Materials science and engineering's pivotal role in sustainable development for the 21st century

Diran Apelian

Perhaps the greatest challenge of the 21st century is to sustain the developmental needs of the world. The economic growth that occurred in developing countries over the past two decades is unprecedented. Materials science and engineering (MSE) innovations will continue to have a pivotal role as an enabling resource to address sustainable development needs. This article focuses on the opportunities for MSE in five key thematic areas: energy, transportation, housing, materials resources, and health.

Introduction

During the past two decades, an astounding one-third of the world population increased its standard of living[1] and did so significantly and in unprecedented ways. However, such profound changes might not be sustainable if society continues on its current path.

As early as the 1700s, Thomas Malthus observed that the population in England was growing geometrically, whereas the food supply was increasing arithmetically.[2] This led him to conclude that a human population would eventually outstrip its ability to find and produce new sources of food, thus leading to a catastrophe that would bring the population down to a more sustainable level. Although agricultural innovations have enabled the support of much larger populations than Malthus could have ever imagined, the real question is whether this can be continued. The answer is clear: only if development occurs sustainably.

Sustainable development is perhaps the most pressing issue of the 21st century. At the same time, it is a remarkable opportunity for practitioners of materials science and engineering (MSE), as many of the approaches to address these challenges are materials-centric.

Context

To provide context for this discussion of sustainable development, it is important to understand the magnitude of the issues confronting society (highlighted in italics in the subsequent paragraphs). Since the 1700s, the volume of goods traded worldwide has increased 800-fold. Between 1910 and 2010, the world's industrial production increased more than 100-fold, and between 1900 and 2000, global consumption of fossil fuels increased by a factor of 50.[3] Although such growth represents remarkable development, it has been accompanied by other changes that call its continuation into question.

World population is projected to rise from the current 7 billion to over 9 billion in the next three to four decades.[4] In comparison, the global population was only 1.6 billion in 1900 and grew to 6.1 billion by the end of the 20th century. Furthermore, the population growth has not been evenly distributed throughout the world, as more growth is occurring in less developed countries. The average population growth rate is hovering around 1.4%, whereas in several African nations, Saudi Arabia, and Afghanistan, the population growth rate is over 3%.

The presence of more people equates with higher *energy usage*. Indeed, whereas population is growing at an average rate of 1.4% a year, energy needs are growing at an average rate of 1.7%. Average energy consumption per capita throughout the world is about 57 GJ. In contrast, it is 230 GJ for the United States and 119 GJ for Europe,[5] and many developing countries seek to emulate these developed nations and their energy consumption habits. Such consumption of energy is not sustainable.

Associated with energy usage is the production of *greenhouse gases,* which have adverse effects on the climate and the environment. The interrelation between human activity and the production of greenhouse gases is illustrated in **Figure 1**. The

Diran Apelian, Worcester Polytechnic Institute; dapelian@wpi.edu
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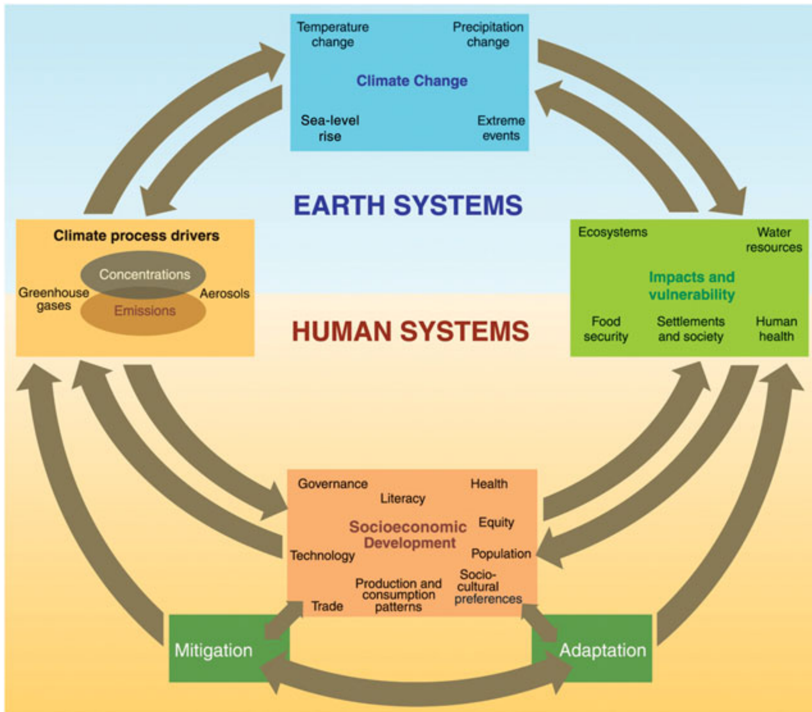

Figure 1. Interactions between human and Earth systems. Socioeconomic developments due to human activity affect climate change. In turn, climate process drivers, and impacts and vulnerabilities due to human activity, affect temperature, precipitation, and sea level and also cause extreme events. (Figure 1.1 from Reference 6 reproduced courtesy of the Intergovernmental Panel on Climate Change.)

overwhelming scientific consensus is that human emissions of greenhouse gases must be reduced in order to avoid catastrophic ecological consequences. For example, the shrinkage of the Grinnell glacier in Montana over 10 decades (1900–2000), documented by the U.S. Geological Survey in a series of photographs,[7] clearly demonstrates the seriousness of the problem.

The basic human necessities of *food and water* are also being taxed. For example, 18% of the world's population lacks access to safe drinking water, and 20% of the world's population is living in absolute poverty (defined as living on less than US$1 per day) and is thus subject to chronic hunger.[8] To exacerbate the situation, 40% of the world's population has no access to sanitation.[8]

Housing and shelter needs of the world are also increasing rapidly, tracking the expansion of population. In 1950, less than 30% of the world's population lived in cities. This number grew to 47% in 2000 and is expected to exceed 60% by 2025.[9] Infrastructure to sustain such a dramatic shift in urbanization is lacking.

Among the major ramifications of urbanization are shifting *transportation* needs. Specifically, the infrastructure that was built for a world of 5 billion in widely dispersed communities cannot sustain more than 7 billion people concentrated in dense population centers. Except in a few countries and major cities, mass transit systems that can efficiently transport large numbers of people are lacking. Systems such as high-speed trains and available lines between major hubs and airports are essential to address these needs.

Material consumption is at an all-time high. Most consumer goods are packaged, resulting in enormous amounts of waste. Given the comparatively small amounts of material recovered and recycled in the overall system, there is much room for improvement. (See the article in this issue by Gaines.) Another major issue is the increasing use of scarce elements, as discussed in detail in the article by Graedel et al. For example, the average smart phone contains more than 50 elements—a good percentage of the periodic table. Yet, few programs have been established to ensure, at the time of purchase, the recovery and recycling of these elements at the end of a component's useful life, despite the fact that inorganic materials are not renewable. Evidence of the need for such programs is clearly provided by the volatility in the prices of rare-earth metals, which have increased dramatically even since the beginning of 2010 (see **Table I**), mainly because of supply and demand issues.

Finally, *health* is perhaps the most critical human need, and life expectancy around the world has increased significantly in recent decades, except in Africa, where it is decreasing in large part due to HIV/AIDS.[10] Health care needs around the world have increased, and the cost of health care delivery has also skyrocketed.

Table I. Recent price volatility of rare-earth metals.

Rare-earth element	Price (US$/kg)			Price increase	
	January 5, 2010	August 5, 2010	August 5, 2011	January 2010 to August 2010	August 2010 to August 2011
Yttrium	10.25	34.50	210.00	236%	508%
Neodymium	22.50	55.25	475.00	146%	756%
Lanthanum	5.60	33.50	165.00	498%	392%
Samarium	3.95	31.80	190.00	705%	497%
Cesium	4.15	33.00	170.00	695%	415%

Critical needs

Although society faces many challenges in the 21st century, this section outlines five distinct societal issues that are materials-centric and can be considered to be most critical for a sustainable future on Earth. These challenges offer a vista of opportunities for the next generation of scientists and engineers, especially the MSE community.

Energy

The global demand for energy is growing even faster than the population, and the escalating demand from developing countries will further exacerbate this situation. The current energy utilization worldwide is about 14 TW, and by the end of the 21st century, it could reach 50 TW.[11] Today, about 80% of the world's energy comes from fossil fuels.[12] In North America, energy generation is responsible for 40% of greenhouse-gas emissions. Some of the ramifications of increasing greenhouse gases on our environment can be seen in **Figure 2**. An important consideration with respect to reducing demand is the need for efficiency in usage, especially in housing/buildings (see the Housing section below) and in the industrial sector.

In terms of supply, there must be a shift away from fossil fuels to renewable energy sources, which generate much lower levels of greenhouse gases. However, with current technology, renewable sources of energy (such as hydroelectricity, biofuels, and geothermal energy) will not be sufficient to meet the energy consumption needs of the world. Nevertheless, materials developments could make solar power, biofuels, and wind power into increasingly important resources. For expanded reliance on solar energy, future materials developments are needed in nanostructured materials and advanced photovoltaic materials such as nanocrystalline-silicon thin films and novel chalcogenides. For fuel cells and bio-derived liquid fuels, developments will need to include advanced catalysts with more accessible surface area, nanostructured catalyst supports, and membranes. For broader use of wind turbines with high power output, there is a great need for the development of high-strength non-rare-earth-based permanent magnets for compact, low-maintenance generators.

In addition, "next-generation" nuclear energy has much to offer as a potential carbon-free baseload energy source (i.e., one that can provide the minimum amount of power needed to meet customer demands on a continuous basis). From a cost perspective, nuclear power also offers advantages over other non-fossil-based energy sources. The Nuclear Energy Institute reports: "Nuclear plants are the lowest-cost producer of baseload electricity. The average production cost [in North America] of 2.14 cents per kilowatt-hour includes the costs of operating and maintaining the plant, purchasing fuel, and paying for the management of used fuel."[13]

Several countries have established initiatives to reduce greenhouse-gas emissions from power production. For example, Tekes, the National Technology Agency of Finland, announced targets for increases in total supply of renewable energy by 40% by the year 2025.[14] However, many more such initiatives are needed, and they are needed on a scale that will make a difference.

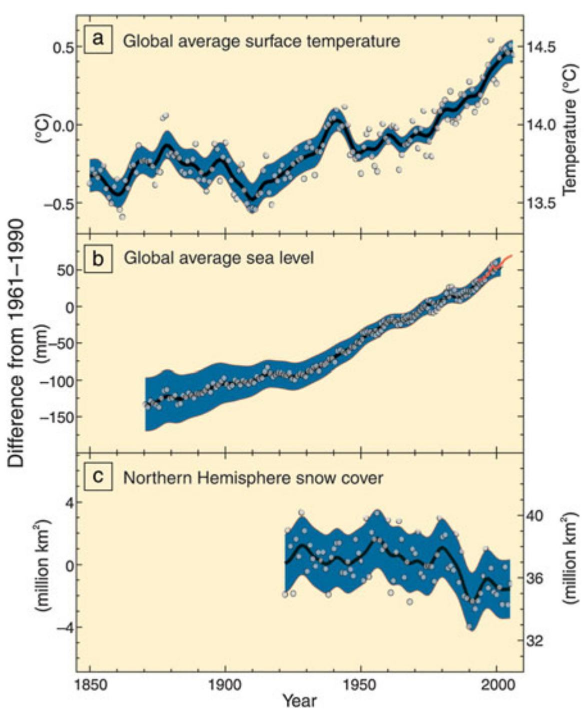

Figure 2. Changes in (a) global surface temperature, (b) global sea level, and (c) Northern Hemisphere snow cover over a period of 150 years (1850–2000). In each graph, "0" on the left vertical axis represents the average value for the period 1961–1990. Solid lines are 10-year averages of annual data (circles), and shaded regions represent uncertainty intervals. For sea level, the blue and red lines are from tide-gauge and satellite data, respectively. Global surface temperatures have risen significantly since the 1950s compared to the period of 1850–1950. Similarly, the sea-level and snow-cover data indicate adverse changes, especially since the 1950s. (Figure 1.1 from Reference 6 reproduced courtesy of the Intergovernmental Panel on Climate Change.)

Transportation

Global use of powered vehicles will increase significantly in the next few decades, especially because some developing countries have been experiencing annual growth rates of around 8% for several years in succession. To meet these growing transportation demands, more sustainable materials and modes of transportation will need to be developed.

For example, public transportation will need to be the dominant means of transporting the masses. This approach has certainly proven effective in Japan, France, and many other European countries. Lightweight structural materials, specifically alloy development and processing, will be the focus of future materials advances in this field, including foamed structures, magnesium-based components, and advanced aluminum alloys that can be selectively stiffened. Future materials will also include innovative material uses such as recyclable composites and biocomposites. For example, Duralin fibers (made by Ceres in the Netherlands) are produced when flax straw is steamed, dried, and cured.[14] Strong and lightweight materials, material source sustainability, and material recyclability will be some of the major factors influencing the development of future materials for transportation needs.

Housing

With increasing world population, the materials research community has an opportunity to make a major impact by developing novel construction materials that are environmentally benign, energy-efficient, and affordable. Shelter needs for the world's population require novel material solutions as well as novel housing designs.

The future will likely witness more energy-efficient homes that use intelligent materials and intelligent designs.[15] As an example, the Institute of Solar Energy Systems in Freiburg, Germany, discovered a means to make use of the temperature-equalizing effect of thick walls by incorporating a concentrated heat-retaining material within a millimeter-thin layer of plaster.[16] The effects on energy savings and pollutant reductions, for example, are significant. The premise is that much more needs to be done in this whole arena of intelligent materials that are "green" and energy-efficient—a fertile area for materials-related discoveries and innovations.

Future developments in housing will also be realized through innovative design and collaboration with architects and builders. The scientific and engineering community has an opportunity to partner with leading architects to address energy-efficient and sustainable construction materials, in addition to satisfying the shelter needs of the entire global population.

Material resources

Between 1960 and 2000, the amount of municipal solid waste generated annually in the United States increased from 88 million tons to 232 million tons (from 80 million tonnes to 210 million tonnes). On average, each American produced nearly 4.5 lb (2.0 kg) of garbage per day in 2000, up from 2.7 lb/day (1.2 kg/day) in 1960.[17] This waste is either burned, emitting pollutants, or deposited in landfills, introducing toxic substances into groundwater and soil.[18] Considering the toxic materials found in municipal solid waste, there is cause for concern.

An additional problem with increased waste is that the materials contained in discarded objects are unavailable for further productive use. For example, one-third of the world's copper is currently found in landfills, rather than being incorporated in useful applications.[19] In contrast, scarce materials, such as rare earths, are meticulously recycled to preserve their supply. Recycling can also be beneficial environmentally and economically. For example, the recycling of 1 kg of aluminum saves up to 6 kg of bauxite, 4 kg of chemical products, and 14 kWh of electricity compared to the production of 1 kg of new aluminum.[20] Future world needs will require materials that are fully recyclable or biodegradable, as well as a whole new paradigm for designing components by adopting a "cradle-to-cradle" philosophy that supports the remanufacturing of components from spent products into new products.

Effective and efficient recycling will be supported by technologies for sorting metals rapidly by composition. Moreover, with increased consumption providing more scrap (e.g., beverage cans) and enabling technologies that allow rapid recycling and rapid composition analysis, it will be possible to produce "new" aluminum ingots solely from scrap, without any ore refining. Because many materials used widely in desirable products are not renewable, the opportunities for resource recovery and recycling are vast.

Health

Life expectancy over the years has increased significantly. During the past five decades alone, life expectancy has risen by 15% (from 69 to 80 years) in North America, and similar trends have been experienced across the globe, except for sub-Saharan Africa.[14] More importantly, not only are people in most areas of the world living longer, but they are enjoying better health as well, thanks to the many advances in medicine, biology, and MSE. Examples include the increased use of biomaterials, implantable medical devices, and tissue engineering. Some of the opportunities for further materials-centered medical innovations are noted below.

Biomaterials have made tremendous advances. For example, the market potential for structural tissue engineering is US$90–100 billion, and for the biomaterials industry, growth in research and development spending is about 24% per year.[21] Recent advances and developments include cornea tissue regeneration, artificial skin, and knee cartilage implantation in the perosteal flap.[21] Devices such as artificial heart valves, coronary stents, and particularly drug-eluting stents have seen significant utilization.[14] These developments are critically dependent on the advances that have been and continue to be made in the materials science and engineering of biocompatible materials.

Implantable medical devices have seen huge growth during the past decade. Hip joints, knees, and many other parts are now being replaced on an almost routine basis. Thus, in the past two decades alone, medical advances have profoundly improved the quality of life for many patients.

From an MSE perspective, there are many exciting opportunities to continue this positive impact on health. For example, major developments are needed in the area of surface modification of biomaterials to better control blood and tissue compatibility, such as through plasma treatment or chemical grafting.[22] Through surface modification, it will be possible to manipulate material attributes such as resistance to infection, resistance to clot formation, lubricity, and wear resistance. A good example is how heparin (an anticoagulant) is covalently coupled to a multilayered base coat of a biomaterial surface.[22] Implants and devices that are also vehicles for drug delivery will be another area for future developments. Tissue engineering coupled with innovative materials for the manufacture of "smart" heart valves is another area for growth and opportunities for future developments. The whole field of biomaterials for regenerative medicine is a fertile area; Stupp[23] recently reviewed these opportunities and cited many examples of the potential use of biomaterials for regenerative medicine. In brief, biomaterials of the future will serve not only mechanical functions; rather, they will be regulators of biological activity.

Major advances in bioorganic–inorganic composites are also likely to continue. Langer and colleagues pioneered the controlled release of large molecules (e.g., polypeptides) using microspheres made of hydrophobic polymers.[24] At present, bioerodible polyanhydrides are being synthesized as vehicles to release both large and small molecules; this field could give rise to the ability to carry out "local chemotherapy."[25] In addition, bioerodible polymers are being developed for use as implantable tissue scaffolds to create liver tissue, blood vessels, nerves, and heart muscle.[24] The hope is that the fusion of biotechnology, nanotechnology, and information technology will allow not only the treatment but also the prevention and curing of disease.

The future is bright for such cutting-edge medical advances as a result of developments in materials engineering. Unfortunately, however, many parts of the globe cannot afford these technologies or do not have access to such medical services. Therefore, from a sustainable health perspective, there is a huge need for the engineering community to develop solutions that will have an impact on the masses and not just a small percentage of the population that has the resources to pay for such "boutique" solutions. In simple terms, there is a burgeoning need for the development of health-related solutions that have an enduring, positive impact on the average global level of health.

For example, breast cancer detection is a routine procedure in most developed countries. Magnetic resonance imaging (MRI) diagnostic techniques have been a major enabling technology for identifying breast cancer in the early stages, such that appropriate treatment can be prescribed and delivered. However, in most developing countries, and particularly on the African continent, many women go undiagnosed for breast cancer, with fatal consequences. To address this problem, the Ludwig research group at Worcester Polytechnic Institute[26] has developed a low-cost radio-frequency coil that can be used for breast cancer screening by MRI. Such a coil design, costing approximately US$150–200, can be used in parts of the world where, at present, there is no diagnostic screening at all.

In a broader sense, global health is affected by many factors beyond just medical care. For example, the World Health Organization has estimated that over 9% of the total burden of disease worldwide can be attributed to lack of access to safe drinking water and adequate sanitation systems.[27] Further, indoor air pollution is estimated to cause approximately 2 million premature deaths per year, mostly in developing countries, with urban outdoor air pollution causing an additional 1.3 million deaths worldwide each year.[28] Opportunities abound for MSE practitioners to have a dramatic impact in both of these areas. For example, IHSAN (Industry's Humanitarian Support Alliance NGO, Inc.) has sponsored the deployment of inexpensive, lightweight, hand-cranked UV-based water-purification systems in communities in Iraq and Kenya.[29,30] An alternative approach is taken by the company Vestergaard Frandsen, whose LifeStraw® product uses 0.2-μm hollow-fiber ultrafiltration membranes to provide clean drinking water upon application of sufficient suction to the mouthpiece of the straw.[31]

High levels of indoor air pollutants, including carbon monoxide and small particulates, result from cooking and heating with solid fuels (e.g., coal and biomass) on open fires or traditional stoves. This significant cause of poor health can be addressed by developing cleaner and more efficient fuels (e.g., biogas) or energy technologies (e.g., solar power) that are also affordable. In addition, more efficient, cleaner-burning cookstoves are being distributed by a number of groups (see, for example, Reference 32). Continuing efforts will be required to make further progress in this area. Likewise, materials-related efforts to improve outdoor air quality, especially in urban areas, will continue to involve the development of cleaner energy technologies, cleaner transportation fuels, and more efficient transportation vehicles, as mentioned in preceding sections of this article and addressed in detail in the Transportation and Energy and Water sections of this special issue.

However, technology alone is not the answer. Leadership is needed in developing national policies not solely by government officials but also by engineers. The role of advocacy that our professional scientific and engineering societies must shoulder is pivotal and needs to be supported.

Conclusions

Society faces grand challenges to sustain continued development in the 21st century. Although this article has focused on the need for technological innovations for charting a sustainable future, it is important to keep in mind that technical innovations are only part of the solution. Just as important is public policy, which influences the behavior of individuals, as well as that of corporations and communities. By implementing sustainable practices in the use of materials, the materials science and engineering (MSE) community will be well-positioned to take a much more active role in shaping public policy in support of sustainable development.

This is also an extraordinary time to make the case for MSE as a profession to the next generation of students. The challenges of sustainable development are so great that our collective ingenuity will be needed to achieve success. We should focus on the positives and the attributes that speak to the next generation of students, namely, making a world of difference through science and engineering. Let us make the case for engineering by linking the profession to societal issues and presenting engineering as an enabling profession.

Acknowledgments

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