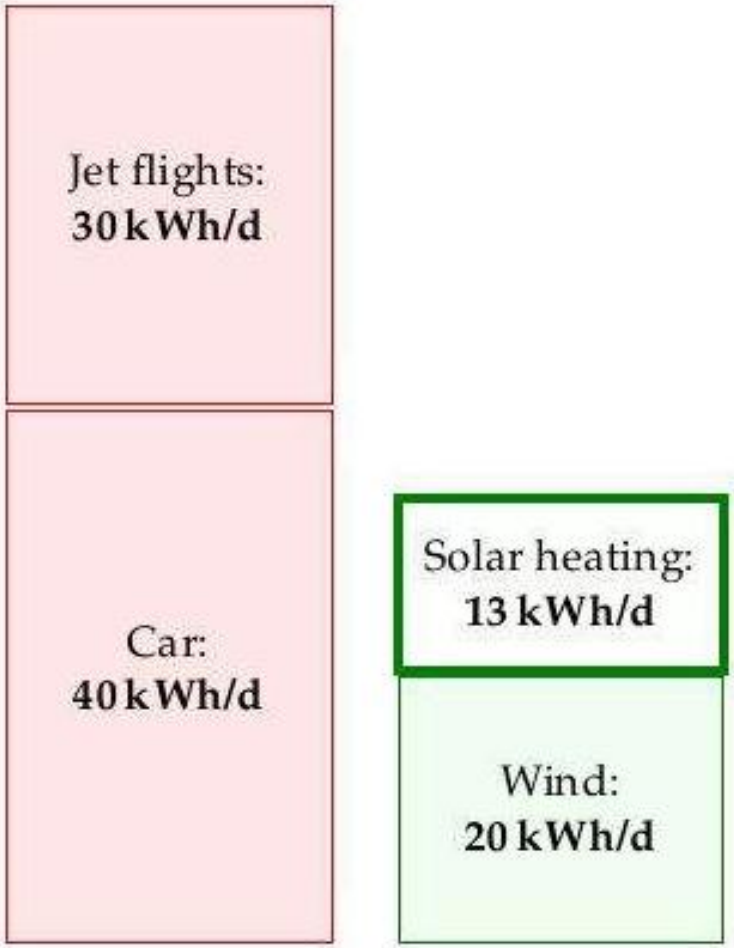
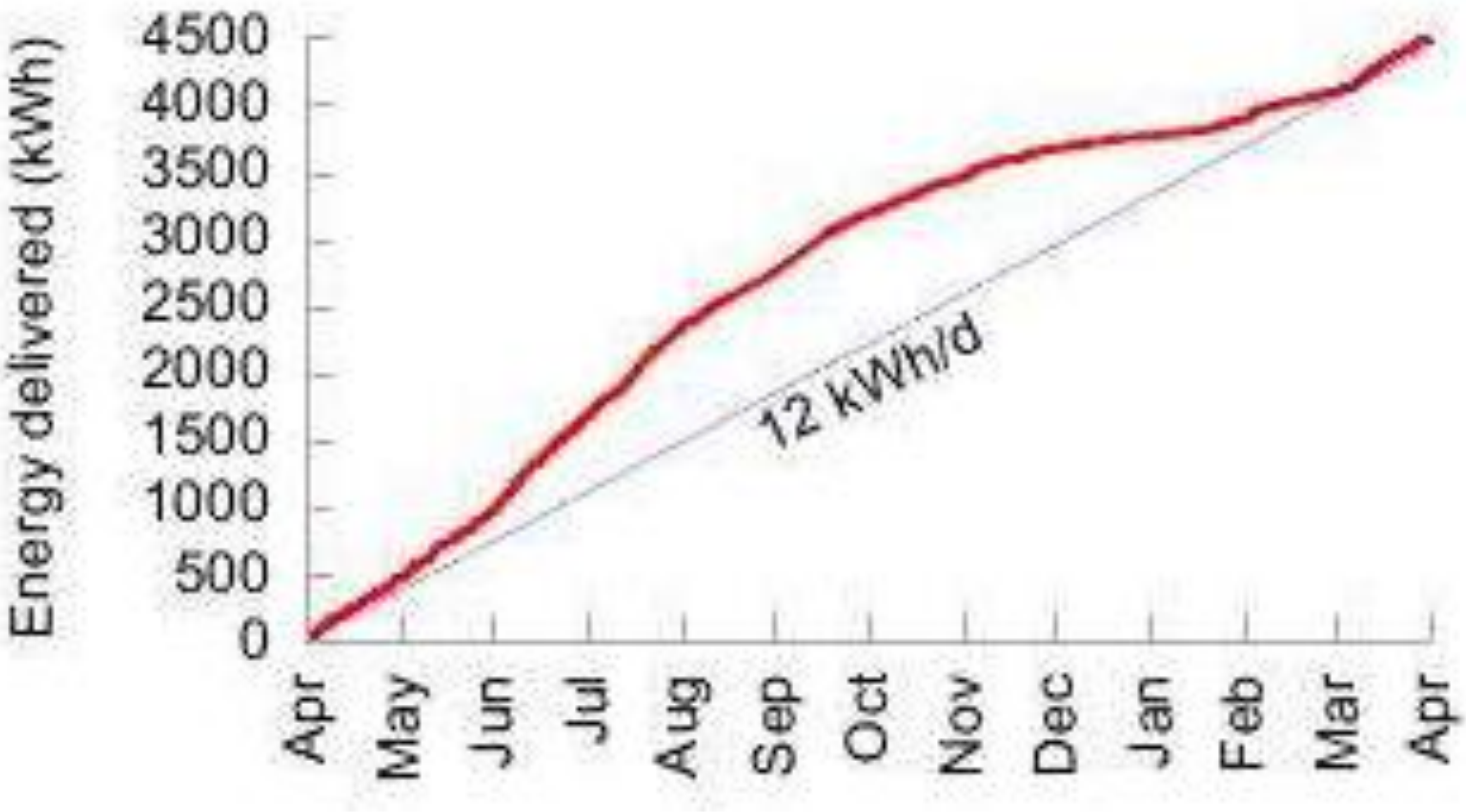


Figure 6.4. Solar thermal: a 10 m^2 array of thermal panels can deliver (on average) about 13 kWh per day of thermal energy.


Energy delivered (kWh)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
12 kWh/d
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr

Fantasy time: solar farming

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

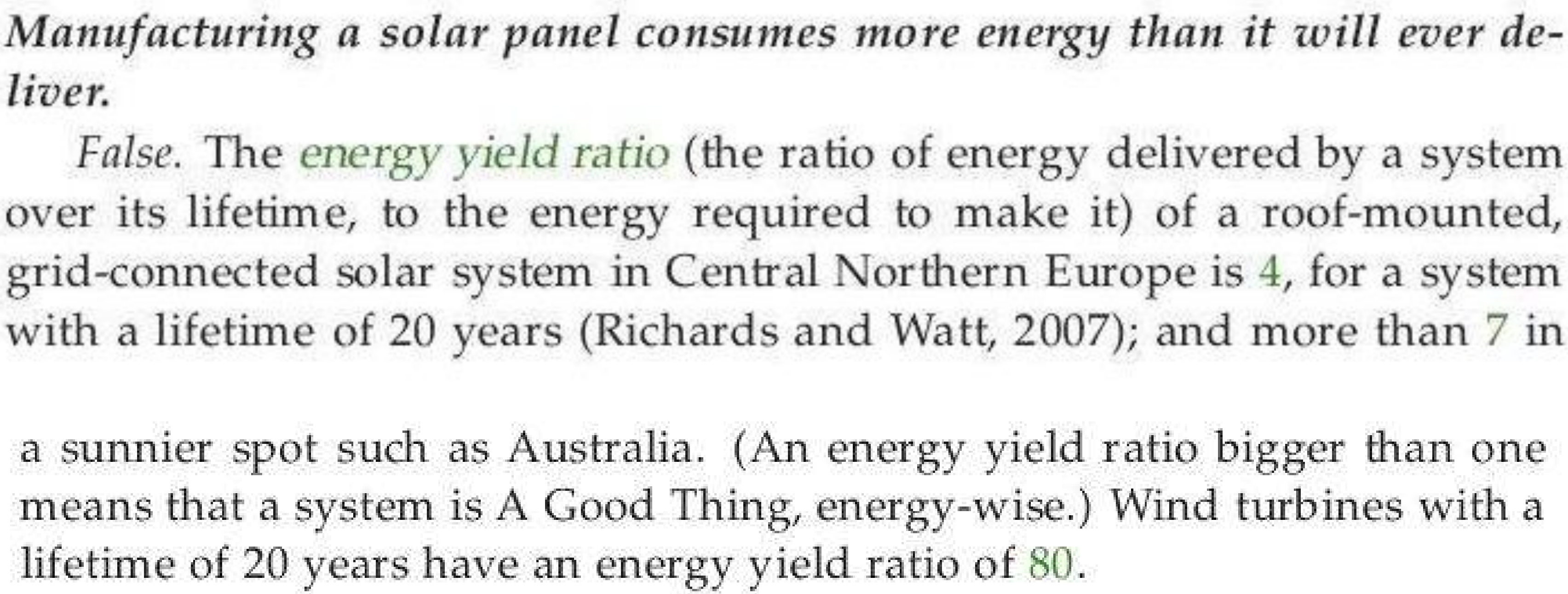
$$\begin{aligned} & 10\% \times 100\,\mathrm{W/m^2} \times 200\,\mathrm{m^2}\ \text{per person} \\ \simeq\ & 50\,\mathrm{kWh/day/person}. \end{aligned}$$

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

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

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

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



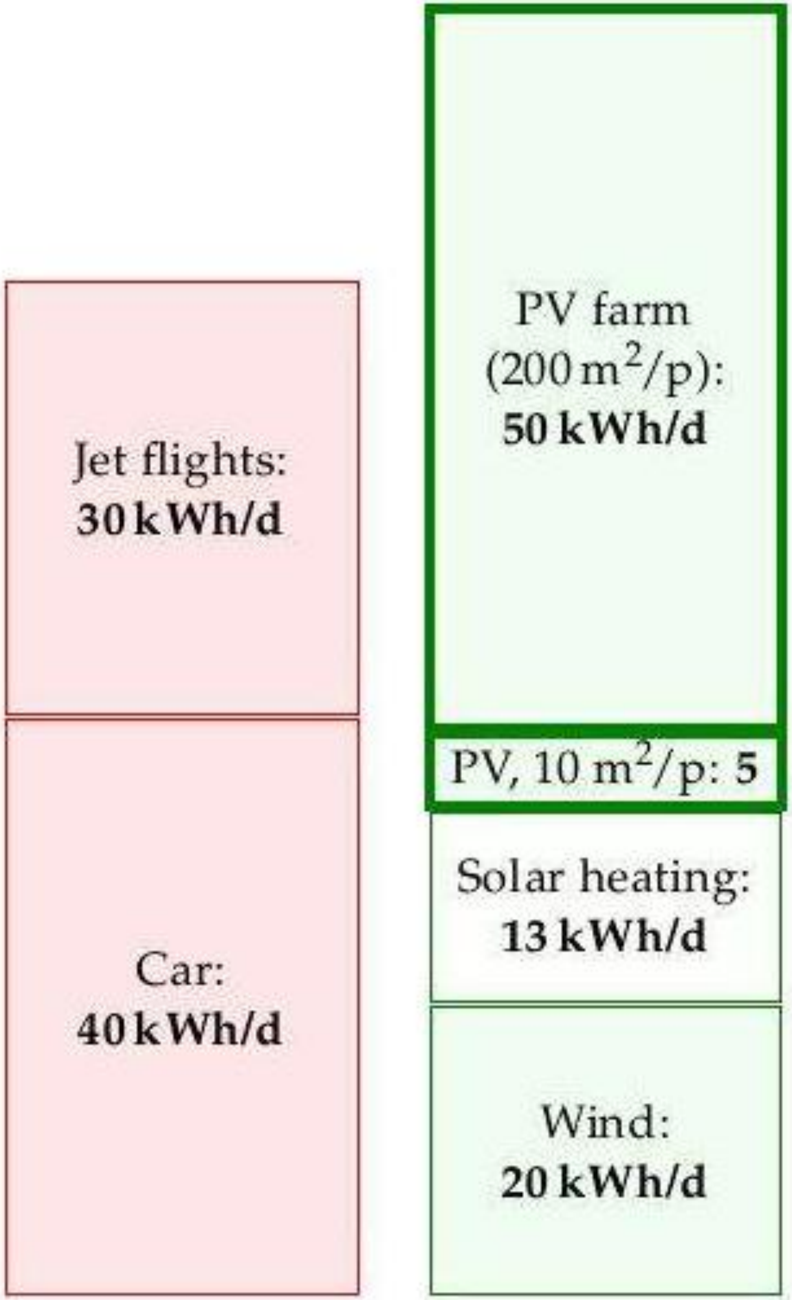
Manufacturing a solar panel consumes more energy than it will ever deliver.

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

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

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

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



Jet flights:
30 kWh/d

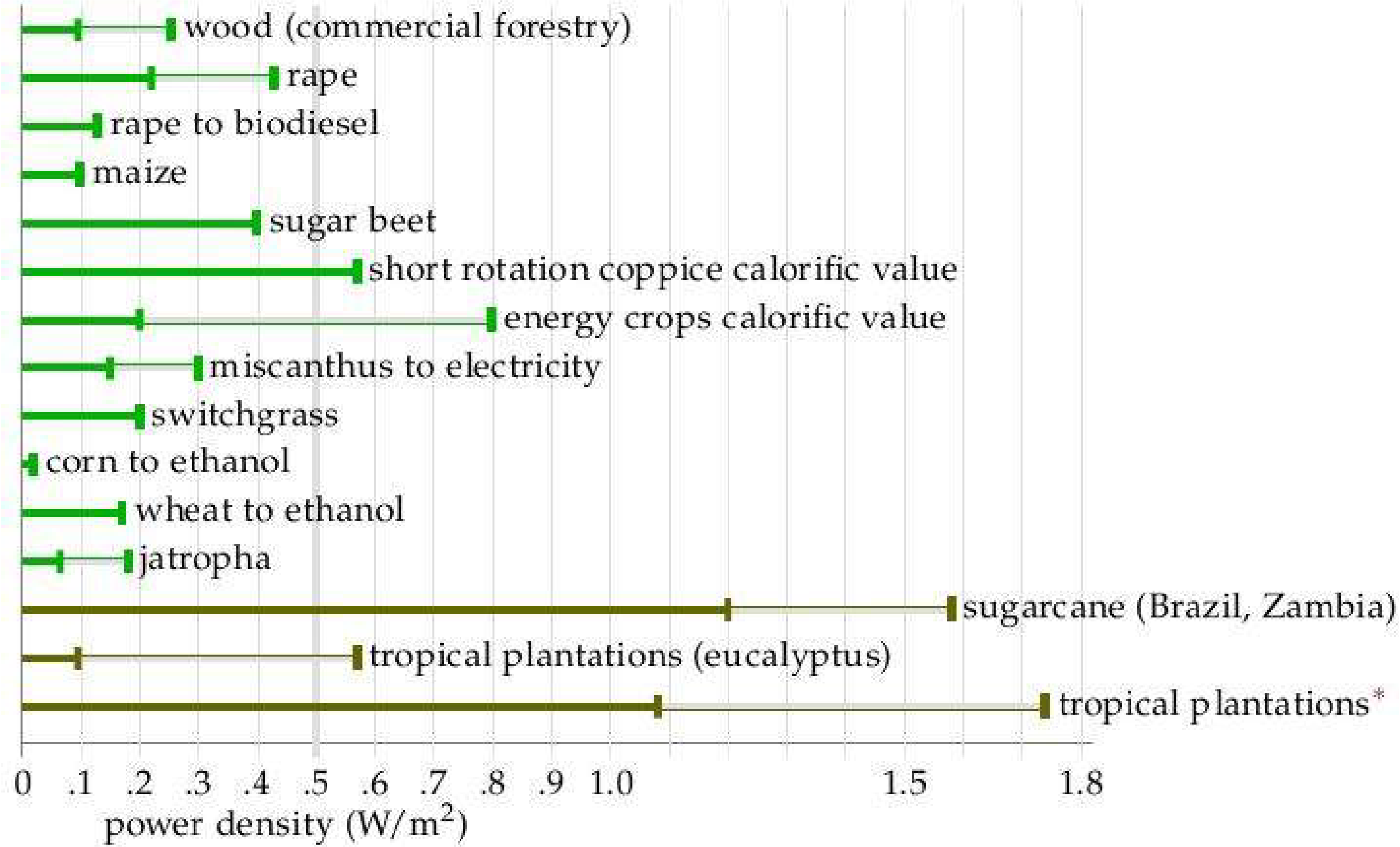
Car:
40 kWh/d

PV farm
($200\,m^2/p$):
50 kWh/d

PV, $10\,m^2/p$: **5**

Solar heating:
13 kWh/d

Wind:
20 kWh/d


wood (commercial forestry)
rape
rape to biodiesel
maize
sugar beet
short rotation coppice calorific value
energy crops calorific value
miscanthus to electricity
switchgrass
corn to ethanol
wheat to ethanol
jatropha
sugarcane (Brazil, Zambia)
tropical plantations (eucalyptus)
tropical plantations*
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.5
1.8
power density (W/m²)

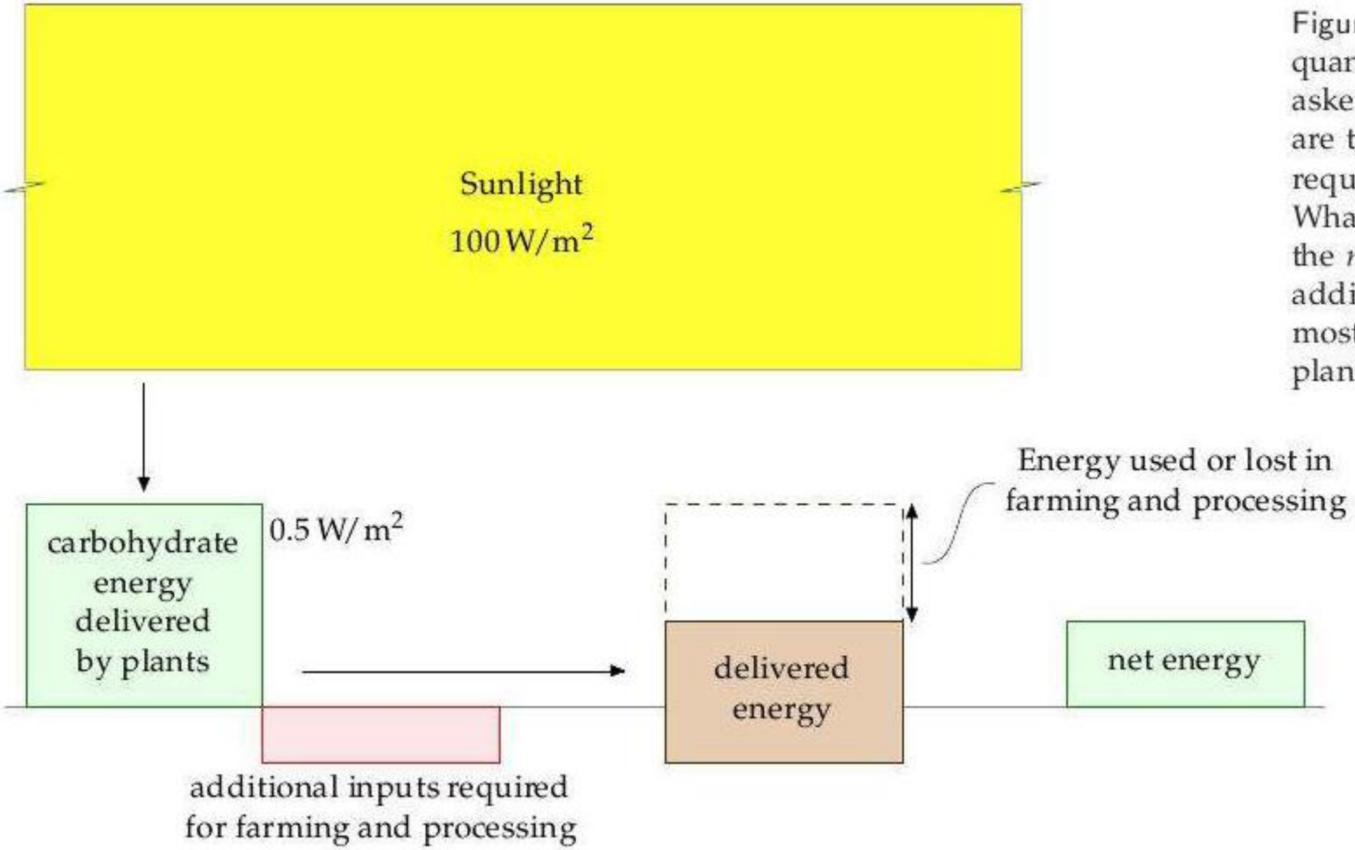


Figure 6.14. This figure illustrates the quantitative questions that must be asked of any proposed biofuel. What are the additional energy inputs required for farming and processing? What is the delivered energy? What is the *net* energy output? Often the additional inputs and losses wipe out most of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

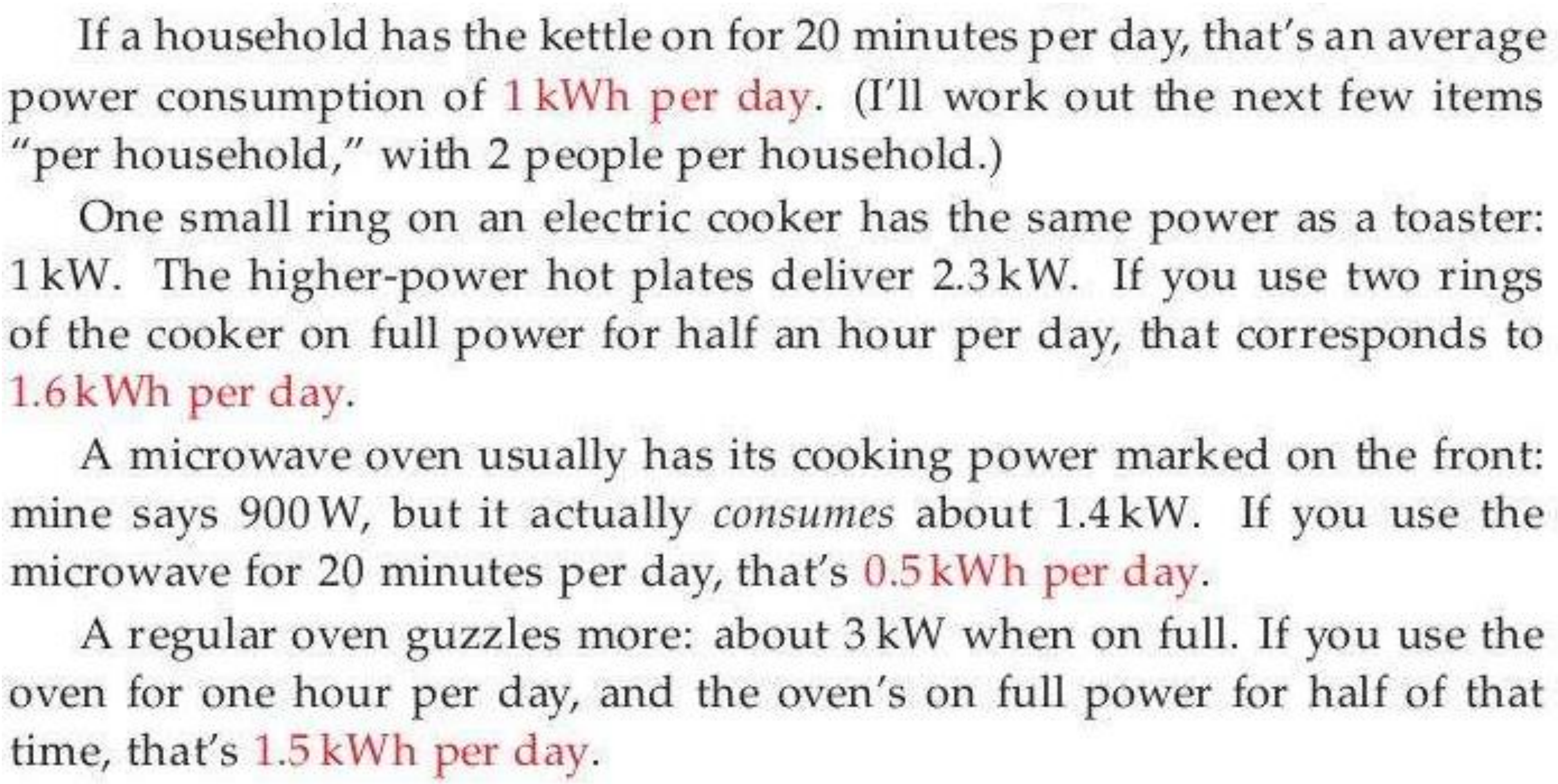
Domestic water heating

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

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

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

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



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

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

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

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

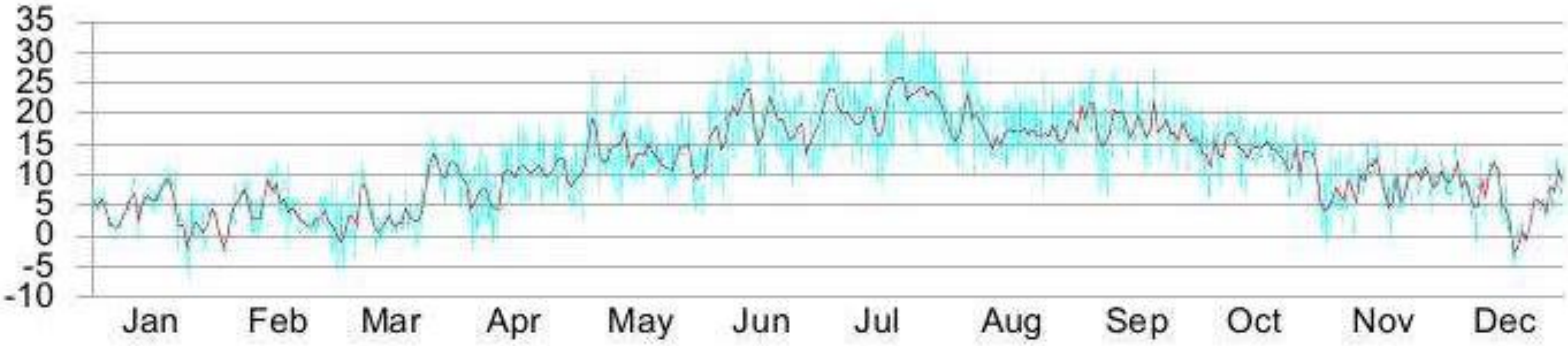
Device	power	time per day	energy per day
Cooking			
– kettle	3 kW	$^1/_3$ h	1 kWh/d
– microwave	1.4 kW	$^1/_3$ h	0.5 kWh/d
– electric cooker (rings)	3.3 kW	$^1/_2$ h	1.6 kWh/d
– electric oven	3 kW	$^1/_2$ h	1.5 kWh/d
Cleaning			
– washing machine	2.5 kW		1 kWh/d
– tumble dryer	2.5 kW	0.8 h	2 kWh/d
– airing-cupboard drying			0.5 kWh/d
– washing-line drying			0 kWh/d
– dishwasher	2.5 kW		1.5 kWh/d
Cooling			
– refrigerator	0.02 kW	24 h	0.5 kWh/d
– freezer	0.09 kW	24 h	2.3 kWh/d
– air-conditioning	0.6 kW	1 h	0.6 kWh/d

Fridge and freezer

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

Air-conditioning

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



Total heating and cooling

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

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

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

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

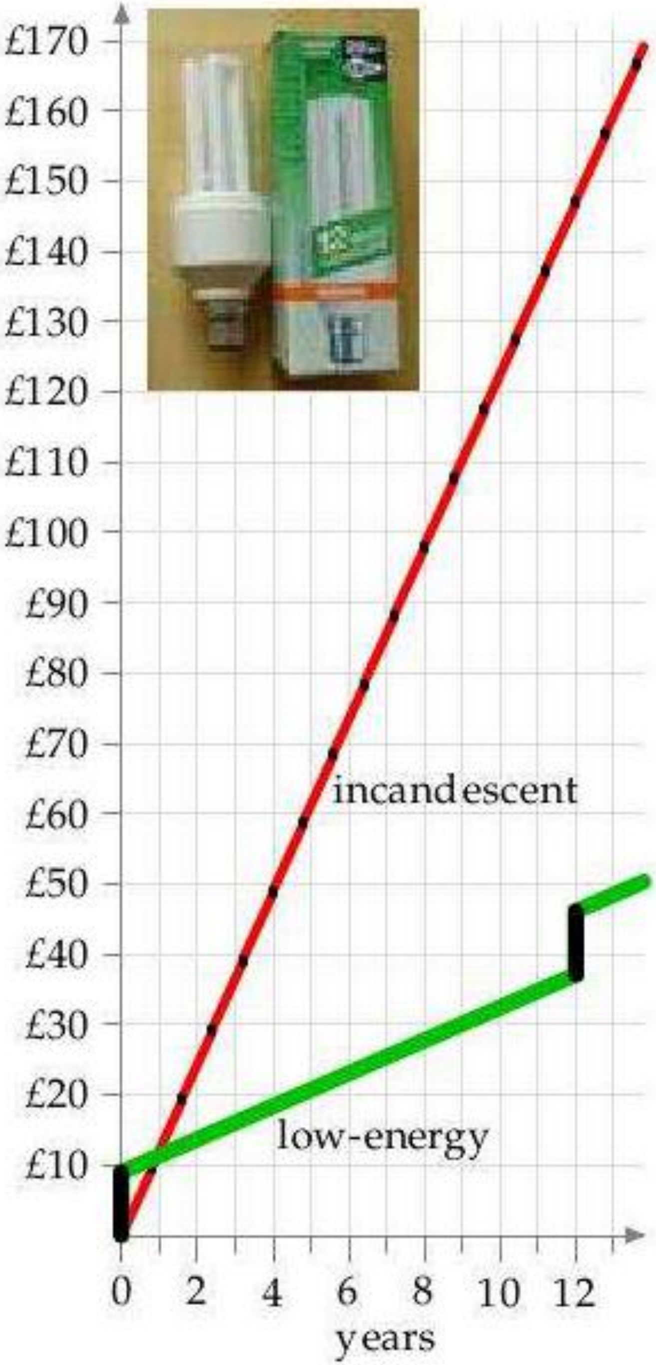
Device	Power	Time per day	Energy per day per home
10 incandescent lights	1 kW	5 h	5 kWh
10 low-energy lights	0.1 kW	5 h	0.5 kWh

The economics of low-energy bulbs

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

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

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



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

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

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

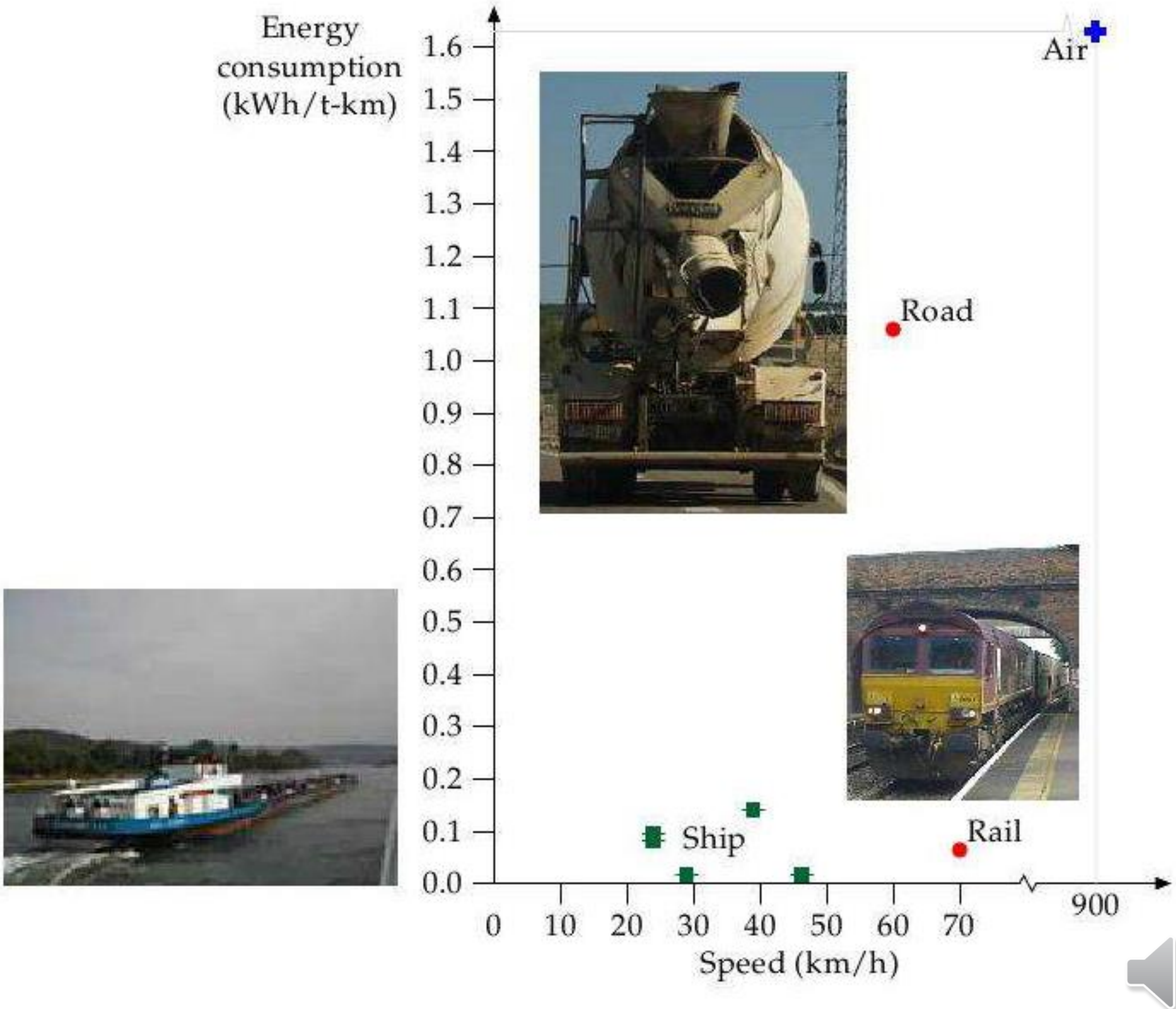
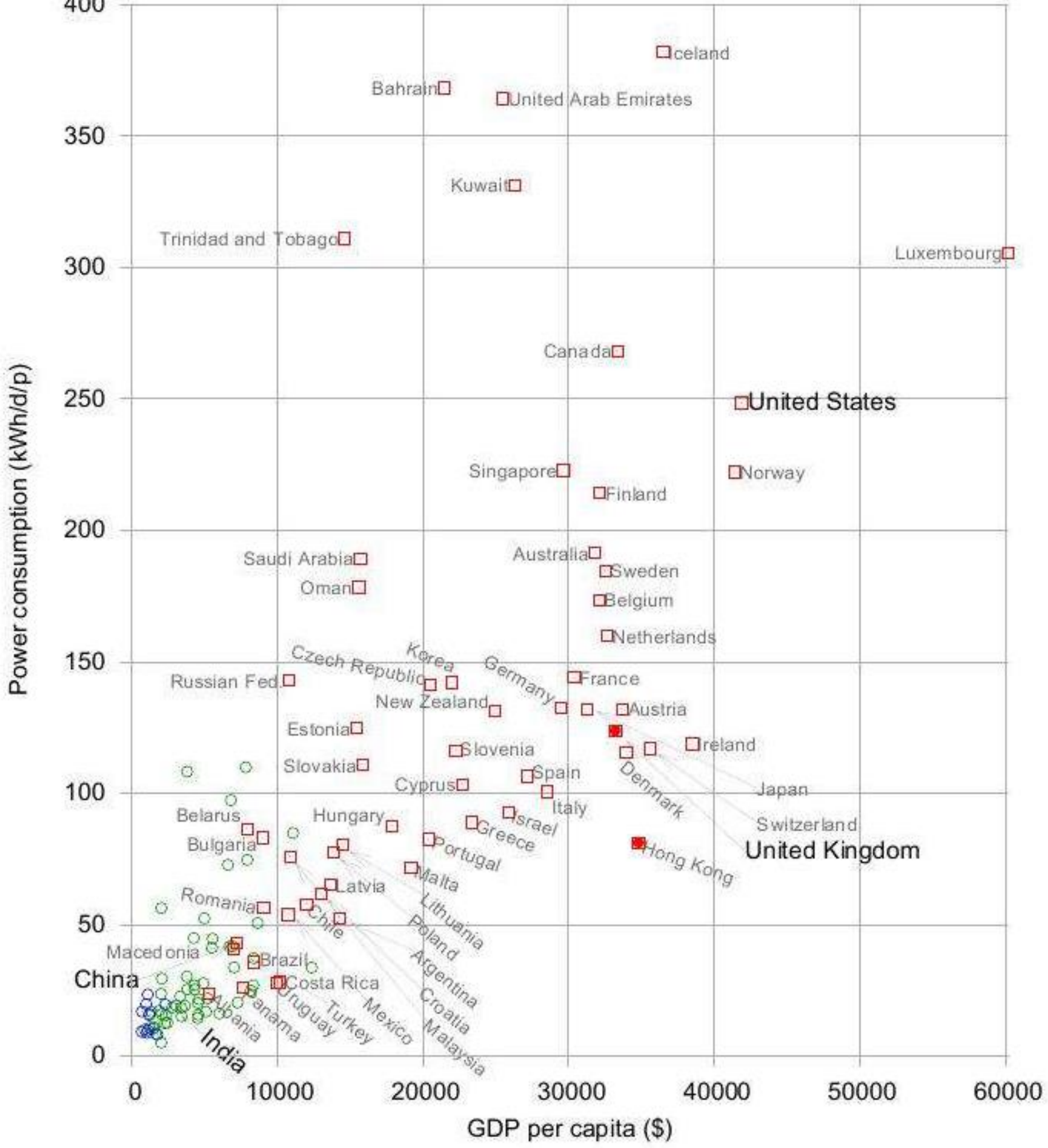

Energy consumption (kWh/t-km)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Air
Road
Ship
Rail
0
10
20
30
40
50
60
70
900
Speed (km/h)

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

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



Power consumption (kWh/d/p)
GDP per capita ($)
400
350
300
250
200
150
100
50
0
0
10000
20000
30000
40000
50000
60000
Iceland
Bahrain
United Arab Emirates
Kuwait
Trinidad and Tobago
Luxembourg
Canada
United States
Singapore
Norway
Finland
Saudi Arabia
Australia
Sweden
Oman
Belgium
Netherlands
Czech Republic
Korea
Germany
France
Russian Fed
New Zealand
Austria
Estonia
Ireland
Slovenia
Slovakia
Spain
Japan
Cyprus
Denmark
Italy
Belarus
Hungary
Israel
Switzerland
Greece
United Kingdom
Bulgaria
Portugal
Hong Kong
Malta
Latvia
Romania
Lithuania
Chile
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Costa Rica
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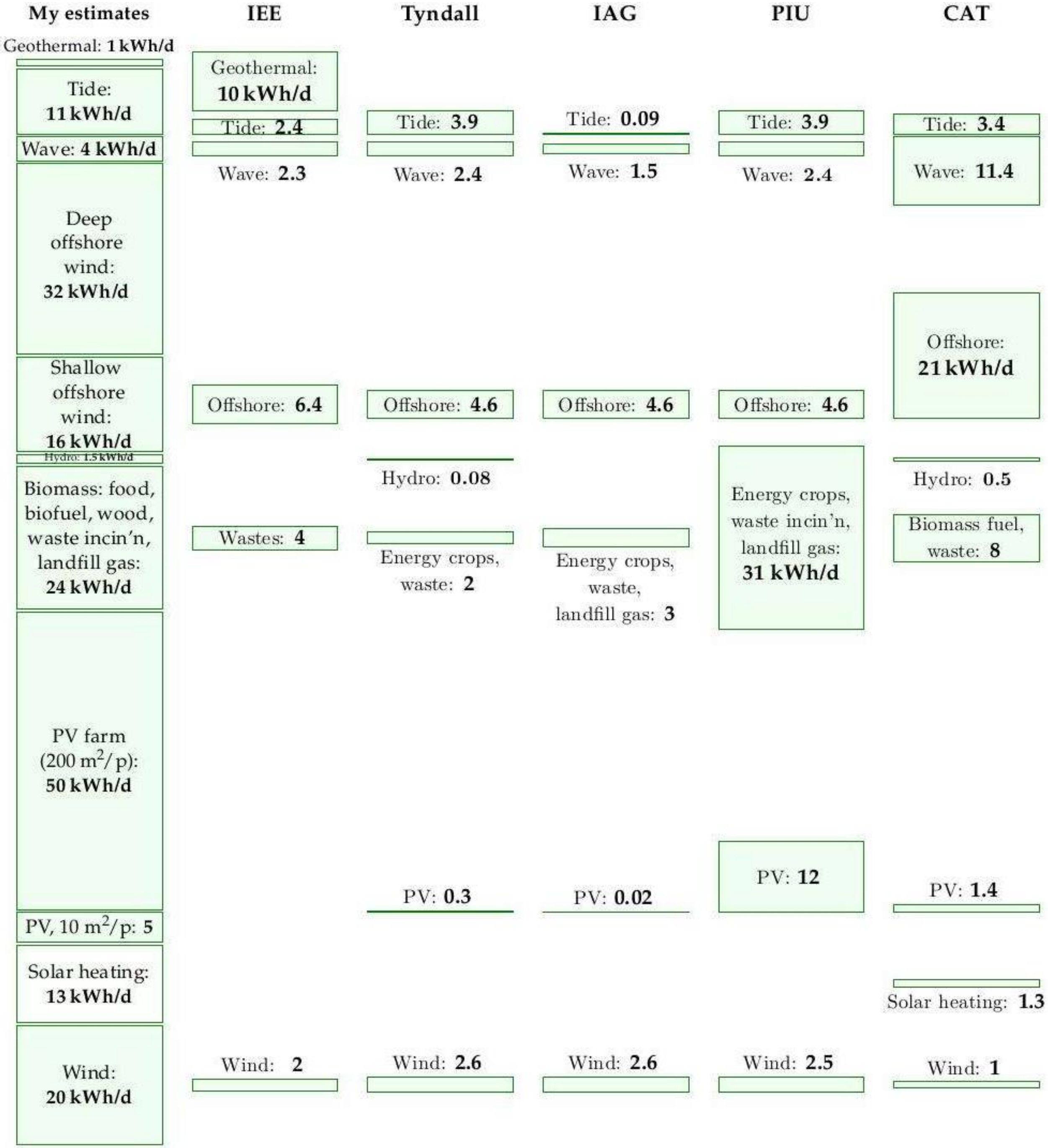
Panama
Uruguay
Turkey
Mexico
Malaysia
India



My estimates	IEE	Tyndall	IAG	PIU	CAT
Geothermal: **1 kWh/d**	Geothermal: **10 kWh/d**				
Tide: **11 kWh/d**	Tide: **2.4**	Tide: **3.9**	Tide: **0.09**	Tide: **3.9**	Tide: **3.4**
Wave: **4 kWh/d**	Wave: **2.3**	Wave: **2.4**	Wave: **1.5**	Wave: **2.4**	Wave: **11.4**
Deep offshore wind: **32 kWh/d**					
Shallow offshore wind: **16 kWh/d**	Offshore: **6.4**	Offshore: **4.6**	Offshore: **4.6**	Offshore: **4.6**	Offshore: **21 kWh/d**
Hydro: 1.5 kWh/d		Hydro: **0.08**			Hydro: **0.5**
Biomass: food, biofuel, wood, waste incin'n, landfill gas: **24 kWh/d**	Wastes: **4**	Energy crops, waste: **2**	Energy crops, waste, landfill gas: **3**	Energy crops, waste incin'n, landfill gas: **31 kWh/d**	Biomass fuel, waste: **8**
PV farm (200 m²/p): **50 kWh/d**					
PV, 10 m²/p: **5**		PV: **0.3**	PV: **0.02**	PV: **12**	PV: **1.4**
Solar heating: **13 kWh/d**					Solar heating: **1.3**
Wind: **20 kWh/d**	Wind: **2**	Wind: **2.6**	Wind: **2.6**	Wind: **2.5**	Wind: **1**

1. In *short-distance travel* with lots of starting and stopping, the energy mainly goes into speeding up the vehicle and its contents. Key strategies for consuming less in this sort of transportation are therefore to *weigh less*, and to *go further between stops*. Regenerative braking, which captures energy when slowing down, may help too. In addition, it helps to *move slower*, and to *move less*.

2. In *long-distance travel* at steady speed, by train or automobile, most of the energy goes into making air swirl around, because you only have to accelerate the vehicle once. The key strategies for consuming less in this sort of transportation are therefore to *move slower*, and to *move less*, and to *use long, thin vehicles*.

forwards. Inevitably this energy chain has inefficiencies. In a standard fossil-fuel car, for example, only 25% is used for pushing, and roughly 75% of the energy is lost in making the engine and radiator hot. So a final strategy for consuming less energy is to make the energy-conversion chain more efficient.

Figure 20.3 shows a multi-passenger vehicle that is at least 25 times more energy-efficient than a standard petrol car: a bicycle. The bicycle's performance (in terms of energy per distance) is about the same as the eco-car's. Its speed is the same, its mass is lower than the eco-car's (because the human replaces the fuel tank and engine), and its effective frontal area is higher, because the cyclist is not so well streamlined as the eco-car.

Figure 20.4 shows another possible replacement for the petrol car: a train, with an energy-cost, if full, of 1.6 kWh per 100 passenger-km. In

Figure 20.3. "Babies on board." This mode of transportation has an energy cost of 1 kWh per 100 person-km.

Figure 20.4. This 8-carriage train, at its maximum speed of 100 mph (161 km/h), consumes 1.6 kWh per 100 passenger-km, if full.

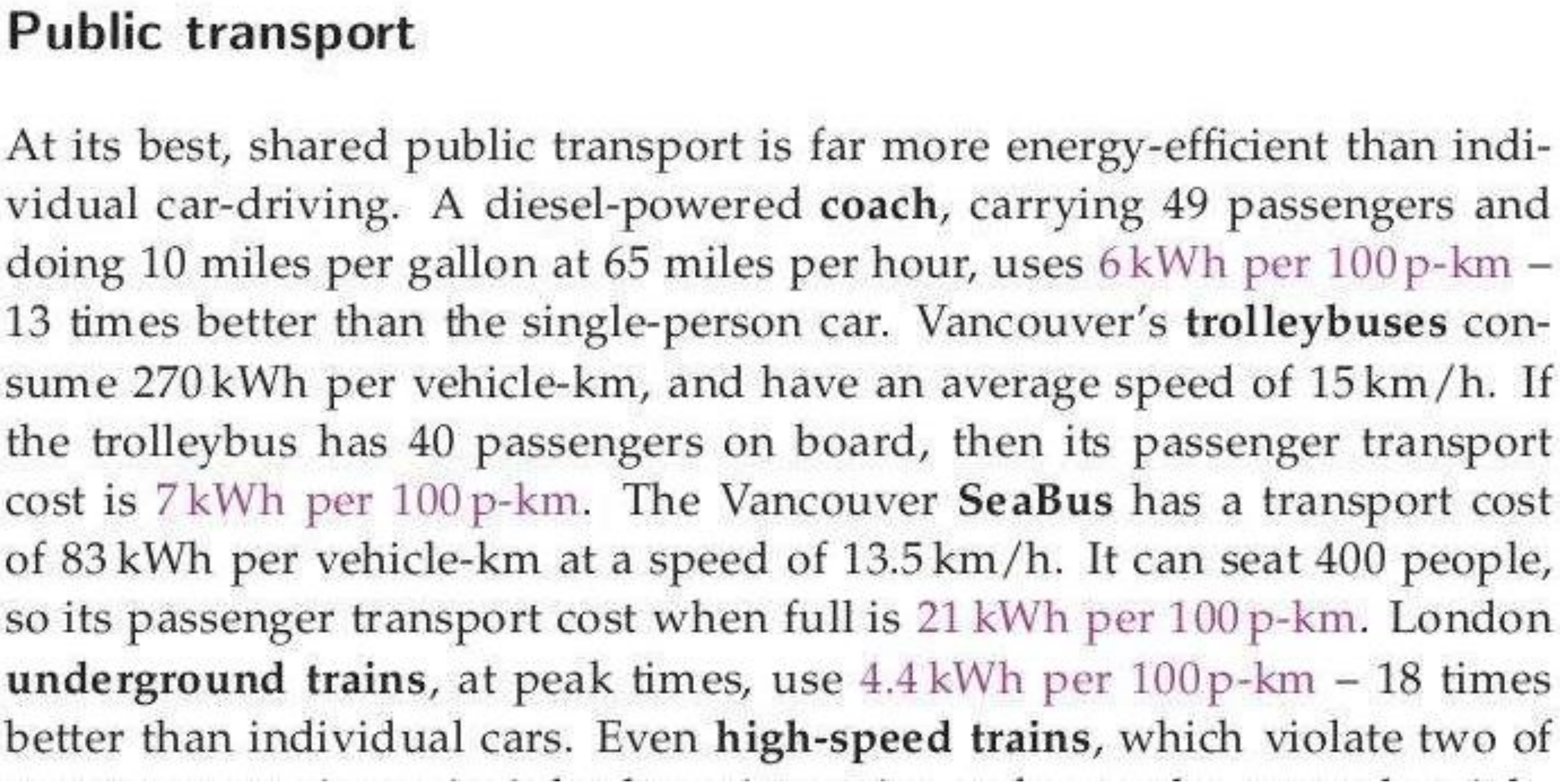
4.4 kWh per 100 p-km, if full

3–9 kWh per 100 seat-km, if full

7 kWh per 100 p-km, if full

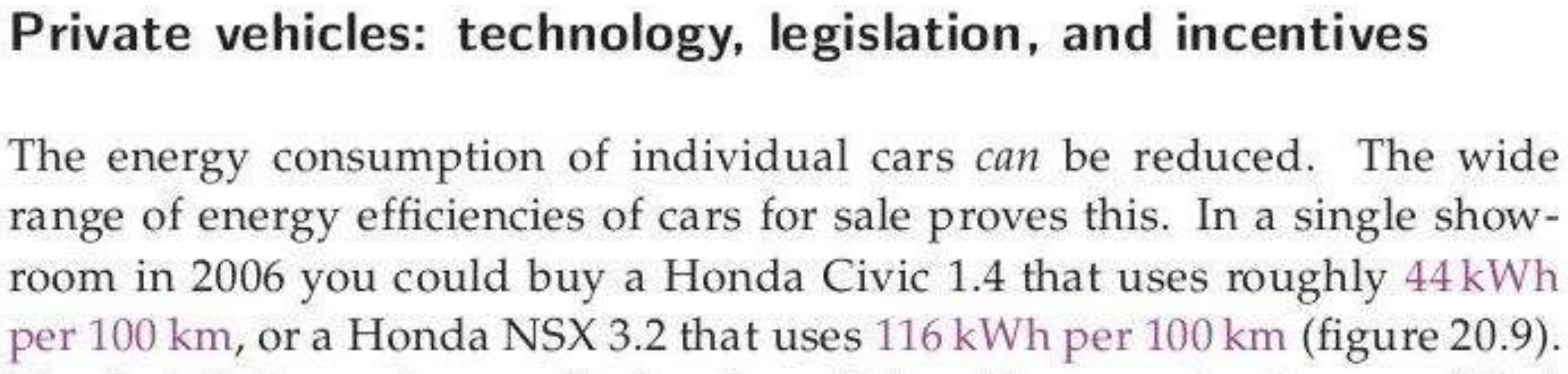
21 kWh per 100 p-km, if full

Figure 20.5. Some public transports, and their energy-efficiencies, when o
best behaviour.
Tubes, outer and inner.
Two high-speed trains. The electric one uses 3 kWh per 100 seat-km; the diesel, 9 kWh.
Trolleybuses in San Francisco.
Vancouver SeaBus. Photo by Larry.



Public transport

At its best, shared public transport is far more energy-efficient than individual car-driving. A diesel-powered **coach**, carrying 49 passengers and doing 10 miles per gallon at 65 miles per hour, uses 6 kWh per 100 p-km – 13 times better than the single-person car. Vancouver's **trolleybuses** consume 270 kWh per vehicle-km, and have an average speed of 15 km/h. If the trolleybus has 40 passengers on board, then its passenger transport cost is 7 kWh per 100 p-km. The Vancouver **SeaBus** has a transport cost of 83 kWh per vehicle-km at a speed of 13.5 km/h. It can seat 400 people, so its passenger transport cost when full is 21 kWh per 100 p-km. London **underground trains**, at peak times, use 4.4 kWh per 100 p-km – 18 times better than individual cars. Even **high-speed trains**, which violate two of



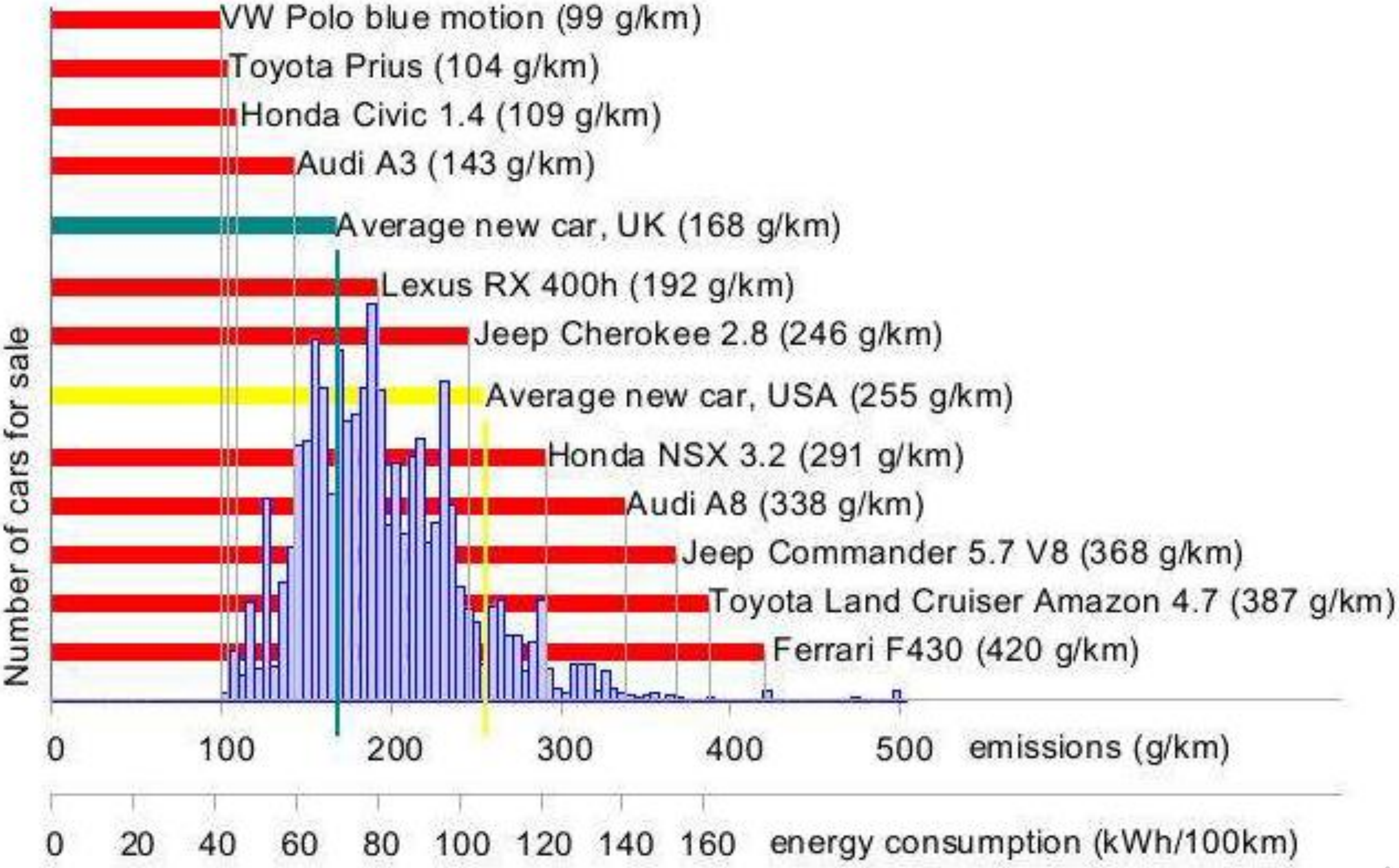
Private vehicles: technology, legislation, and incentives

The energy consumption of individual cars *can* be reduced. The wide range of energy efficiencies of cars for sale proves this. In a single showroom in 2006 you could buy a Honda Civic 1.4 that uses roughly 44 kWh per 100 km, or a Honda NSX 3.2 that uses 116 kWh per 100 km (figure 20.9).

32 kWh per 100 p-km

9 kWh per 100 p-km

	Energy consumption (kWh per 100 p-km)
Car	68
Bus	19
Rail	6
Air	51
Sea	57


VW Polo blue motion (99 g/km)
Toyota Prius (104 g/km)
Honda Civic 1.4 (109 g/km)
Audi A3 (143 g/km)
Average new car, UK (168 g/km)
Lexus RX 400h (192 g/km)
Jeep Cherokee 2.8 (246 g/km)
Average new car, USA (255 g/km)
Honda NSX 3.2 (291 g/km)
Audi A8 (338 g/km)
Jeep Commander 5.7 V8 (368 g/km)
Toyota Land Cruiser Amazon 4.7 (387 g/km)
Ferrari F430 (420 g/km)
Number of cars for sale
0
100
200
300
400
500
emissions (g/km)
0
20
40
60
80
100
120
140
160
energy consumption (kWh/100km)

Regenerative systems using flywheels and hydraulics seem to work a little better than battery-based systems, salvaging at least 70% of the braking energy. Figure 20.17 describes a hybrid car with a petrol engine powering digitally-controlled hydraulics. On a standard driving cycle, this car uses 30% less fuel than the original petrol car. In urban driving, its energy consumption is halved, from 131 kWh per 100 km to 62 kWh per 100 km (20 mpg to 43 mpg). (Credit for this performance improvement must be shared between regenerative braking and the use of hybrid technology.) Hydraulics and flywheels are both promising ways to handle regenerative braking because small systems can handle large powers. A flywheel system weighing just 24 kg (figure 20.18), designed for energy storage in a racing car, can store 400 kJ (0.1 kWh) of energy – enough energy to accelerate an ordinary car up to 60 miles per hour (97 km/h); and it can accept or deliver 60 kW of power. Electric batteries capable of delivering that much power would weigh about 200 kg. So, unless you're already carrying that much battery on board, an electrical regenerative-braking system should probably use capacitors to store braking energy. Super-capacitors have similar energy-storage and power-delivery parameters to the flywheel's.

Figure 20.18. A flywheel regenerative-braking system. Photos courtesy of Flybrid Systems.

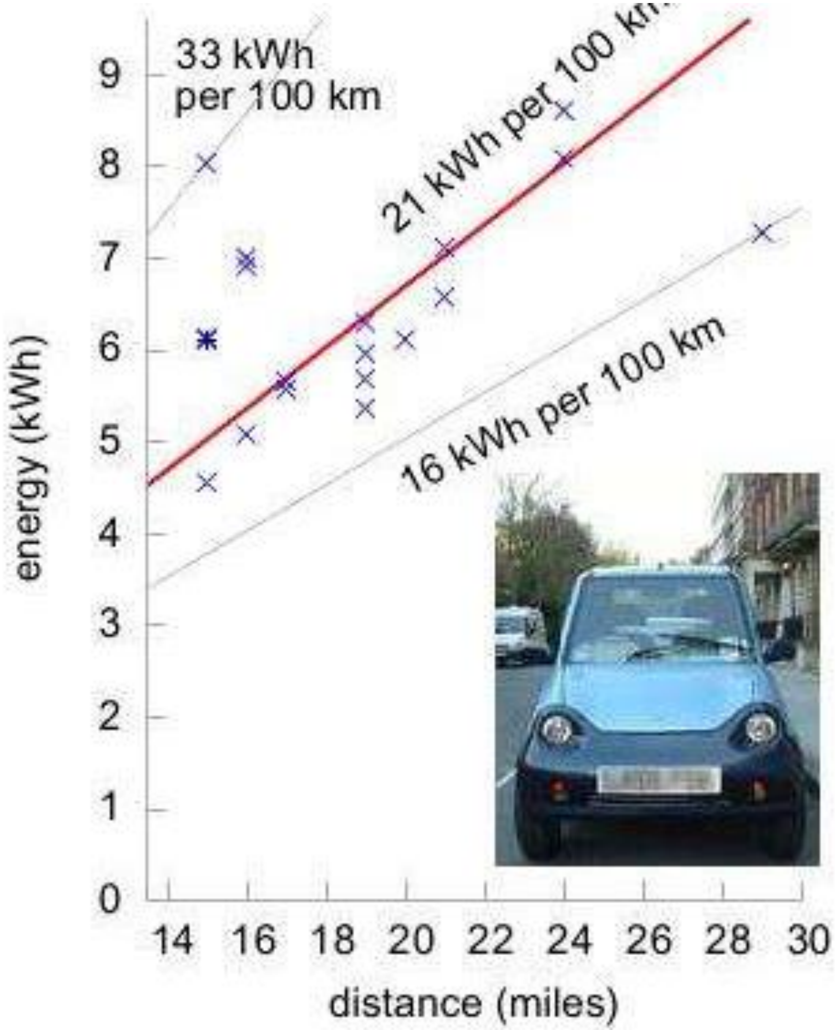


Figure 20.21. Electricity required to recharge a G-Wiz versus distance driven. Measurements were made at the socket.

Electric vehicles

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

The power used to heat a building is given by multiplying together three quantities:

$$\text{power used} = \frac{\text{average temperature difference} \times \text{leakiness of building}}{\text{efficiency of heating system}}.$$

Let me explain this formula (which is discussed in detail in Chapter E) with an example. My house is a three-bedroom semi-detached house built about 1940 (figure 21.1). The average temperature difference between the inside and outside of the house depends on the setting of the thermostat and on the weather. If the thermostat is permanently at 20°C, the average temperature difference might be 9°C. The *leakiness* of the building describes how quickly heat gets out through walls, windows, and cracks, in response to a temperature difference. The leakiness is sometimes called the *heat-loss coefficient* of the building. It is measured in kWh per day per degree of temperature difference. In Chapter E, I calculate that the leakiness of my house in 2006 was 7.7 kWh/d/°C. The product

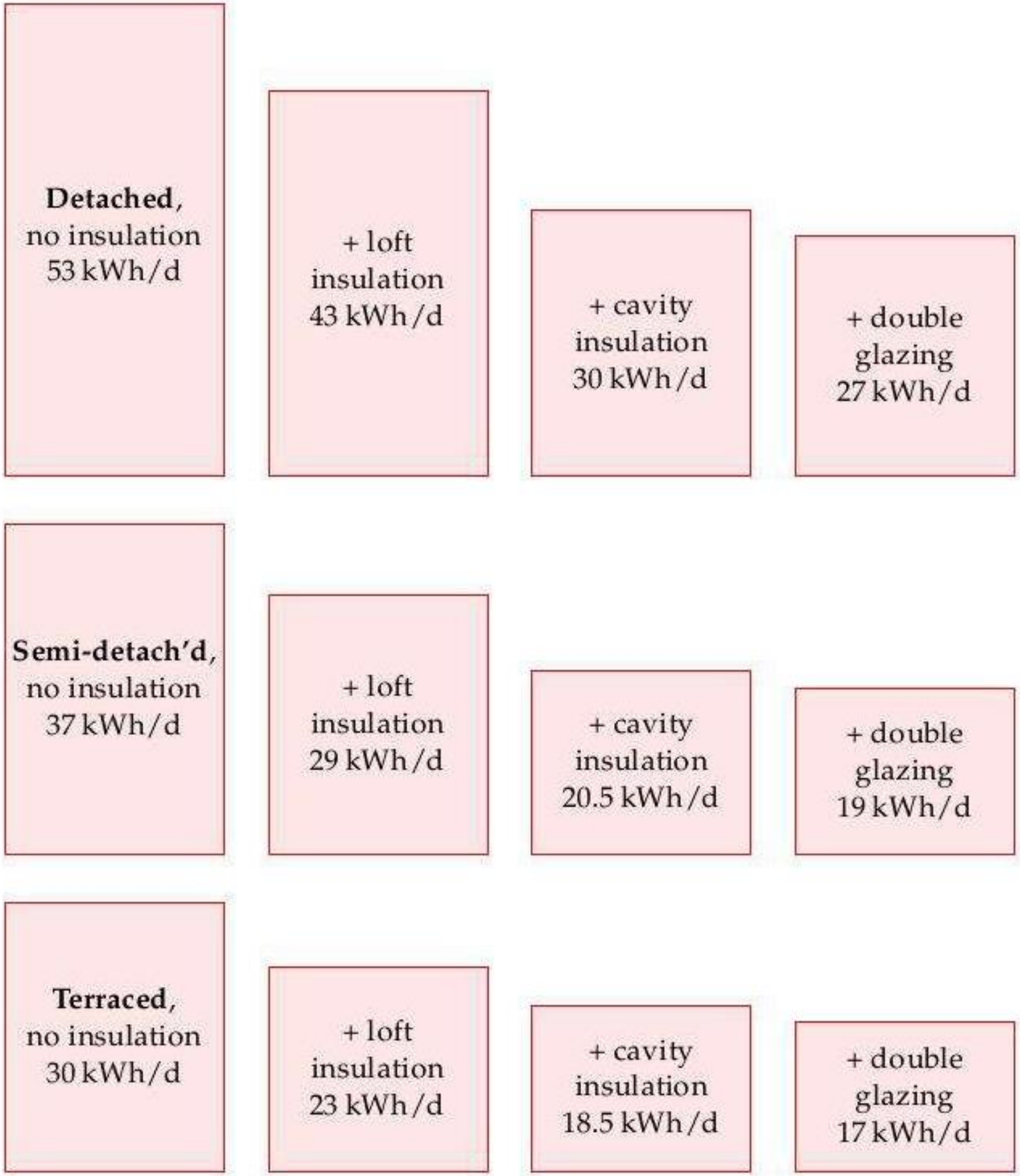
$$\text{average temperature difference} \times \text{leakiness of building}$$

is the rate at which heat flows out of the house by conduction and ventilation. For example, if the average temperature difference is $9\,^\circ\mathrm{C}$ then the heat loss is

$$9\,^\circ\mathrm{C} \times 7.7\,\mathrm{kWh/d/^\circ C} \simeq 70\,\mathrm{kWh/d}.$$

Finally, to calculate the power required, we divide this heat loss by the efficiency of the heating system. In my house, the condensing gas boiler has an efficiency of 90%, so we find:

$$\text{power used} = \frac{9\,^\circ\mathrm{C} \times 7.7\,\mathrm{kWh/d/^\circ C}}{0.9} = 77\,\mathrm{kWh/d}.$$



Detached, no insulation 53 kWh/d

+ loft insulation 43 kWh/d

+ cavity insulation 30 kWh/d

+ double glazing 27 kWh/d

Semi-detach'd, no insulation 37 kWh/d

+ loft insulation 29 kWh/d

+ cavity insulation 20.5 kWh/d

+ double glazing 19 kWh/d

Terraced, no insulation 30 kWh/d

+ loft insulation 23 kWh/d

+ cavity insulation 18.5 kWh/d

+ double glazing 17 kWh/d

Figure 21.3. Estimates of the space heating required in a range of UK houses. From Eden and Bending (1985).

Better buildings

If you get the chance to build a new building then there are lots of ways to ensure its heating consumption is much smaller than that of an old building. Figure 21.2 gave evidence that modern houses are built to much better insulation standards than those of the 1940s. But the building standards in Britain could be still better, as Chapter E discusses. The three key ideas for the best results are: (1) have really thick insulation in floors, walls, and roofs; (2) ensure the building is completely sealed and use active ventilation to introduce fresh air and remove stale and humid air, with heat exchangers passively recovering much of the heat from the removed air; (3) design the building to exploit sunshine as much as possible.

The energy cost of heat

So far, this chapter has focused on temperature control and leakiness. Now we turn to the third factor in the equation:

$$\text{power used} = \frac{\text{average temperature difference} \times \text{leakiness of building}}{\text{efficiency of heating system}}.$$

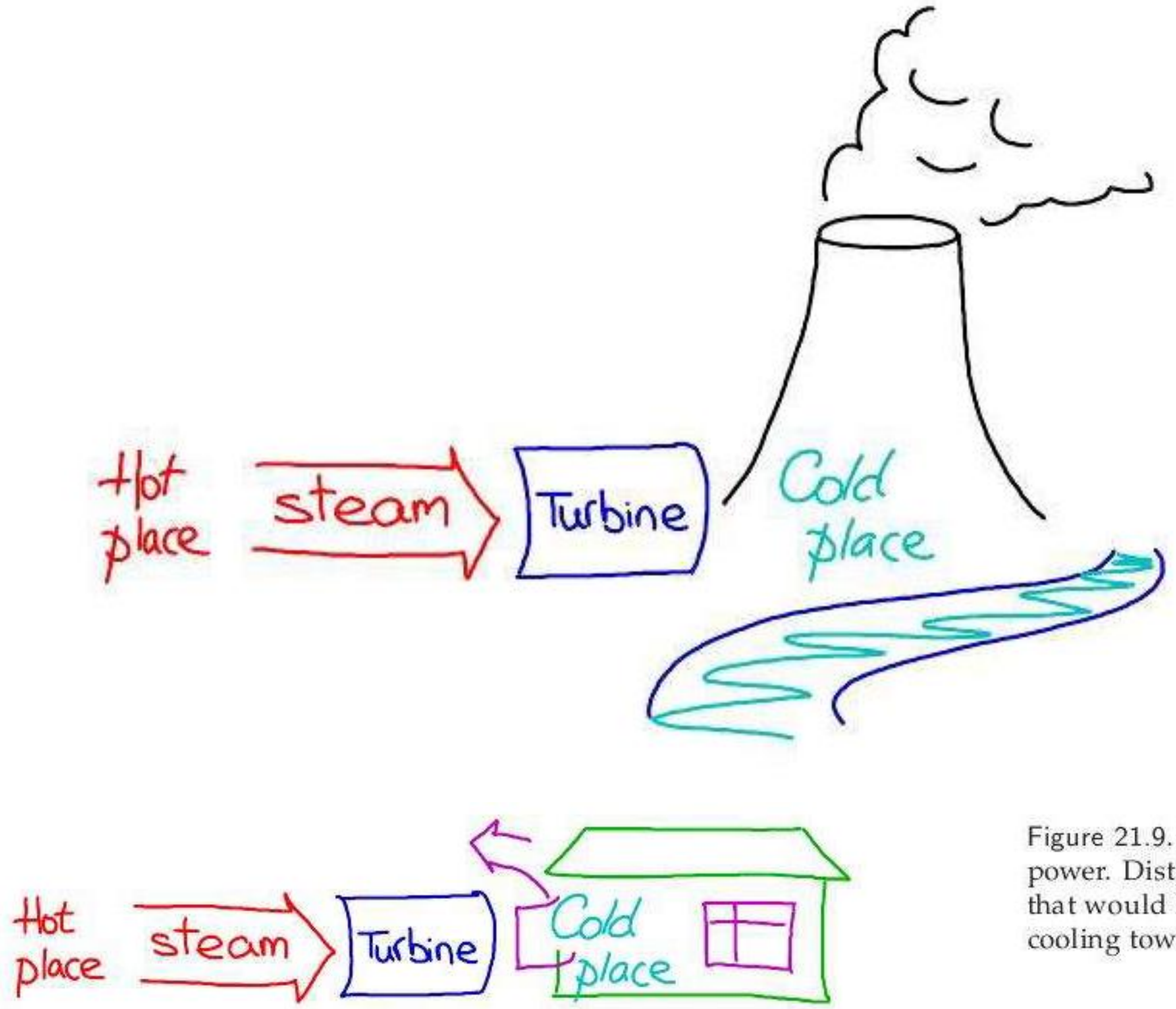
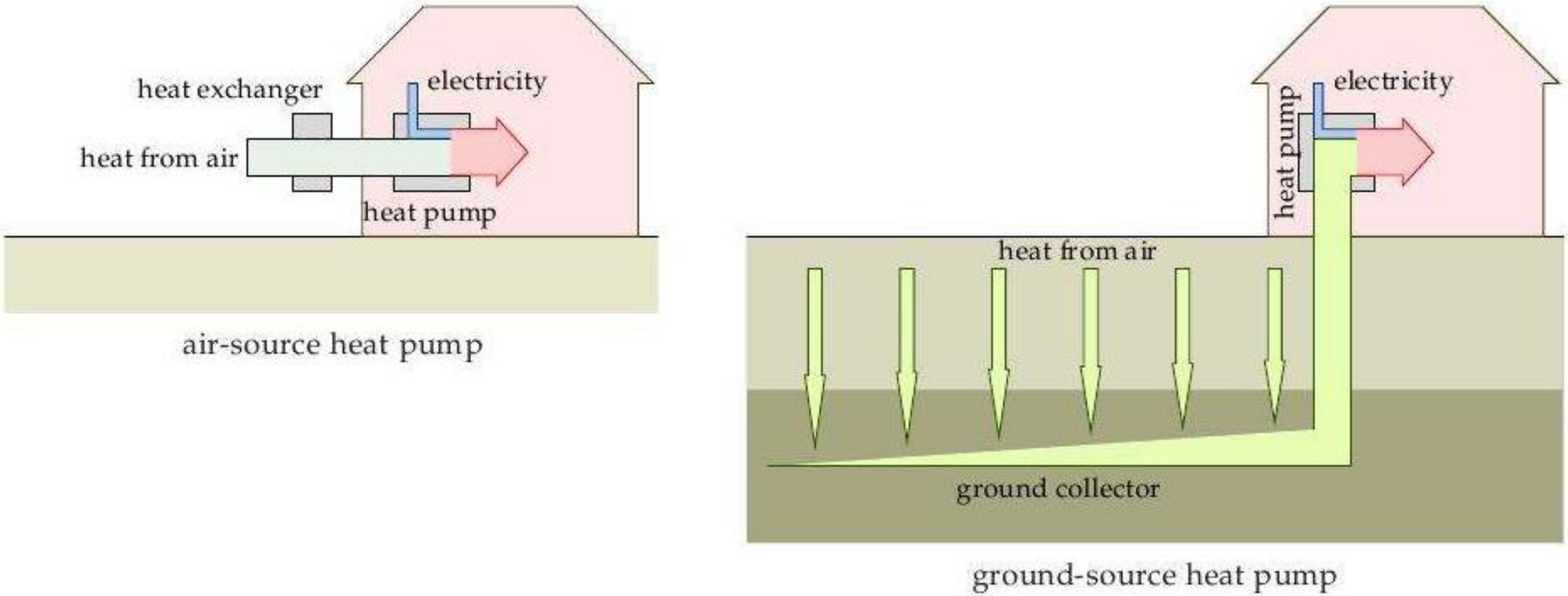


Figure 21.9. Combined heat and power. District heating absorbs heat that would have been chucked up a cooling tower.

Combined heat and power

The standard view of conventional big centralised power stations is that they are terribly inefficient, chucking heat willy-nilly up chimneys and cooling towers. A more sophisticated view recognizes that to turn thermal energy into electricity, we inevitably have to dump heat in a cold place (figure 21.8). That is how heat engines work. There *has* to be a cold place. But surely, it's argued, we could use *buildings* as the dumping place for this "waste" heat instead of cooling towers or sea water? This idea is called "combined heat and power" (CHP) or cogeneration, and it's been widely used in continental Europe for decades – in many cities, a big power station is integrated with a district heating system. Proponents of the modern incarnation of combined heat and power, "micro-CHP," suggest that tiny power stations should be created within single buildings or small collections of buildings, delivering heat and electricity to those buildings, and exporting some electricity to the grid.



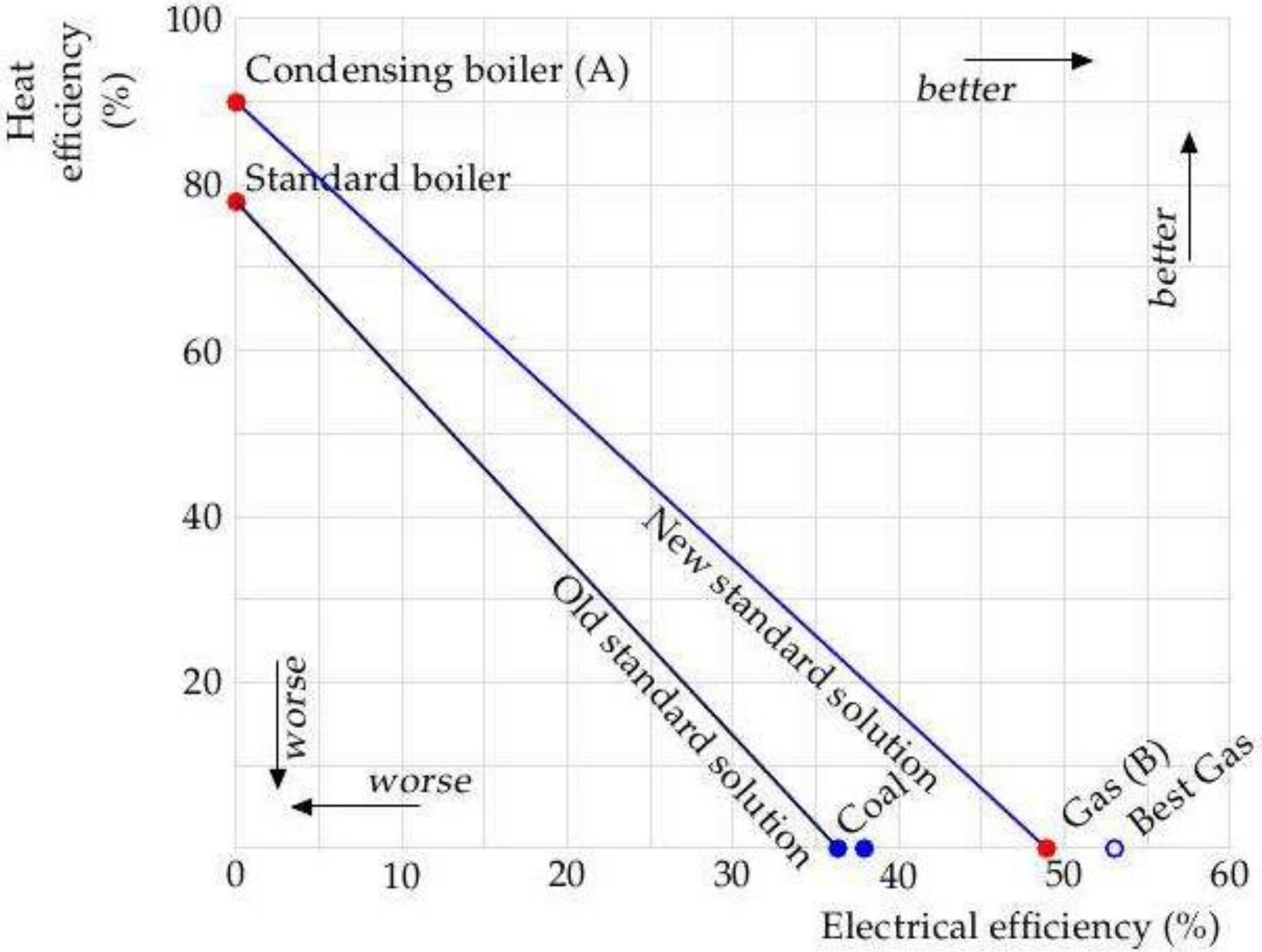
air-source heat pump

ground-source heat pump

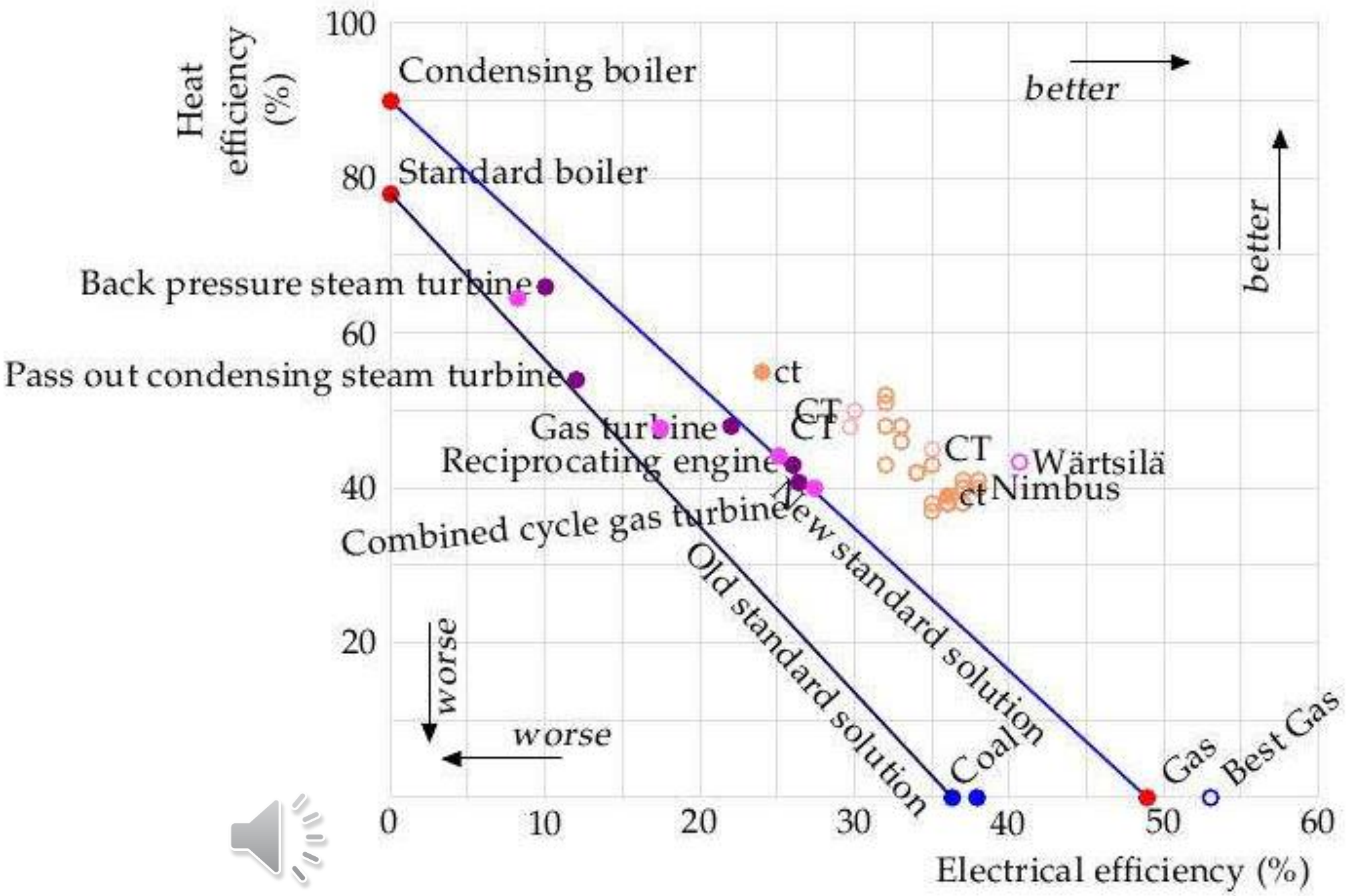
Figure 21.10. Heat pumps.

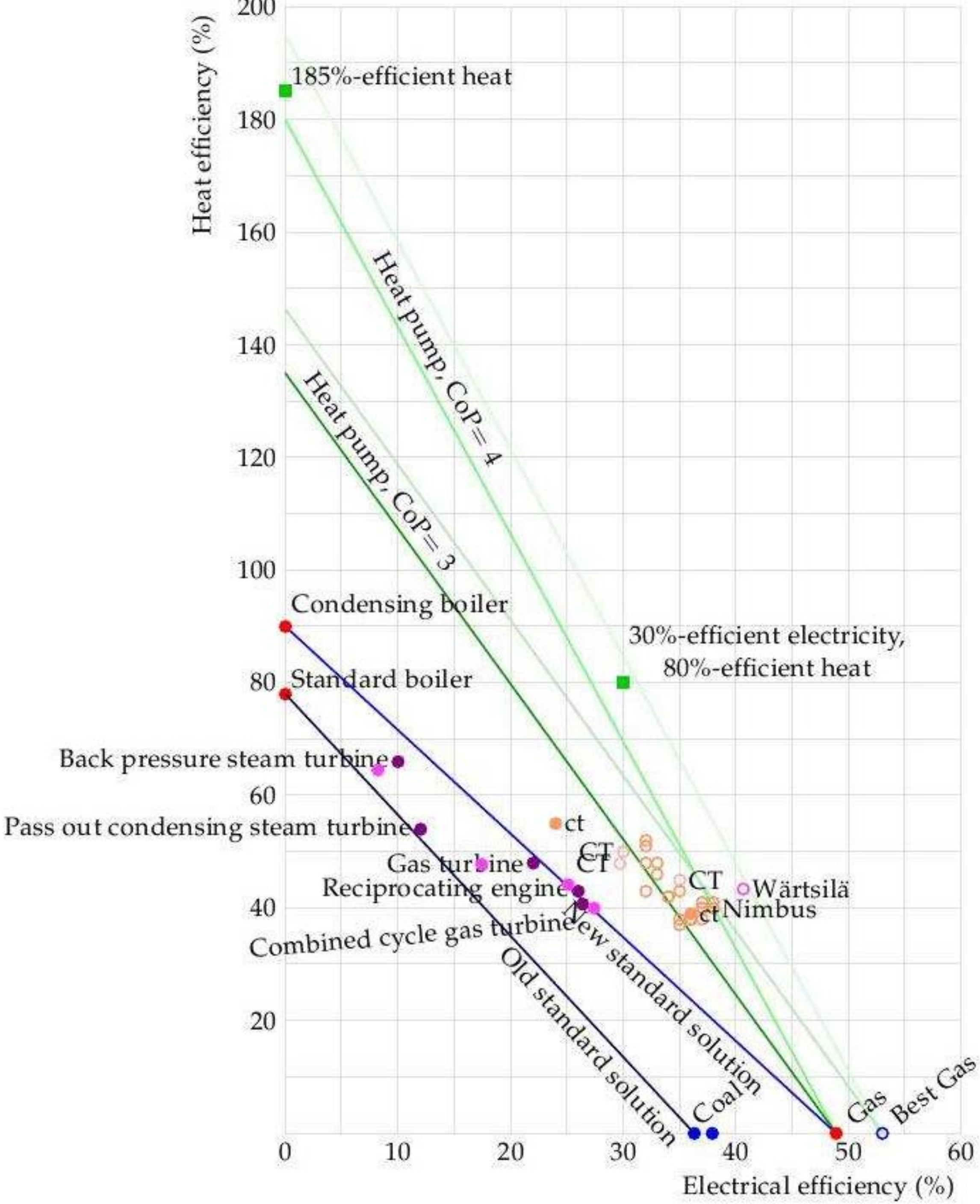
The standard solution with no CHP

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



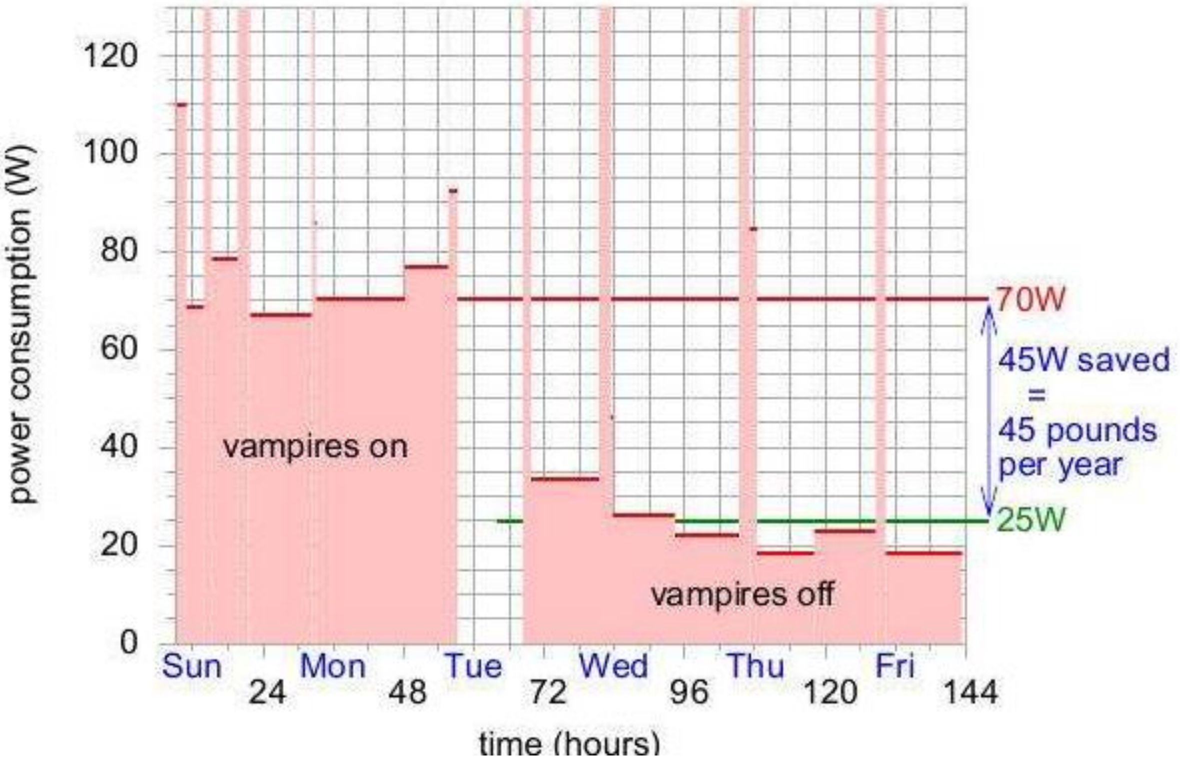
Smarter heating

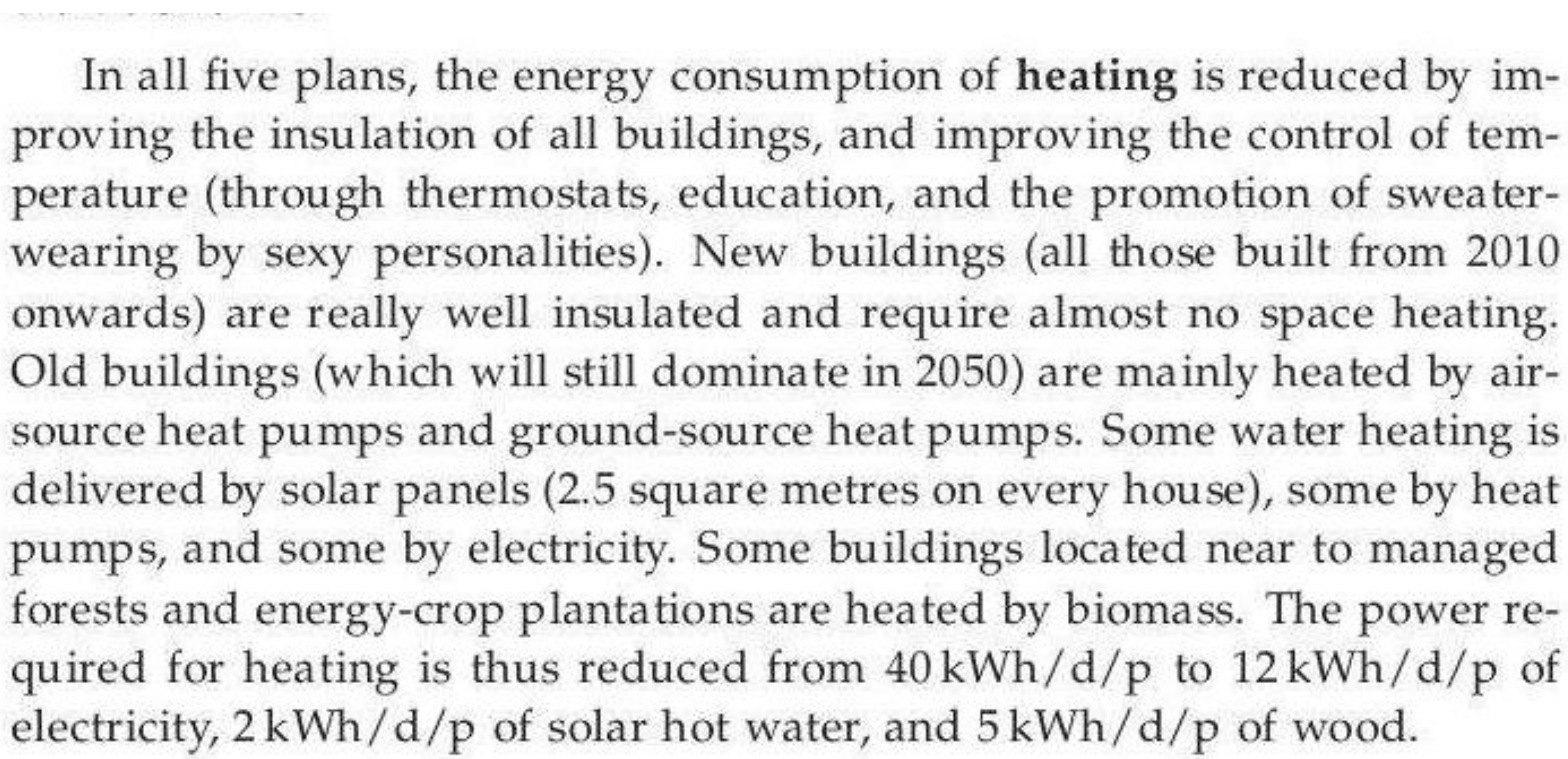



Heat efficiency (%)
Electrical efficiency (%)
200
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
185%-efficient heat
Heat pump, CoP= 4
Heat pump, CoP= 3
Condensing boiler
Standard boiler
30%-efficient electricity,
80%-efficient heat
Back pressure steam turbine
Pass out condensing steam turbine
Gas turbine
Reciprocating engine
Combined cycle gas turbine
ct
CT
CT
CT
ct
Wärtsilä
Nimbus
New standard solution
Old standard solution
Coal
Gas
Best Gas

Efficient electricity use

According to the International Energy Agency, standby power consumption accounts for roughly 8% of residential electricity demand. In the UK and France, the average standby power is about 0.75 kWh/d per household. The problem isn't standby itself – it's the shoddy way in which standby is implemented. It's perfectly possible to make standby systems that draw less than 0.01 W; but manufacturers, saving themselves a penny in the manufacturing costs, are saddling the consumer with an annual cost of pounds.

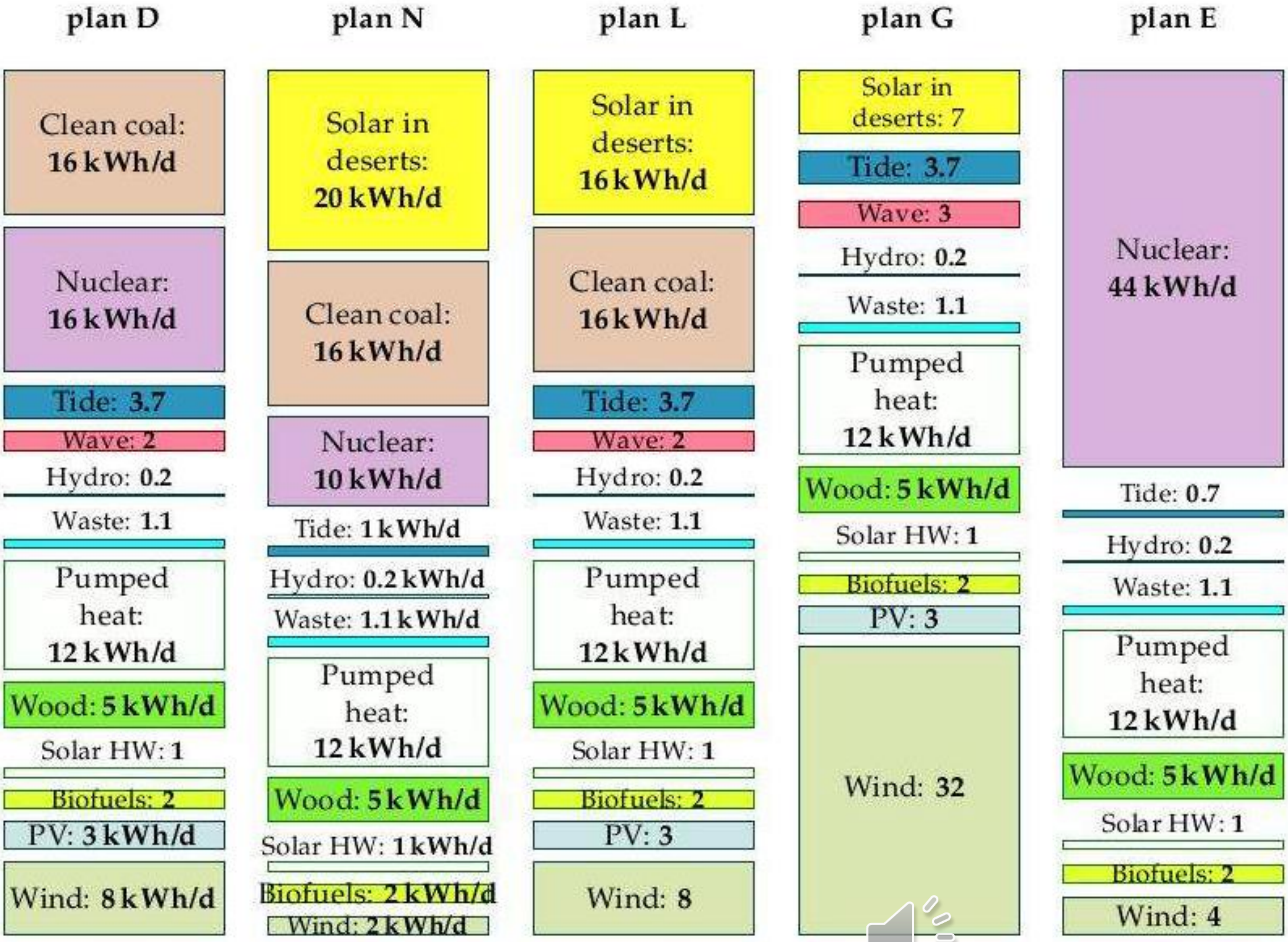




In all five plans, the energy consumption of **heating** is reduced by improving the insulation of all buildings, and improving the control of temperature (through thermostats, education, and the promotion of sweater-wearing by sexy personalities). New buildings (all those built from 2010 onwards) are 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.

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.



plan D

Clean coal: 16 kWh/d
Nuclear: 16 kWh/d
Tide: 3.7
Wave: 2
Hydro: 0.2
Waste: 1.1
Pumped heat: 12 kWh/d
Wood: 5 kWh/d
Solar HW: 1
Biofuels: 2
PV: 3 kWh/d
Wind: 8 kWh/d

plan N

Solar in deserts: 20 kWh/d
Clean coal: 16 kWh/d
Nuclear: 10 kWh/d
Tide: 1 kWh/d
Hydro: 0.2 kWh/d
Waste: 1.1 kWh/d
Pumped heat: 12 kWh/d
Wood: 5 kWh/d
Solar HW: 1 kWh/d
Biofuels: 2 kWh/d
Wind: 2 kWh/d

plan L

Solar in deserts: 16 kWh/d
Clean coal: 16 kWh/d
Tide: 3.7
Wave: 2
Hydro: 0.2
Waste: 1.1
Pumped heat: 12 kWh/d
Wood: 5 kWh/d
Solar HW: 1
Biofuels: 2
PV: 3
Wind: 8

plan G

Solar in deserts: 7
Tide: 3.7
Wave: 3
Hydro: 0.2
Waste: 1.1
Pumped heat: 12 kWh/d
Wood: 5 kWh/d
Solar HW: 1
Biofuels: 2
PV: 3
Wind: 32

plan E

Nuclear: 44 kWh/d
Tide: 0.7
Hydro: 0.2
Waste: 1.1
Pumped heat: 12 kWh/d
Wood: 5 kWh/d
Solar HW: 1
Biofuels: 2
Wind: 4

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

	Capacity	Rough cost		Average power delivered
		total	per person	
52 onshore wind farms: 5200 km^2	35 GW	£27bn – based on Lewis wind farm	£450	4.2 kWh/d/p
29 offshore wind farms: 2900 km^2	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 km^2	48 GW	£190bn – based on Solarpark in Bavaria	£3200	2 kWh/d/p
Solar hot water panels: 1 m^2 of roof-mounted panel per person. (60 km^2 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 km^2	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

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.

- The car speeds up and slows down once in each duration d/v. The rate at which energy pours into the brakes is:

$$\frac{\text{kinetic energy}}{\text{time between braking events}} = \frac{\frac{1}{2} m_{\mathrm{c}} v^2}{d/v} = \frac{\frac{1}{2} m_{\mathrm{c}} v^3}{d}, \tag{A.1}$$

where m_{c} is the mass of the car.

- The tube of air created in a time t has a volume Avt, where A is the cross-sectional area of the tube, which is 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, $c_{\mathrm{d}}A_{\mathrm{car}}$.) The tube has mass $m_{\mathrm{air}} = \rho Avt$ (where ρ is the density of air) and swirls at speed v, so its kinetic energy is:

  $$\frac{1}{2}m_{\mathrm{air}}v^2 = \frac{1}{2}\rho Avt\,v^2,$$

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

  $$\frac{\frac{1}{2}\rho Avtv^2}{t} = \frac{1}{2}\rho Av^3.$$

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

$$\begin{aligned} &\text{power going into brakes} &+&\quad \text{power going into swirling air} \\ &= \tfrac{1}{2}m_{\mathrm{c}}v^3/d &+&\quad \tfrac{1}{2}\rho Av^3. \end{aligned} \tag{A.2}$$

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

$$(m_{\mathrm{c}}/d)\,/\,(\rho A)\,.$$

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

$$m_{\mathrm{c}} > \rho A d.$$

Now, Ad is the volume of the tube of air swept out from one stop sign to the next. And ρAd is the mass of that tube of air. So we have a very simple situation: energy dissipation is dominated by kinetic-energy-being-dumped-into-the-brakes if the mass of the car is *bigger* than the mass of the tube of air from one stop sign to the next; and energy dissipation is dominated by making-air-swirl if the mass of the car is *smaller* (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:

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

and the drag coefficient is $c_{\mathrm{d}} = 1/3$ and the mass is $m_{\mathrm{c}} = 1000\,\mathrm{kg}$ then the special distance is:

$$d^{*} = \frac{m_{\mathrm{c}}}{\rho c_{\mathrm{d}} A_{\mathrm{car}}} = \frac{1000\,\mathrm{kg}}{1.3\,\mathrm{kg/m^3} \times \frac{1}{3} \times 3\,\mathrm{m^2}} = 750\,\mathrm{m}.$$

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:

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

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

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

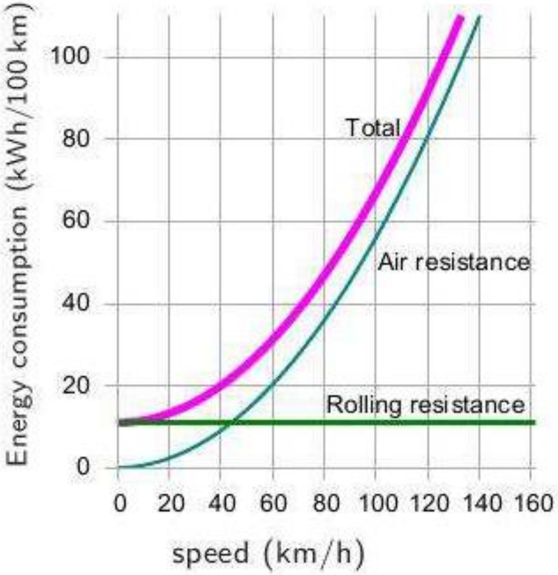


Figure A.9. Simple theory of car fuel consumption (energy per distance) when driving at steady speed. Assumptions: the car's engine uses energy with an efficiency of 0.25, whatever the speed; $c_d A_{car} = 1\,m^2$; $m_{car} = 1000\,kg$; and $C_{rr} = 0.01$.

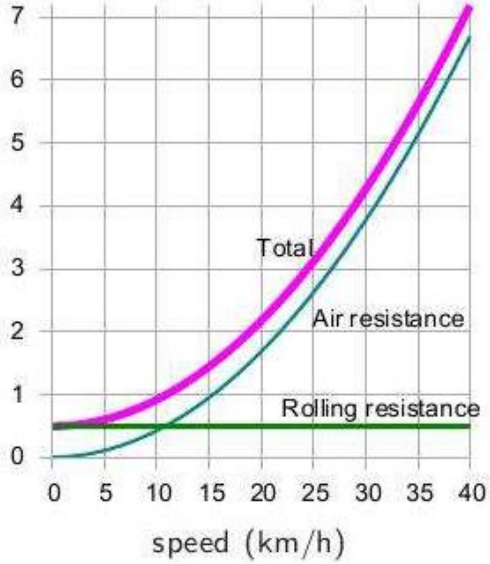


Figure A.10. Simple theory of bike fuel consumption (energy per distance). Vertical axis is energy consumption in kWh per 100 km. Assumptions: the bike's engine (that's you!) uses energy with an efficiency of 0.25,; the drag-area of the cyclist is $0.75\,m^2$; the cyclist+bike's mass is 90 kg; and $C_{rr}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

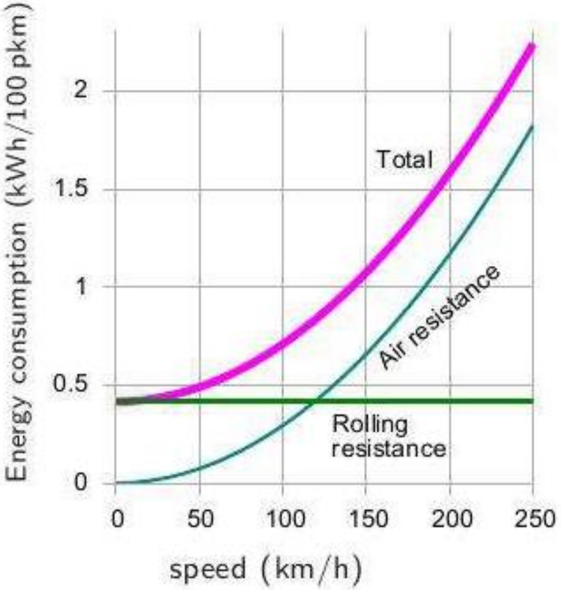


Figure A.11. Simple theory of train energy consumption, *per passenger*, for an eight-carriage train carrying 584 passengers. Vertical axis is energy consumption in kWh per 100 p-km. Assumptions: the train's engine uses energy with an efficiency of 0.90; $c_d A_{train} = 11\,m^2$; $m_{train} = 400\,000\,kg$;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

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.

kitchen	2
bathroom	2
lounge	1
bedroom	0.5

Table E.1. Air changes per hour: typical values of N for

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 $\mathrm{W/m^2/K}$. (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:

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

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

	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		

outside of the building.

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

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

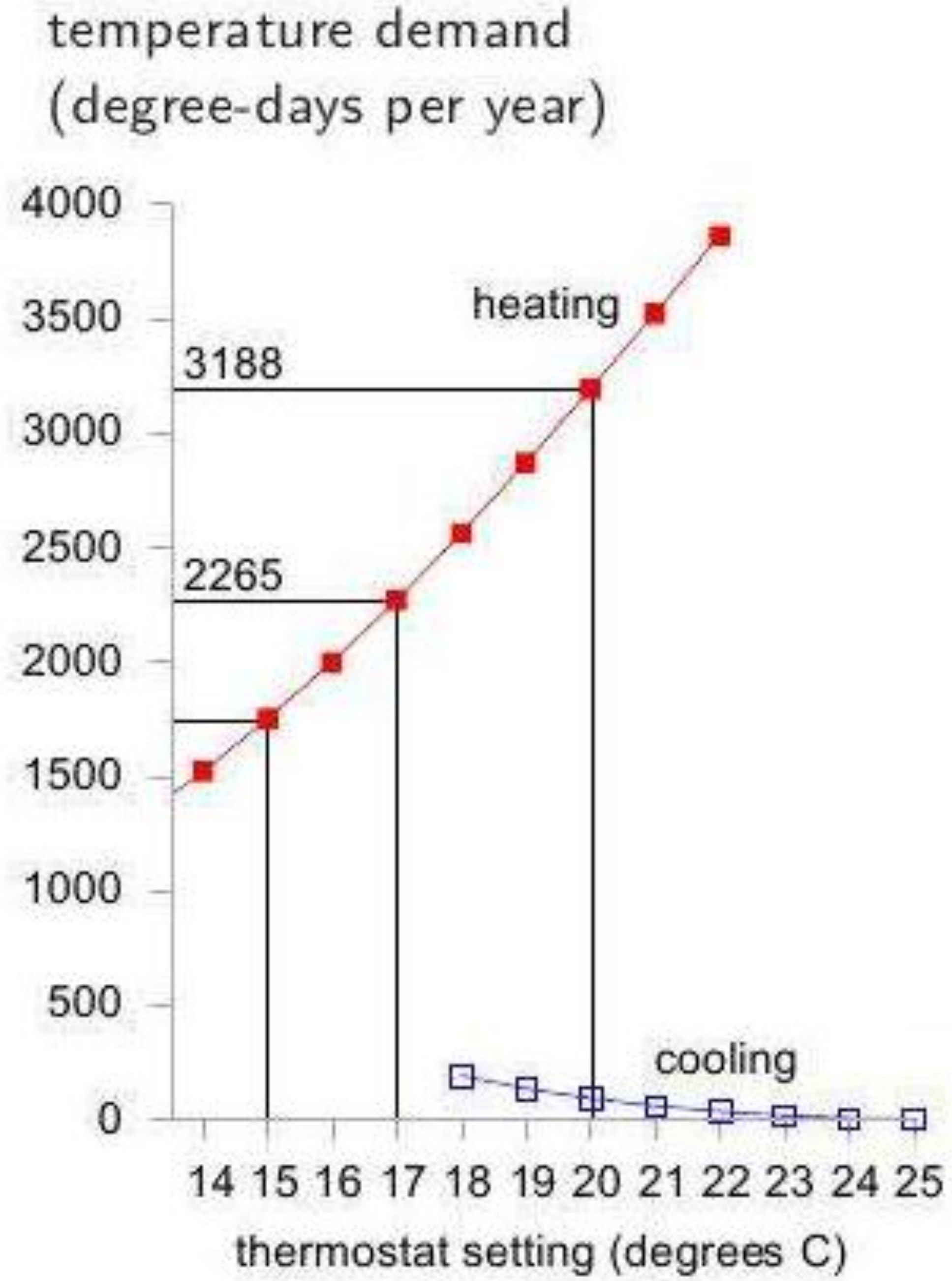
$$\frac{1}{3}NV \times (\Delta T \times \text{duration}).$$

Both these energy losses have the form

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

1. the sum of all the Somethings (adding area × 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 × duration factors (for all the durations).

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


temperature demand
(degree-days per year)
4000
3500
3000
2500
2000
1500
1000
500
0
3188
2265
heating
cooling
14
15
16
17
18
19
20
21
22
23
24
25
thermostat setting (degrees C)

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.

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

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 $\mathrm{W}/^{\circ}\mathrm{C}/\mathrm{m}^2$. The heat-loss parameter of this house (total floor area $88\,\mathrm{m}^2$) is

$$3.7\,\mathrm{W}/^{\circ}\mathrm{C}/\mathrm{m}^2.$$

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 $-1\,^{\circ}\mathrm{C}$ and an internal temperature of $19\,^{\circ}\mathrm{C}$, the temperature difference is $\Delta T = 20\,^{\circ}\mathrm{C}$. If this difference is maintained for 6 hours per day then the energy lost per day is

$$322\,\mathrm{W}/^{\circ}\mathrm{C} \times 120\,\text{degree-hours} \simeq 39\,\mathrm{kWh}.$$

If the temperature is maintained at $19\,^{\circ}\mathrm{C}$ for 24 hours per day, the energy lost per day is

$$155\,\mathrm{kWh/d}.$$

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

Turning the thermostat down to 17 °C, the average rate of heat loss drops to 48 kWh/d. Turning it up to a tropical 21 °C, the average rate of heat loss is 75 kWh/d.

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.

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

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 $140\,\mathrm{m}^2$, 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 $0.28\,\mathrm{W/m^2/^\circ C}$. 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 $0.27\,\mathrm{W/m^2/^\circ C}$, and the floor, $0.22\,\mathrm{W/m^2/^\circ C}$. The windows are double-glazed (U-value $2\,\mathrm{W/m^2/^\circ C}$), 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.

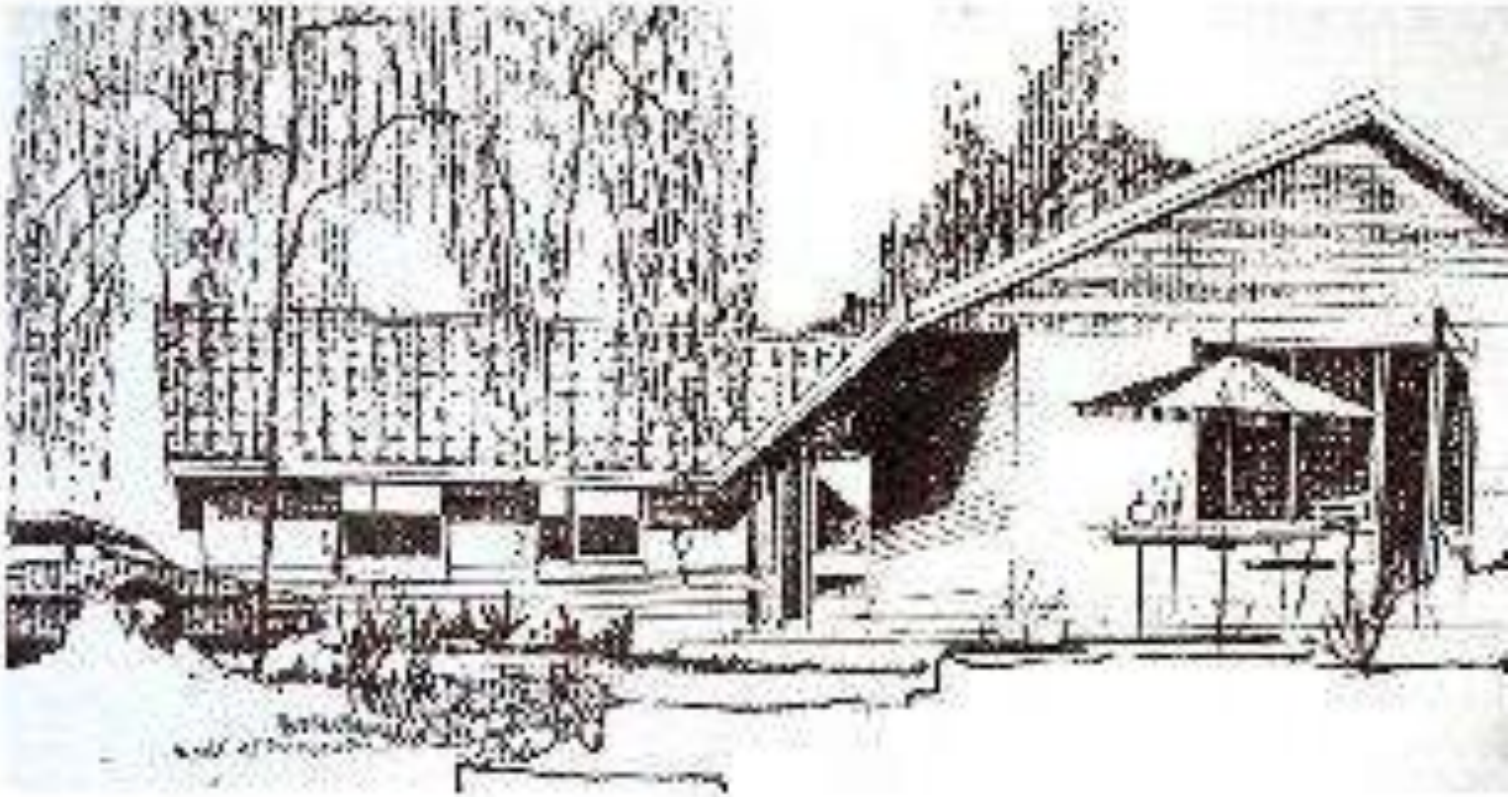
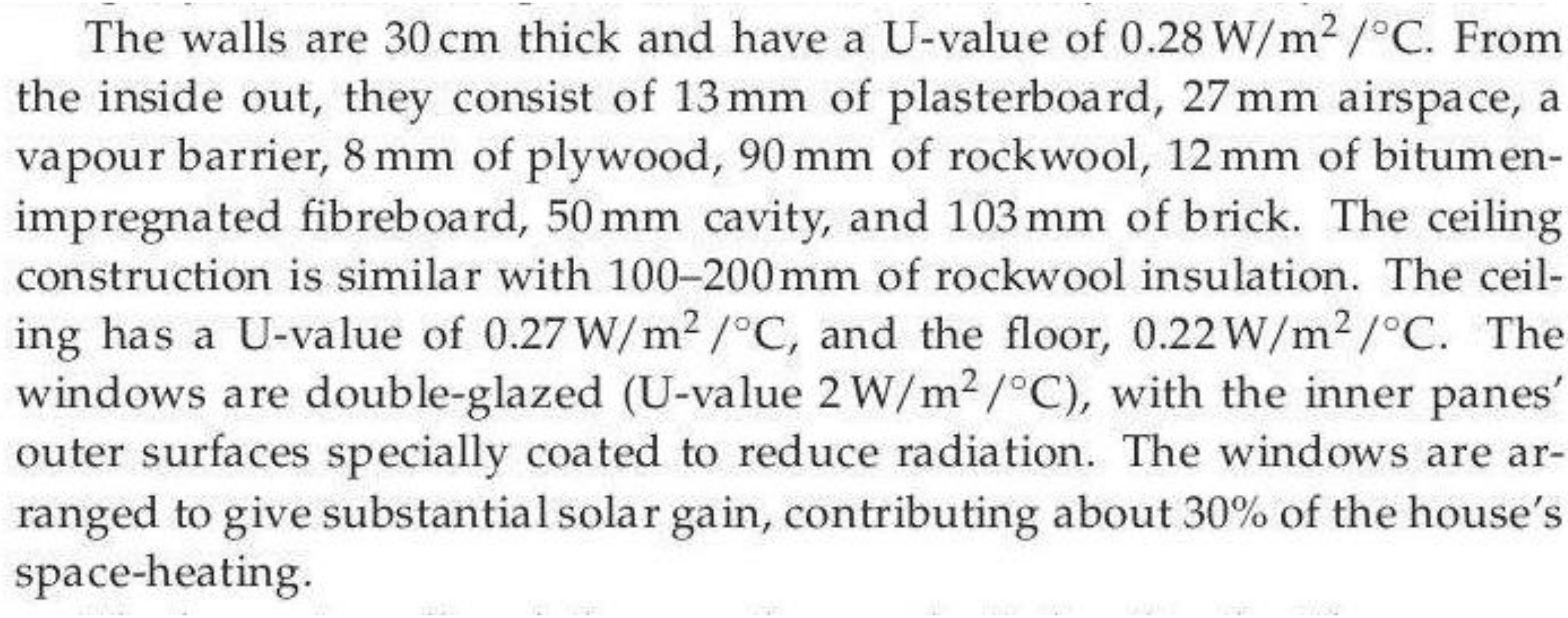


Figure E.10. The Heatkeeper Serrekunda.



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.

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.

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 $400\,\text{m}^2$ 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 ($7.4\,\text{W/m}^2$). The PV system delivers almost 20% of this energy.

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_{in}, by $273.15 + T_{\text{in}}$), 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.

	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

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.

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

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

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

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

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

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

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

$$z_0 = \sqrt{\frac{2\kappa}{C_{\mathrm{V}}\omega}}. \tag{E.7}$$

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

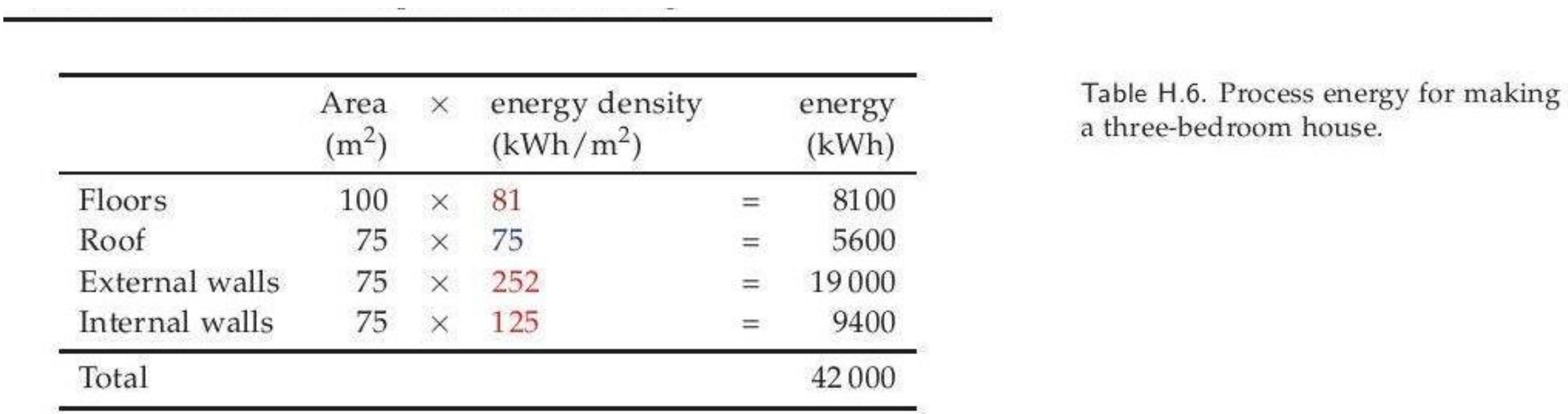
$$\kappa\frac{\partial T}{\partial z} = \kappa\frac{A}{z_0}\sqrt{2}e^{-z/z_0}\sin(\omega t - z/z_0 - \pi/4). \tag{E.8}$$

For example, at the surface, the peak flux is

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

Table H.5. Embodied energy in various walls, floors, and roofs. 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



	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.

1.0 Distributed Generation Basics

1.1 What is Distributed Generation?

Distributed generation (or DG) generally refers to small-scale (typically 1 kW – 50 MW) electric power generators that produce electricity at a site close to customers or that are tied to an electric distribution system. Distributed generators include, but are not limited to synchronous generators, induction generators, reciprocating engines, microturbines (combustion turbines that run on high-energy fossil fuels such as oil, propane, natural gas, gasoline or diesel), combustion gas turbines, fuel cells, solar photovoltaics, and wind turbines.

1.2 Applications of Distributed Generating Systems

There are many reasons a customer may choose to install a distributed generator. DG can be used to generate a customer’s entire electricity supply; for peak shaving (generating a portion of a customer’s electricity onsite to reduce the amount of electricity purchased during peak price periods); for standby or emergency generation (as a backup to Wires Owner's power supply); as a green power source (using renewable technology); or for increased reliability. In some remote locations, DG can be less costly as it eliminates the need for expensive construction of distribution and/or transmission lines.

1.3 Benefits of Distributed Generating Systems

Distributed Generation:

- Has a lower capital cost because of the small size of the DG (although the investment cost per kVA of a DG can be much higher than that of a large power plant).

- May reduce the need for large infrastructure construction or upgrades because the DG can be constructed at the load location.

- If the DG provides power for local use, it may reduce pressure on distribution and transmission lines.

- With some technologies, produces zero or near-zero pollutant emissions over its useful life (not taking into consideration pollutant emissions over the entire product lifecycle ie. pollution produced during the manufacturing, or after decommissioning of the DG system).

- With some technologies such as solar or wind, it is a form of renewable energy.

Can increase power reliability as back-up or stand-by power to customers.

- Offers customers a choice in meeting their energy needs.

1.4 Challenges associated with Distributed Generating Systems

- There are no uniform national interconnection standards addressing safety, power quality and reliability for small distributed generation systems.

- The current process for interconnection is not standardized among provinces.

- Interconnection may involve communication with several different organizations

- The environmental regulations and permit process that have been developed for larger distributed generation projects make some DG projects uneconomical.

- Contractual barriers exist such as liability insurance requirements, fees and charges, and extensive paperwork.

Efficient Power System Design and Engineering

Achieving energy efficiency improvements in power system design is challenged by many of the non-technical barriers outlined in the section Barriers by Stakeholder. Those barriers most relevant to the plant electrical engineering discipline are:

In a large power or process plant, electrical engineering (EE) is often the last discipline to be engaged, after process, mechanical and controls.

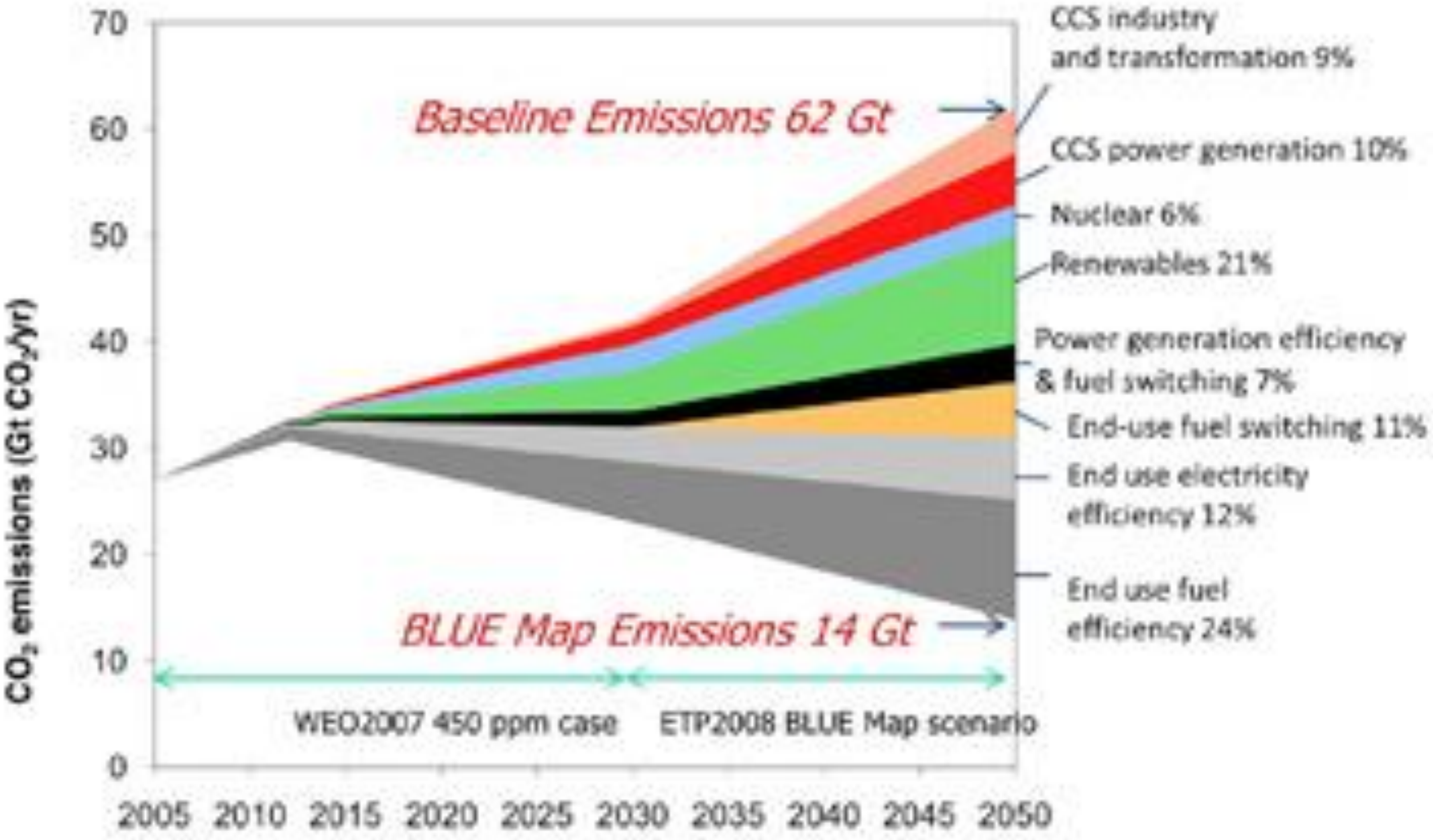
This leaves the EE with little influence to practice efficient integrative design, since most other aspects are now frozen. This of course, has a deleterious effect on the energy efficiency of a plant, as virtually all of the internally consumed energy passes through the electrical system.

−− The power system is also the first to be commissioned, which further restricts the time that the EE can spend on conceptual studies described below.
−− The trend away from turnkey projects and toward multiple suppliers fragments the design and communication, making integrative approaches more difficult.
−− The vital role of power systems to all other plant equipment is the reason why customers often stipulate ‘liquidated damages’ in contracts with their suppliers. This threat of very large opportunity cost from downtime is a subtle deterrent toward newer designs with potentially significantly lower lifecycle costs. (opportunity costs are not as real as wasted energy costs, but often get the same accounting treatment)

Plant Auxiliary Energy Efficiency Improvements

In-plant electrical power, when taken from the generator bus, may be priced artificially low in some utility companies’ auxiliary lifecycle calculations. A process industry customer, however, must always pay high commercial rates (and sometimes penalties), thus providing a strong incentive to improve their auxiliary energy efficiency. Price dis-incentives, regulations permitting cost-pass thru, and other nontechnical barriers are discussed in the handbook section on Barriers to Increased Energy Efficiency.

These barriers may result in sub-optimal energy designs for power plant auxiliaries, most commonly in oversized motors, fans and pumps. These design decisions have particularly negative consequences when the base-loaded plant then moves to a new operating mode at 50–70 percent capacity (see previous section for a discussion of this trend). Auxiliaries such as pumps and fans that use constant speed motors and some form of flow restriction for control will waste much more power when operating under such partial-load conditions.



CO₂ emissions (Gt CO₂/yr)
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Baseline Emissions 62 Gt
BLUE Map Emissions 14 Gt
WEO2007 450 ppm case
ETP2008 BLUE Map scenario
CCS industry and transformation 9%
CCS power generation 10%
Nuclear 6%
Renewables 21%
Power generation efficiency & fuel switching 7%
End-use fuel switching 11%
End use electricity efficiency 12%
End use fuel efficiency 24%

Multiple Benefits of Energy Efficiency

The primary benefits of a increased plant energy efficiency are reduced emissions and energy or fuel costs.

Power plants which operate partially or wholly at full load will have more salable power. At less than capacity, the fuel savings are significant. In coal-fired steam power plants, fuel costs are 60-70% of operating costs.

Operational Benefits

−− Improved reliability/availability. As has been found with stricter safety design regulations, any extra attention to the process is rewarded with improved uptime.

−− Improved controllability: energy is wasted in a swinging, unstable process, partly through inertia in the swings, but mainly because operators in such situations do not dare operate closer to the plant’s optimum constraints.

−− Reduced noise and vibration, reduced maintenance costs.
The following is a more complete list of benefits accompanying energy efficiency design improvements for plant auxiliaries:

Results of Improved Efficiency on Plant Operations and Profitability

−− Better allocation: under deregulation, as utilities dispatch plants within a fleet, heat rate improvement can earn plants a better position on the dispatch list (Larsen, 2007).

−− Avoiding a plant de-rating due to efficiency losses after anti-pollution retrofits or other plant design changes.

−− Improved fuel flexibility—by efficiently using a wider variety of fuels (coal varieties) and, in some cases, increasing the firing of biomass, for example.

−− Improved operational flexibility 1) Improved plant-wide integration between units will reduce startup-shutdown times; this benefit applies mainly to deregulated markets. 2)

The heat rate versus capacity curve is made flatter and lower, which allows the plant to operate more efficiently across a wider loading range.

Plant Investment Benefits

−− Avoiding forced retirement due to pollution non-compliance: An ambitious retrofit programme may save some older plants from early retirement due to noncompliance with regulations.

Motor Power and Efficiency

The power and speed requirements are set by the application’s load profile. For example, in pump and fan applications, the load torque decreases with the square of the speed; this is a direct result of the Affinity Laws discussed in the Pump and Fan systems sections. The power rating of a motor indicates its output mechanical power, often stated in horsepower or kW. Motor electrical (input) power is usually stated in kVA.

Motor Mechanical Power

The motor’s mechanical output power is simply the output torque multiplied by motor speed. In SI units:

$$Pm = T \times N$$

Where:

T = torque, (Nm)
Pm = mechanical power at the shaft (watts)
N = speed, (rad/s)

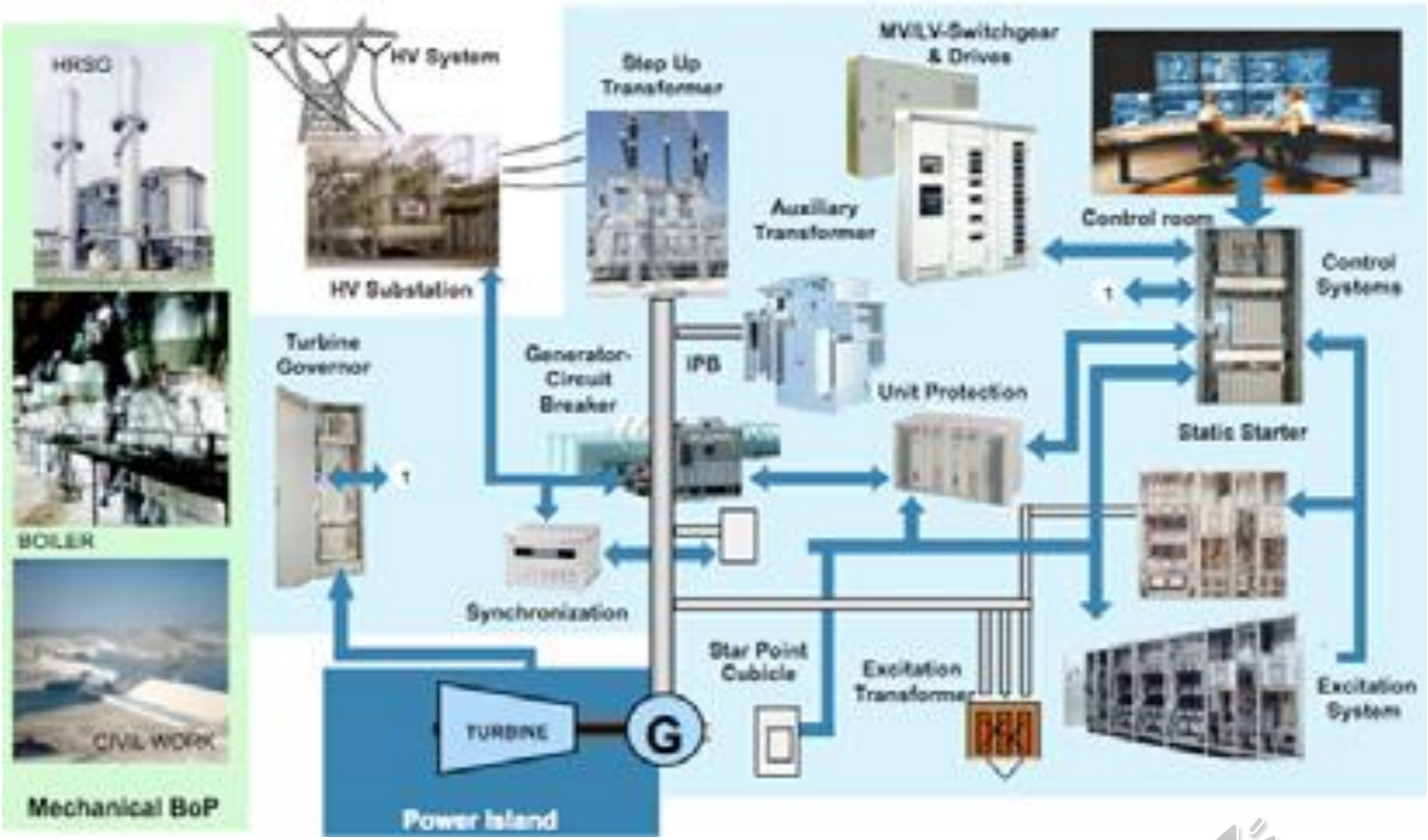
Motor Efficiency

Motor efficiency refers to the amount of input electrical power required to achieve a particular output from the motor. Using the power formula from above, a 100 hp rated motor with 93% efficiency at rated load will draw 89.1 kVA from the supply when running at full load and 0.9 power factor. The motor current at this operating point is shown as the FLA (full load amp) rating on the motor nameplate.

Most motors will the show nominal full load efficiency value on their nameplate as determined by a highly-accurate dynamometer and a procedure described by IEEE Standard 112, Method B. These measurements provide average values from a large test sample of motors.

The motor efficiency of an individual motor in the field can only be determined by field testing methods, such as measurements with a wattmeter.

Statistics on the manufacturer’s test sample provide a minimum efficiency value which also appears as the ‘guaranteed minimum efficiency’ on the nameplate; this value assumes that the worst motor in the sample could have losses as much as 20% higher than the average. These minimum values are in Table 12-8 in NEMA MG-1 (Cowern, Baldor Electric, 2004).
Standard motors tend to operate most efficiently at between 75–110% of full load speed. Smaller motors are less efficient than larger motors.


HRSG
HV System
Step Up Transformer
MV/LV-Switchgear & Drives
HV Substation
Auxiliary Transformer
Control room
Control Systems
1
Turbine Governor
Generator-Circuit Breaker
IPB
Unit Protection
Static Starter
1
BOILER
Synchronization
Star Point Cubicle
Excitation Transformer
Excitation System
CIVIL WORK
TURBINE
G
Mechanical BoP
Power Island

Role of Power Systems in Energy Efficiency

The energy impact of power services is growing due to increased proportion of auxiliary electrical loads as well as the increased variability of plant loading; see the section on Plant Efficiency Trends.

Poor design of in-plant power factor and power quality increases electrical losses, which reduces efficiency and also leads to increased maintenance costs – another good reason to look at power and its application.

The electrical power system has an impact on the reliability of almost all equipment in the plant. Instability in the power system has a multiplier effect that can incur energy penalties due to unstable production and reduced reliability in many other parts of the plant.

Need for an Integrative Design Approach

An integrative systems approach to power systems design is needed due to the interrelated nature of auxiliary loads and the power system; drive power to pumps and fans, energy efficiency, soft-starters, PF correctors, VFDs, harmonic mitigation and phase unbalance are all interrelated technologies and issues.

An electrical upgrade to improve energy efficiency, such as increased use of VFDs, premium efficiency and downsized motors, new transformers etc. should prompt a re-evaluation of the plant power system to ensure that overall efficiency and reliability is not compromised.

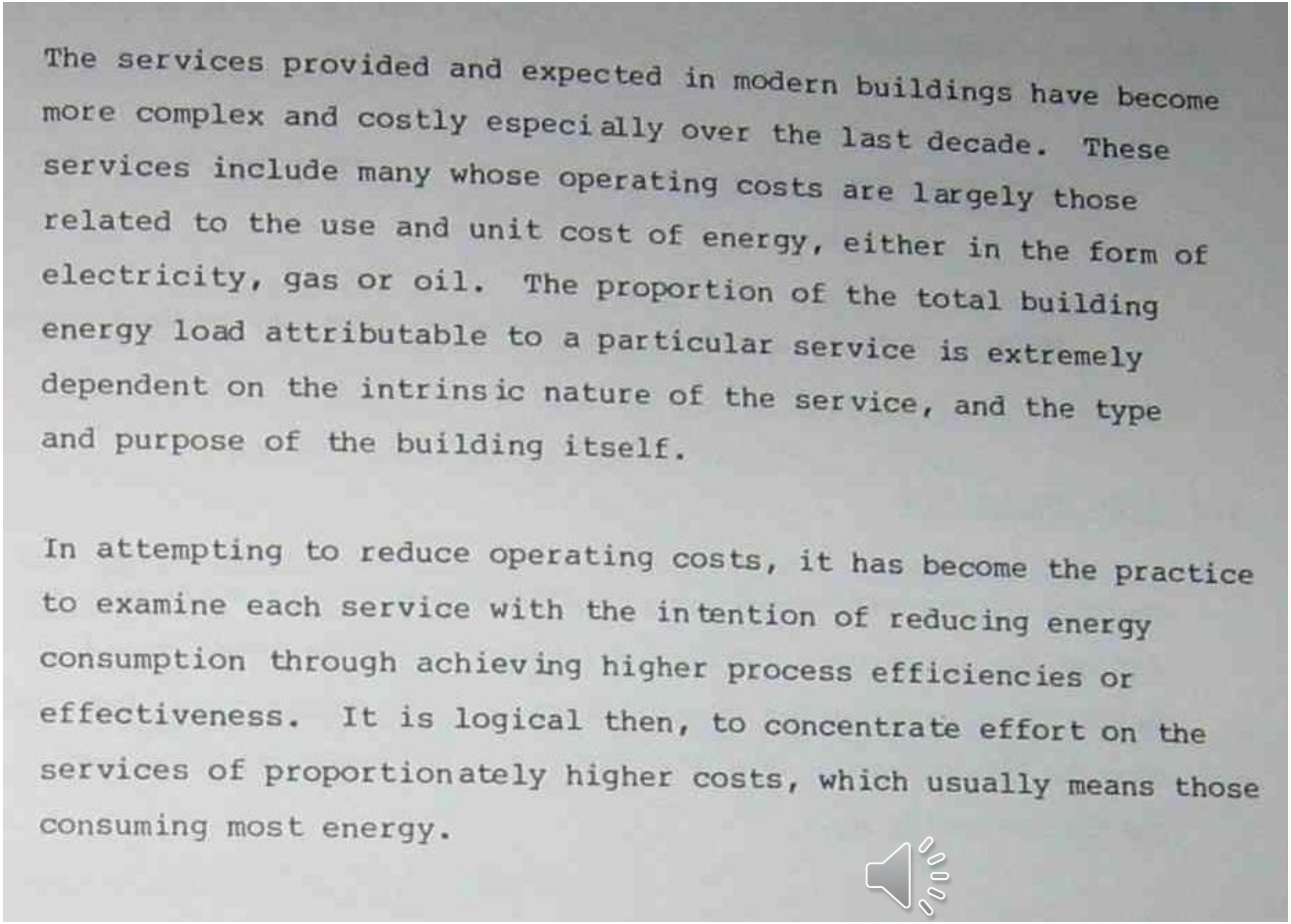
An integrative approach requires the engineer to learn as much as possible about the plant’s loading or load mode, to work closely with the mechanical and process teams towards a prediction, up to 10 years, of how that process load will vary.

Power System – Overview

The purpose of the in-plant power services is to supply electrical power to plant auxiliary process loads, instruments and control systems. The criteria for delivery of this power are:

−− Power quality: allow only tolerable small amounts of harmonics, spikes, sags and swells or phase voltage unbalance.
−− Power factor: control the power factor at all levels of the plant to reduce the losses associated with carrying reactive power.
−− Power level and capacity: supply power to required capacity, at the voltage levels needed, through efficient, right-sized transformers.
−− Power protection & control: allow full automatic or manual control of power distribution to serve the needs of the loads, while protecting those loads and the power system itself from harm.
−− Power distribution & layout: carry power from the source to its destination at the load with minimal losses.
−− Power reliability: supply all the above with high reliability

All of the above design criteria have a direct impact on plant energy efficiency, which is the focus of this module.



The services provided and expected in modern buildings have become more complex and costly especially over the last decade. These services include many whose operating costs are largely those related to the use and unit cost of energy, either in the form of electricity, gas or oil. The proportion of the total building energy load attributable to a particular service is extremely dependent on the intrinsic nature of the service, and the type and purpose of the building itself.

In attempting to reduce operating costs, it has become the practice to examine each service with the intention of reducing energy consumption through achieving higher process efficiencies or effectiveness. It is logical then, to concentrate effort on the services of proportionately higher costs, which usually means those consuming most energy.

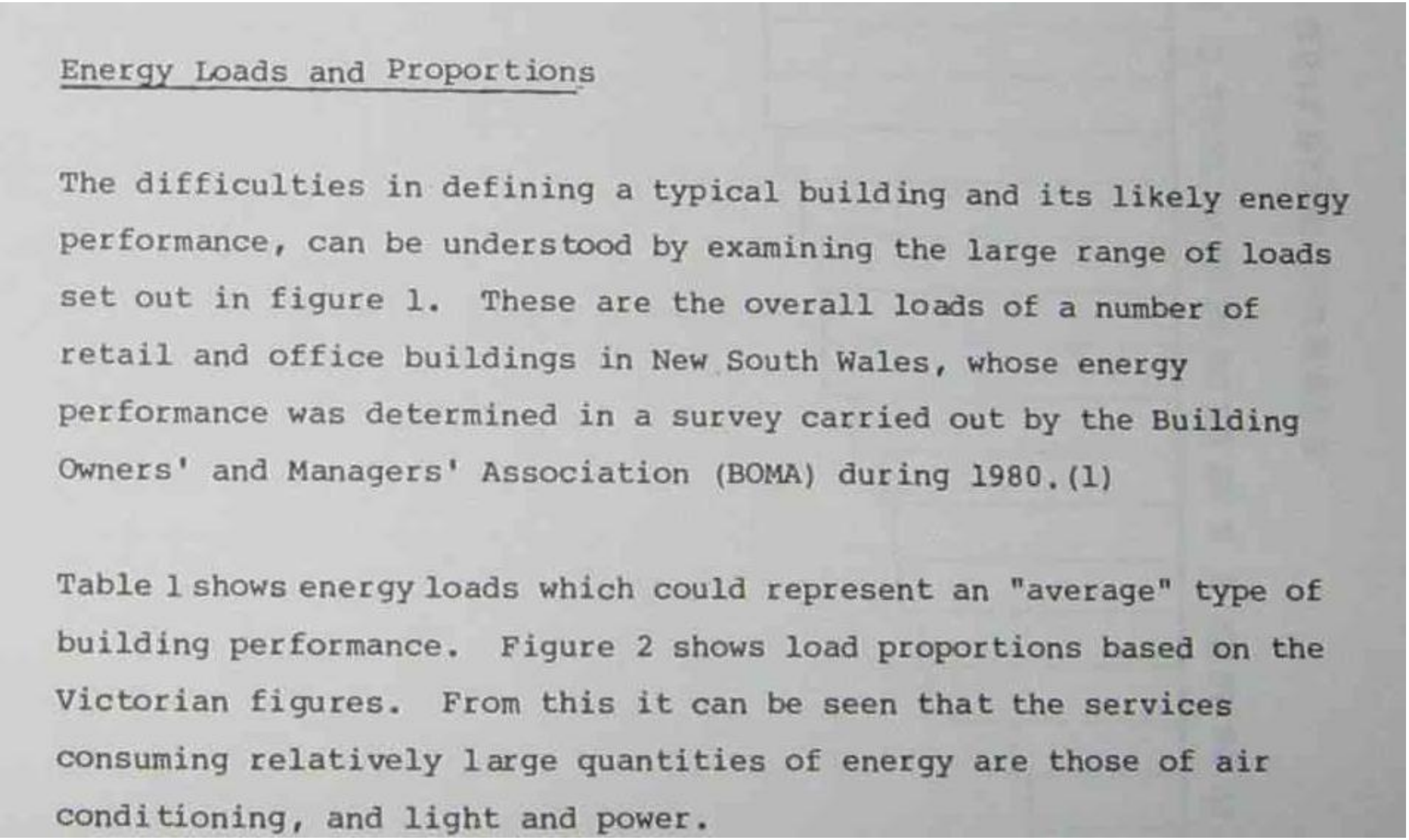
LOAD SOURCES

Buildings range from simple industrial types with minimal attempt at heating or cooling the air, low levels of lighting and low density of occupants, to highly complex multi-storey office blocks fully air conditioned, lights not only for practical purposes but also decoration, and computer-directed monitoring and control of services including security.

Building services whose operation creates energy loads are as follows:

<u>air conditioning</u> - includes base load equipment such as fans and pumps, together with heating and cooling plant.

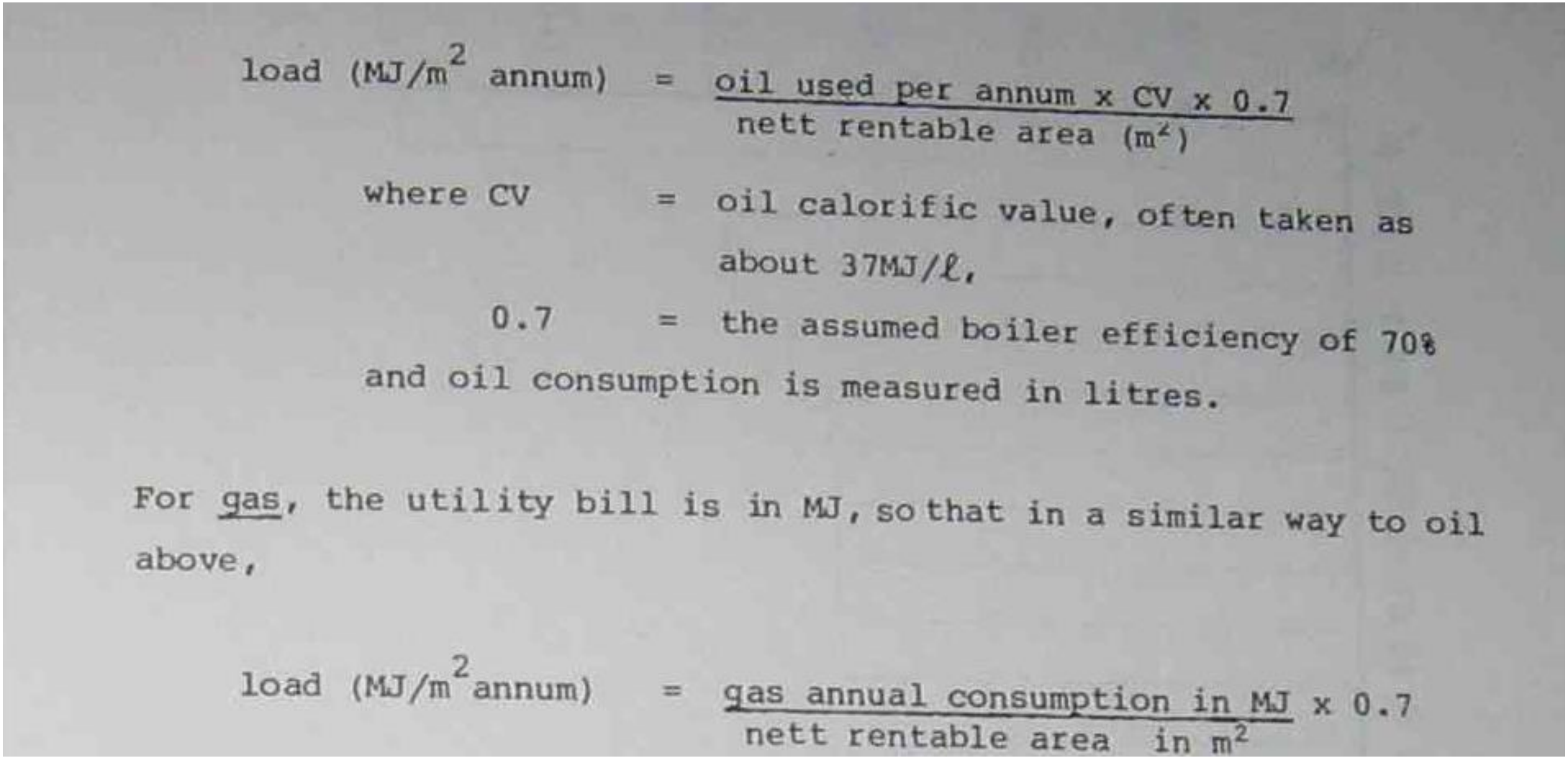
<u>lighting</u> - service lighting is often considered separately from special tenants' lighting requirements.



Energy Loads and Proportions

The difficulties in defining a typical building and its likely energy performance, can be understood by examining the large range of loads set out in figure 1. These are the overall loads of a number of retail and office buildings in New South Wales, whose energy performance was determined in a survey carried out by the Building Owners' and Managers' Association (BOMA) during 1980.(1)

Table 1 shows energy loads which could represent an "average" type of building performance. Figure 2 shows load proportions based on the Victorian figures. From this it can be seen that the services consuming relatively large quantities of energy are those of air conditioning, and light and power.



$$\text{load (MJ/m}^2\text{ annum)} = \frac{\text{oil used per annum} \times \text{CV} \times 0.7}{\text{nett rentable area (m}^2\text{)}}$$

where CV = oil calorific value, often taken as about 37MJ/ℓ,

0.7 = the assumed boiler efficiency of 70%

and oil consumption is measured in litres.

For gas, the utility bill is in MJ, so that in a similar way to oil above,

$$\text{load (MJ/m}^2\text{ annum)} = \frac{\text{gas annual consumption in MJ}}{\text{nett rentable area in m}^2} \times 0.7$$

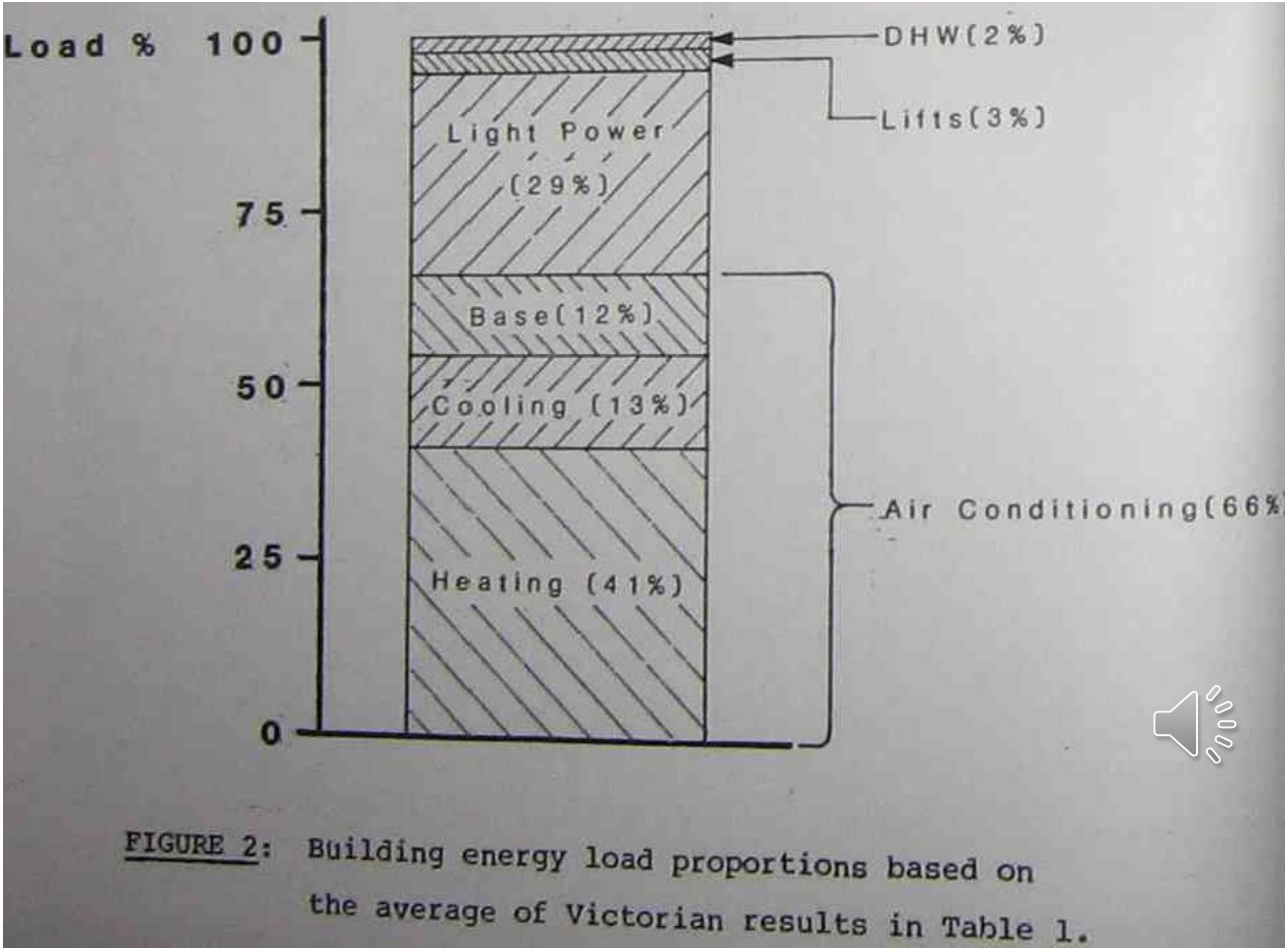
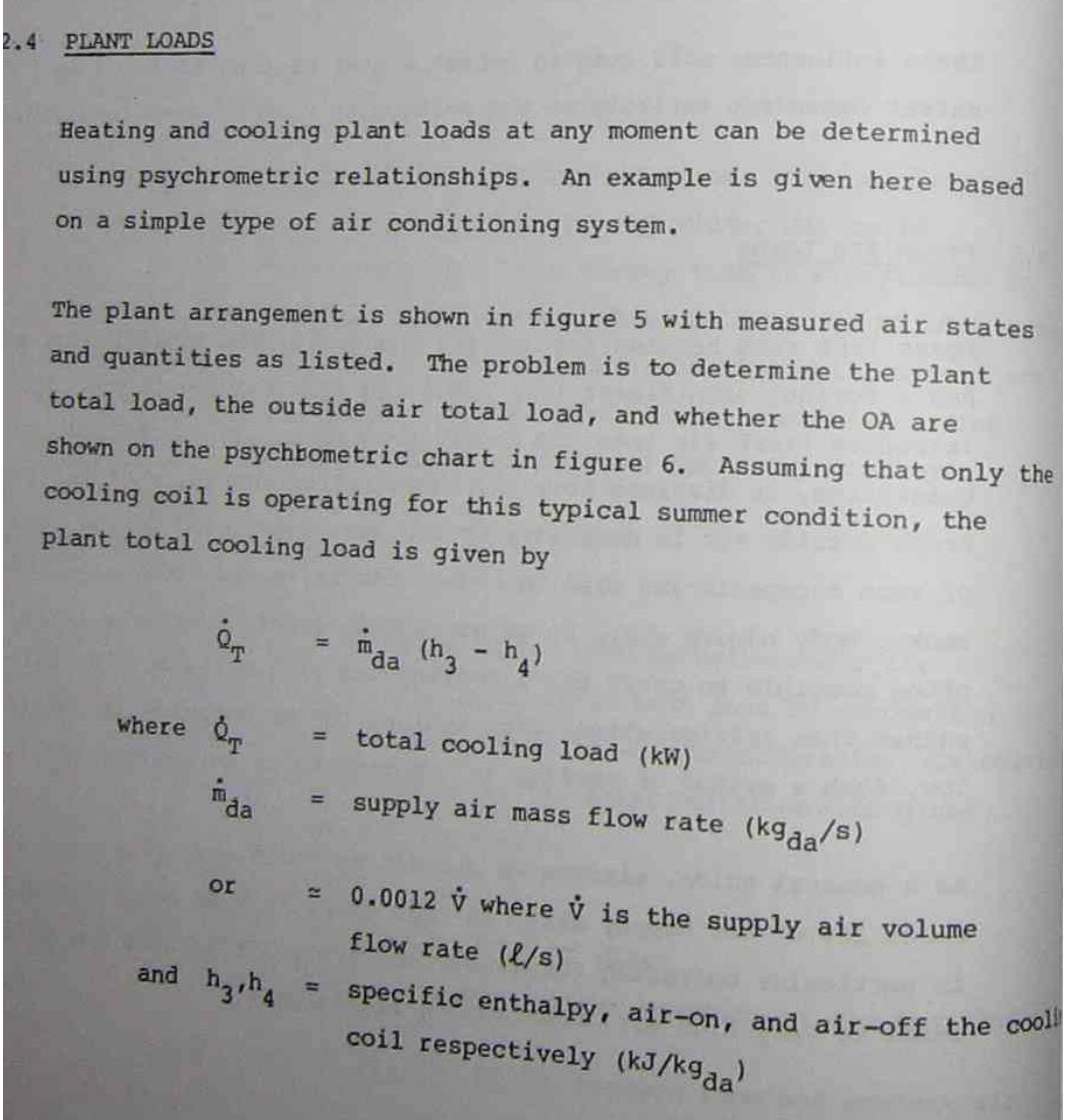


FIGURE 2: Building energy load proportions based on the average of Victorian results in Table 1.



2.4 PLANT LOADS

Heating and cooling plant loads at any moment can be determined using psychrometric relationships. An example is given here based on a simple type of air conditioning system.

The plant arrangement is shown in figure 5 with measured air states and quantities as listed. The problem is to determine the plant total load, the outside air total load, and whether the OA are shown on the psychbometric chart in figure 6. Assuming that only the cooling coil is operating for this typical summer condition, the plant total cooling load is given by

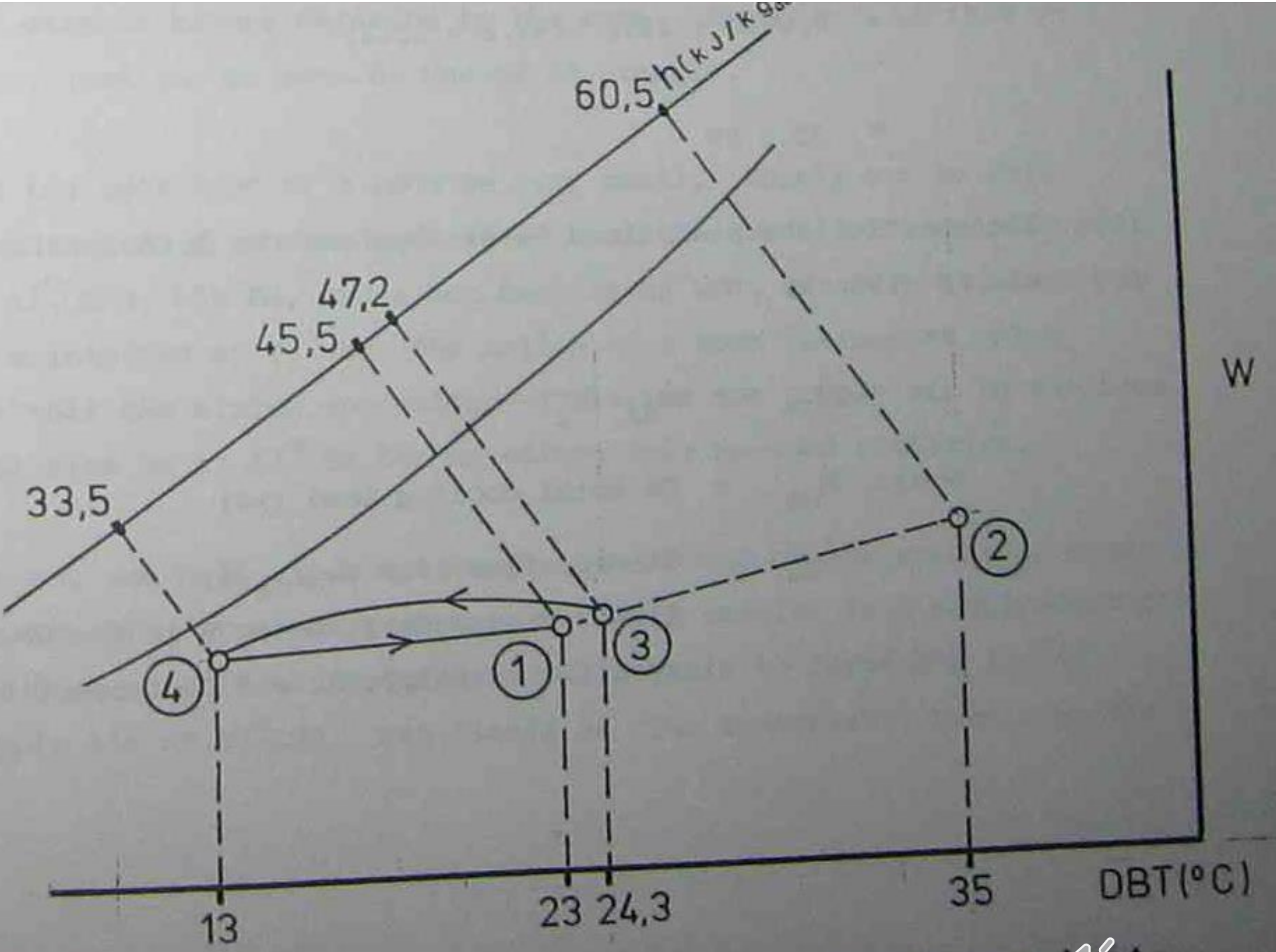
$$\dot{Q}_T = \dot{m}_{da} (h_3 - h_4)$$

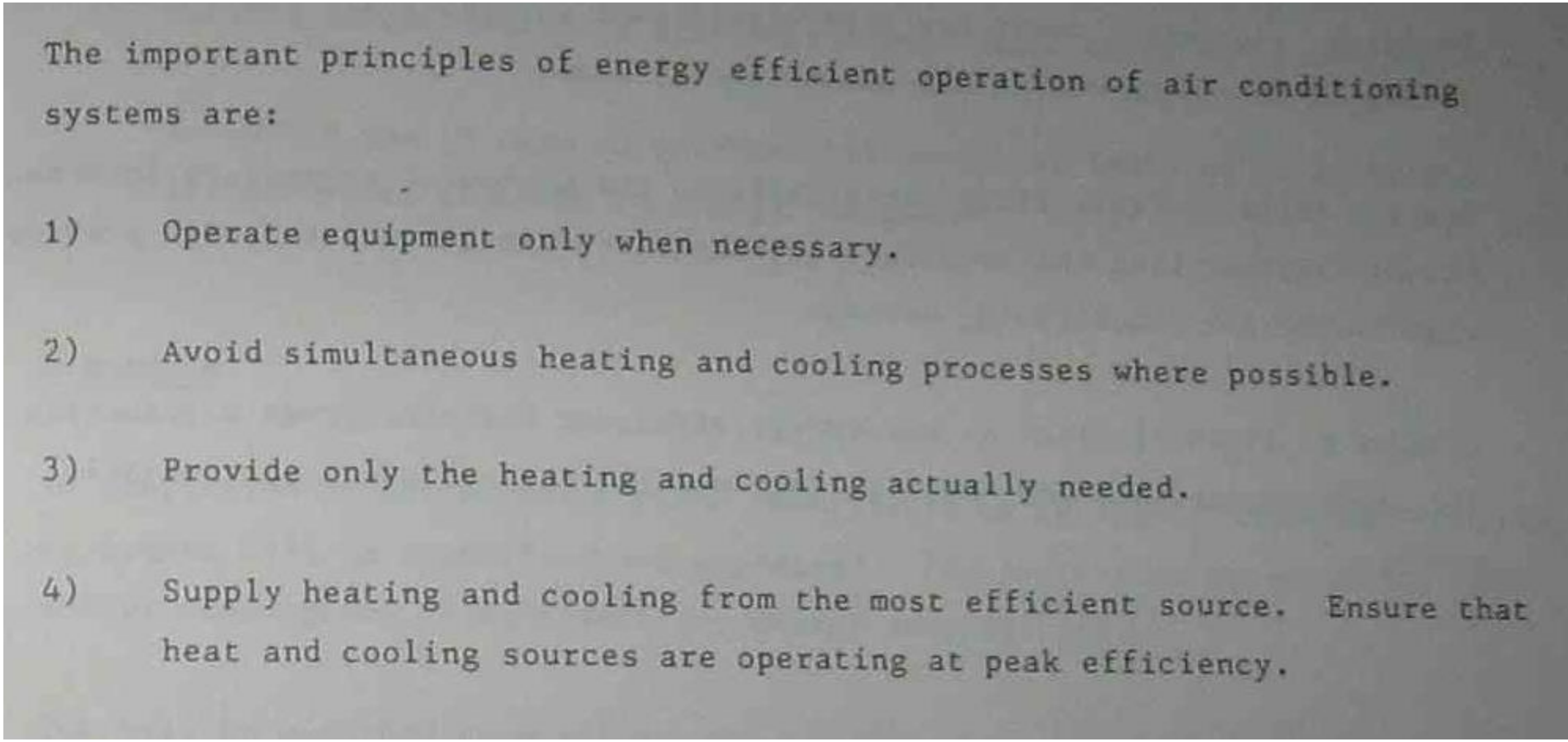
where $\dot{Q}_T$ = total cooling load (kW)

$\dot{m}_{da}$ = supply air mass flow rate (kg_{da}/s)

or $\simeq 0.0012\ \dot{V}$ where $\dot{V}$ is the supply air volume flow rate (ℓ/s)

and h_3, h_4 = specific enthalpy, air-on, and air-off the cooli coil respectively (kJ/kg_{da})


60,5
h(kJ/kg
47,2
45,5
33,5
W
2
3
1
4
13
23
24,3
35
DBT(°C)



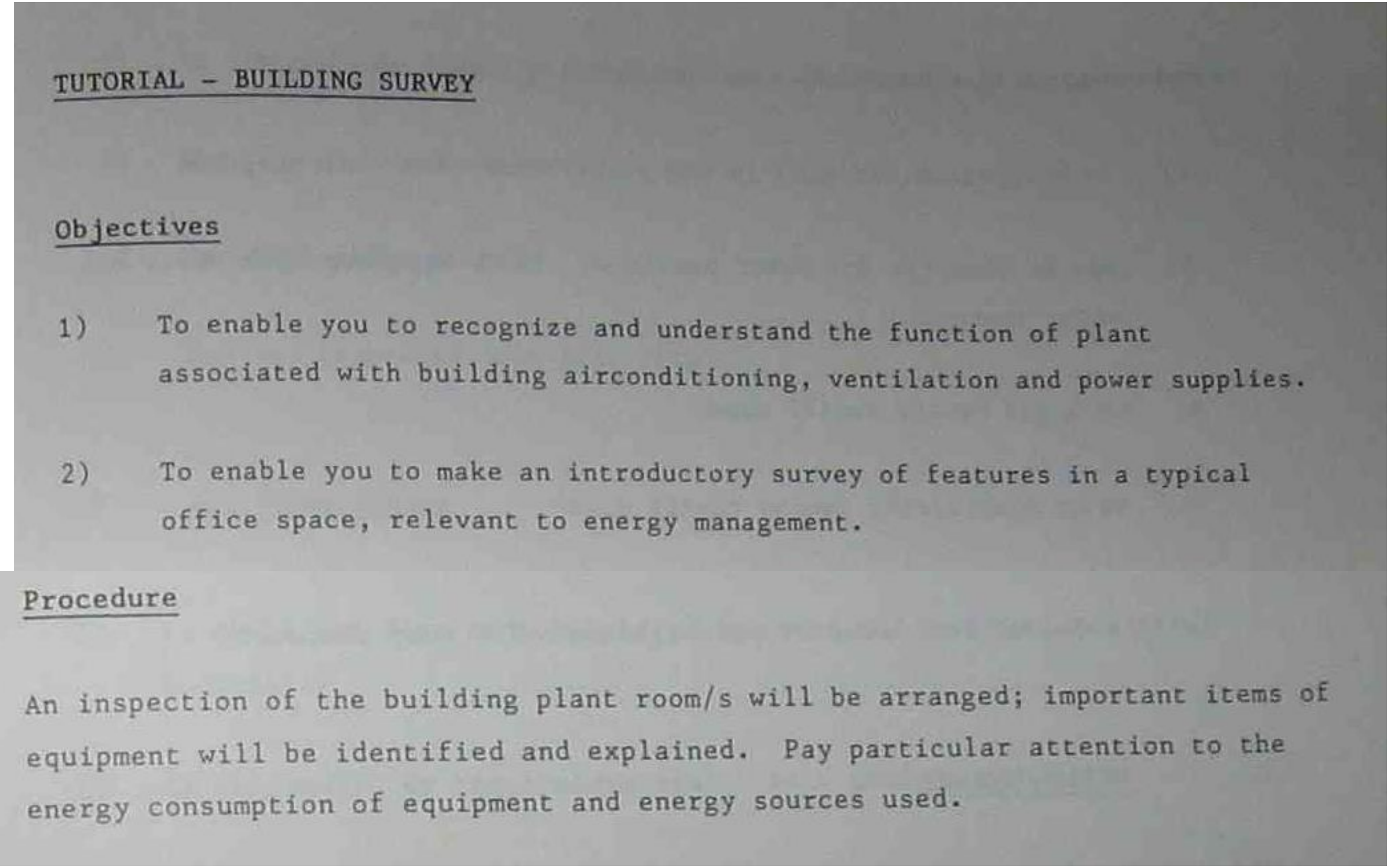
The important principles of energy efficient operation of air conditioning systems are:

1) Operate equipment only when necessary.

2) Avoid simultaneous heating and cooling processes where possible.

3) Provide only the heating and cooling actually needed.

4) Supply heating and cooling from the most efficient source. Ensure that heat and cooling sources are operating at peak efficiency.



TUTORIAL - BUILDING SURVEY

Objectives

1) To enable you to recognize and understand the function of plant associated with building airconditioning, ventilation and power supplies.

2) To enable you to make an introductory survey of features in a typical office space, relevant to energy management.

Procedure

An inspection of the building plant room/s will be arranged; important items of equipment will be identified and explained. Pay particular attention to the energy consumption of equipment and energy sources used.

2.0 LIGHT IS FOR PEOPLE

Artificial lighting would not be required if our buildings were not occupied or visited by people. The sole purpose of expensive lighting installations, is to enable people to perform some physical or visual task and their effectiveness at performing that task is proportional to the quantity and quality of the lighting.

All lighting installations must therefore be designed primarily for the occupants' comfort and task efficiency and of secondary importance is energy conservation and aesthetics. Bricks and mortar do not complain about bad lighting or headaches, the occupants however do.

3.0 GLARE CONTROL

Badly designed or installed lighting can cause discomfort for the occupants. Some sources of discomfort are as follows:-

(a) Direct glare, caused by having a bare lamp or bright luminaire, reflector, or diffuser in direct line of vision.

(b) Reflected glare, where a bright light source is reflected into the eye causing discomfort.

(c) Veiling Reflections, are the result of normal levels of light reflecting off the task, thus reducing the apparent contrast between the task and the background and therefore visibility. This can be most prevalent on glossy paper, where the reflected light causes the text to blend into the background resulting in low contrast.