CANNED HEAT

THERMAL ENERGY STORAGE COULD BECOME A BREAKTHROUGH ENABLING TECHNOLOGY FOR SOLAR POWER. BUT THERE IS STILL SOME WORK TO BE DONE BEFORE IT **REACHES ITS POTENTIAL.**

BY D. YOGI GOSWAMI, SUDHAKAR NETI, ARUN MULEY, AND GEORGE ROE

An artist's rendering of a soon-to-open solar thermal power plant in Ivanpah, Calif. The plant will incorporate tanks to store thermal energy to enable generation of electricity after dark.

All photos courtesy of BrightSource Energy

ONE OF THE BASIC LESSONS OF INTRODUCTORY PHYSICS is that energy can be stored in different forms: the potential energy of water impounded by a dam, the chemical energy of reactants in an explosive, the mechanical energy of a coiled spring, and so on. It's how easily that stored energy can be released—and how it can be turned into work—that determines how useful that form of storage will be. One illustration of the differences of utility for stored energy came to light a few years ago, when laptop computers made headlines for catching fire: a typical lithium-ion battery was said to have nearly same energy per kilogram as a hand grenade.

While that equivalence is certainly eye-catching, many people don't realize that the difference in energy between a large Thermos of near-boiling water and the same amount of tepid water is also roughly the same as the electric energy of laptop battery. But while a laptop battery sometimes can run $100 or more, an insulated bottle containing the same energy can be bought for a fraction of that price. What's more, we are much better at mass-producing insulated containers, or at producing them at large scale, than we are at building large-scale batteries.

Of course, you can't run a computer off a cup of coffee. But one of the most promising forms of renewable energy is solar thermal power, in which mirrors concentrate sunlight onto pipes or two-dimensional receptors filled with water, oil, or low-melting point salts. The primary product of solar thermal power is fluid heated to 400 °C or higher that's capable of generating steam to run a turbine. If plant operators can find a way to store that heat, they could use it to generate electricity well after sundown or even the next morning, turning solar energy from an opportunistic source of electricity to something that's dispatchable and reliable.

For all that potential, however, the cost of large-scale thermal energy storage needs to be reduced before it significantly impacts the energy industry. Research is pointing to some promising new materials that might be able to release stored energy at very high temperatures, which is necessary for higher-efficiency turbines using Brayton or supercritical Rankine cycles. If these research programs pan out, we may someday find that the linchpin of a renewable energy system is heat stored in giant flasks.

MAIN ADVANTAGES OF TES

- Efficiency
- Can store excess energy production for use at peak times.
- Potential for integration with conventional thermal power stations.

When people think of solar power, the photovoltaic panel is what most commonly springs to mind. PV cells are pretty much ubiquitous today—desks sport PV-powered calculators and communications satellites in geosynchronous orbit rely on large photovoltaic panels. Photovoltaic cells generate electricity based on solid state physics and while they have a theoretical maximum efficiency of around 40 percent, most commercially available modules are lucky to reach half that.

Unlike PVs, concentrating solar thermal power is based on more familiar thermodynamics. Mirrors are used to concentrate sunlight to many times its natural power density; at the point of focus, the concentrated light produces heat that is then used to make steam or heat a gas that can be expanded through a turbine to generate electricity. The main advantages of CSP are the potential for integration with conventional thermal power stations (even to the point of using fossil fuels

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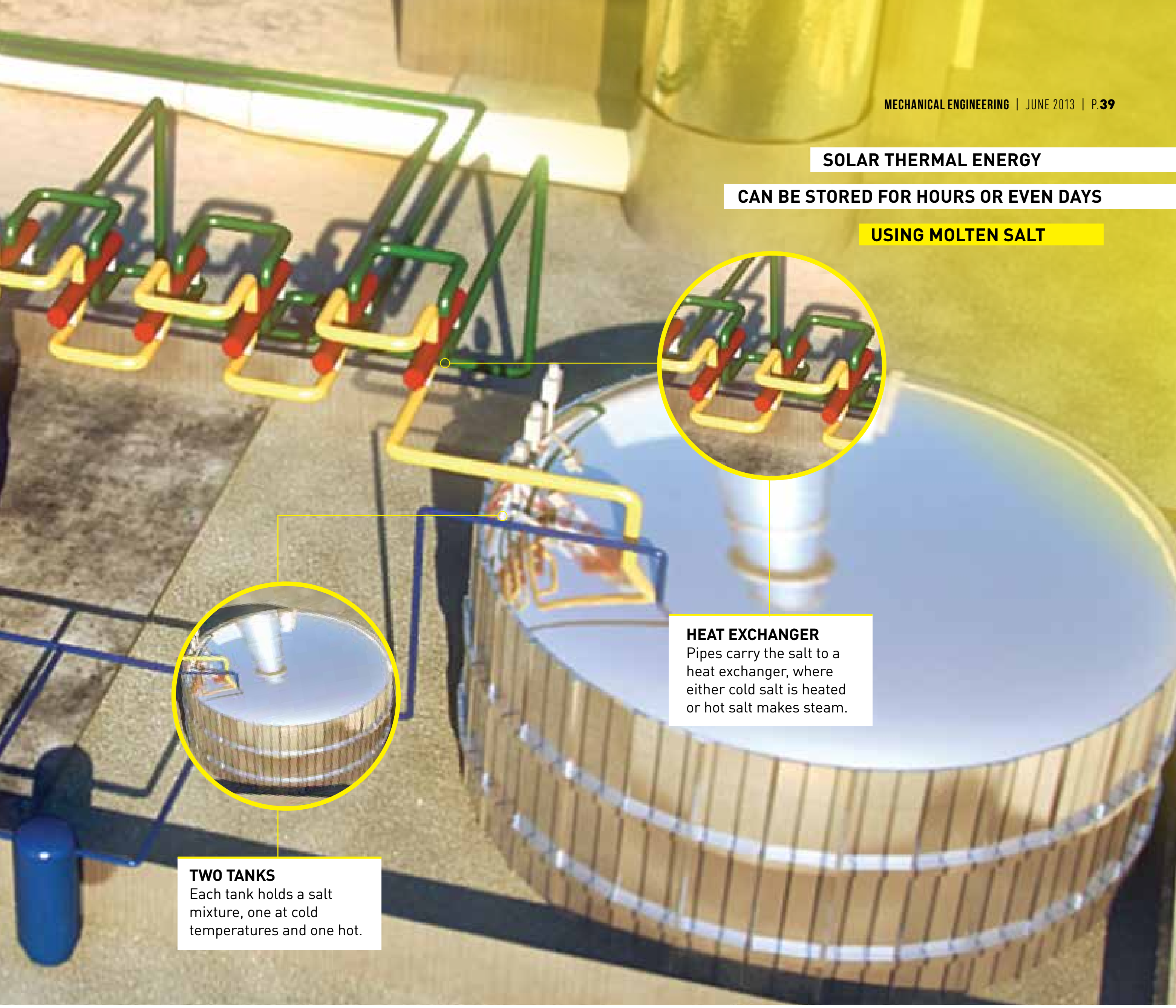


as back-up) and that thermal energy storage can be much more cost-effective and viable than battery storage of electricity.

Another potential advantage for solar thermal power is efficiency. Certain systems, for instance, can achieve very high temperatures, creating the potential to achieve power cycle efficiencies, as high as 50 percent in some cases. Combine that with a solar field efficiency of 60 to 65 percent, and a solar thermal power system could reach efficiencies of over 30 percent, which would be very expensive for PV to achieve. What's more, the heat produced by solar thermal plants isn't useful only for generating electricity; it can be applied any place process heat is needed.

Large commercial solar thermal systems come in a number of types. One version uses long parabolic mirrors to focus sunlight along a line. Gas or fluid in a pipe in that focal line will heat up; depending on the technology, the temperatures may reach 250 to 450 °C. Parabolic troughs have been deployed at facilities such as Kramer Junction in California and Las Vegas, Nevada. Compact linear Fresnel arrays (which divide the single mirror into multiple strips with a single focus) may be used in place of parabolic troughs, though they are limited to lower temperatures because of lower concentration and efficiency.

To get higher temperatures, a two-dimensional array of mirrors is needed. A field of heliostats —mirrors mounted on motorized supports that track the sun—can concentrate sunlight by a factor of 1000 or more and produce temperatures of 500 – 1000 °C. This type of solar thermal technology is the technology to be used at the 393 MW Ivanpah Solar Power Facility in California, scheduled to open this year.

One of the major drawbacks to photovoltaic power is dispatchability: Electricity is made when —and only when—the sun shines. Solar thermal, because it first produces heat rather than electricity, has a way around that problem. Rather than generating electricity immediately, the heated material could be stored in an insulated vessel and used to generate electricity at any time of the day, whether the sun is shining or not.

That thermal energy can be stored in several different ways: as a change in internal energy of a material as sensible heat, as latent heat, as thermochemical changes, or as combination of these. Changing sensible heat simply raises the temperature of a material; the energy stored is a straight function of the change in temperature. Latent heat is the energy needed to change a material from one phase to another—to boil water or melt a salt; a material changes phase without changing temperature at constant pressure. Energy can also be stored through thermochemistry, such as the reversible dissociation of ammonia under heat into nitrogen and hydrogen.

Storing thermal energy as sensible heat is the most straightforward of the three methods, and the one that's the most widely deployed. A wide range of materials from simple concrete to synthetic oils have been tried for storing thermal energy. Indeed, thick, south-facing earthen walls have long been used to store solar energy to heat buildings at night, and depending on the application, a tank of hot water will suffice to store energy cheaply and efficiently.

For thermal energy applications with temperatures below 500 °C, a popular choice is a two-tank storage system: a eutectic mixture of molten salts, such as KNO_3–$NaNO_3$, is stored in a cold tank; energy is added via a heat exchanger and the salt is moved to an insulated hot tank. Bottled up in the insulated tank, the salts retain their heat for hours, even days, until they are pumped through a heat exchanger to make steam.

While the two-tank system is simple, it can be expensive, especially since you need duplicate equipment for both the hot and cold sides of the system.

Sensible heat storage is weak in energy density because it depends on specific heat of the material. Water is one of the best mediums for storing sensible heat, at least at temperatures below 100 °C, but even then the specific heat is only 4,190 joules per kilogram for each degree increase in temperature. Latent heat stores energy much more densely: A kilogram of solidifying magnesium chloride hexahydrate salt, for instance, releases around 167,000 joules.

BOEING HAS IDENTIFIED THERMAL ENERGY STORAGE AS A TECHNOLOGY THAT MIGHT ENABLE IT TO TAKE EXCESS HEAT AND TRANSFORM IT INTO USABLE ENERGY.

An energy storage system based on latent heat released as a material changes phase can be cost-effective. Proper design of such a system can provide for isothermal heat transfer for a significant portion of the stored energy. Energy storage using a so-called phase change material can also be designed with a favorable temperature gradient in the storage tank, which enables a single tank to be used instead of two tanks, further reducing the system costs.

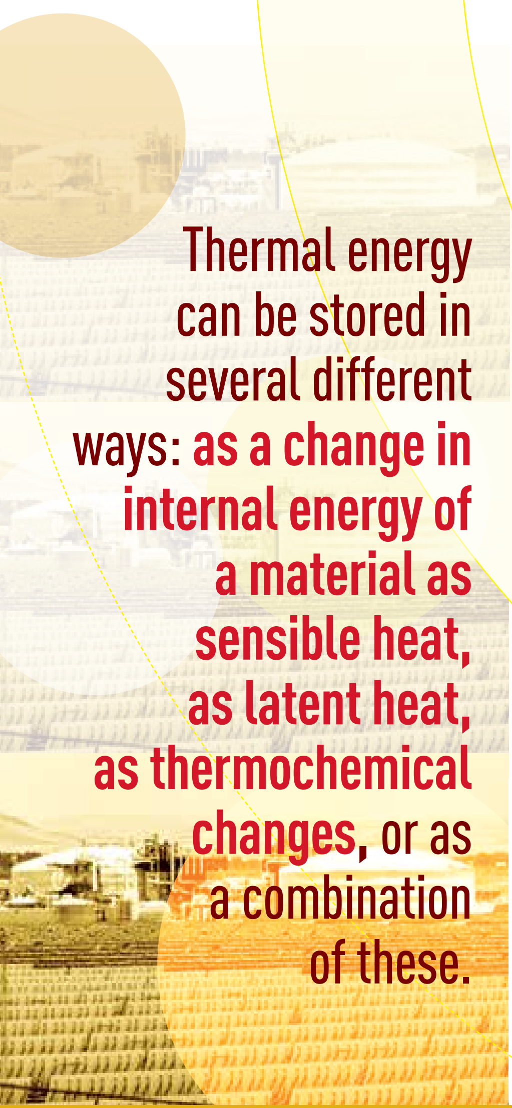
One such PCM-based storage example in Germany involves the use of salts in a tank containing numerous interlaced pipes; oil in the pipes transfers energy to and from the salt during the phase change. The system is straightforward, but there are significant problems. As the salt solidifies, it cakes on the pipes and, because salt is a poor conductor of heat, the transfer of energy from the tank to the pipes can slow or stop.

A better way to store thermal energy is with the use of encapsulated phase change materials—that is, placing the heat-storing medium inside metal or plastic balls or pipes and flowing the heat-transfer fluid around them. In some ways, it inverts the geometry of the single-tank system mentioned above. Use of PCM capsules provides much more surface area for heat transfer and with proper design does not inhibit heat transfer during storage or retrieval of the energy.

In addition to improving the transfer of heat to and from the storage material, there are several other advantages to PCM capsules. At Lehigh University, a system has been designed with capsules filled with materials that have different melting temperatures; that could allow for significant gains in the amount of usable energy that can be stored in the system. What's more, research indicates that, with a PCM aligned with the system operating temperature and using an appropriate encapsulation, costs of storage can be brought down to $15/kWh$_{th}$—even for thermal energy storage around 950 °C. That meets the U.S. Department of Energy goal for capital costs of an energy storage system.

Research into thermal energy storage isn't limited to the confines of government and academia. Private companies are investigating whether they can incorporate thermal storage into some of their systems.

One example is Boeing, which makes large commercial aircraft and multiple military



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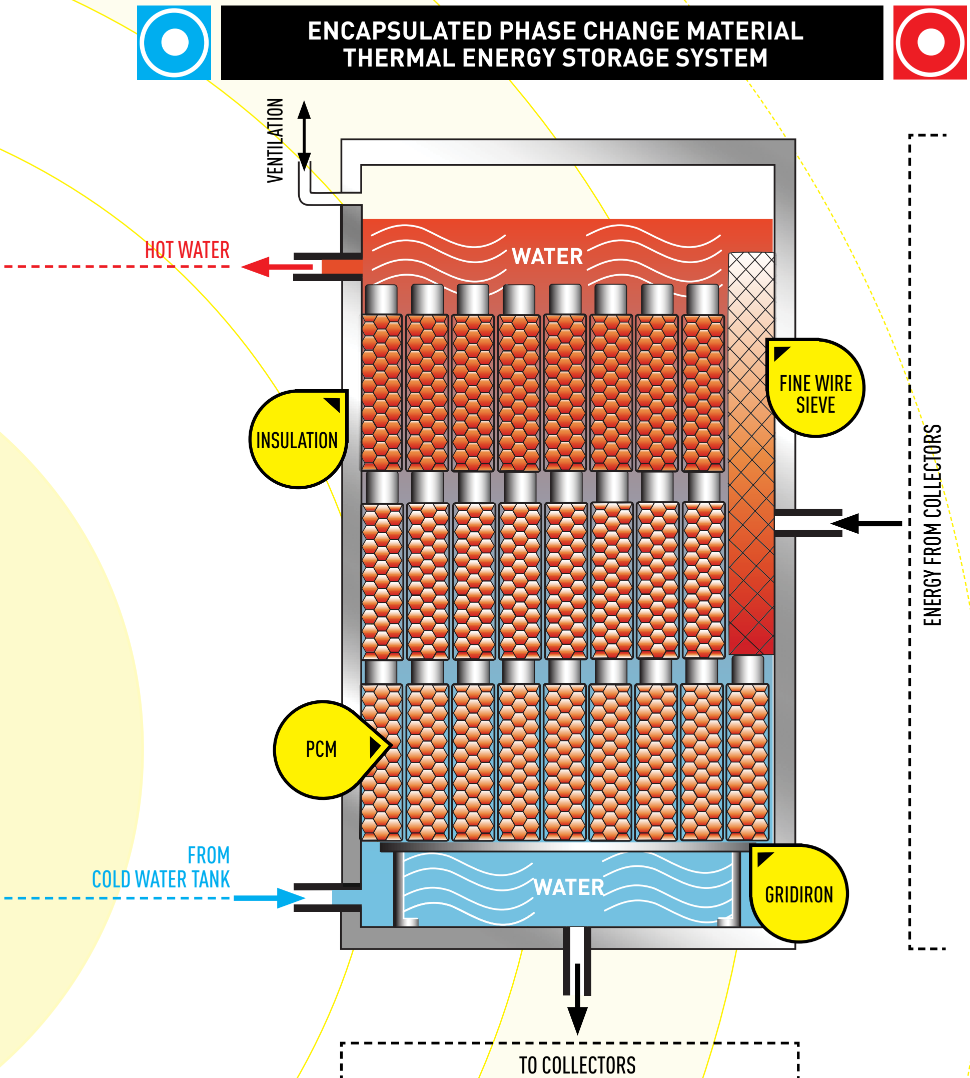

aerospace platforms. In flight, these aircraft produce excess heat in various systems, ranging from the jet engines and hydraulics to aircraft electronics. The company has identified thermal energy storage as a technology that might enable it to take this heat —which would otherwise need to be rejected at some penalty to the overall system performance—and transform it into usable energy.

For instance, it's possible that using a thermal energy storage system, aircraft turn-around times could be reduced in places where cooling of critical components is restricted due to environmental constraints. Or, surplus thermal energy could be stored temporarily until it is either needed to satisfy a local heating requirement or rejected in a "peak-shaving" fashion that enables optimal sizing of the ram air heat exchangers. More ambitiously, waste heat that was captured in a thermal energy storage system could be converted via thermoelectric materials into electricity to provide auxiliary power.

Significant development challenges remain before these potential benefits can be realized—everything from achieving the needed performance parameters (such as temperature, response time, cycle limits, and density) to managing critical interface and integration issues. And, equally important non-technical questions need to be answered, such as regulatory considerations and whether the inclusion of thermal energy storage is economically justifiable.

At several technical and panel sessions at the November ASME International Mechanical Engineering Congress and Exposition in Houston, there was much discussion of cutting edge work in thermal energy storage, including thermal energy storage materials, applications, and systems. Additionally, thought leaders and technical experts from Boeing, Koch Heat Transfer, and ReBound Technology discussed the importance of industrial applications for the aerospace industry, design considerations and technical challenges and future potential for industrial based systems. Authorities from Lehigh University, the University of South Florida, University of Florida, and Pacific Northwest National Laboratory presented their viewpoints on thermal energy storage technologies, materials, and research and development.

There is much work to be done before thermal energy storage becomes a mainstream technology—as well as unexpected challenges to be met. But it's an exciting time to be working

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in this field. There's every reason to believe that thermal energy storage can become a game-changing technology, not only for renewable energy concepts such as concentrated solar power, but wherever energy demand doesn't align exactly with energy supply. ME

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