Engineering Solutions for Sustainability

Engineering Solutions for Sustainability

Materials and Resources

Workshop Report and Recommendations

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American Institute of Mining,
Metallurgical, and Petroleum Engineers

Co-sponsors:
American Society for Civil Engineers
American Institute of Chemical Engineers
Hosted at the École Polytechnique Fédérale de Lausanne,
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About This Report

This publication offers a synopsis of the dynamic, open dialogue on engineering, sustainability, resources, and human needs that took place during the *Engineering Solutions for Sustainability: Materials and Resources* workshop held at the École Polytechnique Fédérale de Lausanne, Switzerland, July 22–24, 2009. The workshop was organized by the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), with logistical and management support provided by the Society of Petroleum Engineers. The event was co-sponsored by the American Society for Civil Engineers (ASCE) and the American Institute of Chemical Engineers (AIChE). The delegates invited to participate in this workshop were selected to ensure a broad range of disciplines, world perspectives, and societal sectors.

This workshop report does not necessarily imply universal consensus of all delegates on all issues raised, nor does it represent an official position of any specific professional society, industry, organization, or agency represented. Rather, it reflects both the diverse perspectives, as well as common themes, that were generated through the workshop process and summarized by the following subcommittee on behalf of the delegation:

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About the Workshop Sponsors

Among the first national engineering societies established in the United States, AIME, ASCE, and AIChE are known as Engineering Founder Societies of the United Engineering Foundation, Inc.,* and collectively encompass a total worldwide membership of 350,000 engineers.

Founded in 1871, the **American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME)** is a non-profit umbrella organization representing more than 130,000 members worldwide within its four separate member societies: Society for Mining, Metallurgy, and Exploration (SME); The Minerals, Metals & Materials Society (TMS); Association for Iron and Steel Technology (AIST); and Society of Petroleum Engineers (SPE).

The **American Society of Civil Engineers (ASCE)**, founded in 1852, represents more than 144,000 members of the civil engineering profession worldwide and is America's oldest national engineering society. ASCE facilitates the advancement of technology, encourages and provides tools for lifelong learning, promotes professionalism and the profession, develops and supports civil engineer leaders, and advocates infrastructure and environmental stewardship.

The **American Institute of Chemical Engineers (AIChe)** was founded in 1908 and now has a membership of 40,000 chemical engineering professionals from 93 countries. AIChE provides resources and expertise to support professional development and growth across the breadth of chemical engineering, from core process industries to emerging areas, such as nanobiotechnology.

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* Other societies of the United Engineering Foundation include the American Society of Mechanical Engineers (ASME) and the Institute of Electrical and Electronics Engineers (IEEE).

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I

Executive Summary

The growing population of this planet depends on the continued development of agricultural and industrial endeavors. These advancements have enabled many around the globe to achieve significant improvement in their social and economic well-being over the past two centuries. This progress, however, has come at a well-documented price in the form of global warming, ozone depletion, soil sterilization, air contamination, pollution of water resources, and other environmental concerns. In addition, the natural resources that are the lifeblood of industrialization are, in many cases, not being managed sustainably—Stocks are dwindling.

Issues of resource depletion and environmental stress are not limited to industrialized societies. Throughout the world in developing nations, many people live in desperate poverty and lack adequate supplies of fresh water, food, and energy. Such situations place their own pressures on the ecosystem and societal infrastructure, while also contributing to widespread human suffering.

The solutions to any of these problems cannot be found in isolation. The challenges are too broad, complex, and interconnected, with decisions made in one part of the world often having unintended consequences on another. Strategies for sustainable resource management need to be global in scope, rather than focused within local or national boundaries. The same holds true

Engineering Solutions for Sustainability, First Edition. American Institute of Mining, Metallurgical, and Petroleum Engineers.

for the disciplines and technologies that can be brought to bear in resolving these issues. An advancement or new approach may address one pressing need, only to create a host of new questions with regards to resource allocation, environmental impact, and economic equity. In particular, any action plans developed within one engineering discipline to support its particular priorities without an appreciation of the impact on others would be extremely short-sighted—Interdependencies of energy and transport or transport and housing, as well as decisions impacting water, food, and health, can be ignored only at our peril. Sustainable engineering concepts are likewise dependent on the collective actions of industry, national governments, local authorities, Non-Governmental Organizations (NGOs), and civil society for their effective deployment, and in some instances, their very existence.

Effectively launching a coordinated approach within the engineering community to delineate, manage, and preserve materials and resources critical to social sustenance first requires consensus on what comprises "sustainable engineering." Such a definition must do more than take into account the diverse perspectives of the array of engineering disciplines. It must also present common principles of practice that can enable engineering decisions to rise beyond immediate problem-solving to take the long view of addressing larger issues of environmental and economic stability.

To lay the groundwork for these foundational concepts, the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) organized *Engineering Solutions for Sustainability: Materials and Resources,* an international workshop held at the École Polytechnique Fédérale de Lausanne, Switzerland, from July 22–24, 2009. Co-sponsored by the American Society for Civil Engineers (ASCE) and the American Institute of Chemical Engineers (AIChE), the workshop convened thought leaders from an array of engineering backgrounds to begin forging a common understanding of the role and responsibility of engineering in achieving global sustainability in the following sectors: transportation, energy, recycling, housing, food, water, and health. A cross-cutting topic area—human resources—was also developed to highlight strategies for unlocking the fullest potential of scientists and engineers to achieve sustainable development. The common thread weaving these sectors together—as well as the various engineering disciplines that impact upon them—was identification of potential ways that the engineering profession could aid in advancing societal sustainability through technological, educational, and public policy solutions. This workshop report distills these findings and offers a blueprint for future action.

DEFINING SUSTAINABILITY

A key workshop outcome was the development of a consensus definition of sustainability as it applies to engineering to provide a common basis for deliberation and action among various disciplines.

Framing this definition is the assumption that demand for energy and resources, a clean environment, and prosperity and equity will remain persistent, even though societal understanding, perceptions, and values regarding sustainability may evolve over time. In addition, irrespective of the relative importance placed on these demands, the path toward sustainability must be a continuous process, fueled by innovative and disruptive technological advances and engineering solutions. Within this context, the workshop delegates identified the following key principles underlying the concept of "sustainable engineering":

- ***Economic:*** The engineered system is affordable.
- ***Environmental:*** The external environment is not degraded by the system.
- ***Functional:*** The system meets users' needs—including functionality, health and safety—over its life cycle.
- ***Physical:*** The system endures the forces associated with its use and accidental, willful, and natural hazards over its intended service life.
- ***Political:*** The creation and existence of the system is consistent with public policies.
- ***Social:*** The system is and continues to be acceptable to those affected by its existence.

UNIFYING THEMES

The complexity of any single sector examined in this project—transportation, energy, recycling, housing, food, water, and health—requires synergistic efforts, not only on behalf of the technical and scientific community, but by many other aspects of society as well, if any meaningful progress is to be made. With a focus on defining common priorities and linkages, six critical overarching themes were identified that could provide a unifying framework in formulating strategy and implementing solutions within this diversity of challenges, issues, and stakeholders. In fact, because these themes account for the array of interdisciplinary factors required to successfully develop and implement sustainable solutions, it is suggested that they be adopted as the preferred validity test for engineering strategies, rather than the current "triple bottom line" approach that only broadly considers social, environmental, and financial elements.

These themes and their supporting concepts are:

- ***Acknowledging the Human Element***
  Sustainability encompasses more than environmental performance. Basic human needs and well-being are key aspects that must be taken into account when evaluating the sustainability of a technology or engineering

alternative. Engineering solutions also need to be culturally compatible and responsive to stakeholders' desires.

- ***Resiliency, Flexibility in Design Technologies and Systems***
  Engineering "performance" must evolve from function, cost, quality, and safety to encompass the environment, human health, and social well-being. Resilience will be an essential aspect in design.
- ***Need for Responsible Resource Use/Resource-Efficient Design***
  Solutions need to be designed for recyclability and to close the loop of material production systems. In addition, investment and policy decisions should be based on high-quality data and a clear understanding of their meaning.
- ***Life-Cycle Assessment and Costing***
  Translation of vague sustainability issues into design objectives and constraints is critical. A reasonable approach would be to use industrial ecology—with its emphasis on materials and resource conservation, life cycle approach, and systems focus—to consider the economic, environmental, social, and cultural dimensions of engineering performance.
- ***Escaping the "Silo Mentality"***
  Sustainable engineering implies the need for a substantial increase in the amount of information and sophistication across disciplinary boundaries. Trans-disciplinary and interactive dialogue must be promoted.
- ***Engineers in All Disciplines Need to Achieve Sustainability***
  Engineering education needs to be reconceptualized to produce sustainable engineers. Sustainable engineering requires professionals for whom engineering education is a lifelong process, not an outcome at any particular stage.

A STARTING POINT FOR ACTION

Both the consensus definition and unifying themes were developed as a bridge linking all engineering disciplines in a focused effort to articulate the role of materials and resources in societal sustenance. From there, strategies can be developed that are sensitive to the interdependencies among all the sectors examined by the workshop delegates, while still being effective in addressing a particular national, industry, business or community goal. Roadmaps detailing specific interdependencies and potential engineering solutions will need to be developed in subsequent forums. As a starting point for these deliberations, the workshop delegates recommended that the following key, cross-cutting initiatives take priority because of their potential transformative impact across all the sectors:

- Early stage development and dissemination of sound, sustainable, and resilient engineering concepts.

- Widespread adoption of a systems (or scenario) approach to engineering.
- Creation of reliable tools/models for measurement of water, energy/carbon, materials footprints, and their interactions.
- Development technologies/approaches for systemic reduction of the human footprint.

A review of sector-specific considerations and technologies salient to the materials and resources issues affecting progress in sustainable development is offered in the subsequent pages of this report. Proceedings and individual presentations from the workshop that informed these conclusions are available at http://www.aimehq.org/news.cfm. Professional societies, educators, and policy makers are urged to use these resources, framed by the principles and recommendations outlined in this executive summary, as a basis for their own topical and system-wide forums organized to further develop and promote engineering solutions for sustainability.

Each passing day brings new demands and stresses upon the world's materials and resources due to (i) economic development and urbanization, (ii) climatic change, (iii) population growth, (iv) higher living standards, and (v) more materials and resources intensive activities.[1] While a goal for *Engineering Solutions for Sustainability: Materials and Resources* was to launch a coordinated, interdisciplinary dialogue among scientific and technical communities to creatively and constructively address these issues, it is also recognized that even the most groundbreaking solutions will not come to pass without the understanding and support of key decision-makers throughout society. The role of engineers and engineering in policymaking, then, is critical. Policies that impact energy creation and use, as well as those that focus on sustainable environmental management, must be based on sound science and engineering. By the same token, any potential technical solutions must be explored in conjunction with an analysis of the policy drivers and impediments to shift to more sustainable practices. This will lay the groundwork for identifying and developing new policy directions that can propel sustainable development through leap frog technologies, while effectively addressing the environmental, economic, and social contrasts that comprise the complex mosaic of our world.

ENDNOTE

1. United Nations World Commission on Environment and Development (WCED). G. Bruntland (ed.), *Our Common Future: The World Commission on Environment and Development*. Oxford, Oxford University Press (1987).

II

Introduction and Process

The delegation of *Engineering Solutions for Sustainability: Materials and Resources* was comprised of 58 science and engineering thought leaders representing industry, government, and academia from 11 industrialized and developing nations. Organized by the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), with logistical and management support provided by the Society of Petroleum Engineers, and co-sponsored by the American Society for Civil Engineers (ASCE) and the American Institute of Chemical Engineers (AIChE), the workshop was designed to pull from the unique perspectives and expertise of an array of disciplines to forge a common understanding of the role and responsibility of engineering in achieving global sustainability. (A complete listing of workshop participants is provided in Appendix A.)

REEXAMINATION OF "SUSTAINABILITY"

An initial common reference point presented to this diverse group was the widely cited definition of "sustainability" developed by the Brundtland Commission—formally known as the World Commission on Environment and Development—which was convened in 1983 by the United Nations General Assembly to examine the interdependence of all sectors of society in achieving sustainable development:

Engineering Solutions for Sustainability, First Edition. American Institute of Mining, Metallurgical, and Petroleum Engineers.

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:
>
> - The concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given;
> - The idea of limitations imposed by the state of technology and social organization to the environment's ability to meet present and future needs."[1]

Using these touchstone concepts as a springboard for discussion, the workshop delegates were charged with examining the role of engineering in achieving societal sustainability in the following sectors: transportation, energy, recycling, housing, food, water, and health. The common thread weaving these sectors together—as well as the various engineering disciplines represented at the workshop—was identification of potential ways that the engineering profession could aid in advancing societal sustainability through technological, educational, and public policy solutions. Providing a framework for this exploration were the following questions:

1. What does sustainability mean for these sectors (transportation, energy, recycling, housing, food, water, and health) and why should we care?
2. What technologies and engineering approaches exist and/or are being used now in these sectors?
3. What technological and engineering advances are in the development and near-commercialization stages?
4. What materials and resources will these technologies require?
5. How do we sustainably produce these materials and resources?
6. How might policies and markets support or limit implementation of these technologies?
7. What about the human element?
8. What are the next steps?

An outcome of these deliberations was the realization that the definition of sustainability posited by the Brundtland Commission is subject to multiple interpretations because the concept is context- and values-dependent. However, it was also determined that certain constants remain—the demand for energy and resources, a clean environment, and prosperity and equity—and that any progress toward sustainability must be continuous, propelled by innovative technological advances and engineering solutions. Within this context, the delegates focused on crafting a consensus definition of sustainability as it applies to engineering to provide a common basis for discussion and action among various disciplines. During this process, a number of thought-provoking perspectives on societal sustainability were raised, including:

- Minerals-, materials-, energy-, and water-efficient manufacturing and recycling with a minimal environmental footprint.

- Reliable supply of resources at an affordable price.
- Sustainability requires systems-level thinking. It is to manage our lives, resources, and environment with care, love, and confidence.
- Sustainability is preventing the depletion of non-renewable resources.
- Sustainability is meeting our food, water, energy, transportation, housing, and health needs with minimal ecological footprint and using the best available science so that our children can continue to live as well or better than us. It is the ability to maintain a reasonable growth rate in economic development and quality of life for all stakeholders through the innovative use of technology. This entails balancing all the elements of capital—natural, physical, human, economic, political, social, and cultural—and making the best use of all we have for the greatest good of the greatest number for the longest time.
- Sustainability is a vision statement in which public and private sector owners, architects, engineers, constructors, and suppliers of all commodities make decisions, select choices, and take actions regarding what is done, how it is done, with what it is done, and where it is done in a responsible, ethical, and equitable way. These decisions, choices, and actions ensure that the quality, abundance, and integrity of the resource base in all of its dimensions are maintained.

From these and other concepts, the workshop delegates identified the following key principles comprising a working definition of "sustainable engineering:"

- ***Economic:*** The engineered system is affordable.
- ***Environmental:*** The external environment is not degraded by the system.
- ***Functional:*** The system meets users' needs—including functionality, health and safety—over its life cycle.
- ***Physical:*** The system endures the forces associated with its use and accidental, willful, and natural hazards over its intended service life.
- ***Political:*** The creation and existence of the system is consistent with public policies.
- ***Social:*** The system is and continues to be acceptable to those affected by its existence.

DEFINING COMMON GROUND

The workshop was structured around a series of plenary and keynote presentations illuminating the needs and issues of each sector. These, in turn, fueled discussion in breakout sessions focused on defining priorities and linkages. A key outcome of this process was the identification of six critical overarching themes that could serve as a unifying framework in the formulation of strategy and implementing solutions—and potentially be adopted as the preferred validity test for engineering strategies, rather than the "triple bottom line" approach that is currently employed. These themes and their defining concepts are:

Acknowledging the Human Element

- What sustainability means will be redefined over time, but it will always encompass more than environmental performance. Basic human needs and well-being are key aspects that must be taken into account when evaluating the sustainability of a technology or engineering alternative.
- Appropriate engineering is engineering done in societal context. Engineering solutions need to be culturally compatible and responsive to stakeholders' desires.
- One challenge for engineers is how to adapt progress to human genetic needs and to design systems to ensure that people not become too sedentary.
- There is a need for changing lifestyle attitudes and approaches, as well as social learning.

Resiliency, Flexibility in Design Technologies and Systems

- A transformational change is needed in engineering design. Engineering "performance" must evolve from function, cost, quality, and safety to encompass the environment, human health, and social well-being.
- Attributes of engineered systems must be identified that will allow societies to deal with uncertainty and react to dramatic, unforeseen changes and challenges. Resilience will be an essential aspect in design.
- Uncertainty should be addressed by increasing options, rather than simplifying the debate.
- There is a growing need for multi-attribute and multi-function, interactive, and intelligent materials, as well as components that have the characteristics of operability, maintainability, and reparability.

Need for Responsible Resource Use/Resource-Efficient Design

- Solutions need to be designed for recyclability and to close the loop of material production systems utilizing the following approaches: direct reuse; reusable components; reprocessing of recycled materials; extracting primary materials; and energy from waste.
- It will be important to balance the need to preserve resources while not avoiding use, as this can stifle growth and condemn many to poverty.
- In some cases, resource use can be reduced by substituting information for natural resources.

- The materials and resources that will be needed to implement engineering solutions to address human needs should be produced in a socially and environmentally responsible manner.
- There is a fundamental misunderstanding about reserves and resources, which has led to unjustified, sometimes alarmist, conclusions. Investment and policy decisions should be based on high-quality data and a clear understanding of their meaning.

Life-Cycle Assessment and Costing

- Translation of vague sustainability issues into design objectives and constraints is critical. A reasonable approach would be to use industrial ecology—with its emphasis on materials and resource conservation, life cycle approach, and systems focus—to consider the economic, environmental, social, and cultural dimensions of engineering performance.
- Each technology choice will have its own material resource content, and set of economic, social, and environmental impacts. Comparisons across alternatives will be important so that long-term implications and tradeoffs among engineering and system designs can be identified.
- Tools should be developed for conventional, environmental, and social life cycle assessment and costing. This will require creation of accurate, condensed impact databases.

Escaping the "Silo Mentality"

- Problems cannot be successfully addressed in a piecemeal fashion.
- Synergies need to be developed across sectors, industries, and boundaries because advances occur at intersections and interfaces.
- Sustainable engineering implies the need for a substantial increase in the amount of information and sophistication across disciplinary boundaries. Trans-disciplinary and interactive dialogue should be promoted.

Engineers in All Disciplines Need to Achieve Sustainability

- Engineering education needs to be reconceptualized to produce sustainable engineers.
- Sustainable engineering requires professionals for whom engineering education is a lifelong process, not an outcome at any particular stage.

CHALLENGES AND OPPORTUNITIES

The subsequent chapters and resources of this report summarize the knowledge exchanged during the dynamic, open dialogue that marked the *Engineering Solutions for Sustainability: Materials and Resources* workshop. These findings have been refined into broader topic areas highlighting linkages between and among the various sectors:

- Human Needs (water, food, health).
- Infrastructure (transportation, housing, urban design).
- The Resource Cycle (energy, mineral resources, materials and recycling, linking technologies to resources).

An additional topic area, Human Resources, was developed to highlight strategies for unlocking the fullest potential of scientists and engineers—through new approaches in education, policy engagement, and holistic design—to achieve real progress in sustainable development.

Each of the topic areas offers an overview of sector-specific considerations in advancing societal sustainability through engineering solutions, while also identifying specific technologies that could serve to accomplish these goals. However, to affect the changes needed in practices, policy, and public perception to make true global sustainability a reality, much more work needs to be done to build upon the concepts and action steps outlined in these pages. In this regard, the report of *Engineering Solutions for Sustainability: Materials and Resources* serves as a challenge, as well as a reference tool, to professional societies, educators, policy makers, and industry leaders. The opportunity to build a legacy of environmental sustainability, economic stability, and social equity for generations to come has never been more pronounced, but it will only be fully realized through synergistic effort of the technical, scientific, and policy making communities.

ENDNOTE

1. United Nations World Commission on Environment and Development (WCED). G. Bruntland (ed.), *Our Common Future: The World Commission on Environment and Development*. Oxford, Oxford University Press (1987).

III

Human Needs (Water, Food, and Health)

INTRODUCTION

The topic of human needs was developed during the synthesis of discussions based on plenary sessions focused on food, water and health. The following speakers presented on topics that provided context for subsequent breakout sessions:

Water

Dan Stevens, Executive Director, Lifewater International
Empowering Access to Safe Water

Julie Zimmerman, Assistant Professor, Environmental Engineering, Yale University
Infrastructure and Governance to Address Sustainable Water Quality, Quantity and Availability

Food

C. S. Prakash, Professor, Genetics, Tuskegee University
Sustainable Food Security: How Can Biotechnology Help?

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Health

Dr. Mikael Rabaeus, Medical Director, Clinique de Genolier
Lifestyle and Health: The Modern Challenge for Engineering

James K. Bartrum, Coordinator, Water, Sanitation, Hygiene and Health, World Health Organization Headquarters
Sustainable and Affordable Health: The Roles of Water Engineering and Water Engineers

Darin Zehrung, Programme for Appropriate Technology and Health (PATH)
Innovative Technology Solutions for Global Health: PATH's Product Development Approach and Experience

WHAT SUSTAINABILITY MEANS FOR HUMAN NEEDS

Within the context of meeting basic human needs, it was determined that sustainability encompasses four dimensions: economic, environment, social, and governance. Concepts presented in the Brundtland Commission's definition of sustainability—*meeting the needs of today without compromising the ability of future generations to meet their own needs*—were examined to develop principles guiding engineering strategies impacting on food, water, and health. More restrictive definitions were discussed, such as, "Nature's resources must only be used at a rate at which they can be replenished naturally." However, the overarching consideration identified was that the materials and resources needed to implement engineering solutions developed to supply human needs should be produced in a socially and environmentally responsible manner.

The "human needs" component of the sustainability definition was also expanded to encompass the concept of human well-being. This involves much more than just meeting the basic needs of water, food and health. Well-being was defined as *a context- and situation-dependent state, comprising basic material for a good life, freedom and choice, health, good social relations, and security.* Another perspective on well-being is to equate it to quality of life.

Understanding the determinants of human happiness and well-being is important in the quest for sustainability. The ability to identify critical non-material factors can help guide decisions on how to best utilize the limited material throughput available. Conventional indicators of human needs and consumption reflect the quantity of physical output (goods and services) of a society, and are generally reported in such monetary terms as Gross Domestic Product (GDP). As a contrasting approach, Bhutan's former King Jigme Singye Wangchuck coined the phrase "Gross National Happiness" (GNH) in 1972, based on sustainability concepts.

There are other possible measures of well-being. One links material consumption and well-being by considering the role of per capita energy consumption as it relates to various objective indicators. Energy use is a good index or proxy for general consumption, as all consumption involves the use of energy. For example, water movement, treatment, and heating amounts to approximately 13 percent of the electricity consumed in the United States. Infant mortality and female life expectancy at birth are two other composite indices of well-being, integrating complex interactions among nutrition, health care, and environmental exposure over an extended period.

A meaningful and satisfying quality of life is possible with considerably less throughput than now occurs in affluent and highly developed countries. A challenge for the future, then, is to determine the best allocation of materials and resources to achieve a desirable living standard. The finding that nonmaterial, quality of life factors are among the most important determinants of both subjective reports of human happiness and objective indices of well-being offers opportunities to organize societies from a sustainable scale perspective. Focusing on the dual objectives of reducing material throughput and increasing qualitative development should allow societies to become more sustainable.

CURRENT SECTOR STATUS FOR WATER, FOOD, AND HEALTH

Water

Rising world populations and consumption are increasing human demand for domestic, industrial, and agricultural water. A parallel concern is the human cost of obtaining water in many cultures. In third or fourth world countries, the process of procuring water can require between 6 to 26 hours per household per month, pulling people away from other important developmental pursuits. A sustainable future must include a strategic approach to preserving and protecting water resources. Countries that squander this precious resource are putting themselves at risk, since water scarcity, through the ages, has been shown to jeopardize food production, human health, economic development, and geopolitical stability.

Most of the surface of the earth is covered with water. (Figure 1 illustrates the distribution of the world's water sources.) Yet, globally, the availability of water per person has declined markedly in recent decades. One third of the world's population now lives in countries experiencing moderate to high water stress.

Expanding populations and wealth, along with other global pressures, will have a direct and significant impact on the sustainability goals, technology selection, and governance strategies that are related to water quality and quantity. Historically, water has been viewed as an almost unlimited resource, with the natural hydrologic cycle ensuring its sustainability over the years. The strong correlation between water and poverty proves that water can actually become a barrier when it is inaccessible and unfit. When it is available and clean, water is a bridge to even greater security and prosperity for the poor.

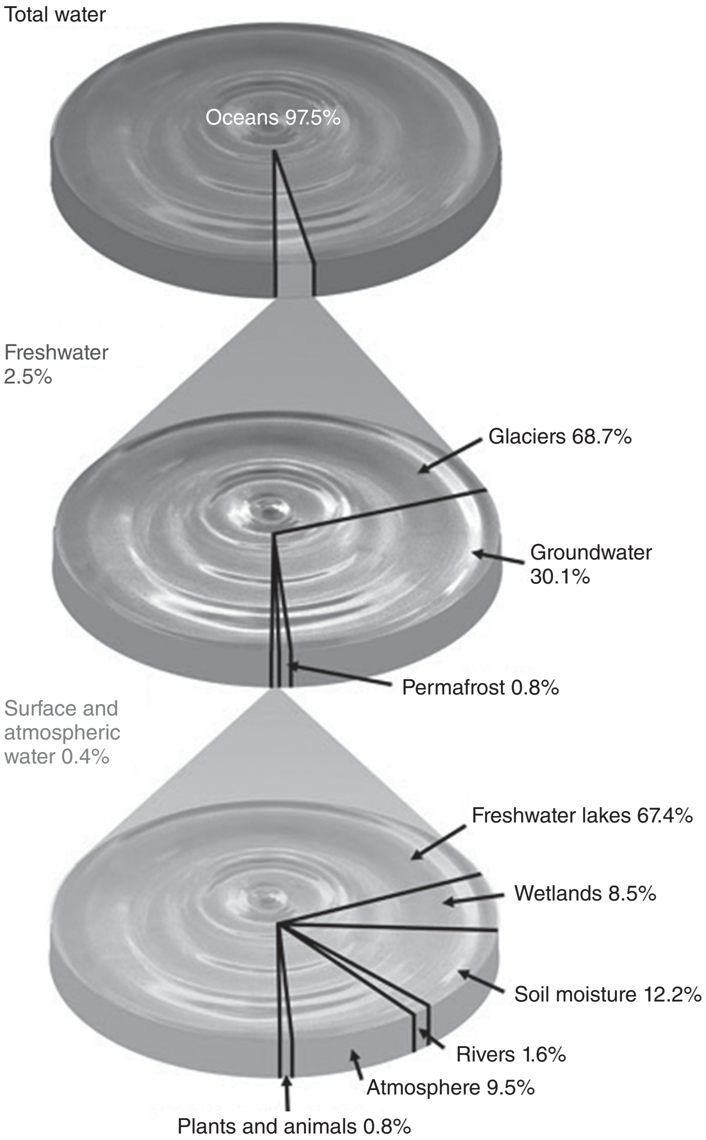

Figure 1: *Earth's Water Balance*
(United Nations Environment Programme [UNEP]. Global Environment Outlook—Environment for Development, 2007)[1]

Industry is also highly dependent on water resources. Table 1 on page 16 provides an example of the daily water requirements for each class of energy produced in the United States. The extraction, refining, and recycling of minerals and materials needed for transportation and housing, as well as telecommunications, are likewise water-intensive activities. However, most developed

TABLE 1: Water Consumption by Energy Type in the United States (DHI Water Policy, 2008)[2]

	Water Consumption	
Energy Type	Total Consumption Per Megawatt Hour (m^3/MWh)	Daily Use for U.S. Energy Production (millions of m^3)
Solar	.0001	.011
Wind	.0001	.011
Gas	1	11
Coal	2	22
Nuclear	2.5	27.5
Oil	4	44
Hydropower	68	748
Biofuel*[*]	178	1958

[*] first generation

countries worldwide take clean water for granted. Peter Brabeck-Letmathe, chairman of Nestlé, put it more bluntly, calling water availability a bigger challenge than energy security. "I am convinced that, under present conditions and with the way water is being managed, we will run out of water long before we run out of fuel."[3]

Food

Water is also the basis for the food chain, with approximately 70 percent of the water used globally expended on agriculture. In developing countries, growing food can consume as much as 90 percent of total water use.[4]

Global aggregate food production currently is sufficient to meet the needs of all. There is a vast disparity in the quality and allocation of these food supplies, however. Of the present world population of 6.5 billion, more than 800 million—nearly all of them living in low-income countries—do not obtain enough protein and calories for energy. Worldwide, a similar—and increasing—number are overfed. In addition, several billion people are experiencing deficiencies of one or more micronutrients, especially vitamin A, zinc, and iodine.

Local food production is critical in preventing hunger and promoting rural development in areas where the poor do not have the capacity to purchase food from elsewhere. Wild foods are likewise important in many developing countries, often bridging the hunger gap created by droughts, civil unrest, and other stresses. In wealthier urban communities, human dependence on ecosystems for food is less apparent, but no less fundamental.

Health

A definition of health is strength, feeling well, and having good functional capacity. Health, in popular idiom, also connotes an absence of disease. The health of a whole community or population can therefore be reflected in measurements of disease incidence and prevalence, age-specific death rates, and life expectancy.

Worldwide, undernutrition accounts for nearly 10 percent of the global burden of disease. Almost all of this occurs in poor countries where food production has not kept up with population increases, particularly in sub-Saharan Africa. Undernutrition is also correlated strongly to poverty in developing countries with high mortality rates. Between one-sixth and one-quarter of the burden of disease is related to childhood and maternal undernutrition.

In developed countries with low mortality rates, diet-related risks—mainly overnutrition combined with physical inactivity—account for between one-tenth and one-third of the burden of disease. Major human health problems are arising from increasingly sedentary lifestyles. Engineering has contributed to this situation by focusing on the reduction of human energy expenditure through such technologies as cars, escalators, and power tools.

As with issues related to food, many health problems throughout the world can be traced back to *the* most basic human need: water. More than 1 billion people lack access to safe water supplies. Approximately 2.6 billion people lack adequate sanitation, leading to widespread microbial contamination of drinking water. Water-associated infectious diseases claim up to 3.2 million lives each year, representing six percent of all deaths globally. The burden of disease stemming from inadequate water, sanitation, and hygiene totals 1.7 million deaths and the loss of more than 54 million healthy life years annually. Investments in safe drinking water and improved sanitation show a close correspondence with improvements in human health and economic productivity. Every day, each person needs 20–50 liters of water, free from harmful chemical and microbial contaminants, for drinking, cooking, and hygiene. The growing concern of providing this basic service to large segments of the human population is highlighted by one of the United Nations Millennium Development Goals, MDG-7, which calls for halving, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation.[5]

ENGINEERING APPROACHES AND TECHNOLOGIES

Engineering can address sustainable fulfillment of human needs if the designs, in themselves, are sustainable. Throughout history, society has pursued—with the best of intentions and noble goals—the challenge of finding specific solutions while ignoring the overall impacts of the science and technology involved. This has sometimes resulted in doing the right things wrong. Biofuels are made from agricultural crops, water is purified with acutely lethal substances, and precious, rare or toxic metals are used to create energy-saving photovoltaics and fluorescent light bulbs. A specific, well-meaning, yet disastrous action was the development of thousands of wells in Bangladesh to remove threats of water-borne diseases, only to result in arsenic poisoning of more than 35 million people. A transformational change is needed in engineering design. Engineering "performance" must evolve from function, cost, quality, and safety to encompass the environment, human health, and social well-being.

As described in the 2008 *Science* article, "Stationarity Is Dead: Whither Water Management,"[6] engineers also need to design for a dynamic, uncertain world. To enhance performance over time, designs must be able to adapt, be resilient, provide emergence, and evolve. This means adopting a systems context to design, in which resilience tends to increase if a system has diversity, redundancy, efficiency, autonomy, adaptability, cohesion, and strength in its critical components. When an organization focuses on resilience, it is prepared to adapt to a new set of circumstances following a disturbance. In comparison, if the organization strives to return to its pre-disaster condition, it makes the same mistakes over and over again. Inherency is another construct that should be employed in engineering design to address the underlying and defining nature of the system. Concepts related to inherency include: reliable, resilient, efficient, and renewable.

A reference point for evolving these concepts into practice in the design phase are the "Twelve Principles of Green Engineering," developed by Anastas and Zimmerman.[7] The principles encompass:

1. Green chemistry.
2. Prevention rather than treatment.
3. Designing for separation.
4. Maximize mass, energy, space, and time efficiency.
5. "Out-pulled" rather than "input pushed."
6. View complexity as an investment.
7. Durability rather than immortality.
8. Need rather than excess.
9. Minimize material diversity.
10. Integrate local material and energy flows.
11. Design for commercial "after life."
12. Renewable and readily available.

ENGINEERING GOALS FOR WATER, FOOD, AND HEALTH

Based on an examination of current and developing technologies and engineering advances, as well as an analysis of the materials and resources that would be required to address the most pressing sustainability issues related to water, food, and health, the following goals and considerations were proposed for each sector:

Water

Goals:

- Accessible.
- Available.
- Using only safe water.
- Affordable.
- Reliable.

The Millennium Council, established by the United States White House in 1998, created a series of development goals, to be implemented in 2015, with the aim of reducing poverty and child mortality. While the majority of the goals are related to reducing hunger—indirectly affecting water demand—two specifically address water supply issues:

- To halve the proportion of people who are unable to access or afford safe drinking water.
- To stop the unsustainable exploitation of water resources by developing water management strategies at local, regional, and national levels that promote both equitable access and adequate supplies.

Technologies and engineering approaches currently being used focus on protecting water quality, including watershed management and wellhead protection. Resource conservation is another tool, as well as reticulated distribution, extraction, and treatment/filtration. Engineers should also consider point-of-use interventions for water that are decentralized, simple, low-cost, socially acceptable, and sustainable with local materials, labor, and maintenance. Lifewater International is an example of an engineering organization that uses these approaches to provide engineering assistance to people without access to safe drinking water or adequate sanitation. Even the most potentially effective solutions, however, will not succeed if the human factor is not taken into account. It is critical, then, to bring together the knowledge of the technical world with what has been learned of practical human dynamics to ensure access to safe water and sanitation facilities.

Food

Goals:

- Healthy.
- Nutritious (safe).
- Accessible.
- Affordable.
- Reliable.

Food technologies overseen by agricultural engineers encompass such strategies as increasing production by enriching soil nutrients; enhancing the nutrition and effectiveness of seeds through bioengineering; developing better water irrigation in distribution and drainage; mechanizing planting and harvesting; expanding the practice of nutriment management; examining crop protectants such as pesticides or herbicides; and generally improving food capture, storage, processing, and distribution. An example of employing scientific advances for the improvement of the food supply is the development of engineered rice that incorporates genes from carrots. This can be used to supplement the diets of those who rely on rice as their primary food source, and as a result, experience deficiencies in vitamin A.

Health

Goals:

- The definition of "human needs" requires fundamental changes.
- Engineers need to lead within their own communities.
- Engineers should look for partners that empower people.
- There is an opportunity for the mining industry to collaborate with NGOs/humanitarian efforts in frontier areas, such as field testing of health technologies and water infrastructure.
- Diminish the water requirements of mining and materials manufacturing.

Engineering goals for health are based on more cutting-edge technologies. However, major breakthroughs in biotechnology, nanotechnology, antimicrobials, artificial organs, diagnostic methods, and machines are generally only available in the first world countries. Linkages also need to be made between health and urban development. As defined by Hancock and Duhl, "A healthy city is one that is continually creating and improving those physical and social environments and expanding those community resources which enable people to support each other in performing all the functions of life and in developing themselves to their maximum potential."[8]

CHALLENGES FOR THE FUTURE

The ability to provide clean and safe water for future generations is significantly challenged by the following drivers:

- Economic development and urbanization add to pollution, threatening quality of supply.
- Climate change, including rainfall patterns and flooding, will alter availability.

- Increasing demand from general population growth, increased economic activity, and higher living standards.
- Increasing demand from more water intensive activities.[4]

A shift from starch-based subsistence diets to protein-based diets likewise requires more agricultural water to support livestock. In terms of industrial demand prospects, ethanol production could be an important demand driver for water beyond 2010. Two liters of water are required to produce one liter of ethanol, separate from the water needed to grow the input crop. One way of managing the water demand is to increase the use of greywater—domestic water generated from dish washing, laundry, and bathing—in the cycle.

Measurement of water footprints may provide the political impetus to make policy changes. A number of available reports disclose data on total volume of water consumed, as well as wastewater discharge. Water footprinting methodology is also being continually developed, disseminated, and supported by the Water Footprint Network (WFN), which has grown out of the work of the closely tied Water Footprint Working Group (WFWG).[9] Corporate leaders are likewise emerging in the areas of water reporting. For example, Barrick Gold, in its sustainability reporting, goes beyond Global Reporting Initiative standards by providing site-specific data for its more than 25 global mining sites on water consumption (absolute and per unit production basis), discharge volumes, and water permit violations.

Enormous challenges also confront the development of a sustainable food supply. The 1996 World Food Summit in Rome defined food security as existing "when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life."[10] The tools of modern science must be put to work to produce enough food to meet increasing and changing food needs, make more efficient use of land already under cultivation, better manage natural resources and reduce pre- and post-harvest losses, and improve the capacity of hungry people to grow or purchase food. Modern agricultural biotechnology is one of the most promising of these developments. It can raise crop productivity, increase resistance to pests and diseases, develop tolerance to adverse weather conditions, improve nutritional value of some foods, and enhance the durability of products during harvesting or shipping. However, considerable resistance to agricultural biotechnology has arisen on the grounds that it poses significant new, ecological risks and that it has unacceptable social and economic consequences. Two specific concerns identified through the workshop process were:

- Genetic engineering with resultant lack of diversity.
- The use of antibiotics in animals without a diagnosed illness.

This leads to the third human need challenge: health. While a grave concern, inadequate health care is responsible for only a small fraction of the unnecessary loss of life that occurs every year. Securing the basic human needs of sufficient food and water is the key to ensuring good health and more sustainable communities worldwide.

ENDNOTES

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IV

Infrastructure (Transportation, Housing, and Urban Design)

INTRODUCTION

The topic of infrastructure was developed at the workshop during the synthesis of discussions based on plenary sessions concerned with transportation and housing. The following speakers presented on topics that provided context for subsequent breakout sessions:

Keynote

Braden Allenby, Professor, Civil and Environmental Engineering, Arizona State University,
Sustainable Engineering in the Anthropocene

Transportation

John Spencer, Director, National Transportation Safety Board
Engineering Solutions for a Sustainable Shipping Industry

Dianne Chong, Vice President, Boeing
Boeing and the Environment: Our Commitment to a Better Future

Engineering Solutions for Sustainability, First Edition. American Institute of Mining, Metallurgical, and Petroleum Engineers.

Salvador Aceves, Group Leader, Energy Conservation and Storage, Lawrence Livermore National Laboratory
Hydrogen-fueled, Carbon-free Transportation

Alan Taub, Executive Director, Research and Development, General Motors Corporation
Materials Challenges for a Sustainable Automotive Industry

Housing

Jorge Vanegas, Director, Center for Housing and Urban Development, Texas A&M University
An Integrated, Community-Based Approach to Sustainable Housing in Disadvantaged Communities

William Rose, Research Architect, Building Research Council, University of Illinois at Urbana
Energy Efficiency, Durability and Historic Preservation

Roderick Lawrence, Professor, University of Geneva, Healthy Cities and Housing
Key Principles for Professional Practices

Infrastructure was defined, for the purposes of this workshop, to incorporate the manufactured products, constructed facilities, and natural features that shelter and support most human activities. This encompasses buildings of all types, communications, energy generation and distribution, green spaces, transportation of all modes, water resources, and waste treatment and management. Manufactured products were included as part of infrastructure, as automobiles are an element of transportation infrastructure. Natural features were also considered part of infrastructure since, for example, wetlands impact waste treatment or lakes contribute to the water supply.

Infrastructure is important to human life and settlements at all scales—from megacities to rural hamlets (Figure 1). The lifecycle of an infrastructure system or component spans its planning, design, construction/manufacture, operation, maintenance, renewal and eventual removal/recycling. Infrastructure is long-lived and its renewal (renovation or rehabilitation) during service life is important for sustainability. Economic activity associated with infrastructure is a large portion of the Gross Domestic Product (GDP) in both developed and developing economies. Investments in infrastructure contribute strong economic returns and can aid in alleviating poverty. Infrastructure is vital to health, safety, and quality of life. Its sustainability is central to the sustainability of all human activities.

Infrastructure impacts every person in one or more of three roles for any specific system. *Users* are those directly served by an infrastructure system. Examples include drivers on a highway or families whose homes are protected by a flood control system. *Producers* of infrastructure products and services

Figure 1: *The Brooklyn Bridge: An Example of a Pioneering and Sustained Urban Infrastructure*

include those who design, finance/insure, build/manufacture, operate and maintain infrastructure systems. In this context, when referring to "engineering" infrastructure systems, disciplines other than engineers—architects, facilities managers, financiers, planners—are included since they play a professional and rational role in the life cycle of an infrastructure system. Finally, *stakeholders* are those affected by the infrastructure system in a role other than that of a user or producer. Examples include people potentially affected by noise from a nearby airport, as well as individuals and businesses whose mail delivery depends on the functionality of that same airport.

SUSTAINABLE AND RESILIENT INFRASTRUCTURE

Sustainability was defined by the Brundtland Commission as *meeting the needs of today without compromising the ability of future generations to meet their own needs*. The concept of *resilience*—possessing power of recovery—has been used to define qualities needed for infrastructure to resist natural, accidental, and willful hazards such as earthquakes, hurricanes, droughts, fires, and terrorism. To integrate these concepts, a *resilience definition of sustainability* was developed, expressing the ability to meet today's needs and be adaptable to changing future needs:

> Enable current and future generations to be resilient to anticipated and unanticipated changes in economic, environmental, political and social systems. This means that infrastructure systems should be adaptable to unforeseen demands and technical capabilities.

Infrastructure must respond to foreseeable and unforeseeable opportunities and challenges. Key to this is considering the functional and physical demands on the system over its intended service life. In the case of a highway, this includes anticipating changes in the numbers and characteristics of vehicles, as well as factoring in how climate change may affect the temperatures, wind velocities, and other environmental exposures to which the highway will be subjected. Advances in bioengineering, nanotechnologies, information and communication technologies, robotics and cognitive sciences can also lead to significant, often unforeseen, changes in users' needs and producers' capabilities. Who thought 30 years ago that broadband access would become a general user need? Climate, lifestyle, macroeconomic, political, and social changes likewise alter demands and resources for infrastructure systems.

Sustainability is achieved in communities and supported by numerous infrastructure systems, rather than in individual infrastructure systems in isolation. Building sustainable communities requires involvement of stakeholders, users, and producers of the various systems, with new paradigms of collaboration, bold approaches to innovative solutions, and integration of infrastructure systems.

ENGINEERING FOR SUSTAINABLE INFRASTRUCTURE

The technologies and engineering approaches that were reviewed in the workshop exist—at least as prototypes or demonstrations—but can be enhanced substantially for greater sustainability. Discussions focused on:

- ***Objectives:*** The qualities sought for infrastructure systems and products.
- ***Products:*** The materials and resources, components and systems, including hardware and software.
- ***Engineering Tools and Practices:*** Applied throughout the whole life cycle of products or systems.

Objectives for sustainability in all its dimensions include: zero waste from construction or manufacture, operation, and removal; culturally responsive and compatible solutions; and affordability in first and life cycle costs. Sustainable energy technologies are vital because energy is both an infrastructure system and essential to all other infrastructure systems. This also exemplifies the interdependence of infrastructure systems—Water for cooling is essential for most electrical generation, and electricity for pumping is essential to most water supply and sewage treatment systems. Integration of infrastructure systems provides important opportunities for conservation and efficiency, including automatic power shedding for buildings, transportation, and water supply to avoid brownouts, and common conduits for utilities to ease their maintenance.

Advanced products highlighted in the workshop were: multi-functional, intelligent, designed materials; "clean" coatings that do not release pollutants during their service lives; corrosion resistant materials; real-time performance monitoring and display for improved controls; and advanced controls, including aircraft to aircraft, as well as ground to air control for air traffic control.

Engineering tools and practices were also reviewed, encompassing: integrated data systems for efficient information access to support decisions for sustainability; life cycle costing tools; life cycle assessment tools with transparent weighting for incommensurate effects for necessary tradeoffs; practical evaluation methods using life cycle costing and life cycle analysis; design for maintenance, recycling, etc.; modeling and simulation techniques with visualization capabilities for non-technical decision makers; lean, integrated project delivery with software and network security for fully automated and integrated project processes; models, data, standards, and procedures for designing materials for sustainability; and regulations and standards. On this last point, standards should be performance-based to support innovations, with consistent, prescriptive standards and codes provided for economical use of conventional materials and practices. A streamlined, integrated acceptance system linking multiple regulatory jurisdictions is needed for efficient acceptance of innovations both nationally and internationally.

These topics can be elaborated for any infrastructure system, with substantial commonality among systems. As an illustration, the following case study is presented.

Case Study: The Automotive Industry

Among the most important automotive objectives for sustainability are: fuel economy; renewable fuels; electric vehicles; intelligent vehicle-highway systems, including vehicle location/speed/destination information for traffic management, as well as vehicle-to-vehicle communication; integrated systems within vehicles and for traffic management; and resolution of conflict between high-performance composite materials and recyclability.

Advanced, fuel-efficient, and sustainable products will incorporate the following characteristics: real-time fuel economy information for drivers; sensor fusion and lower cost sensors; materials, such as shape memory alloys, with a greater range of activation temperatures; engineered nanomaterials and composites; advanced batteries; and infrastructure for refueling/recharging electric and hydrogen vehicles.

Tools and practices for producing these advanced products will include: integrated databases for design, manufacture and distribution; life cycle assessment tools with weighing for incommensurate effects; modeling, simulation, and visualization techniques for design, manufacture, and traffic management; integrated project delivery systems; constitutive models for designing materials; bandwidth and other standards for integration of third party devices; and resource assessments of key materials, including platinum, lithium, and silver.

RESEARCH FOR UNFORESEEABLE ADVANCES

Much problem-focused and applied research, development, and demonstration (RD&D) is needed to advance infrastructure systems, components and products, tools and practices for sustainability. Agendas for such RD&D are readily developed for foreseen advances, exploiting known needs and opportunities. Problem-focused and applied RD&D is important and will lead to most near-term advances (next 20 years), while advances that cannot now be foreseen are likely to be very fruitful over the longer term (20 to 50 years).

Infrastructure is based on all areas of scientific knowledge—physical, life, and social. For this reason, the infrastructure RD&D community must actively monitor all scientific areas for new knowledge and insights that can advance infrastructure. Problem-focused and applied RD&D can then adapt these advances to infrastructure.

Problem-focused RD&D can also lead to unforeseeable advances. Research on objectives can provide improved understanding of the dimensions of sustainability, and of changes in users' and stakeholders' needs from altered behaviors and life styles. New concepts for infrastructure systems and products will arise from infrastructure RD&D and advances in other areas. New tools and practices will be stimulated by advances in other engineering fields and in physical, biological, cognitive, and social sciences.

ADVANCES NEEDED IN MATERIALS AND RESOURCES

A principal objective of the workshop was to identify the advances needed in materials and resources to improve the sustainability of human society.

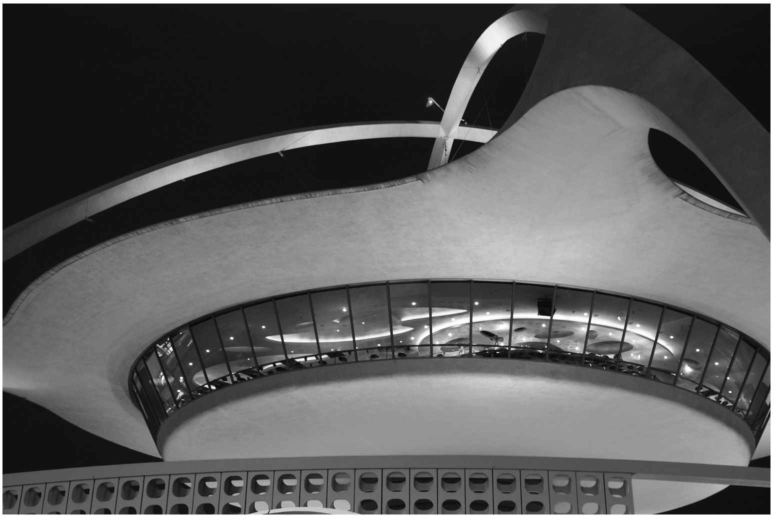

Figure 2: *The Los Angeles Airport "Theme Building": Melding Art, Architecture, and Air Transport*

Advances identified that could contribute to a sustainable infrastructure include: price-related knowledge of materials and resources availability; alternative materials, resources, and processes to provide resilience for price increases and shortages; and materials and resources addressing all dimensions of sustainability from a cradle-to-cradle perspective. Air transportation has particular need for high energy density, sustainable fuel.

Society's infrastructure increasingly consists of complex, adaptive systems integrating built, natural, and human components (Figure 2). As infrastructure systems become more integrated through mediation of information and communication technologies (ICT)—from local sensors to imbedded ICT/net capabilities—education, materials, and resource needs must incorporate an ICT domain. This evolution of infrastructure places major demands on engineering education, professional licensure, and certification of various kinds, to ensure that engineers become more sophisticated in understanding and managing solutions of complex problems.

V

The Resource Cycle

The path to sustainable development requires engineering advancements in a variety of fields, six of which were discussed at the *Engineering Solutions for Sustainability: Materials and Resources* international workshop. In turn, these advancements will require mineral, material, and energy resource inputs. With this in mind, the workshop was organized to facilitate interdisciplinary dialogues between the resource sectors and the end-use technology sectors. Parallel breakout sessions focused on energy and recycling, while the topic of minerals availability was introduced in the keynote session and integrated into some of the subsequent facilitated breakout sessions.

V(A). ENERGY

INTRODUCTION

The topic of energy was developed during the synthesis of discussions based on plenary sessions concerned with energy, as well as linkages created with transportation, minerals, water, and infrastructure. Speakers and their topics were:

Kamel Bennaceur, Chief Economist, Schlumberger
The World Energy Outlook: Post-2012 Climate Scenarios

Engineering Solutions for Sustainability, First Edition. American Institute of Mining, Metallurgical, and Petroleum Engineers.

Hans Teddy Puttgen, Professor and Director, Energy Center EPFL
Future Technological Challenges for the Power Industry

John Corben, Office of the Chief Economist, International Energy Agency
The New Energy Mix

While energy demand grew by nearly 80 percent over the last three decades, there has been little change in the energy mix. Fossil fuels still dominate the primary energy supply with a share larger than 80 percent, and in the absence of major changes in energy and climate policies, the fossil fuel share will still dominate the energy sector with more than 80 percent by the end of the projection period (2030). Despite the rapid absolute growth of renewable energies (e.g. wind, biofuels, and concentrated solar power), the lower cost of producing fossil fuels and the lack of carbon abatement incentives will be major hurdles in the decarbonization of the energy sector. Implications of the energy mix in the business as usual (BAU) scenario are that carbon dioxide (CO2) emissions would rise by 40–42 percent between 2005 and 2030, and more than double by 2050. The 2007 IPCC Fourth Assessment Report[1] has indicated that emissions rising by that order of magnitude could lead to temperature increases on the order of 4 to 7 degrees Celsius in the second half of this century. Even a 50 percent reduction in CO2 emissions by 2050, compared to the 2000 level, would lead to the temperature's rising by 2 to 2.4 degrees Celsius.

WHAT SUSTAINABILITY MEANS FOR THE ENERGY SECTOR

Sustainability was defined by the Brundtland Commission as *meeting the needs of today without compromising the ability of future generations to meet their own needs*. For the energy sector, there is a bifurcation of challenges between the industrialized countries, where the main issues are related to the rational/sober utilization of energy, and emerging economies, where the massive increase in energy production and access could lead to a global increase in emissions. From these circumstances, two main sustainability themes have emerged:

- ***Industrialized Countries:*** Energy efficiency and preservation of the quality of life.
- ***Emerging Economies:*** Provision of enhanced quality of life, associated with significant economic expansion, while minimizing the environmental impact.

Given this bifurcation, the "grand energy challenge" is to develop sufficient energy resources to sustain global development according to the following criteria:

- Lower carbon footprint.
- Cost-effective sources (production, transport, and use).
- Attractiveness to investors (long-term stable return, "lock-in" of choices).

DISCUSSION OF SCENARIOS

The International Energy Agency projects energy demand and supply to 2050. Under the current and planned energy and environmental policies, and in the absence of major supply constraints, energy-related CO2 emissions would rise to 60 Gigatonnes (Gtonnes). Alternatives to the BAU scenario are two primary options of emission reduction:

- Stabilization at the current level of emissions, also referred to as the "550-policy scenario" (550 parts per million (ppm) is the atmospheric greenhouse gas (GHG) level).
- "450- (or BLUE) scenario." This translates into a 450-ppm GHG level or a 50 percent reduction in energy-related emissions by 2050, compared to the 2000 level.

Policy mechanisms in the climate mitigation scenarios would be of various types—between developed economies and other major economies and other countries—as a mix of national policies and measures and international sectoral approaches. This combination of mechanisms would be the most likely outcome of future Conference of the Parties (COP) meetings.

ENERGY MIX AND CARBON ABATEMENT WEDGES

In the absence of major changes in energy-related policies, the share of fossil fuels in the total primary energy supply would remain nearly unchanged from the current level (82 percent) to 2030 (80 percent), with coal increasing its share by 2 percent at the expense of oil. Renewables, such as solar and biofuels, despite a large relative growth, will remain a marginal source of energy.

In the 450-ppm scenario, energy demand still grows by 20 percent, but with a 10 percent reduction in CO2 emissions by 2030. The decrease in energy-related emissions intensity can be achieved through a major reduction share of coal in the energy mix, replaced with renewables and nuclear.

There are seven major carbon abatement wedges (using the Princeton terminology), that all together could contribute to a 48 Gtonnes emissions reduction by 2050 (Figure 1). End-use fuel efficiency with a quarter of the abatement potential is the largest one, followed by renewable (all combined), and CO2 capture and storage (CCS), each amounting to 20 percent. End-use electricity efficiency (12 percent), end-use fuel switching (11 percent), power

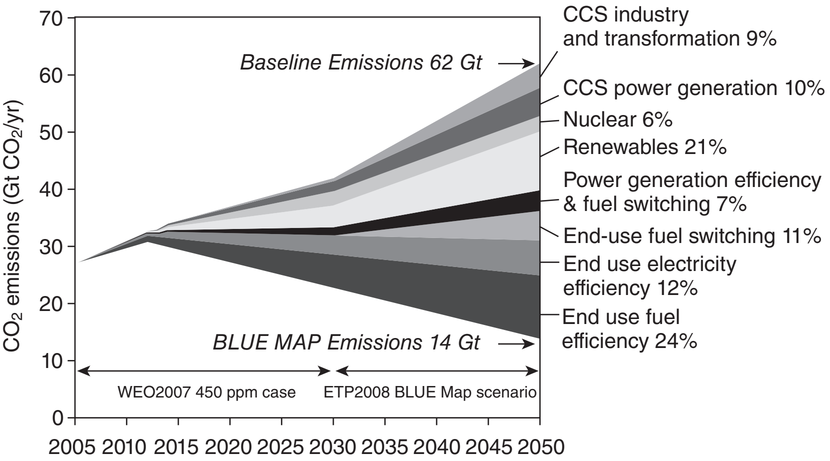

Figure 1: *Carbon Abatement Wedges*
(Source: IEA, Energy Technology Perspectives 2008*, Figure 1, p. 3. ©OECD/International Energy Agency 2008.)*[2]

generation efficiency and fuel switching (7 percent), and nuclear (6 percent) close the list. Marginal carbon abatement costs vary from negative values (generally related to end-use energy efficiency) to values as high as US$500/tonne of CO2 for alternative fuels in transport in a pessimistic technology development scenario.

IMPLICATION OF ENERGY CHOICES ON OTHER RESOURCES (MINERALS, WATER, LAND)

The mineral resource, water, and land-use requirements for each energy choice must be taken into consideration as society develops technology solutions to meets its growing energy needs. For example, the production of liquid hydrocarbons from bitumen and tar sands have large ecological (land-use) footprints and between three and five cubic meters of oil are needed for every tonne of unconventional oil produced. Shale gas production, which has created a “revolution” in North American gas markets over the last few years, requires significant quantities of water for drilling and hydraulic fracturing. The environmental consequences of agricultural production for biofuels include impacts to regional aquifers as well as impacts to biodiversity when rainforests are converted to such uses. New renewable energy and technologies like wind and solar—as well as the telecommunications and automotive industry—will rely on the increased production of a large list of critical elements such as lithium, rare earths, and cobalt.

Whether sourced from virgin ore or recycled inputs, the energy, water, and land requirements to produce these materials can be significant. Both virgin ore and secondary inputs are also not uniformly distributed globally, so the significant energy requirements (and resulting emissions) of transporting these materials to the final end-use market must be accounted for properly. Each energy choice will have its own mineral, material, and water requirements, and each will be accompanied with a set of environmental impacts to air quality, water quality, and biodiversity. It is critical that these tradeoffs be adequately acknowledged and balanced in pursuit of sustainability.

BIFURCATION OF CHALLENGES

The world needs to tackle the global challenges related to energy security, energy poverty, resource constraints and climate change impacts. As energy use varies widely across the world—1.5 billion people do not have access to electricity, for instance (Figure 2)—sustainability infers different focus areas for mature energy markets and energy-poor regions.

The transformation of mature markets to reach the required levels of reduction in emission intensity requires a combination of major policy reforms that would lead to (a) more efficient use of energy, (b) a switch to decarbonized energy sources, and (c) the development of the required infrastructure such as smart grids and energy storage.

A wider access to energy is necessary to enable social and economic development and eradicate poverty in emerging economies. Rural electricity access, cost-effective and low-emission distributed energy generation systems, along with urban planning/re-design, are all required to ensure a reduction in social inequalities and tensions.

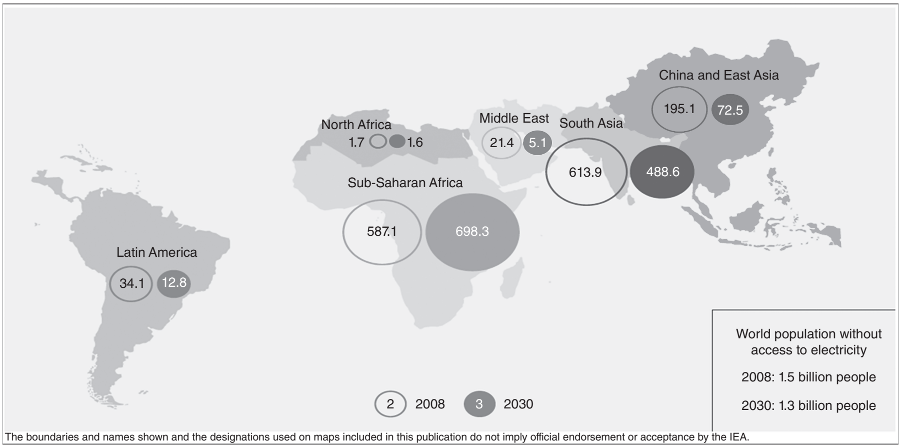

Figure 2: *Populations Without Electricity Access*
(Source: IEA, World Energy Outlook 2009*, Figure 2.10, p. 131. ©OECD/International Energy Agency 2009.)*[3]

MAJOR RESEARCH AND DEVELOPMENT AREAS AND PRACTICES TO ENHANCE SUSTAINABILITY IN THE ENERGY SECTOR

Achieving the ambitious objectives of the 450-ppm scenario would require a major transformation in the way power is generated and the way it is being used, whether in residential, industrial or transportation applications. Governments, through the development of policies and market incentives that encourage technology development, should work with the private sector and the financial sector to step up investment in energy-related research and development (R&D). International cooperation is also required to explore all major options with minimum duplication effort.

The major R&D areas summarized below are needed to enhance sustainability in the energy sector, while being in line with the objectives of decarbonization and expanded access:

Energy Generation from Fossil Fuels

- Improved efficiency, fossil-fuel power generation through the use of ultra-supercritical steam-cycle plants, integrated gasification combined cycle coal plants, and natural gas combined cycle units.
- Cogeneration (combined heat and power) which would apply to coal and natural gas.
- CO2 capture and storage (CCS) with coal or gas plants. There is potential for a significant decrease in the cost of capture, the major part of cost in CCS chain.

Energy Generation from Renewables

- Solar energy is the most abundant energy resource on Earth, but it provides less than 1 percent of today's supply. Concentrated solar power (CSP) has the largest potential from a cost standpoint and could be competitive with fossil fuels within two decades, provided intermittency issues are resolved. CSP has other uses apart from electricity generation, including direct heating/cooling and desalinization and hydrogen production. CSP R&D priorities include materials research (e.g. high temperature-rated materials for receivers), reduced material consumption, and advance modeling techniques. Photovoltaic modules require developments in the area of crystalline silicon, thin films, and nanotechnology.
- Wind energy is currently the fastest growing type of energy, in terms of relative expansion, with most of it land-based. R&D requirements include improved turbines and rotors, new offshore concepts, and high voltage DC cabling technologies.
- Biofuels' expanding production could have major environmental impacts, as indicated by the 2008 "food and fuel" crisis. The most significant developments are expected to be in the area of cellulosic biomass conversion, which are today still at a small-scale demonstration level.

- Geothermal energy development of enhanced geothermal systems (EGS) targets extraction of energy from depths of 3 km to 10 km. R&D focus includes equipment design for high temperature operation, as well as decreasing well cost.
- Hydroelectricity R&D requirements are related to both large hydropower units (low-head technologies) and smaller systems (hybrid wind-hydro, turbines with low ecological impact, low-head operations).
- Marine energy generation, while still at a small scale, could be expanded in the areas of wave energy and current tidal energy, provided environmental impacts are mitigated.

Nuclear Energy

- Innovation options in the nuclear sector include the development of small to medium capacity plants (200–500 megawatts [MW]), evolutionary concepts for the European pressurized water reactor (EPR), Generation IV reactors that reduce waste production, and alternatives to uranium.

Smart Grids

- Smart grids provide an option to optimize the chain that includes distributed energy generation and storage, electricity delivery infrastructure (including transmission and distribution), and end-use systems. R&D priorities encompass integration processes and enabling technologies, such as power conversion and storage.

Energy Efficiency

- Nearly one third of energy consumption is devoted to heating and cooling residential and commercial buildings. It is estimated that recently developed technologies, such heat pumps, vacuum-insulated panels, and high-performance windows could reduce energy consumption by 80 percent. R&D priorities include retrofitting with existing buildings, advanced materials, and integration with the power grid.
- Industry use accounts for one third of the total final energy use, mostly in iron and steel, aluminum, chemicals, cement, and pulp and paper. Many options exist for reducing CO2 emissions, including CO2 capture and storage, combined heat and power (CHP) heat exchangers, and advanced materials.

Transportation

- Emissions from the transportation sector could be reduced by 30 percent by 2050. Major R&D areas related to improving the emission intensity of transportation focus on hybrid, electric, and plug-in hybrid vehicles, hydrogen fuel cell vehicles, and overall fuel efficiency. Priorities include reducing energy storage costs, developing lightweight materials, applying nanotechnology, and advancing fuel cell propulsion systems.

Energy Storage

- Energy storage is an essential component in energy security and efficiency, especially in conjunction with intermittent renewable sources. R&D priorities include mobile storage (batteries), underground thermal energy storage, compressed air storage, and finding alternatives to materials such as lithium.

ENERGY ROADMAPS

The deployment at commercial scale of sustainable energy technologies require major international efforts that combine international agreements for emissions reduction beyond the Kyoto protocol[4], regional and national policies that encourage technology development, legal and regulatory frameworks, and the creation of market and financial incentives for clean energies. Energy roadmaps for individual technologies provide the means to define a timeline between the concept phase and full commercialization, the enablers, the targets, and the investment requirements. Several international and national organizations have developed such energy roadmaps, including those described in the IEA's *Energy Technology Perspectives 2008*.[5] A total of 17 key technology roadmaps are being agreed upon by the stakeholders, five of which have been developed: carbon capture and storage, electric/plug-in hybrid electric vehicles, solar photovoltaic energy, wind energy, and cement production.

V(B). MINERAL RESOURCES

Minerals, metals, and materials are essential to every sector of every nation's economy and will play a determining role in the feasibility of the emerging technologies that sustainability will require. To provide technical background in addressing sustainability themes as they apply to mineral resources, the following information was presented:

Keynote

Andrew Bloodworth, Head of Science for Minerals, British Geological Survey
Future Global Demand for Minerals: Supply Challenges and Sustainability

Highlights:

- Minerals are essential and demand is likely to continue to increase due to new markets for minerals and expanding markets in existing applications.
- Major challenges exist for the maintenance of adequate supplies, many related to sustainable development and the social license to operate.
- There is a fundamental misunderstanding about reserves and resources, which has led to unjustified, sometimes alarmist, conclusions.
  a) Current reserves are unreliable indicators of future availability of minerals.
  b) Clear terminology is essential.
  c) Falling production is not the same as resource depletion.
  d) Investment and policy decisions should be based on high quality data and clear understanding of its meaning.

The British Geological Survey believes that adequate mineral supplies can be maintained into the foreseeable future. Science and technology will have major roles to play:

- Exploration: New deposit models, new locations, new methods.
- Mining Technology: In situ mining, deep high-grade deposits.
- Mineral Processing: Water and energy efficiency, new methods.

WHAT SUSTAINABILITY MEANS TO THE MINING AND MINERALS SECTOR

No single ore deposit or mine is sustainable, but mining (primary production) has an important role to play in sustainable development as a source of essential raw materials, and as an engine of economic development and wealth creation. However, the ability of the minerals and metals industry to make positive contributions to society, and to set the stage that will empower sustainable communities, increasingly depends on its willingness to more universally adopt sustainable mining practices and the capacity of governments to ensure that local, regional, and national benefits of responsible resource development are fully realized.

As Figure 3 illustrates, attitudes within the minerals sector have evolved over time. Initially, discovery and access were the drivers of mineral-related decisions. Property rights, investment, and access to capital then rose in importance. By the late industrial age, the role of workers and their rights began to be recognized. With the birth of the environmental movement, the impacts of mining and mineral processing on water, air, and land started to be addressed to varying degrees. With the emergence of the sustainability paradigm, the need to consult and engage communities about business activities

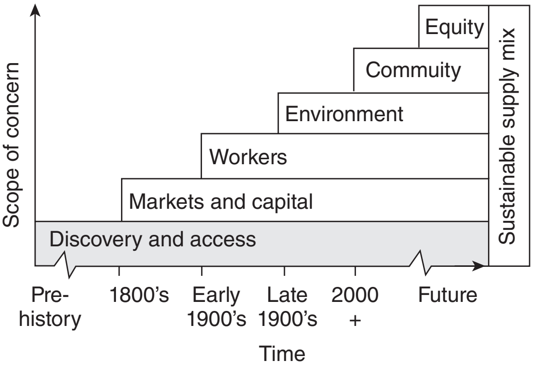

Figure 3: *Expansion of the Scope of Concern about Mineral Supply (Source: Šolar, Shields, and Miller, 2009, p. 306).*[6]

that have the potential to impact their social structure, health, and economy was recognized, as was the importance of stakeholder input to decisions regarding post-mining land use. Most recently, equity within and across generations has been added to the scope of concern. Only when all six of these areas are proactively addressed will it be possible to have a sustainable supply mix, i.e., minerals and metals supplied in a manner that provide a net benefit to society.

Beginning with Canada's Whitehorse Mining Initiative of the mid 1990s and the International Global Mining Initiative in 1999, the minerals industry has undergone a series of critical reviews of its social, environmental and economic developmental performance. In 2002, as part of the Mining, Minerals, and Sustainable Development research project, the North American task group developed a seven-step framework to help mining operators assess how an individual project could contribute to sustainable development for the local community, region, and country. As illustrated in Figure 4 on page 40, these questions address many of the key tenets of sustainability: engagement, people, environment, economy, indigenous communities, governance, and intergenerational considerations. One of the overarching goals of sustainable mining practices is to ensure that the natural capital produced from the mine will be utilized to build a sustainable community that has the financial and human resources to thrive long after the deposit is exhausted and the mine has closed.

Over the past decade, as a result of numerous transparent multi-stakeholder dialogues, as well as international fora and collaborative interdisciplinary research projects, the industry has generated a considerable amount of guidance on how mining practices must evolve for the sector to responsibly fulfill its role in society's transition to sustainability. (See Appendix B, page 74, for references and guidance documents within the minerals sector.) However, these *sustainable mining practices* are not yet widely embraced, and the degree to which they are implemented varies across political jurisdictions, sub-sectors of the industry, and even within enterprises (private, public and state-owned). In 2010 and 2011, the United Nations Commission on Sustainable Development

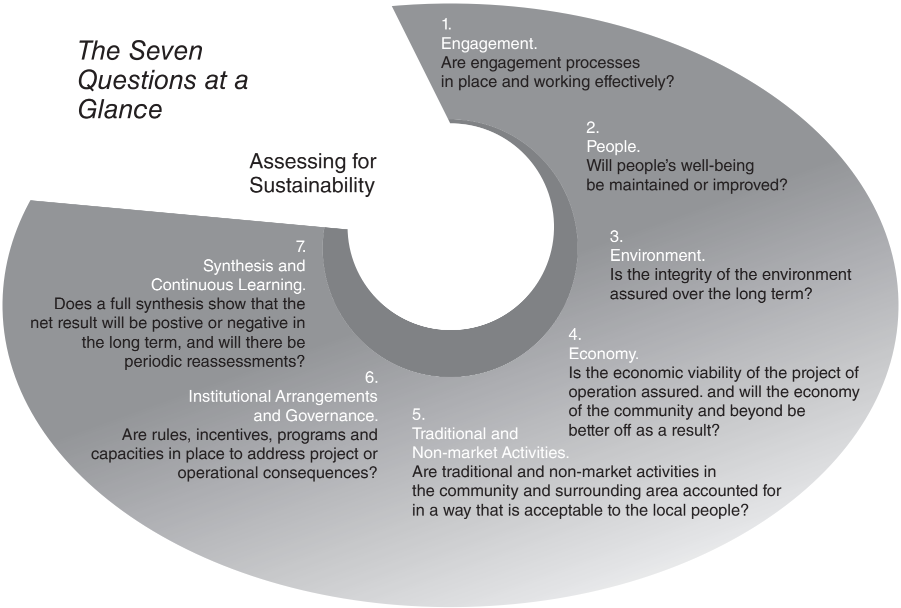

Figure 4: *Assessing How a Mine Project Can Contribute to Sustainable Development (Courtesy the International Institute for Sustainable Development (IISD). Source: "Seven Questions to Sustainability: How to Assess the Contribution of Mining and Minerals Activities," Task 2 Work Group, MMSD North America, Page 1.)*[7]

(CSD)-18 examined the progress that the minerals industry has made in implementing sustainable development principles, and will be making recommendations for further actions.

THE NEED FOR PRIMARY AND SECONDARY SOURCED MINERALS

A *sustainable supply mix*, as indicated in the right hand column of Figure 3 on page 39, can be defined as a combination of primary (virgin ore) and secondary (recycled material) resources that together maximize net benefits of mineral supply across generations. Demand has been met by a combination of these resources for many years, with recycled materials becoming an increasingly important aspect of a sustainable materials supply in the future. The feasibility of using recycled materials will be increased through research, engineering advancements, improved product design for recyclability, and an appropriate combination of political and market incentives.

Currently, the recyclability of products with mineral and metal content differs depending upon the original design of the product and the manner in which it has been disposed. Certain metals are highly amenable to re-capture (e.g., aluminum, gold, lead, copper, and platinum group metals). Due to emerging processing technologies, other metals have the potential to become highly amenable to recycling. Once adequate post-consumer volumes become available, doing so will become an economically viable activity. (Examples are provided in the "Materials and Recycling" section of this chapter, beginning on page 46.)

Currently, the recyclability of many other mineral commodities is either not feasible or warranted due to the nature of the use, the relative abundance and distribution of the resource, the energy and water requirements of recycling or the cost of recycling as compared to the cost of producing virgin materials. In addition, certain minerals that are essential to new technologies only occur in trace quantities in the current products, making the potential stream of recycled material too small to fulfill expected demand. In these cases, new sources of minerals must be continuously identified, developed, and produced in a socially and environmentally responsible manner.

MINERAL AVAILABILITY

Mineral resources are not distributed evenly or uniformly across the globe. Geologic processes, such as volcanism and mountain-building through tectonic activity, as well as wind and water erosion, oxidation, climactic events, and plant, animal, and bacterial processes all contribute to mineral occurrences. Our understanding of these processes and our ability to identify and quantify occurrences varies across the mineral commodity spectrum. Discovering, accessing, developing, producing, and distributing these minerals and mineral products to locations with adequate capacity to produce the materials that society requires is limited by the five dimensions of mineral availability: geologic, technical, environmental and social, political, and economic.

As suggested in Table 1, the extent and manner to which these dimensions of availability are addressed within various political jurisdictions can have profound impacts on global material supply. A sustainable and globally integrated society could theoretically access and leverage all of the minerals resources required to implement the transformative technologies under consideration. However, international cooperation and trade, including the sharing of technical expertise, will be required to maintain supplies of these minerals that "underpin power, water, housing, and transport provision, and are central

TABLE 1: Five Dimensions of Mineral Availability (National Research Council, 2008)[8]

Geologic Availability	Does the mineral resource exist?
Technical Availability	Can we extract and process it?
Environmental and Social Availability	Can we produce it in an environmentally and socially responsible manner?
Political Availability	How do governments influence availability through their policies and actions?
Economic Availability	Can we produce it at a cost users are willing and able to pay?

to the technologies that are helping to promote [human] development and social equity in developing countries."[9] Political agreements that are transparent and fair to both the producing and consuming signatories could lead to mutual and global benefits to resource availability.

RESEARCH AND DEVELOPMENT FOR SUSTAINABLE MINING PRACTICES

Significant innovations in manufacturing and engineering have occurred since the dawn of the Industrial Revolution. However, it is only in the last half century that there has been a more prominent emphasis on the safety of personnel, environmental quality, and equity, as illustrated in Figure 3 on page 39. To be compatible with sustainable development, mining practices and technologies of the present and future must be economically feasible, contribute to positive community development, fairly share risks and benefits within and across generations, and have low environmental footprints. Proper sustainability assessments of mine projects must consider how the project might facilitate the rehabilitation and improvement of previously degraded ecosystems. Specific attention to the entire life cycle of a mine, from exploration to project development, operations, closure, and post-closure must become the frame of reference for any assessment of a given mine project's contributions to sustainable development. The minerals sector has also recently developed guidance on materials stewardship, recognizing the interrelated roles of primary and secondary production in the full-life cycle of resources required by society, as illustrated in Figure 5.

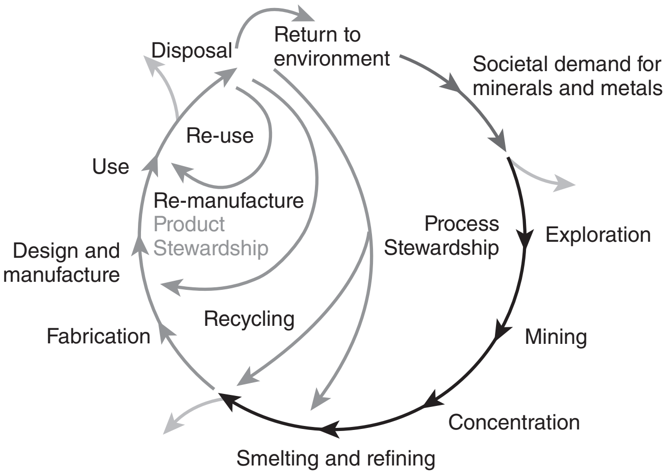

Figure 5: *The Scope of Material Stewardship Encompasses Process and Product Stewardship (International Council of Mining and Metals, 2006)*[10]

EXISTING AND EMERGING TECHNOLOGIES AND ENGINEERING APPROACHES

In its 2002 report, *Evolutionary and Revolutionary Technologies for Mining*, the National Research Council of the United States identified key mining and minerals research and development goals for exploration, mining, and mineral processing, as summarized in Table 2. Many of the technological advances summarized in this table have overlapping or complementary applicability in the recycling and resource recovery sector discussed on page 46.

Water Use

Reducing the water footprints of mining and minerals processing must remain a high research and mine management priority. From the development of new processing technologies, to the wider adoption of sound water management practices (e.g., increased water treatment and recycling, the use of environmentally benign dust-suppression chemicals to reduce road-watering intensity and frequency, etc.), to improved efficiencies in mine dewatering, firms are taking an integrated water management approach. For instance, with the modernization and expansion of Molycorp's Rare Earths Mine in Mountain Pass, California, a process that once required 850 gallons per

TABLE 2: Opportunities for Research and Development in the Minerals Sector (Adapted from National Research Council, 2002)[11]

Exploration	Geologic Modeling & Mapping
	Geochemical/Geophysical Methods
	Drilling Technology
Mining	Mine Visualization, Imaging and Quality Analysis
	Cutting and Fragmentation
	Ground Control
	Materials Handling
	Mining Systems
	Improved Machine Performance
	In-Situ Well-Field Operations
	Bore-Hole Excavation
	Hydrometallurgical Advances
Mineral Processing	Comminution/Grinding
	Gravity Separation
	Magnetic/Electrostatic Separation
	Ore-Sorting Separation
	Flotation and Selective Flocculation
	Hydrometallurgy and Chemical Processing
	Biotechnology

minute (gpm) to produce 10,000 tons of product per year is expected to use less than 30 gpm upon completion.[12] Goldcorp also redesigned their water management system at the Porcupine mine, allowing for higher water recirculation in the mill, reducing effluent treatment run time by approximately one month.[13] Finally, The Minerals Council of Australia is developing a Framework for Water Accounting to promote "consistent and transparent reporting and communication of water resource management in the minerals industry."[14]

Energy Use, Intensity, and De-Carbonization

Over the past few decades, mine operations have implemented numerous initiatives and measures resulting in significant efficiencies and reduction in energy use and carbon emissions. Steam management initiatives at Cominco's Trail operation in Canada has reduced energy consumption by 26 percent and decreased CO2 emissions per tonne of metal by 33 percent.[15] The power plant at BHP Billiton's West Cliff Mine in Australia is the world's first power plant to use coal mine ventilation as fuel and is expected to reduce GHG emissions by 250,000 tonnes carbon dioxide equivalent (CO2E) per year.[16] Using advanced process controls and other efficiency measures, Iron Ore Company of Canada (Rio Tinto) was able to reduce its energy use per tonne of product by 13 percent.[17] Through optimizing mill liners, installing more energy efficient third stage grinding, and improving fragmentation of open pit blasts, the Williams Mine was able to reduce energy usage by 15–18 percent.[18]

In addition to implementing waste-heat recovery and co-generation projects, a number of mining companies have initiated feasibility assessments of renewable energy (such as solar, wind, and geothermal) on their mine sites. Barrick has implemented solar and wind energy projects on or near their projects in the United States, Argentina, and Chile, while Lihir Gold has developed geothermal power that supplies more than half of its operational requirements in Papua New Guinea.[19] Some mining operations are converting a portion of their diesel consumption to biofuels. Barrick and Goldcorp are developing pilot bio-gas plants near their mining operations. Jatropha crops, yielding more than four times as much fuel per hectare as soybean and more than 10 times that of corn, will be harvested from rehabilitated mined lands. Newmont is working with non-profits to create a Kyoto-compliant permanent forest carbon sink of mallee trees in Australia capable of capturing more than 119,000 tonnes of carbon over a 50-year life.[20]

Stakeholder Engagement

A proper sustainable development assessment of any project—mining or otherwise—requires consultation with all stakeholders, with due consideration of future generations. This engagement must occur in all stages of the project life cycle as communities and expectations, as well as new knowledge and understanding, change over time. For example, during the planning phase, the Diavik Diamond Mine initiated an open public engagement process. In the resulting Socio-Economic Monitoring Agreement, Diavik committed to maximizing project-related employment opportunities and establishing training programs for aboriginal and non-aboriginal residents of the Northwest Territories of Canada. Operations employment in 2009 was 35 percent aboriginal, 32 percent northern non-aboriginal, and 35 percent other Canadian.

Robotics

The use of robotics, particularly in sub-surface environments that may pose unacceptable risk to human life, is a promising area of research and development. The uranium mines of Saskatchewan have been successfully mining highly radioactive ores for a number of years using automated shovels and trucks to mine high-grade ores. LKAB, an international minerals group based in Sweden, uses remote-controlled production drilling and loading, as well underground rail transport, in their iron ore mines, enabling greater efficiency of process control.

Mined Materials Management

As economics and technologies change, mineral wastes can be reprocessed to recover lower grade remnants left behind by previous generations. Alternatively, minerals with limited utility and/or concentrations that do not merit economic extraction with current technologies may become a desirable product at a future date. Proper management of these piles, accounting for segregation of material types for leaching and/or future aggregate potential, should become an integral part of the mining engineering planning process. Current practices typically send all materials not classified as “ore” into heterogenous stockpile locations, compromising the potential for future use and recovery.

Tailings Management

Currently the transport and storage of processing waste products (tailings) utilize large quantities of water. Technologies are now in practice, but can be improved, that provide for “dry-stacking” of these products. Technologies in development could potentially utilize tailings—often pure silica-feldspar-mica sands—for other commercial uses. Processes have been patented for the re-compaction and “baking” of these materials to form sheets and blocks that can be readily cut, nailed and fitted as useful building materials for commercial and domestic construction. The products are found to be highly adaptable, can be readily sawed, and nailed or screwed in place, and possess high insulation capabilities.[21]

ADVANCES IN ENGINEERING AND TECHNOLOGIES NEEDED

Priorities for continuous improvement, as well as research and technological development necessary for achieving sustainability goals, were identified for the mining and mineral processing sector as follows:

- Optimization of extraction technologies to maximize mining and processing recovery of desired mineral products, including the conversion of waste products to useful byproducts and effective management of materials (both hazardous and non-hazardous).
- Reliable management of harmful and hazardous mined and processed materials that currently have no alternative.
- Development of mining and processing technologies compatible with environmental protection and conservation of biodiversity.
- Integrated landscape management to restore mined lands to functioning ecosystems and/or transition and regenerate them to other socially and economically beneficial uses.
- Development of mining and processing technologies that minimize utilization of scarce, but renewable, resources such as clean water, clean air, and energy.
- Integration of health and safety, for both workers and communities, in all aspects of design and implementation.

V(C). MATERIALS AND RECYCLING

The United States consumes a third of all raw materials worldwide and approximately 1000 pounds of metals per capita—despite representing only five percent of the global population.[22] As global economies strengthen (e.g., within developing countries such as China and India), this consumption disparity will inevitably shrink, adding even greater pressure on materials sustainability.

In addition to being used for structural components, metals and metal-derived components are employed by all types of industry in the manufacturing of commodities, including electronics, chemicals, and energy generation. The world usage of steel exceeds a billion metric tonnes, followed by aluminum at over 30 million metric tonnes. Consumption of other common metals, such as copper and nickel, stand at approximately 10 million metric tonnes and 1.5 million metric tonnes, respectively. Use of precious metals, such as gold and platinum, are at approximately 2500 metric tonnes and 225 metric tonnes. The United States is the largest consumer of these metals and metal-derived products. The economic value of the ability to recycle and reuse these high tonnage metallic resources cannot be overemphasized. Any country's economic health is intimately intertwined with its ability to conserve its natural resources. Besides conservation, two other aspects of recycling make economic sense: secondary production costs are only a fraction of the cost of primary metal making; and disposal of metal-bearing wastes causes environmental hazard.

Despite growing efforts to recycle metals, recent reports by the U.S. Geological Survey (USGS)[23] show that half of the domestic post-consumer metal scrap reclaimable from retired products is not recovered, while primary metals production fulfills two thirds of existing manufacturing needs. Use of primary metals in lieu of scrap increases global energy consumption, as well as the production of greenhouse gases. While a wide range of recycling technologies is available for materials such as electronics scrap and end-of-life vehicles, technologies still need to be developed or adjusted for other waste streams. In addition, without effective collection of end-of-life devices and production scraps, the system will not work, even when the best technologies are developed. Ensuring mobilization and collection of goods is the starting point for the recycling chain.

Applying a systems approach will require that metal alloys be designed to meet performance requirements, while increasing recyclability. Advanced technologies to separate and identify tolerance of scrap metal input also need to be developed. This will require investment in basic science and resource recovery and recycling technologies.

The following sections examine the two main segments of the material industrial base: structural materials and functional materials.

Structural Metals/Materials

Commonly used materials for structural applications are: light metals (aluminum, magnesium, titanium); non-ferrous metals (copper, nickel); and ferrous metals. Though the industries are distinctly different, what they have in common is the need to recover resources, increase recycling, and reduce carbon footprint and energy use. For example, recycling iron and steel saves 74 percent of energy and 86 percent of emissions compared with primary production. Other energy savings are similarly quite impressive: 95 percent for aluminum; 85 percent for copper; 60 percent for zinc; and more than 80 percent for plastics.

The aluminum industry has pursued recycling as a means to reduce energy costs and pollution, and as a result, has gained economic advantage and provided societal benefit. Since 1960, domestic aluminum producers have increased the use of scrap three-fold as a percentage of total aluminum production. In 1995, U.S. primary aluminum smelters produced 3.4 million metric tons of aluminum at an average energy cost of 15.4 kWh/kg of aluminum.[24] Recovery and recycling of scrap aluminum provide large energy savings since secondary smelting consumes only ~5% of the energy required to produce primary aluminum. Additionally, primary smelting of a kilogram of primary aluminum releases 1.5 Kg of CO2 and significant, but lesser amounts, of CO, SOx, CF4, HF, perfluoro carbon, and carbonyl sulfide into the environment.[25] In contrast, secondary production of aluminum, using scrap input, requires only remelting—a far cleaner process with little or no hazardous waste.

Recycling of used beverage containers (UBC) and automobiles represent two major sources of recycled aluminum. The imposition of deposits and availability of collection centers for beverage cans by many states have encouraged consumer-centric aluminum recovery and closed-loop recycling. Today, UBC's are used to manufacture new containers within a cycle time as low as 90 days. In 2005, 51 billion UBC's were recycled to produce new can stock.[26] Recovery of aluminum from automotive scrap poses greater challenges and generally results in mixed scrap, comprised of wrought and cast aluminum alloys covering a range of alloying elements and compositions. Separation technologies that are rapid, accurate, and effective need to be developed and adopted to address this situation. Several areas where research and development would improve resource recovery and recycling include:

- In-line, real-time, operator-friendly, continuous non-contact sensors and methods to identify and separate scrap/chips.
- Methods to remove impurities from the melt (e.g., magnesium, iron, lead, lithium, silicon, and titanium in molten aluminum).
- Processes that can produce high-quality metal (similar to primary quality) from mixed scrap.
- Alloys that are recyclable, as well as an index for recyclability and strategies for tagging materials in order to enhance their recyclability.

Functional Materials

High value metals, metallic compounds, and intermetallics are used in functional applications, such as electronic, photovoltaic, magnetic and other electro-optic and electro-mechanical devices. Consumer goods, such as sporting equipment, vehicles, and appliances, employ many valuable metals. Common metals used for these applications include precious metals, copper, silicon, aluminum, magnesium, titanium, refractory metals, lanthanides, rare-earth metals, and alkaline-earths.

For many of these devices, the recycling chain consists of a large number of often locally operating actors in the first steps of the chain—collection and separation and sorting (pre-processing)—while the number of actors in final metal recovery is limited. The latter operate on a global basis, sourcing material from all over the world to recover metals in a highly efficient and environmentally sound way, while leveraging the effects of economies of scale necessary for the high-tech processes.[27]

Electronic components, including end-of-life computers, printed circuit boards, light emitting diodes, capacitors, RF transmitters/receivers, phones, batteries, and lamps, use a high tonnage of valuable and precious metals, even though the contents per unit/device can be very low, simply because of the sheer number of units sold per year.[28] While electronic scrap recycling has been embraced globally and the use of technology is on the rise, the processing chain is neither fully optimized nor efficient in complete value recovery. Further optimization of precious metals recovery from mechanical pre-processing of e-scrap, as well as increased use of existing best available technology end-processing for final metal recovery of base and precious metals is necessary.[29,30,31] This will lead to quick wins in increasing the recovery of precious metals and other valuable metal resources, as well as averting the environmental impacts of substandard recycling processes.

Another important avenue in closing the loop is ensuring the collection of end-of-life electronics, for without collection, the entire recycling chain has no material to process. While highly efficient recycling processes for rechargeable batteries are operating on an industrial scale,[32,33] the main challenge is the actual mobilization and collection of the batteries. The recovery and recycling of these metals is essential for both economic and environmental reasons. Just as critical is the need for resource recovery and recycling of photovoltaics.[34,35] In this industry, the recycling technologies for metal recovery from a number of production wastes, e.g. CIGS scraps, germanium cuttings and CdTe residues, are already operational on an industrial scale.[36]

ENDNOTES

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3. Populations Without Electricity Access: IEA, *World Energy Outlook 2009*.
4. The Kyoto Protocol is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), aimed at fighting global warming. The Protocol was initially adopted on December 11, 1997 in Kyoto, Japan and entered into force on February 16, 2005. As of November 2009, 187 states had signed and ratified the protocol.
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VI

Human Resources

INTRODUCTION

The topic of human resources—specifically, the scientists and engineers who must be engaged to meet the world's sustainability challenges—was explored during the following keynote presentation:

> Diran Apelian, Howmet Professor of Engineering and Director, Metal Processing Institute, Worcester Polytechnic Institute
> *Human Capital Needs for Sustainable Development for the 21st Century: The Role of Engineers, Their Recruitment and Educational Imperatives.*

Because of their cross-cutting nature, the concepts that were presented infused the discussions in the workshop breakout sessions that eventually developed the other topics covered in this report.

A WORLD OF NEW OPPORTUNITY—AND CHALLENGES

Engineering education and the profession are confronting a challenging crossroads. Some see it as a crisis, while others view it as an opportunity for positioning the science and engineering community to better meet the challenges

Engineering Solutions for Sustainability, First Edition. American Institute of Mining, Metallurgical, and Petroleum Engineers.

of the 21st century. As Charles Dickens cited in the opening phrase of *A Tale of Two Cities*, "It was the best of times, it was the worst of times."

Globalization of the economy has amplified the impact of technology on modern societies in ways that could not have been predicted. The connectivity provided by the Internet has generated new markets for products and services, and has also made labor available that is often both educated and cheap. This is likely to have a profound impact on the distribution of wealth in both the developed and the developing part of the world and may, in particular, alter the socio-economic structure of countries where the general well-being of the population has been taken for granted. That education plays a role in the prosperity of nations is not debated, but many authors, like Landes,[1] argue that it is specifically the presence of both knowledge and know-how that determines how well off societies are. The education of engineers is, therefore, critical to every nation to ensure the prosperity of its citizens, based on the following premises:

- Knowledge and know-how determine how well off societies are compared to other societies.
- Standard of living hinges on the ability to educate a large number of sufficiently innovative engineers.
- Research and development spending fuels innovation.
- Creation of wealth is related to a nation's ability to make products that other nations want to purchase.

The modern professional identity of engineers emerged in the early eighteenth century with the establishment of the École Polytechnique in France and the founding of professional engineering societies in England. The current way of educating engineers, including the structure of the curriculum, was established by the early twentieth century. The last major shift in engineering education occurred in the United States more than half a century ago when the role of science in the educational program increased significantly.[2] Although some evolution has taken place since then, those changes have been relatively modest and the basic structure and course content of a modern engineering program is very familiar to someone educated in the sixties. Moreover, the engineering curricula developed in the West are the curricula being taught in developing countries, perhaps with more intensity.

The time for another major re-examination of engineering education is overdue.

That the world has changed in fundamental ways during the last decade or two is self-evident. Computers have fundamentally transformed the ability to deal with information and data. Society is rapidly moving toward a world where—for all practical purposes—people can *process information infinitely fast, store an infinite amount of data, and transmit data instantaneously*, to paraphrase a statement made by Henry B. Schacht, the first chairman and chief executive officer (CEO) of Lucent Technologies Inc. in his commencement speech at Worcester Polytechnic Institute (WPI) in 2001. As a result of the emergence of the Internet, knowledge has been "communalized." Everybody has access to information about anything and—perhaps equally important—knowledge is no longer "owned" by the experts. Computers have also empowered the average man and woman to create products that previously required large corporations with significant resources. In many aspects of digital media, if something can be imagined, it can be created. As computer speed and software advances, this trend will continue until, in the not-so-distant future, a high school student with a laptop will have the capability to create a full-length movie with virtual actors of the quality currently only produced by major filmmakers. The same transformation is likely to happen to the creation of engineered artifacts, although the timeframe may be somewhat longer. Ordering components online and receiving them in the mail is now part of everyday life, and e-manufacturing—where the customer sends an electronic description of a part to a manufacturer that makes it and mails it back—is emerging.

The globalization of the world economy affects everyone. The motion of labor-intensive, but low-skill industries, to countries with low labor costs is not new. Such transfer has been largely responsible for the low cost and abundance of most manufactured goods. Today, however, the rise in education in nations where salaries are low, coupled with the connectivity that makes this cheap and educated talent widely available, are gradually changing the nature of jobs worldwide.

The mechanization of labor and advances in transportation, taking place during the last century, in tandem with the more recent information revolution and globalization of the economy, has brought unprecedented opportunities and challenges. On the positive side is that the increase in material wealth makes it—for the first time in history—realistic to talk about eliminating extreme poverty.[3] On the negative side is the possibility—for the first time in history—that human consumption of materials and energy may irreversibly damage the entire global environment.[4] Engineering in the new world is, therefore, both a daunting and an exciting undertaking.

BUILDING "LEARNING ORGANIZATIONS"

To compete in the "knowledge era," organizations have to be capable of learning and embracing a culture of learning in order to improve products and services continuously. Learning organizations are those where information and knowledge flow freely throughout the institution, not just from the top down. In the learning organization, every worker and every work site is a listening post for new ideas and product improvements. The mass production organizations of large corporations, big government, and higher education do not have that kind of sensitivity. The dilemma is that by merely installing flexible technology and flexible work systems and giving workers the autonomy to exploit the new flexibility have proved to be insufficient. Empowering people without enabling them with skills necessary to use their new autonomy is really a hollow exercise.

In a global economy driven by relentless innovation, what a company knows has become as important as what it produces. Success in the marketplace is increasingly linked to an organization's ability to manage and leverage its intellectual capital, the intangible and often invisible assets—knowledge and competence of people, intellectual property, and information systems—that do not show up directly on the bottom line, but are just as valuable as financial assets.

The dramatic changes in today's economy are fueled by technology, global competition, and deregulation. These forces are likely to accelerate in the years ahead and cannot be ignored or legislated out of existence. They require a new way of working, a new paradigm of the workplace, and investment in society's most important capital—its human assets.

Education models and paradigms for the engineering profession need to address these critical issues.

THE ENGINEER OF THE 21ST CENTURY

Engineering education has changed in the past to adjust to the needs of society. The evolution must continue to address current and future needs. With many approximations and generous error bars, the major trends in engineering education can be summarized by the following classifications.[5]

19th Century and First Half of the 20th Century: The Professional Engineer

As engineering became a distinct profession, early engineering programs focused on providing their graduates with considerable hands-on training. However, the role of science and mathematical modeling slowly increased and gained acceptance.

Second Half of the 20th Century: The Scientific Engineer

Technological progress, including the successful harnessing of nuclear energy, as well as geopolitical realities as materialized by *Sputnik*, drove home the need for engineers to be well-versed in science and mathematics and the engineering curriculum adjusted. This structure has, to a large degree, continued until the present time, although "design" content increased slowly. In the early nineties, it was clear that more than science was needed and many schools started to emphasize non-technical professional skills, such as teamwork and communications.

The 21st Century: The Entrepreneurial/Enterprising Engineer

The rapid changes that the world is currently going through, coupled with changes in engineering education that started to take place in the nineties, are likely to result in an extensive re-engineering of engineering education. While the new structure will, almost certainly, continue to be based on a solid preparation in mathematics and sciences, it is likely to emphasize the professional role of the engineer, and then demand new qualifications suited for the new world order.

It is impossible to say what the engineering profession will look like a hundred years from now. The intense discussions that are currently taking place[6,7,8,9,10] among leaders of the profession and educators suggest that innovation will be a central theme. The premise is that skill is a commodity and that routine engineering services will be available from low cost providers that can and will be located anywhere in the world. Engineering education, therefore, needs to add value beyond just teaching skills. This does not mean that future engineers will not possess skills. Quite the contrary, they will have to be more technically proficient than those today who practice narrowly defined tasks. This new breed of engineers must constantly be able to gather information and decide on a course of action, including what tools are needed for a given task. The technical skills, the people skills, and the innovation required of the future engineer can be summarized—with only modest exaggerations—as follows:

- ***Know Everything:*** Find information about anything quickly and know how to evaluate and use the information. The entrepreneurial engineer has the ability to transform information into knowledge.
- ***Do Anything:*** Understand engineering basics to the degree that he or she can quickly assess what needs to be done, can acquire the necessary tools, and use these tools proficiently.
- ***Work with Anybody, Anywhere:*** Possess the communication skills, team skills, and understanding of global and current issues necessary to work effectively with other people.
- ***Imagine and Make the Imagination a Reality:*** Exhibit the entrepreneurial spirit, the imagination, and the managerial skills to identify needs, come up with new solutions, and see them through.

Achieving the first goal—knowing everything—is relatively easy. Search the Internet for any concept and an abundance of information can generally be accessed in a matter of seconds. The communalization of knowledge, mentioned earlier in this chapter, makes it essential that the professional engineer be able to judge the quality of the information that he or she acquires. Teaching how to deal with this vast array of available information and to judge its relevance and quality will be the educational challenge.

As to the second goal, engineers have always learned as they tackle new challenges. The explosion in the availability of tools, however, suggests that engineering educators must rethink how students are prepared in the foundation of their disciplines. Computer programs that do virtually anything, from conducting simple calculations, to simulating complex systems, to designing a complete engineered artifact, empower the modern engineer to do more than his or her predecessors could ever imagine. However, these tools not only require that the engineer knows how to use them. Engineers must also possess the ability to assess what tool is appropriate for a given task and then be able to evaluate the result in a critical way. The importance of common sense will be even greater when design and analysis are done exclusively on the computer. While teaching engineering students how the physical world works is at the core of engineering education today, re-examining how to teach the fundamentals of engineering science to students is needed. Knowing the scale of phenomena and the distribution of knowledge over multi-scales are critical attributes.

In addition to the changes in the technical skills engineers must possess, their non-technical professional skills must be suited for the modern way of doing engineering. Considerable progress has already been achieved in the United States to make communication in the broadest sense an integral part of the engineering curriculum.[3,11] Most programs now require their graduates to exhibit proficiency in oral and written communications and to be able to work on diverse teams. Engineering, possibly more than most professions, requires accurate and efficient communications. In today's global society, the ability to communicate takes on a much broader meaning. Not only are engineers frequently working on products that will be made in a different country and marketed to people of different cultures, but product engineering is increasingly done by teams consisting of people located in different nations and with diverse cultural backgrounds. Such interactions obviously present enormous potential for misunderstanding and conflicts. As illustrated by Ron Zarella, chief executive officer of Bausch and Lomb, during a globalization workshop at WPI:

> "We make a product called Interplak. The electromechanical design for this home plaque-removal device is done in Germany and Japan. The batteries are supplied from Japan, the motors are built in the People's Republic of China, the charging base is made in Hong Kong, the precision molded plastic pieces are manufactured in Atlanta, the brush head is made in Ohio, and the final assembly is done in Mexico."

Preparing young engineers to work in a worldwide community is no longer something that engineering schools can treat as an extracurricular activity, available only to those who have the time and resources to spend an extra semester abroad. Every student must now develop the attitudes and skills necessary to function globally, right from the time they first enter the workforce.

Finally, the engineer of the future must be able to do more than just perform technical tasks. There have always been extraordinary engineers who have had the imagination, vision, dedication, and endurance to change the world. Those who do not possess these traits have, in the past, been able to make a living performing routine engineering tasks. The young engineers of the future must, on the other hand, all be extraordinary. They will not be able to enjoy the comfort of well-paid jobs where routine tasks are performed more or less unchanged year after year. More and more, the engineer of the future will be responsible for creating new ideas and solutions and seeing them through. Innovation has already been identified as one of the most important factors in the future prosperity of both nations and individuals.[1,9,10,12] However, not only must the engineer innovate, he or she must be able to help the innovation become a reality. The education of the engineers of the future must prepare them to see new opportunities, as well as to give them the skills needed to marshal the resources to realize their ideas.

SOCIETAL ISSUES AND ENGINEERING AS AN ENABLING PROFESSION

Innovation, creativity, and entrepreneurship, as well as the societal context of engineering, ought to be central to the new engineering curriculum. Linkages between the engineering profession and societal needs ought to be explicitly articulated, as this will inspire and attract students to the profession.

Engineers solve problems, make things happen, and enhance the quality of life on this planet. This has been a constant. What has changed over time have been the needs of society and how engineers have responded to those needs. During the late 1800s, engineers are credited with profound innovations and inventions to meet the needs of the Industrial Revolution. Engineers made things, built bridges, and established mass production. In so doing, they transformed the Western world from an agrarian society to an industrial one. In the 1900s, with the advances in solid-state physics and the understanding of the atomic structure, engineers learned science and became scientists because they needed the science base to solve the problems facing society. This included everything from defense technologies to the development of the semiconductor and the electronic materials revolution, among many other inventions.

For the 21st century, engineers need to be enterprising and must lead to address the needs of a global society. With 20 percent of the world population living in absolute poverty, 18 percent of the population lacking access to safe drinking water, 40 percent having no access to sanitation, energy consumption increasing at a higher rate than population growth, and healthcare needs and expectations out pacing health care delivery, there is no doubt that the engineer of the future needs to be a social scientist, as well as an enterprising leader to meet these needs.

At present, public perception of engineers and engineering does not reflect reality. It is a fact that many top industrialists and successful CEOs are engineers. Surgeons and physicians have a first degree in engineering, as well as bankers and financial tycoons. There is no limit to what engineers can do. The image of engineering needs to reflect the boundless opportunities and lifestyles that await those who pursue this course of study.

In the early 1900s, engineering educators did not pay attention to management issues and essentially allowed management to leave the engineering curriculum. This was a mistake. Interestingly, the mathematician Laplace, who was one of the founding directors of the École Polytechnique, in France, said, "The École Polytechnique should aim to produce young people destined to form the elite of the nation and to occupy high posts in the state."[13] This was the view of the Polytéchnicien back in 1794. Perhaps it is time to revert back to this image and engage young people about the leadership opportunities that engineering offers. Also, the message regarding engineering as a career path is fragmented, as articulated by civil engineers, mechanical engineers, metallurgists and materials scientists and engineers, electrical engineers, petroleum engineers, and chemical engineers. To be effective in presenting the full measure of all that engineering offers, as well as its impact on society, a strong, unified message is needed.

During the next century, the world population will increase to about 9.5 billion people (from 6.5 billion) and much of this growth will occur in developing nations. Societal needs regarding energy resources, transportation, housing needs, packaging materials/recycling, and biomaterials and health will only escalate. The challenges presented for a sustainable development of the globe are immense. This is precisely why engineering should be so attractive to the next generation. The case needs to be made that engineering is an enabling profession, with the connection between engineering and sustainable development of the globe made explicit.

To educate engineers ready to face the challenge of ensuring a sustainable world for all people, the profound changes that have transformed society in the last few decades must be embraced and progress needs to be made to ensure that the engineering profession is a social enterprise. There is a need to educate engineers that are more akin to the French Polytéchnicien model: professionals who understand the societal context of their work, have an understanding of the human dimension around the globe, coupled with innovation and creativity. The challenge is daunting, both in academia as well as in industry. It will be appropriate to conclude by remembering what the Red Queen says to Alice in *Through the Looking Glass*: "Now, here, you see, it takes all the running you can do to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

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VII

Linking Technologies to Resources

Before society can make informed decisions about the technologies it will deploy to sustainably meet its needs, a more comprehensive grasp of the dynamics between primary and secondary raw material supply is required, as well as a better appreciation of the complex interrelationships between a viable energy supply mix and the production of these raw materials. Likewise, a deeper understanding is needed of the suite of engineering advancements that will depend on these raw materials. The development of enhanced, accurate insight encompassing the many variables related to supply, demand, and utilization of the world's precious resources is an issue that cross cuts all of the sectors examined in this report—and one that must be addressed so that effective policy mechanisms can be deployed that will incentivize society's transition to a sustainable future.

As an initial step to addressing this need, a Technology and Resources Matrix (Figure 1 on pages 62–63) was prepared in conjunction with the *Engineering Solutions for Sustainability: Materials and Resources* international workshop to correct common misconceptions about reserves, resources, and recyclability, and to promote societal understanding about the complexity of its raw material supply. Input was provided by workshop delegates, as well as other mineral, material, and energy industry professionals over the year following the workshop, held July 22–24, 2009. This collaborative effort was made

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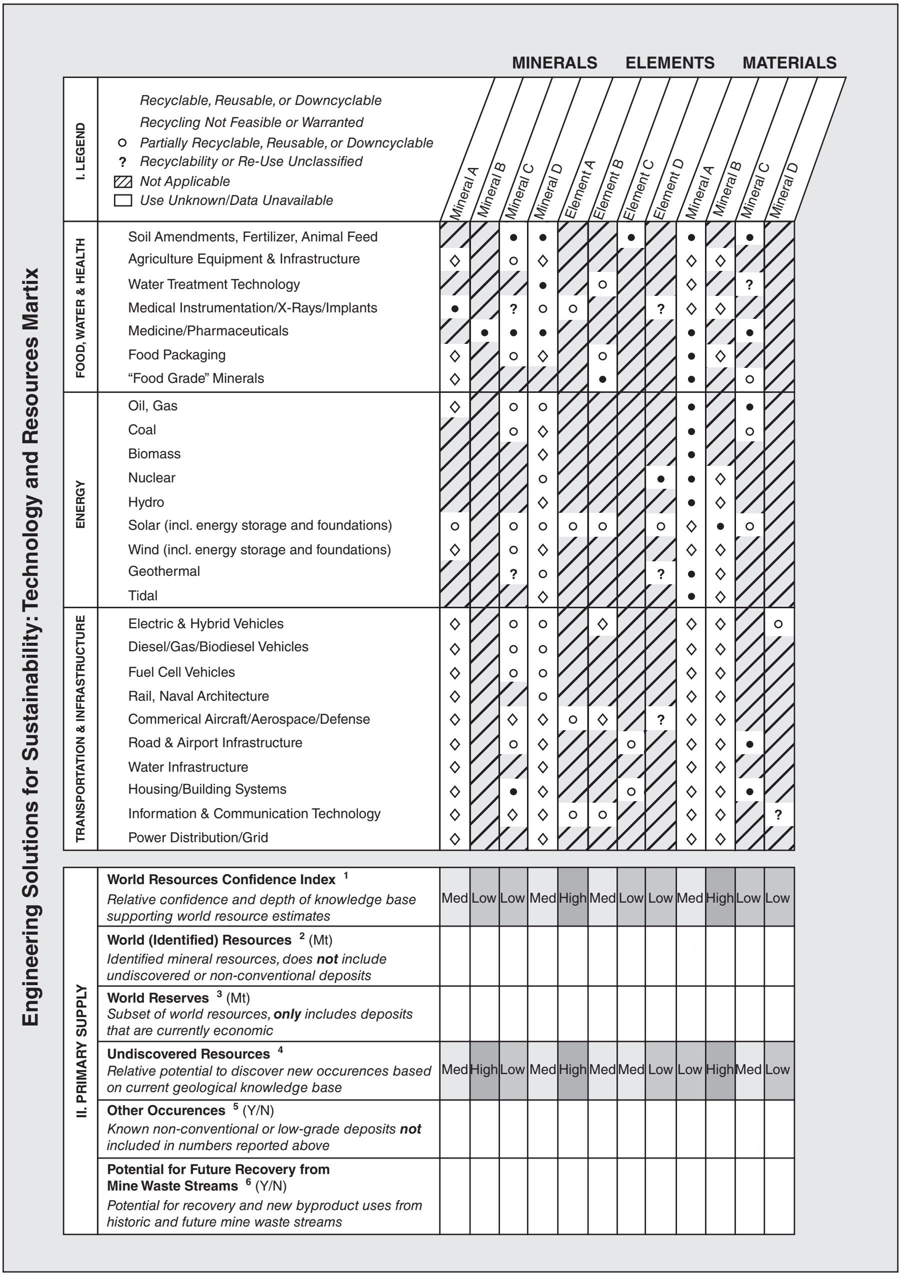

Engineering Solutions for Sustainability: Technology and Resources Matrix

I. LEGEND

Recyclable, Reusable, or Downcyclable
Recycling Not Feasible or Warranted
○ *Partially Recyclable, Reusable, or Downcyclable*
? *Recyclability or Re-Use Unclassified*
▨ *Not Applicable*
☐ *Use Unknown/Data Unavailable*

		MINERALS				ELEMENTS				MATERIALS			
		Mineral A	Mineral B	Mineral C	Mineral D	Element A	Element B	Element C	Element D	Mineral A	Mineral B	Mineral C	Mineral D
FOOD, WATER & HEALTH	Soil Amendments, Fertilizer, Animal Feed	▨	▨	●	●	▨	▨	●	▨	●	▨	●	▨
	Agriculture Equipment & Infrastructure	◇	▨	○	◇	▨	▨	▨	▨	◇	◇	▨	▨
	Water Treatment Technology	▨	▨	▨	●	▨	○	▨	▨	◇	▨	?	▨
	Medical Instrumentation/X-Rays/Implants	●	▨	?	○	○	▨	▨	?	◇	◇	▨	▨
	Medicine/Pharmaceuticals	▨	●	●	●	▨	▨	▨	▨	●	▨	●	▨
	Food Packaging	◇	▨	○	◇	▨	○	▨	▨	●	◇	▨	▨
	“Food Grade” Minerals	◇	▨	▨	▨	▨	●	▨	▨	●	▨	○	▨
ENERGY	Oil, Gas	◇	▨	○	○	▨	▨	▨	▨	●	▨	●	▨
	Coal	▨	▨	○	◇	▨	▨	▨	▨	●	▨	○	▨
	Biomass	▨	▨	▨	◇	▨	▨	▨	▨	●	▨	▨	▨
	Nuclear	▨	▨	▨	○	▨	▨	▨	●	●	◇	▨	▨
	Hydro	▨	▨	▨	◇	▨	▨	▨	▨	●	◇	▨	▨
	Solar (incl. energy storage and foundations)	○	▨	○	○	○	○	▨	○	◇	●	○	▨
	Wind (incl. energy storage and foundations)	◇	▨	○	◇	▨	▨	▨	▨	◇	◇	▨	▨
	Geothermal	▨	▨	?	○	▨	▨	▨	?	●	◇	▨	▨
	Tidal	▨	▨	▨	◇	▨	▨	▨	▨	●	◇	▨	▨
TRANSPORTATION & INFRASTRUCTURE	Electric & Hybrid Vehicles	◇	▨	○	○	▨	◇	▨	▨	◇	◇	▨	○
	Diesel/Gas/Biodiesel Vehicles	◇	▨	○	○	▨	▨	▨	▨	◇	◇	▨	▨
	Fuel Cell Vehicles	◇	▨	○	○	▨	▨	▨	▨	◇	◇	▨	▨
	Rail, Naval Architecture	◇	▨	▨	○	▨	▨	▨	▨	◇	◇	▨	▨
	Commerical Aircraft/Aerospace/Defense	◇	▨	◇	◇	○	◇	▨	?	◇	◇	▨	▨
	Road & Airport Infrastructure	◇	▨	○	◇	▨	▨	○	▨	◇	◇	●	▨
	Water Infrastructure	◇	▨	▨	◇	▨	▨	▨	▨	◇	◇	▨	▨
	Housing/Building Systems	◇	▨	●	◇	▨	▨	○	▨	◇	◇	●	▨
	Information & Communication Technology	◇	▨	◇	◇	○	○	▨	▨	◇	◇	▨	?
	Power Distribution/Grid	◇	▨	▨	◇	▨	▨	▨	▨	◇	◇	▨	▨

II. PRIMARY SUPPLY	**World Resources Confidence Index** [1] *Relative confidence and depth of knowledge base supporting world resource estimates*	Med	Low	Low	Med	High	Med	Low	Low	Med	High	Low	Low
	World (Identified) Resources [2] (Mt) *Identified mineral resources, does **not** include undiscovered or non-conventional deposits*												
	World Reserves [3] (Mt) *Subset of world resources, **only** includes deposits that are currently economic*												
	Undiscovered Resources [4] *Relative potential to discover new occurences based on current geological knowledge base*	Med	High	Low	Med	High	Med	Med	Low	Low	High	Med	Low
	Other Occurences [5] (Y/N) *Known non-conventional or low-grade deposits **not** included in numbers reported above*												
	Potential for Future Recovery from Mine Waste Streams [6] (Y/N) *Potential for recovery and new byproduct uses from historic and future mine waste streams*												

***Figure 1:** Technology and Resources Matrix*

II. SECONDARY SUPPLY	**Is Recycling Feasible in Some Applications?** [7] (Y/N) *Using current techology, economics, and infrastructure*												
	Old Scrap Recycling for the U.S. [8] *Post-consumer waste available as % of apparent supply*												
	New Scrap Recycling for the U.S. [9] *Manufacturing waste available as % of apparent supply*												
	% of U.S. Supply Met by Recycled Inputs [10] *Includes new and old scrap in apparent supply*												
	% Post-Consumer Sourced Material [11] *An estimate of recycled consumer scrap vs primary material in new products*												
	Global Recycling Rates [12] (%)												

1 A ranking of the relative degree of our current confidence and depth of knowledge base to support current world resource estimates.
2 Resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. (USGS Mineral Commodity Summaries 2010; United Nations Framework Classification for Fossil Energy and Mineral Resources 2009)
3 That part of the reserve base which could be economically extracted or produced. (USGS Mineral Commodity Summaries 2010; United Nations Framework Classification for Fossil Energy and Mineral Resources 2009)
4 Resources only postulated to exist. (USGS Mineral Commodity Summaries 2010; United Nations Framework Classification Fossil Energy and Mineral Resources 2009)
5 Materials that are too low grade or for other other reasons are not considered potentially economic. (USGS Mineral Commodity Summaries 2010; United Nations Framework Classification for Fossil Energy and Mineral Resources 2009)
6 Waste streams with potential to become available for recovery through changes in project economics and/or research and development of new mining and processing technologies.
7 Recycling or re-use is feasible in intermediate and/or post-consumer (end-of-life) production stages using available technology, existing recycling infrastructure, and economics.
8 Old scrap as percent of supply. (USGS Circular 1196. Flow Studies for Recycling Metal Commodities in the United States; USGS Minerals Yearbook; United Nations Framework Classification for Fossil Energy and Mineral Resources 2009)
9 New scrap as percent of supply. (USGS Circular 1196. Flow Studies for Recycling Metal Commodities in the United States; USGS Minerals Yearbook; United Nations Framework Classification for Fossil Energy and Mineral Resources 2009)
10 Percent of U.S. supply met by new and old scrap as defined in (8) and (9) above.
11 Caveat: The data required to make such estimates will be difficult to obtain, and although some components may be available, the estimate will be lacking in confidence.
12 The definition of this metric and the potential sources of data are still under review. Suggestions welcome.

Figure 1: *(Continued)*

possible by contributions of mineral, energy, materials, and recycling experts representing the following professional societies and organizations:

- United States Geological Survey (USGS)
- Society for Mining, Metallurgy and Exploration (SME)
- The Minerals, Metals & Materials Society (TMS)
- Association for Iron and Steel Technology (AIST)
- American Society of Civil Engineers (ASCE)
- Society of Petroleum Engineers (SPE)
- Mining and Metallurgical Society of America (MMSA)
- Northwest Mining Association (NWMA)

CLASSIFICATION METHODOLOGY, CRITERIA, AND DEFINITIONS

Based on discussions within each of the workshop's thematic areas, 26 specific categories of end-use were selected. Experts from the minerals, metals, and materials community were then consulted to identify if and to what extent each mineral, element or material had any direct or indirect application in the category of end-use.

A mineral (fuel and non-fuel), element or material was classified in the matrix if its use was identified in any aspect (direct or indirect) of the respective end-use category. The relative recyclability, down-cyclability or potential for reuse was then classified using the definitions:

- ***Recyclable or Reusable Application:*** Recycling is feasible in intermediate and post-consumer (end-of-life) recycling stages using available technology, existing recycling infrastructure, and economics. The classification also includes minerals, metals or materials that have the potential to be reused in a similar or other application.
- ***Recycling Not Feasible or Warranted:*** For many industrial minerals and metals, recycling is not feasible due to the nature of the use. The properties (e.g., physical, chemical, presence of trace impurities, etc.) of certain metals and materials do not allow for recycling with existing technology. In addition, if significant volumes of end-of-life products are not yet available for post-consumer recycling, commercial technologies and recycling infrastructure have not yet been developed, so the mineral, material or metals are not currently recyclable in the respective end-use category.
- ***Partially Recyclable or Re-Usable:*** This classification is used if some, but not all, applications or components of technologies falling within the end-use category are amenable to recycling. Although recycling technologies may be commercially deployed by some companies, the presence of trace impurities, other quality specifications or logistical constraints limit the widespread application of recycling in the respective end-use category.
- ***Recyclability Unclassified:*** End use is identified, but recyclability is unknown or has not been classified.
- ***Not Applicable:*** Mineral, metal, or material is not applicable to the respective end-use category.

The Technology and Resources Matrix also incorporates information that summarizes current understanding of primary and secondary raw material supply compiled from available public statistics. The "Primary Supply" section presented on the Matrix includes estimates for known global resources, reserves, and a broad assessment of current understanding of undiscovered and non-conventional resources. The "Secondary Supply" section offers a summary of recycling and resource recovery rates. The relative recyclability and potential for reuse of each mineral, element, and material across these varying end-uses were classified using the footnoted definitions presented at the end of the Matrix. It is important to note that the absence of information is just as telling. This serves as an indication of where additional information, research, and collaboration between the private, public, and civil sectors could be of great benefit. Suggestions and contributions are welcome.

DIRECTION FOR FUTURE OPPORTUNITY

Presented in draft form, the Technology and Resources Matrix is a communication tool that offers an overview of the relative roles that primary (virgin ore) and secondary (scrap) materials currently play in meeting society's demand within the context of the technologies and end-uses discussed during the workshop. This integrative matrix will provide some guidance on the greatest opportunities for additional research and policy action in each respective discipline. A collaborative effort among multiple professional societies in the engineering and science community continues with the aim to provide a more comprehensive online version of this communication tool.

VIII

The Path Forward

Ongoing improvement in the quality of life, fueled by technological advancement, has been a driver in human history since primitive times. In the last century, however, the pace of this progress is at risk of outstripping the Earth's ability to sustain the needs and expectations of those who live on it. Key to addressing these challenges is early stage development of sound and sustainable engineering concepts that are implemented with awareness and sensitivity to their potential impacts on other sectors of society. At the same time, the availability of the materials and resources these engineering solutions will require is contingent upon the collective decisions of industry, national governments, and local authorities, as well as Non-Governmental Organizations (NGOs) and civil society.

The complexity of these issues, coupled with the fragility of the resources and social systems at their epicenter, requires that all parties involved transcend their individual domains of expertise and look to create synergies across sectors, industries, disciplines, and political interests. The considerations and unifying themes identified through the *Engineering Solutions for Sustainability: Materials and Resources* workshop offer a framework for the cultivation of these types of efforts. In addition, this report documents an array of key technologies within each sector examined by the workshop delegates that could make a measurable difference in managing the Earth's finite resources more sustainably for the benefit of all its people. (A summary of these sector-specific advances is presented in Appendix C on page 77.)

Engineering Solutions for Sustainability, First Edition. American Institute of Mining, Metallurgical, and Petroleum Engineers.

A goal of the *Engineering Solutions for Sustainability: Materials and Resources* workshop was to begin defining a path forward for the engineering community to bring its collective wisdom and expertise to bear on the tremendous pressures weighing on the world's resource requirements, environment, and social systems. While general priorities and interdependencies have been surfaced through this process, it is critical that the momentum continue in other forums focused on developing and deploying sustainable and resilient engineering systems. The resources and tools presented in this report have laid the foundation for a productive interdisciplinary dialogue. The challenge is now put to other professional societies, educators, industry leaders, and policy makers to build upon it.

Appendix A

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Kamel Bennaceur, Schlumberger, France
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Serge Rueff, Switzerland
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Carol Russell, US Environmental Protection Agency, USA
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Deborah Shields, Colorado State University, USA
Francis Slakey, American Physical Society, USA
Mark Smith, Molycorp Minerals LLC, USA
Jack Spencer, NTSB, USA
Dan Stevens, Lifewater International, USA
Priscilla Tamez, ITESM, Mexico
Alan Taub, General Motors Corporation, USA
Brough Turner, Ashtonbrooke, USA
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Darin Zehrung, Path, USA
Julie Zimmerman, Yale University, USA
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Appendix B

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MINERALS SECTOR REFERENCES AND GUIDANCE DOCUMENTS

Editor's Note: *The following organizations or multi-stakeholder initiatives have generated considerable guidance on mining and sustainable development which is too numerous to list in detail. However, most of this guidance can be retrieved from the respective digital libraries of the websites summarized below.*

- Since 2001, the International Council of Mining Metals (ICMM), has published considerable guidance on mining and sustainable development spanning topics ranging from biodiversity, human rights, socio-economic development, stakeholder engagement, health and safety, mine closure and legacy issues, materials stewardship, artisanal mining and indigenous peoples. Over 200 research publications, toolkits and guidance documents and fact sheets can be downloaded from the organizations' website (www.icmm.com).
- The Mining, Minerals and Sustainable Development (MMSD) project was an independent, multi-disciplinary research project undertaken from 2000-2002 that explored how the mining and minerals sector could contribute to society's global transition to sustainable development. All working papers, final reports, bulletins, and workshop notes are available at the International Institute for Environment and Development (IIED) website (http://www.iied.org/sustainable-markets/key-issues/business-and-sustainable-development/mining-minerals-and-sustainable-development).
- The Mining Certification Evaluation Project (MCEP), initiated in 2002, was a three-year research project that investigated the feasibility of developing a social and environmental performance certification for the minerals industry. The project history, final reports, working group notes, articles, public comments and other supporting documents are being maintained by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (http://www.minerals.csiro.au/sd/SD_MCEP.htm).

- Beginning in 2003, an international conference series known as Sustainable Development Indicators in the Minerals Industry (SDIMI) was launched and the Milos Declaration was adopted and endorsed by the leading professional, scientific and engineering organizations in the minerals community. Topics and themes covered include sustainability assessments, life-cycle assessment, product stewardship, reducing GHG footprints, community impacts and overcoming barriers to uptake of sustainability innovations. Proceedings for each event are available through http://www.sdimi.org/sdimi_past.htm.
- The Green Mining Initiative is a research program recently created by Natural Resources Canada to help the Canadian mining industry address its environmental issues and to find alternatives to existing technologies. The research focus consists of four pillars: footprint reduction, innovation in waste management, ecosystem risk management, and mine closure and rehabilitation. (http://www.nrcan.gc.ca/mms-smm/nmw-smc/gmi-gmi-eng.htm)
- The International Cyanide Management Code (ICMI) is a voluntary gold industry program promoting responsible management of cyanide (www.cyanidecode.org).
- The International Network for Acid Prevention is an organization of international mining companies seeking responsible mineral development through the prevention of acid rock drainage (ARD) and metal leaching. The group recently developed the Global Acid Rock Drainage (GARD) Guide, a world-wide reference document of best practices in the field of ARD (http://www.inap.com.au/GARDGuide.htm).
- The National Orphaned/Abandoned Mines Initiative (NOAMI) is an ongoing multi-stakeholder dialogue between various Canadian jurisdictions, industry, aboriginal communities and non-profit organizations focused on resolving abandoned mine issues. Considerable guidance, toolkits and case studies have been developed in each of the following topical areas: Information gathering, Community Involvement, Legislative and Institutional Barriers to Collaboration, Funding Approaches and Jurisdictional Legislative Reviews (www.abandoned-mines.org).
- In addition to developing the Towards Sustainable Mining reporting framework, the Mining Association of Canada has prepared the comprehensive Energy and GHG Emissions Management Guidance Document for the mining sector (www.mining.ca).

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Appendix C

Summary of Sector-Specific Advances

The following outlines major advances identified within each sector examined by the delegates convened for the *Engineering Solutions for Sustainability: Materials and Resources* international workshop. Common themes that emerged as action items across the sectors include practical and reliable tools/models for measurement of water, energy/carbon, materials impact and their interactions, as well as technologies/approaches for systemic reduction of the human footprint. Further research and development of these advances is recommended to address pressing materials and resources sustainability issues.

Human Needs (Water, Food, and Health):
Measurement of water footprint; genetic engineering with adequate built-in diversity; antibiotics free-meat products.

Infrastructure:
Low cost sensors and sensor fusion; active/responsive materials (e.g., shape memory alloys) with a greater range of activation stimuli (e.g., temperatures); engineered nanomaterials and composites; advanced batteries; infrastructure for refueling/recharging electric and hydrogen vehicles; high-energy density, sustainable aircraft fuels; alternative materials, resources, and processes to provide resilience for price increases and materials shortages.

Energy:
Improved efficiency fossil-fuel power generation through the use of ultra-supercritical steam-cycle plants, integrated gasification combined cycle coal

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plants, and natural gas combined cycle units; carbon dioxide (CO2) capture and storage; high temperature rated materials for concentrated solar power receivers; advance modeling techniques; improved turbines and rotors, new offshore concepts and high voltage DC cabling technologies for wind energy; more efficient biomass conversion technologies; extraction of geothermal energy from depths of 3km to 10km; equipment design for high temperature operation; nuclear reactors with reduced utilization, as well as alternatives to, uranium; smart grids that encompass integration of power conversion and storage; lightweight materials for energy storage.

Minerals, Metals, and Materials Extraction:
Development of mining and processing technologies that minimize utilization of scarce, but renewable, resources such as clean water, clean air, and energy; reliable management of harmful and hazardous mined and processed materials for which no alternative uses currently exist; integrated landscape management to restore mined lands to functioning ecosystems and/or transition and regenerate them to other socially and economically beneficial uses; integration of health and safety (for both workers and communities) in all aspects of design and implementation.

Resource Recovery and Recycling:
Establish an index for recyclability; strategies for tagging materials in order to enhance their recyclability; in-line, real-time, operator-friendly, continuous non-contact sensor and methods for waste material separation (e.g., scrap/chips); methods to produce high-quality metal (similar to primary quality) from mixed scrap.

Human Resources:
Develop engineering education systems (training materials and protocols) that embrace a more holistic design paradigm in which engineering “performance” must evolve from function, cost, quality, safety, environment, human health, and social well-being. Engineering education must also recognize and appreciate the need for transparent governance, continual stakeholder engagement, and engineering design systems that endure over the entire life cycle of the technologies and materials that society deploys.