

a sunnier spot such as Australia. (An energy yield ratio bigger than one means that a system is A Good Thing, energy-wise.) Wind turbines with a lifetime of 20 years have an energy yield ratio of 80.

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

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

Solar biomass

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

George W. Bush, February 2006

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

1. We can grow specially-chosen plants and burn them in a power station that produces electricity or heat or both. We'll call this "coal substitution."
2. We can grow specially-chosen plants (oil-seed rape, sugar cane, or corn, say), turn them into ethanol or biodiesel, and shove that into cars, trains, planes or other places where such chemicals are useful. Or we might cultivate genetically-engineered bacteria, cyanobacteria, or algae that directly produce hydrogen, ethanol, or butanol, or even electricity. We'll call all such approaches "petroleum substitution."
3. We can take by-products from other agricultural activities and burn them in a power station. The by-products might range from straw (a by-product of Weetabix) to chicken poo (a by-product of McNuggets). Burning by-products is coal substitution again, but using ordinary plants, not the best high-energy plants. A power station that burns agricultural by-products won't deliver as much power per unit area of farmland as an optimized biomass-growing facility, but it has the

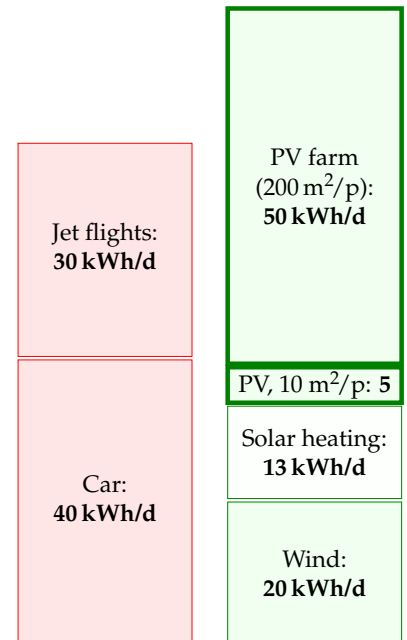


Figure 6.9. Solar photovoltaics: a 10 m² array of building-mounted south-facing panels with 20% efficiency can deliver about 5 kWh per day of electrical energy. If 5% of the country were coated with 10%-efficient solar panels (200 m² of panels per person) they would deliver 50 kWh/day/person.

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

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

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

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



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

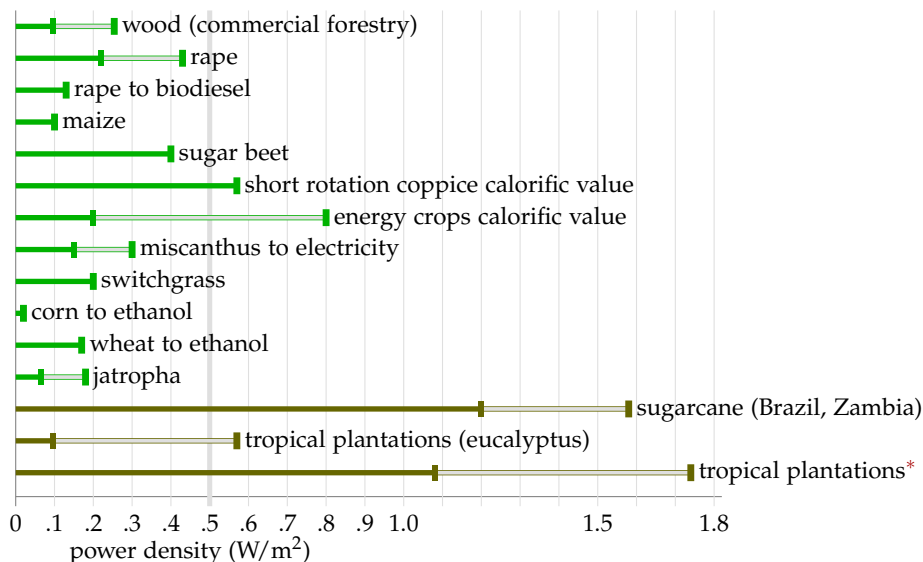


Figure 6.11. Power production, per unit area, achieved by various plants. For sources, see the end-notes. These power densities vary depending on irrigation and fertilization; ranges are indicated for some crops, for example wood has a range from $0.095\text{--}0.254 \text{ W/m}^2$. The bottom three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

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

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

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

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

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

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

Notes and further reading

page no.

- 38 ...*compensate for the tilt between the sun and the land*. The latitude of Cambridge is $\theta = 52^\circ$; the intensity of midday sunlight is multiplied by $\cos \theta \simeq 0.6$. The precise factor depends on the time of year, and varies between $\cos(\theta + 23^\circ) = 0.26$ and $\cos(\theta - 23^\circ) = 0.87$.
- *In a typical UK location the sun shines during one third of daylight hours*. The Highlands get 1100 h sunshine per year – a sunniness of 25%. The best spots in Scotland get 1400 h per year – 32%. Cambridge: 1500 ± 130 h per year – 34%. South coast of England (the sunniest part of the UK): 1700 h per year – 39%. [2rq1oc] Cambridge data from [2szckw]. See also figure 6.16.

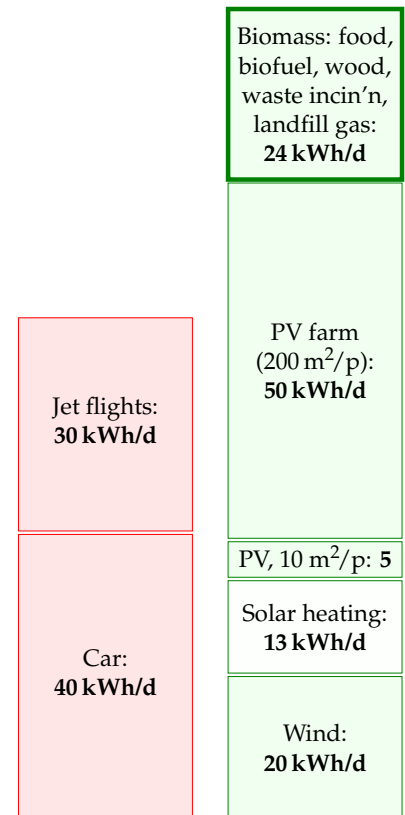


Figure 6.12. Solar biomass, including all forms of biofuel, waste incineration, and food: 24 kWh/d per person.

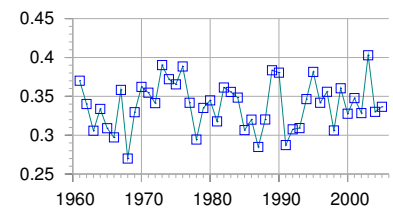


Figure 6.13. Sunniness of Cambridge: the number of hours of sunshine per year, expressed as a fraction of the total number of daylight hours.

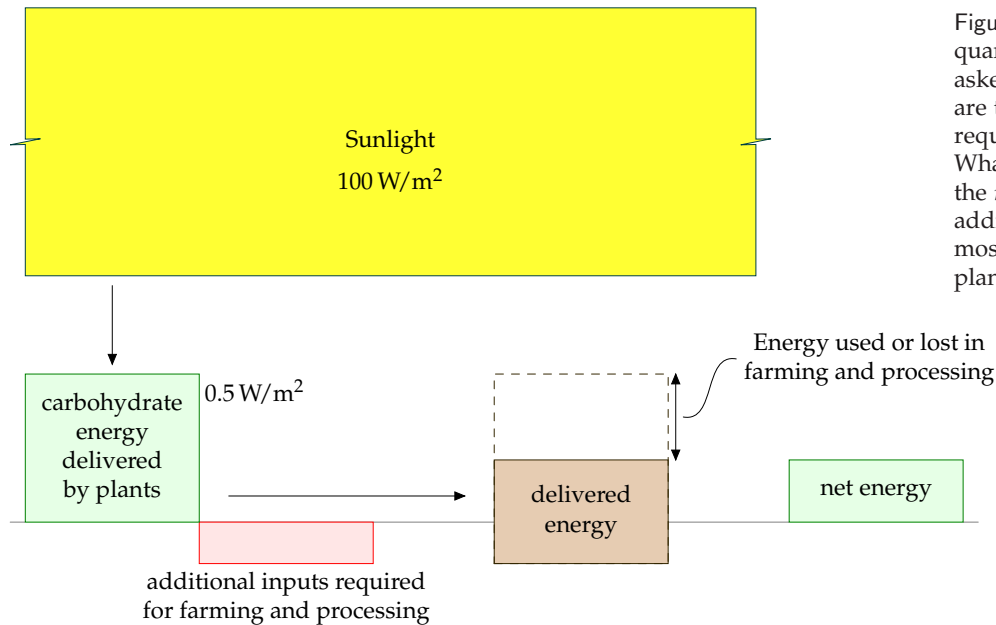


Figure 6.14. This figure illustrates the quantitative questions that must be asked of any proposed biofuel. What are the additional energy inputs required for farming and processing? What is the delivered energy? What is the *net* energy output? Often the additional inputs and losses wipe out most of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

38 *The average raw power of sunshine per square metre of south-facing roof in Britain is roughly 110 W/m^2 , and of flat ground, roughly 100 W/m^2 .* Source: NASA “Surface meteorology and Solar Energy” [5hrx1s]. Surprised that there’s so little difference between a tilted roof facing south and a horizontal roof? I was. The difference really is just 10% [6z9epq].

39 *... that would be about 10 m^2 of panels per person.* I estimated the area of south-facing roof per person by taking the area of land covered by buildings per person (48 m^2 in England – table I.6), multiplying by $1/4$ to get the south-facing fraction, and bumping the area up by 40% to allow for roof tilt. This gives 16 m^2 per person. Panels usually come in inconvenient rectangles so some fraction of roof will be left showing; hence 10 m^2 of panels.

– *The average power delivered by photovoltaic panels...*

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

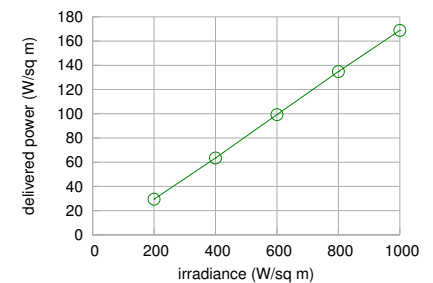


Figure 6.15. Power produced by the Sanyo HIP-210NKHE1 module as a function of light intensity (at 25°C , assuming an output voltage of 40 V). Source: datasheet, www.sanyo-solar.eu.

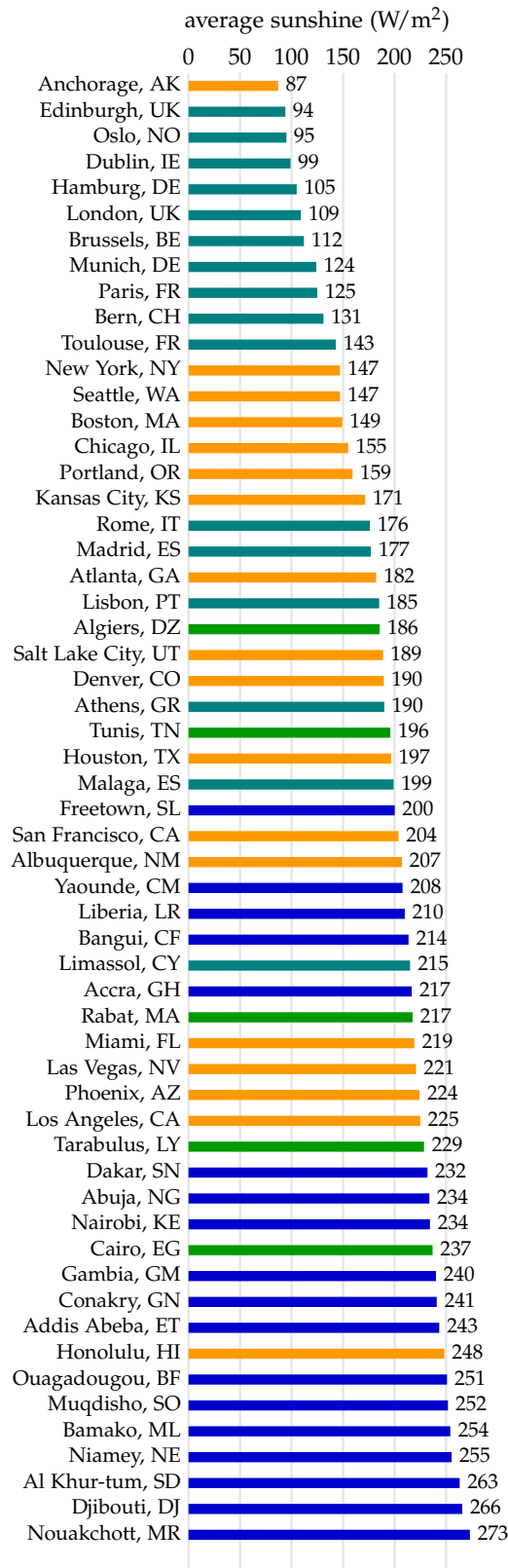
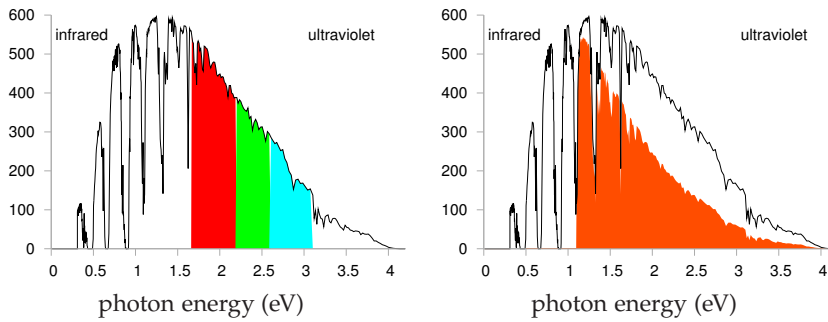


Figure 6.16. Average power of sunshine falling on a horizontal surface in selected locations in Europe, North America, and Africa.





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

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

- *A device with efficiency greater than 30% would be quite remarkable.* This is a quote from Hopfield and Gollub (1978), who were writing about panels without concentrating mirrors or lenses. The theoretical limit for a standard “single-junction” solar panel without concentrators, the Shockley–Queisser limit, says that at most 31% of the energy in sunlight can be converted to electricity (Shockley and Queisser, 1961). (The main reason for this limit is that a standard solar material has a property called its band-gap, which defines a particular energy of photon that that material converts most efficiently. Sunlight contains photons with many energies; photons with energy *below* the band-gap are not used at all; photons with energy *greater* than the band-gap may be captured, but all their energy in excess of the band-gap is lost. Concentrators (lenses or mirrors) can both reduce the cost (per watt) of photovoltaic systems, and increase their efficiency. The Shockley–Queisser limit for solar panels with concentrators is 41% efficiency. The only way to beat the Shockley–Queisser limit is to make fancy photovoltaic devices that split the light into different wavelengths, processing each wavelength-range with its own personalized band-gap. These are called multiple-junction photovoltaics. Recently multiple-junction photovoltaics with optical concentrators have been reported to be about 40% efficient. [2t17t6], www.spectrolab.com. In July 2007, the University of Delaware reported 42.8% efficiency with 20-times concentration [6hobq2], [21sx6t]. In August 2008, NREL reported 40.8% efficiency with 326-times concentration [62ccou]. Strangely, both these results were called world efficiency records. What multiple-junction devices are available on the market? Uni-solar sell a thin-film triple-junction 58 W(peak) panel with an area of 1 m². That implies an efficiency, in full sunlight, of only 5.8%.

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

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

Figure 6.17. Part of Shockley and Queisser’s explanation for the 31% limit of the efficiency of simple photovoltaics.

Left: the spectrum of midday sunlight. The vertical axis shows the power density in W/m² per eV of spectral interval. The visible part of the spectrum is indicated by the coloured section.

Right: the energy captured by a photovoltaic device with a single band-gap at 1.1 eV is shown by the tomato-shaded area. Photons with energy less than the band-gap are lost. Some of the energy of photons above the band-gap is lost; for example half of the energy of every 2.2 eV photon is lost.

Further losses are incurred because of inevitable radiation from recombining charges in the photovoltaic material.

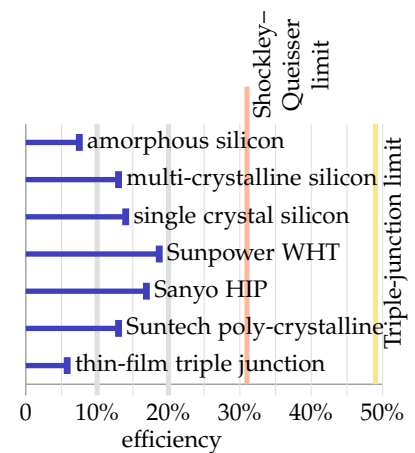


Figure 6.18. Efficiencies of solar photovoltaic modules available for sale today. In the text I assume that roof-top photovoltaics are 20% efficient, and that country-covering photovoltaics would be 10% efficient. In a location where the average power density of incoming sunlight is 100 W/m², 20%-efficient panels deliver 20 W/m².

41 *The Solarpark in Muhlhausen, Bavaria.* On average this 25-hectare farm is expected to deliver 0.7 MW (17 000 kWh per day).

New York's Stillwell Avenue subway station has integrated amorphous silicon thin-film photovoltaics in its roof canopy, delivering 4 W/m^2 (Fies et al., 2007).

The Nellis solar power plant in Nevada was completed in December, 2007, on 140 acres, and is expected to generate 30 GWh per year. That's 6 W/m^2 [5hzs5y].

Serpa Solar Power Plant, Portugal (PV), "the world's most powerful solar power plant," [39z5m5] [2uk8q8] has sun-tracking panels occupying 60 hectares, i.e., 600 000 m^2 or 0.6 km^2 , expected to generate 20 GWh per year, i.e., 2.3 MW on average. That's a power per unit area of 3.8 W/m^2 .

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

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

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

– *Figure 6.10.* In the USA, *Miscanthus* grown without nitrogen fertilizer yields about 24 t/ha/y of dry matter. In Britain, yields of 12–16 t/ha/y are reported. Dry *Miscanthus* has a net calorific value of 17 MJ/kg, so the British yield corresponds to a power density of 0.75 W/m^2 . Sources: Heaton et al. (2004) and [6kq77]. The estimated yield is obtained only after three years of undisturbed growing.

– *The most efficient plants are about 2% efficient; but the delivered power per unit area is about 0.5 W/m^2 .* At low light intensities, the best British plants are 2.4% efficient in well-fertilized fields (Monteith, 1977) but at higher light intensities, their conversion efficiency drops. According to Turkenburg (2000) and Schiermeier et al. (2008), the conversion efficiency of solar to biomass energy is less than 1%.

Here are a few sources to back up my estimate of 0.5 W/m^2 for vegetable power in the UK. The Royal Commission on Environmental Pollution's estimate of the potential delivered power density from energy crops in Britain is 0.2 W/m^2 (Royal Commission on Environmental Pollution, 2004). On page 43 of the Royal Society's biofuels document (Royal Society working group on biofuels, 2008), *Miscanthus* tops the list, delivering about 0.8 W/m^2 of chemical power.



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

In the World Energy Assessment published by the UNDP, Rogner (2000) writes: “Assuming a 45% conversion efficiency to electricity and yields of 15 oven dry tons per hectare per year, 2 km² of plantation would be needed per megawatt of electricity of installed capacity running 4,000 hours a year.” That is a power per unit area of 0.23 W(e)/m². (1 W(e) means 1 watt of electrical power.)

Energy for Sustainable Development Ltd (2003) estimates that short-rotation coppices can deliver over 10 tons of dry wood per hectare per year, which corresponds to a power density of 0.57 W/m². (Dry wood has a calorific value of 5 kWh per kg.)

According to Archer and Barber (2004), the instantaneous efficiency of a healthy leaf in optimal conditions can approach 5%, but the long-term energy-storage efficiency of modern crops is 0.5–1%. Archer and Barber suggest that by genetic modification, it might be possible to improve the storage efficiency of plants, especially *C4 plants*, which have already naturally evolved a more efficient photosynthetic pathway. *C4 plants* are mainly found in the tropics and thrive in high temperatures; they don’t grow at temperatures below 10 °C. Some examples of *C4 plants* are sugarcane, maize, sorghum, finger millet, and switchgrass. Zhu et al. (2008) calculate that the theoretical limit for the conversion efficiency of solar energy to biomass is 4.6% for *C3* photosynthesis at 30 °C and today’s 380 ppm atmospheric CO₂ concentration, and 6% for *C4* photosynthesis. They say that the highest solar energy conversion efficiencies reported for *C3* and *C4* crops are 2.4% and 3.7% respectively; and, citing Boyer (1982), that the average conversion efficiencies of major crops in the US are 3 or 4 times lower than those record efficiencies (that is, about 1% efficient). One reason that plants don’t achieve the theoretical limit is that they have insufficient capacity to use all the incoming radiation of bright sunlight. Both these papers (Zhu et al., 2008; Boyer, 1982) discuss prospects for genetic engineering of more-efficient plants.

- 43 *Figure 6.11.* The numbers in this figure are drawn from Rogner (2000) (net energy yields of wood, rape, sugarcane, and tropical plantations); Bayer Crop Science (2003) (rape to biodiesel); Francis et al. (2005) and Asselbergs et al. (2006) (jatropha); Mabee et al. (2006) (sugarcane, Brazil); Schmer et al. (2008) (switchgrass, marginal cropland in USA); Shapouri et al. (1995) (corn to ethanol); Royal Commission on Environmental Pollution (2004); Royal Society working group on biofuels (2008); Energy for Sustainable Development Ltd (2003); Archer and Barber (2004); Boyer (1982); Monteith (1977).
- 44 *Even just setting fire to dried wood in a good wood boiler loses 20% of the heat up the chimney.* Sources: Royal Society working group on biofuels (2008); Royal Commission on Environmental Pollution (2004).