Access to clean water is a daily challenge for 1.8 billion people in the developing world. The United Nations has set a goal of ensuring safe drinking water for all by 2030.

Filtering safe drinking water through granulated ceramics

Modular filters based on silver-coated ceramic granules provide sustainable, affordable access to clean water when water treatment infrastructure is lacking.

By Reid Harvey, Mike Chu, and John Hess

The world is thirsty for safe drinking water. But too many do not have access, especially in developing regions. Silver-treated ceramic granule filters offer an affordable, sustainable option for purifying water in households, and even on municipal scales.

Introduction

Worldwide, the predominant problem with drinking water is a prevalence of pathogen contamination. According to a United Nations fact sheet,[1] 80 percent of wastewater reenters the environment untreated. An estimated 1.8 billion people use water sources contaminated with pathogens from untreated urban wastewater, agricultural runoff, and other contaminated water sources, which expose them to increased risk of water-borne pathogens such as cholera, dysentery, typhoid, and polio. The problem is most pronounced in countries at the lower end of the economic spectrum that tend to lack wastewater management infrastructure such as sewer systems and water treatment plants.

Systematic challenges

Municipal water treatment involves the use of chemicals, coagulation, flocculation, and filtering through sand, along with such exotic approaches as ultraviolet and reverse osmosis. Implementing these types of water treatment systems in the developing world could work technically, but is difficult to sustain and is limited by problems with delivering water. In addition, municipal treatment can be too expensive for poor communities to implement.

On the household scale, inexpensive water treatment usually involves the use of chlorine, which requires a level of education for testing and dosing that presents a barrier to those who may never have been to school. Boiling contaminated water is an alternative. Even so, of the various household alternatives, only boiling is one purification method that has achieved scale.[2] However, those whose daily income is below poverty levels cannot afford fuel for boiling.

Other forms of acquiring clean water include solar distillation (setting a bottle of water in the sun for six hours) or rainwater catchment. However, these, too, are not sustainable nor user-friendly. Additionally, rainwater catchment depends on the bounty of the sky.

In much of the developing world, water is collected by women as part of their household duties. In their collection of water, these women may walk or stand in line for hours every day. Water collected this way is most often pathogen-contaminated, and, worldwide, well over a thousand small children die every day because of their drinking water.[3] Small children with immature immune systems get diarrhea, which leads to dysentery and death. Parents may not recognize the warning signs in time to give children life-saving oral rehydration therapy.

United Nations priority

The United Nations identified 17 Sustainable Development Goals (SDGs) comprising a roadmap "to achieve a better and more sustainable future for all" by 2030.[3] Clean Water and Sanitation—Goal 6—is both a consumer product and a human right. According to the UN, sanitation and drinking water improvements have led to "over 90% of the world's population now [having] access to improved sources of drinking water." However, the UN calls for increased investment in freshwater management and local-level sanitation systems, especially in at-risk regions of Sub-Saharan Africa, Central Asia, Southern Asia, Eastern Asia, and Southeastern Asia.

Solutions proposed for the developing world tend to focus on conventional municipal water treatment, often on a smallish scale. Unfortunately, many such development efforts have failed in the past owing to little provision by the donor for maintenance after the first couple of years.

Point-of-use water treatment

The need for point-of-use water treatment in the developing world for rural areas is obvious. However, point-of-use water treatment in urban areas, where the delivery infrastructure from municipal treatment tends to be damaged or non-existent, is also needed to avoid delivering water that gets recontaminated on its way to communities.

Modular, portable solutions that do not rely on other plant facilities and infrastructure—such as reliable electricity service—may offer an effective pathway to providing clean, safe water for millions of people. Chemical-free water purification systems also are desirable, as chemicals introduce a supply chain dependency and require physical plants or other infrastructure to implement. Low cost and ease of maintenance are urgent priorities.

Heavy metals exert a toxic effect on pathogens that generally renders them harmless. Unfortunately, consuming

United Nations Sustainable Development Goals[3]

1. No poverty
2. Zero hunger
3. Good health and well-being
4. Quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation, and infrastructure
10. Reduced inequalities
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life below water
15. Life on land
16. Peace, justice, and strong institutions
17. Partnerships for the goals

United Nations targets for achieving Goal 6: Clean water and sanitation

1. By 2030, achieve universal and equitable access to safe and affordable drinking water for all
2. By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
3. By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
4. By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
5. By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
6. By 2020, protect treatment, recycling, and reuse technologies
7. Support and strengthen the participation of local communities in improving water and sanitation management

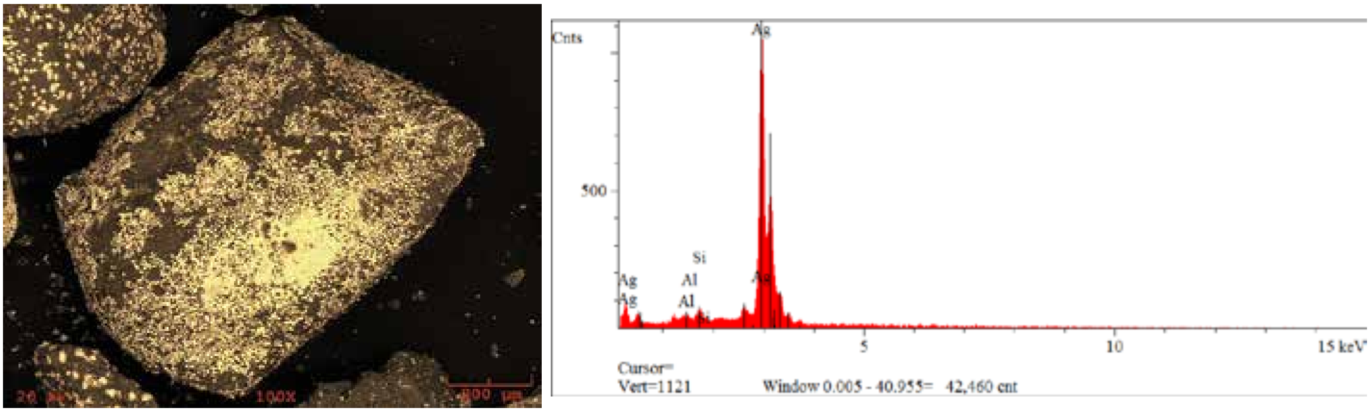

Figure 1. (a) Scanning electron micrograph showing bright regions of silver deposits on ceramic granules. (b) Energy dispersive spectroscopy X-ray spectrum confirms localized silver deposits on an aluminosilicate clay particle.

even small amounts of heavy metals can harm people. Silver, however, has no deleterious health effect for those ingesting minute amounts, and it has long been exploited for its antimicrobial properties, even in ancient times. Since the 1970s nanoscale silver has been used as the active antimicrobial ingredient in drinking water purification systems.[4] Because of the prevalence of silver-containing water purification systems, the EPA[5] set a standard for leached silver levels not to exceed 0.1 milligrams per liter (100 micrograms per liter).

For at least 10 years researchers have worked on impregnating porous clay-based ceramic filters with colloidal silver as simple water purification systems using local clay resources and not requiring infrastructure such as electricity. These silver-ceramic filters have been shown to be effective water purifiers. Oyanedel-Craver and Smith[6] made cylindrical filters from clay-rich soil, water, grog, and flour and applied silver by either dipping or painting. They measured filters exposed to water contaminated with Escherichia coli (E. coli) and found they removed 97.8 to 100 percent of the pathogen.

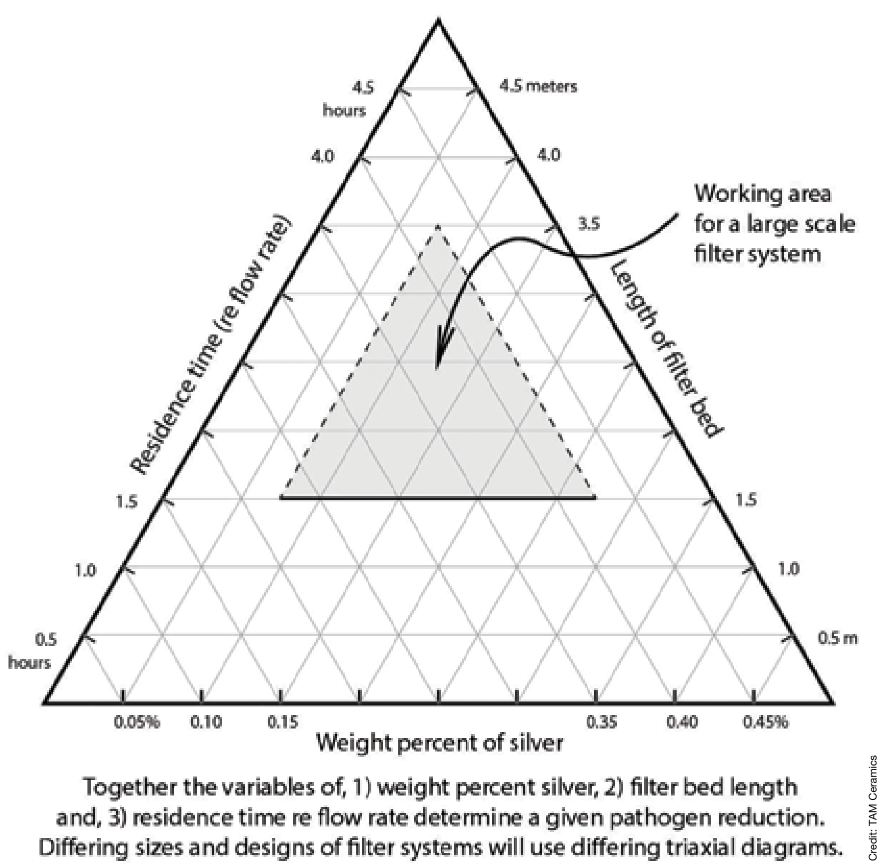

Figure 2. Triaxial diagrams aid optimization of filter system design by demonstrating relationship between amount of silver, filter bed length, and flow rate. The area shaded grey represents the region of optimal filter design. Diagrams will vary based on filter system size and design.

Filter effectiveness requires pathogens to encounter the silver to experience its lethal influence. Thus, a filter using silver-treated granules will expose large surface areas of silver, and the granular media introduces more pathways for contaminated water to wash past silver.

The lead author (Harvey) first developed a water filter media during a 2003 visit to Kathmandu, Nepal, in response to an urgent need for water, sanitation, and hygiene (WASH). Working with a local pottery along with a local NGO and UNICEF systems, monolithic candle filters of common earthenware red clay went into thousands of low income homes and into large-sized filter systems for 800 schools of rural districts. The use of red clay suggested the reproducibility of the model, and a subsequent such project was implemented in Kenya.

TAM Ceramics (Niagra Falls, N.Y.), long a manufacturer of high-purity ceramic granular media, has licensed the technology from the lead author (Harvey) and is optimizing a water filter media with silver-coated ceramic gran-

Credit: TAM Ceramics

Figure 3. A granulated media water filter suitable for households costs $3 to $6.

ules. As pathogens flow through the granulated filter bed they are deactivated through the oligodynamic effect from repeated contact with the silver.

For the granulated filter media, the inventive step in development was simply to crush and granulate a silver treated candle filter. This granulated media was then put into sections of thin-walled PVC pipe, ending up with a remarkably low-cost system of household water treatment. This approach is as innovative today as it was in 2003 Kathmandu, considering the dearth of sustainable technologies. Mere clay is indeed the way.

To functionalize the filter media, fired ceramic granules are treated with a silver solution followed by a second firing to bond the silver (Figure 1a). X-ray energ dispersive spectroscopy confirmed the presence of silver on the granules (Figure 1b).

We tune granule particle size distribution to the customer's filter design and application, within sensible limits. In general, coarser particles give a fast flow rate, while finer particles give a slower flow rate and longer residence time. Triaxial diagrams, such as Figure 2, help with establishing optimal conditions with respect to particular filter containment, size, and design.

The filter itself, shown in Figure 3, is not very large. A community-sized system containing four 8-inch PVC "candles" filled with silver-coated ceramic media produces up to 100 gallons of clean water per hour. A household-sized filter produces up to two liters of clean water per hour and costs $3 to $6. These systems should last about 10 years.

Testing effectiveness

The number of pathogen–silver contacts is determined by the amount of silver, the length of the granulated filter bed, and the residence time of the pathogens. Pathogen reduction varies with the amount of silver used in treatment, between 99.90 percent and 99.99999 percent (log 3 to log 7 effectiveness). While filter media providing log 3 pathogen reduction would be appropriate for such applications as hand washing, filter media yielding log 7 pathogen reduction should be acceptable in clinics or hospitals.

Water with 99.9999 percent (log 6) pathogen reduction is considered suitable for drinking. However, in worst case scenarios, a log 3 reduction or even less is arguably an acceptable, pragmatic threshold that could work for greater numbers of vulnerable populations.

TAM continuously works with certified laboratories to refine test set-up and procedures. Testing for E. coli reduction assures that the filter media does its job getting people safe drinking water. Small children are especially vulnerable to E. coli, never having had a chance to develop immunities. Filter granules have been shown to reduce E. coli between log 3 and log 7. The filter lifetime will be no less than 10 years, but can be greater if requested.

Municipal water utility treatment traps pathogens with slow sand, which allows about one percent to get through. A subsequent step with chlorine or a look-alike disinfectant destroys the one percent of pathogens that slip through slow sand filtration. In contrast, for prospective municipal-scale applications, TAM's filter media has the advantage of combining filtration and disinfection into a single step.

A scalable future

TAM's granulated ceramic filter systems are genuinely sustainable in addition to being suitable for filters of any size—a first. For the developing world, since 2003 there has been an emphasis on household water treatment, on a point-of-use basis. Now, however, large-scale filter systems offer an altogether new paradigm for delivering safe water to entire communities. Clean, safe water can be made available for everyone simply by the force of gravity. These filters offer clean water at accessible prices, too. A household-scale filter costs $3 to $6.

Is water a human right, a consumer product, or both? Despite intense debate, the question remains unresolved. However, TAM Ceramics suggests that sustainability be a qualification to help answer the question of rights versus cost.

Systems based on filter media are sustainable and low cost. The cost of the filter media will be as low as possible when granules are manufactured in close proximity to the market, a step that will happen once the market has been established. In addition, these filters are more user friendly than competing water purification systems.

Ceramists are uniquely positioned in their capacity at getting people safe drinking water and clean air around cook stoves, as well as industry from the grassroots. There is arguably no other approach to manufacturing that makes possible so much fundamental industrial development. Of the 17 Sustainable Development Goals, nearly all are addressed squarely by the capabilities of ceramists—it all starts with safe drinking water and environmental health.

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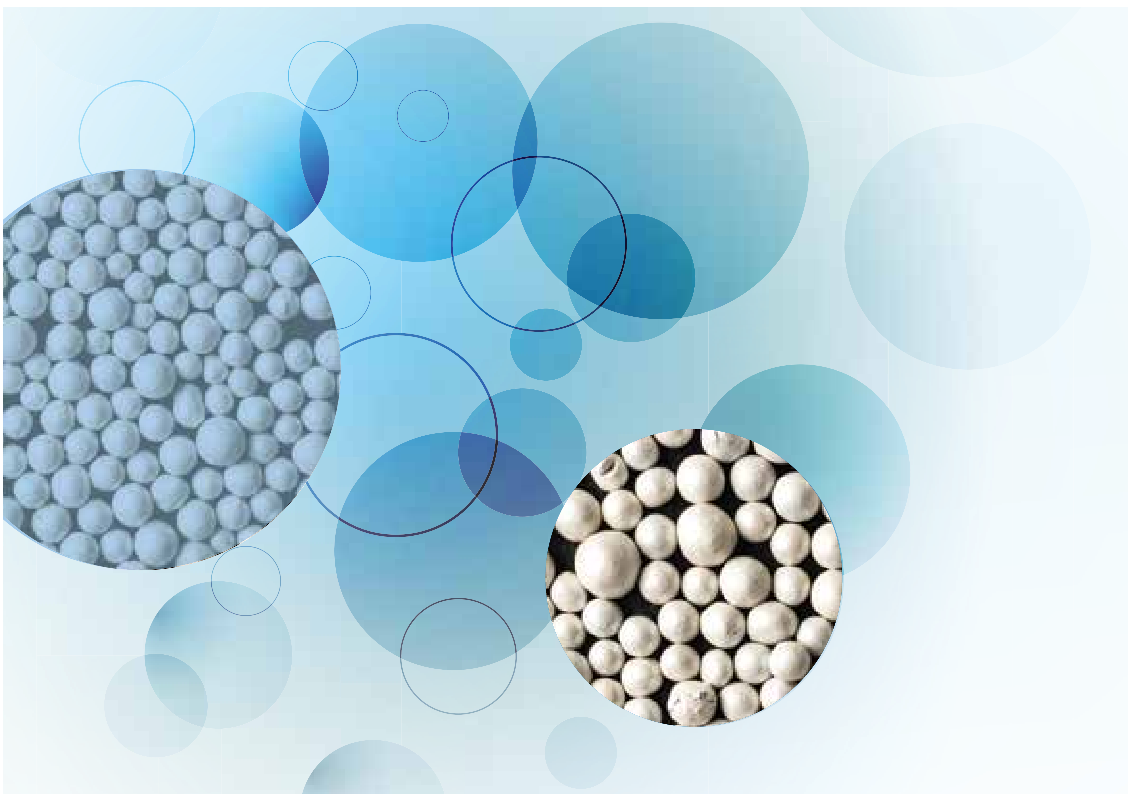

Credit: Golisano Institute for Sustainability at the Rochester Institute of Technology

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.

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

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

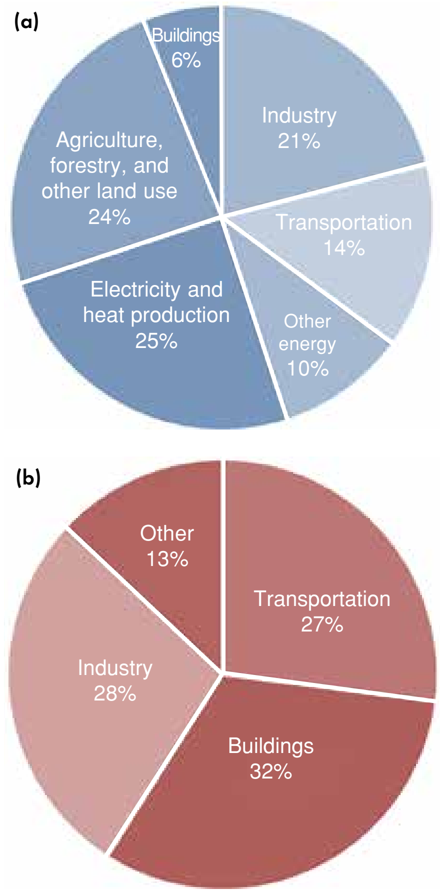

Figure 1: (a) Global greenhouse gas emissions by sector (2010), total emissions were 49 Gt CO_2eq.[2] (b) Global energy demand by end use sector (2010), total energy demand was 366 EJ.[2]

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]

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.

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