

CONCLUSION

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Global demand for energy will more than double by mid-century and more than triple by the century's end. Meeting this demand is society's foremost challenge for achieving vibrant technological progress, economic growth, and political stability over the next 50 years. Incremental advances in existing energy technologies will not bridge the gap between today's production and tomorrow's needs. Additional energy sources must be found over the next half-century with the capacity to duplicate today's energy output.

The Sun is the champion of energy sources. It delivers more energy to Earth in an hour than we use in a year from fossil, nuclear, and all renewable sources combined. Its energy supply is inexhaustible in human terms, and its use is harmless to our environment and climate. Despite the Sun's immense capacity, we derive less than 0.1% of our primary energy from sunlight.

The enormous untapped potential of the Sun is a singular opportunity to meet our future energy needs. The Basic Energy Sciences Workshop on Solar Energy Utilization examined three routes for converting sunlight to useful energy through electricity, fuels, and heat. These energy conversion products couple naturally into our existing energy networks. The Workshop identified 13 high-priority research directions with the potential to eliminate the huge gap separating our present tiny use of the solar resource from its immense capacity. Bridging this gap requires revolutionary breakthroughs that come only from basic research. We must understand the fundamental principles of solar energy conversion and develop new materials that exploit them.

There is considerable common ground underlying the three conversion routes of sunlight to electricity, fuel, and heat. Each follows the same functional sequence of capture, conversion, and storage of solar energy, and they exploit many of the same electronic and molecular mechanisms to accomplish these tasks. A major challenge is tapping the full spectrum of colors in solar radiation. The absorbing materials in the current generation of photocells and, artificial photosynthetic machines typically capture only a fraction of the wavelengths in sunlight. Designing composite materials that effectively absorb all the colors in the solar spectrum for conversion to electricity, fuel, and heat would be a crosscutting breakthrough.

Captured solar energy must be transported as excited electrons and holes from the absorber to chemical reaction sites for making fuel or to external circuits as electricity. Nature transmits excited electrons and holes without energy loss through sophisticated assemblies of proteins whose function we are just beginning to understand with genome sequencing and structural biology. These "smart materials" react to the local molecular environment to protect their precious cargoes and hand them off to neighboring functional units when the molecular stage is properly set. Understanding and adapting nature's methods of electron and hole manipulation would create revolutionary new approaches to transferring captured solar energy within materials.

Materials discoveries often launch revolutionary new development routes. Photovoltaic conversion is now looking at a host of new materials to replace silicon, including inexpensive organic semiconductors ("plastic photocells"), thin polycrystalline films, organic dye injectors,

and quantum dots. Quantum dots are especially exciting for their tunable absorption wavelength, their quantum conversion efficiency above 100% through multiple-exciton generation, and their easy fabrication through self-assembly. The diversity of new materials in accessible nanoscale architectures promises to spawn breakthroughs in photovoltaic concepts and performance that could break the 50% efficiency level.

Solar thermal conversion is one of the most promising directions of solar energy research. Almost all our existing energy networks rely on heat and heat engines as essential links, from industrial processing of chemicals to electricity production to space heating itself. Most of the required heat is produced by combustion of fossil fuels, but it could be supplied as effectively by solar thermal conversion. Solar concentrators produce temperatures up to 3,000°C, far hotter than conventional furnaces and capable of driving reactions like splitting water or decomposing metal oxides that produce chemical fuel without expensive catalysts. Lower-temperature heat can be used to drive steam engines that produce electricity from sunlight with 30% efficiency, higher than the present generation of commercial photocells. Reduced cost, higher efficiency and longer lifetime for solar space-heating systems would create enormous energy impact. Promising breakthrough directions for solar thermal research are materials that can withstand the high temperatures and corrosive chemical environments in solar furnaces, and materials for high-capacity, slow-release thermal storage. The ability to accumulate heat during the day, possibly storing it in an embedded phase transition, and release it in a controlled manner at night would enable solar thermal applications to operate 24 hours per day.

Research in solar energy conversion sits squarely at the intersection of physics, chemistry, biology and nanoscience. Photosynthesis is the most successful solar energy converter on Earth, converting 90 TW of solar energy to sugars and carbohydrates. Through advances in structural biology, genome sequencing, and proteomics, we are learning the molecular pathways of photosynthesis, and beginning to reproduce some of its simpler functions in artificial self-assembled structures in the laboratory. The insights generated by these fascinating studies will enable us to produce faster-growing energy crops; adapt the cheap, efficient catalysts of enzymes to synthetic solar conversion schemes; and create artificial molecular machines that turn sunlight, water, and CO₂ into chemical fuel. Photovoltaic systems are turning to organic semiconductors and metal oxide-organic dye composites for cheaper high performance materials. Organic molecules display a host of novel photo-excitation and electron transfer phenomena that open promising and still-uncharted new horizons for photovoltaic conversion. Biology provides energy conversion paradigms that are qualitatively different from those of hard materials. The biological concepts of self-repair and defect-tolerant networks give plants lifetimes of 30 years or more. Their application to artificial photovoltaic and solar thermal conversion systems promises to dramatically extend their useful lives.

The physical, chemical, and biological pathways of solar energy research meet in nanoscience. Top-down and bottom-up fabrication of complex nanoscale architectures enables assembling and interconnecting functional molecular units for solar energy capture, conversion, and storage with precision and reliability never before attainable. Scanning probe microscopies on the benchtop, electron microscopy with atomic resolution, and in situ experiments at high-intensity X-ray and neutron sources can now reveal the structure and dynamics of solar conversion at the molecular level. Sophisticated quantum chemistry simulations using density functional theory can now predict the electronic and structural behavior of multithousand atom clusters like those that

mediate solar conversion. These emerging tools of nanoscale fabrication, characterization, and simulation bring fundamental understanding and control of the molecular mechanisms of solar energy conversion within reach. The cross-fertilization of nanoscale biology, chemistry, and physics is a new feature that creates fascinating interdisciplinary routes to solar conversion. The strong need for doubling our energy output in the next half-century, the singular capacity of the sun as a source of clean, abundant energy, and rapid advances in the physics, chemistry and biology of solar conversion at the nanoscale are compelling motivation for a coordinated basic research program on solar energy utilization.

