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Chairman Weber, Ranking Member Veasey, members of the Subcommittee, thank you for this opportunity to address the future research opportunities for solar energy, and the many benefits that advanced solar technologies can deliver for our nation.

My name is Martin Keller, and I'm the Director of the U.S. Department of Energy's National Renewable Energy Laboratory, or NREL, in Golden, Colorado. My career has included research positions in the private sector and more than a decade within the National Lab complex. Before coming to NREL in 2015, I was the Associate Lab Director, and led the DOE BioEnergy Science Center, at Oak Ridge National Laboratory in Tennessee. I previously conducted technology development for a San Diego-based start-up company, and I hold a Doctorate degree in Microbiology from the University of Regensburg in Germany. My entire career has been about integrating foundational science into important new applications. This experience has given me a deep understanding of and profound appreciation for the role that federally supported scientific research can play in maintaining our nation's leadership in science and innovation—and also, how those accomplishments can drive U.S. competitiveness.

In my view, the subject of today's hearing could not be more timely, nor more important to the energy future of our country. For although solar energy accounts for 1.8 percent of U.S. electrical generation today, it is on a remarkable trajectory of growth, with tremendous longer-term potential. Total installed photovoltaic capacity surpassed 40 gigawatts in 2016—a record year—nearly double the rate of growth seen in 2015. For the first time, solar ranked as the nation's leading source of new electric generating capacity on an annual basis, with 39 percent of all *new* electricity generation capacity in the country coming from solar. And the benefits are increasingly seen nationwide: some 22 states each added more than 100 megawatts last year.

This also means that solar energy is becoming a significant economic force. The Solar Foundation reports that more than 260,000 Americans are employed in the solar industry, with 51,000 jobs added in 2016. This marked the fourth consecutive year of more than 20 percent growth, and the number of solar jobs has nearly tripled since 2010.

Since I arrived at NREL, one of the most exciting aspects of our work has been in the field of solar energy. In the four decades of work we've done at NREL, we have made incredible progress on bringing solar technologies into the mainstream. And because of this work, we are at the point where solar is becoming competitive with conventional power from the grid in many parts of the country. But just as innovation for the automobile didn't stop when that technology reached parity with the horse, we cannot afford to slow our progress on innovating solar technology just because we are reaching parity with the grid.

To give you an idea of how far we've come: The first photovoltaic, or PV, cell produced electricity equal to 4 percent of the energy it absorbed from the sun—what we refer to as 4 percent conversion efficiency. The solar cells based on that technology cost about $300 a watt. Today, costs have plummeted. The price of commercially available modules is tipping toward 30 cents a watt, and record research cells based on advanced technologies are approaching 50 percent efficiency.

Despite this remarkable progress, there is still much more that remains to be done. Solar technology has great unmet potential. But to reach that potential, foundational scientific R&D and the breakthroughs it can produce are needed to accomplish the goals for a competitive U.S. market, 50-year product lifetimes, wholesale power prices (i.e., 3 cents/kWh), positive grid impact, and power anywhere the sun shines.

Transformative Solar Science

Energy provides the foundation for our economy. As such, it is imperative that the United States continue to be an innovative leader in advanced energy, including PV technology. Investments in research over recent decades have enabled U.S. industries to establish leadership positions. Examples include First Solar (leading in cadmium telluride, CdTe, modules), SunPower (leading in high-efficiency silicon modules), DuPont (leading in materials that are critical components of PV cells), and 1366 (providing conventional silicon-wafer alternatives). Continued early-stage research will provide the foundation for the next generations of solar technologies, creating new business opportunities and jobs, and sustaining our leadership role in global solar innovation.

Fundamental science underpins every aspect of what we do in photovoltaics. This is not just true for the cell materials, but also for the necessary power electronics, energy storage, and grid integration of solar energy. This science ranges from new materials discovery for solar absorbers, to new and low-cost manufacturing technologies, new contact materials, tandem junctions, module encapsulation materials, high-bandgap semiconductors, and new rapidly charging battery materials.

It even extends to newly developed intelligent and autonomous control algorithms that operate at every level in the energy system, from module to grid, in a cyber-secure manner. These autonomous control algorithms allow a solar power system to coordinate seamlessly with utilities and grid operators, to meet the nation's needs for reliable and dispatchable energy.

Fundamental science—in the fields of materials science, chemistry and electrochemistry, semiconductor physics, and computational sciences—is enabling revolutionary advances that lead not just to grid-scale reliable energy, but also to new applications. Lightweight PV materials are becoming increasingly important to the U.S. military, which is seeking advanced PV for powering vital computers and communication systems for soldiers on the ground, and a host of other mobile applications. Lightweight and high-efficiency PV may additionally give drones the commanding power of perpetual flight. NREL currently has several solar R&D projects for the Pentagon that delve deeply into the science behind new manufacturing processes, for established materials like gallium arsenide (GaAs), and CdTe, that could further drive down costs and give U.S. industry a competitive advantage.

NREL, together with other labs, academic institutions, and industry partners, is pushing forward with science and engineering in each of these areas. For instance, NREL has teamed with the Stanford Linear Accelerator, or SLAC, on fundamental computational materials discovery by design, to explore new synthetic approaches and to integrate these materials in new solar concepts. Materials discovery remains a consequential force for innovation, beginning with the solar absorbers that produce electricity, to the interfacial materials that make up a cell, to module materials, and all the way to the power electronics and power-system components that connect modules to the grid.

Driving Current Technologies to the Next Stage

Some decades ago, NREL developed the multijunction solar cells that are now deployed on satellites and the Mars rover. These cells are currently much too expensive to employ in terrestrial applications, but NREL is working to bring this technology back to Earth. By employing novel deposition methods and new chemistries, we have shown that these cells can be made at much lower cost, which would make them attractive for applications where efficiency is of utmost importance—like applications having limited area availability, such as (military) drones, automotive applications, and to enable soldiers to carry far fewer batteries in the field.

By pioneering new defect chemistries, interface control, and dopants, NREL recently demonstrated that cadmium telluride technology can achieve module efficiencies greater than 20 percent, upending decades of our common understanding of this technology. U.S.-

based First Solar is working with NREL to employ this innovation in their product. We believe that through material science, interface research, and device design advancements, we can achieve a target of 28 percent cell efficiency in coming years, which is a significant feat that could challenge silicon's dominance of the market and create a competitive advantage for the United States.

The Potential of Perovskites

The new materials and technologies we see before us today could lead to an accelerated renaissance in solar energy. Perovskite materials are prime candidates to fulfill this potential and are one of the most exciting areas of solar research today. Perovskites have demonstrated extraordinary progress in recent years, with the promise of increasing PV efficiencies while meeting lower-cost targets. NREL is a world leader in this technology, and we work with major academic groups and startup companies worldwide.

We have shown that solar modules from these materials could be produced by extremely rapid manufacturing processes such as roll-to-roll techniques. Imagine solar cells being produced at the rate of speed that a newspaper is produced on a commercial printing press. These materials can potentially also deliver very high efficiencies when employed in a tandem configuration—but again, produced using low-cost production methods.

We are optimistic that this potential revolution in PV technology could yield a tectonic shift in U.S.-based solar manufacturing. The time is right for creating a central hub for perovskite research, to solidify U.S. leadership in this area, by bringing together industry, universities, and national labs to empower a revolution in photovoltaic technology, and swiftly bring perovskites to commercial markets.

The EFRC and DuraMAT Research Collaboration Models

Successful solar research has often depended on strong collaborations, with support from the DOE Office of Energy Efficiency and Renewable Energy (EERE) and the DOE Office of Science programs at NREL. For example, Energy Frontier Research Centers have been and will continue to be pivotal in propelling solar energy into new territories. NREL has a major role in two EFRCs that have been transformative in their fields. The Center for Next Generation of Materials Design is led by NREL through a consortium with Lawrence Berkeley National Laboratory, SLAC National Accelerator Laboratory, and a series of universities. This EFRC partnership has pioneered advanced computational methods to discover new materials for solar energy conversion. Within the Center for Advanced Solar Photophysics, which is led by Los Alamos National Laboratory, NREL has discovered that quantum dot perovskites can be used as a top cell in new tandem solar devices, increasing their efficiency. Within the Solar Photochemistry core program, NREL discovered that under some conditions, perovskites can have extremely slow carrier cooling, potentially enabling ultra-high-efficiency solar cells without needing to create tandem structures. Clearly, Office of Science work funded through EFRCs and core programs are a successful model for technology innovation.

Another recently developed collaboration is the EERE-Solar Energy Technologies Office's DuraMAT program—a four-laboratory consortium led by NREL. Teaming closely with academia and industry, NREL, Sandia National Laboratories, Lawrence Berkeley National Laboratory, and SLAC are tackling the challenge of establishing durable materials for PV modules. DuraMAT's work includes identifying the types of stresses that a PV module encounters from the nanoscale to the module scale; investigating the installation and maintenance techniques that may affect degradation or failure; and developing an underlying understanding of resulting performance and cost ramifications. Again, fundamental science at multiple length scales and time scales is at the core of this important work to extend the life of solar modules and add value for the U.S. solar industry.

Storage for Solar Energy

As solar energy expands its reach, we will inevitably reach a point where storage technologies will be needed. Most of today's storage research focuses on utility-scale storage and batteries for electric vehicles. However, the technical requirements of storage for solar on homes, or for communities, differs considerably from these two areas. A complementary research agenda focused on new chemistries and materials could create scientific discoveries for new storage technology solutions that are needed for distributed solar energy.

Coupling storage with solar power also creates the ability to "island" the system—essentially isolating the individual system's generation capacity while still providing round-the-clock electricity. We're currently working with the Department of Defense on innovative solutions to power remote locations where no grid exists and where fuel is challenging, expensive, and dangerous to deliver. Another application is providing power when the grid is unavailable, such as during and after natural disasters that take down critical grid infrastructure.

Solar Integration Innovation

To have a reliable, resilient, and secure energy system in the United States—one that is second to none—we must integrate all the pieces of the energy puzzle. And that includes grid, load, generation, storage, controls, and operation. As distributed solar generation becomes a larger part of the generation mix, our electric grid systems have the potential to become even stronger, with greater flexibility and resilience. Energy integration at this complex level presents a deep scientific challenge—one in which intelligent control algorithms are being developed to operate in a cyber-secure, autonomous manner. With a dedicated effort from the DOE and the National Labs, this kind of autonomous energy grid could transform the electric system as we know it today.

Concentrating Solar Power

Concentrating solar power, or CSP, uses the sun's heat, rather than its light as in PV, to produce electricity. The cost of electricity generated by CSP has plummeted from 21 cents per kilowatt-hour in 2011, to about 10 cents in 2016. A unique feature of CSP technologies is that they can have built-in energy storage and still come in at an electricity cost of 10 cents per kilowatt-hour. In this way, CSP could provide grid operators the added flexibility in generation sources that they will need to manage an increasingly dynamic electric grid. To further reduce cost, additional breakthroughs and fundamental scientific understanding are critical. The primary challenge is to integrate a new, revolutionary thermodynamic system that operates at higher temperatures than the traditional system, but that yields substantially higher operating efficiencies.

During the last year, scientists and engineers at NREL, Sandia, and other National Labs worked closely with industry and academic researchers to develop a CSP Gen3 Roadmap. The roadmap identifies the R&D challenges along three pathways—molten-salt, solid-particle, and gas-phase receivers. All three pathways have the potential to achieve the goal of electricity at 6 cents per kilowatt-hour.

Solar for Fuels and Other Critical Needs

As solar power becomes more prevalent in the United States, we will have new opportunities to use surplus solar power in ways that will increase our power system's economic competitiveness. Solar-to-X refers to converting solar electricity or heat to something else of value, such as solar-to-fuels, solar-to-heat, solar-to-hydrogen, or solar-to-chemicals, such as ammonia. In addition to improving existing storage and demand-management strategies, cost-effective solar-to-X options could be used to help drive a resurgence in U.S. industry and manufacturing, with the attendant economic and job-creation benefits. This will require a sustained scientific research effort along each of these multiple pathways.

Solar energy conversion to fuels is still in the research stage, but holds great promise to contribute to future U.S. energy needs over the longer term. Several encouraging paths have emerged—for example, solar thermochemical, photo-electrochemical, high-temperature electrolysis, photo-thermal, and others. In particular, concentrating solar thermal systems and photo-thermal processes may be ideally suited for large-scale solar-fuel production, and they could significantly reduce electricity consumption for large-scale hydrogen production from water-splitting, as well.

Unleashing the Ultimate Potential of Solar

The power of the sun is naturally everywhere on Earth. If we're able to tap into that power anywhere, we would revolutionize how we make and use energy. Breakthroughs in solar-generation technologies that are lightweight, flexible, durable, and highly efficient will open the door for new, valuable applications. The concept of "solar everywhere"—on buildings, on vehicles, along roads, or built into equipment and devices—would be a game-changer for energy consumers everywhere. Based on current economic analyses, it is estimated that solar power costs could be reduced by two-thirds or more simply by integrating PV layers into the materials we use every day. Understanding how this can be done safely, efficiently, and cheaply is the challenge before us.

Recent breakthroughs in module-level power electronics, lower operating temperatures, and defect-tolerant materials such as perovskites that can be applied directly and rapidly to a surface, are making integrated PV an attractive option. One example is silicon panels. They are already being installed on trucks with refrigeration, reducing fuel consumption, and enabling trucks to run longer before batteries run down. Solar sunroofs are on a million cars across the globe. Thin-film PV technologies are being adapted to lightweight, flexible applications. Research suggests that there may be other, new, inorganic materials that are non-toxic and low-cost even at large-scale deployment, that merit further study. Each of these areas is ripe with possibility, and each will require dedicated research efforts to bring them to fruition.

In Conclusion

Fast-forwarding to 2050, current analysis suggests that U.S. electricity generation will be a widespread, bi-directional commodity that is valued through new market structures that put a price on location, use, and ancillary services provided by the power being produced.

The research concepts discussed here focus largely on energy-sector benefits to be gained from technological progress. That work takes on even greater importance when we consider one overarching fact: the United States is blessed with one of the best solar resources in the world. We would do ourselves and our children and grandchildren a disservice if we do not put this abundant and inexhaustible energy resource to work for us all.

There is still important early-stage research to do to improve cost, performance, reliability, integration, and applicability of solar energy. The U.S. can stay at the innovation forefront only with a continued federal investment. We should not underestimate the degree to which other nations are currently ramping up their own government-supported solar energy research efforts. If we fail to maintain our innovation leadership in this space, it is certain that others will be happy to take our place.

Without exaggeration, I can say that researchers at NREL and around the country are excited and eager to tackle the challenges ahead and to bring about the important advances in solar technology that we need for our energy future.