8. Hydroelectricity

Hydroelectric plants transform the gravitational power of rainfall into electricity $\Rightarrow$ For hydroelectricity, you need altitude and rainfall.

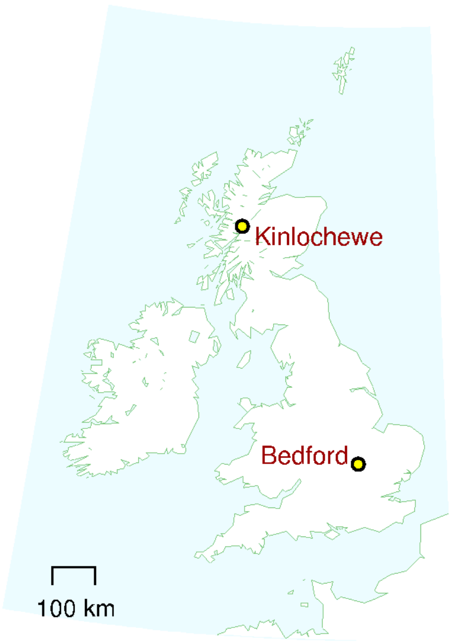
The upper limit on the amount of energy that can be extracted from the gravitational power of rainfall over area A in one year:

$$\boxed{\int_A \text{rainfall}(a) \times \rho_{water} \times h(a) \times g \;\; da}$$

where rainfall(a) is the rainfall (in m per year) at location a, $h(a)$ is the altitude of location a (in m), ρ_{water} is the density of water (1000 kg/m^3) and g the strength of gravity (10 m/s^2).

Hydropower in Britain

Assumption: We divide Britain into two areas: the lowlands (South of Britain) and the highlands (North of Britain). We assume the rainfall in every part of the lowlands (highlands) is equal to the rainfall in Bedford (Kinlochewe).



Question: What is the upper limit of power (in W/m^2 and in kWh per day per person) that can be generated by hydroelectricity in Britain?

Data: Population of 60 million Brits, 162,000 km^2 of lowland areas, rainfall in Bedford 584 mm per year, average lowland altitude above sea-level is equal to 100 m, 78000 km^2 of highland areas, 2278 mm of rainfall per year in Kinlochewe and average highland altitude is 300 m above sea-level.

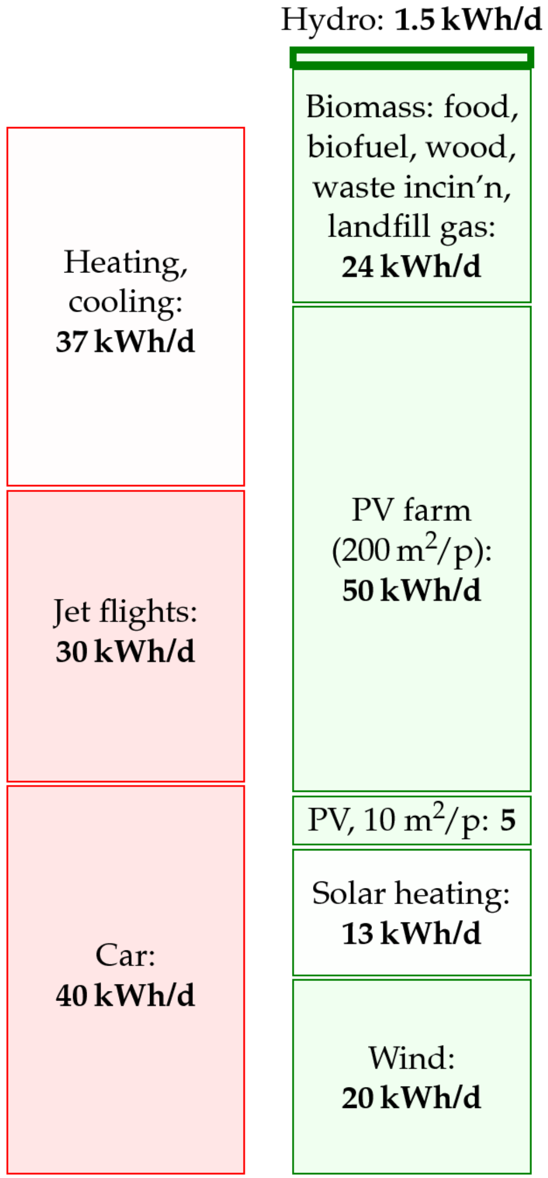
Power in W/m^2 in the lowlands: $\frac{0.584 \times 100 \times 1000 \times 10}{3600 \times 24 \times 365} \simeq 0.019\ W/m^2$.

Power in W/m^2 in the highlands: $\frac{2.278 \times 300 \times 1000 \times 10}{3600 \times 24 \times 365} \simeq 0.216\ W/m^2$.

Power in W/m^2 in Britain: $\frac{0.019 \times 162000}{162000+78000} + \frac{0.216 \times 78000}{162000+78000} \simeq 0.09\ W/m^2$.

Power in kWh/d per person: $\frac{0.09 \times 4000 \times 24}{1000} \simeq$ 8 kWh/d per person.

Estimate of plausible practical limit? 20% of the upper limit ⇒ around 1.5 kWh/d per person can be generated by hydropower.
Actual power from hydroelectricity in the UK is 0.2 kWh/d per person.



The Three Gorges Damp on the Yangtze River

Maximum generation capacity is 22,500 MW. China has a population of 1,344,130,000. Assuming that the dam always operates at full capacity, it will generate in kWh/d per person for the people of China: $\frac{22500 \times 10^6 \times 24}{1000 \times 1344130000} \simeq$ 0.40 kWh/d per person.

9. Light

Four main types of electrical lamps:

Incadescent lamp. A filament wire is heated to a high temperature by an electric current passing through it, until it glows. Note that a *halogen lamp* is an incandescent lamp that has a small amount of a halogen gas added.

Fluorescent lamp. Electricity is used to excite mercury vapor. The excited mercury atoms produce short-wave ultraviolet light that then causes a phosphor to fluoresce, producing visible light.

Sodium-vapor lamp. Gas-discharge lamp that uses sodium in an excited state to produce light. Used for street lighting (yellow color).

Led lamp. Solid-state lamp that uses light-emitting diodes.

Luminous efficiency

Luminous efficiency is a measure of how well a light source produces light. It is the ratio of luminous power (the perceived power of light) to power. It is expressed in lumens per watt. When expressed in dimensionless form, this value may be called overall luminous efficiency or simply the lighting efficiency.

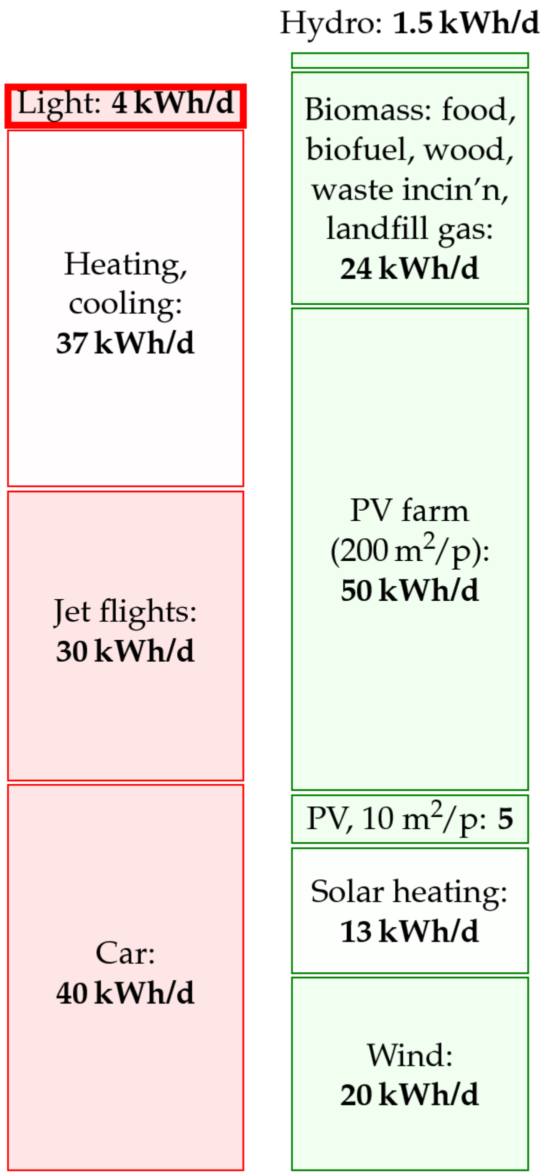
Example of luminous efficiency:

Type	Lumi. eff. (lm/W)	Overall lumi. eff.
Candle	0.3	0.04%
Tungsten incadescent	5-17.5	0.7-2.6%
Fluorescent - best	80-100	12-15%
Low pressure sodium lamp	100-200	15-29 %
LED - best for now	69.0 - 93.1	8.1 - 12%
LED - theoretical limit	260.0-300.0	38.1-43.9%
Ideal monochr. 555 nm source	683	100%

Estimating the amount of power for lightning

Assumptions. Every home has (i) 10 incandescent lights of 100 W used 5 h per day and (ii) 10 low-energy lights of 10 W used 5 h per day. We also assume an average of two people living in each home and that lighting workplaces, hospitals, schools and other buildings requires half the amount of power used for lighting homes.
$\Rightarrow$ Power for lighting:

$$\frac{10 \times (110) \times 5}{1000} \times \frac{1}{2} \times 1.5 \simeq \text{4 kWh/d per person}$$



What about street lights and lights on cars?

Street lights. Lighting motorways in Wallonia consumes 105,000 MWh per year. Wallonia has a population of 3,5 million people. That's $\frac{105000 \times 10^6}{1000 \times 365 \times 3.5 \times 10^6} =$ 0.08 kWh/d per person $\Rightarrow$ seems that neglecting street lights was a reasonable assumption, especially given the very generous lighting of motorways we have in Wallonia.

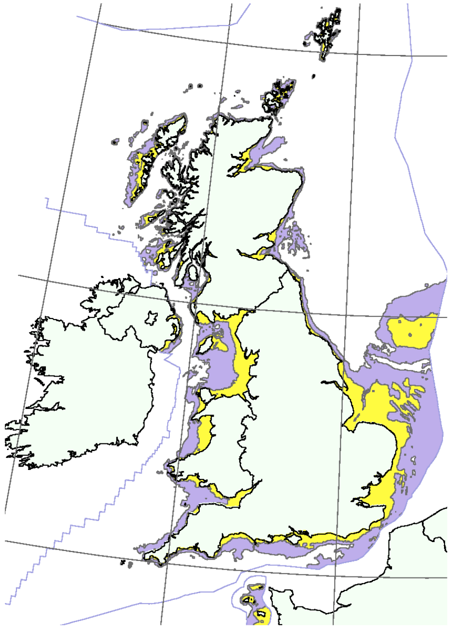
Car lights. Assuming that (i) a car has four lights totalling 100 W, (ii) the efficiency of the motor is 25%, (ii) the efficiency of the generator 60%, (iii) the lights are always switched on and (iv) a person uses a car one hour per day. That's $\frac{100}{0.6 \times 0.25 \times 1000} \simeq$ 0.6 kWh/d per person.

8. Offshore wind

At sea, winds are stronger and steadier than on land. Offshore wind farms in the UK have an estimated power per unit area of around 3 W/m^2 (50% larger than the power per unit area of land-based wind farms). We will assume that this is an appropriate figure for all offshore wind farms in the UK.

To estimate the area of sea that could be covered by wind farms, we distinguish between **shallow offshore wind** (depth less than 25 m) and deep offshore wind. We limit **deep offshore wind** to places where the depth is less than 50 m.

Deep offshore wind is at present not economically viable.



UK territorial water with depth less than 25 m (yellow) and depth between 25 m and 50 m (purple).

Shallow offshore

Shallow area around 40,000 km^2 $\Rightarrow$ average power from shallow wind farms occupying the whole of this area is $40,000 \times 10^6 \times 3 =$ 120 GW or $\frac{120\times10^9\times24}{1000\times60\times10^6} \simeq 48$ kWh/d per person.

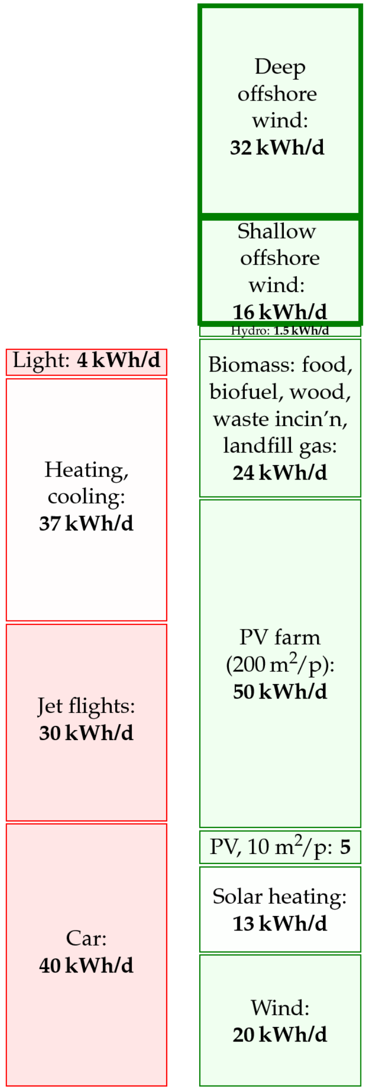
Because of requirements for fishing corridors and fishing areas, we must reduce the plausibly available area. We assume an available fraction of one-third (already an optimistic view !) $\Rightarrow$ Maximum plausible power 16 kWh/d per person.

How many 3 MW windmills are needed to generate 16 kWh/d per person? If we assume a load factor of 0.3, one windmill produces $\frac{3\times10^6\times24\times0.3}{1000\times60\times10^6} = 0.00036$ kWh/d per person $\Rightarrow$ more than 44,000 turbines are needed!!!

Deep offshore

The area with depths between 25 m and 50 m is about 80,000 km^2. If one third was to be used for wind farms, deep off-shore wind could deliver a power of 32 kWh/d per person.

Note: more than 88,000 3 MW turbines are needed to produce this power. At 2 million euros per MW installed, that would cost 528 billion euros.



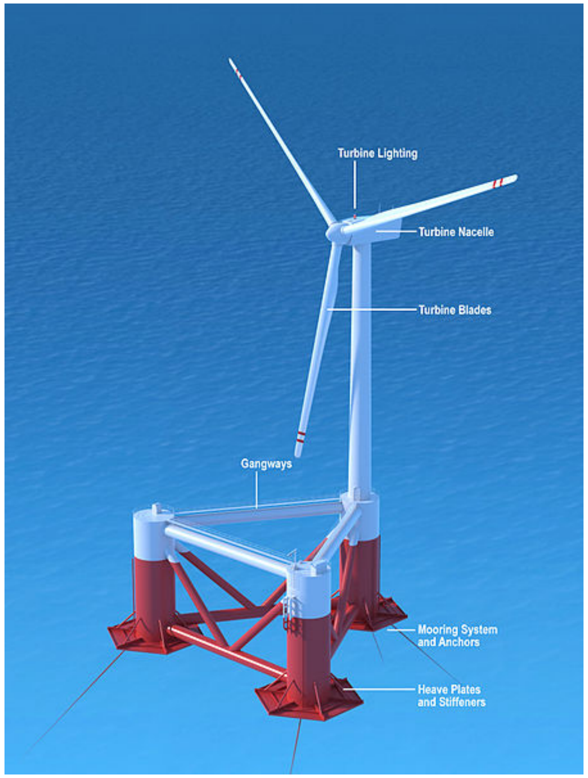
Cost to birds

Opponents to (offshore) wind farms often advocate that they kill too many birds!

Let us do the math. In Denmark, it has been estimated that 30,000 birds are killed every year by wind turbines. Installed wind capacity in Denmark is equal to 3,500 MW. By assuming that the number of birds killed per year grows linearly with the installed wind capacity, the 360 GW of wind capacity to be installed to generate 48 kWh/day would kill $30,000 \times \frac{360 \times 10^9}{3500 \times 10^6} \simeq 30,000 \times 102 \simeq$ **3 million birds**.

That sounds a lot until you know that cats kill 55 million birds per year in the UK.

Floating wind turbines: game changers?



Floating wind turbines can be installed in places where the sea is up to a few hundred meters deep. The technology is not yet fully mature. The picture above shows a 2 MW floating wind turbine installed 5 km offshore in Portugal.

11. Gadgets

How much power do TVs, computers, Xboxes, Playstations, vacuum cleaners, smart phones and other gadgets consume?

There are possibly four different **power consumption modes** for gadgets:
[A] On and active: e.g. when a sound system is actually playing sound
[B] On and inactive: the device is switched on but doing nothing.
[C] Standby: the device is explicitly asked to go to sleep or standby.
[D] Switched off: the device is completely switched off but is still plugged into the mains.

Note: Standby power, vampire power or phantom load are terms used to refer to the electric power consumed by electronic and electrical appliances while they are switched off or in standby mode.

Power consumption of various gadgets

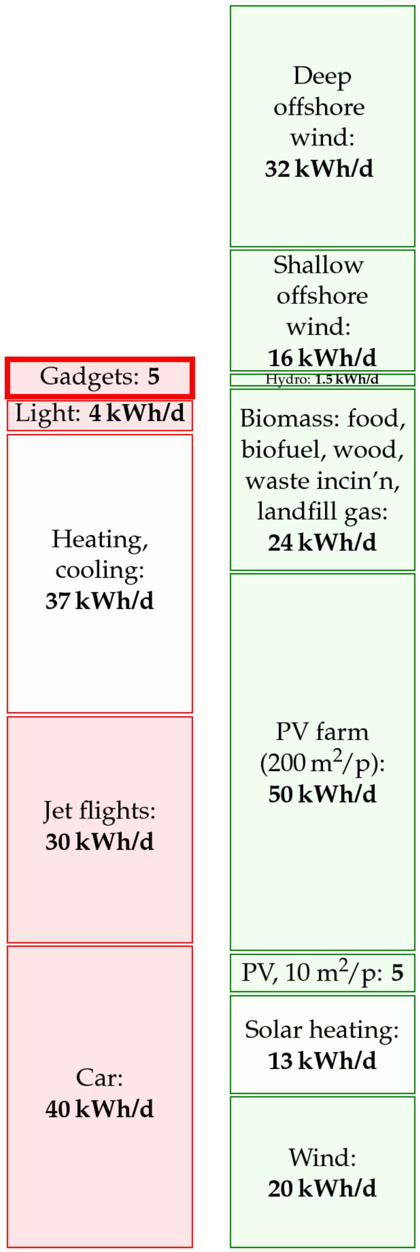
Gadget	on and active	on and inactive	standby	off
Computer box	80	55	2	2
Laser printer	500	17		
LCD display	34		2	1
Laptop computer	16	9	0.5	0.5
DVD player	7	6		
Xbox	160		2.4	
TV	100		10	
Mobile phone charger	5	0.5		
Clock on microwave oven	2			
Vacuum cleaner	1500			

Remember: non-stop use of 40 W per person $\Rightarrow$ 1 kWh/d per person.

A plausible use of these various gadgets for one person: (i) 5 hours of TV per day (100 W); TV on standby the rest of the time (10 W); (ii) laptop on 3 hours per day (16 W); (iii) 3 hours of Xbox per day (160 W); (iv) mobile phone charger on and active two hours per day (5 W) and on but inactive the rest of the day (0.5 W); (v) 20 minutes of vacuum cleaning per day (1500 W). This corresponds to an energy consumption of $(0.5+0.19)+0.048+0.480+(0.010+0.0105)+0.5 =$ 1,548 kWh/d.

Other gadgets such as mowers, bedside radio alarm-clocks, etc. have not been considered here. Furthermore, data-centres used by gadgets consume more than 0.5 kWh per day per person.

We estimate that **information systems and other gadgets** could easily use 5 kWh/d per person.



Mythconceptions

What should you answer to people who say:

There is no point in my switching off lights, TVs, and phone chargers during the winter. The "wasted" energy they put out heats my home, so it's not wasted.

Case I - The home is being heated by electricity which is directly converted into heat (ordinary bar fires, blower heaters). They are right but they should probably change their heating system.

Case II - The home is being heated by electricity but uses heat pumps. Heat pumps deliver 3-4 units of heat for every unit of electricity so they should switch off their electric appliances.

Case III - The home is heated by fossil fuels or biofuels. Better idea to switch off the gadgets. Indeed, 90% of the energy contained in fossil fuels or biofuels can be turned into heat for the home while if the fuel is burned in a power station to generate electricity, only around 50% of energy can be turned into electricity (and 8% of the electricity is also lost in the transmission system).

12. Wave

The **wave creation** mechanism:

SUN $\Rightarrow$ WIND (second-hand solar energy) $\Rightarrow$ WAVES (third-hand solar energy)

In open water, waves are generated whenever the wind speed is greater than about 0.5 m/s. The longer the wind blows, and the greater the expanse of water over which the wind blows, the greater the *height* of the waves stocked up by the wind.

If the wind has been caressing the water's surface for long enough, the speed of the waves equals the speed of wind.

Losses in viscosity are minimal: a wave of 9 seconds period would have to go around the world three times to loose 10% of its amplitude.

If waves travel in a particular direction and encounter objects that absorb their energy, the sea beyond the object is calmer. Waves deliver a power per unit *power per unit length* of coastline.

Questions? [A] How much energy is there in waves? [B] How can this energy be collected?

How much energy in waves?

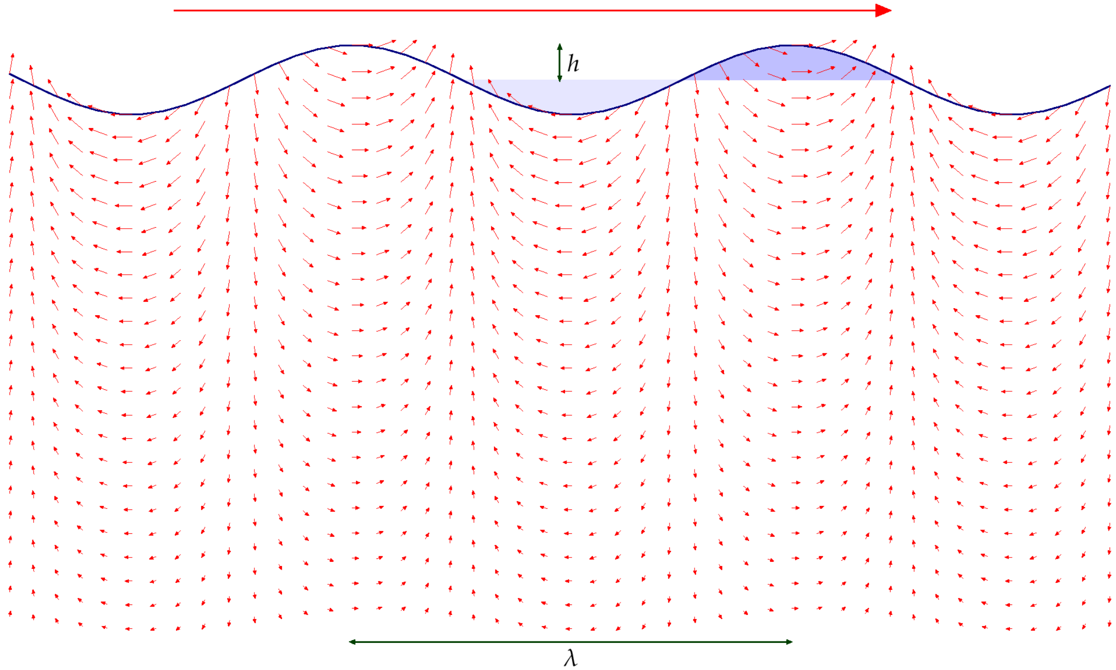
Energy comes in two forms: potential energy and kinetic energy. Potential energy is required to move all the water from the throughs to the crests. Kinetic energy is associated with the water moving around.

The energy in waves can be estimated from the period T of the waves (the time between crests) and an estimate of the height h of the waves.

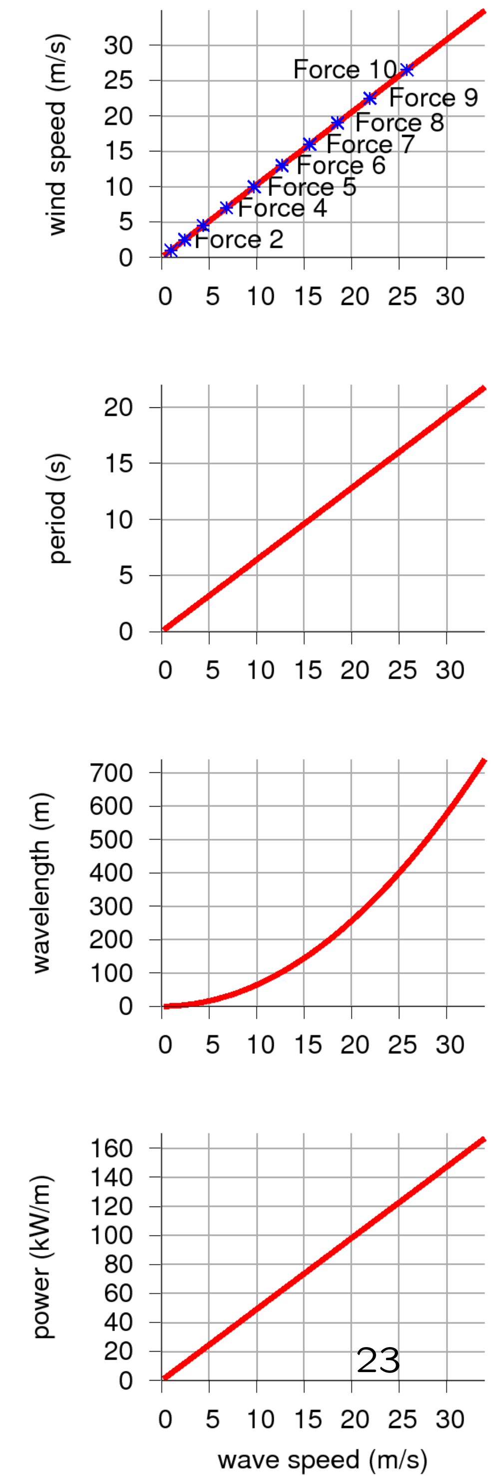
1. The relation between v and T. Result from the theory of deep-water waves:

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

Example: if $T = 10$, $v = 16$ m/s and wavelenth $\lambda = vT = 160$ m.



2. Estimating the potential energy in waves. Based on the figure above, the potential energy passing per unit time, per unit length, is $P_{\text{potential}} \simeq \frac{m^* g\overline{h}}{T}$ where m^* is the mass per unit length of the shaded crest and $\overline{h}$ the difference in height between the center of the shaded crest and the center of the shaded trough. We take as approximations: $m^* \simeq \frac{1}{2}\rho h(\lambda/2)$ and $\overline{h} \simeq h$. Since $\lambda = vT$, we have $P_{\text{potential}} \simeq \frac{1}{4}\rho g h^2 v$.

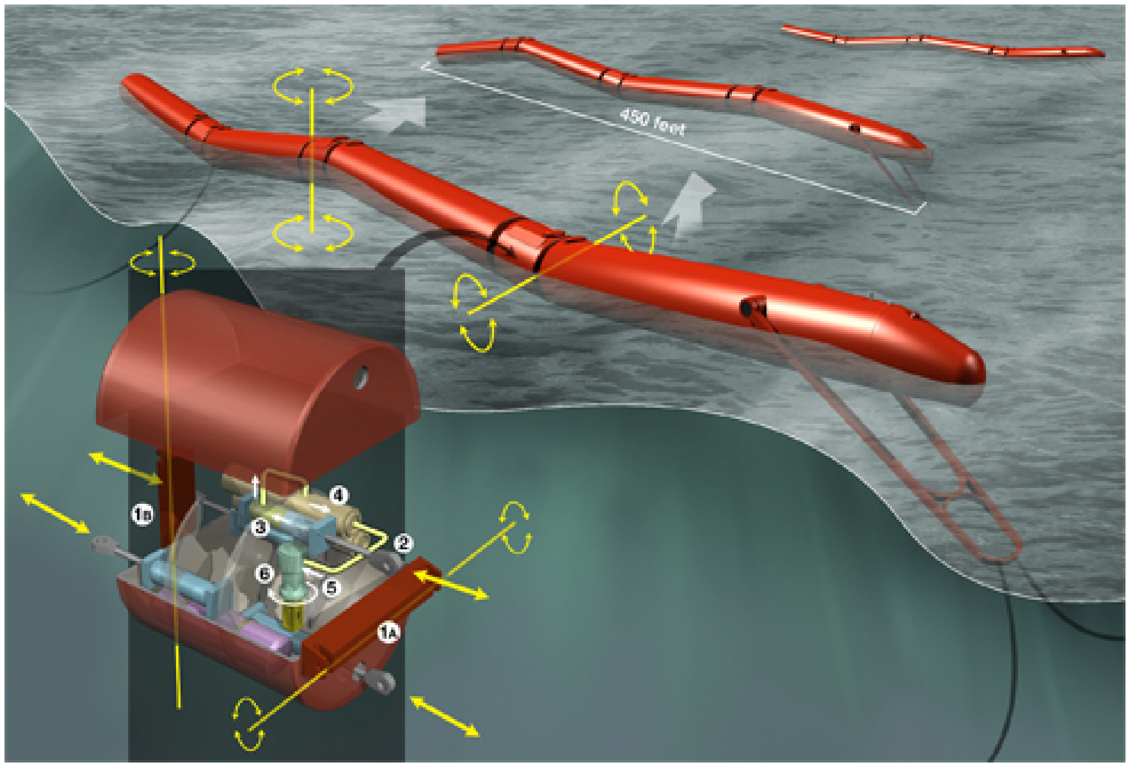


3. Estimating the kinetic energy of waves. Waves have kinetic energy equal to their potential energy. See e.g. (http://hyperphysics.phy-astr.gsu.edu/hbase/waves/powstr.html#c2) $\Rightarrow$ $P_{\text{kinetic}} \simeq \frac{1}{4}\rho g h^2 v$.

4. Final answer. Power per unit length of wave front is equal to $P_{\text{total}} = \frac{1}{4}\rho g h^2 v$ or $\frac{1}{8\pi}\rho g^2 h^2 T$.

Typical characteristics of waves from the Atlantic ocean: $T = 10$ s and $h = 1$ m $\Rightarrow$ $P_{\text{total}} \simeq 40$ kW/m.

Pelamis devices for collecting energy in deep-water

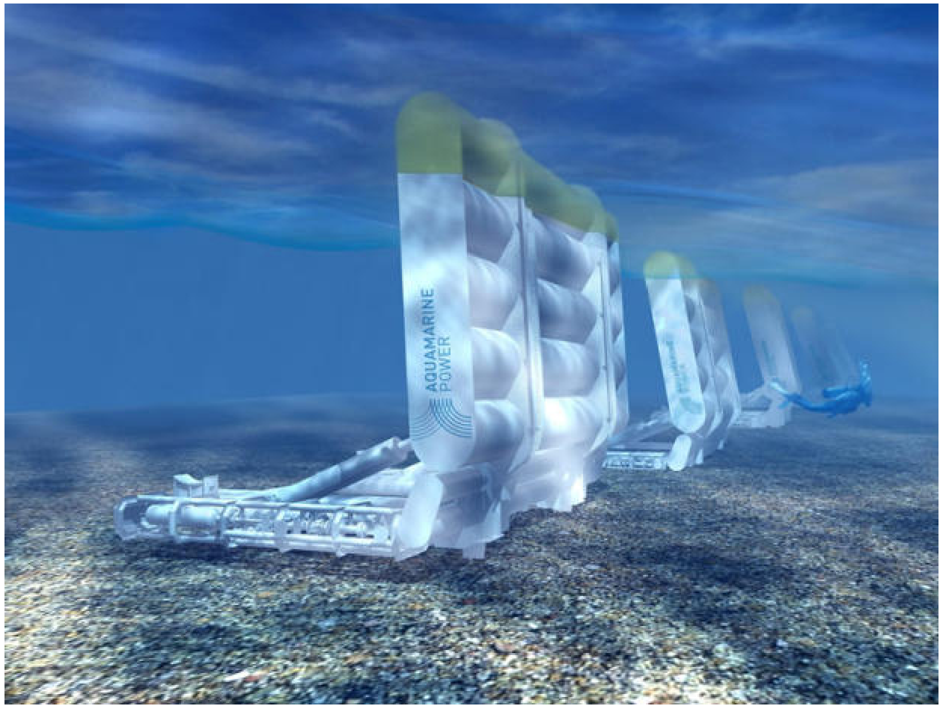


Each snake like device is 130 m long and made of four segments, each 3.5 m in diameter. Maximum power output is 750 kW. Each weighs 350 tons (without ballast) or 500 kg per kW (a 3 MW offshore wind turbine weights 500 tons or 170 kg per kW).

The waves make the snake flex, and these motions are resisted by hydraulic generators producing electricity. *Effective cross section of 7 m*, i.e., for good waves it extracts 100% of the energy that would cross 7 m.

On a wave farm, 39 devices in a row would face the principal wave direction, occupying an area of ocean about 400 m long and 2.5 km wide. The company says that such a wave farm could deliver about 6 kW/m in the Atlantic.

The Oyster for shallow water

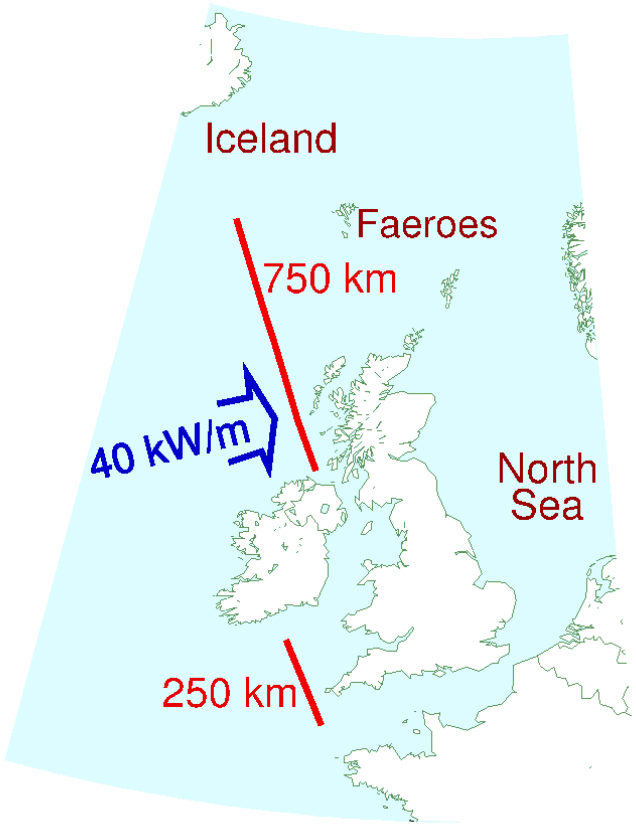


The power converter sways back and forth with the movement of the waves and this movement of the flap drives two hydraulic pistons that pump high-pressured water through three sub-sea pipeline to an onshore hydro-electric water turbine. The turbine then drives an electrical generator, which converts the wave energy into electricity.

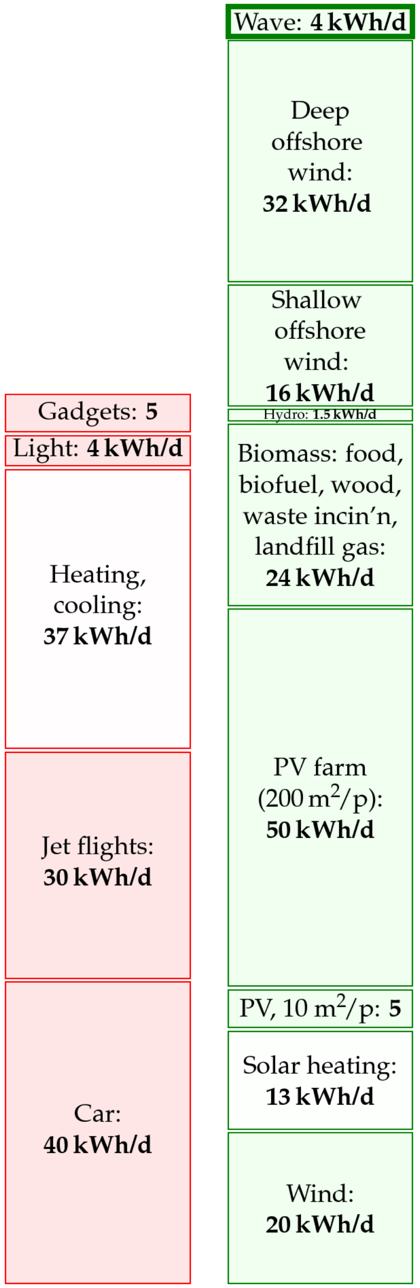
Problem with shallow waters: 70% of the energy in ocean waves is lost through bottom-friction as the depth decreases from 100 m to 15 m. However, it is still predicted that an Oyster would have a bigger power per unit mass of hardware than a Pelamis.

How much power for Britain from the waves?

Upper bound: 1000 kilometers of coastline with the Atlantic. The power of the Atlantic waves is about 40 kW/m. UK population is 60 million. 100% of the energy contained in water can be transformed into electricity. $\Rightarrow$ $\frac{40 \times 24 \times 1000 \times 1000}{60 \times 10^6} \simeq$ 16 kWh/d per person.



More realistic assumptions: 500 kilometers of coastline could be exploited (which is already a very generous assumption !!!); machines can be 50% efficient at turning incoming wave power into electricity (which is again a lot since Pelamis wave farms installed on the Atlantic are only expected to produce 6 kW/m) $\Rightarrow$ Power from waves = 4 kWh/d per person.



13. Food and farming

A moderately active person with a weight of 65 kg consumes food with a chemical energy of 2600 "Calories" per day. 1 food "Calorie" = 1000 chemist "Calorie" = 4184 joules $\Rightarrow \frac{2600\times4184}{3600\times1000} \simeq 3$ kWh per day.

Calories in big mac: 495 $\Rightarrow$ 0.6 kWh.

Questions: How much energy do we actually consume to get our 3 kWh per day?

Answer: If we put aside the cost of moving and packing food, we would have a 3 kWh per day for vegetarians. Otherwise, we need to analyze where the food comes from and how much energy has been used to produce it.

Energy cost of milk

Assumptions: 1 liter of milk per day per person; a typical dairy cow produces 16 liters per day; a cow weighs 450 kg and has similar energy requirement per kilogram to a human; cows are vegetarian; 670 calories in one liter of milk.

Questions: [A] How much energy is required to produce 1 liter of milk per day per person? [B] What is the ratio between the energy contained in a liter of milk and the energy needed to produce this liter of milk?

Answer: [A] $\frac{1}{16} \times \frac{450}{65} \times 3 \simeq$ 1.3 kWh/d per person.
[B] 670 calories $\simeq \frac{670 \times 4184}{1000 \times 3600} \simeq 0.78$ kWh $\Rightarrow$ the ratio is equal to 0.566 or, in other words, from an energy point of view milk production is 56% efficient.

Note: Estimate based on measured values is 1.5 kWh/d.

Energy cost of eggs

A "layer" eats 110 g of chicken feed per day with a metabolic content of around 3.3 kWh/kg. Layers yield 290 eggs per year on average. One egg contains 80 calories.

Questions: [A] How much energy is required to produce one egg per day per person? [B] What is the energy efficiency of egg production?

Answer: [A] $0.110 \times 3.3 \times \frac{365}{290} \simeq$ 0.45 kWh/d
[B] 80 calories $\simeq \frac{80 \times 4184}{1000 \times 3600} \simeq$ 0.092 kWh $\Rightarrow$ energy efficiency of egg production $\frac{0.092}{0.45} \simeq$ 19%.

Energy cost of meat

Data: (I) 240 grams of meat per day per person: one third chicken, one third pork and one third beef. (II) Time to rear a chicken $\simeq$ 50 days, a pig $\simeq$ 400 days and a cow 1000 days. (III) An animal is 66% meat. (IV) Calories/kg in this mix of meat: around 2000 $\simeq$ 2.32 kWh.

Questions: [A] How much energy per day per person for eating this meat? [B] What is the energy efficiency of producing this mix of meat?

Answer: [A] In order to eat x kg of an animal per day, we need $\frac{(x \times \text{number of days to rear an animal})}{\text{fraction meat in animal}}$ of kilos of this animal alive $\Rightarrow$ We need $\frac{0.080 \times 50}{0.66} \simeq 6$ kg of chicken, 48 kg of pork and 120 kg of beef, thus we need 174 kg of live animal. If their energy input per kg is similar to that of humans, the energy per person per day required to produce this meat is equal to $\frac{174}{65} \times 3 \simeq$ 8 kWh/d per person.

[B] Energy efficiency $= \frac{2.32}{8 \times \frac{1000}{240}} \simeq 0.07$.

Question: Is answer [B] an argument in favor of vegetarianism?

Probably, but don't jump to conclusions too quickly! For example, in some places there are no better ways to capture the power of sunlight than sheep!!!

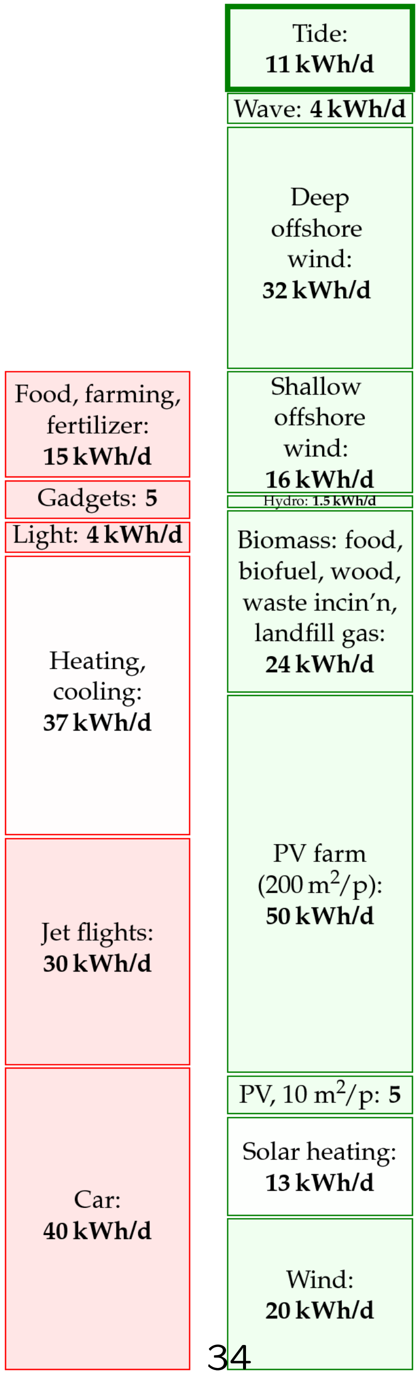
Estimating the power required to make food for one person

We assume a diet of 3 kWh per day with (i) 1 liter of milk, (ii) two eggs, (iii) 240 g of meat and, (iv) where the rest of the energy income would be from vegetables.

Energy in i+ii+iii $= 0.78 + 2 \times 0.092 + 0.240 \times 2.32 \simeq 1.5$ kWh $\Rightarrow$ Energy in iv $= 1.5$ kWh

Energy for producing i+ii+iii+iv $= 1.5 + 1 + 8 + 1.5 =$ 12 kWh/d

To this number, we need to add the embodied energy in fertilizers (2 kWh per day per person) and the energy for farm vehicles, machinery, heating (greenhouses), lighting, ventilation and refrigeration (0.9 kWh per day according to UK estimates) $\Rightarrow$ Total power $\simeq$ 15 kWh/d per person.



What would you answer to people who say:

$\boxed{\text{The energy footprint of food is so big that it's better to drive than to walk.}}$

The answer depends on many things: the type of food you are eating (are you a vegetarian? Do you eat cats (which mostly eat meat)? etc.), the energy cost of driving, the additional amount of energy spent on walking, etc.