A colloquium on the status and challenges in science for decarbonizing our energy landscape

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An Arthur M. Sackler Colloquium titled "Status and Challenges in Science for Decarbonizing our Energy Landscape" was held at the Arnold and Mabel Beckman Center in Irvine, California in October 2018. The papers that follow in this issue of PNAS (1–7) stem from that activity, which addressed a topic of compelling interest and importance to our community from a perspective often not addressed.

It is evermore clear, based on incontrovertible climate evidence, that the way we produce and use energy must transition rapidly from what we have done in the past. Population growth, urbanization, and the need for both energy and materials to support this evolution has led to environmental alteration that can only be explained by human activity. As the Intergovernmental Panel on Climate Change and others have emphasized over the last several decades, the average annual temperature of planet Earth has been increasing with greater annual increments. The origin of the increase and its consequences are the greater amounts of CO_2 in the atmosphere from approximately 284 parts per million at the start of the industrial revolution to 316 parts per million in 1956, when detailed records were initiated, to 415 parts per million in 2018 (8–12). The well-known "greenhouse" gas effect of CO_2 for trapping heat has been described in detail and extends to other polyatomic molecules, such as methane, that are present in much smaller amounts (although their respective greenhouse gas effects may be greater on a molecular basis).

The challenges we face and the necessary solutions that must be undertaken are being addressed at many levels, including technological, governmental, regulatory, and lifestyle. The first of these depends at its fundamental core on scientific discoveries and advances on which technology is built. For the reduction of annual CO_2 emissions from man-made sources, it is essential that we move away from carbon-based fossil fuels (coal, oil and gas, with the last of these employed as a short-term substitute since it yields more heat per unit CO_2 evolved than coal or oil). Other ways of generating and storing energy without producing CO_2 must be developed, which in turn rely on scientific advances to make this possible. Where we are in terms of science to address this technological challenge was the focus of the Sackler Colloquium.

Following overview lectures by former Secretary of Energy Ernest Moniz of the Massachusetts Institute of Technology, and former Director of the Advanced Research Projects Agency–Energy Arun Majumdar of Stanford University, lectures and discussions on the scientific progress and challenges on the generation and storage of renewable energy were given. Speakers included: Thomas Jaramillo (Stanford University), Fikile Brushett (Massachusetts Institute of Technology), Sossina Haile (Northwestern University), David Ginley (National Renewable Energy Laboratory), Michael Aziz (Harvard University), Linda Nazar (University of Waterloo), Yet-Ming Chiang (Massachusetts Institute of Technology), John Turner (National Renewable Energy Laboratory), Raffi Garabedian (First Solar Inc.), Karen Goldberg (University of Pennsylvania), Lee Lynd (Dartmouth College), Daniel Nocera (Harvard University), Harry Atwater (California Institute of Technology), Eli Yablonovitch (University of California, Berkeley), and Thomas J. Meyer (University of North Carolina at Chapel Hill). Moderators and discussion leaders were Tom Mallouk (Pennsylvania State University), Sharon Hammes-Schiffer (Yale University), and the authors of this Introduction. The full program can be viewed at: http://www.nasonline.org/programs/nas-colloquia/completed_colloquia/decarbonizing-our-energy.html, while the presentations and discussions conducted during the Colloquium can be seen in full

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at: https://www.youtube.com/playlist?list=PLGJm1x3XQeK3MBYldrPidvT-RRCNVh-QJ.

The papers presented in this colloquium (1–7) describe aspects of the ongoing science delivered at the meeting and discuss challenges and areas of research needed to achieve removal of carbon from our energy sources or mitigation of its effects. There are overview papers on carbon-free energy production and storage (1, 2), a technoeconomic analysis of ethanol to fuels (3), as well as specific investigations on renewable energy storage through electrolysis research (4), photoelectrosynthetic cells for water oxidation (5), and carbon monoxide reduction chemistry (6). There is even an article on a different approach to cement, one of the developed world's most important materials and, at the same time, one of industry's biggest producers of CO_2 in our atmosphere (7).

At this time of needing to decarbonize our energy landscape, it is important to recognize that renewable energy production and renewable energy storage, while intimately linked, may in fact be separable. For example, electric cars employ batteries that have to be recharged, whereas fuel cell vehicles generally use hydrogen that must be added to the vehicle once it is consumed. The common thread is a fundamental chemical reaction that is thermodynamically favorable (the term "spontaneous" may be used) that produces electrons and positive charge (so-called "holes") that do the required work. During the last several decades, efforts to produce electric cars and fuel cell vehicles have increased with real, working vehicles brought to market. In some ways they can be viewed as complementary, with fuel-cell vehicles better-suited as trains and long-haul trucks, and battery-driven vehicles as personal cars and light-duty trucks. But these two approaches can also be viewed as "competing" technologies. Both offer paths to decarbonization, each with its own challenges to surmount and applications to address. Both will be employed as we move away from reliance on oil, with competition and complementarity between them driving scientific discovery capable of translation to a variety of carbon-free energy technologies.

The use of such vehicles in the transportation of people and cargo may also lead to wider changes in how energy is distributed from the more centralized approach in the developed world to one in which energy production and use are more distributed. The latter may actually be easier to implement in the developing world in which a centralized infrastructure does not exist or is only partially present.

The 2019 Nobel Prize in Chemistry for the discovery of lithium-ion batteries to John Goodenough, Stan Whittingham, and Akira Yoshino was richly deserved. The fundamental work of these award recipients has over the past three-plus decades set the stage for translation into practical application in all sorts of devices, but basic research on lithium-ion batteries and batteries in general continues today in order to make them more efficient, reliable, and safer on the scale needed for transportation and the electricity grid. In the realm of photosynthesis for energy applications, similar fundamental challenges abound. Can an energy system be implemented based on renewable H_2 produced from artificial photosynthesis (or inexpensive photovoltaic electrical energy coupled with water electrolysis), which when combined with oxygen from the atmosphere in a fuel cell produces water as the only chemical product (energy is the other)? What are its challenges?

What is important to realize is that while we have both batteries and fuel cells to do work, neither is perfect and both offer abundant opportunities in fundamental science that will lead to important advances in our future energy landscape.

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