Credit: Golisano Institute for Sustainability at the Rochester Institute of Technology

Glasses, ceramics, and metals are critical to a clean energy and mobility transition

Understanding the intensity and criticality of materials used in clean energy production, low emission transportation, and lighting helps engineers design solutions for a more sustainable world.

By Alexandra Leader and Gabrielle Gaustad

The continued growth and development of our economies comes with significant attendant environmental impacts. Across the globe, raw material usage for both energy generation and manufacturing alike has increased exponentially, and the growth is likely unsustainable. Hurricanes, massive forest fires, and unprecedented flooding have become increasingly recurrent phenomena in the past few years, likely caused and/or exasperated by the impacts of climate change. Anthropogenic greenhouse gas emissions, generated by the sectors shown in Figure 1a, are proven contributors to climate change. Fortunately, the minerals, metals, glass, and ceramics industries embraced these challenges as opportunities to drive groundbreaking work in their fields. For example, they developed clean energy technologies to address electricity and heat production, building, industry, transportation, and other energy categories, tackling a total of 76 percent of the total global greenhouse gas emitting sectors.[1] These technologies, however, also require material consumption; understanding their use and supply is key to ensuring overall sustainability.

A greener, safer world

Clean energy technologies are vital for addressing climate change not only in developed countries but also in developing countries, which will continue to increase their material and energy consumptions and emissions as they reach lifestyle parity with developed nations. According to the World Resources Institute, the per capita greenhouse gas emissions for developed countries are on average approximately four times those of developing countries.[3] It is of paramount importance to provide developing countries the opportunity to progress, and clean energy technologies can help them to potentially leapfrog currently industrialized nations by avoiding having their energy infrastructure based on fossil fuels.

The United Nations Sustainable Development Goals identified 17 sustainability goals for the year 2030, a few of the most relevant here being the need for affordable and clean energy, decent work and economic growth, and reduced inequalities.[4] Many technologies were established to assist with reaching the goals while mitigating environmental damage. We will refer to these technologies as clean energy technologies, because even though they still have environmental footprints, these technologies aim to be less harmful to the environment than comparative incumbent technologies. Such advances should help create a cleaner and safer world, with less greenhouse gas emissions, pollution, and toxicity. While these technologies are imperfect, they continuously become more efficient and contain fewer hazardous and critical materials.

Life-cycle assessment (LCA) is a common tool used to determine the environmental consequences of a product or process over the entirety of its lifespan. The assessment can be used to compare different options or to find "hotspots" within a product or process that are most detrimental to the environment. For example, how do we know that the mining and production processes for critical materials and clean energy technologies do not outweigh the benefits?

The sustainability science community conducted several LCAs to answer these types of questions. For the case of lithium ion batteries, Stamp et al. used lifecycle analysis to examine whether the production process for lithium could possibly outweigh the benefits of using electric vehicles compared to internal combustion engines. They found that the environmental impacts of lithium production would only be prohibitive if seawater was used to produce lithium carbonate in the future. With the current methods of brine and ore production, the benefits of electric vehicles outweigh the negative impacts associated with lithium production.[5]

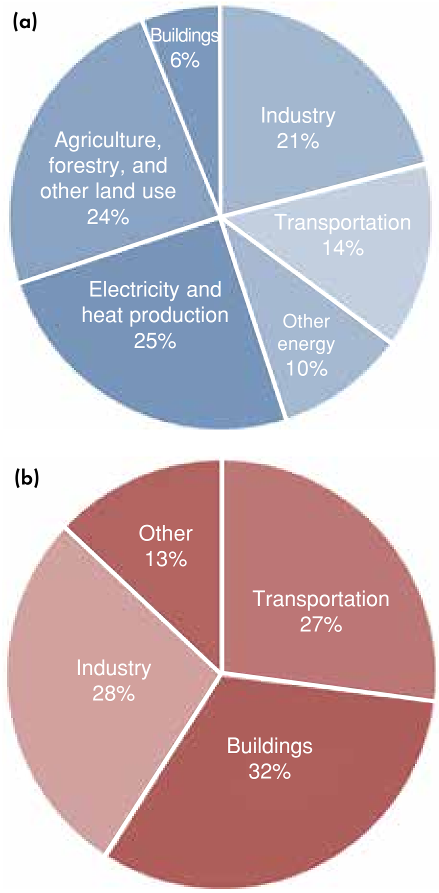

Figure 1: (a) Global greenhouse gas emissions by sector (2010), total emissions were 49 Gt CO_2eq.[2] (b) Global energy demand by end use sector (2010), total energy demand was 366 EJ.[2]

Critical materials for clean technologies

In the literature, many materials are identified as critical in seven categories of clean technologies. These categories include: the clean energy production technologies of solar panels, wind turbines, and gas turbines; the low emission mobility technologies of fuel cells, batteries, and motors; and the energy efficiency technology of efficient lighting devices. Each of these technologies relies on a set of materials, some of which are readily available, and others that are vulnerable to supply disruption, price instability, and/or high embodied energies. While different organizations define a material's "criticality" slightly differently, criticality can be described generally as the risk associated with the use of a specific material, stemming from the likelihood of a supply disruption or price spike, combined with the impact of such an event occurring.

An example of how criticality is defined is seen in how the US Department of Energy (DOE) identifies materials that are critical to clean energy technologies. The DOE uses two measures to define criticality: "supply risk" and "importance to clean energy."[6] Supply risk can come from a material having a high production concentration (geographically), high concentrations in politically unstable regions, large environmental impacts (that might be subject to environmental regulations), low recycling rates, and low substitutability. For the case of clean energy technologies, the DOE's "impact" measure of importance to clean energy technology is most relevant to this article; however, in other cases, importance to healthcare, military applications, or consumer electronics may be considered.

The DOE report titled "Critical Materials Strategy" analyzes forecast demands for 16 elements based on a range of material compositions in permanent magnets (in wind turbines and electric vehicles), batteries (in electric vehicles), semiconductors (in solar), and phosphors (in efficient lighting). To deal with the uncertainty of material intensity, level of global clean energy deployment, and market share, various scenarios are employed to capture high and low ranges in each of these uncertainty categories. The ability of supply to meet projected demand is then weighted at 40 percent for calculating the "supply risk" portion of the element's criticality, while the demand itself made up 75 percent of the "importance to clean energy" criterion. Without getting into the details of each scenario and element, we would instead point to the chosen methodology and the results that put dysprosium, terbium, europium, neodymium, and yttrium on the list of critical elements in the short and medium term; cerium, indium, lanthanum, and tellurium as near critical in the short term; and lithium and tellurium as near critical in the medium term.[6]

Many studies used different methods for calculating metrics that measure material criticality, including an article by Graedel and Nuss that quantitatively scores the criticality of 62 elements.[7] A review article by Erdmann and Graedel is helpful in summarizing such studies.[8] Some examples of more prolific metrics include those revolving around the quantity of material resources available, the cost of the material, and market concentration (often measured by the Herfindahl-Hirschman index). For example, in a study by Olivetti et al., they analyze the criticality of lithium, cobalt, manganese, nickel, and carbon in different Li-ion battery chemistries[9] using the metrics of reserves/primary mine production, fraction of production from the top-producing country, geopolitical stability of the top producing countries, the byproduct or primary product nature of the materials, the ability of supply to meet demand projections, and the viability of recycling. Overall, the study showed that cobalt is the primary concern for Li-ion batteries in the short term, but with potential for scaling concerns for lithium as well (as Li-ion batteries are expected to experience rapid uptake in the coming years).[9]

Through literature review, we identified the critical metals, ceramics, and glasses contained in the previously described clean energy production, low emission mobility, and energy efficiency technologies shown in Table I. The three types of clean energy production technologies considered here are solar panels, wind turbines, and natural gas turbines.

Within the solar panel category, materials are listed for cadmium-tellurium (CdTe), crystalline-silicon (c-Si), and copper-indium-gallium-selenide (CIGS). In 2016, approximately 6 percent of the world's solar production was in thin-film solar, with 3.8 percent of that being CdTe and 1.6 percent being CI(G)S. The remaining 94 percent of solar production in 2016 was comprised of mono- and multi-silicon at 24.5 percent and 69.5 percent, respectively.[10] In CdTe solar cells the cadmium and tellurium make up the active (or absorber) layer in a ratio of approximately 48:52.[11] Typically, the absorber layer will have a thickness of approximately 1-3 µm,[12] yet the range found can be as large as 1-10 µm. In CIGS solar cells the indium and gallium are contained in the absorber layer, which ranges between 1-2.5 µm.[13] Recently, studies have examined replacing some of the indium content with more gallium in order to increase the bandgap, allowing for greater efficiencies.[14] In crystalline silicon solar panels, silver is used in the screen-printing pastes, especially for its low electrical resistivity.[15] Tin and indium are used in the transparent conducting oxide layers.[10]

In wind turbine technology, we specifically consider the permanent magnets used in direct-drive wind turbines. In 2015, approximately 23 percent of globally installed wind capacity relied on NdFeB permanent magnets, which can contain neodymium, dysprosium,

Table I: Metals, ceramics, and glasses in clean energy production, low emission mobility, and energy efficiency technologies. For a list of table references, check the online version of *ACerS Bulletin*.

			Glasses and ceramics	Glasses and Ceramics Sources	Metals	Metals Sources
Clean energy production	Solar panels	CdTe	SnO_2, Zn_2SnO_4, ZnO, SnO_2, Cd_2SnO_4	[1, 2]	Cd, Te, Ni, Cr, Mo	[3-9]
		Crystalline silicon	c-Si	[10]	Ag, Sn, Ni	[6]
		CIGS	ZnO, NaO, CaO, SiO_2	[11, 12]	In, Ga, Se, Sn, Ni, Cr, Mo	[3-6]
	Wind turbines	Permanent magnet	$Sr_6Fe_2O_3$, $Ba_6Fe_2O_3$, Si_3N_4	[13, 14]	Dy, Nd, Mo, Tb, Pr	[6, 15-21]
	Gas turbines	Superalloy coating	Y_2O_3-ZrO_2, CMC, Si_3N_4, 1-xBaO·xSrO·Al_2O_3·2SiO_2, $0 \leq x \leq 1$, Al_2O_3, Si_3N_4, SiC	[14, 22]	Co, Ni, Re, Hf, Mo, Y	[23, 24]
Low emission mobility	Fuel cells	SOFC	Ni/YSZ, $LaMnO_3$, LSCF, ScSZ, LSGM, YSZ, LSM, LSC, $LaMnSrO_3$, La(Sr, Mn, Ca)CrO_3	[14, 25-27]	Y, La, Ce, Co, Sm, Gd, Sr, Ni	[26, 28]
		PEM			Pt	[5, 19, 29, 30]
	Batteries	Li-ion	$LiCoO_2$, $LiMn_2O_4$, $LiFePO_4$, $LiMn_{1.5}Ni_{0.5}O_4$, $LiNiMnCoO_2$, $LiNiCoAlO_2$, $Li_4Ti_5O1_2$	[31, 32]	Li, Co, Ni, Mn, Dy, Pr, Nd, V, Tb	[5, 19, 33-35]
		NiMH			Pr, Nd, La, Co, Mn, Ni, Ce, V, Tb, Dy	[5, 15, 18, 33, 36, 37]
	Motors	Permanent magnet	$Sr_6Fe_2O_3$, $Ba_6Fe_2O_3$, Si_3N_4	[13, 14]	Dy, Pr, Nd, Co, Tb	[5, 15, 16, 18, 21, 36, 38]
Energy efficiency	Lighting devices	CFL	BAM, CAT, LAP, YAG, GaAs, GaN, InGaN	[39]	Ga, La, Ce, Tb, Eu, Y, Gd, Mn, Ge, In	[5, 39, 40]
		LFL	BAM, CAT, LAP, YAG, GaAs, GaN, InGaN	[39]	La, Ce, Tb, Eu, Y, Mn, Ga, Ge, In	[5, 39, 40]
		LED	$Y_3Al_5O_{12}$:Ce^{3+}, YAG, LuAG, GAL, $LaPO_4$:Ce, Tb, $BaMgAl_{10}O_{17}$:Eu & (Sr, Ca, Ba)$_5$(PO_4)3Cl:Eu, Y_2O_3:Eu, $(Y,Eu)_2O_3$, InGaN	[39, 41-43]	In, Ga, Ce, Eu, Y, Gd, La, Ni, Tb, Ge, Ag, Sn	[40]

praseodymium, and terbium. The other 77 percent used electromagnetic generators containing steel and copper for their functionality, neither of which are considered critical materials.[16] Wind turbines can be classified into two major categories: geared and gearless (direct-drive). Gearless, direct-drive turbines operate best at low speeds and have the advantages of better overall efficiency, lower weight, and fewer maintenance requirements.[16] Geared turbines, on the other hand, will operate at higher speeds on smaller turbines (< 5MW) and contain few or no rare earth elements.[16] Pavel et al. estimate that permanent magnets could be dematerialized from currently containing 29-32 percent Nd/Pr and 3-6 percent Dy to 25 percent Nd/Pr and <1 percent Dy by 2020.[16] Direct substitution for rare earth elements will be challenging, but efforts are being focused on finding new magnet compositions and/or using different components that don't rely on rare-earth-containing permanent magnets at all.[16]

Natural gas turbines may not typically be considered a clean energy technology. However, it is widely agreed that natural gas, while still an imperfect finite resource, is a cleaner alternative than coal. Gas turbine blades have to withstand high centrifugal stresses and are exposed to extreme temperatures,[17] so the superalloy coating on the blades contains critical materials to address these challenges. Currently, nickel-based superalloys contain rhenium and hafnium (for their high temperature properties) to achieve sufficient refractoriness.[17,18] Rhenium is often the focus of dematerialization efforts because it is used in much greater quantities in the superalloys than hafnium. In addition, rhenium has a history of price volatility, and after the large price spike in 2007, companies that use rhenium, such as General Electric, began to apply methods such as dematerialization and in-house recycling to reduce their risk.[19] Alloys have been designed containing half as much, or no, rhenium, but at this point none can match the high temperature creep resistance of the superalloys currently used.[20] About 80 percent of rhenium production is a byproduct of copper mining, adding to its criticality.[20]

For clean mobility we focus on electric vehicle components, including the energy sources of fuel cells and batteries as well as the permanent magnets in the motors. We considered permeable exchange membrane (PEM) and solid oxide fuel cells (SOFCs), and lithium-ion (Li-ion) batteries and nickel metal-hydride (NiMH) batteries. Currently PEM fuel cells dominate the fuel cell electric vehicle marketplace, with little or no SOFCs present. While NiMH batteries are currently the dominant battery choice for hybrid electric vehicles, some expect numbers as high as 70 percent of hybrid electric and 100 percent of plug-in and full electric vehicles to use lithium ion batteries by 2025.[21] Of primary concern are the rare earth elements in the permanent magnets and NiMH batteries, lithium and cobalt in the Li-ion batteries, and platinum in the fuel cells.[22]

Finally, in representation of energy efficiency technologies we choose three types of light bulbs: compact fluorescent lightbulbs (CFLs), linear fluorescent lightbulbs (LFLs), and light-emitting diodes (LEDs), all of which are more energy efficient than traditional incandescent bulbs. In lighting, most of the critical materials (especially rare earth elements) are found in the lamp phosphors.[23] The phosphor is coated on the inside of the bulb and therefore the quantity of rare earths used often varies directly with the size of the bulb (especially for linear fluorescents).[6] Europium and yttrium create red, terbium produces green, and europium gives blue phosphors.[24] LEDs use fewer rare earths than fluorescent bulbs; however, they also contain gallium and indium in their semiconductor diodes.[23]

The materials used in the technologies listed in Table I are required in certain quantities per effective unit of output. This so called "material intensity" is important, especially as a metric of comparison between two or more materials within a technology or between two or more comparable technologies. For example, when discussing the quantity of tellurium per CdTe solar panel, depending on the application, it would be less useful to speak in terms of tellurium per panel but rather to discuss the intensity of tellurium in mass per kW of solar capacity. Identifying material intensities of important materials for clean energy technologies is the first step to selecting technologies that not only have the desired properties and costs as has been done historically, but that also have lower social, environmental, and economic impacts. While material intensity is an important indicator in terms of quantity of material that is being used per functional output of the technology, it is also important to consider the more qualitative aspects of the materials these technologies contain, such as their degree of criticality, as previously discussed.

Engineering a better world

By better understanding the materials used in clean technologies and their implications in terms of environmental impact, social impact, and potential for supply disruption, we can engineer solutions for a better, more sustainable world. This trend of considering broader implications when selecting materials is becoming more common. When designing products, many firms have started thinking more comprehensively about material qualities beyond the traditional material properties and price, considering recyclability, carbon and water footprints, overall lifecycle impacts, supply risk, and social implications. Material selection software continues to integrate sustainability impacts to aid engineers and scientists in making properly robust but environmentally aware material decisions. Computational material discovery efforts also aid in producing low impact materials by design. A variety of this work uses machine learning to look at common recipes that result in the combination of desired properties, an efficient production or scale-up technique, and an understanding of the likely environmental impacts.

Many studies consider material requirements on the basis of meeting various climate change mitigation targets. These studies are important to consider as they reflect on the larger picture of whether we have the quantity of materials necessary to produce these clean energy technologies to the extent needed to mitigate climate change to various levels, as described in the individual studies. For example, Alonso et al. considered only rare earth elements in wind turbines and electric vehicles and found that if atmospheric CO_2 is to be kept at 450 ppm, neodymium and dysprosium may experience an increase in demand of more than 700 percent and 2600 percent, respectively (from 2010 numbers), by 2035.[25] Another analysis by Grandell et al. identifies potential "bottlenecks" for critical metal supply through 2050. They consider solar, wind turbines, fuel cells, batteries, electrolysis, hydrogen storage, electric vehicles, and efficient lighting as clean energy technologies. Silver is identified as the most likely issue, alongside other potential bottlenecks for tellurium, indium, dysprosium, lanthanum, cobalt, platinum, and ruthenium. Their stance is that these bottlenecks could prove enough to render the IPCC renewable energy scenarios "partly unrealistic from the perspective of critical metals."[26] A paper by Jacobson and Delucchi theorizes the impact of providing "all global energy with wind, water, and solar power." In terms of material limitations, they conclude that such a system would likely not be inhibited by the availability of bulk materials but other materials, such as neodymium, platinum, and lithium, would need to be recycled, substituted out, or found in new deposits.[22] Finally, a study by Bustamante and Gaustad considers a very specific case study of tellurium in CdTe solar cells. They find that tellurium availability is likely to dampen CdTe adoption; however, they go on to explain that this is more likely to occur due to the byproduct nature of tellurium rather than its overall resource quantity. Based on the current supply infrastructure for tellurium—in which it is a byproduct mineral—they predict that tellurium availability is insufficient to meet even conservative demand estimates.[27]

Material criticality is dynamic, and as clean energy technologies evolve, so are the material compositions and forecasted adoption rates. We must be proactive in designing clean energy technologies in terms of our material choices so as to use those materials that are not only cost effective and functional but also sustainable. It is also important that we continue predicting and monitoring the material requirements for clean energy technology demand so as not to impede the implementation of the technologies that will play a critical role in providing a cleaner, safer, and more sustainable world.

About the authors

Alexandra Leader is a Ph.D. candidate in Sustainability at the Golisano Institute for Sustainability at the Rochester Institute of Technology. Gabrielle Gaustad is Dean of the Inamori School of Engineering at Alfred University. Contact Leader and Gaustad at aml5814@rit.edu and gaustad@alfred.edu, respectively.

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National Science Foundation awards in the Ceramics Program starting in 2018

By Lynnette D. Madsen

As an independent federal agency of the United States government, the National Science Foundation (NSF) funds basic research conducted at America's colleges and universities. NSF's Ceramics Program in the Division of Materials Research resides within the Mathematical and Physical Sciences Directorate. There are six other science and engineering research and education directorates at NSF, including Engineering.

The mission of the Ceramics Program is to support fundamental scientific research in ceramics (e.g., oxides, carbides, nitrides, and borides), glass-ceramics, inorganic nonmetallic glasses, ceramic-based composites, and inorganic carbon-based materials. The program aims to increase fundamental understanding and to develop predictive capabilities for relating synthesis, processing, and microstructure of these materials to their properties and ultimate performance in various environments and applications. Proposals relating to discovery or creation of new ceramic materials are welcome, as are the development of new experimental techniques or novel approaches. The Ceramics Program supports research at universities and colleges of all sizes, from research universities to colleges that serve undergraduates. The principal investigators (PIs) of these projects include faculty at all levels from assistant to full professors.

This article marks the fourth annual summary of NSF Ceramics Program awards to appear in *ACerS Bulletin* [1,2,3] and the second year that the Ceramics Program has been piloting no-deadlines for submissions (NSF 16-597). This approach has been used in the Geosciences and Engineering Directorates at NSF and by foreign agencies. In June 2018, the Engineering Directorate announced removal of deadlines for many of its core programs (NSF 18-082).[4]

Eliminating deadlines better accommodates the schedules of PIs and encourages submission of emerging ideas. In addition, it opens the door to better proposal quality and spreads the workload for reviewers and NSF program directors more evenly throughout the year, resulting in quicker review and award cycles. Under this pilot, PIs submitting to the Ceramics Program are requested to suggest reviewers, and annual budget requests are typically $110,000 to $160,000 per year for each project, subject to the availability of funds; smaller budgets are permissible. Budgets in excess of $160,000 per year may be returned without review.

The number of full proposals received by the Ceramics Program continues to be fewer than years with a deadline. However, the number of submissions increased significantly between 2017 and 2018. There are about 130-150 active awards in the Ceramics Program at any given point in time.

Table 1 provides a key to types of grants awarded in FY 2018 by the NSF Ceramics Program, and Table 2 lists FY 2018 awards. Detailed information on any NSF award is available by adding the 7-digit award number to the end of www.nsf.gov/awardsearch/showAward?AWD_ID= or by searching the NSF awards database. Additional ceramics research is supported through centers, group grants, instrumentation awards, and other programs focused on one or two investigators (e.g., in the Engineering Directorate).

FY 2019 began Oct. 1, 2018, and the first awards have appeared. NSF recommends submitting full proposals 9–12 months before the funds are needed to allow six months for review and time to process awards. Supplemental proposals are best submitted in February. In particular, NSF encourages supplemental requests for the addition of veteran and underrepresented minority graduate students to projects (through MPS-GRSV: NSF 15-024 and AGEP-GRS: NSF 16-125), Career–Life Balance supplements (for leaves of absence for dependent care responsibilities), collaborations with NIST (NSF-NIST 11-066), and interactions with industry (through GOALI or INTERN NSF 17-091). PIs must acknowledge NSF support in any publications or presentations. An example of appropriate wording is: "This material is based upon work supported by the National Science Foundation under Grant No. (NSF grant number)." Annual reports are due in the spring (regardless of anniversary date). All products listed in the reports should acknowledge NSF support. See www.nsf.gov/funding for full information about proposal submission and award requirements.