

INTRODUCTION

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The supply and demand of energy determine the course of global development in every sphere of human activity. Sufficient supplies of clean energy are intimately linked with global stability, economic prosperity, and quality of life. Finding energy sources to satisfy the world's growing demand is one of society's foremost challenges for the next half-century. The importance of this pervasive problem and the perplexing technical difficulty of solving it require a concerted national effort marshalling our most advanced scientific and technological capabilities.

THE ENERGY CHALLENGE

The world now uses energy at a rate of approximately 4.1×10^{20} joules/yr, equivalent to a continuous power consumption of 13 trillion watts, or 13 terawatts (TW). Even with aggressive conservation and energy efficiency measures, an increase of the Earth's population to 9 billion people, accompanied by rapid technology development and economic growth world-wide, is projected to produce more than double the demand for energy (to 30 TW) by 2050, and more than triple the demand (to 46 TW) by the end of the century. The reserves of fossil fuels that currently power society will fall short of this demand over the long term, and their continued use produces harmful side effects such as pollution that threatens human health and greenhouse gases associated with climate change. Alternative renewable fuels are at present far from competitive with fossil fuels in cost and production capacity. Without viable options for supplying double or triple today's energy use, the world's economic, technological, and political horizons will be severely limited.

SOLAR ENERGY

Our primary source of clean, abundant energy is the sun. The sun deposits 120,000 TW of radiation on the surface of the Earth, far exceeding human needs even in the most aggressive energy demand scenarios. The sun is Earth's natural power source, driving the circulation of global wind and ocean currents, the cycle of water evaporation and condensation that creates rivers and lakes, and the biological cycles of photosynthesis and life. Covering 0.16% of the land on Earth with 10% efficient solar conversion systems would provide 20 TW of power, nearly twice the world's consumption rate of fossil energy and the equivalent 20,000 1-GW_e nuclear fission plants. These comparisons illustrate the impressive magnitude of the solar resource, providing an energy stream far more potent than present-day human technology can achieve.

All routes for utilizing solar energy exploit the functional steps of *capture*, *conversion*, and *storage*. The sun's energy arrives on Earth as radiation distributed across the color spectrum from infrared to ultraviolet. The energy of this radiation must be captured as excited electron-hole pairs in a semiconductor, a dye, or a chromophore, or as heat in a thermal storage medium. Excited electrons and holes can be tapped off for immediate conversion to electrical power, or transferred to biological or chemical molecules for conversion to fuel. Natural photosynthesis produces fuel in the form of sugars and other carbohydrates derived from the reduction of CO₂ in the atmosphere and used to power the growth of plants. The plants themselves become available

as biomass for combustion as primary fuels or for conversion in reactors to secondary fuels like liquid ethanol or gaseous carbon monoxide, methane, and hydrogen. We are now learning to mimic the natural photosynthetic process in the laboratory using artificial molecular assemblies, where the excited electrons and holes can drive chemical reactions to produce fuels that link to our existing energy networks. Atmospheric CO₂ can be reduced to ethanol or methane, or water can be split to create hydrogen. These fuels are the storage media for solar energy, bridging the natural day-night, winter-summer, and cloudy-sunny cycles of solar radiation.

In addition to electric and chemical conversion routes, solar radiation can be converted to heat energy. Solar concentrators focus sunlight collected over a large area to a line or spot where heat is collected in an absorber. Temperatures as high as 3,000°C can be generated to drive chemical reactions, or heat can be collected at lower temperatures and transferred to a thermal storage medium like water for distributed space heating or steam to drive an engine. Effective storage of solar energy as heat requires developing thermal storage media that accumulate heat efficiently during sunny periods and release heat slowly during dark or cloudy periods. Heat is one of the most versatile forms of energy, the common link in nearly all our energy networks. Solar thermal conversion can replace much of the heat now supplied by fossil fuel.

Although many routes use solar energy to produce electricity, fuel, and heat, none are currently competitive with fossil fuels for a combination of cost, reliability, and performance. Solar electricity from photovoltaics is too costly, by factors of 5–10, to compete with fossil-derived electricity, and is too costly by factors of 25–50 to compete with fossil fuel as a primary energy source. Solar fuels in the form of biomass produce electricity and heat at costs that are within range of fossil fuels, but their production capacity is limited. The low efficiency with which they convert sunlight to stored energy means large land areas are required. To produce the full 13 TW of power used by the planet, nearly all the arable land on Earth would need to be planted with switchgrass, the fastest-growing energy crop. Artificial photosynthetic systems are promising routes for converting solar energy to fuels, but they are still in the laboratory stage where the principles of their assembly and functionality are being explored. Solar thermal systems provide the lowest-cost solar electricity at the present time, but require large areas in the Sun Belt and breakthroughs in materials to become economically competitive with fossil energy as a primary energy source. While solar energy has enormous promise as a clean, abundant, economical energy source, it presents formidable basic research challenges in designing materials and in understanding the electronic and molecular basis of capture, conversion, and storage before its promise can be realized.

THE WORKSHOP ON SOLAR ENERGY UTILIZATION

The U.S. Department of Energy (DOE) Office of Basic Energy Sciences held a Workshop on Solar Energy Utilization on April 18–21, 2005, in Bethesda, Maryland, to examine the challenges and opportunities for the development of solar energy as a competitive energy source. The workshop brought together 200 participants representing the basic science and technology of solar energy utilization. Participants were drawn from academia, industry, and national laboratories in the United States, Europe, and Asia, with interdisciplinary expertise spanning physics, chemistry, biology, materials, and engineering. Their charge was to identify the technical barriers to large-scale implementation of solar energy and the basic research directions

showing promise to overcome them. The workshop focused on the grand challenges in solar energy research, where scientific breakthroughs will produce revolutionary, not evolutionary, progress in bringing solar conversion a significant share of the energy marketplace.

The workshop comprised panels that examined the conversion of solar energy into three end products: solar electricity, solar fuels, and solar thermal conversion. The chairs of the panels and subpanels were drawn from universities, research institutions, and national laboratories. Pat Dehmer, Director of DOE's Office of Basic Energy Sciences, launched the opening plenary session of the workshop, presenting the charge to participants and the scope. Energy experts from academia and industry set the stage with plenary talks on future energy demand, potential sources of supply, the impact of energy on environment, and the status of commercial solar technologies. Scientists from the DOE's Office of Energy Efficiency and Renewable Energy briefed the participants on the accomplishments and outlook for its solar energy programs. The chairs of the workshop panels presented the current scientific status and the grand challenges in solar electric, solar fuels, and solar thermal conversion.

Following the opening plenary session, the participants divided into panels and subpanels examining solar electric, solar fuels, and solar thermal conversion options (see Appendix 3 for the workshop schedule). Each of these panels invited expert speakers to analyze the grand challenges and scientific routes to achieve them. The sub-panels then developed a set of high-priority research directions with potential to produce revolutionary, not evolutionary, breakthroughs in materials and processes for solar energy utilization. These Priority Research Directions (PRDs) are the major output of the workshop and are presented in this report.

SOLAR ENERGY OUTLOOK

The scientific stage is set for rapid progress in solar energy research. The last five years have seen rapid advances in nanoscience and nanotechnology, allowing unprecedented manipulation of the nanoscale structures controlling solar capture, conversion, and storage. Light interacts with materials on the scale of its wavelength, a few hundred nanometers. Energy capture occurs via excited electron states confined by defect structures or interfaces to dimensions of tens of nanometers. Conversion of excited electrons to fuels such as ethanol, methane, or hydrogen occurs in chemical reactions at the scale of molecules. These nanoscale processes have never been more accessible to observation and manipulation. Advances in fabrication of nanoscale structures by top-down lithography and bottom-up self-assembly are rapidly broadening our horizons for creating and interconnecting the functional units for capture, conversion, and storage of solar energy. Parallel advances in experimental tools that probe complex systems at ever shorter length and time scales by electron, X-ray, and neutron scattering at major facilities and by the explosion of scanning probe microscopies at the benchtop are now revealing secrets of electron transfer, catalytic activity, and chemical transformation that have long been hidden. Advances in density functional theory coupled with multinode computational clusters now enable accurate simulation of the behavior of multithousand atom complexes that mediate the electronic and ionic transfers of solar energy conversion. These new and emerging nanoscience capabilities bring a fundamental understanding of the atomic and molecular processes of solar energy utilization within reach.

The revolution in biology is a second major force enabling rapid progress in solar energy research. The twin triumphs of genome sequencing and protein production promise unprecedented control of the natural assembly process of photosynthetic systems, with deeper insights into the role of specific proteins in mediating specific functions. Natural photosystems show remarkable robustness, often functioning effectively for decades through sophisticated systems of protein repair and replacement, and by implementing defect-tolerant networks of redundancy. We are on the verge of understanding these powerful natural longevity mechanisms, and of applying them to our own designs for synthetic molecular machines. Self-repair and defect tolerance are powerful new paradigms that we can adapt from nature to extend the life of artificial solar conversion systems by many decades. Structural biology now allows determination of the atomic positions of biocatalysts like hydrogenase and the solar water-splitting complex in Photosystem II to the 3.5 Å level. Such information brings us tantalizingly close to the ability to reproduce their structures and functions artificially. This is the kind of breakthrough that will generate qualitatively new routes to solar energy conversion: deconstruction of natural solar energy converters followed by reconstruction of artificial variants that maximize targeted objectives. While such scientific capability is within sight, bringing it within reach requires further breakthroughs in biology and nanoscience.

THE REPORT

This report presents information on several levels. The Executive Summary describes the motivation and challenge of meeting world energy demands over the next century with the solar resource. It presents in capsule form the research opportunities and the scientific gaps to making sunlight a significant player in the energy marketplace. The Technology Assessments describe the present state of commercial technology for utilizing solar energy. The Panel Surveys of Solar Electric, Solar Fuel, and Solar Thermal Conversion present the scientific basis of each of these fields and the grand challenges that must be met for solar energy to become competitive with fossil fuel in supplying our energy needs. The Priority Research Directions represent the collective wisdom of the workshop and are its most specific output. They identify the high-priority research directions that address the grand challenges of solar energy utilization and promise revolutionary progress in bringing solar energy to its full potential in the energy marketplace.