5. Planes

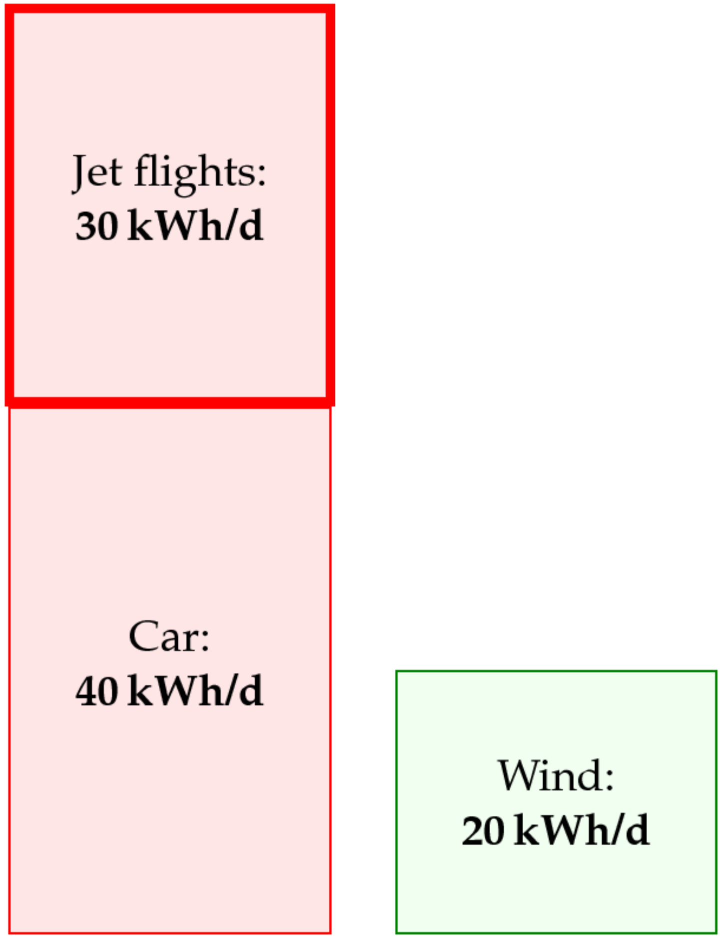
Data/assumptions: (i) one intercontinental trip per year per person on a Boeing 747-400 (ii) an airplane with 240,000 liters of fuel and with full capacity (416 passengers) can travel 14,200 km (iii) the calorific value of fuel is 10 kWh/liter (iv) the distance of a typical long range intercontinental trip is around 10,000 km (v) the plane is 80% full.

Question: What is an estimate of the energy consumption of one person in our favorite unit (kWh per day)?

If the length of the trip was 14,200 km and the plane 100% full:

$$\frac{2 \times 240,000 \text{ liter}}{416 \text{ passengers}} \times 10 \text{ kWh/liter} \times \frac{1}{365 \text{ days}} \simeq 33 \text{ kWh/day}$$

Let us assume that consumption of the plane is a constant linear function of the number of kilometers it flies (questionable assumption because much fuel is burned at takeoff and fuel consumption increases with weight) $\Rightarrow$ estimated consumption $= 33 \times \frac{10000}{14200} \times \frac{100}{80} \simeq$ 30kWh/day.



Comments

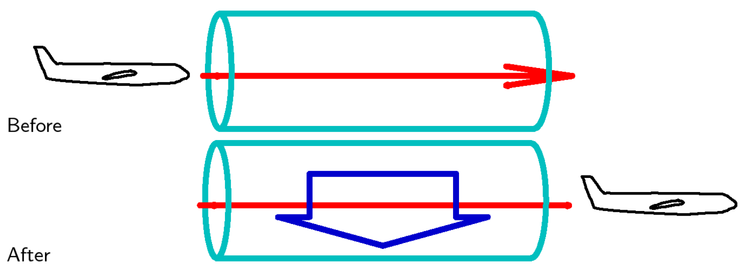
- We would not consume significantly less if we were to travel on slower planes.
- No redesign of a plane is going to radically improve its efficiency.
- Energy gains could be made by having fuller planes and better air-traffic management

	energy per distance (kWh per 100 p-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

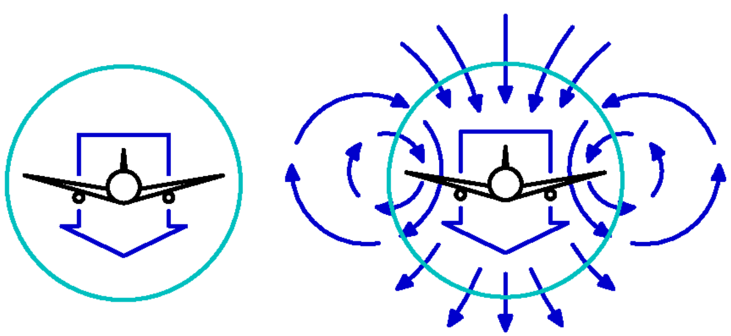
- Flying creates other gases in addition to CO_2 (water, ozone and indirect greenhouse gases). CO_2-equivalent $\simeq$ CO_2 emissions $\times$ (factor 2 or 3).

Technical notes on planes

Energy spent on two things: (i) throwing air down to push up the plane and create the lift (ii) overcoming the drag.



Model adopted: plane encounters a stationary tube of air of section A_s. After a time t, it pushes a length $v \times t$ of this tube downwards with speed u where $v =$ speed of plane.



Cartoon A little closer to reality

Questions: What is the value of u? What is the value of the power required for lifting the plane (P_{lift})? What is P_{drag} (A_p is the frontal area of the plane and c_p its drag coefficient)? What is the energy per distance travelled? What is the optimal speed for energy efficiency?

Computation of speed u: We suppose that a constant force F_{on_tube} is applied to the tube of length $v \times t$ during a time period t. Since $F_{on\_tube} = m_{tube} \times acc.$ and $u = acc. \times t$, we have $F_{on\_tube} t = \rho v t A_s u$. Since this force must be equal to the force of gravity exerted on the plane (mg), we can write:

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

Computation of P_{lift}:

$$\begin{aligned} P_{lift} &= \frac{\text{kinetic energy of tube}}{\text{time}} \\ &= \frac{1}{t}\frac{1}{2} m_{tube} u^2 \\ &= \frac{1}{2}\frac{(mg)^2}{\rho v A_s} \end{aligned}$$

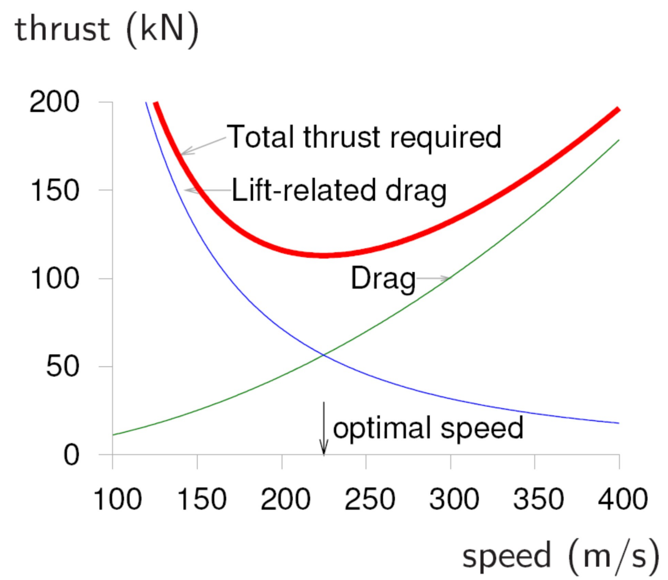
Computation of P_{drag} : $P_{drag} = \frac{1}{2} c_d \rho A_p v^3$

Energy per distance travelled: by assuming an efficiency ϵ (typical value around $\frac{1}{3}$) for the plane engines, we have

$$\frac{\text{energy}}{\text{distance}} = \frac{1}{\epsilon}\frac{(P_{lift} + P_{drag})t}{vt} = \frac{1}{\epsilon}\left(\frac{1}{2}c_d\rho A_p v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}\right)$$

Optimal speed for fuel efficiency when $\frac{1}{2}c_d\rho A_p v^2 = \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s} \Rightarrow v_{opt} = \sqrt{\frac{1}{\rho}\frac{mg}{\sqrt{c_d A p A_s}}}$.

From there, energy per unit of distance at optimal speed is equal to $\frac{1}{\epsilon}\left(\frac{c_d A_p}{A_s}\right)^{\frac{1}{2}} mg$.



Thrust to keep a Boeing 747 moving.

Energy per unit weight (of the entire craft) per unit of distance at optimal speed (gross transport cost) is equal to $\frac{1}{\epsilon}\left(\frac{c_d A_p}{A_s}\right)^{\frac{1}{2}} g$.

Value that depends only on the engine efficiency, the ratio $\frac{A_p}{A_s}$ defined by its shape and the drag of the plane!

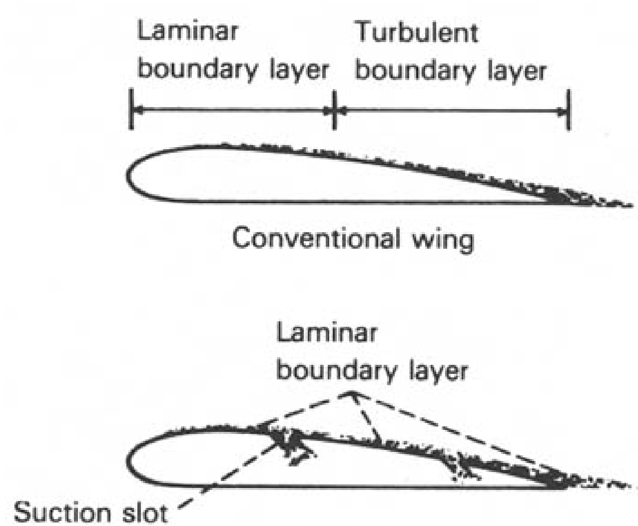
Typical values for the energy per unit weight per unit of distance are in the order of 0.4 kWh/ton-km.

Comments: (i) these results are not valid for a supersonic flight where our "tube model" is invalidated (ii) the tube model also applies to hydrofoils or other high-speed watercrafts (where values for c_d or $\frac{A_p}{A_s}$ may, however, significantly differ from those for airplanes).

Can planes be improved?

[A] Engine efficiency could be boosted a little by technological progress. [B] Planes could be lighter so as to reduce the net transport cost.

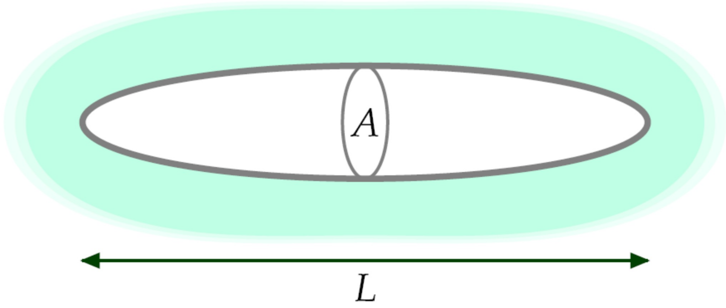
[C] The aerodynamics community says that the shape of the plane could be improved slightly by switching to blended-wing bodies.



[D] Drag coefficient could be reduced somewhat by laminar flow control, a technology that reduces the growth of turbulence over a wing by sucking a little air through small perforations of the surface.

Other ways of staying up: airships

Main problem with planes: benefits from reduced air resistance by slowing them down is more than cancelled by having to throw air down harder. So why not change strategy and being as light as air by using an enormous helium-filled balloon?



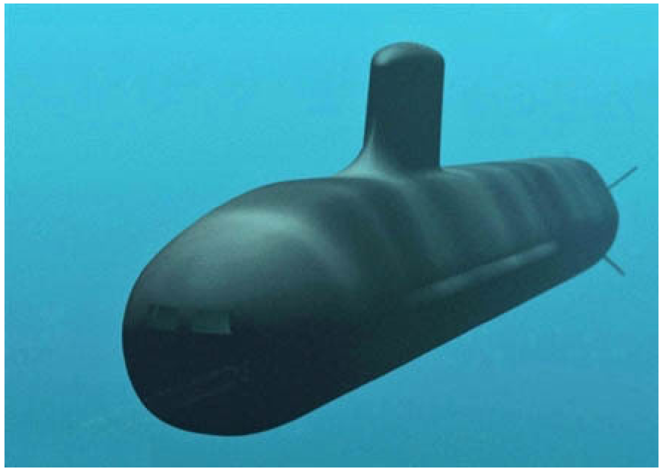
Let us assume the balloon is ellipsoidal. The volume is equal to $V = \frac{2}{3}AL$ and its mass is equal to $m_{total} = \rho V$. If it moves at speed v, the force of air resistance is $F = \frac{1}{2}c_d A\rho v^2 \Rightarrow$ Energy per unit distance per unit mass ($\frac{F}{\epsilon m_{total}}$) is equal to $\frac{3}{4\epsilon}c_d\frac{v^2}{L}$.

Let us plug number in $\frac{3}{4\epsilon} c_d \frac{v^2}{L}$. Assume a speed of 80 km/hour (three days for crossing the Atlantic), efficiency of $\epsilon = \frac{1}{4}$ and $L = 400$ m (Hindenburg was 245 m long), $c_d = 0.03$ (same value as for a Boeing 747) $\Rightarrow$

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

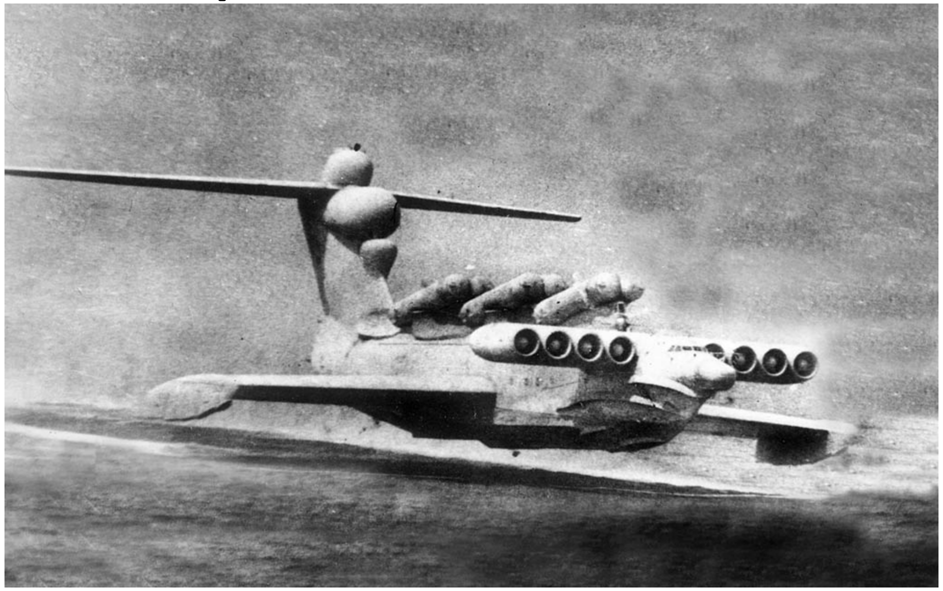
If useful cargo made up half of the vessel's mass $\Rightarrow$ net transport cost of 0.06 kWh/t-km, similar to rail transport.

Question: What is the gross transport cost (in kWh per ton-km) of a submarine of identical shape as the airship here above?



Other ways of staying up: water-skimming wingships

Ekranoplan



Pelican

Ground-effect aircraft: flies very close to the surface, obtaining its lift by sitting on a cushion of compressed air sandwiched between its wings and the nearest surface.

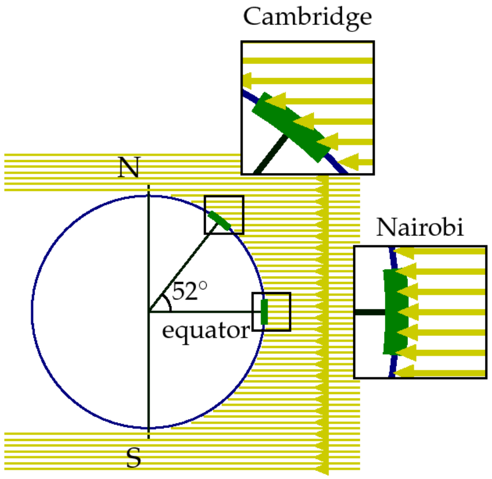
Comments: most of the energy expenditure is associated with air resistance and not for creating the air-cushion. It may have a freight-transport cost of about half of an ordinary aeroplane.

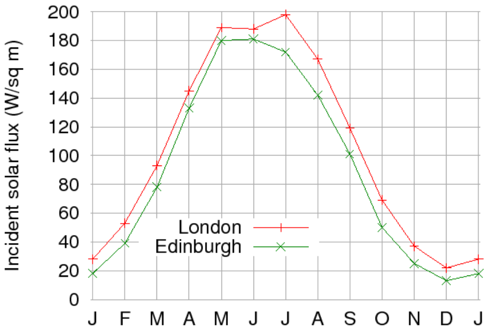
6. Solar Energy

Power of raw sunshine at the equator at midday on a cloudless day: 1000 W/m^2

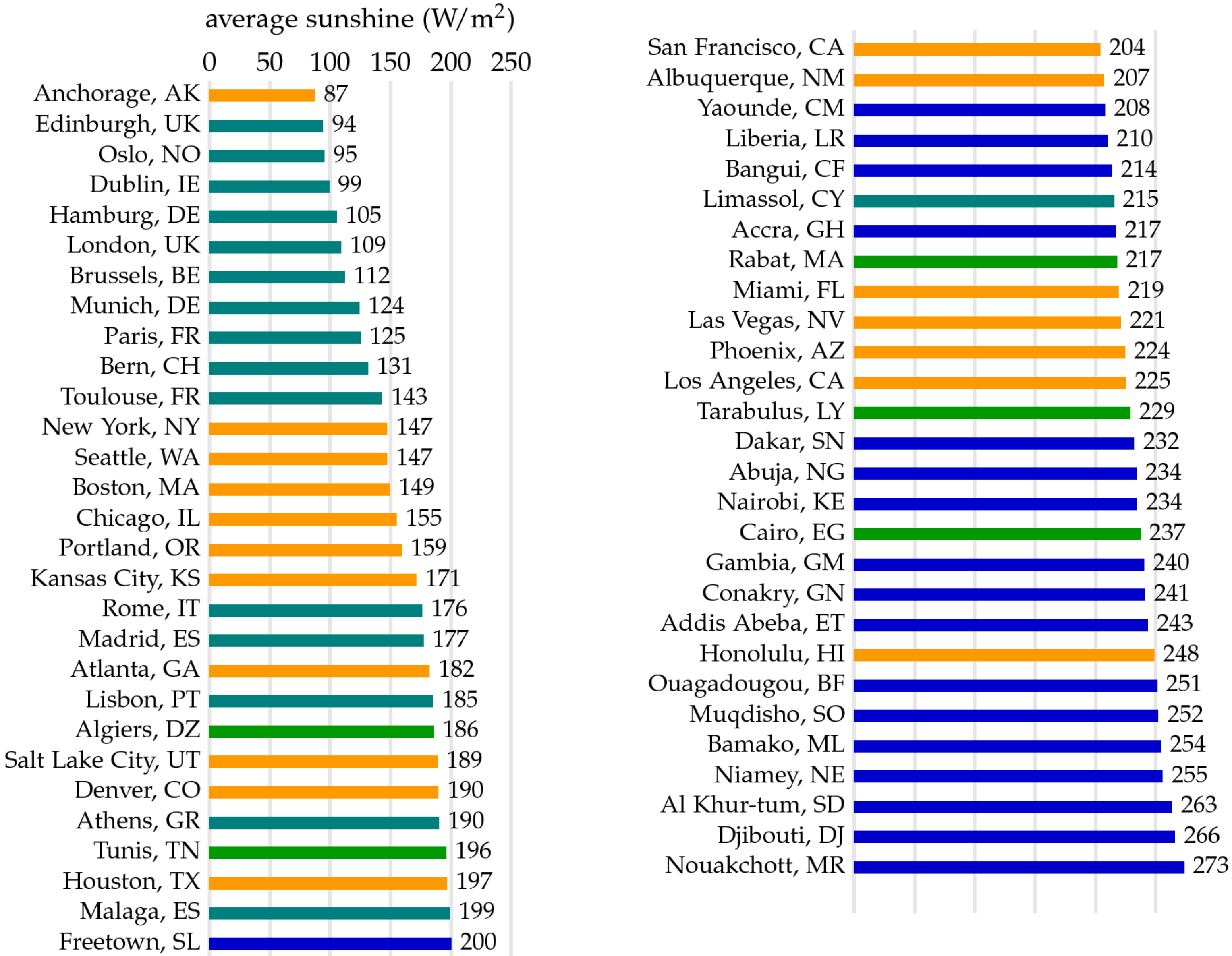
Corrections to be made to get power per m^2 of *land area* in Britain.

1. Compensate between the tilt of the sun and the land ($\simeq$ 60% of reduction).
2. Not midday all of the time. $\frac{\text{average intensity}}{\text{midday intensity}} =$ 32%
3. Clouds. In the UK, the sun shines just 34% of daylight hours.
4. Seasonal effects





$\Rightarrow$ Power/m^2 per square meter of south-facing roof in Britain $\simeq$ 110 W/m^2. Power per square meter of flat ground $\simeq$ 100 W/m^2.



average sunshine (W/m^2)
0
50
100
150
200
250
Anchorage, AK 87
Edinburgh, UK 94
Oslo, NO 95
Dublin, IE 99
Hamburg, DE 105
London, UK 109
Brussels, BE 112
Munich, DE 124
Paris, FR 125
Bern, CH 131
Toulouse, FR 143
New York, NY 147
Seattle, WA 147
Boston, MA 149
Chicago, IL 155
Portland, OR 159
Kansas City, KS 171
Rome, IT 176
Madrid, ES 177
Atlanta, GA 182
Lisbon, PT 185
Algiers, DZ 186
Salt Lake City, UT 189
Denver, CO 190
Athens, GR 190
Tunis, TN 196
Houston, TX 197
Malaga, ES 199
Freetown, SL 200
San Francisco, CA 204
Albuquerque, NM 207
Yaounde, CM 208
Liberia, LR 210
Bangui, CF 214
Limassol, CY 215
Accra, GH 217
Rabat, MA 217
Miami, FL 219
Las Vegas, NV 221
Phoenix, AZ 224
Los Angeles, CA 225
Tarabulus, LY 229
Dakar, SN 232
Abuja, NG 234
Nairobi, KE 234
Cairo, EG 237
Gambia, GM 240
Conakry, GN 241
Addis Abeba, ET 243
Honolulu, HI 248
Ouagadougou, BF 251
Muqdisho, SO 252
Bamako, ML 254
Niamey, NE 255
Al Khur-tum, SD 263
Djibouti, DJ 266
Nouakchott, MR 273

Turning raw solar power into useful power

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

2. Solar photovoltaic: generating electricity.

3. Solar biomass: using trees, bacteria, algae, corn, etc. to make energy fuels, chemicals, or building materials.

4. Food: same as solar biomass except that the plants are used to feed humans or animals.

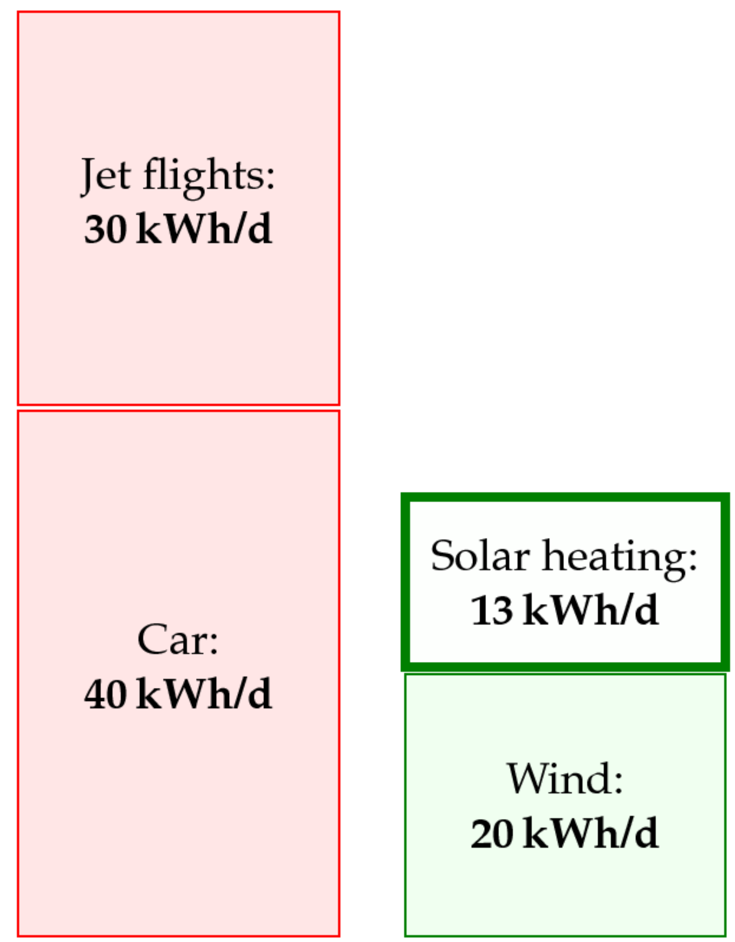
Solar thermal

Simplest technology: panel to make hot water.

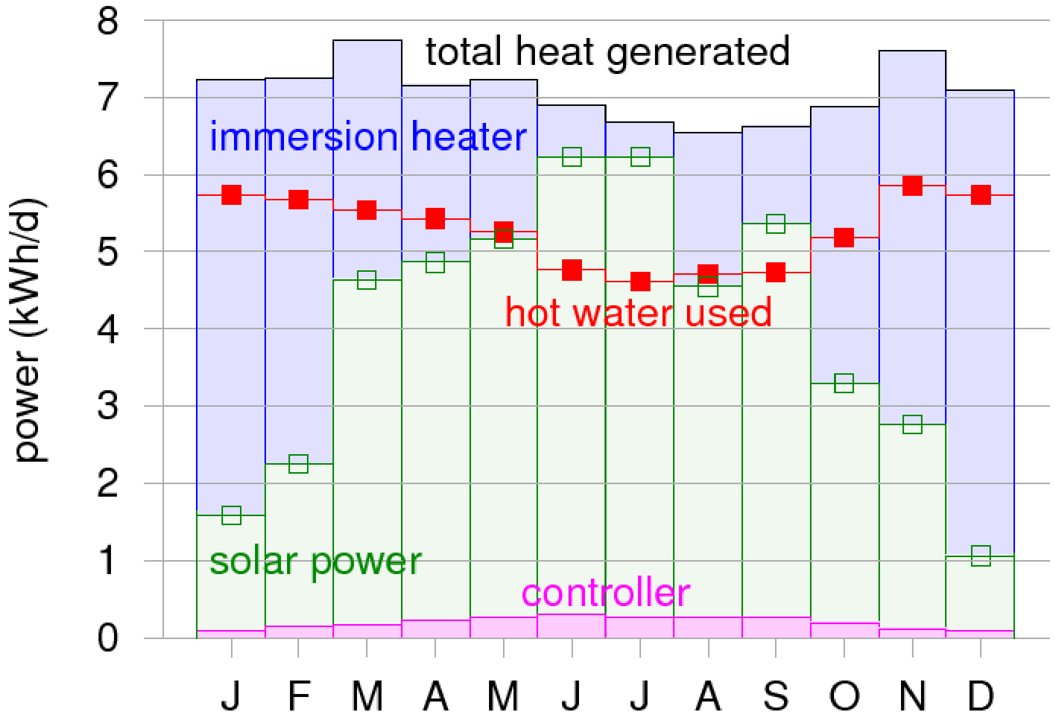
Assumptions: *All* south-facing roofs covered with solar thermal plants - that's around 10 m^2 of panels per person. Panels are 50% efficient at using the 110 W/m^2 to heat water ⇒

Solar heating could deliver: 13 kWh per day per person

Comments: Low-grade energy that cannot be exported to the grid; captured heat may not be in the right place (less square meters of roofs per person in cities); may deliver energy non-uniformly through the year.



Example: the Viridian solar test house

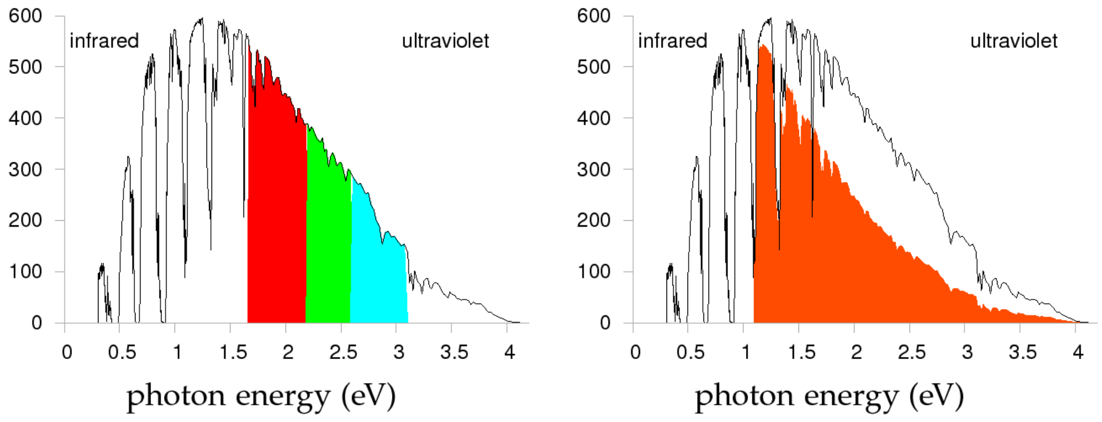


Information. Green: Solar power generated by 3 m^2 panels; Blue: supplementary heat required ; Red: heat in hot water used; Magenta: electrical power required to run the system.
Consumption of the average European household (100 liters of 60 °C water). Average solar power from the 3 m^2 of panels: 3.8 kWh/d.

Solar photovoltaic

Photovoltaic panels convert sunlight into electricity. Typical efficiency of 10%; expensive ones 20%. A mass-produced device with efficiency of 35% would be remarkable.

Fundamental laws of physics of physics limit the efficiency of solar panels since (i) they cannot capture energy photons with energy less than the *band gap* of the photovoltaic material (ii) Photons with energy greater than the band-gap may be captured, but all the energy in excess of the band gap is lost.



Left: Spectrum of mid-day sunlight. Shows the power/density in W/m^2 per eV of spectral interval. **Right:** Energy captured by a single band-gap at 1.1 eV.

Innovations: [A] Multiple-junction photovoltaics that split the wavelengths between different wavelengths, processing each wavelength-range with its own band-gap [B] Optical concentrators that can reduce cost per watt produced and increase efficiency.

Assumptions: Every person has 10 m^2 of 20%-efficient solar panels. They are installed to cover all south-facing roofs. They will deliver:

$20\% \times 110\ W/m^2 \times 10\ m^2 \simeq$ 5 kWh per day per person

Comments: (i) In practice we would have to choose whether to use the 10 m^2 of roofs for thermal or photovoltaic panels. Here we will just choose to add up these two numbers to the production stack. (ii) PV panels are about four times more expensive than solar panels and deliver only half as much energy. (iii) Best "energy-efficient" solutions: mirrors that focus sunlight on PV units, which deliver both electricity and from which hot water is "collected".

Solar farming

Solar farming: deployment of PV panels all over the countryside.

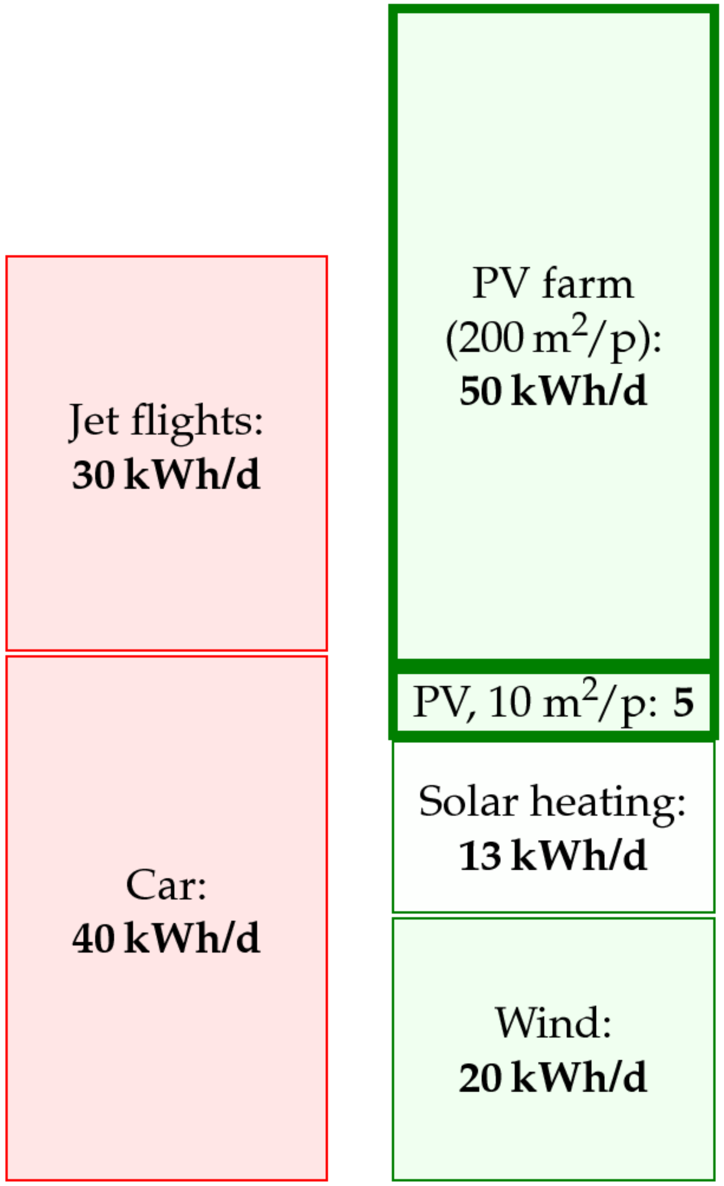
Assumption: 5% of the country covered with 10% photovoltaic panels (200 m^2 per person); 100 W/m^2

Solar farming can deliver : $10\% \times 100\ W/m^2 \times 200\ m^2$ per person $\simeq$ 50 kWh/day/person.

Comments: [A] Solar farming can coexist with windmills that cast few shadows on the ground.
[B] Producing energy from solar panels is three times more expensive than the market rate.

Solar photovoltaic farm in Bavaria. 6.3 MW peak. Average power per unit area $\simeq$ 5 W/m^2

[C] 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 solar system in Central Europe is 4, for a system with a lifetime of 20 years, and **7** in sunnier spots. Wind turbines have a ratio of 80.
[D] Unlikely that more than 5% of the land (200 m^2 per person) will be used for solar farming even if there are 2800 m^2 of arable land per person in Britain (and 48 m^2 of building, 114 m^2 of gardens, 60 m^2 of roads and 69 m^2 of water)
[E] Panels are not going to be necessarily more efficient (remember the theoretical limit) but they will be less expensive to produce (economies of scales for the production process; less energy required for production).



Solar biomass

Four main routes to get energy from solar-powered biological systems:

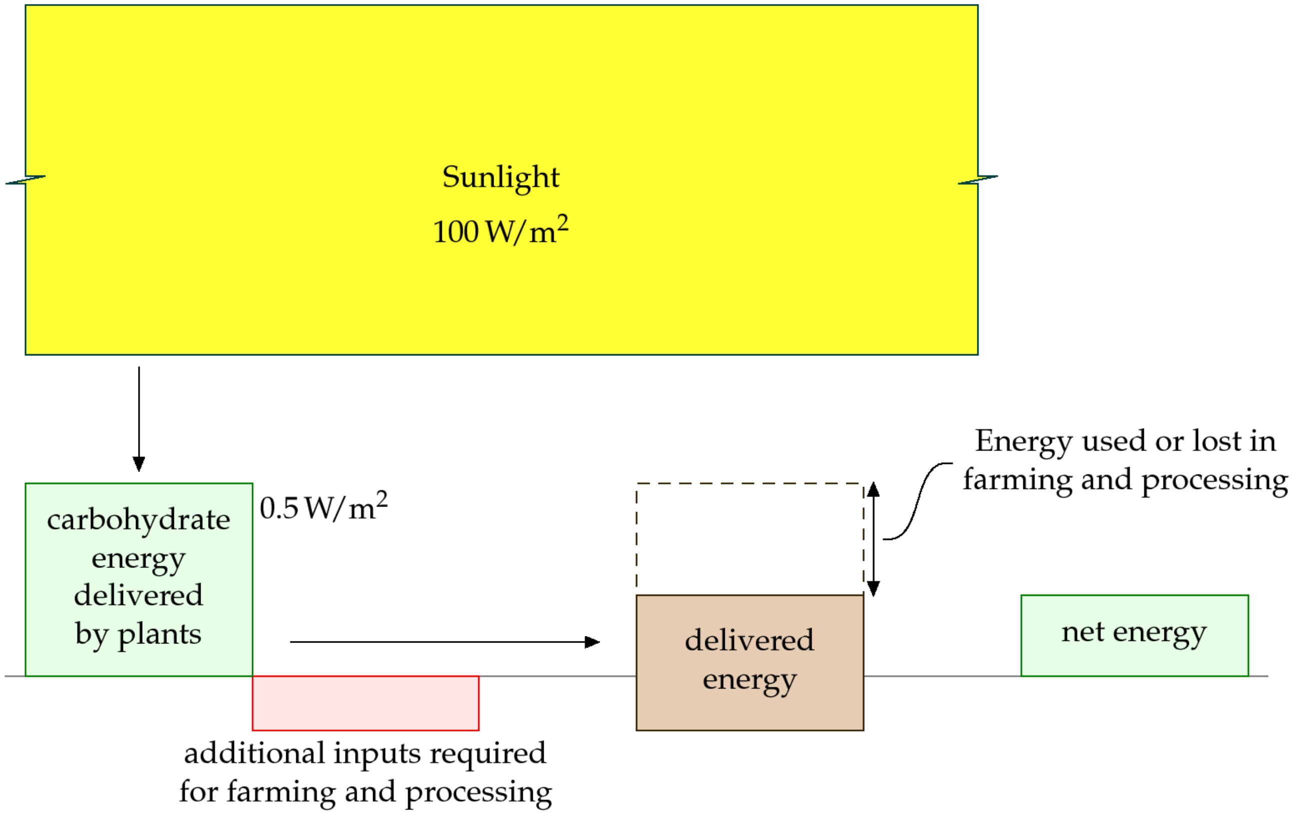
1. We can grow specifically-chosen plants and burn them to produce electricity or heat or both. We call this **coal substitution**.

2. We can grow specifically chosen plants (sugar cane, corn, etc) and turn them into ethanol or biodiesel that can be used for example to power cars or planes. Or we might cultivate genetically-engineered bacteria, cyanobacteria or algae that directly produce hydrogen, ethanol or butanol. We call such approaches **petroleum substitution**.

3. We can take by-products from other agricultural activities and burn them or turn them into biofuels.

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

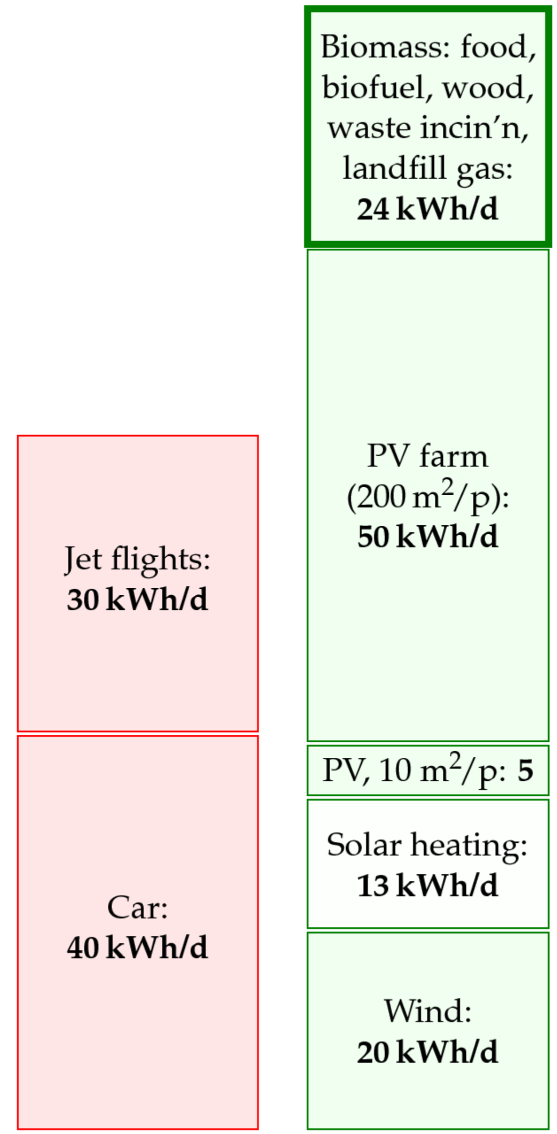
For all these processes, the first staging post for the energy is a chemical molecule (or several) as a carbohydrate ⇒ We can get an upper bound on the power obtained from any of these processes by estimating how much power could pass through that first staging post. All subsequent steps involving tractors, animals, chemical facilities, power stations can only lose energy.



The harvestable power of sunlight in Britain is 100 W/m^2. Most efficient plants in Europe are about 0.5%-efficient at specific light levels in turning solar energy into chemical energy. $\Rightarrow$ Plants might deliver 0.5 W/m^2.

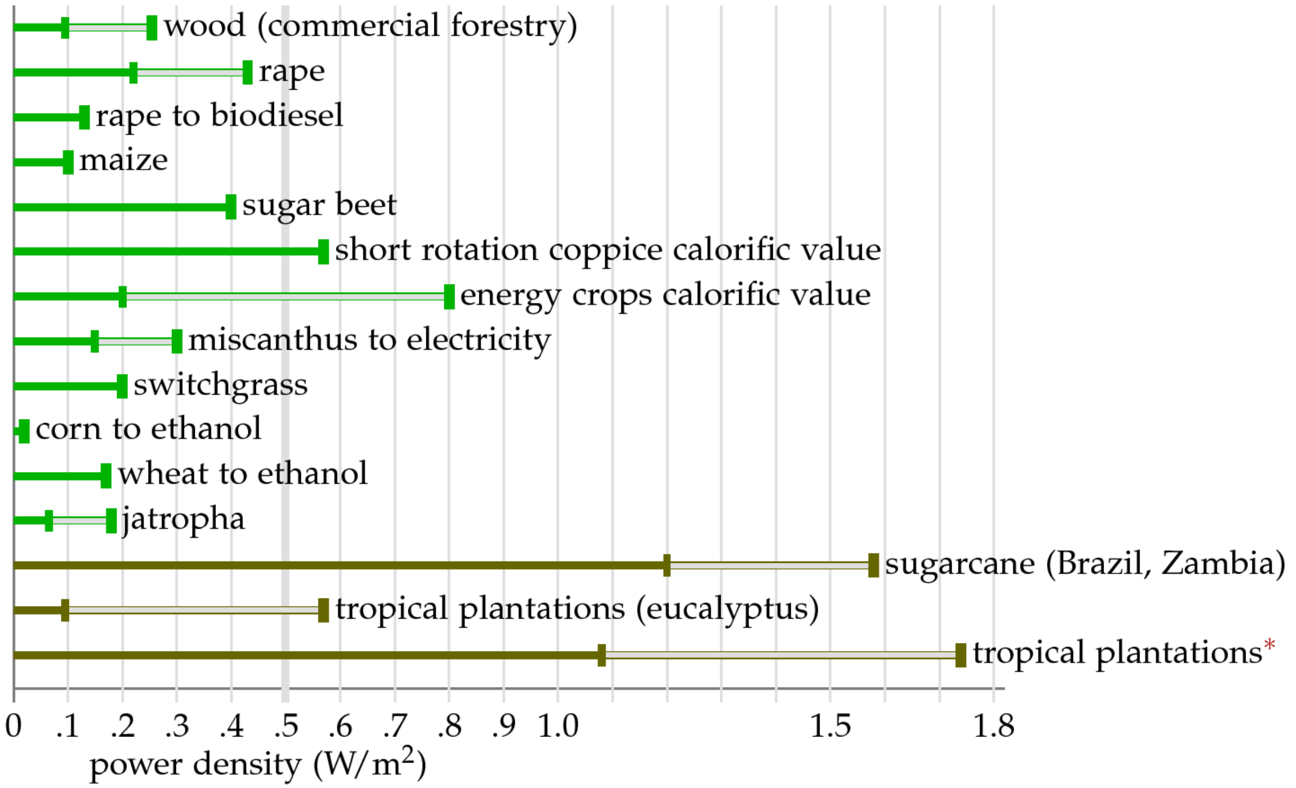
Assumptions: We devote 75% of the country for bionenergy, that is 3000 m^2 of land per person, and assume that only 33% losses occur along the processing chain (optimistic assumption).

Bioenergy can deliver : $0.5\ W/\ m^2 \times 3000\ m^2$ per person $\times$ 67% $\simeq$ 24 kWh/d per person.



Comments: [A] Extremely generous assumptions have been made to obtain 24 kWh/d per person for biomass.

[B] In tropical plantations, genetically modified plants can deliver up to 1.8 W/m^2 with fertilizer application and irrigation.

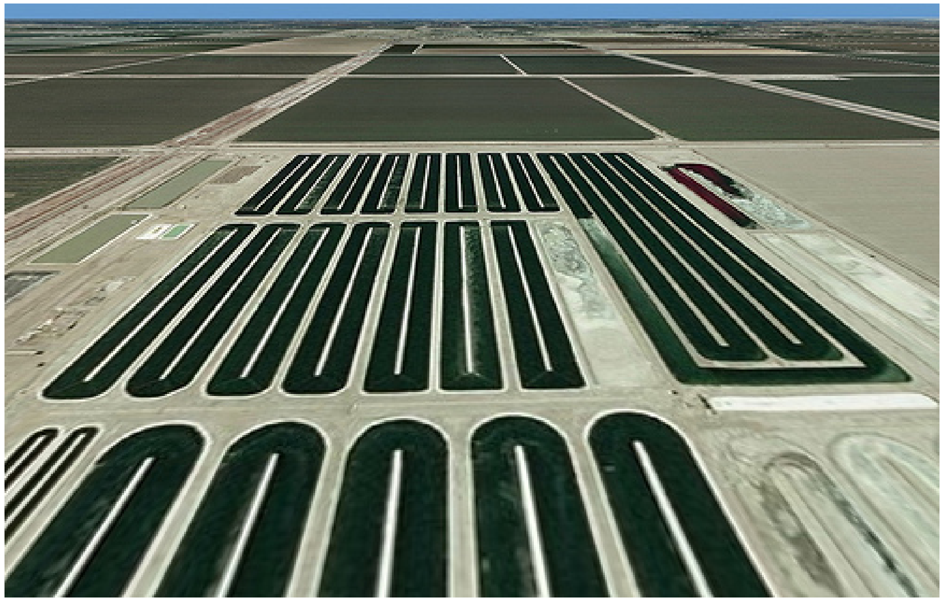


What about algae?

Algae are plants that are not more efficient at photosyntheis than their terrestrial cousins.

But in water with enriched carbon dioxide they can produce up to **4 W/m^2**. They require however 60 g of CO_2 per m^2 per day.

If all the CO_2 from all UK power stations was captured (roughly 2,5 tons per year per person), it could service 115 square meters per person of algae-ponds (6% of the country).
This would produce $\frac{4\times24}{1000} \times 115 \simeq$ 11 kWh per day per person.



And about algae that produces hydrogen?

Hydrogen can be produced directly from the photosynthetic system, right from step one while carbohydrates require many chemical steps. This could be potentially a much more efficient way for producing energy.

Research studies have suggested that genetically modified algae covering 11 hectares in the Arizona desert could produce 300 kg of hydrogen per day. Hydrogen contains 39 kWh per kg ⇒ algae-to-hydrogen facility would deliver 4.4 W/m^2.

7. Heating and cooling

We explore how much power is spent on:

1. Domestic heating.

2. Hot air - at home and at work

3. Cooling (air-conditioning + fridge and freezer).

Heating for bath/shower, cooking and cleaning

Bath and shower. *Data/Assumptions:* (i) Typical bath-water 50 cm $\times$ 15 cm $\times$ 150 cm $\simeq$ 110 liters (ii) Taking a shower uses 30 liters (iii) Water enters in the house at 10°C and the temperature of the bath/shower is 50°C (iv) Heat capacity of water is equal to 4200 J per liter per °C $\Rightarrow$
Energy for a bath $= 110 \times (50 - 10) \times 4200 \simeq 18$ MJ $\simeq$ 5 kWh
Energy for a shower $\simeq$ 1.4 kWh.

Kettle. Power up to 3 kW. If used 20 minutes per day, it consumes 1 kWh per day.

Electric cooker. Small ring, power of around 1kW. Large ring around 2.3 kW. If used at full power half an hour a day, it consumes 1.6 kWh per day.

Microwave. Cooking power of around 900 W but consumes 1.4 kW. If used 20 minutes per day, it consumes around 0.5 kWh per day.

Oven. 3 kW at full power. If used one hour per day at half power, it consumes 1.5 kWh per day.

Dishwasher. 1.5 kWh per run.

Washing machine. Uses 80 liters of water per load, with an energy cost of 1 kWh if the temperature is set to 40 °C.

Tumble dryer. 3 kWh per load.

Domestic iron. Power 2.5 kW. For 1 hour of ironing, 2.5 kWh is consumed.

Heating for bath/shower, cooking and cleaning counts for around 12 kWh per day per person.

Hot air - at home and at work

This small electric heater has a power of 1 kW.

Strategy for estimating the energy used per day: we assume that a person needs two small electric heaters to get warm for six months per year .

Consumption for hot air is 24 kWh per day per person.

Living in luxury: the patio heater at home

Consumes 15 kW. If used for four hours per day for three months, you use an extra 15 kWh per day.

Cooling

Air-conditioning. In countries where the temperature gets above 30 °C, air-conditioning is seen as a necessity. Britain has, however, little need for air-conditioning.

A window mounted electric air-conditioning unit consumes around 0.6 kW of electricity for more than 2 kW of cooling. If it is used 12 hours per day, 30 days per year, its average consumption will be 0.6 kWh/d.

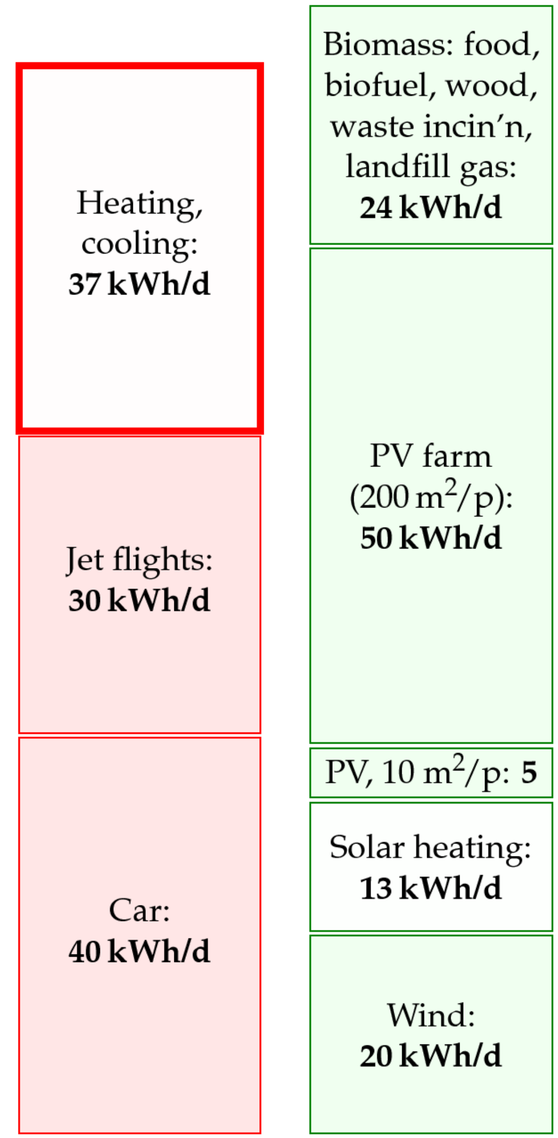
Fridge and freezer. Consumption of around 20 W on average, that's roughly 0.5 kWh/d in average.

We conjecture that the estimated energy cost of cooling is around 1 kWh/d/person.

Total heating and cooling

37 kWh/d per person (12 for non-air heating; 24 for hot air and 1 for cooling)

Rough estimates are compliant with national statistics. Nationally, the average *domestic* consumption for space heating, water and cooking is 21 kWh per day per person. In the *service sector*, it is 8.5 kWh/d/p. And for *workplace heating*, it is 16 kWh/d/p. Total: 45 kWh/d per person. Answer close to our guess.



Technical notes on heating buildings

In a perfectly sealed and insulated building, heat would remain forever and there would be not need for heating. Two dominant reasons why buildings lose heat are:

1. **Conduction.** Heat flowing through walls, windows and doors

2. **Ventilation.** Hot air trickling out through cracks, gaps and deliberate ventilation ducts.

In standard models for heat loss, both these heat flows are proportional to the temperature difference between the air inside and the air outside.

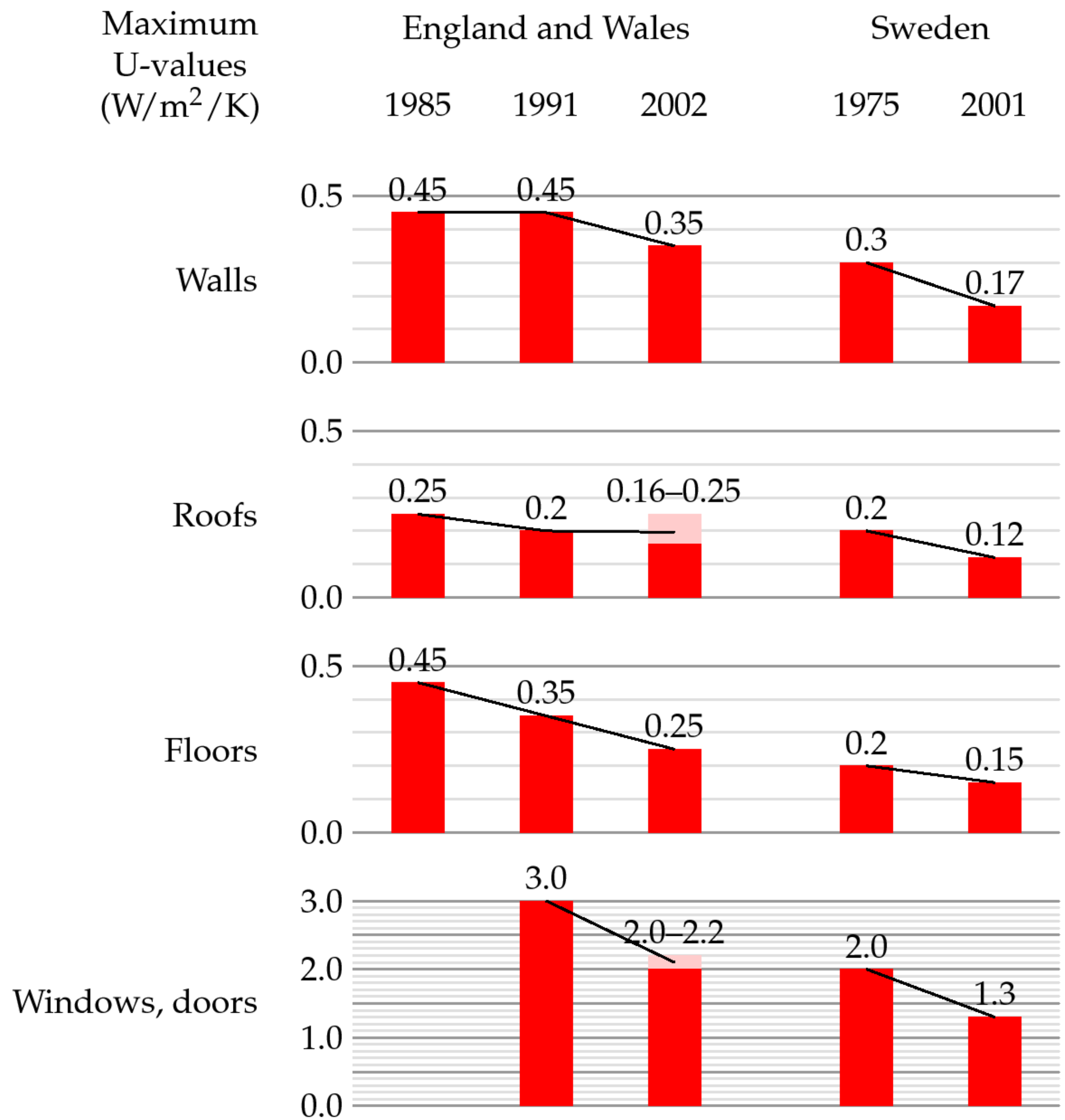
Conduction loss

Product of three things: (i) area of the wall (ii) a measure of conductivity known as "$\mathcal{U}$-value" or thermal transmittance, usually expressed in W/m^2/K and the temperature difference (ΔT).

$$\boxed{\text{power loss} = \text{area} \times \mathcal{U} \times \Delta T}$$

$\mathcal{U}$-values of objects that are in series (e.g., wall and its inner lining) can be combined the same way that electrical conductances combine:

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


Maximum
U-values
(W/m²/K)
England and Wales
Sweden
1985
1991
2002
1975
2001
Walls
0.45
0.45
0.35
0.3
0.17
Roofs
0.25
0.2
0.16–0.25
0.2
0.12
Floors
0.45
0.35
0.25
0.2
0.15
Windows, doors
3.0
2.0–2.2
2.0
1.3
0.5
0.0
3.0
2.0
1.0

Ventilation loss

Product of (i) the number of changes N of the air per hour, (ii) the volume V (in m^3) of the space (iii) the heat capacity C of the air (1.2 kJ/m^3/K) and (iv) the temperature difference ΔT between the inside and the outside.

$$\underset{\text{(watts)}}{\text{power}} = C\frac{N}{1\text{h}}V(\text{m}^3)\Delta T(\text{K}) = \frac{1}{3}NV\Delta T$$

Typical values for N: 2 for kitchen, 2 for bathroom, 1 for lounge, 0.5 for bedroom.

Recommended *minimum rate of air exchange* between 0.5 and 1 for providing adequate fresh air for human health, for safe combustion of fuels and for preventing building damage from excess moisture.

Energy loss and temperature demand

Total energy loss for one period = Something $\times \int_{\text{period}} \Delta T(t) dt$

where:

[A] Something is the sum of all area $\times\ \mathcal{U}$ (roofs, walls, windows) and of $\frac{1}{3}NV$. Something is often called the **leakiness** of building or its *heat-loss coeffient*

[B] $\int_{\text{one year}} \Delta T(t) dt$ is often called the **temperature demand** over one year. Often expressed as a number of "degree-days".

Temperature demand in Cambridge in 2006 for different thermostat settings: