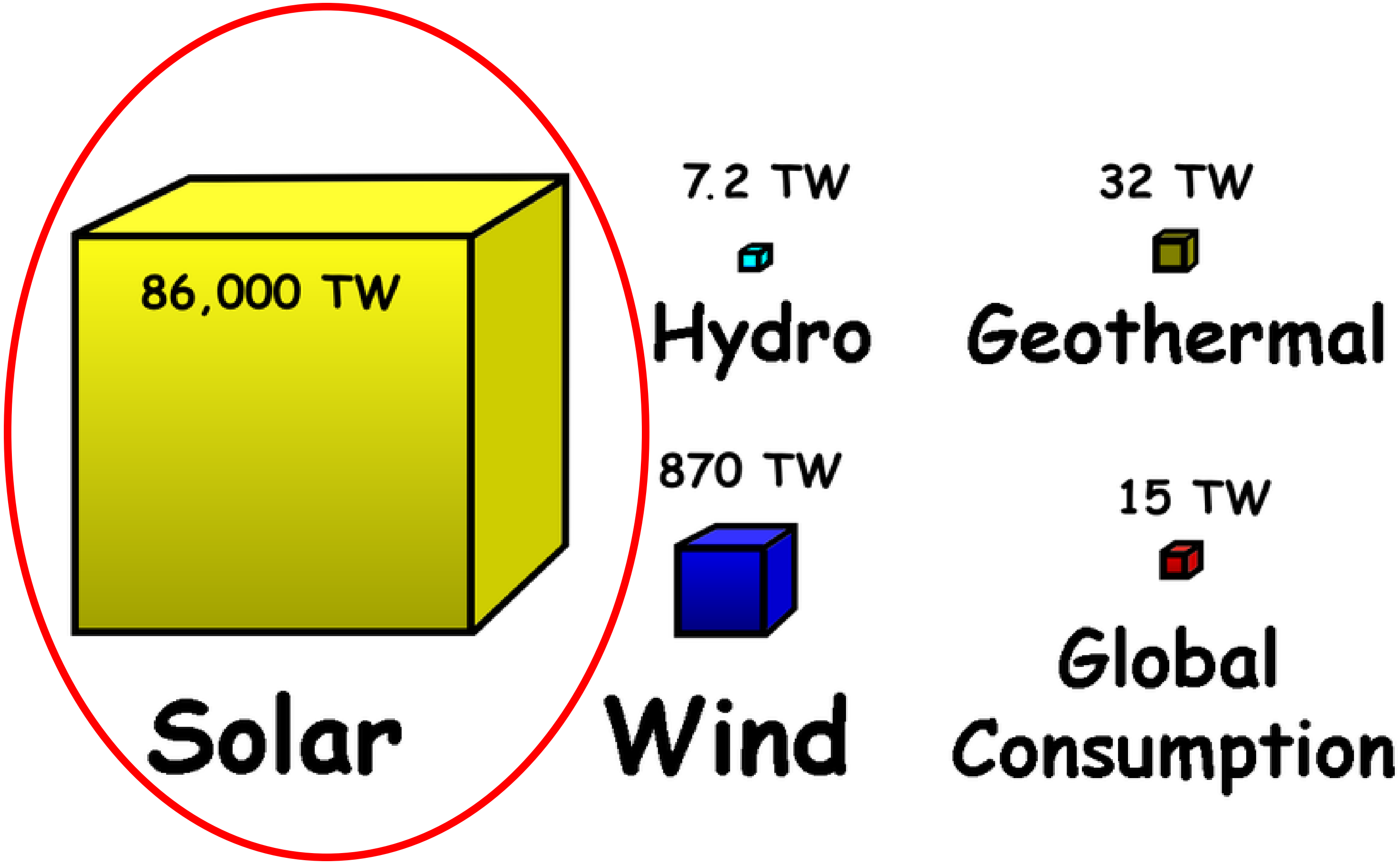
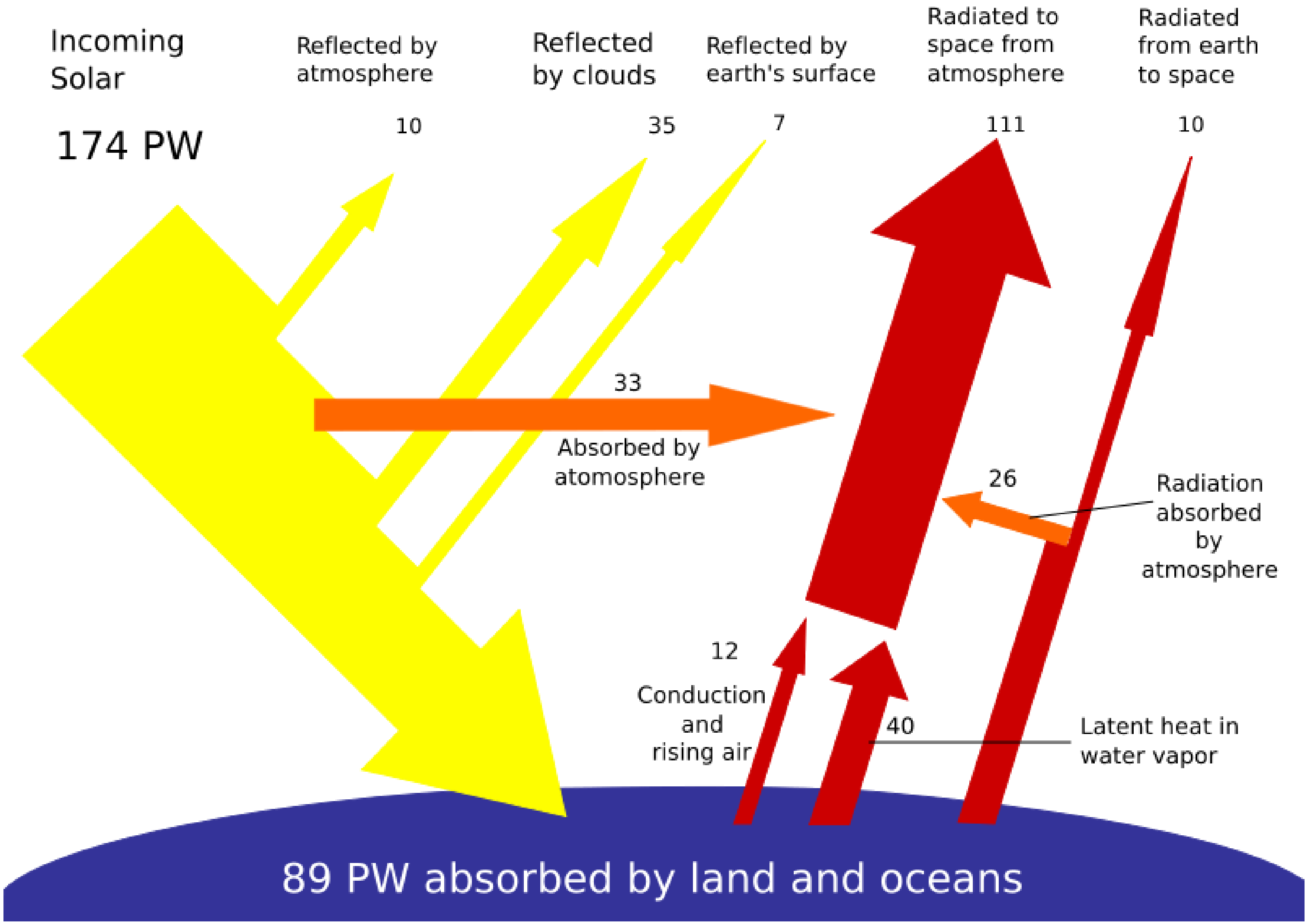
Solar power (direct)

-- the “greenest” of all energy sources, a one that dwarfs all other available energy sources combined (including those who are “transformed” forms of solar energy).





Breakdown of the incoming solar energy

SOME IMPORTANT DEFINITIONS:

SOLAR CONSTANT: the total power of solar electromagnetic radiation that falls on a unit surface area at a vertical angle above the Earth atmosphere: s = 1.37 kW / m^2 (it's the average value)

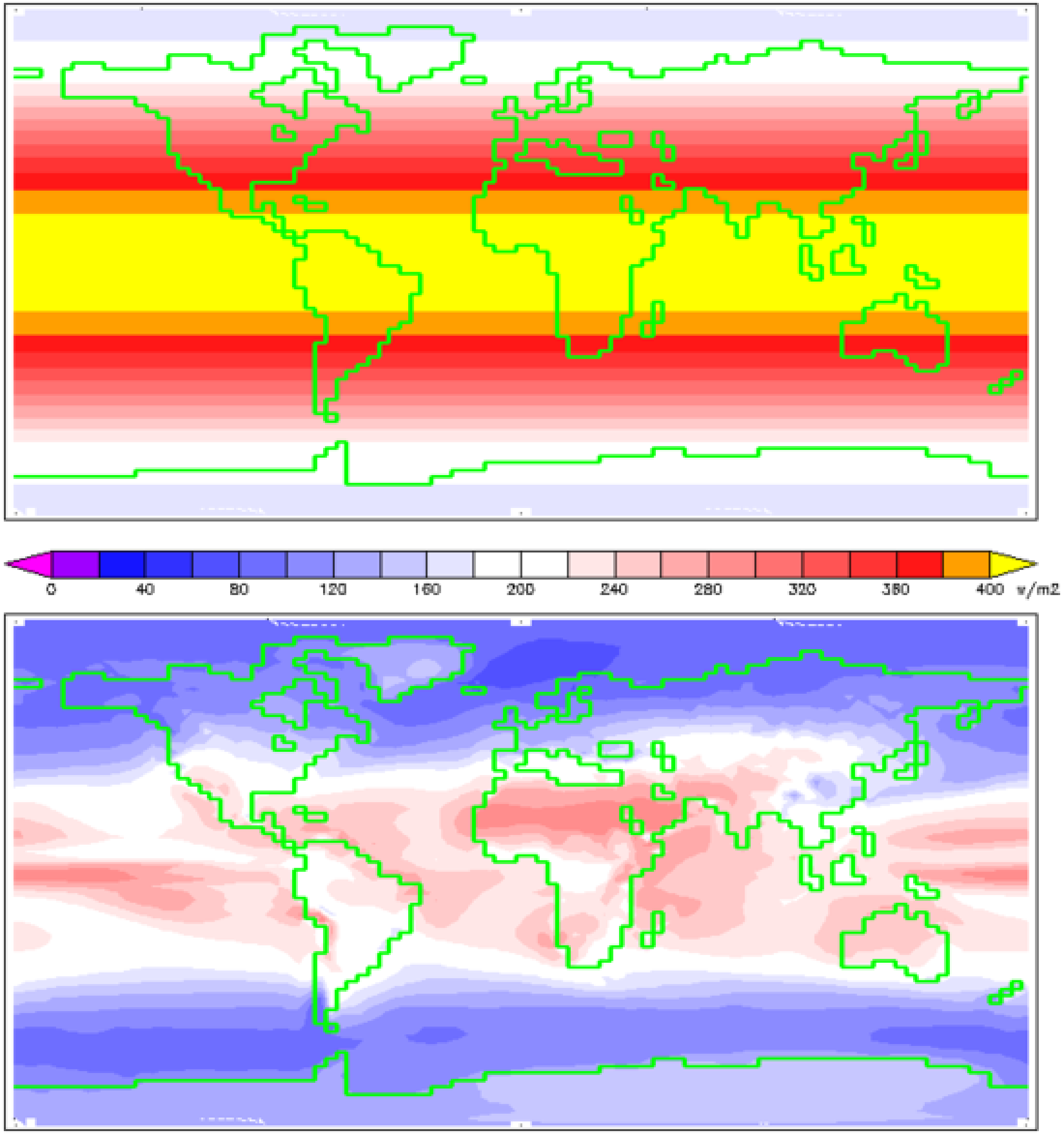
The effective value at the Earth surface on a sunny day is 0.8 – 1.0 kW / m^2.

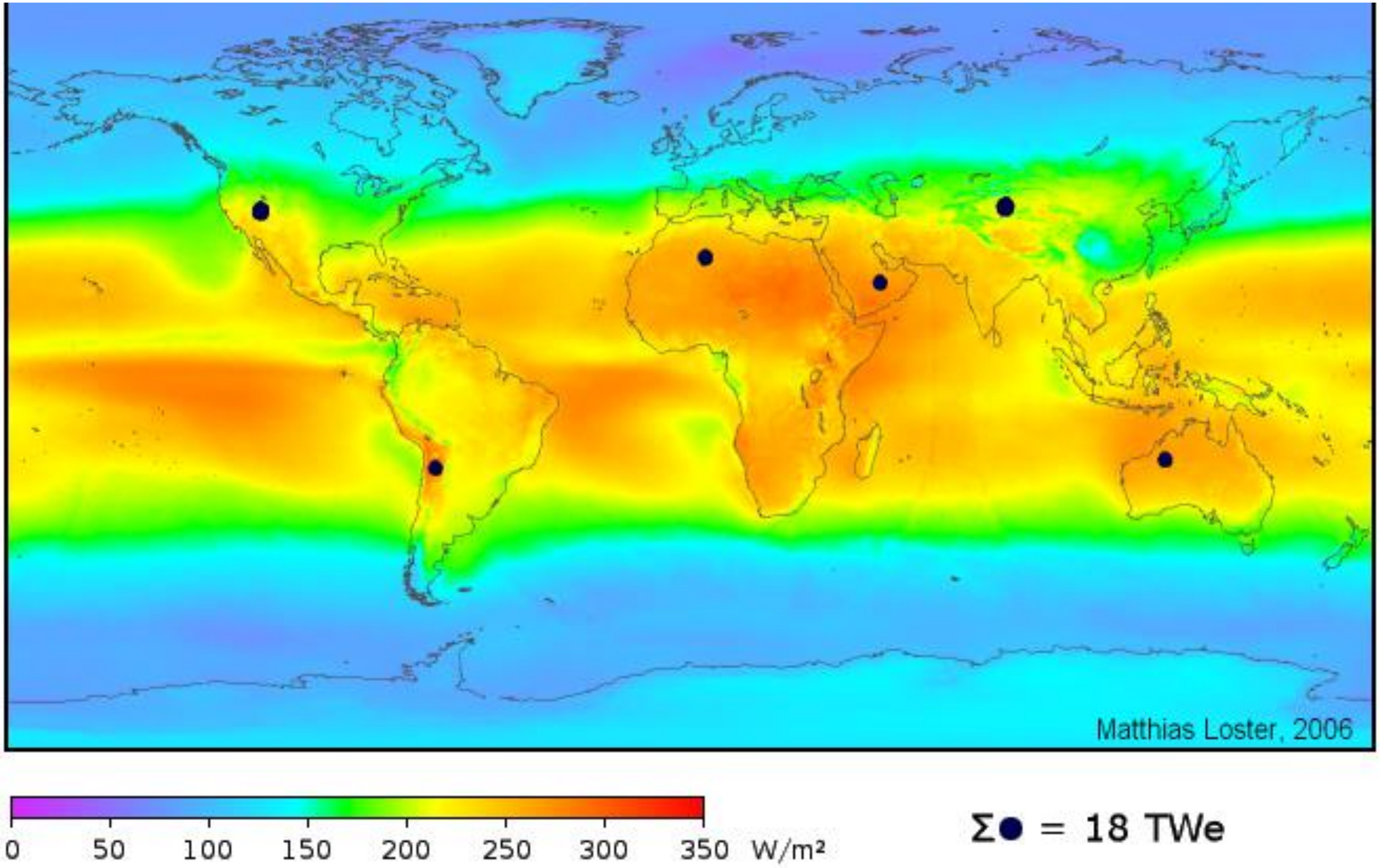
INSOLATION (not to be confused with *insulation,* or with *shoe insoles*): a measure of solar radiation energy received on a given surface area in a given time. It is commonly expressed as a 24-hour average irradiance in Watts per square meter (W/m^2)

Annual insolation:

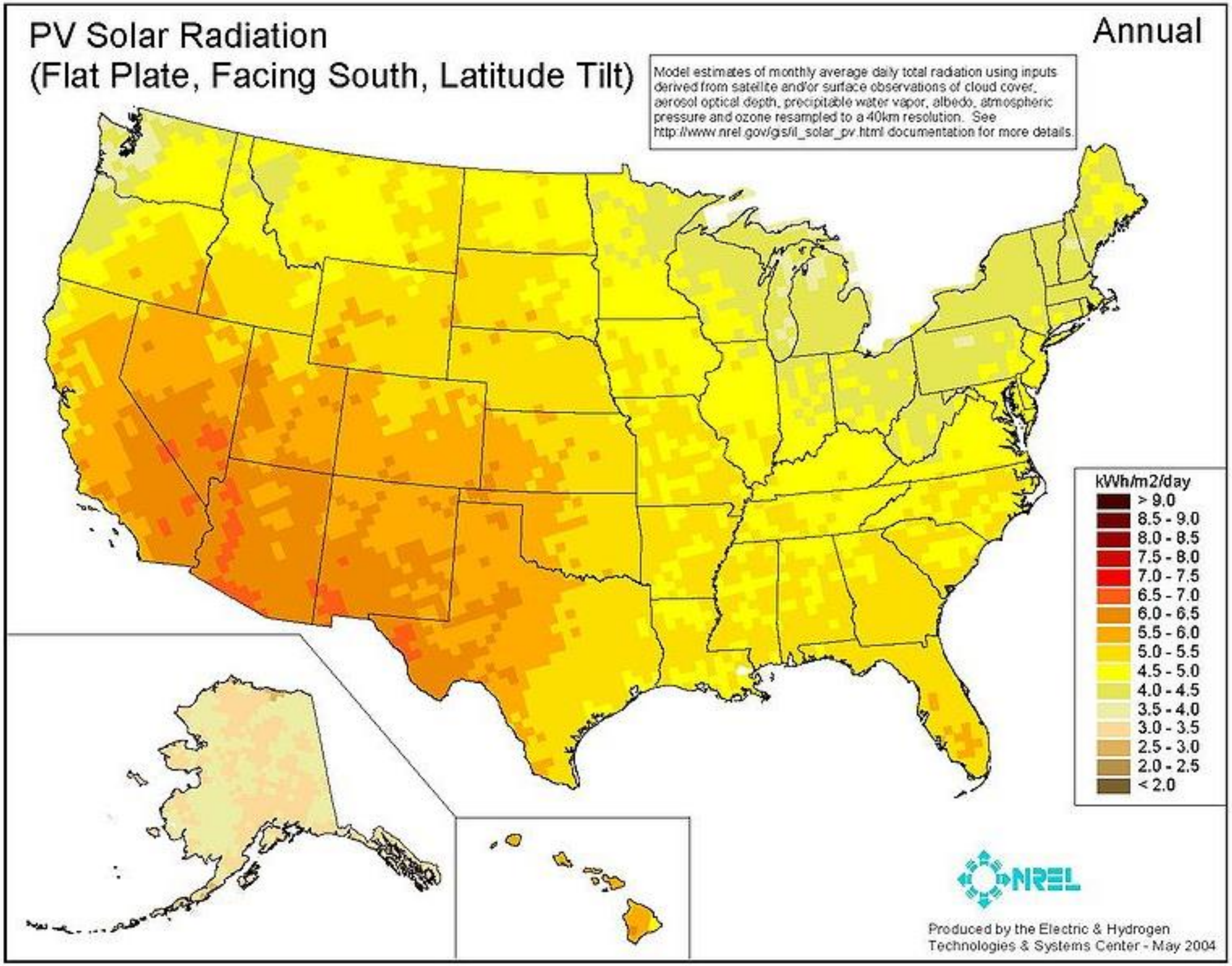
-- at the top of the
Earth atmosphere

-- at the Earth surface





Average insolation showing land area (small black dots) required to replace the world primary energy supply with solar electricity. 18 TW is 568 Exajoule (EJ) per year. Insolation for most people is from 150 to 300 W/m² or 3.5 to 7.0 kWh/m²/day.



PV Solar Radiation
(Flat Plate, Facing South, Latitude Tilt)

Annual

Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_solar_pv.html documentation for more details.

Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

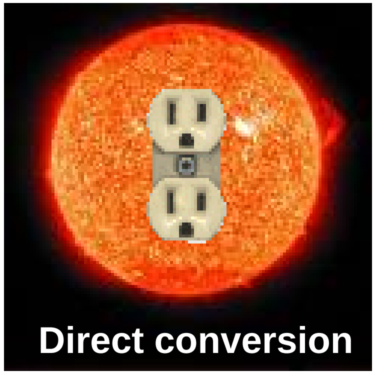
Methods of harnessing solar energy:

We can divide them into two groups:

- The conversion of solar power to electrical power;
- All other methods – many of them are as old as human civilization – for instance, agriculture or horticulture, or laundry drying. Rooftop water heaters or sun-tanning :o)) are more recent inventions

We will focus on the first group of methods, i.e., on generating "solar electricity".

There are two major methods of converting sunlight to electricity:



(a joke, of course)

-- direct conversion using photovoltaic cell panels; this method is used at all power levels, from single household installations up to multi-MegaWatt power plants.

-- methods known as "concentrating solar power" (CSP) or "solar thermal conversion". Essentially, they are a combination of the old existing technology (thermal engine, e.g., a steam turbine plus a generator) with new methods of generating heat from sunlight, not from fuel burning. CSP is used in the "high end" installations (tens or even hundreds of MWs) and medium-size ones, but not at the single-household level.

Since we already know a lot about thermal engines, we will first discuss the "solar thermal conversion" methods.

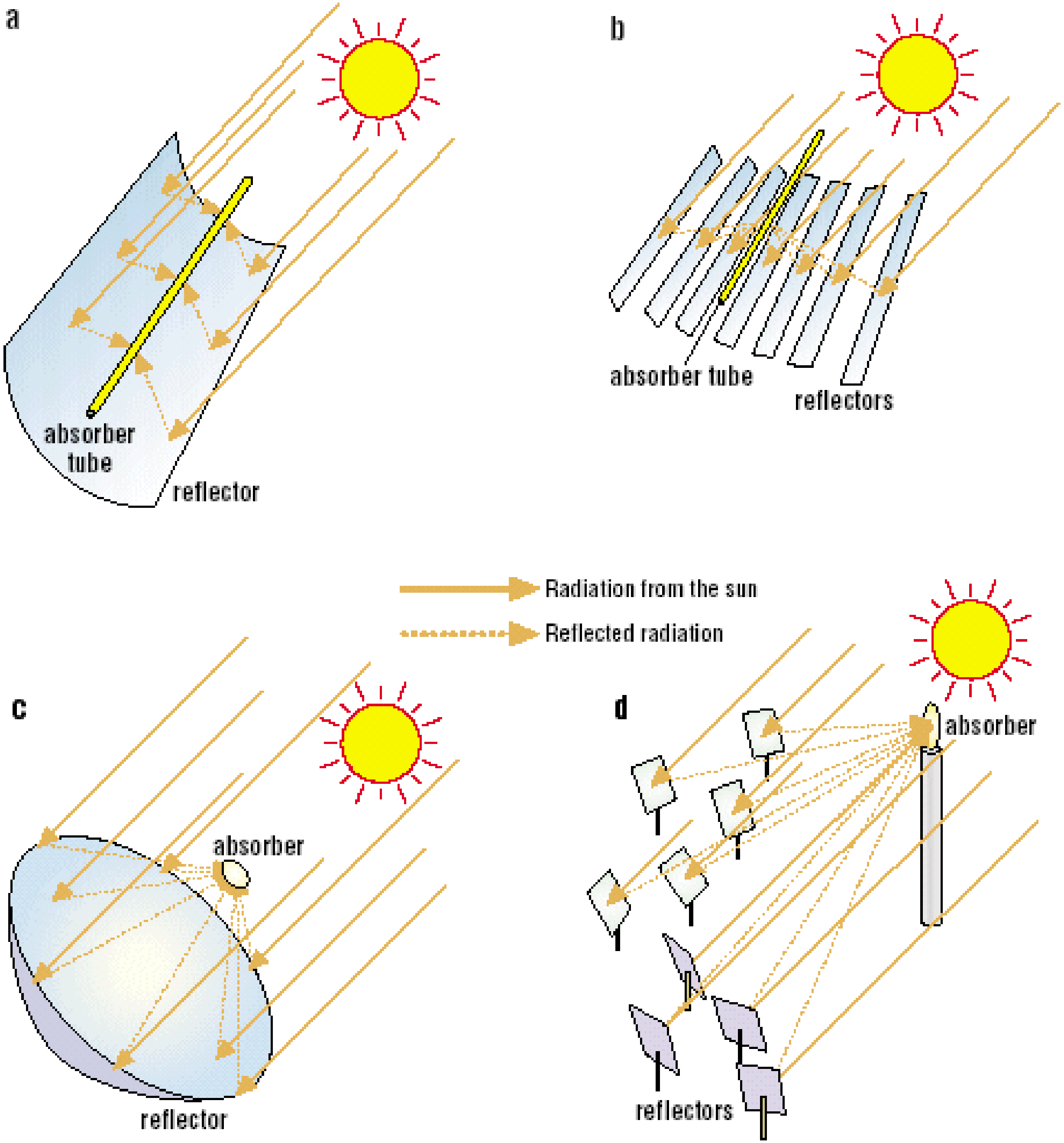
Types of sunlight collectors used in CSP plants:

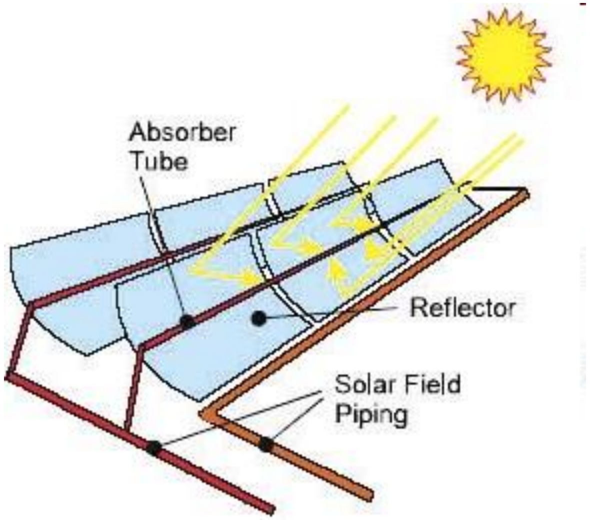
(a) Parabolic trough;

(b) The so-called “Fresnel mirror”; similar to (a), but somewhat cheaper.

(c) Parabolic mirror with a Stirling engine (medium power level);

(d) CSP tower technology, using flat mirors and a heat collector on a tower top.

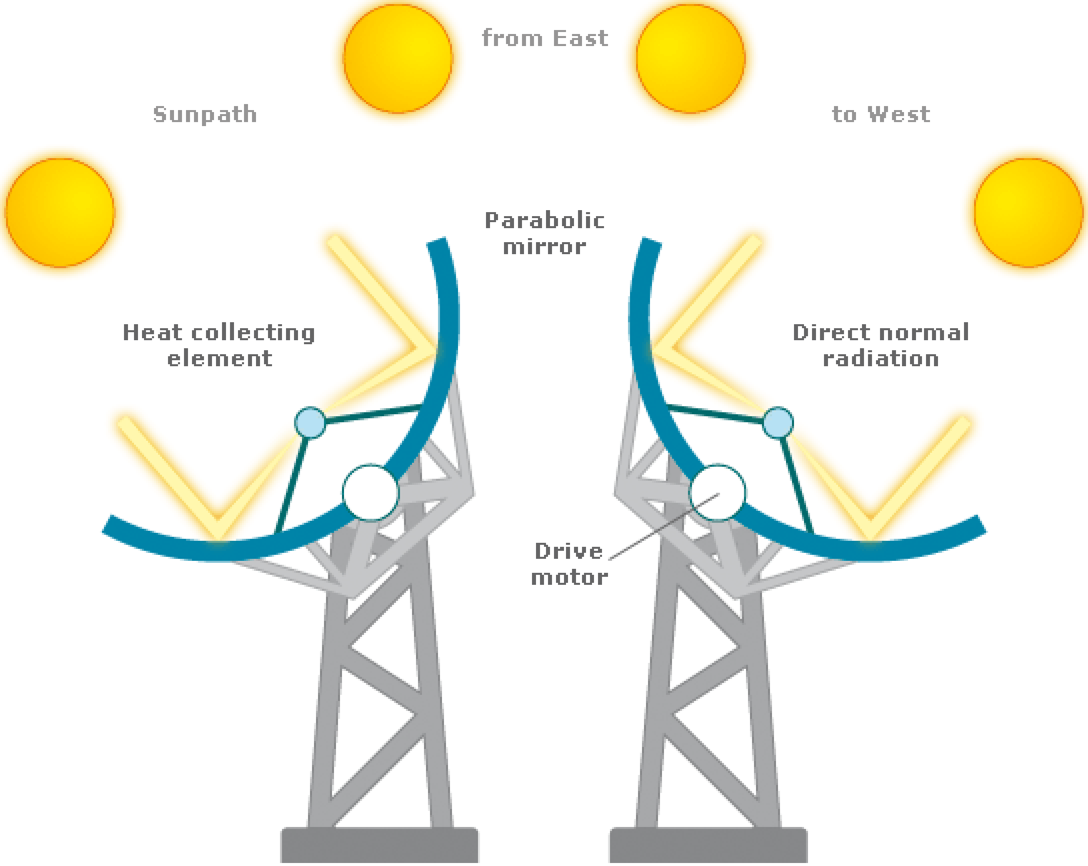




Explanation how a parabolic trough works.

A single parabolic trough unit.

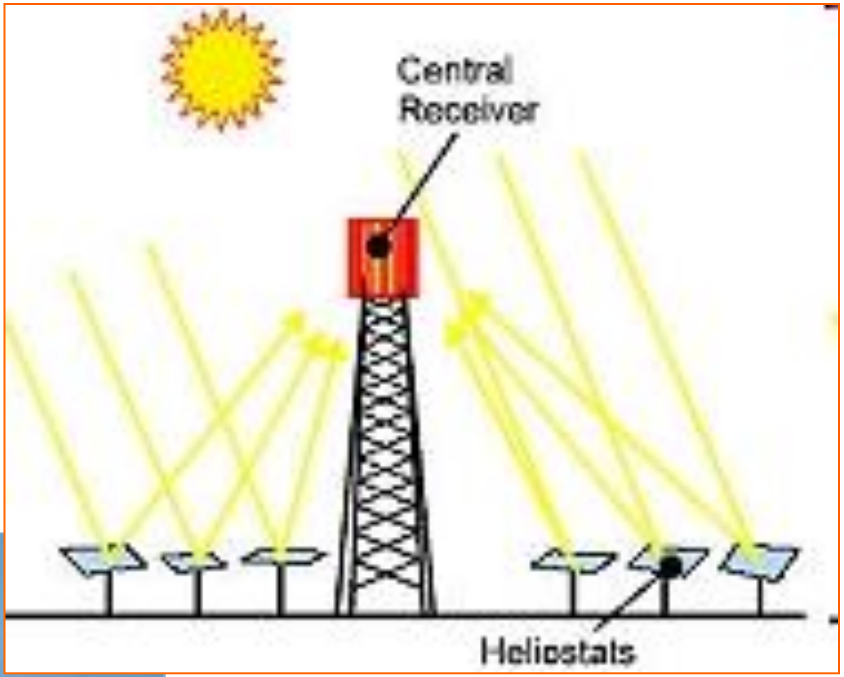
A large number of parabolic troughs arranged into rows in a multi-MW CSP plant.


from East
Sunpath
to West
Parabolic mirror
Heat collecting element
Direct normal radiation
Drive motor

The Fresnel mirror technology

CSP tower technology:

How it works →



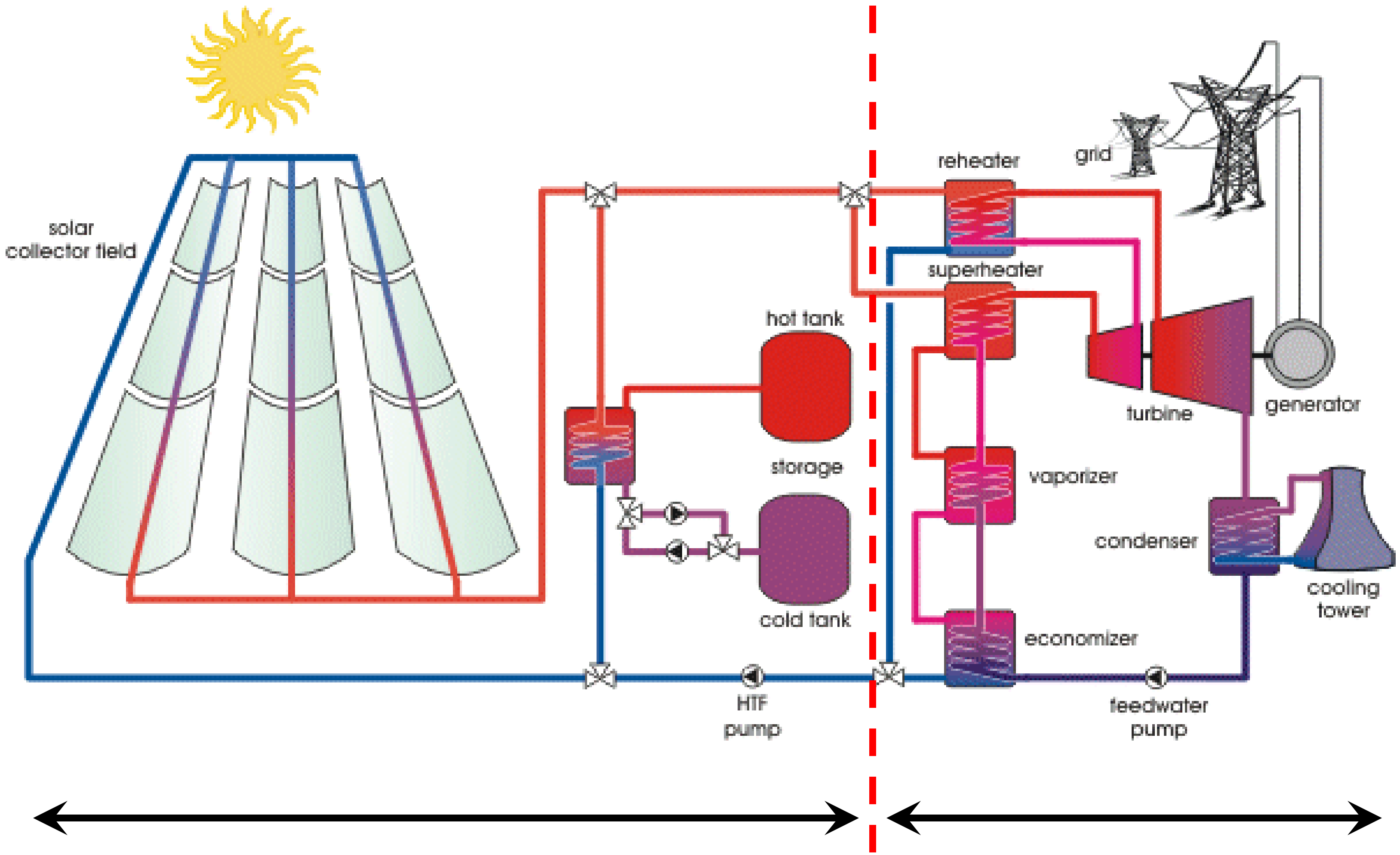
An existing power plant. On a misty day the beams from individual mirrors become visible, producing a spectacular effect!

One highly attractive aspect of CSP power plants: the capability of storing the daytime-collected thermal energy.

There are several possible storage schemes – one that is receiving strong attention is the use of huge tanks filled with certain salts. The solar heat is used for melting the salt. Later, during the heat recovery phase, the salt solidifies, releasing a considerable amount of *latent heat* (it's called the *latent heat of fusion*).
The process is analogous to ordinary water freezing, in which a latent heat of 334 kJ/kg is given away by liquid water – however, water freezes at 0 centigrades.

CSP plants with heat storage can generate power for several hours after the sunset.

Schematic of a CSP plant with energy storage capability



“new technology” part: solar collectors and a tank system for storing thermal energy.

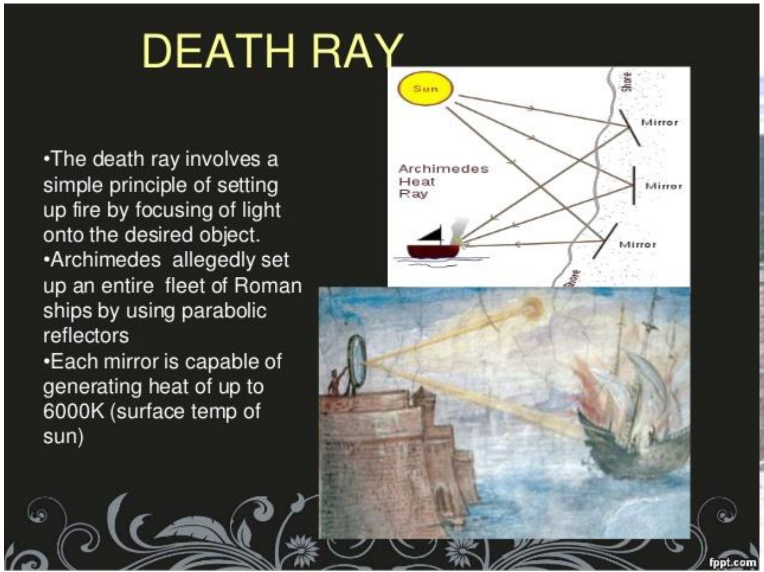
“old technology” part: a steam turbine plus Generator.

Concentrated Solar Power (CSP) plants

Concentrated Solar Power (CSP) plants convert thermal energy from the sun to electric power the same way thermal power plants do – the only difference is that in the latter the thermal energy is released by burning fuels.

In a CSP plant the sun rays are first focused, or “conce Archimedentrated”, on a heat-collecting element. One method is to put a boiler on a high tower, and place a large number of mirrors – called “heliostats” – on the field surrounding the tower. Each heliostat reflects the solar rays and directs them to the boiler (the same way as we send away flashes of sunlight using a “signal mirror” – as shown, e.g., in this Youtube clip; by the way, the thing the gentleman holds is not a cell phone, but a framed rectangular mirror looking very much like a cell phone).

By the way, the legend says that as many as 22 centuries ago, the Greek philosopher and inventor Archimedes used reflections from many mirrors focused on Roman galleys to set them afire – during the siege of the town Syracuse at Sicily by Roman fleet. At that time, they did not have mirrors similar to these we use today – the legend says that Archimedes used instead polished soldiers’ shields. This beautiful legend is over 1000 years old – but it is only a legend, tests carried out at modern times with as many as 400 participant holding replicas of highly polished ancient Greek shields showed that with such “heliostats” one could lit a bonfire 50 yards away, but not an object half a mile away.



DEATH RAY

- The death ray involves a simple principle of setting up fire by focusing of light onto the desired object.
- Archimedes allegedly set up an entire fleet of Roman ships by using parabolic reflectors
- Each mirror is capable of generating heat of up to 6000K (surface temp of sun)

So, the modern CSP tower plants work very much the same way as Archimedes did in the legend.

Concentrated Solar Power (CSP) plants with thermal storage

CSP plants have one very important “potential”. Namely, all energy collected during the sunshine hours needs not to be used right away – **some part of it may be stored to be used later!** After the sunset! It is very important! The hours after the sunset are still “peak hours”, during which the demand for electric power is really high.

But how to store thermal energy? In principle, it’s not very difficult. Take a body, either a solid or a liquid and warm it up with part of the energy collected during sunlight hours – and then, after sunset, start taking this energy away, use it for making steam, send this steam to the turbines, and you get your power.

Yet, there is a small problem… not even a small one. Namely, when you keep adding heat to your “storage body”, its temperature gradually increases – it will be proportional to the amount of the heat stored. In Week One, it was told that the amount of heat ΔQ transferred to a body, and the resulting increase of the body’s temperature ΔT are related as:

$$\Delta Q = C \bullet \Delta T,$$

where the coefficient C is the “heat capacity” of the body, depending of its mass and the substance it is made of. Conversely,

$$\Delta T = \Delta Q/C.$$

It means that if heat is gradually taken away from the body, its temperature gradually decreases. And here is the problem! Why? Because all kind of thermal engines, steam turbines included, are “very unhappy” if the temperature of the “hot source” from which they draw thermal energy does change during the process they deliver work. An ideal situation for them is if the temperature of the “hot source” remains constant as long as the engine delivers power.

Fortunately, there is a remedy – one has to use as the “storage body” a substance exhibiting a thermal process known as a “phase transition”.

A phase transition is something that you all know very well. Ordinary ice, as you know, is a solid form of water, H_2O – a “more professional” term used by physicists is *solid phase*. Then, liquid water is the *liquid phase*. And what we call “steam” or “water vapor” is the *gaseous phase* (or, more simply, *gas phase*) of water.

Any process in which water changes its phase from one to another is called a *phase transition*. “Melting” is transition from a solid (ice) phase to a liquid phase (chemists call it “fusion” – but not physicists). “Freezing”, or “solidification” is reverse transition, from a liquid phase to a solid phase. “Evaporation” is transition from a liquid phase to a gas phase – “boiling” is a fast evaporation process. And the reverse of evaporation is “condensation”.

An important fact is that each phase transition is associated with a transfer of heat, called the *latent heat of a phase transition*. To melt one kilogram of ice, one needs to transfer 334 kilo-Joules of heat to it – in other words, the latent heat of ice melting is 334 kJ/kg.

Let's consider the ice melting process in greater detail. Say, let's begin with a one kilogram sample of ice of temperature -10 °C (= 263 K). We gradually deliver heat. The specific heat of ice is 2.108 kJ/kg-K – it means that after delivering each portion of 2.108 kJ, the sample temperature increases by 1°C (= 1 K). And after we have delivered 21.08 kJ, the sample temperature reaches 0°C (= 273K), which is the melting point of ice.

We keep delivering heat – but now the temperature doesn't grow any more, it stays at 0°C. However, the ice starts melting, more and more of it changes to liquid water. Yet, only after we deliver as much as 334 kJ, all ice is melted and our sample is changed to liquid water – now, if we keep delivering heat, the temperature starts rising again. The specific heat of liquid water is 4.187 kJ/kg-K, so that now, after delivering each "heat portion" of 4.187 kJ, the water temperature increases by another 1°C.

If we cool down our water sample by **taking heat away**, the process is reversed. After reaching the temperature of 0°C "from above", the water starts freezing – but its temperature remains unchanged until we take away a total of 334 kJ of heat – at this moment, all water is changed to ice and from now on, if we keep taking away heat from it, its temperature will start decreasing.

Water is not good as a medium for “heat storage”, because it, yes, gives away heat – but at 0°C. So, why did we spent so much time to discuss it? Well, we did so because water freezing and ice melting are phenomena that everybody knows very well. But now we need to talk about other substances which **are** good candidates for heat-storing media. Let’s specify what conditions such a medium must satisfy:

(a) melting temperature should be about the same as the typical temperature of steam used by steam turbines;
(b) its latent head of melting/solidifying should be possibly high; and
(c) last but not least, it should be a relatively inexpensive substance.

It turns out that the best candidates are certain salts known of “nitrates”, of the formula $Me(NO_3)_N$, where Me = an atom of a metal. So, we have $LiNO_3$, $NaNO_3$, KNO_3, $Mg(NO_3)_2$, $Ca(NO_3)_2$, and so on. $LiNO_3$ has a record-high latent heat of solidifying, 360 kJ/kg, but one has to forget it because the price of Lithium is already high and probably will become much higher in the near future (because it’s of crucial importance for electric cars!). The latent heat of Magnesium and Calcium nitrates is not very high – but two salts from the list, $NaNO_3$ and KNO_3, have both attractive melting temperature (306 and 337 °C, respectively), and relatively high latent heat of solidifying (175 and 100 kJ/kg, respectively). And they are inexpensive because they are widely used as fertilizers, and therefore they are manufactured in large quantities (after Google, the price per metric ton of fertilizer-quality $NaNO_3$ is \$300-400, and of KNO_3 is \$700-800).

A list of CSP plants over the globe, active, under construction, and planned, is given in this Wikipedia article. However, those with no storage capacity and those with such capacity are listed together in the tables, so finding the ones with storage capacity requires much patience.

Type equation here.

Latent heat storage – properties of some promising materials

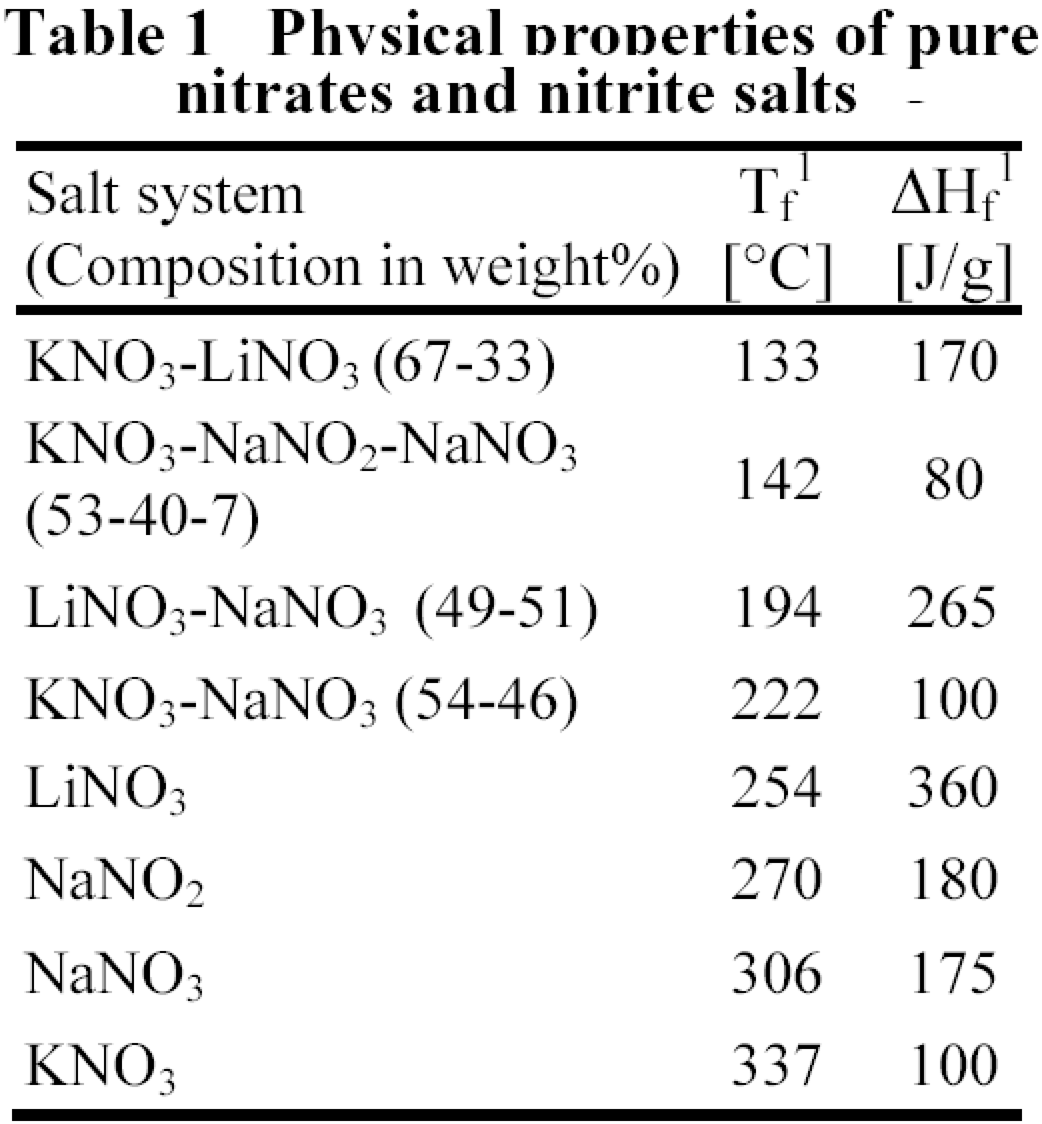


Table 1 Physical properties of pure nitrates and nitrite salts

Salt system (Composition in weight%)	T_f^1 [°C]	ΔH_f^1 [J/g]
KNO_3-$LiNO_3$ (67-33)	133	170
KNO_3-$NaNO_2$-$NaNO_3$ (53-40-7)	142	80
$LiNO_3$-$NaNO_3$ (49-51)	194	265
KNO_3-$NaNO_3$ (54-46)	222	100
$LiNO_3$	254	360
$NaNO_2$	270	180
$NaNO_3$	306	175
KNO_3	337	100

For comparison: Latent heat of fusion for H2O (in other words, of water freezing) is 334 J/g (or kJ/kg)

Another highly interesting CSP technique is the use of a parabolic circular mirror with a thermal engine placed at its focal point. Particularly useful for this are *Stirling Engines* because of their small size.

Such units typically generate up to 10 kW of electrical power, so they should be classified as medium-power CSP devices.

We will discuss the “strengths and weaknesses” of the CSP plants after talking about the alternative technology of generating solar electricity – namely, by using panels of semiconductor solar cells.

I would enable us to compare the “plusses” and “minuses” of the two methods.