Solar

Solar Power

The power of raw sunshine at midday on a cloudless day is 1000W per square metre. That’s 1000W per m^2 of area oriented towards the sun, not per m^2 of land area.

Yearly average solar power incident to a place on Earth?

Solar Power

The power of raw sunshine at midday on a cloudless day is 1000W per square metre. That's 1000W per m^2 of area oriented towards the sun, not per m^2 of land area.

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 (for England)

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%.

We lose power because of cloud cover. In a typical UK location the sun shines during just 34% of daylight hours.

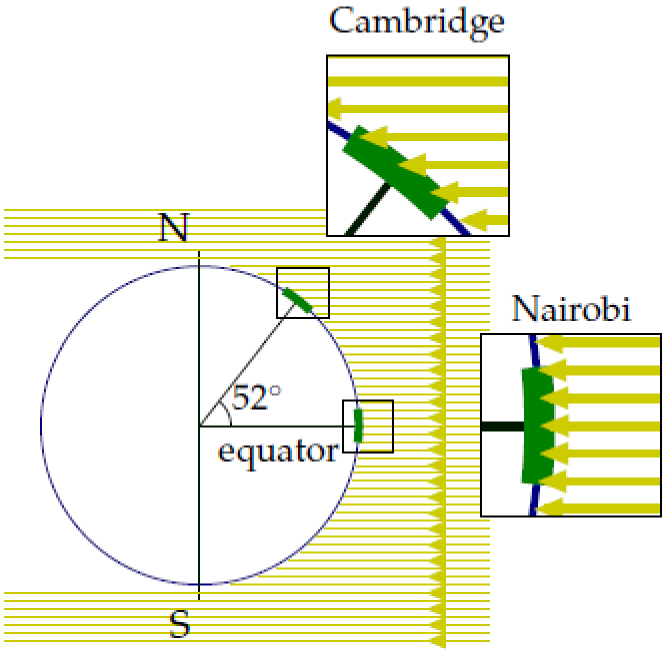


Figure 6.1. Sunlight hitting the earth at midday on a spring or autumn day. The density of sunlight per unit land area in Cambridge (latitude 52°) is about 60% of that at the equator.

Solar Power

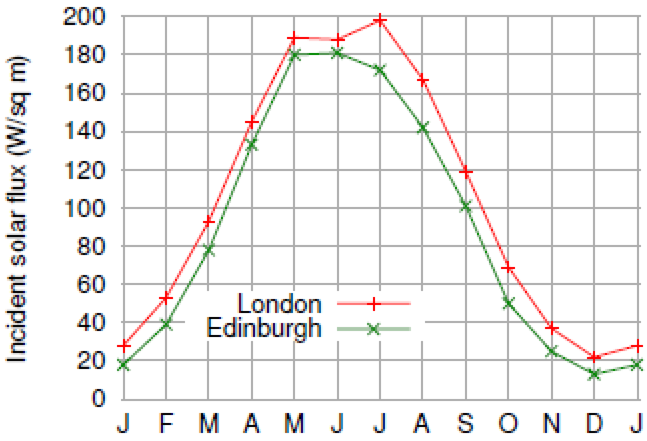


Figure 6.2. Average solar intensity in London and Edinburgh as a function of time of year. The average intensity, per unit land area, is 100 W/m^2.

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

2. **Solar photovoltaic**: generating electricity.

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

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

Solar Thermal

Let’s imagine we cover all south-facing roofs with solar thermal panels – that would be about 10m^2 of panels per person – and let’s assume these are 50%-efficient at turning the sunlight’s 110W/m^2 into hot water. Multiplying

$$50\% \times 10\text{m}^2 \times 110\text{W/m}^2 = 550\text{ W}$$

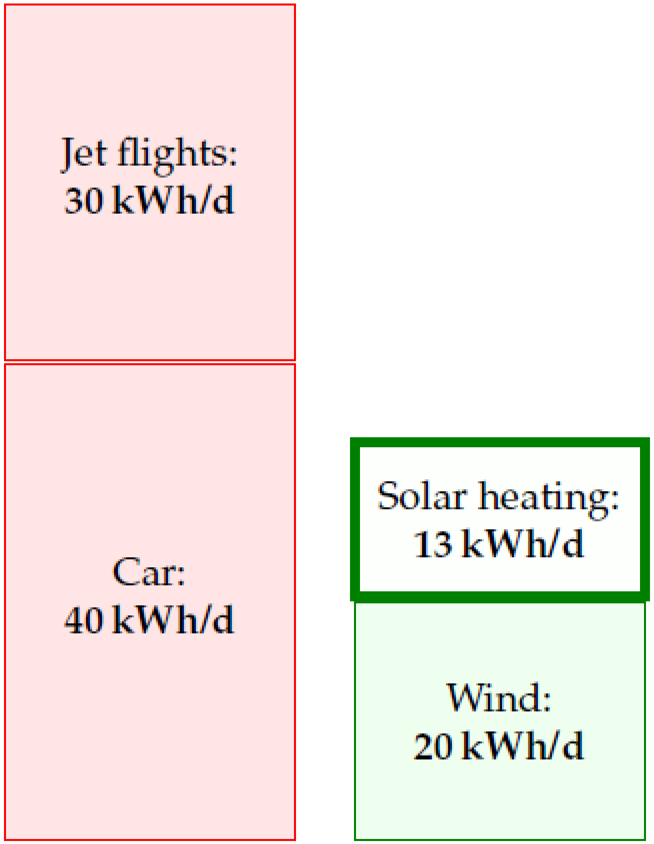
we find solar heating could deliver

13 kWh per day per person.

Solar Thermal

Solar power generated by a 3m^2 hot-water panel (green), and supplementary heat required (blue) to make hot water in the test house of Viridian Solar. (The photograph shows a house with the same model of panel on its roof.) The average solar power from 3m^2 was **3.8 kWh/d**. The experiment simulated the hot-water consumption of an average European household – 100 litres of hot (60 °C) water per day. The 1.5–2 kWh/d gap between the total heat generated (black line, top) and the hot water used (red line) is caused by heat-loss. The magenta line shows the electrical power required to run the solar system. The average power per unit area of these solar panels is **53W/m^2**.

Solar Thermal



Jet flights:
30 kWh/d

Car:
40 kWh/d

Solar heating:
13 kWh/d

Wind:
20 kWh/d

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

Solar Photovoltaic

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

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

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.

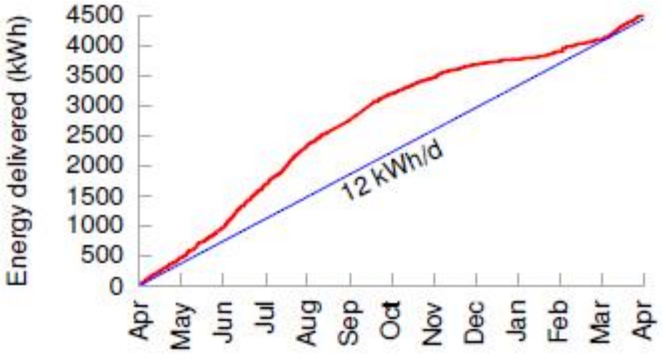


Figure 6.5. Solar photovoltaics: data from a 25-m^2 array in Cambridgeshire in 2006. The peak power delivered by this array is about 4 kW. The average, year-round, is 12 kWh per day. That’s 20 W per square metre of panel.

Solar Farming

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

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:

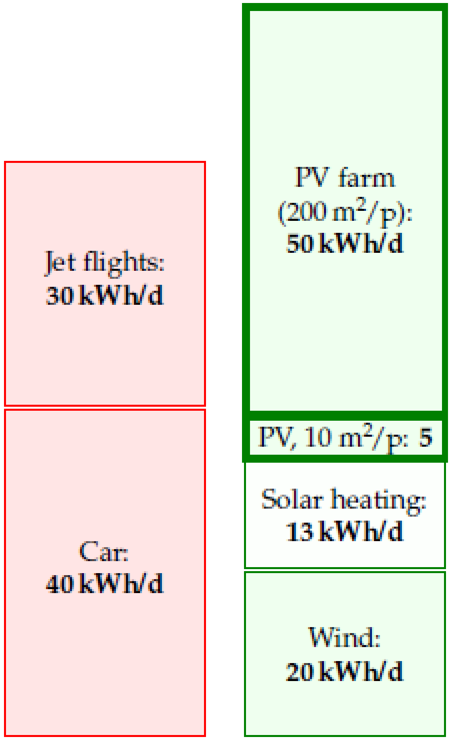
$10\% \times 100\text{W/m}^2 \times 200\text{m}^2$ per person $\simeq$ **50 kWh/day/person**.

Assuming only 10%-efficient panels.

The power density (the power per unit area) of such a solar farm would be

$10\% \times 100\text{W/m}^2 =$ **10W/m^2**.

Solar Farming



Jet flights:
30 kWh/d

Car:
40 kWh/d

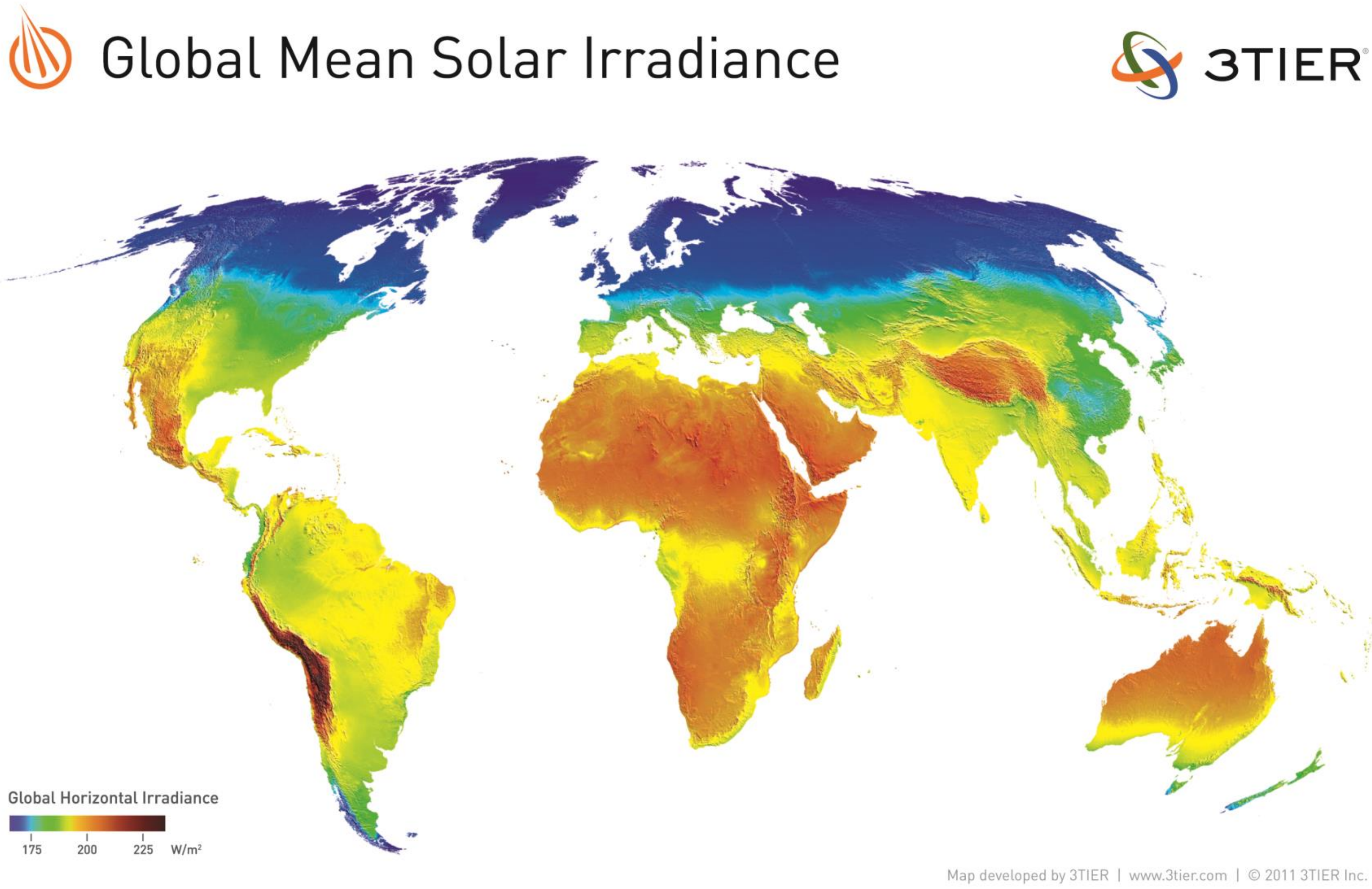
PV farm
(200 m^2/p):
50 kWh/d

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

Solar heating:
13 kWh/d

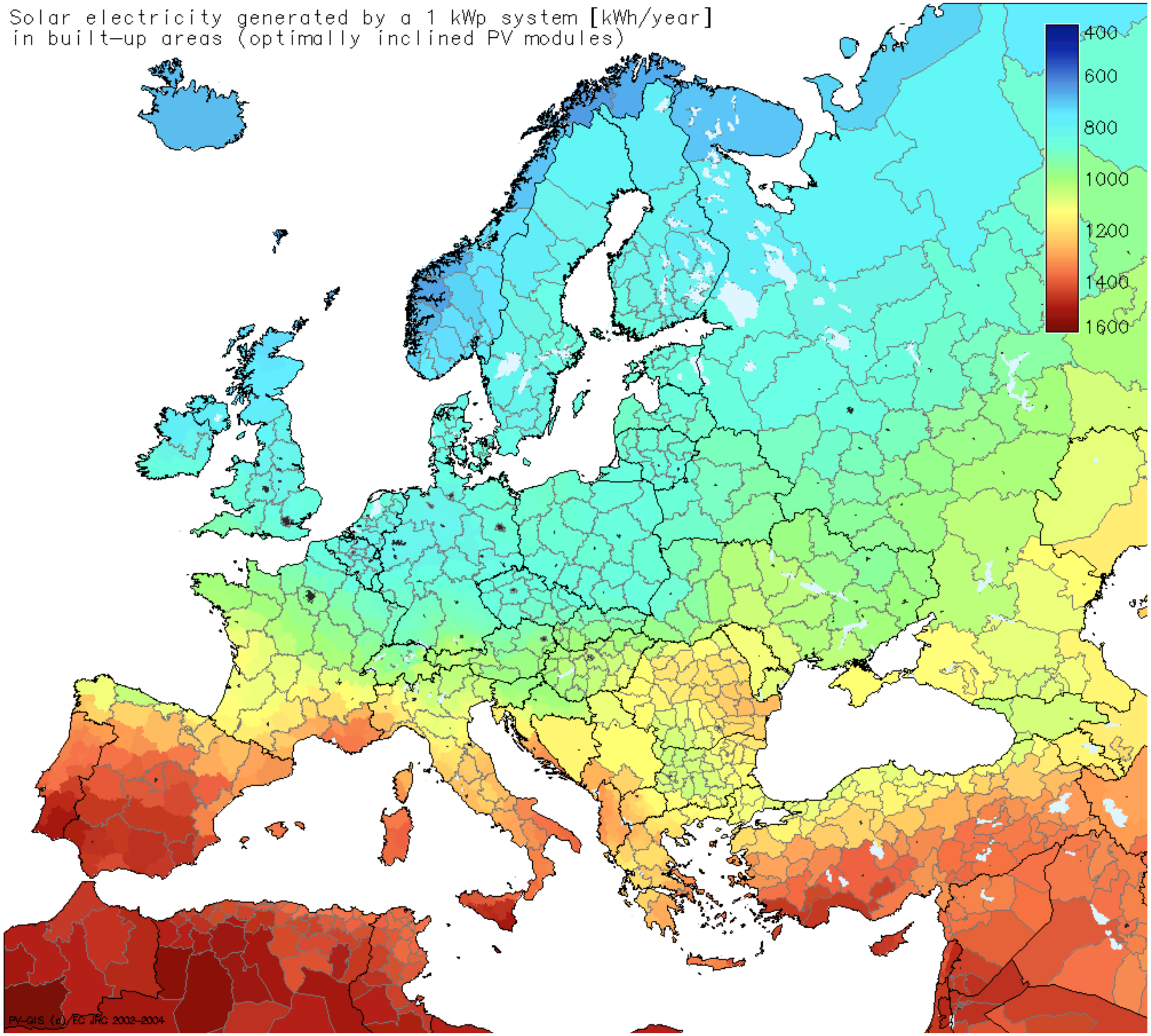
Wind:
20 kWh/d

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



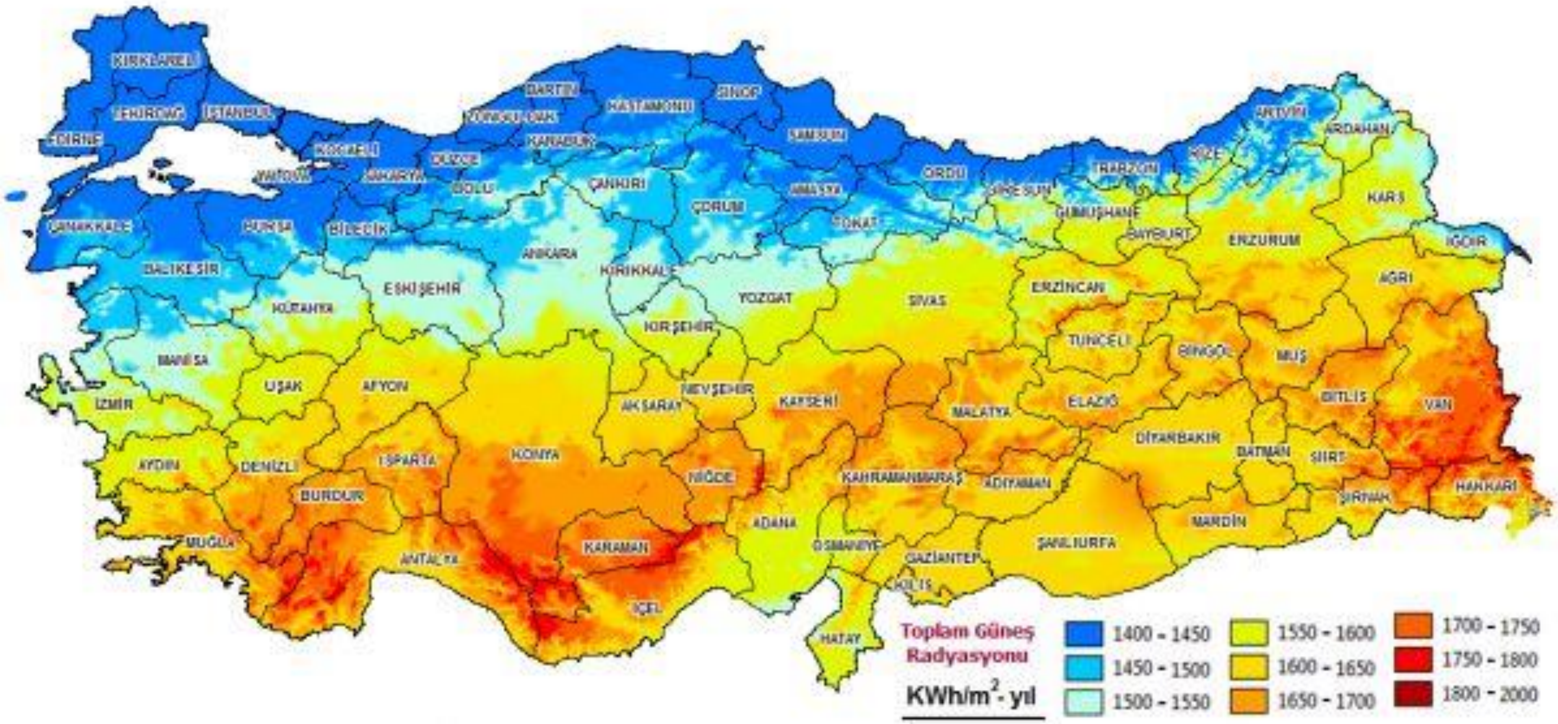
http://www.gogreen.cr/global-wind-and-solar-maps.html

European Solar Energy Map



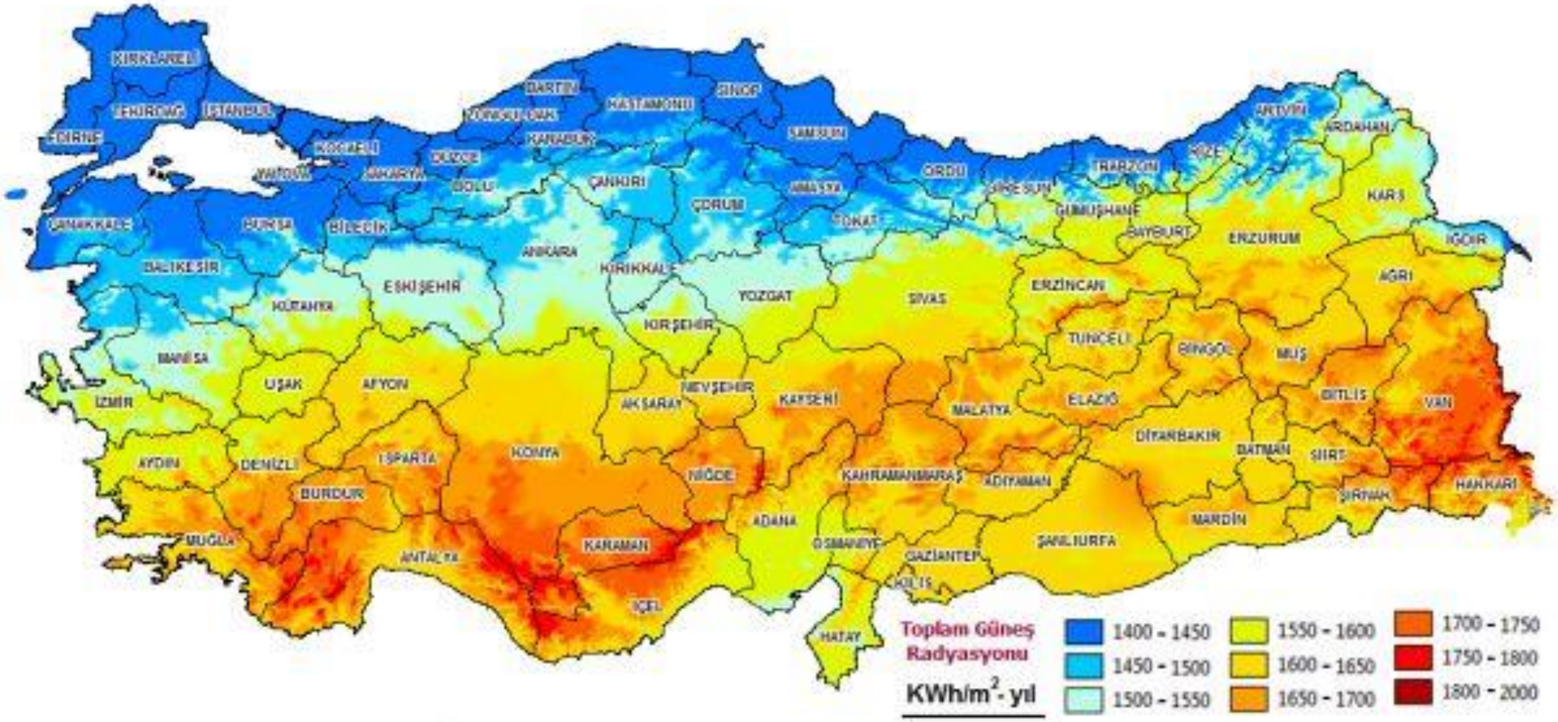
Solar electricity generated by a 1 kWp system [kWh/year]
in built-up areas (optimally inclined PV modules)

Türkiye Güneş Enerjisi Haritası



1000 kWh / m^2 – yıl = ? W / m^2

Türkiye Güneş Enerjisi Haritası



1000 kWh / m^2 – yıl = 2740 Wh / m^2 – gün = 114 W / m^2

Solar Biomass

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.

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.

Solar Biomass

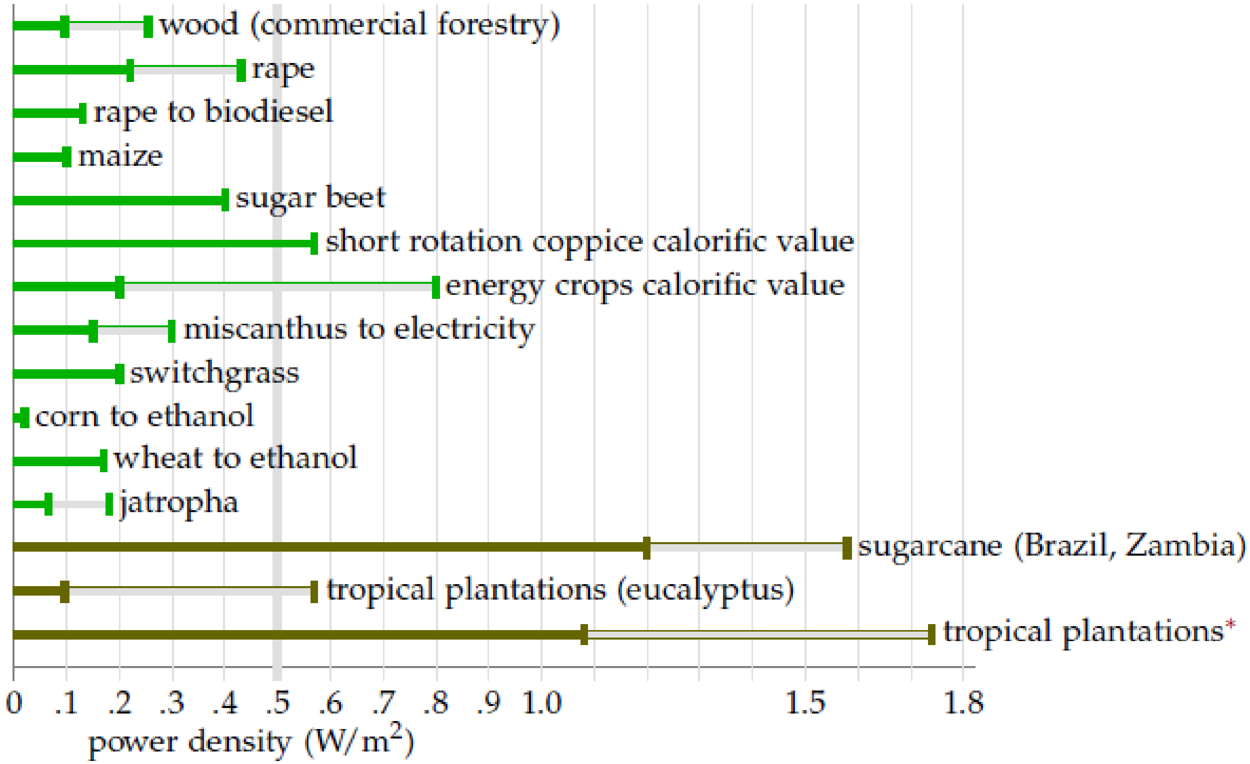


Figure 6.11. Power production, per unit area, achieved by various plants. For sources, see the end-notes. These power densities vary depending on irrigation and fertilization; ranges are indicated for some crops, for example wood has a range from 0.095–0.254 W/m^2. The bottom three power densities are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

Solar Biomass

The average harvestable power of sunlight in Britain is 100W/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 2W/m^2; however, their efficiency drops at higher light levels, and the best performance of any energy crops in Europe is closer to **0.5W/m^2**.

Let’s cover 75% of the country with quality green stuff. That’s 3000m^2 per person devoted to bio-energy. So the maximum power available, ignoring all the additional costs of growing, harvesting, and processing the greenery, is:

0.5W/m^2 × 3000m^2 per person = **36 kWh/d** per person.

Solar Biomass

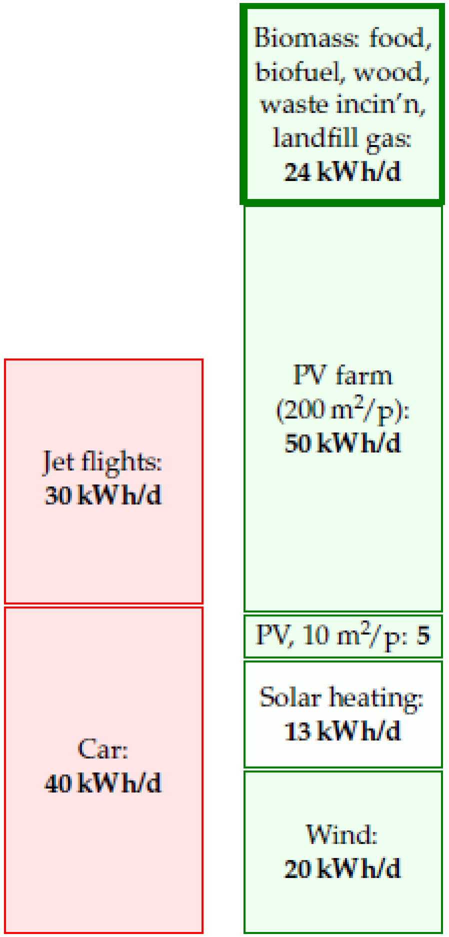


Figure 6.12. Solar biomass, including all forms of biofuel, waste incineration, and food: 24 kWh/d per person.

Solar Biomass

Petroleum substitution

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

Britain's main biodiesel crop, rape Şalgam

Typically, rape is sown in September and harvested the following August. Currently 450 000 hectares of oilseed rape are grown in the UK each year. (That's 2% of the UK.) Fields of rape produce 1200 litres of biodiesel per hectare per year; biodiesel has an energy of 9.8 kWh per litre; So that's a power per unit area of 0.13 W/m².

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

Sugar beet to ethanol Şeker pancarı

Sugar beet, in the UK, delivers an impressive yield of 53 t per hectare per year. And 1 t of sugar beet makes 108 litres of bioethanol. Bioethanol has an energy density of 6 kWh per litre, so this process has a power per unit area of 0.4 W/m², not accounting for energy inputs required.

Figure D.2. Oilseed rape. If used to create biodiesel, the power per unit area of rape is 0.13 W/m². Photo by Tim Dunne.

Bioethanol from sugar cane

Şeker kamışı

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

Bioethanol from corn in the USA

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

Cellulosic ethanol from switchgrass

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

Jatropha also has low power per unit area

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

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

What about algae?

Algae are just plants, so everything I've said so far applies to algae. Slimy underwater plants are no more efficient at photosynthesis than their terrestrial cousins. But there is one trick that I haven't discussed, which is standard practice in the algae-to-biodiesel community: they grow their algae in water heavily enriched with carbon dioxide, which might be collected from power stations or other industrial facilities. It takes much less effort for plants to photosynthesize if the carbon dioxide has already been concentrated for them. In a sunny spot in America, in ponds fed with concentrated CO_2 (concentrated to 10%), Ron Putt of Auburn University says that algae can grow at 30 g per square metre per day, producing 0.01 litres of biodiesel per square metre per day. This corresponds to a power per unit pond area of $4\,\mathrm{W/m^2}$ – similar to the Bavaria photovoltaic farm.

Plant	Power per unit area (W/m^2)
Rape	0.13
Sugar beet	0.4
Sugar cane	1.2
Corn	0.02
Switchgrass	0.2
Jatropha	0.18
Algae	4

Documentary

Here comes the sun