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Editorial

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Photonics and Light Science Wish List from COP21 in Paris

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One of the most significant world events during the International Year of Light was the 2015 United Nations Climate Change Conference (COP21) meeting among nations in Paris from November 30th to December 12th 2015. A key result of this meeting was an agreement between 196 nations to set a goal of limiting global warming to a global average atmospheric temperature rise of less than 2 °C with respect to preindustrial levels, with a stretch goal to limit warming to 1.5°. Cynics may abound when it comes to discussing climate change, but ponder just for a moment how remarkable it is for 196 nations to agree, even in principle, on anything, let alone something this bold and potentially consequential. French President Francois Hollande remarked to Paris conference participants that they will look back years from now and reflect on "What was the meaning of our lives, what did we achieve ...", going on to predict that "one thing will come up time and again: you will be able to say that on the twelfth of December you were in Paris for the agreement on the climate. And you will be able to be proud to stand before your children and your grandchildren."

A key factor that made this historic agreement possible and more successful than previous climate summits, was that it called upon each nation to develop its own action plan. Success for these plans depends on each signatory nation having good options for both policy changes that limit carbon emissions, and access to new technologies. Technology advances are needed for energy generation and efficiency, as well as transformative lifestyle changes that allow us to decouple increases in quality of life worldwide from increased energy use and climate change. United Nations Secretary General Ban Ki-moon proclaimed that "with these elements in place, markets now have the clear signal they need to unleash the full force of human ingenuity and scale up investments that will generate low emissions, resilient growth," adding that "what was once unthinkable has now become unstoppable." In other words, world political leaders acknowledge the vital role of technological innovation-driven commercial activity to actually bringing about a low carbon world. Moon and the others who gathered in Paris are looking to scientists and technologists to lead the world with their power to innovate. This sets the stage for advanced nations that are the biggest carbon emitters, such as China and the United States, to lead via innovation coupled to financial resources that can develop carbon-curbing technology options that can be implemented in nations around the world.

OK, so what can we do? What does our field of photonics have to do with energy and climate change? Photonics can do a lot for energy and climate change, when you consider the possibilities. Below is a noncomprehensive top 10 "wishlist" for photonics innovations that I believe has the potential, if developed and widely adopted, to move the needle on both decarbonizing energy generation and changing our lifestyle. The first five have to do with solar and thermal energy conversion and management; the second five reach into technologies that could transform our communications and transportation infrastructure.

1. *Upconversion and downconversion for adding efficiency to silicon solar cells*: Photovoltaics is now an approximately $100B (U.S.)/year industry with a worldwide panel manufacturing capacity of >50 GW, making it the world's largest optoelectronics industry sector. The staple of today's photovoltaics industry is a crystalline silicon flat plate solar panel that has seen dramatic cost reduction in recent years as a by product of mass manufacturing. At the same time, its basic element, the silicon solar cell, is reaching toward its efficiency limits. New technologies that could add even as little as 1% added efficiency, if sufficiently low in cost and easy to implement, could have a GW-scale impact on photovoltaic power generation. One approach is to use downconversion, for example via exciton fission embedded near the solar cell surface, to harvest the blue photons ordinarily dissipated non-radiatively near the solar cell front contact. Another is upconversion, since silicon solar cells fail to absorb and convert photons below the bandgap at 1100 nm. Thus efficient upconversion chromophores that can operate at solar power densities are needed, which is an enormous photonics challenge, but if realized have potential to add 1% efficiency to silicon solar cells.
2. *30% efficiency flat plate microconcentrator solar module*: As noted above, silicon currently dominates photovoltaics, and flat plate silicon modules account for >90% of worldwide solar manufacturing. Increased efficiency is one of the biggest levers available to further reduce the cost of solar energy. In their current form, silicon modules will not be able to exceed or even reach 30% conversion efficiency. High radiative efficiency, but higher cost, semiconductors such as gallium arsenide have the potential to boost cell and module efficiency, but can do so much more quickly if used in concentrator rather than flat plate solar modules. Concentrator modules have demonstrated efficiencies as high as 36% but have failed to date to achieve market impact because their costs are higher than for flat-plate silicon modules. If monolithic arrays of low-cost microscale optical elements could be designed to enable a flat-plate form factor concentrating module, there is reason to believe we could see cost-effective, mass-manufacturable photovoltaic modules with >30% efficiency, with huge impact.
3. *Artificial photosynthesis: durable >20% efficiency photoelectrochemical water-splitting hydrogen generator*: Solar photovoltaics are on a path to producing ever cheaper electricity during peak generation conditions, but solar power is intermittent and photovoltaics cannot store

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electric energy. One transformative approach to storage would be artificial photosynthesis, the direct conversion of sunlight to chemical fuels, the simplest of which is hydrogen, by photoelectrochemical water-splitting. In recent years, researchers have developed designs and materials for devices with longer durability and increase efficiency. A real breakthrough would be achievement of a manufacturable photoelectrochemical water-splitting hydrogen generator with >20% efficiency and lifetime measured in years, similar to the warranty periods offered for today's photovoltaic modules.

4. *Radiative cooling of urban buildings that lowers city temperatures by 2°*: Well over half the energy used in the urban world is used in buildings, most of which are remarkably inefficient from a thermal energy management point of view, generating so-called urban heat islands of elevated local temperature in many cities, exacerbating demand for air conditioning. Photonics technologies to reduce energy use from heating and especially from air conditioning are large opportunities. This requires being more sophisticated than we have been historically about radiative emission from building materials. An intriguing step in this direction is the recent demonstration, by Shanhui Fan and co-workers at Stanford University, of solar-reflective but infrared-emissive materials that can achieve "daytime radiative cooling", lowering the material temperature relative to ambient by radiating thermal power to the ultimate cold background of deep space. A crisp goal for photonic design of thermal radiation materials would be to design building and paving materials, which, when implemented, would lower city temperatures worldwide by 2°.
5. *Cost-effective space-based solar power*: Solar power on earth is intermittent due to weather variability and the diurnal sun cycle, but one place where the sun shines almost continuously is in space. Realization of space-based solar power could enable "baseload" solar power, that is, continuously dispatchable electricity 24 h a day, without the need for large-scale electricity storage. Since the early days of space exploration, technologists have dreamed of designs for space-based solar power systems that could harvest solar energy and beam it to earthbound receivers at infrared or microwave frequencies. For the most part such schemes have been located somewhere between imagination and science fiction, owing to the costs of orbital launch and huge capital requirements for a complete system. However, there is no fundamental reason why space solar power systems cannot achieve order of magnitude reductions in mass per generated watt of electricity (and, thus, also cost/watt). Photonic design, both for solar power systems and for beamed power transmission, would be key to a feasible space-based solar power system. This idea may also get some help from advances in space launch reusable rocket technology, yielding further launch cost reductions.
6. *Chip-based optical interconnects for reduced computer power consumption*: The electronics revolution in the last few decades has yielded integrated circuits with staggering computational power; just look down at your phone for the evidence. However, energy use by electronics in our increasingly cloud-based information world is growing at about double the rate of general energy use. A significant fraction of the energy use in integrated electronics comes not from the transistors in integrated circuits, but from the electrical wires carrying electronic signals. So, data communications is increasingly turning to photonics technologies for solutions. There are now kilometers of optical fibers in a typical data center, carrying signals from one electronic server backplane to another, and photonics is now poised to reach into the circuit board level. However, at present there are no comprehensive schemes for on-chip optical interconnects that could relieve the on-chip communication bottleneck presented by metallic wires. Solving this problem could potentially lead to leaps in circuit clock speed, further boosting computational power per device and accelerating development of the circuit hardware needed for exascale computing.
7. *Low-cost lidar system for autonomous vehicles*: Changing the way the world drives could result in enormous energy savings and lifestyle transformations by changing patterns of vehicle ownership and use, altering urban traffic flows and even the layout of future cities. While "Google cars" and other prototype autonomous vehicles are conducting road trials, the widespread adoption of autonomous vehicle technology will require breakthroughs in powerful, low-cost systems for vehicle navigation, collision avoidance, and intervehicle communication. A key element of such systems may include a lidar-like photonic scanning beam system operating at infrared wavelengths. Such a system must be capable of scanning with depth perception the three-dimensional scene around the vehicle with rapid refresh rate and recognizing and distinguishing between, for example, a stop sign and a pedestrian. Low-cost integrated optical phased array chips that couple large arrays of optical elements to form and steer beams are critical for this technology.
8. *Solution to efficiency droop for efficient low-cost solid-state lighting*: Solid-state lighting driven by advances in III-nitride semiconductor technology is poised to grow rapidly and displace incandescent and fluorescent lighting in many parts of the world, resulting in huge primary energy savings due to the efficiency gains by solid state lighting. But these solid-state devices often do not operate at their peak efficiencies because of an effect known as "efficiency droop", causing solid-state lighting devices to operate with decreased efficiency at higher current densities. Researchers have argued for and against many mechanisms for this effect, including nonradiative Auger recombination and current leakage of injected carriers out of the device active region. A robust solution to efficiency droop would enable us to advance toward an ultimate efficiency light emitting diode design for lighting.
9. *"LiFi" light-based lighting and ultrahigh bandwidth wireless optical communication*: One potential dual solution to lighting and indoor wireless communications is to use lasers rather than light-emitting diodes for lighting and to impress communications signals onto the optical beams used for general lighting. Some researchers believe that a transition to lasers for solid-state lighting could be the most effective solution to the efficiency droop problem described above. Moreover, lasers are already used as high speed telecommunication devices; modulating

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datastreams on visible laser carrier signals could enable us to surpass a hundred-fold the current radio frequency bandwidth limits in future high capacity wireless data communications.

10. *Compact optical quantum systems for sensing and computation without helium cryogens*: One of the most intriguing areas of photonic science is quantum optics, where advances in component and system architecture could revolutionize our use of computing and lower both energy use and cost per operation. Scientists are devising experiments that test the foundations of quantum mechanics and phenomena that could lead to future quantum systems for communication, sensing, and computation. Photonics is an attractive stratum upon which to build quantum systems because of the long coherence time of photons in free space and dielectric media and the opportunity for chip-based integration using components similar to those now employed by silicon photonics. Key challenges for integrated photonic quantum systems include the following: generating more than a few correlated photons simultaneously on a chip, elements that can serve as long-lived optical memories, and few-photon nonlinear elements for switching. Ideally, these elements could enable systems with long quantum coherence times at temperatures that could avoid use of He as a cryogen.

Many worthy ideas have been omitted from this short list. Please send me your own thoughts and ideas for photonics advances that can make a difference for energy use and lifestyle patterns that can combat climate change.

■ AUTHOR INFORMATION

Notes

Views expressed in this editorial are those of the author and not necessarily the views of the ACS.

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