A Progress Review of the Nanotechnology for Solar Energy Collection and Conversion (*Solar*) NSI

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Solar energy is a promising alternative energy source that can help mitigate global climate change, reduce dependence on foreign oil, improve the economy, and protect the environment. The Solar Nanotechnology Signature Initiative (NSI) was launched in 2010 based upon the realization that the levelized cost from solar energy technology was not yet economically competitive with conventional fossil fuel technologies. The white paper[1] for this initiative identified new innovations and fundamental breakthroughs that would overcome the limits of existing technologies and help accelerate the development of economical solar energy technologies. The goals of the Solar NSI were to improve understanding of conversion and storage phenomena at the nanoscale; improve nanoscale materials, characterization, and properties for solar technology; and help enable economical nanomanufacturing of robust devices. To advance these goals, the seven Federal agencies[2] participating in this NSI identified the following three thrust areas to focus their R&D efforts:

1. Improve photovoltaic solar electricity generation with nanotechnology.
2. Improve solar thermal energy generation and conversion with nanotechnology.
3. Improve solar-to-fuel conversions with nanotechnology.

The spotlight provided by the formation of the Solar NSI brought together representatives from agencies participating in the National Nanotechnology Initiative (NNI) to address strategically important technical areas identified in the 2010 white paper, thereby seeding an interagency community of interest. Several examples of the accomplishments and collaborations of the Federal agencies participating in the Solar NSI are noted below.

The Solar NSI has provided a valuable spotlight on critical scientific challenges facing solar technologies and on the programs within the participating agencies that address these issues. The strength of these interactions and the active community that has developed make the continued focus of a signature initiative unnecessary. Although these important activities will continue, fiscal year 2015 will be the last year they are reported under the NSI mechanism, and the NSI spotlight will transition to other high-priority areas for the NNI.

Accomplishments

Since the 2010 launch of the Solar NSI, participating agencies have supported many projects that have addressed the technical obstacles identified in the white paper. These projects have not only developed the foundation for future success, they have already produced significant achievements, a few of which are highlighted below, categorized by thrust area.

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[1] www.nano.gov/NSISolar

[2] Department of Energy, National Institute of Standards and Technology, National Science Foundation, Department of Defense, Intelligence Community, National Aeronautics and Space Administration, and U.S. Department of Agriculture/National Institute of Food and Agriculture

Thrust 1: Improving Photovoltaic Solar Electricity Generation with Nanotechnology

Nanotechnology can help overcome current performance barriers and substantially improve the conversion of solar energy into electricity. The Solar NSI has supported an integrated, multidisciplinary, experimental, and theoretical effort to drive transformational changes in the way solar cells are conceived, designed, and manufactured.

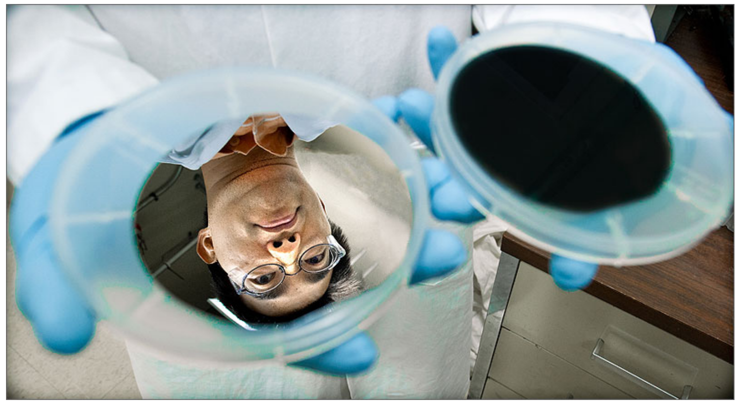

Figure 1. A silver wafer reflects the face of an NREL research scientist before the wafer is washed with a mix of acids that etch holes, absorbing light and turning the wafer black. (Source: Dennis Schroeder/NREL)

The Department of Energy (DOE) Solar Energy Technologies Office[3] supported a research team at the National Renewable Energy Laboratory (NREL) that earned an R&D 100 Award. The Black Silicon Nanocatalytic Wet-Chemical Etch emerged from work by NREL photovoltaic researchers who demonstrated that "black silicon" solar cells (Figure 1), which have been chemically etched to create a texture that appears black, can better absorb the sun's energy.[4] The research team created nanoscale features in silicon using catalytic etching of metals by nanoparticles. This development enabled the demonstration of a new world record for energy conversion efficiency by black silicon solar cells of 18.2%. NREL licensed the technology to Natcore Technology in 2011.[5]

An illustration of a project evolving from the research and development stage to that of applied technology involves a silicon nanowire investigation. Researchers were able to achieve a wire array solar cell with 95 percent light absorption, 9% conversion efficiency, and an 80 percent fill factor. The final breakthrough lay in achieving this result using only 1% of the silicon normally used in a thin-film cell. This project, initially sponsored by the DOE Office of Science, was picked up by the DOE Solar Energy Technologies program. The work resulted in the formation of a startup company that raised venture capital and won an incubator research award from DOE.[6]

National Aeronautics and Space Administration (NASA) efforts in solar energy research are focused on improving the performance and space environmental durability of photovoltaic technologies that provide large amounts of power for spacecraft and habitats covering a wide range of NASA mission requirements.[7] The potential for increased solar cell conversion efficiency through more efficient use of the solar spectrum by the incorporation of quantum structures (dots and rods) into the solar cell structure and carbon nanotubes and graphene to improve charge transport is the primary focus of these efforts. Such

[3] www.energy.gov/eere/renewables/solar
[4] www.nrel.gov/news/features/2010/1519
[5] www.natcoresolar.com/news/natcore-receives-exclusive-license-from-nrel-to-develop-black-silicon-solar-cells/
[6] www.energy.gov/eere/sunshot/past-sunshot-incubator-projects
[7] www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_10_nanotechnology_final.pdf

modifications to the solar cell structure could also improve radiation hardness, decrease mass, and improve the structural flexibility of future devices. These nanotechnologies could potentially lead to the development of conformal, radiation-hard photovoltaic materials with efficiencies in excess of 30% that could be incorporated into the outer structure of a habitat or rover and provide additional power to charge onboard batteries.

The Department of Defense (DOD) and NASA funded a multi-university effort and performed internal research investigating novel InAs/GaAs-based intermediate-band solar cell concepts. NASA Glenn Research Center assisted the National Reconnaissance Office (NRO) by growing indium arsenide (InAs) quantum dots for high-efficiency solar cells in cooperation with EMCORE and the Rochester Institute of Technology, which has a NASA Space Act Agreement. The Air Force Research Laboratory also co-funded this project.

One example of a Solar NSI participant supporting the evolution of an R&D breakthrough to large-scale domestic manufacturing is the Intelligence Community (IC). In 2012, the IC, through the NRO, supported the transition of quantum dot solar cell technology to a major manufacturer of commercial solar cells. This technology is essential in achieving up to 35% efficiency in space-based solar cells and greater than 40% efficiency in terrestrial solar cells. This invention is expected to provide an increase of up to 23% in power for U.S. satellites.[8]

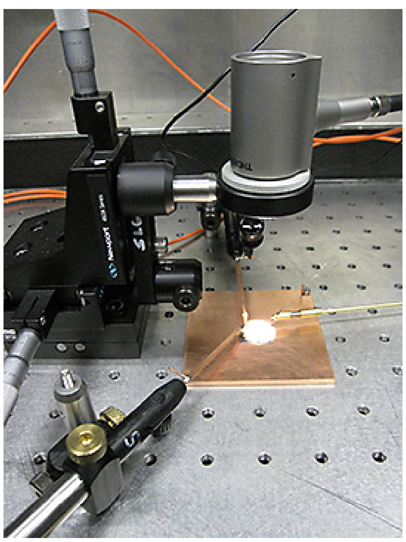

Figure 2. NIST Super-Continuum Laser Solar Simulator. (Source: NIST)

Participating agencies have also developed tools to support nanotechnology for solar energy research. The National Institute of Standards and Technology (NIST) Super-Continuum Laser Solar Simulator (Figure 2)[9] has contributed to research in support of the Solar NSI by enabling localized, illuminated characterization of nanostructures in photovoltaic materials. This laser-based solar simulator produces a spectral distribution almost identical to sunlight at wavelengths of 450–1750 nm, and does so in a readily focused beam that can be easily adapted to examine the latest generation of nanoscale, multicell, and multi-layer photovoltaic (PV) configurations. NIST has also applied scanning microwave microscopy to PV materials and is refining scanning microwave probe technology for improved reliability. Transient laser spectroscopy methods are being employed to directly measure nanoscale charge carrier processes in organic PV materials to improve solar cell efficiencies. NIST has developed *in situ* measurements of the nanoscale structure of organic PV materials under processing conditions that enable correlation between processing methods and device performance.

Thrust 2: Improving Solar Thermal Energy Generation and Conversion with Nanotechnology

Utility-scale solar projects are generally categorized in one of two basic groups: concentrating solar power (CSP) and photovoltaic.[10] Improvements can be achieved in parabolic trough, solar tower, and dish

[8] www.nano.gov/sites/default/files/pub_resource/nni_2013_budget_supplement.pdf
[9] www.nist.gov/pml/div686/grp09/super-continuum-laser-solar-simulator.cfm
[10] www.nrel.gov/docs/fy12osti/51137.pdf

collectors through the use of innovative liquid heat transfer fluids that contain nanoparticles and high-efficiency solar optical absorption materials and coatings. Nanoengineered thermoelectric materials can also improve the conversion of thermal energy to electricity.

In a program called Nanoparticle-Enhanced Ionic Liquids (NEILs) under the DOE SunShot Initiative, the Savannah River National Laboratory performed research to better understand the thermal stability of ionic liquids (ILs).[11] The approach of this project is to determine thermal stability for both the neat ILs and the nanoparticle-enhanced ionic liquids, evaluate binary mixtures of ILs, and identify best candidates to investigate with the addition of nanoparticles. NEILs are a distinct subset of organic compounds that are fundamentally different from traditional molecular solvents and inorganic molten salts because of their low melting temperature and ionic nature. At the end of this project, Savannah River intends to have developed a fluid capable of operation at 500 °C in a parabolic trough system. This is approximately 100 °C higher than most commercially available systems.

Another example is the development of a nanoparticle-based material for solar thermal energy applications designed to absorb and convert to heat more than 90% of the sunlight that it captures. The University of California at San Diego, under the SunShot-supported High-Performance Nanostructured Coating program,[12] developed a new low-cost and scalable process for fabricating spectrally selective coatings (SSCs) to be used in solar absorbers for high-temperature concentrated solar power systems. These refractory, nanoparticle-based coatings achieved an effective solar absorbance greater than 94% and an effective infrared emission lower than 7% at 750 °C. This could enable high thermal conversion efficiencies (≥ 90%) and increased temperature ranges for heat-transfer fluids (≥ 650 °C). The research being pursued under this project employs surface-protected semiconductor nanoparticles, which are fabricated by a highly scalable particle synthesis method with desired size distributions. By engineering the material properties and morphologies of the nanoparticle coating, the proposed SSCs simultaneously possess the attributes of high performance, low cost, and high-temperature durability.

The DOE Energy Frontier Research Centers (EFRCs) also address the technical challenges identified in Thrust 2. The following are two EFRC examples:

- The mission of the Center for Solar and Thermal Energy Conversion (CSTEC)[13] at the University of Michigan is investigating the fundamental processes that govern the efficiency of solar and thermal energy conversion in nanostructured, complex, and low-dimensional inorganic, hybrid, and organic materials. CSTEC researchers are using femtosecond-pulse lasers to modify thermoelectric materials. They can write "nanotracks" by scanning the laser to create a fast, convenient way to produce unidimensional nanostructured thermoelectric materials.
- The Solid-State Solar Thermal Energy Conversion Center (S^3TEC)[14] at the Massachusetts Institute of Technology (MIT) aims to develop transformational solid-state technologies to convert solar energy into electricity via heat by advancing the fundamental science of energy carrier coupling and transport, designing new materials, and inventing cost-effective manufacturing processes. The center has demonstrated flat-panel solar thermoelectric generators with a 4.6% solar-to-

[11] www.techportal.eere.energy.gov/technology.do/techID=910,
[12] www.energy.gov/sites/prod/files/2014/01/f7/csp_review_meeting_042413_jin.pdf
[13] www.energyfrontier.us/sites/all/themes/basic/pdfs/CSTEC.pdf
[14] www.energyfrontier.us/sites/all/themes/basic/pdfs/S3TEC.pdf

electric conversion efficiency at standard conditions, a level that is seven to eight times higher than previously reported values.

NIST also supports research to address the challenges of Thrust 2 through measurements of nanofluids for solar thermal applications, as well as the characterization of thin-film nanostructured thermoelectric materials. Additionally, IC-sponsored research addressing the technical issues identified in Thrust 2 include research on carbon nanotube based thermoelectric materials for direct conversion of solar energy and solar panel waste heat, as well as the determination of material and manufacturing process qualification standards.

Thrust 3: Improving Solar-to-Fuel Conversions with Nanotechnology

Artificial systems that are inspired by the natural photosynthesis process can use nanomaterials to produce useful chemical fuels (or feedstocks for high-value-added chemical products) directly from sunlight. As was the case with the first two thrust areas, DOE supports numerous projects that address the technical challenges outlined in this thrust. Six EFRCs are performing research related to Thrust 3, including one focused on designing and synthesizing molecular electrocatalysts that efficiently convert solar energy into chemical bonds in fuels.

Support from DOE's Advanced Research Projects Agency (ARPA-E) has yielded significant results in Thrust 3. Researchers at Arizona State University have utilized photosynthetic microorganisms to produce liquid fuels and fuel precursors directly from solar energy. These researchers have modified photosynthetic bacteria so that they continuously convert sunlight and CO_2 into fatty acids, thereby optimizing the solar-to-fuel conversion process. This approach is unique, given that most biofuels research focuses on increasing cellular biomass, not on excreting fatty acids.

Scientists at DOE's Lawrence Berkeley National Laboratory and the University of California at Berkeley have created a hybrid system of semiconducting nanowires and bacteria that use artificial photosynthesis to convert sunlight, CO_2, and water into fuel (Figure 3).[15] In this system the researchers grow an "artificial forest" of silicon and titanium oxide nanowire heterostructures. Once the nanowire array is grown, they add bacteria that produce enzymes known to selectively catalyze the reduction of CO_2. The CO_2 is then reduced to acetic acid, and genetically engineered *E.coli* is used to synthesize targeted chemical products.

[15] www.sciencedaily.com/releases/2015/04/150416132638.htm

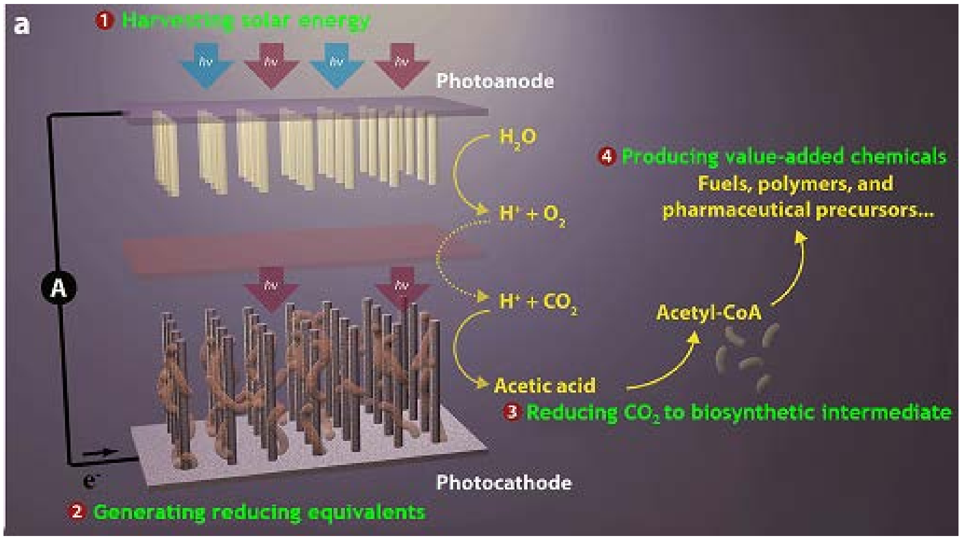

Figure 3. This breakthrough artificial photosynthesis system has four general components: (1) harvesting solar energy, (2) generating reducing equivalents, (3) reducing CO_2 to biosynthetic intermediates, and (4) producing value-added chemicals. (Source: Berkeley Lab)

An example of a NIST project that addresses Thrust 3 is the development of measurement methods for artificial photosynthetic bionanomaterials. The Metrologies for Nanobiomaterials in Artificial Photosynthesis[16] program at NIST aims to make fundamental measurements of the reaction chemistry and catalytic intermediates in catalyst nanoarchitectures for water oxidation.

By studying Photosystem I, a nanoscale protein found in leafy vegetables, Vanderbilt University researchers have developed a way to combine the natural process of photosynthesis that converts light into electrochemical energy with silicon, the material used in solar cells. The U.S. Department of Agriculture's National Institute of Food and Agriculture supported this research,[17] which resulted in the development of a thin-film prototype that can provide enough power through solar energy to drive devices such as calculators or cell phones.

Collaborations

Interagency collaboration has facilitated progress for the Solar NSI and laid the foundation for future success. Enhanced cross-agency communication has led to heightened knowledge of ongoing and planned activities within these agencies, allowing for greater leveraging of resources through mechanisms such as collaborative programs. Individual agency-funded or mission-specific programs also have benefited from improved awareness of complementary activities at other agencies, and have been developed in the context of broader Federal activities.

Workshops and conferences are a significant collaborative activity among participating agencies and also engage industry and academia. In each of the five years following the release of the white paper, participating agencies have worked together to co-sponsor and attend a variety of events in support of the Solar NSI. These workshops and conference sessions have focused on many different topics and have

[16] www.nist.gov/cnst/erg/nanobiomaterials.cfm
[17] portal.nifa.usda.gov/web/crisprojectpages/0201527-photosystem-i-nanoscale-photodiodes-for-creating-photoelectrochemical-devices.html

encouraged new collaborations by supporting a dialogue across the research and development spectrum, thereby extending the community of interest among participating agencies, academia, and industry.

As the Nation's leading supporter of energy-related research and development, DOE is at the center of many of the activities of this signature initiative's diverse effort. DOE supports an extensive portfolio of research and development projects for solar energy collection and conversion, many of which incorporate nanoscale materials and devices. DOE-sponsored research is conducted at national laboratories, universities, and in private industry across the country. At least thirteen of the DOE EFRCs focus on some aspect of solar to electric energy conversion,[18] and a significant fraction of the research in these centers can be classified as nanoscience.

Although DOE is the natural hub for many of the Solar NSI's activities, significant collaborative efforts have been leveraged across the participating agencies, including cooperative research within the national laboratories, interagency review panels, and jointly funded research programs. One example is the joint National Science Foundation (NSF) and DOE Funding Opportunity Announcement in 2011 for the Foundational Program to Advance Cell Efficiency (F-PACE),[19] in connection with DOE's SunShot Initiative. F-PACE supported 18 projects that received $35.8 million over three years, including high-efficiency solar cell materials research at NREL that complements the black silicon technology described above.

Another example of interagency collaboration is the Air Force Office of Scientific Research and NSF Emerging Frontiers in Research and Innovation solicitation entitled Two-Dimensional Atomic-layer Research and Engineering (2-DARE)[20] that had two competitions in 2014 and 2015 for four-year group awards. This topic addresses fundamental challenges in the creation of 2D materials and their hybrids, scalable manufacturing strategies, characterization tools and methods, and novel devices. The 2-DARE research may lead to solar cells, among other technologies, that exploit the unique properties of stacked, heterogeneous layers.

Collaborations to Engage Industry

Industry engagement is critical to ultimately realizing the potential of solar energy. By working together to engage industry in workshops as well as research and development efforts, participating agencies have achieved a better understanding of what is necessary to translate laboratory advances into market applications.

[18] Energy Frontier Research Centers Technical Summaries, revised 31 August 2015. www.science.energy.gov/~/media/bes/efrc/pdf/technical-summaries/ALL_EFRC_technical_summaries.pdf
[19] www.nsf.gov/news/news_summ.jsp?cntn_id=119222&org=NSF&from=news
[20] www.nsf.gov/pubs/2015/nsf15502/nsf15502.htm

Key aspects of the Solar NSI have been addressed by collaborative research centers involving industry. For example, in 2010 DOE initiated the Joint Center for Artificial Photosynthesis (JCAP),[21] an Energy Innovation Hub aimed at developing revolutionary methods to generate fuels directly from sunlight (Figure 4). JCAP is led by the California Institute of Technology in primary partnership with DOE's Lawrence Berkeley National Laboratory. Other key partners include the Stanford Linear Accelerator Center National Accelerator Laboratory, the University of California at Irvine, and the University of California at San Diego. JCAP has assembled a world-class, multidisciplinary, and highly collaborative research and development team "under one roof" with the goal of addressing basic science and technology challenges for the development of an efficient, sustainable, and economically viable solar fuel generation system. This collaboration resulted in the application of nanowires and bacteria to artificial photosynthesis described above. As suggested by the name Energy Innovation Hub, JCAP also plays a role as a center of coordination and collaboration for the larger community of solar fuels researchers. The cross-disciplinary collaborations fostered by JCAP will help advance and accelerate progress in highly promising areas of energy science and engineering from the early stage of research to the point where the technology can be handed off to the private sector. Approximately 20% of JCAP's activities involve nanotechnology.

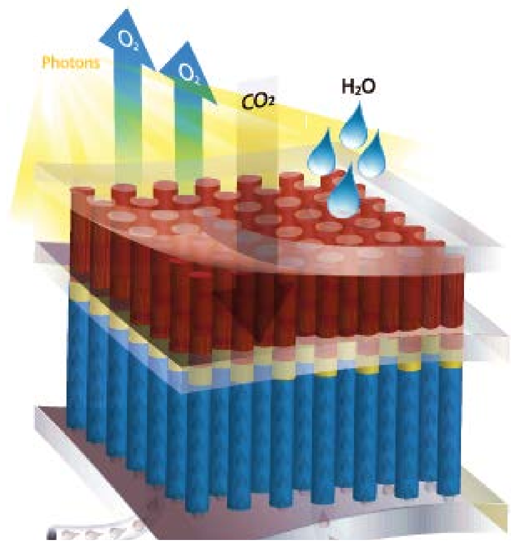

Figure 4. Taking inspiration from the way a leaf uses sunlight to transform water and carbon dioxide into fuel. (Source: JCAP)

In 2011, the Engineering Research Center for Quantum Energy and Sustainable Solar Technologies (QESST),[22] jointly funded by NSF and DOE, was established at Arizona State University. The QESST center works with companies to advance solar technologies toward commercialization. Research in this center focuses on developing a fundamental understanding of electronic excitations, relaxation, and transport in nanostructured materials, leading to materials with charge collection efficiencies in excess of the single-junction solar cell limit. QESST researchers are working with SolarWorld Industries America Inc. to develop technology for a novel silicon ingot growth process by which the material for solar cells is manufactured, and with Technic Inc. to eliminate the use of silver in the manufacturing of solar cells and replace it with copper, a more abundant and less costly material.

The Silicon Solar Consortium[23] is an NSF Industry/University Cooperative Research Center, which relies primarily on industry funding, with minority NSF funding. This center has created a multi-university, multi-company culture that addresses the science, technology, and manufacturing issues the silicon photovoltaic materials industry must solve in order to meet the future needs of advanced silicon solar cell manufacturing and commercialization. In addressing these goals, this center also provides graduate

[21] www.solarfuelshub.org/
[22] qesst.asu.edu/
[23] www.mse.ncsu.edu/sisoc/

students with photovoltaic materials and device expertise to meet future workforce needs. Industrial members include Applied Materials, DuPont Electronic Technologies, and Dow Corning.

The DOE SunShot Incubator program[24] is aimed at transferring new solar technologies into the market. It provides early-stage assistance to help startup companies, through incubator awards as discussed above, cross technological barriers to commercialization, while encouraging private sector investment. The program has supported a variety of projects that use nanotechnology to drive down the cost of solar power installations.

The Army Research Laboratory (ARL) is working with industry (MicroLink Devices, EMCORE); academia (University of Texas, University of California at Los Angeles, University College London); and other U.S. Government laboratories (National Renewable Energy Laboratory) to develop low-cost, high-efficiency gallium arsenide based solar cells that use quantum dots, quantum wells, and surface nanostructures to enhance the spectral response and absorption properties of portable power sources for the dismounted soldier. Under internal and Small Business Innovation Research programs, ARL is developing special electrically conducting antireflection coatings that work efficiently over a very large range of incident angles to eliminate the need for bulky light-tracking hardware. It is also developing nanostructured back surface reflectors to enhance absorption through light trapping and wave guiding. The goal of this research is the development of a new generation of flexible, conformable, and lightweight energy sources to lighten the burden on and extend the mission times for the soldier.

These examples of collaborative agency and industry endeavors are accelerating the widespread implementation of scientific breakthroughs and have helped to ensure that the research and development projects being supported by participating agencies yield results that can be efficiently transformed into industrial applications.

The Impact of the Nanotechnology for Solar Energy Collection and Conversion NSI

Agencies participating in the Solar NSI have a broad and strong portfolio of solar energy research activities involving nanotechnology that support the goals of this signature initiative. The spotlight provided by the initiative has put a focus on the technical challenges identified in the white paper. The projects supported over the past five years have contributed to significant advances in all three thrust areas.

Collaboration has involved participating agencies, industry, and academia, and has taken many forms, including co-sponsored, broadly attended, multi-agency workshops and conferences; jointly planned and implemented workshops and conferences; interagency review panels; and jointly funded research programs.

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[24] www.energy.gov/eere/sunshot/sunshot-incubator-program

Figure 5. Solar panels on the roof of the Sangre de Cristo Arts and Conference Center in Pueblo, CO. (Source: Dennis Schroeder /NREL)

The impact of this cross-agency and industry collaboration is already apparent. Companies are commercializing products and services using nanotechnology characterization, fabrication, instrumentation, and materials for solar energy collection and conversion that were developed through NNI investments and collaborative efforts (Figure 5). These efforts coordinated through the Solar NSI have resulted in technology being translated from research into products, enhancing U.S. competitiveness, and fueling job creation.

Although there is still more research and development to be done, the Solar NSI has demonstrated that nanotechnology can significantly improve solar photovoltaic, solar thermal, and solar-to-fuel technologies. The DOE SunShot Initiative is well positioned to continue driving nanotechnology-enabled solar research, manufacturing, and market solutions to make the abundant solar energy resources in the United States more affordable and accessible for Americans. The collaborations between DOE and the other agencies that were catalyzed by the Solar NSI will continue as appropriate, however the formal NSI mechanism is no longer needed now that these collaborations are well established. Consequently, fiscal year 2016 will be the last year the Solar NSI is reported under the NSI mechanism.