Nanomaterials and Sustainability

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Nanostructuring adds a tremendous degree of tunability to the optical, electronic, magnetic, tribological, and chemical properties of matter. As a result, nanostructured materials already play major roles in the many technologies and industries that provide the comfort and convenience of our everyday lives. However, although there are examples of nanostructured materials that currently enhance sustainable technologies, such as for batteries and electrolyzers, the potential impact of nanoscale materials on sustainability has likely not nearly been realized when one considers that the nanostructure−property−composition exploration phase space is almost infinite. We can find inspiration from nature, which builds and assembles nanostructured materials into hierarchical biological structures to perform the enormously complex functions of life, all the while doing so with a relatively small set of elements that are sustainably sourced.[1] This contrasts with current technology, where performance demands tend to require a greater and greater diversity of elements from the periodic table, some of which are very challenging to be sustainably sourced or recycled.[2]

These were the topics for discussion at the Nanomaterials & Sustainability workshop held on May 4, 2023, as part of the annual Advanced Photon Source/Center for Nanoscale Materials Users Meeting. The workshop had more than 180 registrants and consisted of 12 invited talks covering a diverse range of subjects that included the impact of nanomaterials on sustainable energy solutions, nanostructured biomaterials, and sustainable manufacturing with nanomaterials. The speakers were each asked to provide examples of sustainability challenges and how nanomaterials could address those challenges. What follows is a summary of those contributions, organized into three topical areas: Nanostructured Materials for Sustainable Energy Solutions, Nano-bio Hybrid Materials for Energy and CO_2 Reduction, and Sustainable Manufacturing at the Nanoscale. A schematic of the connections of these three topics as they relate to the nanomaterials and sustainability theme of this paper is shown in Figure 1.

Nanostructured Materials for Sustainable Energy Solutions. Surging global energy demands along with growing environmental concerns related to climate change have spurred great interest in recent years for a reduced carbon emission economy that utilizes low carbon footprint renewable energy sources such as wind and solar systems. Energy, of course, takes on many forms, including chemical, optical, electrical, mechanical, thermal, nuclear, or a combination of them. Each of these forms of energy can be harvested, converted into another form, managed, or stored. The aim of a large part of the scientific community is to increase the efficiency of energy
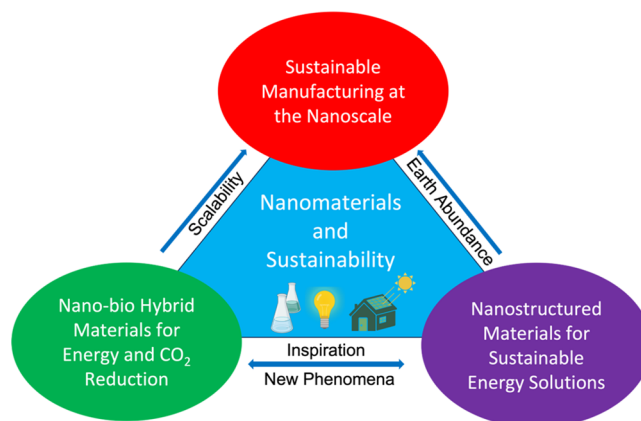
Figure 1. The importance of nanomaterials and sustainability to science and technology is schematically illustrated via the interconnections of three topical areas: Nanostructured Materials for Sustainable Energy Solutions, Nano-bio Hybrid Materials for Energy and CO_2 Reduction, and Sustainable Manufacturing at the Nanoscale.

harvesting and conversion as well as the durability of energy-related devices. As noted above, in this complex equation, one has to add the need to increase the use of abundant and recyclable materials and to minimize the use of toxic materials.

The evolution of materials science in the past decades is one of the strongest allies of the energy transition, by enabling the proposition of a plethora of new materials that vary in composition (alloys, nanocomposites), dimension (3D, 2D, 1D, 0D), and geometry (nanoarchitectured structures). Nanostructures and nanostructured materials have rapidly produced new paradigms and phenomena that have begun to impact the sustainable energy landscape. Examples of proposed ideas by topic from the Nanomaterials & Sustainability workshop follow.

Energy Storage. Mobile energy storage solutions enabled by electrochemical energy storage (EES) technologies to power electric vehicles will further reduce the dependence on high carbon emissions fossil fuels. Although today's rechargeable lithium-ion batteries (LIBs) have transformed portable
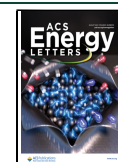
electronics, meeting large-scale grid storage and electrified transportation demands presents greater challenges. Burgeoning energy and transportation markets have a hard-pressed and urgent need for EES to provide coveted energy, power, life, safety, and low cost while utilizing more sustainable raw materials. Meeting these challenges will require innovative approaches and transformative concepts to design and discover new materials, and nanostructuring can play a significant role.

Electroceramics and their tailored nanostructures are promising materials widely used as intercalation electrodes for LIBs. As the name implies, intercalation electrodes operate by reversibly accepting (intercalation) and releasing (deintercalation) lithium ions during cycling. Nanostructuring these materials is an effective means to produce efficient exposure of electrolyte to the ceramic material via increased surface area, thereby improving charge transport. Traditionally, researchers have focused on highly ordered crystalline intercalation oxides, driven by a general belief that ordered crystals having little or no intermixing between Li and the transition metal (TM) sublattice are required in order to achieve facile Li diffusion, and hence high capacity. However, in the past decade, transition metal oxides (TMOs) with structural disorder (amorphous) have emerged as promising storage materials for anchoring more guest ions or reaction intermediates during electrochemical processes, owing to improved adsorption and storage of charge carriers compared to ordered oxides.

Evidence has shown that TMOs with cation-disordered sites have the potential to offer higher capacity and better stability compared to ordered oxides. Interestingly, despite their structural dissimilarities, the synthesis of cation-disordered materials has thus far been based on the same chemical processes as their well-ordered counterparts. In current synthetic approaches, the disordered material is typically entropically stabilized using higher temperatures. However, researchers have recently demonstrated alternative approaches to stabilizing disordered TMO electrodes by subjecting them to different external stimuli (e.g., Li ion, ion irradiation).[3,4] The hypothesis is that amorphous nanostructures represent a high-energy state that can undergo an amorphous-to-crystalline transformation under far-from-equilibrium stimuli. Inducing crystallization of nanostructured amorphous metal oxides under external stimuli is therefore an exciting new avenue for creating rare TMO electrode materials with high capacity, power, and stability for enhanced energy storage systems.

Thermal Transport. Theoretical studies of silicon nanostructures, in several cases confirmed by experiment, show that thermal transport diverges from the classic Fourier law. The ramifications are that thermal conductivity in several silicon nanosystems is no longer an intrinsic property, and thus it does not obey the Fourier law which describes well the diffusive phonon transport. It specifically fails when ballistic or quasi-ballistic transport become predominant and phonon filtering effects are produced, as in a 2D-3D network of nanowires, a crystalline/amorphous nanocomposite, or diameter-modulated nanowires.[5] Hydrodynamic heat transfer has also been observed in both pristine and core/shell silicon nanowires.[6] In composite materials of crystalline nanoinclusions inside an amorphous silica matrix, phonons can effectively sense the existence and the orientation of the neighboring nanoinclusions and hop from one nanoinclusion to another accordingly, showing phonon tunneling behavior. Asymmetric core/shell nanowires have been used to demonstrate thermal rectification due to variable axial and radial phonon

propagation and confinement. Finally, very recently, phonon interference patterns have been reproduced in a nanoporous silicon structure, showing similarities with the Young double-slit experiment for photons. All of these examples show new paradigms to create breakthrough energy technologies based on nanomaterials, with primary goals being heat management and energy harvesting. This work further allows the proposition of new functionalities such as so-called thermotronics—the reduction of the device sizes, the increase of their efficiency and lifetime, and the technology of the Internet of Things (IoT). Using silicon as the main material for such devices lies in the scope of developing new strategies for both energy and materials economy, materials management and recycling, replacing critical raw materials, and using green and non-ecotoxic materials. From the fundamental point of view, these physical phenomena require a new theoretical framework which can explain non- or beyond-Fourier thermal transport.

Solar Energy Conversion and Catalysis. There are many nanostructured materials that are being researched for solar energy conversion or photocatalysis for solar fuels.[7] Much of this research is driven by the reactivity of nanoscale surfaces, where high surface-to-volume ratios, strain, and/or the presence of environmentally exposed defects make for enhanced rates of chemical/catalytic activity. One example is semiconductor nanocrystals which can be synthesized reliably over a wide range of composition, shape, bandgap, and size. The availability of an active surface for chemical modification in semiconductor nanocrystals makes it possible also to design and synthesize a variety of semiconductor molecular hybrids. Such hybrid assemblies have applications in light energy conversion processes such as light to electricity (e.g., solar cells), electricity to light (e.g., light-emitting devices), and light to chemicals (e.g., photocatalysis). By carefully selecting molecules with sensitizing or catalytic properties, one can introduce a hybrid architecture with tailored properties. In addition, the ability to tune the bandgap of semiconductor nanocrystals through size variation (e.g., metal chalcogenides) or compositional control (e.g., metal halide perovskites) offers another knob to modulate light energy capture. Future research opportunities include the design of new semiconductor—molecular hybrids, the understanding of the mechanisms of energy and electron transfer processes, and the assembly of these materials into devices that can deliver desired light energy conversion processes.

Similarly, nanoporous materials, which in a sense are the inverse of nanoparticle systems, also show great promise for sustainability applications. One key example are metal—organic frameworks (MOFs), a class of highly porous crystalline materials that are constructed from zero- or one-dimensional inorganic chains in combination with multitopic organic ligands. They have received great attention recently due to their large surface area, tunable porosity, and easy preparation, which lead to their versatile applications including gas storage and separation, sensing, catalysis, and drug delivery.[8] However, the use of MOFs as semiconducting light absorption and charge transport (CT) materials has received little attention due to their low electrical conductivity. While some work has been done in the study of the electronic properties of conductive MOFs, it is still in its early stages, and a majority of such research focuses on material design principles and conductivity measurements, leaving the fundamental understanding of CT mechanism underexplored—yet the latter is essential for the further development of this class of materials

to be exploited in optoelectronics, solar cells, and photocatalysis. From a fundamental perspective, CT in solids or polymeric materials can be described by either of two general mechanisms: hopping transport and band-like charge transfer.[9] These mechanisms require low-energy pathways for CT which can be realized through two synthetic approaches from a chemical perspective: the through-bond approach and the through-space approach. While the literature relies mainly on computational modeling results as support for different types of CT mechanisms in MOFs, the robust nature of MOFs and compositional complexities together with the possible coexistence of CT pathways in a single material has led to electronic structures which are still poorly understood by both experimental and computational methods.

A key to understanding these structures and developing them for sustainability applications is spectroscopic characterization, including particularly time-resolved spectroscopies. As illustrated in Figure 2, key processes related to optimizing
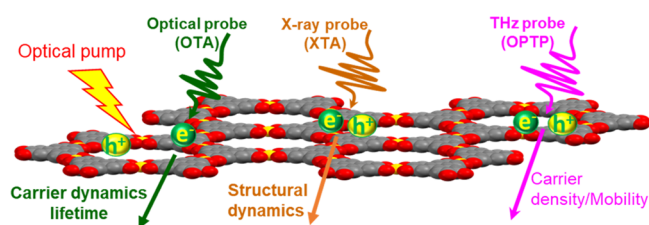

Figure 2. Diagram showing different pump−probe techniques and the information obtained from each technique.

semiconductor behavior can be measured through advanced two-dimensional (2D) spectroscopic techniques such as optical transient absorption (OTA), X-ray transient absorption (XTA), and optical pump terahertz probe (THz-OPTP). These techniques are based on the initial generation of free carriers and promotion into excited states from a pump pulse. Choice of this pump pulse is based on understanding of the system, which includes an experimental hypothesis to be examined. A secondary probe pulse whose choice also depends on the experimental design introduced at different delay times after the pump pulse is used to investigate the effects of the latter. The outcomes from these experiments, as depicted in Figure 2, include charge carrier and structural dynamics, where information about the CT mechanism can be inferred together with the overall photoconduction.

Plasmonic Nanostructures for Green Chemical Manufacturing and Solar Fuels. Plasmonic nanostructures have emerged as an exciting new class of catalysts for directing chemical reactions using light instead of heat or electricity. Optical excitations of localized surface plasmon resonances (LSPR) in metal nanostructures provide a route to generate amplified electromagnetic fields, energized charge carriers, and electron−hole pair excitations on the nanoparticle surface.[10] These photophysical effects can coax species adsorbed on the nanoparticle surface to undergo chemical reactions along excited-state pathways and at rates that are not otherwise accessible thermally. Examples range from dissociation of strong bonds at lower temperatures, generation of reactive radicals and species, multielectron multiproton redox chemistry, and thermodynamically uphill fuel-forming reactions. The promise of the plasmonic chemistry or plasmonic catalysis approach is that optical excitation would eliminate the need for harsh process conditions used in production of conventional chemicals (such as high temperatures and pressures), precious metal catalysts (such as Pt or Pd), or energetic reagents produced by high-carbon-impact processes (such as H_2 from methane reforming). This would open up a path to sustainable, solar-powered processes for the manufacturing of valuable chemicals and fuels, such as ammonia.[11] However, for this promise to be realized, important avenues remain to be explored and key advances remain to be made. First, it would be desirable for plasmonic catalysts to be based on earth-abundant elements rather than the coinage metals, particularly gold, that have dominated this area. Plasmonic oxides, sulfides, and nitrides, which have emerged in the past decade, can be prime candidates for sustainable materials for plasmonic catalysis; however, considerable research is needed to ascertain if these nanomaterials host the salient carrier photophysics and photochemical activities that underlie plasmonic catalysis with coinage metal nanostructures. These investigations would need to draw from the current state of mechanistic understanding of plasmonic catalysis, which is itself incomplete. There is therefore a need to develop a comprehensive, electronic picture of plasmon-induced chemistry based on ultrafast electronic, vibrational, and X-ray spectroscopies and time-dependent quantum mechanical methods. Questions also remain about the true contribution of non-thermal effects relative to photothermal effects that always accompany plasmonic excitation, the maximum quantum efficiency achievable in light-to-chemical energy conversion with plasmonic light absorbers, and if plasmonic excitations of charge carriers provide truly unique access to modes of chemical reactivity when compared with band gap excitations in semiconductors. Finally, attempts at technology translation will be predicated on scale-up and technoeconomic analysis of plasmonic photoreactors and catalytic nanomaterials synthesis.

Nano-bio Hybrid Materials for Energy and CO_2 Reduction. *Artificial Photosynthesis.* There is a growing demand for the sustainable production of industrially important chemicals, materials, and fuels using new environmentally friendly schemes. Inspiration comes from naturally occurring processes, such as enzyme catalysis and photosynthesis, that involve both "dark" and light-driven conversion of energy into chemical molecules. Chemical transformations carried out through natural mechanisms are highly selective and specific, can occur under ambient conditions, and are accompanied by harmless emissions into the environment. For example, natural photosynthesis has evolved as a complex catalytic reactor powered by sunlight to convert water and carbon dioxide into multi-carbon glucose molecules to store energy for the needs of plants or bacteria.

However, while optimal for living organisms, biological mechanisms can be slow or costly to address humanity's energy and environmental problems. Inspired by nature's mechanisms for capture, conversion, and storage of solar energy, scientists created the concept of light-driven processes that mimic nature and called it *artificial photosynthesis*. The first artificial water-splitting photosynthesis, pioneered by Fujishima and Honda in 1972, was carried out in a photoelectrochemical (PEC) cell, incorporating the archetypal TiO_2 semiconductor and platinum electrodes, under UV light irradiation. If both of the electrodes are imaginarily fused and scaled down to a hybrid nanostructure, the light energy conversion can be achieved "wirelessly" through photocatalysis. To date, both PEC and photochemical approaches have not only mimicked the steps of natural photosynthesis, water-
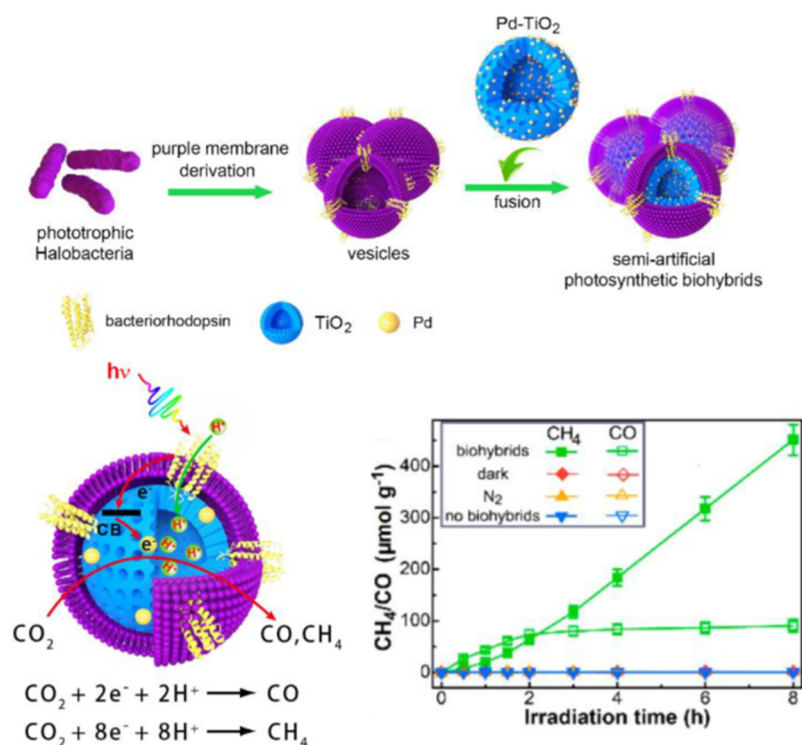
Figure 3. (Top) Assembly of a nano-bio hybrid. (Bottom left) Proposed mechanism of photosynthetic CO_2 reduction to value-added chemicals by a nano-bio hybrid. (Bottom right) Photocatalytic CH_4 and CO formation under various conditions. Adapted from ref 14. Copyright 2019 American Chemical Society.

splitting, and carbon dioxide fixation, but have gone even further toward converting greenhouse gases into value-added chemicals. Over the past five decades, extensive development of artificial systems, which typically include photosensitive semiconductors and cocatalysts, often noble metals, has focused on balancing their catalytic activity and stability, improving selectivity and efficiency of light absorption, optimizing reaction conditions, separating products, and reducing toxicity to the environment and cost.

Hybrid Nanoarchitectures. Among ongoing efforts, integration of specificity, selectivity, and environmental friendliness of natural machineries with the strengths of synthetic nanomaterials is gaining momentum. In the resulting nano-bio hybrid architectures, semiconductor or photonic nanostructures provide photoexcited electrons instead of organic high-energy cofactors to energize biosynthetic pathways and perform chemical transformations, while biomachineries preassembled by nature bring to the table such unique properties as chemical reaction specificity, wavelength-selectivity, and reactivity through proton-coupled electron transfer (PCET). Recent successful examples include the integration of non-photosynthetic whole-cell machinery or isolated enzymes with photoactive synthetic nanostructures into a photosynthetic hybrid catalyst systems.[12,13]

Key limitations here include the sensitivity of bacterial cells to oxygen and hence the cost of anaerobic cultures, the compatibility and efficiency of energy transfer at the biotic–abiotic interface, the necessary costs for cell viability, and enzyme isolation and stability.

To circumvent these limitations, a distinct type of hybrid has been developed that includes as a building block the light-gated proton pump bacteriorhodopsin (bR), a non-enzymatic retinol-centered protein capable of creating a proton gradient across a microbial purple membrane (PM) and inorganic nanostructures, such as semiconductor TiO_2 and photonic Au, Ag, or Ag/Au. These nano-bio hybrids have been applied for light-driven hydrogen evolution and photosynthesis of organic energy storage ATP molecules. Recently, an artificial photosynthesis strategy for carbon dioxide reduction was developed by integrating PM isolated from *Halobacterium* with hollow mesoporous semiconductor $Pd-TiO_2$ nanoparticles (Figure 3). In these hybrid catalytic systems, a proton pump bR functions as a photosensitizer that injects light-excited electrons into the conduction band of TiO_2 while retaining its natural biological function as a visible-light-driven proton pump. Thus, photo-induced electrons and protons accumulated within a confined nano-bio architecture act in concert, allowing catalytic reactions via proton-coupled multi-electron-transfer processes at significantly reduced potential requirements. The nano-bio architecture converted CO_2 into CO and CH_4 under $\lambda > 420$ nm light in water at pH 7 and room temperature with ascorbate as a sacrificial electron donor, with a pronounced selectivity of over 95% toward methane.[14] This approach provides an alternative minimalistic reconfigurable toolkit for designing photosynthetic bio-inspired and bio-enabled nano-architectures for sustainable energy applications.

Sustainable Manufacturing at the Nanoscale. *Development of Green Nanolubricants.* It is estimated that approximately 23% of the world's total energy consumption can be attributed to tribological contacts.[15] The lubrication industry relies heavily on oil-based lubricants due to their ability to minimize friction and wear losses while maintaining durability. However, the disposal of oil waste, as well as the presence of hazardous additives, presents significant environmental and health concerns. In line with the decarbonization objective of achieving net carbon neutrality by 2050, the
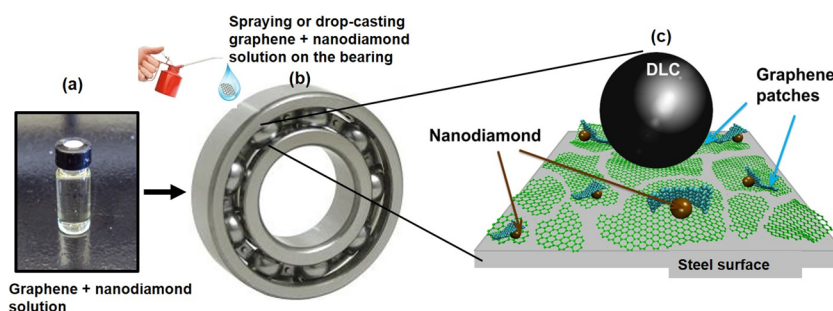
Figure 4. Schematics of a graphene/nanodiamond-based superlubric solid lubricant coating developed at Argonne National Laboratory showing application from (a) solution to (b) bearing. The schematic in (c) shows a diamond-like carbon (DLC) ball sliding on nanodiamond/graphene patches. Adapted from ref 16. Copyright 2015 American Association for the Advancement of Science.

development of biodegradable lubricants has become increasingly critical for the lubrication industry contributing toward building a sustainable society.

In this context, there is a growing interest in the utilization of nanomaterial-based solid lubricants that offer several advantages, such as the absence of hazardous waste, lower cost, and greater durability. At Argonne National Laboratory, significant progress has been made in developing a series of solid nanolubricants based on graphene/nanodiamond and its derivative (Figure 4).[16] These lubricants have demonstrated outstanding wear and friction properties, including the remarkable phenomenon of superlubricity (nearly zero friction) at high contact pressures, in diverse environments, and with long-lasting effectiveness. Moreover, the efficacy of these lubricants in reducing friction and wear losses has been demonstrated at an industrial scale in key sectors such as the automotive industry's metal stamping process and the oil and gas industries as protective coatings for mechanical shaft seals. Collaborative efforts with industry partners have enabled successful demonstration at the industrial scale. Importantly, these materials can be applied using a simple air-spray coating process, making them scalable over large areas at significantly lower costs compared to traditional thin-film coatings. At the nanoscale, the intricate nature of tribochemistry plays a pivotal role in the formation of a tribolayer, effectively reducing friction and wear. The 2D structure of these lubricants facilitates excellent adhesion to the base substrate, resembling chemical bonding while enabling smooth shearing between the deposited layers. The dynamic behavior of 2D flakes resembles that of semiliquid or crystalline oil, resulting in exceptionally low friction and wear. These exceptional characteristics of nanolubricants hold great promise for advancing the development of oil-free solid lubricants in various practical applications. Furthermore, they offer significant potential in contributing to the decarbonization objectives of the lubrication industry.

Nanomaterials for Fuel Cells and Electrolyzers. Nanomaterials offer a multitude of opportunities to address and enhance sustainability across most industries. In addition to contributing to sustainable technologies such as fuel cells and electrolyzers, nanomaterials can also be deployed to enhance the sustainability of energy-intensive industrial operations as well as to more efficiently utilize our natural resources. One major challenge in the development of sustainable electrolyzer and fuel cell technologies involves the reality that critical minerals, including iridium and platinum, are essential to achieving higher performance while offering the necessary durability and stability under an electrolyzer's extremely

aggressive high-voltage and acidic operating conditions.[17] At commercial electrolyzer deployment scales, the demand for Ir is forecasted to outstrip the worldwide production of Ir (Figure 5). A number of approaches are being pursued to mitigate this
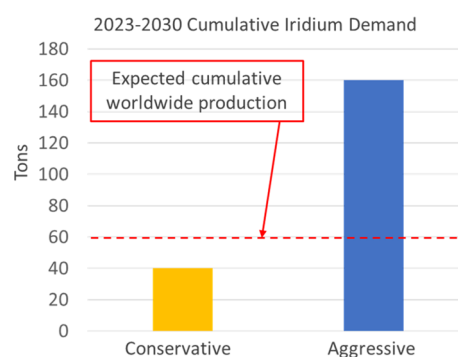

Figure 5. 2030 cumulative iridium demand. Conservative at 80–100 GW at 40% PEM; aggressive at 80% PEM.

challenge, including renewed efforts in recycling across the electrolyzer value chain, from recovering platinum group metals (PGMs) from low-value, dilute manufacturing waste to recycling end-of-life electrolyzer stacks. Additionally, new catalyst formulations are being developed that aim to utilize less mg Ir/cm^2 without sacrificing performance. Current strategies being pursued involve the incorporation of Nb- and Ru-containing IrO_x materials, both as mixed oxides and as supported structures, both to reduce Ir usage and to derive performance advantages from incorporated Nb and Ru. Recent results indicate that high-surface-area IrO_x, $IrRuO_x$, and $IrRuO_x/NbO_x$ demonstrate stability in high-efficiency proton exchange membrane (PEM) water electrolyzers over 1400 h of testing.[18] To push boundaries even further, driving nanoscale IrO_x catalyst structures to even smaller particle sizes is effective in reducing crystallite sizes and increasing catalyst surface areas, techniques which demonstrate promise in achieving similar electrolyzer performance under polarization with lower Ir loading levels.[18]

The Science of Scale-Up and Nanomaterials Manufacturing. Materials to enable next-generation technologies are increasingly structured at the nanoscale, whether for flexible electronics, industrial catalysts, quantum computing, battery materials, or other applications. The benefit for industry stems from tunable properties as desired via precisely controlling the size, morphology, and composition by adjusting synthesis conditions and appropriate functionalization. However, the

critical bottleneck in harvesting the benefits of advanced nanomaterials is in their low availability. Furthermore, industry still struggles to translate discovery lab inventions into tangible technological applications. Nanomaterials are notoriously difficult to scale up to a commercial level, even though they can be manufactured by using a variety of methods, either "top-down" or "bottom-up".[19] The historical three-stage scaling method (i.e., lab-scale/pilot-scale/large-scale) based on increasing the volume of a batch reactor cannot satisfy the requirement of manufacturing of nanomaterials, as it is hard to maintain the required nanostructure and properties.

One approach that is uniquely suited for nanomaterial synthesis and scale-up with superior process control and material performance is the application of a continuous-flow reactor (CFR).[20] Particle size and morphology are controlled via temperature, pressure, flow rate (residence time), process chemistry, and precursor concentration. All parameters can be easily and reproducibly controlled due to the superior and predictable mass and heat transfer capabilities of a CFR. Continuous-flow syntheses present *multiple benefits*: 1) excellent homogeneity leads to narrow particle size distribution, 2) a fully automated computer-controlled system expedites process optimization to achieve desired nanoparticle properties, 3) processes can be run in conditions that are difficult or impossible to achieve otherwise, e.g., rapid heating/cooling leads to ultrasmall nanoparticles, and 4) scalable architecture provides the tools for seamlessly moving from benchtop process optimization to production. Furthermore, 5) the modular design of a CFR system allows for multistage synthesis of complex nanocomposite materials in a single-pass process, as well as for parallel synthesis for scaling-up large amounts of nanomaterials in the multipass.

For a CFR, the reaction can also be monitored as a function of distance along the flow path, which provides the opportunity to conduct time-resolved studies using an in situ real-time method, e.g., APS X-ray tools, for *elucidating the fundamentals*. The feedback can be used to optimize processes and reactor design. With additional assistance of machine learning/artificial intelligence (ML/AI) capabilities, the CFR process can be readily automated, accelerating development of novel materials and their manufacturing to address the highly time-consuming problem of multiparameter optimization.

Moreover, surfaces and interfaces plays key roles in not only enabling the synthesis of ultrasmall high-quality nanomaterials (controlling agglomeration) but also scaling up the process (allowing for higher precursor concentration). It is crucial to understand surface phenomena by conducting computer simulations and experimental validation such that a deep knowledge of the relationship between particle formation (nucleation and growth), physicochemical properties, and material performance can be developed and the material can be scaled-up.

We have described the opportunities and examples of possible contributions of nanomaterials to sustainability efforts, as presented at the Nanomaterials & Sustainability Workshop. There are considerable opportunities and research efforts across the globe addressing clean energy solutions. However, while the case for nanomaterials to realize new technologies is very strong, it is also true that the emergence of nanotechnology is partly responsible for the extension of the palette of materials used by humanity. One need only note that a smartphone requires twice more elements than all life-forms on Earth.[2] Thus, our challenge in nanoscience research is to ultimately advance nanotechnology applications while balancing performance with considerations of elemental abundance and environmental impact as a whole.

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Notes
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