Basking in the Sun

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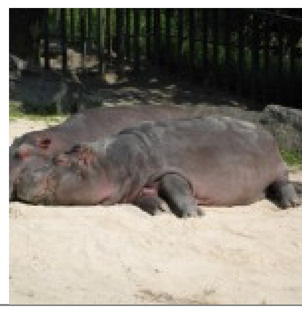
This is a guest post by Tom Murphy. Tom is an associate professor of physics at the University of California, San Diego. This post originally appeared on Tom's blog Do the Math.

Who *hasn't* enjoyed heat from the sun? Doing so represents a direct energetic transfer—via radiation—from the sun's hot surface to your skin. One square meter can catch about 1000 W, which is comparable to the output of a portable space heater. A dark surface can capture the energy at nearly 100% efficiency, beating (heating?) the pants off of solar photovoltaic (PV) capture efficiency, for instance. We have already seen that solar PV qualifies as a super-abundant resource, requiring panels covering only about 0.5% of land to meet our entire energy demand (still huge, granted). So direct thermal energy from the sun, gathered more efficiently than what PV can do, is automatically in the abundant club. Let's evaluate some of the practical issues surrounding solar thermal: either for home heating or for the production of electricity.



Heat as Something Useful

In physics classes, I often catch myself repeating the mantra that **heat** is a *disordered*, *useless* state of energy that is generically the endpoint of an energy flow process. For example, the energy allocated to the fast-spinning wheel of an upside-down bicycle will slowly drain away as the wheel stirs the air, makes sound, and suffers friction at the bearing. Every one of these energy paths results in heat, until 100% of the invested energy is dissipated and the room is a tad warmer as a result. We will never reassemble the lost energy into useful form, once entropy has claimed it. All of this is true enough, but I feel very awkward uttering the words that heat is the graveyard of energy flow, and must place an asterisk on the statement.

The asterisk is that the *overwhelming majority* of our societal energy consumption makes use of heat—over 90% in the U.S.! So heat does not deserve the bad rap as a worthless waste product. Rather, *heat runs our world*! Sometimes we just want the heat directly, via: natural gas for furnaces, hot water, and cooking; heating oil for the home; and gas and coal for industrial process heat. This accounts for 20% of our total energy demand, leaving about two-thirds of our total energy consumption in the form of heat that powers heat engines for electricity production, transportation, and machinery. In short, all the energy we get from fossil fuels, nuclear, and biomass derives from heat. That's hardly useless!

Radiant Heat

The Sun transmits its energy to Earth across the emptiness of space via radiation. Each square meter of surface at a temperature, T, emits radiation at a rate of σT^4, where T is expressed in Kelvin (important!) and $\sigma = 5.67\times10^{-8}$ W/m²/K⁴. This constant is easy to remember via the sequence 5-6-7-8. Ignoring for now the subtleties of greenhouse gases, the surface of Earth—typically at 288 K—emits 390 W/m². The Sun, on the other hand, at 5800 K, emits 64 MW per square meter!

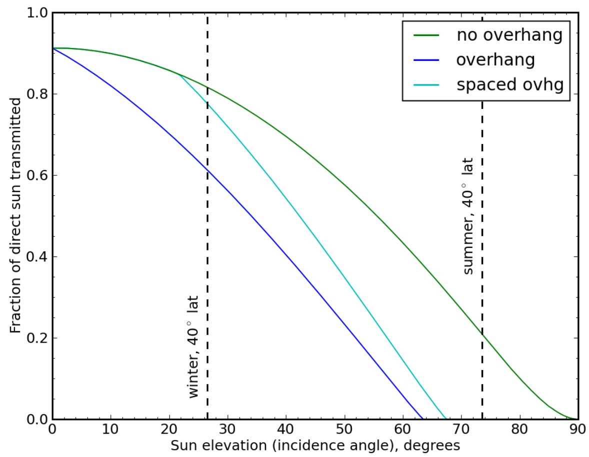
Summing over the area of the spherical Sun, at 109 times the radius of Earth, we find the total radiant power of the Sun to be a whopping 3.9×10^{26} W. Now *that's* a light bulb! The Sun's radiant energy spreads into all directions, creating a sphere of light. At the distance of the Earth, that sphere has an area of $4\pi r^2 \approx 2.8\times10^{23}$ m², where r is the mean Earth-Sun distance. Dividing these huge figures, we find that the radiant intensity at Earth is **1370 W/m²**—which I hope will be a familiar number by now for Do the Math readers.

We can also turn the σT^4 relation on its head and say that a patch of full sun (at the ground) receiving 1000 W/m² corresponds to a radiant temperature of 364 K, or a blistering 91°C. This means that a black panel in full sun could get this hot if no paths other than radiation were available for cooling the panel. We would then say that the panel is in radiative equilibrium with the Sun. But air can carry away heat by convection. The self-convection of a hot, flat plate will be about 10 W/m² per degree of difference between the panel and the surrounding air. Requiring the sum of radiative and convective losses to add up to the input power of 1000 W/m² yields a solution of about 55°C (328 K; 131°F) if the surrounding air is at 20°C. This assumes that the plate has no heat paths available through the (insulated) back side. If, on the other hand, it is a thin panel allowing convection on both sides, it will be cooler—although the "heat rises" phenomenon will suppress heat flow on the back side relative to the front, if the plate is indeed level. Just for fun, if we get an additional 5 W/m²/K of convective loss off the back, the equilibrium temperature drops to 47°C (117°F). It all seems reasonable.

Passive Solar: Putting Heat to Use

The simplest way to replace fossil fuel energy with solar energy is called a *window*. A single uncoated piece of glass will transmit 92% of visible light (the rest reflected) when light comes straight in (down to 75% at a 20° grazing incidence, 60% at 10° grazing). The glass is opaque to ultraviolet light and mid- to far-infrared (IR) light, but lets over 95% of the unreflected incident solar spectrum pass.

Considering that windows in houses/buildings tend to be vertical, we can evaluate the energy input through windows, taking transmission loss, reflection loss, and angular foreshortening into effect. Because the Sun is higher in the sky in the summer, the window appears foreshortened to the direct sunlight, and also reflects more. So a south-facing window automatically admits more heat in the winter than in the summer, with no adjustment. Putting an overhang over the window —ideally with some vertical space between the window and overhang—can eliminate the summer noon-time contribution entirely. The figure below illustrates the fraction of incident direct-sun energy (think 1000 W/m²) admitted by the window. Vertical reference lines indicate the noon-time elevation of the sun at a latitude of 40° for the winter and summer solstices. The noon-day sun will be somewhere between these values all year. Adjustment to other latitudes involves a simple shift of the dashed lines by the latitude difference.



Fraction of incident direct energy (perpendicular to rays) making it through a vertical window. The overhang extends an amount that is half the window height, and optionally is spaced 0.2 window-height-units above the top of the window.

So it is not a stretch to admit energy in excess of 500 W/m² into your home in winter sun. You can stack up the equivalent of a dozen or so space heaters pretty quickly.

Drab Winter?

Sounds great, but winters are not always the sunniest of times. However, it's not as bad as you might fear. Every photon of visible light that makes it through your window—even if coming from a drab gray cloud—deposits the same amount of heat no mater how convoluted its path from the Sun. Indeed, a measurement campaign in my home has revealed that the attic gets surprisingly warmer (10°C, or 18°F) than the ambient air even on a day of heavy clouds when my solar PV system only caught one-quarter of the usual amount of light. So we can use the NREL database for a flat plate collector (in this case, a window) oriented south at a 90° tilt to represent the amount of energy a window would grab. The following table indicates the equivalent number of full-sun hours per day during the heating months for Seattle, WA (on the poor end), St. Louis MO (a representative U.S. average solar city), and San Diego (my home).

City	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Seattle, window	2.7	1.7	1.3	1.5	2.2	2.8	3.0
Seattle, full sun	2.3	1.1	0.9	1.0	1.7	2.5	3.1
St. Louis, window	3.8	3.2	3.0	3.5	3.7	3.4	3.1
St. Louis, full sun	4.1	2.9	2.4	2.9	3.2	3.6	4.3
San Diego, window	4.4	4.6	4.5	4.5	4.3	3.9	3.2
San Diego, full sun	5.3	4.9	4.5	4.5	4.8	5.1	5.8

The table also includes the number of equivalent full-sun hours per day a 2-axis concentrating system would recover, which is a good proxy for the average daily number of hours of direct sun. The window can often get more energy than is present in full sun due to the diffuse gain, which is the case for six out of the seven months for Seattle in the table above.

If a house had four large windows facing south, each 2 m wide and 3 m tall, a typical Seattle day in December would deposit 900 W/m² (from earlier graph, low elevation sun) times 24 m², or about 22 kW of power for about 1.3 hours. This amounts to 28 kWh of energy (corresponding to about 1 Therm of natural gas energy).

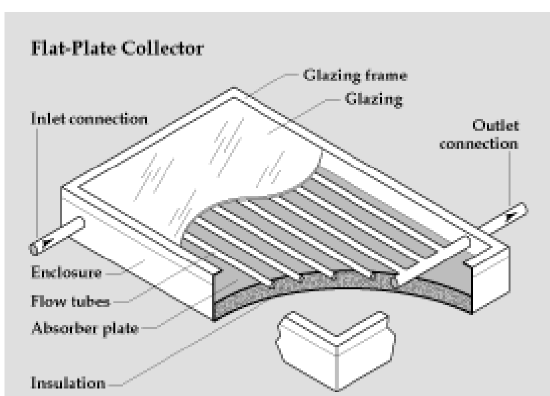
To make this amount of heat work, the house must be extraordinarily well insulated, use fancy windows, and be draft-free—using a heat recovery ventilator. But such feats can be accomplished in passive home design, even in climates that would appear to be completely hostile to the notion of passive solar heating.

It is also often advantageous to have several days' worth of thermal storage in the home to average out the sunny and cloudy days. A dark, massive rock or brick wall can do the job—preferentially opposite the huge south-facing windows to directly soak up the solar input. At a specific heat capacity of 1000 J/kg/K and a density of 3000 kg/m³, a rock wall 0.5 m thick and matching our 24 m² window footprint will see a temperature rise of about 2°C for every hour of sunlight poring onto it. A good sunny day pumping five hours of solar energy into the mass would raise its temperature 10°C, so that lazy air pulling off heat at 2 W/m²/K would initially pump out 2400 W of power after the sun is down (assuming the back of the wall is insulated), and provide about 2 days of heat with no additional input.

Of course a number of engineering challenges surround clever passive solar thermal design, and I should pull away before the post gets bogged down (too late, you say?). Perhaps I will return to the topic later. For now, it is worth understanding that the amount of solar radiation incident on a house can be sufficient to provide heating even in unfavorable climates. I should add one caveat: that passive heating may be sufficient 90% of the time, requiring either backup heat or—preferably—flexibility in dealing with a colder house the other 10% of the time.

Hot Water

Using the sun to heat water is a very similar concept. We saw that a flat black plate in the sun can get pretty toasty. In practice, flat panel collectors can hang onto about 60% of the incident solar energy, transferring this to the water. Heat paths via radiation through the glass on the front, convection of air within the panel, and conduction through the back and mounting frame all contribute to loss. For radiative loss, radiation from the black panel is intercepted by the glass (thermal IR is not transmitted by glass), warming it up. This can then radiate both skyward and back to the absorber. A second piece of glass (double-pane) can cut down radiation losses, by returning approximately half of what would otherwise have been lost off the front panel. Some fancy units evacuate air to minimize convective loss, and the backs can be insulated to reduce loss. Given all these thermal leaks, holding on to 60% of the incident energy is pretty impressive.



Example construction of simple flat-panel collector.

Let's assume your household requires 300 liters of hot water each day—the equivalent of four "long" 10 minute showers at a healthy flow of 8 liters per minute. This, by the way, is *far* more than I believe is really necessary for a household—even if it is typical. If the water comes in at 10°C, and is heated to 60°C, then we need to supply 15,000 kcal of energy—following the definition of the kilocalorie. Considering 60% efficiency and allowing for some daily loss in storage, we need to provide 30,000 kcal of solar input each day, amounting to 35 kWh of energy. As it turns out, tilting a panel to 54° in St. Louis gives at least 3.5 hours of full-sun-equivalent (1000 W/m²) even in December, so that we need 10 m² of panels (a bedroom's size).

Two panels on roof provide hot water.

Solar Thermal Electricity

The relatively low temperatures achieved by flat panels in the sun do not encourage exploitation in the form of heat engines for making electricity. But we can fix this through the simple act of **concentration**. No—not simply thinking really hard about it. Much like a magnifying glass can be used to burn paper, any piling-up of solar flux can elevate the temperature. I have personally melted pennies, boiled water, and turned sand into glass with a large hand-held Fresnel lens. Even a bunch of flat mirrors directing sunlight onto a common spot can create formidably high temperatures.

Concentration is expressed as a ratio, so if I take a circular magnifying glass 100 mm in diameter that makes an image of the sun 1 mm across, the concentration factor is 10,000 (the ratio of areas). Using our radiative relation, the resulting 10 MW/m² corresponds to a temperature of 3600 K! That kind of temperature will melt any metal, if you put the concentrated light onto a fleck of metal smaller than the bright spot. Typical boilers in power plants produce a hot temperature of about 1000 K. Achieving a comparable temperature via solar input requires a concentration in excess of 60.

One downside is that concentration implies tracking, which adds to complexity. Two-dimensional concentration—like a magnifying glass—requires two-axis control to keep the hotspot on the small target. One-dimensional concentration—such as a parabolic trough—only requires tracking along one axis. The concentration ratio of a 1-D concentrator is roughly the square-root of the 2-D variety, but that's okay if we only need concentration ratios around 100 or so. One-dimensional concentration is also far more forgiving of imperfections in the reflector shape (can be made more cheaply).

Another downside of concentration is that it requires real direct sunlight to work. Can you see a sharp shadow on the ground? If not, concentration is effectively dead. In essence, the concentrator is forming an image of the sun—sometimes a stretched-out linear image in the case of trough collectors. Forming images of clouds onto the collector will not get it very excited. It needs the real thing. Comparing the effective yield for tracking configurations at different sites gives some sense for how some places are differently advantaged to exploit solar thermal. In general, desert areas do very well.

City	Flat Panel at Lat.	1-axis, N–S	2-axis
Seattle, WA	1.4/**3.7**/5.7	0.4/**2.5**/5.2	0.9/**2.9**/5.5
St. Louis, MO	3.1/**4.8**/5.9	1.5/**3.5**/5.3	2.4/**4.1**/5.5
San Diego, CA	4.6/**5.7**/6.5	3.8/**4.1**/4.9	4.5/**5.3**/6.3
Dagget, CA	5.2/**6.6**/7.4	3.5/**6.6**/9.6	5.4/**7.5**/9.7

The table above gives average daily yields (kWh/m²/day, or equivalent hours at 1000 W/m²) for three types of solar collection in four locations, each entry giving worst-month/**yearly-average**/best-month values. The first is for a flat plate tilted to the site latitude (appropriate for PV or hot water), followed by 1-axis concentration tilting along a N-S axis, and finally a 2-axis concentration configuration. Solar thermal makes the most sense in areas where more energy will be collected than with PV panels—but this is not a rigorous criterion, since solar thermal offers some advantages over PV, as we'll discuss in a bit. In the table above, only Dagget, California—in the Mojave desert— has concentration beating flat-panel PV for total energy. Other desert cities in the Southwestern U.S. likewise are favorable toward solar thermal electricity. But it's definitely a location-dependent technology.

Solar Thermal Schemes

Schemes abound: 1) power towers where an array of individually-steered flat mirrors are angled to put sunlight at the top of a tower in the middle of the array; 2) satellite-dish-looking segmented bowls with a heat engine at the focus; 3) parabolic trough arrays with a hot-oil-carrying pipe running down the focus; 4) and others topologies, I am sure.

Solar "power tower" outside Barstow, CA.

Taking the simple parabolic trough as an example, about 70% of the incident energy makes it into the 400°C fluid running within the central pipe. Heat carried by the oil makes steam to turn turbines, in the traditional power plant sense. The efficiency of the power plant portion is in the usual ballpark of 30%. These two factors alone produce 20% efficiency, but other losses tend to push it down to 15% or so. The troughs are typically oriented north-south, with daily tracking (e.g., pivot about the hot pipe). Self-shadowing becomes an issue, mitigated by providing ample room between collectors. If you want to track the sun as low as 15 degrees elevation with no shadowing, for instance, only one-fourth of the land area is utilized. East-west orientations are also possible, performing less well year-round, but more uniformly throughout the year.

Parabolic trough collectors.

Parabolic troughs are pretty neat, I think, for a variety of reasons. First, the parabolic shape accomplishes focus independent of the slant angle of the light in the direction along the axis: mathematical perfection no matter the angle. This leads to the second serious advantage—already discussed—of single-axis tracking along a north-south axis. The ability to transport the heat along the axis using a fluid/pipe is unique to this design, making it convenient to schlep the heat around where you want it. Finally, because the shiny material only needs to be bent in one direction (*far* easier than a bowl-shape), the reflectors are relatively inexpensive to make.

Evaluating a realized example, the Nevada Solar One plant has a 64 MW nominal capacity, generating 134 million kilowatt-hours of energy per year. Dividing these two implies about 2100 hours of full-power operation per year, for a duty cycle of 24%, or 5.7 hours per day. The NREL database for Las Vegas expects a north-south single-axis tracker to get an average of 6.2 hours per day horizon-to-horizon. So not too far off. The plant cost $266 million to build, amounting to $4.15 per Watt. Pretty similar to installed solar PV. The plant occupies about 1.6 km² of land, computing to 40 W/m² at nominal full power. This is 4% of the incident 1000 W/m² (at the height of summer), which is pretty close to what we would guess for a 15% efficient collector occupying 25% of the land area. I love it when the numbers make sense!

A Storage Boon

One serious perk to solar thermal—not yet exploited as fully as it might be—is thermal storage. Make hay when the sun shines, and squirrel it away for overnight use. All solar thermal plants have short-term immunity from intermittency due simply to the thermal mass in the system. Solar thermal plants are designed with varying degrees of storage, many just aiming for several hours to better follow the peak demand curve into the evening. But as renewables gain dominance over fossil fuels (as I'm hoping they do), storage will become increasingly important. To my mind, the ratio of storage to collection is pretty straightforward to change (i.e., bigger vat of hot fluid), so that in principle solar thermal plants could achieve days of storage with little added complexity. We can't say this about PV or wind. And storage efficiency for a large container grows linearly with the tank's dimension, since it the energy contained scales like volume, while thermal loss paths tend to scale with area.

One of the Winners

We looked at three categories of using heat from the Sun: passive home heating, hot water, and solar thermal electricity. Virtually anything involving direct use of solar energy—as opposed to hydroelectric, wind, waves, etc. as secondary and tertiary derivatives of solar input—is bound to end up on the **abundant** side of the story. And so it is with these three, although perhaps given that the first two are confined to the meager area represented by rooftops and/or windows—rather than the entire land area—they should more fairly be stashed in the “potent” box.

Solar thermal electricity definitely joins the camp as an abundant resource. Some of the other abundant resources described to date (nuclear breeders, geothermal depletion, and more to come) present technical hurdles or other practical barriers that diminish my excitement for them. I won’t claim that solar thermal electricity has no difficulties (reflectors get dusty/abraded by desert sands, for instance). But it’s pretty low-tech, utilizes over a century of experience in running heat engines, allows storage to be an integral part of the design, and is super-abundant on the scale of things. All the same, we have found yet another viable way to make electricity, doing little to directly address a liquid fuels shortage.

The low-tech nature of solar thermal makes it especially robust in tough times. I can imagine personally designing and building a passive solar home, flat-plate thermal collectors for hot water, and even a parabolic trough to create steam. I can’t say the same about a PV panel, a nuclear reactor, or geothermal wells kilometers deep. It gets my vote.

We’ll see nuclear fusion next week. Sound familiar?