SOLAR ENERGY

How much strikes the earth?

How much can my house get?

ENGS-44 Sustainable Design

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12 January 2012

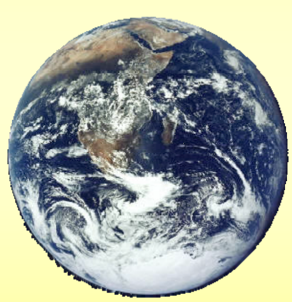
Renewable Energy Possibilities

Solar
1.2×10^5 TW on Earth's surface
36,000 TW on land (world)
2,200 TW on land (US)

Wind
2-4 TW extractable

Biomass
5-7 TW gross (world)
0.29% efficiency for all cultivatable land not used for food

Tide/Ocean Currents
2 TW gross



Hydroelectric
4.6 TW gross (world)
1.6 TW technically feasible
0.6 TW installed capacity
0.33 gross (US)

Geothermal
9.7 TW gross (world)
0.6 TW gross (US)
(small fraction technically feasible)

(*Source*: George Crabtree, Materials Science Division, Argonne National Laboratory)

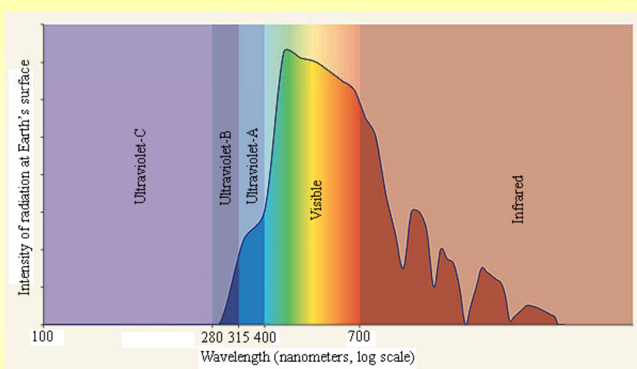
The amount of incident solar energy on earth each year

= 160 times the world's proven resources of fossil fuels

= 1,500 times the world's annual energy use.

Three mechanisms of heat transfer:

- **conduction** (molecular agitation in the material)
- **convection** (movement of carrying fluid)
- **radiation** (electromagnetic waves)



(http://www.nature.com/)

Solar energy is carried across empty space from the sun to the earth by radiation of electromagnetic waves (infra-red, visible & ultra-violet).

Most of this radiation is in the visible spectrum, to which the atmosphere is quite transparent.

Two basic laws of heat radiation:

1. All objects emit radiation. The hotter they are, the more they radiate.

   The emitted radiation flux (energy per unit area and unit time), E, is given by:

$$E = \sigma T^4$$

where T = absolute temperature in degree Kelvin (= °C + 273.15)
σ = 5.67 x 10^{-8} W/(m^2.K^4)

or where T = absolute temperature in degree Rankine (= °F + 524)
σ = 1.71 x 10^{-9} Btu/(ft^2.hr.R^4)

2. The radiation emitted by a body at absolute temperature T fills a spectrum, with peak at wavelength λ given by:

$$\lambda = \frac{2898\ \mu\text{m}\,.\,K}{T\ (\text{in K})} = \frac{5216\ \mu\text{m}\,.\,R}{T\,(\text{in R})}$$

Thus, the hotter the body, the shorter the emitted wavelengths.

Consequence of Rule 1:

One way to provide heat to an object is to expose it to a hotter body. The hotter, the better. Hence, solar exposure is much better than exposure to a warm piece of earth or even a fire.

Consequence of Rule 2:

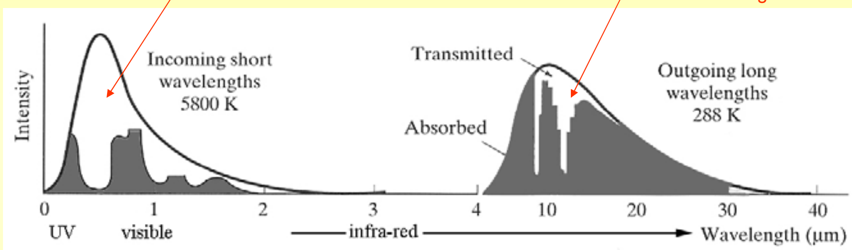
Because the sun is so hot (T = 5750 K = 9,890°F), it emits most of its radiation around λ = 0.50 μm, which not coincidentally falls in the visible range.

The earth and our houses are not as hot (around T = 72°F = 295 K) and emit their radiation around λ = 10 μm, in the infra-red range. We need an infra-red camera to "see" this radiation.

Radiation from sun and from earth

Atmosphere very transparent in the visible range

Atmosphere very opaque in infra-red range



↑ from sun

↑ from earth

The atmosphere and window glass are mostly transparent to visible light but quite opaque in the infra-red range.

From sun to earth:

Being at 5750 K, the sun emits 6.2 x 10^7 W/m^2.

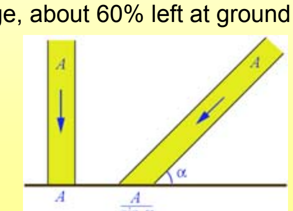
Given the size of the sun (R_{sun} = 696,000 km) and the distance from the sun to the earth (d = 149,476,000 km), we can calculate the amount of the solar radiation arriving at the earth:

$$1372 \text{ W/m}^2 = 435 \text{ Btu/(hr.ft}^2)$$

at normal incidence.

The preceding figure is the solar radiation arriving at the outer edge of the earth, which is the upper atmosphere. What actually strikes the earth surface is somewhat less because of partial absorption and reflection by the atmosphere, especially clouds (in average, about 60% left at ground level).

A further reduction is caused by oblique incidence (radiation spread over a larger area).



Value of the incident solar radiation flux I at ground level?

The value of I varies with
- Latitude (solar declination, more tangential at high latitudes)
- Length of path through the atmosphere (oblique incidence)
- Climate (cloudiness factor)

On a clear day:

$$I_{\text{clear sky}} = A\,e^{-B/\sin\alpha}$$

where α = solar altitude
(angle of sun above horizon).

Month	A (Btu/ft^2.hr)	B
Jan	390	0.142
Feb	385	0.144
Mar	376	0.156
Apr	360	0.180
May	350	0.196
Jun	345	0.205
Jul	344	0.207
Aug	351	0.201
Sep	365	0.177
Oct	378	0.160
Nov	387	0.149
Dec	391	0.142

The angle α of the sun above the horizon, at any given place and time, depends on 3 variables:

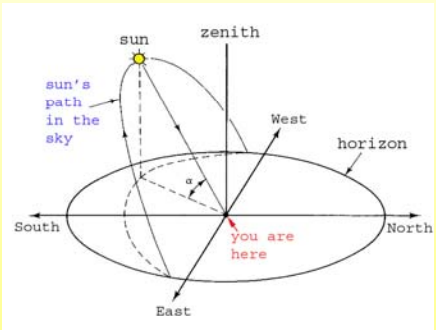
- The latitude of the location, φ ($0^o < \varphi < 90^o$)
- The day of the year, n ($0 \leq n \leq 365$)
- The hour of the day, h (counted + and – from local noon)

The trigonometric formula is:

$$\sin\alpha = \sin\varphi\,\sin\delta + \cos\varphi\,\cos\delta\,\cos(15^o h)$$

in which δ is the solar declination
(angle of sun above equatorial plane):

$$\delta = 23.5^o\,\cos\left(360^o\,\frac{n-172}{365}\right)$$



Look for key values of α :

$$\sin\alpha = \sin\varphi\,\sin\delta + \cos\varphi\,\cos\delta\,\cos(15^o h)$$

Over the course of the day, the sun is highest at noon (h = 0):

$$\begin{aligned}\sin\alpha &= \sin\varphi\,\sin\delta + \cos\varphi\,\cos\delta \\ &= \cos(\varphi-\delta) \\ &= \sin(90^o-\varphi+\delta) \quad \rightarrow \quad \alpha = 90^o+\delta-\varphi\end{aligned}$$

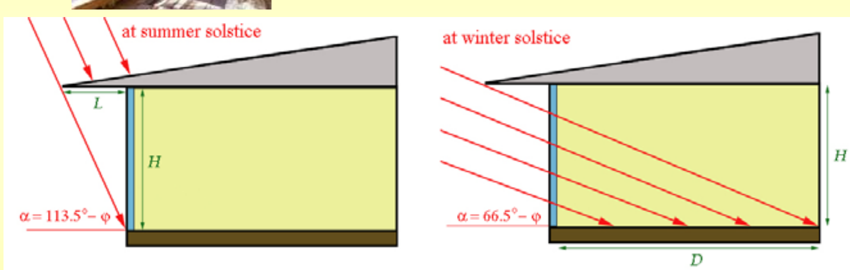
in which $\delta = 23.5^o\,\cos\left(360^o\,\dfrac{n-172}{365}\right)$

Spring equinox (22 March):	n = 81	$\rightarrow$ δ = 0	$\rightarrow$ α = 90º – φ
Summer solstice (21 June):	n = 172	$\rightarrow$ δ = +23.5º	$\rightarrow$ α = 113.5º – φ
Fall equinox (20 September):	n = 263	$\rightarrow$ δ = 0	$\rightarrow$ α = 90º – φ
Winter solstice (21 December):	n = 355	$\rightarrow$ δ = –23.5º	$\rightarrow$ α = 66.5º – φ

(http://www.iron-to-live-with.com/ apartment/source/4.html)

Overhang lengths and room depths can be calculated to adjust for this seasonal effect.

Usually, we need to
- maximize the uptake of winter sun and
- eliminate the uptake of summer sun.



$$L = \frac{H}{\tan\alpha} = \frac{H}{\tan(113.5^o-\varphi)} = H\,\tan(\varphi-23.5^o) \qquad D+L = \frac{H}{\tan\alpha} = \frac{H}{\tan(66.5^o-\varphi)} = H\,\tan(\varphi+23.5^o)$$

for $\varphi \geq$ 23.5º

So, if you know the height H of the ceiling, you can calculate the length L of overhang and depth D of the room.

PASSIVE SOLAR HEATING 195

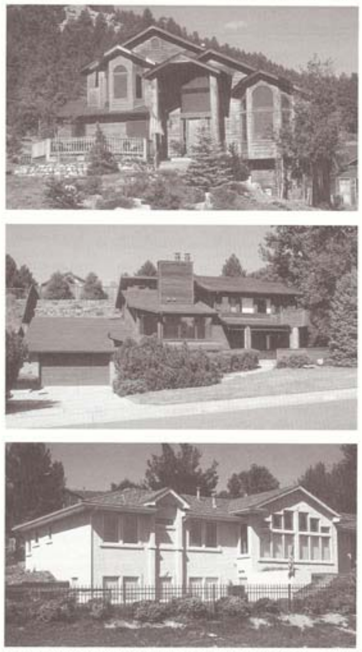


Figure 11-2.
Passive solar energy can be designed into any style home, as shown here.

Note the shade provided by the overhangs.

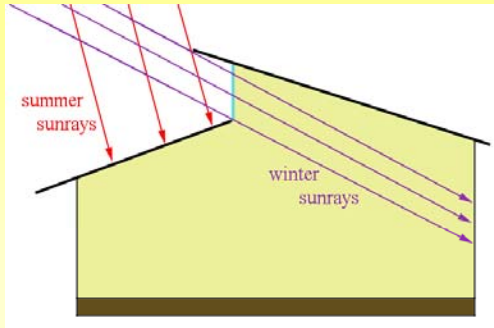
(From *The New Ecological Home* by Daniel D. Chiras, 2004)

Wise use of overhangs to provide shading against excessive solar intake

(http://www.strawbalehomes.com/solar1.html)

This house under construction in Durango, Colorado features straw-bale construction (excellent insulation) and passive solar design. Note the shade provided by the overhangs. Clerestories (in-roof windows) provide solar radiation to the back of the house.

How clerestory windows work

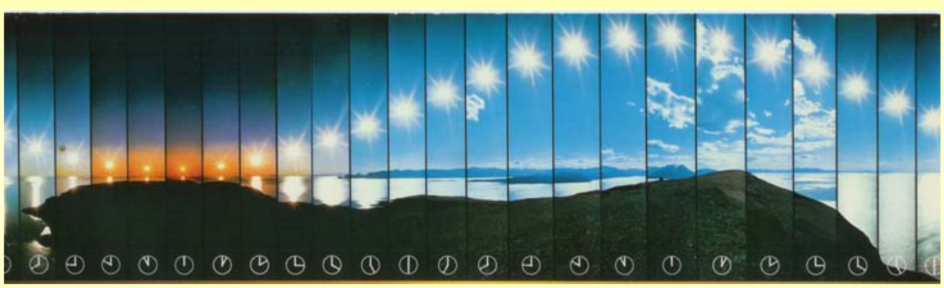



(http://www.oregonlive.com/environment/index.ssf/2008/04/27-week/)

Clever combination of clerestory windows and photovoltaic cells on roof below:

Winter sun → heat into house
Summer sun → electricity

The sun does not just move up and down in the sky, it also moves across the sky, rising in the East and setting in the West … and occasionally not setting at all.

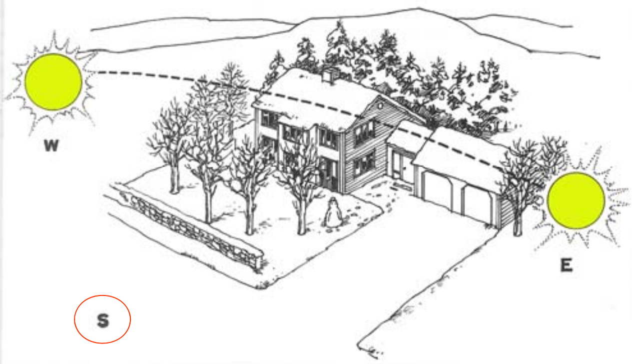

Island of Loppa, 70^{o}N, North Norway, 21-22 July (Credit: Husmo foto, Boks 231)

Taking into account the azimuth angle (sweep angle) into account is complicated.

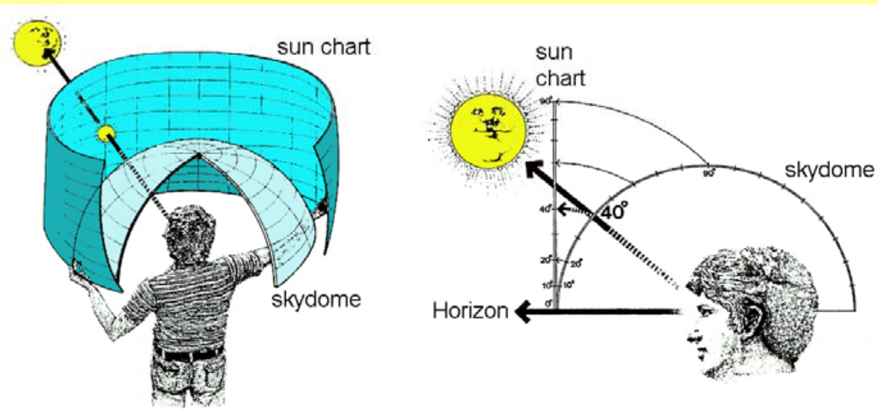
Solar Principle #1

Orient the house properly with respect to the sun's relationship to the site.

Use a compass to find true south, and then by careful observation site the house so that it can utilize the sun's rays from the east, south, and west during as much of the day and year as possible. In orienting the house, take into account features of the landscape, including trees and natural land forms, which will buffer the house against harsher weather or winds from the north. Deciduous trees on the sunny sides of the site will shade the house from excess heat during the summer months, but will allow the winter sunlight to reach the house and deliver free solar energy.

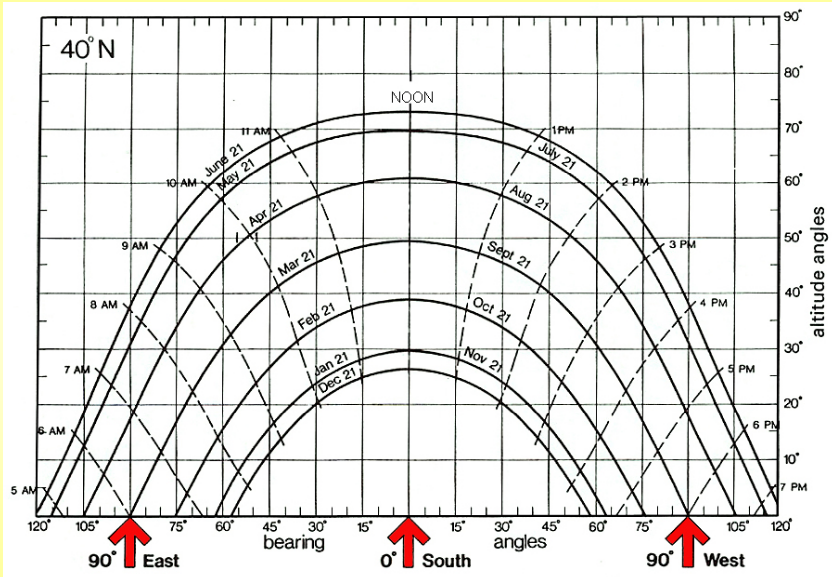


The Passive Solar House, by James Kachadorian, Chelsea1997



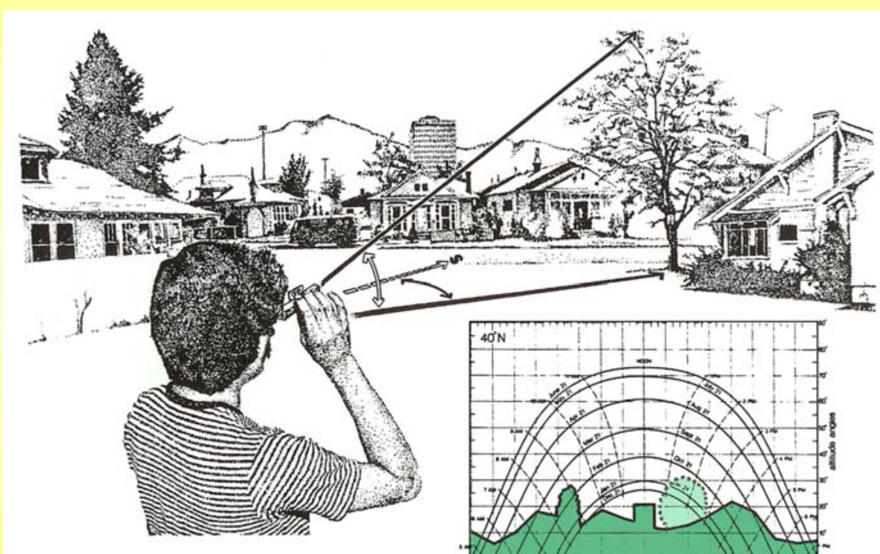
Skydome and associated cylindrical sun chart (Mazria, 1979)

Sun paths drawn on cylindrical sun chart. These are published.



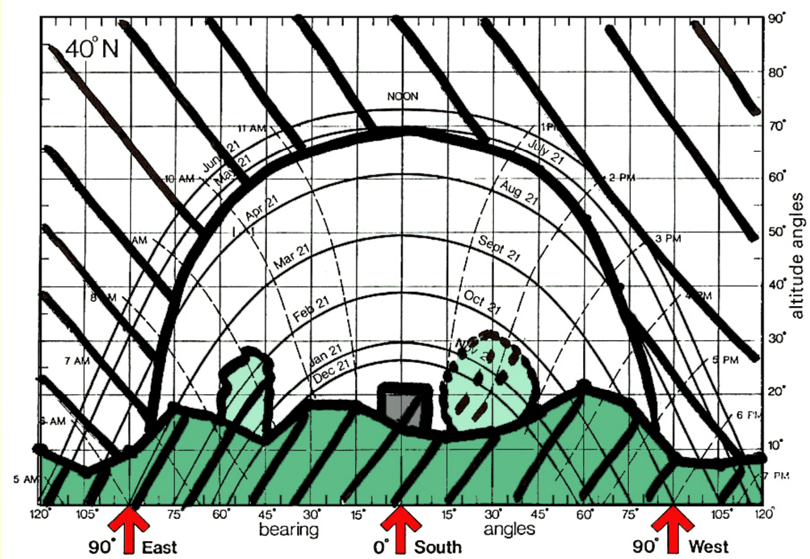
Sun chart for 40°N (Mazria, 1979)

Adding the obstructions (●), including the seasonal ones (●)



Construction of a site skyline for a south-facing surface (Mazria, 1979)

Finally, blocking the undesirable solar incidences of the summer



Solar radiation chart overlayed on solar window (Mazria, 1979)

For a first estimate (not adjusting for vegetation), one simply distinguishes between east, south, west and north facing walls of the structure, and use a so-called **Solar Heat Gain Factor** (SHGF) for each side.

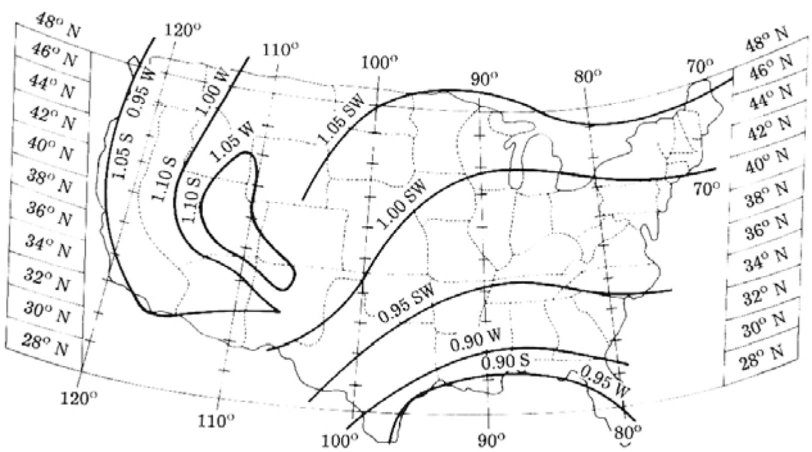
For 40°N, SHGF values
(in BTUs per ft^2 per day, for average cloudiness in the USA):

In practice, use local cloudiness factor

Month	# days	East	South	West	North	% sun
January	31	452	1,626	452	0	46%
February	28	648	1,642	648	0	55%
March	31	832	1,388	832	0	56%
April	30	957	976	957	0	54%
May	31	1,024	716	1,024	0	57%
June	30	1,038	630	1,038	0	60%
July	31	1,008	704	1,008	0	62%
August	31	928	948	928	0	60%
September	30	787	1,344	787	0	57%
October	31	623	1,582	623	0	55%
November	30	445	1,596	445	0	46%
December	31	374	1,114	374	0	46%

Then apply a Shade Coefficient (multiply by 0.88) to account for partial reflection by glass if sunlight is captured inside of a window.

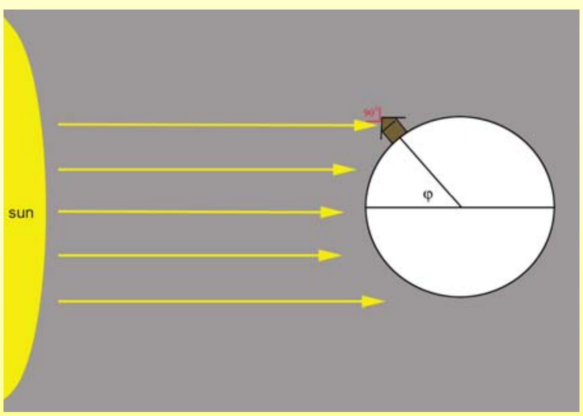
A small correction, often skipped:
Multiply previous values by this geographic factor to account for atmospheric clarity:



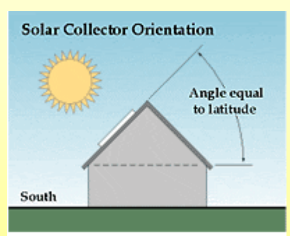
Estimated atmospheric clearness factor in the United States for nonindustrial localities. S and W represent summer and winter, respectively. (Adapted with permission from ASHRAE, *Handbook of Fundamentals*, 1981.)

The previous calculated values were for vertical surfaces (like most windows). One can optimize the design by orienting the collection surface so that it intercepts sun rays at a better angle.

This is particularly important for solar panels placed on a roof. The southern roof slope can be chosen to face the sun rays perpendicularly.



The Rule:



A well functioning solar house needs to perform the following three functions simultaneously:

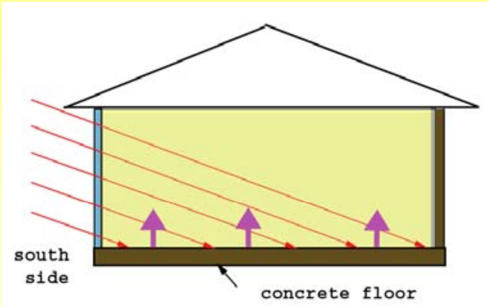
1. Capture the necessary solar energy,
2. Store heat during day for continued use through the night,
3. Distribute the heat effectively through the various rooms.

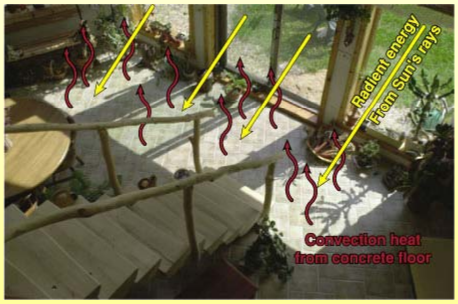
The set of these three functions is called ***Direct Solar Gain***.

The preceding slides dealt with 1.
The next couple of slides give an advanced glimpse of 2. and 3.

To store solar energy for later use:

Have a concrete slab as floor to absorb the heat and radiate it back at a later time. This is called using a "thermal mass".

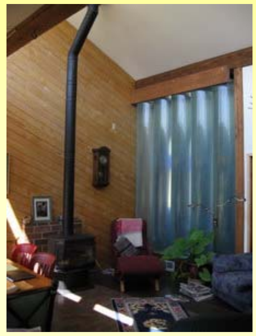




(http://solar.steinbergs.us/solar.html)

Calculating the necessary thermal mass will be the subject of a subsequent lecture.

Some alternative storage methods:



(www.strawbalehomes.com/)

water drums…

(www.ehponline.org/)

masonry walls or
stone/brick fireplaces

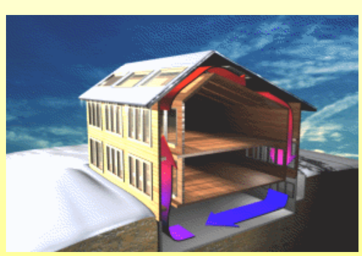
… or why not a pool?

(http://www.dandelionfarm.org/dandelion3.html)

Distribution of heat by unforced ventilation (warm air rises and cold air sinks under buoyancy forces – the "chimney effect") is tricky business.

Effective designs provide for adequate passageways and exhaust openings.

Estimating the airflow and temperatures at various points in the structure is best accomplished by computer simulations.



(http://enertia.com/Science/)