An array of 4 heliostats used for natural lighting and direct space heating.

The Promise of Small Heliostats

The engineer behind Boston-based start-up Practical Solar explains why heliostats will play a role in the future of solar power—but not in the (enormous power tower) way you might think.

By Bruce Rohr

Most people are genuinely surprised when they first learn that a single square meter of sunlight striking the earth contains around a kilowatt of power—similar to a hairdryer or electric space heater. Just as surprising is the fact that only twenty square meters of sunlight would be required to supply all the heat, hot water and electricity to a typical home in New England in the dead of winter if 100 percent of this sunlight was converted into useful energy.

Nature won't allow 100 percent conversion efficiency, but there is little doubt that new processes and systems can be developed to greatly improve the state of the art. Traditional solar thermal collectors will always be limited by physics in this department. For reasons I will go into later, only higher temperatures can improve the efficiency problem, and only concentrating solar power (CSP) systems can produce these higher temperatures.

This is where heliostats come into play. A heliostat is simply a mirror that rotates on two axes to reflect sunlight onto a fixed spot. Even though the sun marches across the sky, the spot of reflected light remains stationary. Multiple heliostats can concentrate sunlight onto a single target (e.g. a thermal receiver). Since mirrors have minimal reflection loss, each heliostat reflects approximately its area in sun energy—a kilowatt per square meter.

It seems inevitable that heliostats will play an important role in making solar energy fully competitive with fossil fuels. But not the kind of large-scale power tower systems that the U.S. government spent upwards of $100 million creating (and now lie rotting in the California desert). While I hope the large-scale heliostat projects planned in Australia and Spain fare better, the heliostats I imagine becoming mainstream are small by comparison—around 1 square meter of reflective area. While they still offer the improved conversion efficiency of a larger-scale system, they can make use of the limited land in suburban and even urban environments. For a number of reasons that I'll detail later on, small heliostats also promise to be more reliable—and more cost-effective per square meter of reflective area. The U.S. government's "Solar One" and "Solar Two" projects were far too costly per square meter, and it's unclear whether they ever worked properly.

The Science behind Heliostats and CSP

Heliostats, and more generally concentrated solar power (CSP), make sense because of fundamental laws of physics. Perhaps the most important of these principles is the Second Law of Thermodynamics. A good example of this law is the following: Take two glasses of water, one hot and the other cold, and place them close to together. We all know intuitively that the hotter glass will grow colder and the cold glass will get hotter until both glasses are at the same temperature. The amount of thermal energy stayed constant but the cold glass gained energy at the expense of the hot glass. Energy can only be extracted if there is a difference in temperature between the two glasses, and the greater this difference, the higher the efficiency in extracting useful energy.

CSP and heliostats theoretically offer much higher solar-thermal efficiency because they use the energy of many suns on a smaller surface area. Heat loss from any surface is linearly proportional to its surface area. If surface area is halved, then heat loss is halved. Heat loss is also proportional to the temperature difference between a hot surface and a cold environment (although not in a strictly linear way, heat losses increase to the 4th power at very high temperatures). These two straightforward principles place strong constraints on passive solar energy systems when higher temperatures are desired.

Poolside heliostat providing natural lighting to a house over 200 feet away.

An array of 6 heliostats used for concentrating solar power—its not visible in this photo, but they're focused on a prototype thermal receiver.

In passive systems, the surface area and loss increase in direct proportion to the amount of energy collected. With heliostats, the loss due to surface area doesn't increase with the amount of solar energy collected, but remains fixed. For example, a heliostat array designed to collect 100 m^2 of solar energy could direct all this energy onto a surface of about 0.5 m^2, whereas a passive system would require a surface area of the full 100 m^2. The energy loss in the heliostat system would only be 0.5/100 = 0.005 (0.5 percent) that of the passive system. Hence, high temperatures and high efficiency can be attained with heliostats that are impossible with passive systems.

The Second Law has the same implications for heat engines (gasoline, diesel, sterling, turbine engines, etc.). The greater the difference between the engine's inlet and outlet temperatures, the more efficient it is (in a gasoline engine, this would be the burning fuel temperature versus the exhaust temperature). But the *maximum* efficiency of *any* heat engine is limited to the following:

$$\textit{Efficiency} = 1 - \frac{\textit{Outlet Temperature}}{\textit{Inlet Temperature}}$$

It doesn't matter how clever the engineer is. This theoretical efficiency can be approached but never reached. It's the way the universe works. For instance, a heat engine with inlet and outlet temperatures of boiling water (373° Kelvin) and room temperature (298° Kelvin), has a maximum efficiency of 20 percent. The achievable efficiency in most engines is less than half the theoretical maximum, so the realizable efficiency is actually less than 10 percent. Only higher temperatures can improve the efficiency, and in terms of solar, only CSP systems can produce these higher temperatures.

But what about thermal loss through air, you may wonder. Small heliostats often reflect sunlight to targets 200 or more feet away. When sunlight travels through air it loses intensity very gradually. On average, about 1,350 watts/m^2 hit the outer reaches of earth's atmosphere and about 1,000 watts/m^2 reach the earth's surface. However, over a distance of 100 meters the loss is less than a quarter of one percent. This is true even at extremely low temperatures when the air is most dense. This means a heliostat can collect and transmit power over significant distances essentially without loss. Acres of sunlight can be harvested and delivered to a desired location like a thermal receiver, or one heliostat can direct a small sunny spot into a dark north-facing window located hundreds of feet away, virtually without loss. There is some loss due to the reflectors (mirrors) themselves. For example, the heliostats manufactured by Practical Solar use standard 1-foot-square glass mirror tiles that have decent reflectivity (about 85 percent) and retail for about $1.25.

Heliostats Right Now

So if heliostats make so much sense, why aren't they already mainstream? Although a person holding a mirror has little problem orienting the mirror so the reflected sunlight is directed to a desired target, it is maddeningly difficult for a machine to do this same seemingly simple task. This degree of difficulty has discouraged small companies from marketing small inexpensive heliostats, leaving heliostat development mostly to national governments and large publicly traded companies, which develop large-scale projects. The only exceptions that I am aware of (other than Practical Solar) are two companies in Germany that manufacture small heliostats. But these heliostats are used exclusively for daylighting and are too costly to be practical for heating or power applications.

Daylighting is also an important appli-ation for the Practical Solar heliostat system. A single Practical Solar heliostat targeting a north-facing window (that otherwise receives little sunlight) will supply the equivalent light of forty 100-watt incandescent light bulbs and 600 watts of heat, greatly improving the livability of the room and perhaps even the health of the inhabitants. But there are some important differences between this small-scale heliostat system and others that have come before it that make it well-suited for a host of other applications as well. The cost is lower, the installation can be done by hand, and the programming and control can be performed with user-friendly software on a standard PC.

These breakthroughs make small-scale heliostats more accessible and cost-effective. Several heliostats will make a real difference in the cost of heating a house. With the addition of a solar receiver to heat water, a thermally insulated water tank and some simple controls, it's possible to heat an entire house. Other applications that could easily be made compatible with heliostats include thermal desalination and absorption chilling.

Side view of heliostat shows the stabilizers that strengthen the mirror frame against strong winds.

Although I first started thinking about small-scale heliostats 20 years ago, it would not have been possible then to create this system. Small heliostats are a reality now because of advancements in several technologies, not a single over-reaching invention. First, the cost of structural materials has steadily risen over the past two decades while highly automated computer-controlled machining centers have lowered the cost of small precision mechanical parts. Second, home computers have become ubiquitous in the developed world, allowing complex control of heliostat arrays at very low cost. Third, the cost of position encoders and other electro-mechanical devices has greatly decreased. (Our heliostats can direct a beam of sunlight onto a target 100 feet from the heliostat to an accuracy of 5 inches.)

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Why Bigger Is Not Better

As I have already mentioned, small heliostats (about 1 m^2 reflective area) have some important potential advantages over the huge heliostats used in utility scale power towers:

- **Ruggedness**. Small heliostats are comparatively stiffer and more rugged without being bulky and heavy. Per unit area of reflecting surface, they need only be a fraction of the weight of larger heliostats.
- **Cost.** It follows that because they are lighter they use less material in their construction and therefore potentially

cost less per unit of reflecting area. Practical Solar's current pricing is $995 per heliostat. When VCRs were first introduced they cost $1,500 and weighed 30 lbs. Ten years after their introduction they cost $150 and weighed 6 lbs. A small heliostat is far less complex than a VCR. Using high production manufacturing techniques, we expect the cost of heliostats will also go down significantly over time.

- **Ease of Installation**. Small heliostats can be installed completely by hand without power tools. The installation of even a modest field of small heliostats isn't beyond the abilities of a handy homeowner.
- **Aesthetics**. Since they stand less than 5 feet tall, they are relatively unobtrusive. In most settings they blend into the background, reflecting their surroundings.
- **Opportunity.** Small heliostats can be used to harvest sunlight in locations that previously weren't suitable for solar energy systems. There are millions of properties in the US that have a sunny spot far removed from the house. Delivering just a few square meters of sunlight (a few thousand watts) can make a big difference.

Heliostats in the Future

Heliostats alone don't turn sunlight directly into electricity, nor do they constitute an integrated hot water system. Heliostats can be used by themselves for natural lighting and direct space heating, but otherwise they must be paired with other products like a thermo-electric device, a concentrating photovoltaic device or a heat engine. Many of these devices already exist and could be adapted for use with heliostats. Since small-scale heliostat systems are only just now entering the consumer market, there is not yet a compatible receiver system available—but there will be soon.

There are also exciting new technologies on the horizon that could continue to expand heliostats' usefulness. For example, companies around the world are developing ever less expensive and more efficient concentrator cell technologies. A company in Newton, Massachusetts called eM-TECH is developing a new type of thermo-electric material that will convert a temperature difference into an electrical current with astonishing efficiency at low cost. An electrical conversion efficiency of 35 percent or even higher is possible—with the remaining 65 percent of the energy going toward heating hot water.

As technology evolves and costs drop, small heliostats (whether or not they are Practical Solar's) will likely become common. Heliostat systems have the potential to meet the energy requirements of millions of residences and small businesses—and myriad other applications. Like wind power and water power before it, solar power is there for anyone who has the technology to harvest it. And 1,000 watts/m^2 is simply too great to ignore.

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Bruce Rohr is the founder of Practical Solar, Inc., a manufacturing company based in Boston that in February 2009 introduced the world's first hand-installable, PC-controlled heliostat system. Mr. Rohr also founded Cambridge Technology, Inc. in 1980, a manufacturer of scientific instruments and high-precision laser scanning equipment.