SOLAR ENERGY WAS ONCE VIEWED AS PIE IN THE SKY. Photovoltaic cells might be suitable for running pocket calculators or communications satellites, but they could not compete with electricity from conventional power plants.

BUT RECENT ADVANCES in the production of photovoltaic panels have driven down the cost of solar power. Estimates for the levelized cost of electricity from PV range from 10 to 30 cents per kWh. And though this is still higher than the cost of generation from a newly built coal-fired thermal power station, solar power could be the cheapest electricity available in some areas within a few years, according to data from the Energy Information Agency.

Solar energy supplanting coal in producing electricity would be a milestone, but it would scarcely be the end of fossil fuel. Of the nearly 80 quadrillion Btu of oil, gas, and coal that the U.S. consumes each year, only 25 quads—about 31 percent—are used to generate electricity.

Carbon-based fuels are critical to many sectors, such as transportation. Even if electric vehicles become common, it seems unlikely that airplanes will ever be battery powered. Process heat is another important application for fossil

FOSSIL FUELS HAVE A NUMBER OF INDUSTRIAL USES BEYOND ENERGY

fuel combustion, and most industrial hydrogen is produced via the cracking of natural gas.

Solar energy is usually considered in terms of making electricity, but it also has the potential to supplant fossil fuels in the production of liquid fuels, and in driving endothermic industrial processes. Solar thermochemical processes are feasible, and a solar power concentration process that harnesses sunlight's infrared energy is the best suited technology for making solar fuels a reality.

* * *

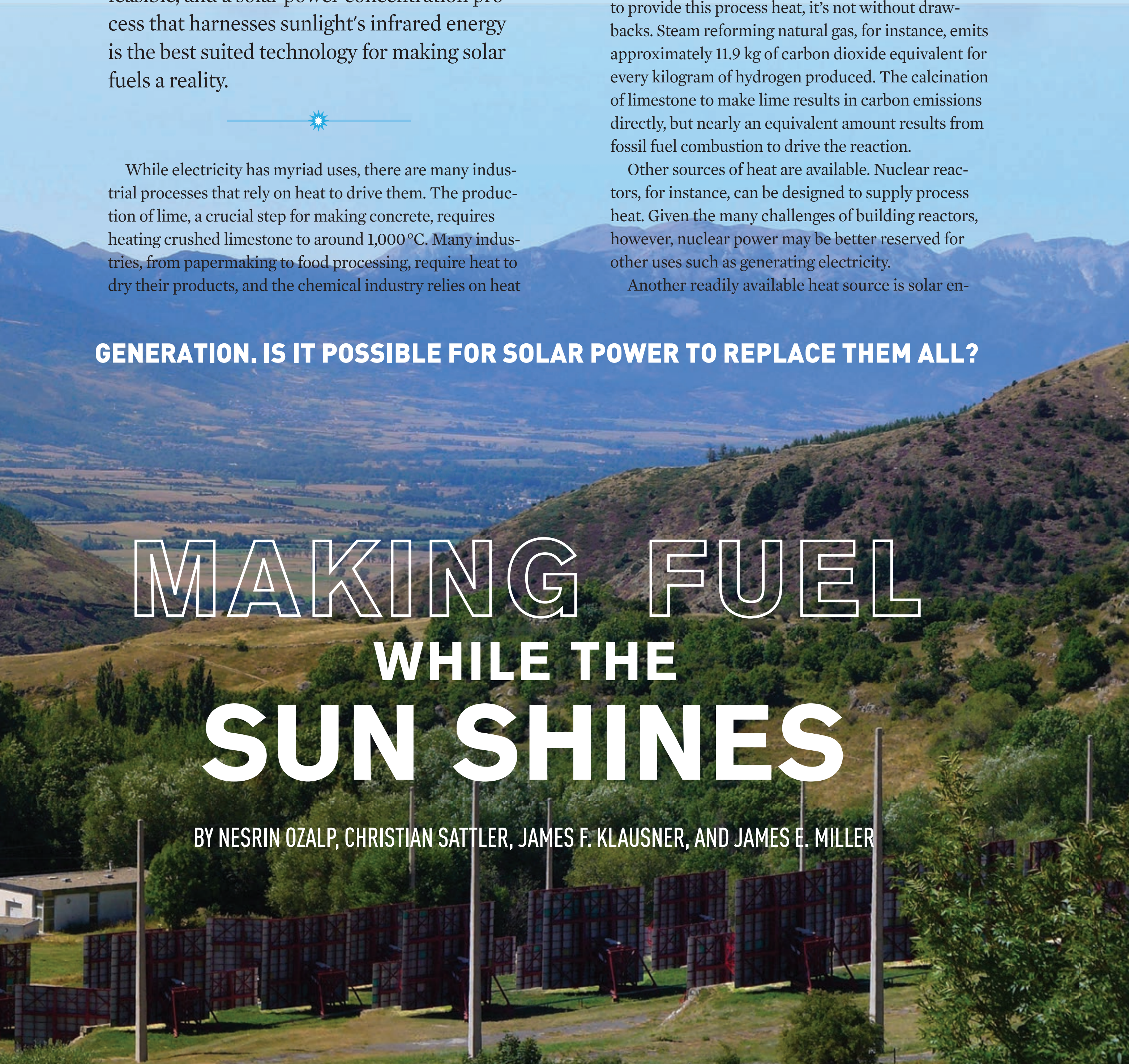
While electricity has myriad uses, there are many industrial processes that rely on heat to drive them. The production of lime, a crucial step for making concrete, requires heating crushed limestone to around 1,000 °C. Many industries, from papermaking to food processing, require heat to dry their products, and the chemical industry relies on heat to drive many reactions.

Process heat is used to produce valuable materials used in other parts of the industrial chain. Hydrogen, which is often derived from the endothermic steam reforming of natural gas, is used to produce crucial commodities such as methanol and ammonia, and is used extensively in the petroleum industry to upgrade crude oil through various hydrotreating processes.

While it's convenient to use fossil fuel combustion to provide this process heat, it's not without drawbacks. Steam reforming natural gas, for instance, emits approximately 11.9 kg of carbon dioxide equivalent for every kilogram of hydrogen produced. The calcination of limestone to make lime results in carbon emissions directly, but nearly an equivalent amount results from fossil fuel combustion to drive the reaction.

Other sources of heat are available. Nuclear reactors, for instance, can be designed to supply process heat. Given the many challenges of building reactors, however, nuclear power may be better reserved for other uses such as generating electricity.

Another readily available heat source is solar en-



GENERATION. IS IT POSSIBLE FOR SOLAR POWER TO REPLACE THEM ALL?

MAKING FUEL
WHILE THE
SUN SHINES

BY NESRIN OZALP, CHRISTIAN SATTLER, JAMES F. KLAUSNER, AND JAMES E. MILLER ergy. The sun provides an average of around 1,000 watts per square meter of power during daylight hours, which by itself provides enough for some low-temperature processes such as food drying. (Some tomatoes are marketed as “sun-dried” for good reason.) Small reflectors have enabled solar-powered water heaters to be economical for domestic use.

To obtain the temperatures needed for large industrial processes, however, large arrays of mirrors are necessary. These arrays collect the sunlight falling on many square meters or even hectares and reflect it on receivers that heat up. A concentration factor of 500 to 1,000 can yield a temperature at the receiver well over 700 °C. A solar furnace in Odeillo, France, for instance, focuses light from about 2,000 square meters of mirrored surface onto a spot 60 cm across to produce temperatures in excess of 3,200 °C—easily hot enough to vaporize iron or nickel.

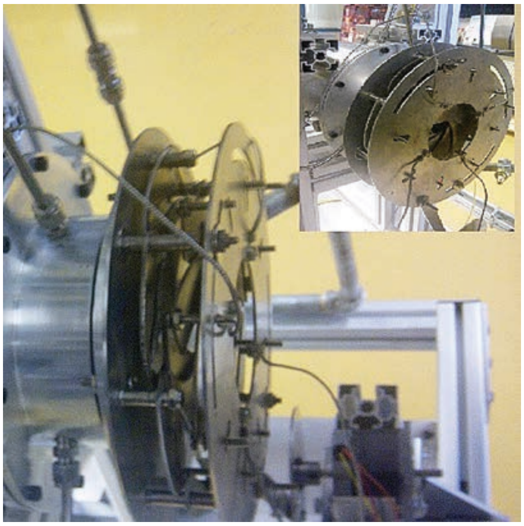
Vaporizing iron may have limited practical uses, but many industrial processes can be driven by heat from a large solar concentrator. Several research teams—including some that we have participated in—have shown the practicality of making hydrogen from water splitting via solar thermal reactions. In the most basic framework, steam flows over a high temperature metallic substrate, and as steam oxidizes the metal, hydrogen is released. Concentrated solar energy is then used to reduce the metal so that the cyclical steam oxidation can be repeated.

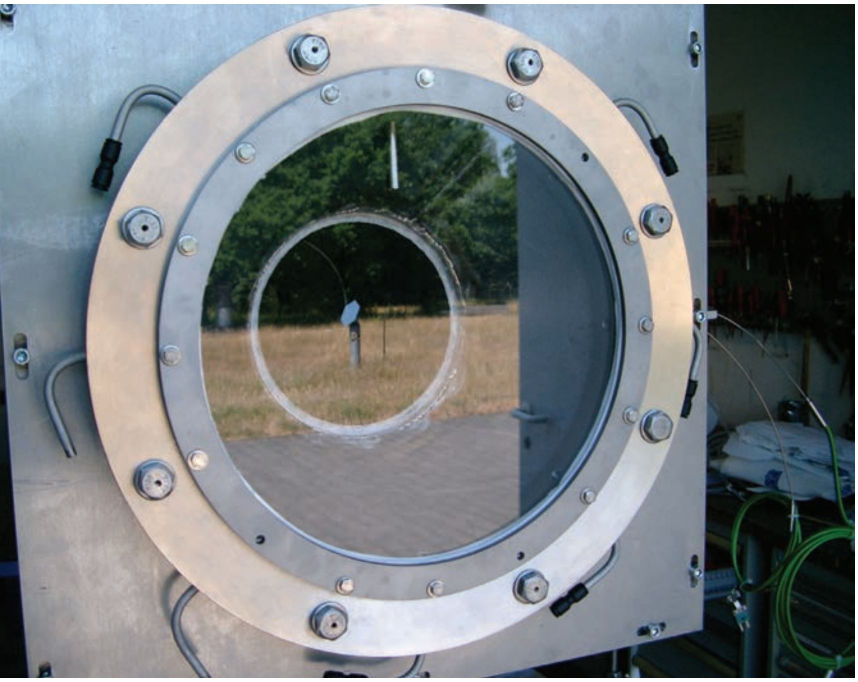
Such processes could entirely eliminate the emissions of carbon dioxide associated with fuel combustion. Other groups are working to use solar heat to crack methane for hydrogen production, which would produce fewer carbon and other hazardous emissions than current industrial practices.

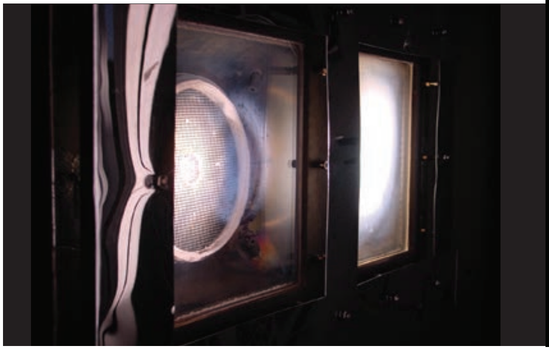
One route to making hydrogen from natural gas via solar thermochemical processes produces carbon black instead of carbon dioxide as a byproduct. Carbon black is the most important technical carbon product after metallurgical coke. An important additive for rubbers, inks, batteries, and several polymers, it is also used in power generation, soil amendment, and environmental remediation. This method of hydrogen production could potentially provide the double benefit of being both CO_2-free and cost-effective, with the production of marketable carbon products defraying the expense of hydrogen. It is also possible to produce carbon nanotubes from natural gas by tuning the cracking process conditions.

Another area in which solar commodity production may have advantages over traditional industrial practice is in the separation of pure metal and oxygen from metal oxides found naturally in many ore deposits. For example, the use of solar thermochemistry to produce metallic magnesium from magnesium oxide appears to be quite promising. Advanced aluminum-magnesium alloys are essential in keeping vehicles, such as the new Ford F150

Solar reactors up close: A single-chamber reactor (below) for thermochemical reduction of metals; a two-chamber reactor at the German Aerospace Center (below right) for producing hydrogen; an iris mechanism (above right) for controlling incoming thermal power.







Facilities such as the Mont-Louis Solar Furnace (above) and the Odeillo Solar Furnace (right and on the opening pages) concentrate sunlight to conduct thermochemical experiments.

SOLAR FUELS CAN PROVIDE A STABLE AND STRATEGICALLY IMPORTANT ENERGY RESOURCE; SOME MAY CONSIDER THEM TO BE THE IDEAL SOLUTION FOR SUSTAINABLE ENERGY INDEPENDENCE.

production model, as lightweight as possible.

Solar thermochemistry could potentially have the biggest impact in the production of hydrogen-derived fuels which would be capable of replacing those derived from fossil fuels. Hydrogen can be used directly as a fuel, and advances in fuel cell technology may one day make it an attractive substitute for gasoline or diesel. But it is also possible to use solar heat to drive processes to create fuels that are compatible with the existing hydrocarbon infrastructure.

For example, methanol is readily produced via the catalytic reaction of hydrogen with carbon dioxide. This process has been commercialized with renewable hydrogen and recovered CO_2 by Carbon Recycling International.

Alternatively, solar thermochemical processes can produce carbon monoxide from carbon dioxide and hydrogen from water, or both can be produced from the solar steam reformation of methane, and the resulting gas mixture can be used to produce more conventional liquid fuels via the Fischer-Tropsch process. (That process is used today to make synthetic fuels, but the heat to drive the reactions comes from the combustion of a portion of the fossil fuel feedstocks.) Solar thermochemistry could plausibly produce a significant fraction of the world's transportation fuels in the long-term, as technological advancements continue increasing efficiencies and driving down costs.

IN SPITE OF THEIR APPEAL, solar thermochemical processes have the same drawback that direct solar power has: the transient and diurnal nature of sunshine. Fossil fuel-powered process heat provides the sort of constant temperatures and continuous operation that simplify industrial processes and controls. Fluctuations of available solar radiation—over the course of a day, across different types of weather, and from season to season—present considerable challenges for potential solar-thermal systems. Although there are economically affordable and commercially available solutions to some of those problems, substantial research and development is still required.

One common approach to dealing with fluctuations of solar energy is storing a fraction of the solar radiation as thermal energy. This can be done at a scale that manages short-term, transient variability such as the passing of a cloud or, if more energy is stored, to allow continued production for several hours after sunset. High temperature sensible heat storage in ceramic powders would enable such a process.

Several non-storage solutions can control the power and temperature of endothermic processes rendered through concentrated solar energy approaches that reduce peak power include the partial focusing/defocusing of the sun-tracking mirrors and the use of shuttering devices that can block a fraction of the sunlight entering the receiver. Varying the mass flow rate according to the incident solar flux is another widely used technique to maintain semi-constant temperature inside a reactor.

It would be best not to simply waste the solar power. The heliostat array can account for up to 60 percent of the capital costs of a solar thermal facility; so if possible, facilities should be designed to make full use of the light falling on the mirrors.

One promising approach to obtain semi-constant temperatures inside a solar reactor is an iris-like aperture mechanism that adjusts the area of the opening through which solar energy enters the reaction chamber. The mechanism can dynamically increase or decrease the aperture as the solar flux changes. Such a mechanism has the potential to stabilize internal reactor operating conditions by minimizing radiation losses through the aperture and by responding to the fluctuations in solar flux by regulating the aperture area.

The optimum aperture size depends on the magnitude of direct normal insolation. For a particular time of the day, depending on the magnitude of direct normal insolation, there exists an optimum aperture size that can maintain the desired level of temperature inside the reactor. The power intercepted by the aperture as a function of its diameter can be calculated using the mean concentration ratio of the paraboloidal concentrator and the normal beam insolation.

An aperture size of 4 cm, for instance, intercepts a maximum of about 5.5 kW for a peak noon-time normal beam insolation of 981 W/m^2; in the morning and evening, when the insolation drops to 200 W/m^2 the same aperture size intercepts only 1.12 kW—a reduction of a factor of 5. To compensate, the aperture could open up to let in more radiation in the morning and evening, or conversely could iris down at midday so as to have a constant flux all day.

In order to compensate this dramatic change in power intercepted from morning to evening, a variable aperture might be used where the optimum size is set according to the incoming power level. Such a mechanism would conveniently work for smaller concentrating devices, such as solar furnaces.

When coupled with an energy recovery system that absorbs the sunlight that doesn't pass through the aperture, such a mechanism could make full use of the installed capacity of the heliostats irrespective of fluctuating solar radiation. For commercial solar tower installations, however, the proper control of the heliostat field will be more economical.

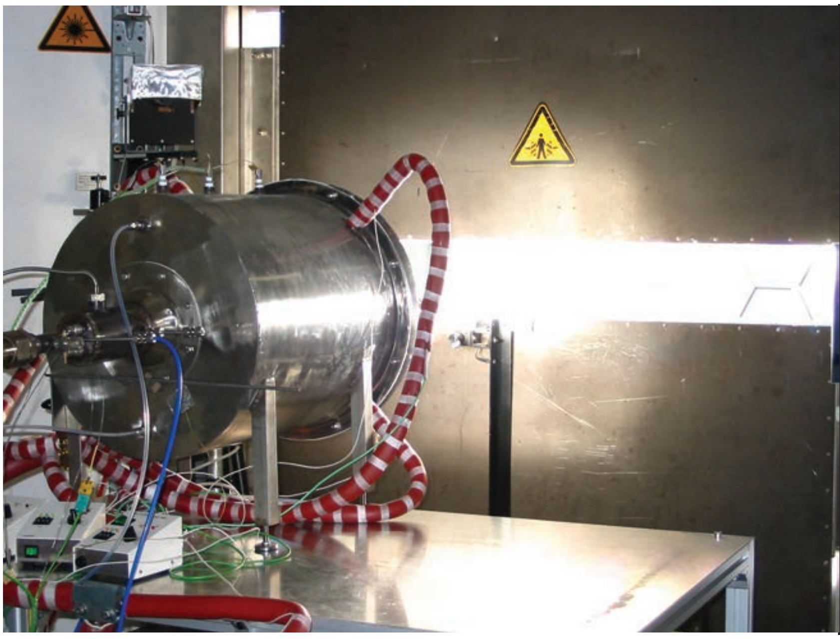
WHILE TECHNICAL CHALLENGES CAN BE MET, the factors that will ultimately determine whether solar fuels and commodities gain widespread acceptance are mostly economic. That's not the same as pure cost considerations: In markets where cheaper competitors are available, it's possible for a technology to gain an economic advantage if it meets other goals.

For solar fuels, one key benefit is the security of supply. Unlike fossil fuels, which are subject to depletion and to wide swings in prices due to the international nature of their markets, solar radiation will be available indefinitely and therefore is not dependent on economic and political changes. This means solar fuels can provide a stable and strategically important energy resource; some may consider them to be the ideal solution for sustainable energy independence.

Another strong case for solar-driven endothermic processes to supplement or even replace (over time) fossil-fueled endothermic processes concerns health. In many urban areas around the world, air pollution due to the combustion of carbon fuel is a major issue. Cleaner burning fuels from solar thermochemical processing would likely be welcomed in many places, especially China, which has notoriously opaque air.

One way in which air quality has been improved over the past century is the gradual replacement of carbon with hydrogen in commonly used fuels. Coal, which is mostly carbon by weight, was supplanted by oil and gasoline, mixtures that contain around twice as many hydrogen atoms as carbons, and then by methane, which has a hydrogen-to-carbon ratio of 4 to 1.

A solar fuel process to produce a syngas could increase the hydrogen ratio to around 6 to 1, or even remove the carbon component entirely if pure hydrogen was the final product. The benefit for society in the reduction



To Learn More

The following publications discuss many of the topics covered in this article.

M. Roeb and C. Sattler, "Isothermal water splitting," *Science*, 341, 470–471 (2013).

A. Singh, F. Al-Raqom, J. Klausner, J. Petrasch, "Production of hydrogen via an iron/iron oxide looping cycle: Thermodynamic modeling and experimental validation." *International Journal of Hydrogen Energy*, 37, 7442–7450 (2012).

E.B. Stechel and J.E. Miller, "Re-energizing CO_2 to fuels with the sun: Issues of efficiency, scale, and economics," *Journal of CO_2 Utilization*, 1, 28–36 (2013).

N. Ozalp, A. Toyama, D. Jayakrishna, R. Rowshan, and Y. Al-Hamidi, "Effect of camera-like aperture in quest for maintaining quasi-constant radiation inside a solar reactor." *ASME Journal of Mechanical Design*, 133, 021002–021008 (2011).

R.E. Bird and R.L. Hulstrom, "Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces," Technical Report No. SERI/TR-642-761, Golden, Colo. (1981).

S. Usman and N. Ozalp, "Numerical and optical analysis of solar power level adaptable solar reactor." *Heat Transfer Engineering*, 35(16/17), 1405-1417 (2014).

or elimination of carbon pollution, both in terms of local health effects and global climate issues, may more than outweigh the price differential between solar fuels and the existing fossil fuels.

Solar fuels can also perform in places where electrical power is difficult or impossible to tap. Battery-powered airplanes may be impractical, but in the 1980s, when the oil crises of the 1970s were still a fresh memory, researchers demonstrated the practicality of hydrogen-fueled aircraft. It would take an effort to create a hydrogen-powered air fleet because the existing infrastructure would take decades to replace, but converting aviation to clean fuels would be a major step toward reducing global air pollution. In the meantime carbon-based solar fuels for aeronautic applications could be produced using the Fischer-Tropsch process.

Although much work still needs to be accomplished to make solar fuels and commodities readily and easily available, research into solar thermal processes has been marked by rapid progress in recent years, with interest in the field steadily growing.

ASME has a major role in making the technology viable. This article is a follow up to the Heat Transfer Division-sponsored panel, "Clean energy as a building mark of this millennium," held at ASME IMECE in November 2013. ASME journals, such as the *Journal of Solar Energy Engineering* and the *Journal of Heat Transfer,* among many others, have recently published groundbreaking research advancing the field.

The first law of thermodynamics states that energy cannot be created. But if mechanical engineers apply themselves to optimizing processes to make thermochemically derived solar fuels and commodities viable, it will be the next best thing. They will have transformed a ubiquitous but diffuse resource into the backbone of a clean and green economic future. ME

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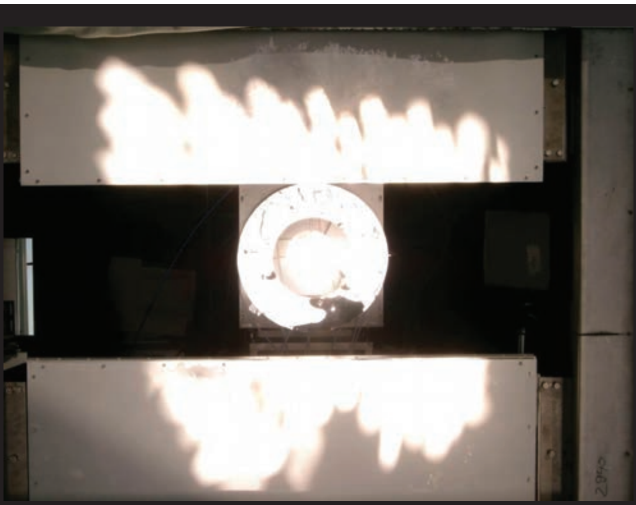
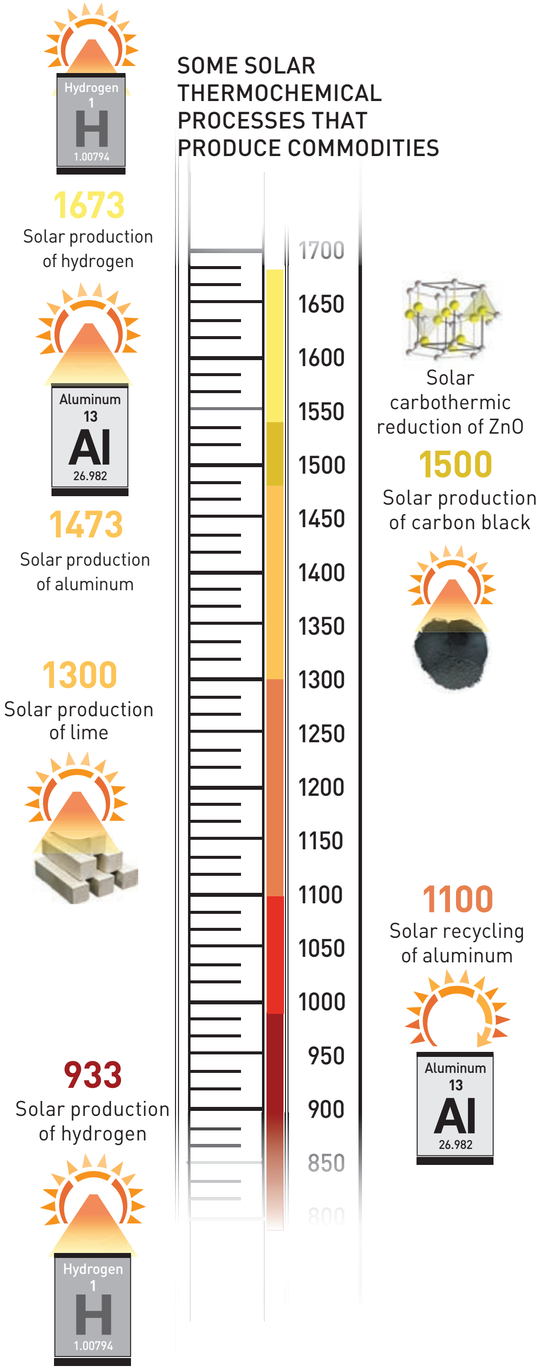


At left, a thermochemical reactor splitting water to make hydrogen. Above, a high-temperature solar reactor producing fuel.



SOME SOLAR THERMOCHEMICAL PROCESSES THAT PRODUCE COMMODITIES

Various thermochemical processes can be driven by the heat obtained via concentrated solar power. Because some reactions are possible through different chemical pathways, there may be more than one temperature at which a commodity material can be produced. (All temperatures in Kelvin.)