

# Chapter 9

## Implications: Convergence of Knowledge and Technology for a Sustainable Society

**Mamadou Diallo, Bruce Tonn, Pedro Alvarez, Philippe Bardet, Ken Chong, David Feldman, Roop Mahajan, Norman Scott, Robert G. Urban, and Eli Yablonovitch**

In October 2011, the world population reached seven billion (Coleman [2011](#)). Several scenarios of world population growth based on projections by the United Nations (UN) and the United States Census Bureau (Wikipedia Commons [2012](#)) estimate that the world population will reach eight billion to ten billion by 2050. The global challenges facing the world are complex and involve multiple

---

Corresponding editors M.C. Roco ([mroco@nsf.gov](mailto:mroco@nsf.gov)) and W.S. Bainbridge ([wbainbri@nsf.gov](mailto:wbainbri@nsf.gov)).

M. Diallo

California Institute of Technology, Pasadena, CA, USA

Korea Advanced Institute of Science and Technology, Daejeon, South Korea

B. Tonn

University of Tennessee, Knoxville, TN, USA

P. Alvarez

Rice University, Houston, TX, USA

P. Bardet

George Washington University, Washington, DC, USA

K. Chong

National Institute of Standards and Technology, Gaithersburg, MD, USA

D. Feldman

University of California, Irvine, CA, USA

R. Mahajan

Virginia Polytechnic Institute and State University, Blacksburg, USA

N. Scott

Cornell University, Ithaca, NY, USA

R.G. Urban

Johnson & Johnson Boston Innovation Center, Cambridge, MA, USA

E. Yablonovitch

University of California, Berkeley, Berkeley, CA, USA

interdependent areas. Every human being requires food, water, energy, shelter, transportation, healthcare, and employment to live and prosper on Earth. A great challenge facing the world in the twenty-first century is to continue to provide better living conditions to all people while minimizing the impact of human activities on the global environment. The United Nations 1987 World Commission on Environment and Development, commonly referred to as the Brundtland Commission, defined “sustainable development” as that “which meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland 1987). The commission called the three pillars of sustainability social, economic, and environment—suggesting that sustainability requires convergence of all three.

This chapter discusses the convergence of knowledge, technology and society (CKTS) for ensuring a sustainable society and a healthy, secure, and peaceful world. The focus is on sustainable solutions to our global problems, as the world’s population continues to grow and as demands for basic commodities (e.g., food, water, and energy); finished goods (e.g., cars, airplanes, and cell phones); services (e.g., shelter, transportation, and healthcare); employment, and better living standards continue to increase in the next 20 years.

## 9.1 Vision

### 9.1.1 *Changes in the Vision over the Past Decade*

During the last 10 years, (1) population growth; (2) the demand and sustainable supply of energy, clean water, food, and critical materials; and (3) global climate change have emerged as being among the most critical problems facing society and the global economy in the twenty-first century (Diallo and Brinker 2011).

During the last decade, significant progress has been made in information and communication technologies (ICT). Several new ICT devices such as smart phones, e-pads, and other computing and communication devices have been developed. Such devices are using an increasing amount of energy and critical metals, and new methods are underway to reduce consumption of energy in electronic devices and to utilize less critical metals or replace them with nanostructured materials based on earth-abundant elements.

The emergence of industrial ecology as a well-established science is another important development of the last 10–20 years. Industrial ecology has provided new tools for assessing and minimizing the impact of industrial activities on the environment; these tools include (1) *material flow analysis* (MFA), (2) *life-cycle analysis* (LCA) and (3) *design for environment* (DFE) (den Hond 2000). Advances in earth-systems science are also providing new tools to probe the impact of human activities on Earth’s climate and ecosystems (see Chap. 3 of this book). During the

last 20 years, a consensus has gradually emerged that human activities have become the main drivers of global environmental change (IPCC 2007a; Rapport 2007; Rockström et al. 2009a, b). Although Earth has experienced many cycles of significant environmental change, the planet's environment has been stable during the past 10,000 years, commonly referred to as the Holocene period (Zalasiewicz et al. 2010). This stability is now threatened as the world's population and demands and competition for basic commodities, finished goods, and services continue to increase in the foreseeable future (Moyo 2012).

A group of investigators from the Stockholm Resilience Center led by Johan Rockström have argued that human activities could put the "Earth System" outside a stable state, with significant or catastrophic consequences. Rockström et al. (2009a, b) subsequently proposed the concept of "planetary boundaries" (PB) as a unifying framework for (1) describing the impact of human activities on the environment and (2) determining a "safe operating space for humanity with respect to the functioning of the Earth System" (Rockström et al. 2009b). They suggested planetary boundaries for nine global, regional, and local environmental processes, as shown in Table 9.1.

### 9.1.2 *The Vision for the Next Decade*

The Brundtland Commission's definition of sustainability, the planetary boundaries concept, and the MFA, LCA, and DFE tools, taken together, provide an integrated and coherent framework for addressing our global needs for basic commodities, finished goods, services, decent employment, and better living standards, while minimizing the impact of human activities on Earth's climate and ecosystems as the world population reaches eight to ten billion by 2050. This chapter focuses on several critical problems in global sustainability where CKTS-based solutions will likely have the greatest impacts over the next decade, including energy and water, food and agriculture, human health and well-being, rural and urban communities, and materials supplies and utilization. Here we articulate and discuss the implementation of a vision of societal sustainability based on the following premises (Fig. 9.1):

- Sustainability is determined by the coupled interactions between: (1) population growth and human needs, (2) societal and cultural values, (3) the human-built environment, and (4) Earth system's boundaries.
- Sustainability is enabled by the convergence of knowledge and technologies developed by (and for) society (CKTS).

The overarching theme of this chapter is that CKTS will be critical to "*realizing the future we want for all*" (UN System Task Team 2012), that is, a sustainable, healthy, secure, and peaceful world.

**Table 9.1** Planetary boundaries with proposed boundary and current values of the control variables (Source: Rockström et al. 2009b)

Earth-system process	Control variable	Proposed boundary	Current status	Preindustrial value
Climate change	1. Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	2. Change in radiative forcing (watts per m <sup>2</sup> )	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N <sub>2</sub> removed from the atmosphere for human use (millions of tons per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tons per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km <sup>3</sup> per year)	4,000	2,600	415
Changes in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical pollution	For example, amount emitted to, or concentration of, persistent organic pollutants, plastics, endocrine disrupters, heavy metals, and nuclear waste in the global environment, or the effects thereof on ecosystem and functioning of Earth system	To be determined		

## 9.2 Advances in the Last Decade and Current Status

To continue to survive and thrive on Earth, Rockström and colleagues (2009a, b), as noted above, suggest that humanity must stay within defined planetary boundaries for a range of key ecosystem processes so as to avoid catastrophic environmental changes (Table 9.1). More to the point, they believe that we have already transgressed three of these nine boundaries: (1) atmospheric carbon dioxide (CO<sub>2</sub>) concentration, (2) rate of biodiversity loss, and (3) input of nitrogen into the biosphere.



**Fig. 9.1** Vision for achieving societal sustainability in the next 10 years and beyond. Four main factors will be considered as key determinants of societal sustainability in this chapter: (1) Earth system’s boundaries, (2) population changes, (3) societal needs, infrastructure, and governance and (4) enabling converging knowledge and technologies (Courtesy of M. Diallo)

In the case of global freshwater, Rockström et al. (2009a, b) argue that “the remaining safe operating space for water may be largely committed already to cover necessary human water demands in the future.”

To address the interrelated questions of societal sustainability, population growth and human needs, social and cultural values, and built and natural environments, the following sections provide a background discussion (the status) for each of the target sustainability goals to set the stage for a subsequent assessment of how CKTS will advance these goals in the next 10 years and beyond.

### 9.2.1 Population Growth and Structure

A scientific consensus about long-term demographic trends has not emerged, and it is unclear how many people the Earth can support, even assuming continued technological progress (Cohen 1995). More than two centuries ago, Thomas Malthus (1798) argued that human population growth would always consume resources faster than they could be produced, leaving most people living in abject poverty or dying from disease, starvation, and warfare. However, technological growth seemed to prove Malthus wrong, as wealth grew faster than population, lifting ever greater fractions of humanity into prosperity. By the middle of the twentieth century, a new perspective emerged, called demographic transition theory, that was far more optimistic.

A background assumption was that the institutions of society naturally adjust to changing conditions, for the improved functioning of society as a whole, and thus for most individuals who dwell within it (Parsons and Shils 1951). In the distant past, high childhood death rates required women to give birth to many children, so that enough would live to adulthood and produce children themselves. Thus, high mortality was balanced by high fertility. Then, technological advances reduced childhood deaths, but for a time the fertility rate remained high because societies require time to adjust to changing conditions—what is called cultural lag (Ogburn 1922). Eventually, the fertility rate will come down, according to demographic transition theory, until it is again in balance with the mortality rate, and the human population will be stable (Davis 1963). During the period of cultural lag, there will be a population explosion, but it will naturally subside as society adjusts.

In the 1960s, doubts began to be voiced from many quarters, both about the demographic transition theory and about the general idea that societal institutions like the family naturally adjust in a manner to maximize their functionality. Some critics focused on the continuing population explosion itself (Ehrlich 1968), while others argued that the theory failed really to explain how any kind of new balance could naturally emerge (Knodel and van de Walle 1979). Although countries like China could for a while forcibly limit fertility in order to promote economic growth, most countries do not have that option (Baochang et al. 2007). Now a new public debate is emerging, around two demographic issues that will impact the ability of converging technology to provide its anticipated benefits to humanity, and which may be addressed through societal convergence: humanity's changing age structure and disparate fertility rates.

The first issue is the changing age structure. Low fertility coupled with an increasing life span shifts the age distribution toward the later years of life. This trend is slow but apparently inexorable. For example, the fraction of the United States population under age 18 declined from 25.7 % in 2000 to 24.0 % in 2010, as the percent age 62 and older increased from 14.7 % to 16.2 % (Howden and Meyer 2011). The aging of the population is a major challenge to the healthcare system, as increasing fractions of the population suffer chronic disorders that perhaps can be managed but not currently cured. More broadly, huge economic challenges result from the fact that increasing fractions of the population are retired, including many people who lose jobs in late middle age and are unable to reenter the workforce because no employer will hire them.

Specific converging technologies will offer many partial solutions for one or another age-related problem, but general societal convergence must provide a general solution. One major possibility is instituting a new custom in developed countries, such that most workers at a certain age in a given profession are assisted with training and placement to enter entirely new fields of work, ones better suited for their advancing years. For example, someone in a job that requires heavy lifting or manual labor may no longer be able to perform the tasks, whether from fatigue or arthritis, but could very well do other kinds of work if properly trained, given suitable technologies to work with. Instituting this new system would require many

changes in how education and business operate, and could be successful only in the context of general societal convergence.

The second issue is the disparity in fertility rates across different populations around the globe. In developed countries, on average, each woman must bear 2.1 children to sustain a stable total population, but already all countries of the European Union have dropped below that replacement rate (Bainbridge 2009). As of 2007, even before the changing age distribution had its full effect, in 14 European countries, deaths outnumbered births. Although the fertility rate for the United States in the period 2005–2010 was almost exactly the 2.1 replacement rate, 26 countries have fertility rates of 5.0 or greater, none of them in Europe or the Americas (United Nations 2012).

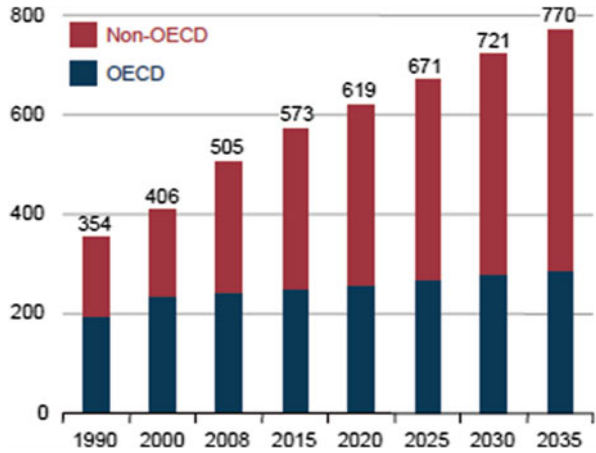
In order to achieve population stability in a democratic context, societal convergence will need to achieve three primary goals: (1) universal prosperity, so that no society is underdeveloped with the consequent pre-transition high fertility rate, (2) a cooperative economy, so that potential parents are not forced to compete so hard at work that they are discouraged from having children, and (3) gender fairness, so that women are not penalized for their reproductive function, and those who choose to have several children are appropriately assisted by the wider community. Exactly how converging technologies can contribute to these goals remains to be worked out, through research and innovation that combines social with technological elements (Cáceres-Delpiano 2012; Staff and Mortimer 2012). A related issue is how demographic convergence can be fine-tuned to achieve precise population stability at a level that maximizes human well-being and free choice.

### ***9.2.2 Energy and Water***

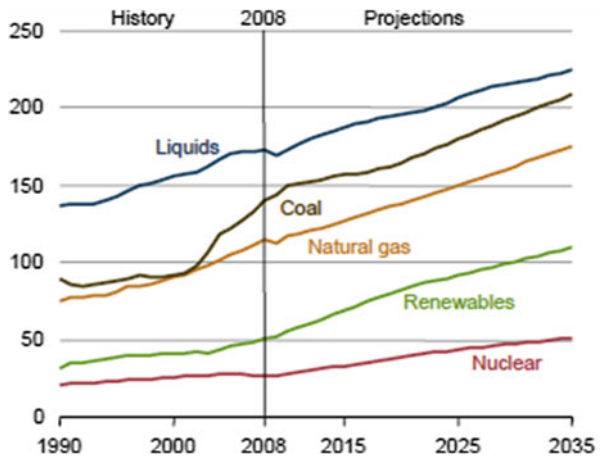
Energy and water supplies are strongly coupled. Power plants require abundant amounts of water to produce electricity, from 38 L per 1,000 kWh for natural gas to 180,900–969,000 L per 1,000 kWh for biodiesel. Conversely, the production and delivery of clean water requires a lot of energy (Webber 2008).

The development of hydraulic fracturing (commonly referred to as “fracking”) has vastly increased the amounts of natural gas that can be extracted from shale gas formations during the last decade (DOE 2009b). Because natural gas is considered to be the “cleanest” among fossil fuels, it has become the transition fuel toward a post-fossil-energy society powered by renewable energies (DOE 2009b). However, the production of shale gas by fracking requires large amounts of water (2–4 millions of gallons per well) and is often carried out in proximity to valuable sources of surface water and groundwater (DOE 2009b). Although the increased production of natural gas from shale oil formations has resulted in tangible economic benefits for the United States, including both lower gas prices and less dependence on oil imports, substantial concerns remain about the adverse impact of fracking and shale gas production on water resources (both quantity and quality) and greenhouse gas (GHG) emissions.

**Fig. 9.2** World energy consumption in quadrillion Btu from 1990 to 2035 (EIA 2011; ©EIA, used by permission)



**Fig. 9.3** World energy consumption in quadrillion Btu from 1990 to 2035 (EIA 2011; ©EIA, used by permission)



**Energy**

The availability of abundant, low-cost, and carbon-neutral energy is arguably the greatest challenge of the twenty-first century. The worldwide demand for energy is expected to increase by 40 % in the next 20 years (Fig. 9.2) (EIA 2011).

Figure 9.3 shows that fossil fuels will continue to provide a significant amount of the energy used worldwide in the foreseeable future. During the last 20 years, a consensus has gradually emerged that increasing emissions of GHG such as carbon dioxide from the combustion of fossil fuels (coal, petroleum, and natural gas) are among the key drivers of global climate change (IPCC 2007a).

Although significant progress is being made toward developing more efficient and safer nuclear energy fuels and reactors (see Sect. 9.8.2 below), the utilization of low-cost and non-GHG-emitting renewable energies might be the most sustainable solution to global climate change. During the last 10 years, significant advances have been made in the development and deployment of renewable energy sources, including



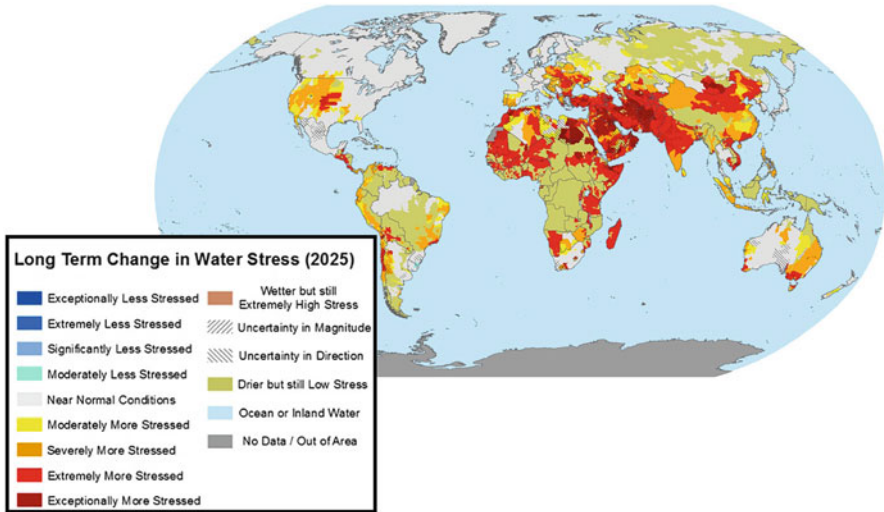
biomass. Biomass can be burned directly to generate electricity, or it can be converted to liquid biofuels (i.e., ethanol and biodiesel). Because transportation accounts for approximately 33 % of CO<sub>2</sub> emissions in the United States and 66 % of oil consumption (Davis et al. 2008), significant research efforts are being devoted to the conversion of non-food plants (e.g., grasses) to liquid biofuels. In 2007, BP formed the Energy Biosciences Institute (EBI) as a way to initiate a major R&D program in cellulosic biofuels and fossil fuel microbiology (see <http://www.energybiosciencesinstitute.org/>). BP funded the EBI at the level of \$50 million per year for 10 years. Its core R&D programs are being implemented by a team of scientists and engineers from the University of California at Berkeley, the Lawrence Berkeley National Laboratory, the University of Illinois at Urbana-Champaign, and BP.

During the last 10 years, significant progress also has been made in solar energy generation technologies. Solar energy has become the most attractive source of renewable energy due to its abundance, versatility, and ease of implementation with minimum environmental impact in terms of water consumption and land usage (Lewis 2007; Brinker and Ginger 2011). Key advances in solar energy generation include the development of (1) thin-film gallium arsenide (GaAs) photovoltaics (PV) cells with high efficiency (~23 %) (see <http://altadevices-blog.com/>) and (2) more efficient silicon PV cells. This has led to a significant drop in the cost of electricity produced from solar PV to \$1 per Watt. The new GaAs solar cells are being scaled-up for commercialization by the California start-up company Alta Devices (<http://altadevices.com/>). Because renewable energy sources such as solar PV and wind power produce electricity intermittently, their large-scale implementation will require more efficient energy storage devices and electric grids. Thus, significant progress has also been made toward development of (1) low-cost batteries and supercapacitors with high energy and high power density, and (2) smart grids for improved delivery of solar-derived electricity (Brinker and Ginger 2011; WWF 2011).

As renewable energy sources become more affordable and efficient, energy demand continues to rise in many sectors, including in information and communications technologies. The invention of the smart phone, for example, is among the most important advances in ICT hardware during the last 20 years. In 2010, the number of cell/smart phones in use worldwide was estimated to be 5.3 billion (Moyo 2012), causing a significant energy demand. Large amounts of critical materials will also be needed as the worldwide demands for mobile/smart phones continue to increase. There is a growing consensus that the development and large-scale implementation of renewable energy generation and storage technologies will require sizeable amounts of valuable and critical metals such as copper, lithium, titanium, gallium, rare-earth elements (e.g., neodymium and europium), platinum group metals (e.g., platinum and palladium), and precious metals (e.g., gold and silver) (Diallo and Brinker 2011; Fromer et al. 2011).

## Water

The availability of clean water is a critical problem facing society and the global economy in the twenty-first century. Already there is insufficient availability of



**Fig. 9.4 Predicted long-term changes in water stress (2025).** Water stress is expected to grow 2–8 times worse in many places by 2025 (Figure: World Resources Institute; Iceland 2011; data provided courtesy of the Coca Cola Company). The A1B scenario (In assessing the physical science bases of climate change, IPCC Working Group I developed a series of emissions scenarios for the future: “The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies)”); see <http://www.ipcc.ch/ipccreports/tar/wg1/029.htm#storya1>) of the Intergovernmental Panel on Climate Change (IPCC) assumes a “future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies” with a “balanced” portfolio of fossil fuels and renewable energy sources (Bates et al. 2008, Figure 9.4; ©IPCC, used by permission)

clean water for human consumption, agriculture, and industry. Many regions of the world are experiencing higher demands for clean water while freshwater supplies are being stressed (Shannon et al. 2008; Diallo and Brinker 2011). The number of people living in water-stressed areas will continue to increase in the next decades as the amount of available freshwater decreases due to global climate change (Bates et al. 2008). By 2025 (Fig. 9.4), it is estimated that approximately 50 % of the world population will live in water-stressed areas (Iceland 2011).

To alleviate future water shortages and stresses, considerable research efforts have been devoted during the last decade to develop more efficient and cost-effective technologies to reclaim and reuse wastewater (Shannon et al. 2008; McCarty et al. 2011; Pennisi 2012; Logan and Rabaey 2012). Approximately 70–90 % of the water used in agriculture, industry, and human consumption is returned to the environment

as wastewater (Shannon et al. 2008). Wastewaters contain organics, including nutrients (nitrogen and phosphorous) and compounds with fuel values. A recent study suggests that the fuel values of organics in wastewater per gram of solids (dry weight) range from 17.7 to 28.7 kJ (Heidrich et al. 2011). Current wastewater treatment plants are not sustainable; they spend significant amounts energy to destroy (i.e., mineralize) valuable organic compounds in wastewater. In the United States, the treatment of organic-rich wastewater consumes approximately 3 % of the electrical power produced (McCarty et al. 2011).

Significant progress has been made in the development of technologies to extract clean water, energy, and valuable compounds from wastewater (McCarty et al. 2011; Pennisi 2012; Logan and Rabaey 2012). Microbial fuel cells (MFCs) have emerged as promising platforms for converting organic compounds in wastewater to electricity (Logan and Rabaey 2012). However, McCarty et al. (2011) argue that integrated and anaerobic wastewater treatment systems would be more efficient and cost-effective than MFCs at extracting both clean water and energy from wastewater. A proposed integrated anaerobic wastewater treatment system would combine conventional solid–liquid separation with the latest developments in microbiology and membrane technology—anaerobic membrane bioreactors (McCarty et al. 2011).

In addition to wastewater reclamation and water reuse, low-energy desalination technologies with reduced environmental footprint (e.g., brine generation) also will be required to alleviate future water shortages and stresses (Shannon et al. 2008; Diallo and Brinker 2011; Elimelech and Phillip 2011). Saline water (including brackish water and seawater) constitutes ~97 % of the water on Earth. Key advances in desalination during the last 10 years include the following:

- Discovery of fast water transport through carbon nanotube membranes (Holt et al. 2006).
- Preparation of thin-film composite reverse-osmosis (RO) membranes with embedded nanoparticles (e.g., zeolite) that achieve higher flux (~1.2 times) than commercial RO membranes (Jeong et al. 2007).
- Preparation of low-pressure and ion-selective nanofibrous composite membranes with high water flux (Park et al. 2012).
- Progress in the preparation of biomimetic desalination membranes with embedded aquaporin channels (Tang et al. 2012).
- Emergence of forward osmosis (FO) as a potential low-energy desalination technology (Wang et al. 2012).

### 9.2.3 *Agriculture and Food*

While productivity has been a consistent and important goal in agricultural R&D, there has been significant increased emphasis on sustainability over the last 10 years. Indeed, the concept of sustainability of agriculture has been much discussed

and was addressed in the National Research Council (NRC) report on sustainable agriculture (2010), wherein four goals are used to define sustainable agriculture:

- Satisfy human food, feed [for animals], and fiber needs, and contribute to biofuels needs
- Enhance environmental quality and the resource base
- Sustain the economic viability of agriculture
- Enhance the quality of life of farmers, farm workers, and society as a whole

Modern agriculture has had an impressive history of increasing productivity that has led to abundant, safe, and affordable food, fiber, and recently, biofuels. Farmers today are meeting expanding demands for both domestic and international markets on the same acreage as a century ago as a result of technological innovations, economies of scale, consolidation of food processing and distribution, and advanced retailing. During the decade, U.S. agriculture has continued to become increasingly dependent on large-scale, high-input farms that specialize in a few crops and concentrated animal production practices; for example, 2 % of U.S. farms are responsible for 59 % of U.S. farm products (NRC 2010). In contrast, small- and medium-sized farms, which represent more than 90 % of the total farmers, manage about half of U.S. farmland. Advances in biotechnology, automation and precision agriculture, conservation tillage, and livestock systems have maintained and increased yields.

*Biotechnology crops* as of 2011 (Clive 2011) are utilized in 29 countries and are reaching 160 million hectares. The use of crops derived from biotechnology has yielded several benefits:

- Contribution to food, feed, and fiber security, and self-sufficiency, including more affordable food, by increasing productivity and economic benefits sustainably at the farm level.
- Conservation of biodiversity through land-saving technologies. Higher productivity on the current 1.5 billion hectares of arable land can preclude deforestation and protect biodiversity.
- Contribution to alleviation of poverty and hunger. For example, biotech has made significant contribution to incomes of approximately 15 million small resource-poor farmers in developing countries in 2011, primarily in cotton, maize, and rice.
- Reduction of agriculture's environmental footprint by reducing pesticide use, saving on fossil fuels, decreasing CO<sub>2</sub> emissions, and increasing efficiency of water usage.

*Precision agriculture* is a systems approach for site-specific management of crop production systems. The foundation of precision agriculture rests on geospatial data techniques for improving the management of inputs and documenting production outputs (Reid 2011). A key technology enabler for precision farming resulted from the public availability of the U.S. global navigation satellite system (GNSS). GNSS has provided highly accurate and high-resolution data for mapping yields and moisture content. Advances in precision agriculture benefited greatly from the

design of new machinery, including precision planters, sprayers, fertilizer applicators, and tillage instruments.

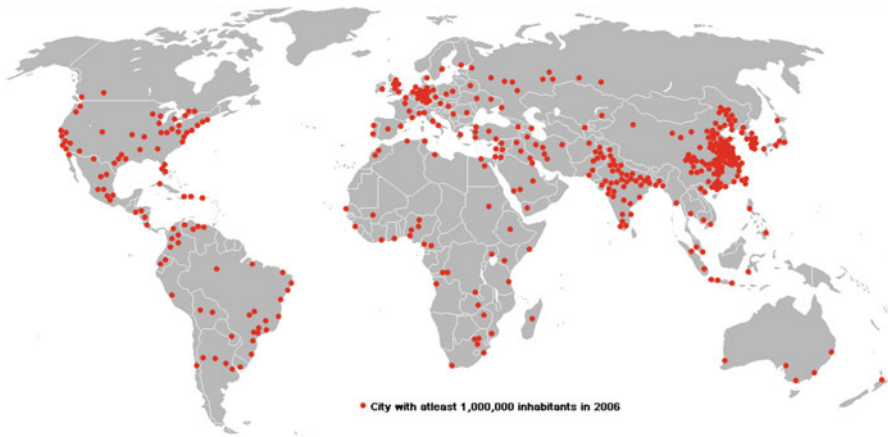
*Conservation tillage systems* are methods of soil tillage that can have both environmental and economic benefits. Conservation tillage leaves a minimum of 30 % of crop residue, or at least 1,100 kg/ha of small grain residue, on the soil surface during the critical soil erosion period (NRCS 2012). The most significant advantage is less soil erosion due to wind and water. Conservation tillage systems also benefit farmers by reducing fuel consumption and soil compaction. Conservation tillage, although developed a number of years ago, has gained limited adoption in the United States during the last decade and was used on 44 million hectares, which constituted approximately 38 % of all U.S. cropland by 2004.

*Livestock systems.* Positive environmental gains along with considerable gains in livestock systems have been achieved during the past decade. In the United States, advances in animal nutrition, management systems, and genetics have resulted in a large increase in annual milk yield of dairy cattle. Capper et al. (2009) report a four-fold increase in milk yield in 2007 compared to that of 1944, with 84.3 billion kg produced in 2007 compared to 53 billion kg in 1944 with 64 % fewer cows. Carbon emissions and total emissions per unit of milk were reduced by 66 % and 41 %, respectively. Similar results for emissions per unit of product have been achieved in the beef and poultry industries.

### 9.2.4 Human Health and Wellness

Equitable health and wellness policies are critical to a sustainable society. Over the course of the last century, tremendous medical advances have consistently increased life span across the globe. Early in the 1900s, the discovery and use of antibiotics, followed in the middle of the century by widespread dissemination of effective vaccines, dramatically reduced the morbidity and mortality associated with infections (Oeppen and Vaupel 2002; Christensen et al. 2009). Later in the century, biochemistry-based advances led to new drugs for patients with elevated blood lipids (Tobert 2003), and for cases where lipid deposition had already resulted in clinically relevant occlusions, coronary stents were developed that sufficiently restored cardiac function—both life-saving developments (Tobert 2003). Advances in surgical techniques and molecular tissue typing/matching allowed, along with the development of optimized immunosuppressive treatments and the ability to surgically transplant whole organs from one person (alive or deceased) to another, thus giving “a second life” to those with whole-organ failure (King and Meier 2000). Over the course of this century, steady advances in life span are expected, and CKTS will be enabling many of these new life-extending discoveries.

Interrelated with advances in medicine, wellness knowledge, and technologies are issues of medical accessibility and affordability. Life span expectations are influenced by the gross domestic product of a given population, but factors such as obesity, diet, exercise, tobacco smoking, and drug and alcohol use can confound



**Fig. 9.5** Map showing urban areas with at least one million inhabitants in 2006. Only 3 % of the world's population lived in cities in 1800; this proportion had risen to 47 % by 2000, and reached 50.5 % by 2010. By 2050, the proportion may reach 70 % (Source: Wikimedia Commons 2007)

positive health outcomes for wealthier populations. A more detailed and in-depth discussion of CKTS and human health and wellness can be found in Chap. 5 of this report.

### 9.2.5 *Urban and Rural Communities*

Vibrant and healthy communities are the backbones of a sustainable society. Rural communities in many parts of the world face an array of poverty-related challenges, including lack of infrastructure, housing, access to quality health-care, education, and a steady means of income, as discussed in Sect. 9.8.4 of this chapter. One of the most significant challenges to global sustainability is the emergence of large urban communities comprised of millions of people. The rapid growth of megacities with tens of millions of people is a global phenomenon that began to accelerate at the close of the last century and continues today. Over two thirds of the world's urban residents live in cities in Africa, Asia, and Latin America (Fig. 9.5; Wikimedia Commons 2007). Further, since 1950, the urban population of these regions has grown fivefold, and in Africa and Asia, urban population is expected to double by 2030 (UNPF 2007). These are also the regions where megacities—such as Mumbai, Shanghai, Beijing, Calcutta, Lagos, Mexico City, Rio de Janeiro, and Cairo—have become most common.

Megacities impose numerous environmental and resource impacts that until a generation ago were insufficiently appreciated. They challenge the achievement of a sustainable society in three major ways. First, megacities impose huge stresses upon regional freshwater supplies and water quality. In part, this is because most

large cities are often located some distance from the water sources needed to support them. As a result, they must divert water from outlying rural areas. Large cities also generate huge volumes of wastewater, which is costly to treat and, if left untreated, can contaminate local wells and streams—a growing problem, especially in many developing nations. Wastewater generation is itself exacerbated by urban sprawl, which leads to increased paving of city streets and commercial districts, contributing to pollutant runoff and diminished groundwater recharge, as well as increased consumption of water for parks and outdoor residential use (increasing evapo-transpiration and taxing local supplies). While greater concentrations of people in cities may lower unit costs for many forms of urban infrastructure (Satterthwaite 2000), the need to expand water supply and treatment networks over vast distances increases the likelihood of distribution system leaks.

Second, megacities impose huge burdens on energy systems, infrastructure, and human health and hygiene. The quest to modernize growing urban areas has led to a desire to afford them with a higher quality of life, adding to demands for additional energy. Energy demands are expected to grow by some 60 % over present needs by 2030 in developing countries. While virtually every source of energy depends on water, one rapidly growing energy source in much of the developing world is biofuels such as ethanol, which can be produced by converting biomass, including trees, grasses, left-over agricultural residue from harvesting crops, and even algae. Biofuels firmly link agriculture and energy production with dramatic impacts upon fresh water. The need to expand water supply and treatment and energy infrastructure can also enormously strain existing capacity and outrace development capacity—as well as place inordinate pressure on the outlying regions from whence in-migration occurs (UN 2009).

Third is another energy–water interconnection: as cropland is diverted from food to energy-crop production, and as developing countries restrict imports of food to encourage more domestic farming and greater food security, food prices are likely to rise. We have already seen this occur as the result of corn-based ethanol production in many countries. As food prices rise, the cost of water used for production of both food and biofuel crops, and the cost to treat the new sources of water supply contamination resulting from this higher production also rise because of higher demand for water (IPCC 2007b).

## ***9.2.6 Materials Supply and Utilization***

### **Minerals and Critical Metals**

Minerals are key building blocks of the sustainable economy of the twenty-first century. They have become the primary sources of the variety of metals used to fabricate the critical components of numerous products and finished goods, including airplanes, automobiles, cell/smart phones, and biomedical devices (NRC 2008). The application of CKTS to critical metal supply/utilization has

thus far received little attention (Diallo and Brinker 2011). However, recent stresses in the global market of rare-earth elements (REEs) have brought the sustainable supply of critical metals to the forefront in the United States and other industrialized countries (Diallo and Brinker 2011; Fromer et al. 2011). In addition to REEs (e.g., neodymium and dysprosium) and platinum-group metals (PGMs) (e.g., platinum and rhodium), significant amounts of copper, silver, indium, lithium, and gallium will be needed to build the renewable energy technologies of the twenty-first century.

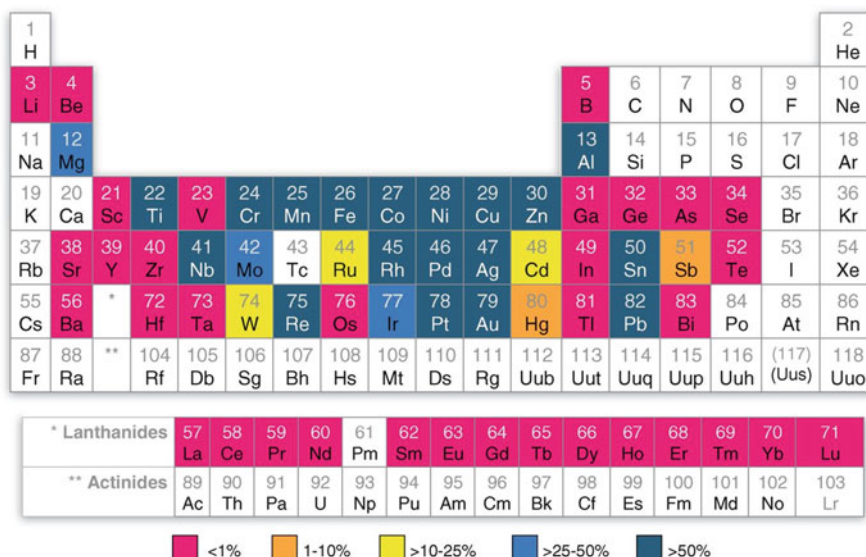
Recently, the uses of critical materials in renewable energy technologies have been the subject of extensive discussions (Fromer et al. 2011; DOE 2011). To ensure that the availability of critical metals will not adversely impact the development and deployment of renewable energy systems, the U.S. Department of Energy (DOE) through the Advanced Research Projects Agency Energy (ARPA-E) has recently initiated a broad range of research programs to develop rare-earth alternatives in critical technologies (REACT) (ARPA-E 2011). The initial focus of the REACT program is on building new magnets for electric vehicles and wind turbines using earth-abundant elements such as iron, nickel, manganese, and aluminum as building blocks. In 2013, the DOE established an “Energy Innovation Hub” led by Ames National Laboratory to address challenges in critical materials for energy generation, conversion, and storage, including (1) mineral processing/purification, (2) manufacturing, (3) substitution, and (4) recycling (DOE 2013). It is worth mentioning that the end-of-life recycling rate (EOL-RR) is very low for most of the critical materials that will be used to build the sustainable products, processes, and industries of the future (Reck and Graedel 2012; UNEP 2011b; Fig. 9.6).

## **Carbon-Based Materials and Biomass**

Carbon-based materials derived from petroleum are the building blocks of a broad range of essential products and finished goods, including plastics, solvents, adhesives, fibers, resins, gels, and pharmaceuticals. Steep increases in the cost of petroleum and geopolitical concerns over the sustainable supply of oil and GHG emissions have made biomass an attractive feedstock for the chemical industry (Gallezot 2012; Tuck et al. 2012). During the last 10 years, significant research efforts have been devoted to the conversion of biomass to valuable chemicals. Three main conversion strategies that are being explored include:

- Chemical and/or biological conversion of biomass into small and intermediate molecules that are subsequently utilized to prepare specialty and fine chemicals
- Chemical conversion of biomass into a mixture of small molecules with similar functionalities that are subsequently employed to produce commodity and performance chemicals
- Chemical functionalization of biomass to produce new functional polymers that are converted to performance chemicals





**Fig. 9.6** Global estimates of end-of-life recycling rates for 60 metals and metalloids: 30 are <1 %; 2 are 1–10 %; 3 are 10–25 %; 3 are 25–50 %; only 18 are over 50 % (Reck and Graedel 2012, Adapted from a figure in Graedel et al. 2011; ©AAAS, Reprinted with permission)

## 9.2.7 Climate Change and Clean Environment

### Climate Change Mitigation

Global climate change is a formidable challenge facing human society and the environment in the twenty-first century. During the last two decades, a scientific consensus has gradually emerged that increasing emissions of GHG such as CO<sub>2</sub> from the combustion of fossil fuels are the key drivers of global climate change (IPCC 2007a). Currently, fossil fuels provide approximately 80 % of the energy used worldwide (IPCC 2005). Thus, the utilization of non-CO<sub>2</sub>-emitting renewable energy sources might be the most effective means of reducing GHG emissions (IPCC 2011). Although various non-GHG-emitting and carbon-neutral renewable energy sources are being developed/deployed (see Sect. 9.2.2), the world will continue to burn significant amounts of fossil fuels in the foreseeable future. During the last decade, significant progress has been made in the development of novel GHG mitigation strategies, including carbon capture and storage (CCS) (IPCC 2005) and CO<sub>2</sub> conversion to fuels and useful products (Diallo and Brinker 2011). Relevant examples include:

- More efficient and selective sorbents for CO<sub>2</sub> capture, release, and storage, including metal organic frameworks (MOFs) (Britt et al. 2009) and zeolitic imidazolate frameworks (ZIFs) (Phan et al. 2010)

- Conversion of CO<sub>2</sub> to fuels and organic chemicals using microbial electrosynthesis (Logan and Rabaey 2012)
- Conversion of CO<sub>2</sub> to cement using seawater and low-cost sources of alkalinity (Service 2012)

In addition to CCS and CO<sub>2</sub> conversion, geoengineering is being considered as a potential climate mitigation technology. To alleviate public and regulatory concern over the global/regional environmental impact of climate mitigation by “solar radiation management” using stratospheric aerosols (Keith et al. 2010), less risky and “soft” geoengineering technologies that “touch gently on biological and social systems” are being developed (Olson 2012). Recent progress includes the invention and field evaluations of the Ice911 technology to slow ice melting in Arctic regions (Field 2012). The Ice911 concept is predicated on the use of light-colored and lightweight materials to cover and protect “water or areas in danger of melting” (Field 2012).

## Clean Environment

Industrial manufacturing has a heavy environmental footprint. First, it requires significant amounts of land, energy, water, and materials. Second, it generates a lot of wastes (gaseous, liquid, and solid) and toxic by-products that need to be disposed of or converted into harmless products. “Green manufacturing” might be the most efficient means to reduce and (eventually) eliminate the release of toxic pollutants into the soil, water, and air. Green manufacturing encompasses a broad range of approaches that are being used to:

- Design and synthesize environmentally benign chemical compounds and processes (green chemistry)
- Develop and commercialize environmentally benign industrial processes and products (green engineering)

During the last 10 years, significant advances have been made in green engineering and green chemistry (Schmidt 2007). The SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing led by the University of Arizona is exploring the utilization of “Environment, Safety & Health (ESH) factors as design parameters in the development of new processes, tools, and protocols for semiconductor manufacturing” (see <http://www.erc.arizona.edu/vision.htm>). The NSF Center for Sustainable Materials Chemistry (CSM) led by Oregon State University is exploring the utilization of water-based chemistries for “producing very high-quality thin films and patterns” for the next generation of semiconductor devices (see <http://sustainablematerialschemistry.org/>). The CSM is also employing green chemistry to develop new materials for energy applications, including electro-catalysts, solid-state ionic conductors, and high dielectric constant materials.

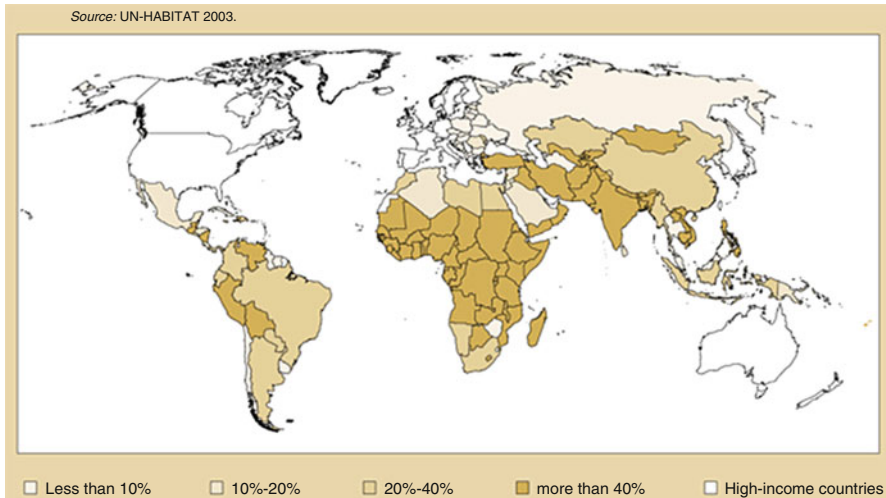
Although green manufacturing could reduce and (eventually) eliminate the release of toxic pollutants into the soil, water, and air, its large-scale implementation

by industry will take decades. Thus, more efficient and cost-effective technologies are still needed to (1) detect and monitor pollutants (environmental monitoring), (2) reduce the release of industrial pollutants (waste treatment), and (3) clean polluted sites (environmental remediation). During the last 10 years, the application of engineered nanomaterials to sensing and detection devices has enabled the development of a new generation of advanced monitoring and detection concepts, devices, and systems for various environmental contaminants (Fan et al. 2004; Vaseashta and Dimova-Malinovska 2005; Rickerby and Morisson 2007; Wang et al. 2008; Aravinda et al. 2009).

Advances in nanotechnology have also enabled development of more efficient and cost-effective environmental remediation technologies (Savage and Diallo 2005; Tratnyek and Johnson 2006). Nanoscale zero valent iron (NZVI) particles have proven to be very efficient redox-active media for the degradation of organic contaminants, especially chlorinated hydrocarbons (Lowry and Johnson 2004; Liu et al. 2005; Song and Carraway 2005). Dendritic nanomaterials, which consist of highly branched nanoscale polymers, have been successfully employed as supramolecular hosts and ligands to extract environmental pollutants from aqueous solutions; these toxins include inorganic pollutants, heavy metals, and biological and radiological compounds (Crooks et al. 2001; Diallo et al. 2004; Birnbaum et al. 2003; Balogh et al. 2001). More recently, Diallo and coworkers successfully utilized low-cost hyperbranched polymers to develop a new generation of high-capacity and selective anion exchange and chelating resins to remove pollutants such as perchlorate and boron/borate from contaminated water (Chen et al. 2012; Mishra et al. 2012).

### ***9.2.8 Human Progress, Societal Values, and Economic Development***

Two important goals of global sustainability are to achieve “inclusive” economic and societal development, which benefits all people while minimizing the impact of human activities on Earth’s climate and ecosystems (UN System Task Team 2012). Currently, there are wide disparities in living standards and income between people living in developed and developing countries (UN System Task Team 2012). According to the International Labor Organization (ILO), approximately one billion people in the world are malnourished, and more than 200 million are unemployed (ILO 2011). In 2008, about 1.3 billion people in the world live on less than \$1.25 a day (ILO 2010). Nearly one third (~2.4 billion people) of the world’s population in 2015 will lack access to improved water supply and sanitation (UNICEF and WHO 2009.) More to the point, approximately 900 million people live in slum-like conditions (UN Millennium Project 2005). In Sub-Saharan Africa, 60–70 % of the people live in slums (Fig. 9.7).



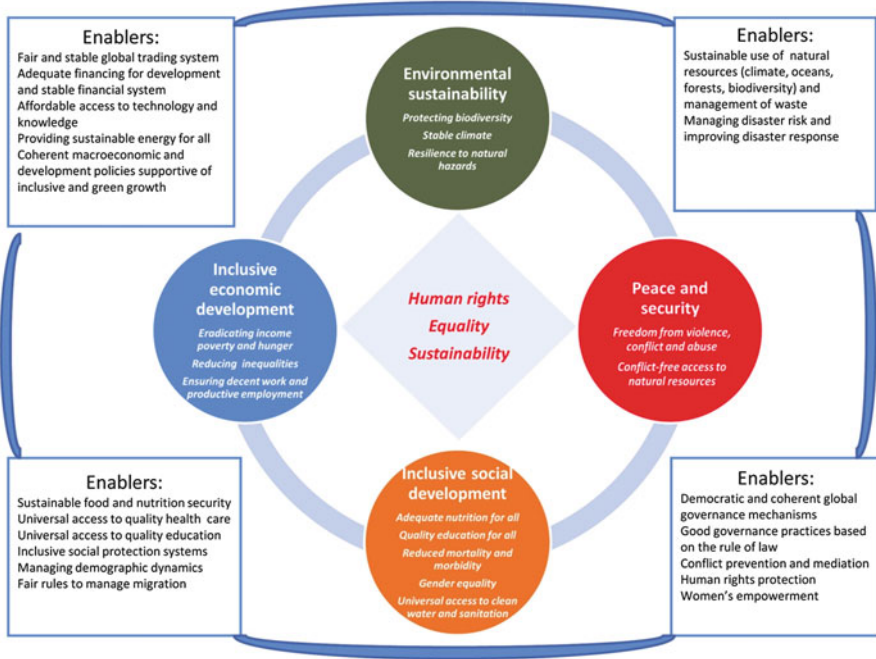
**Fig. 9.7** Share of urban populations living in slums, *percent* (UN Millennium Project 2005, Chapter 2, p. 27, Map 2.4; ©UN-Habitat 2003, used by permission)

Since the adoption of the Millennium Development Goals in 2000 by the United Nations (UN Millennium Project 2005), significant advancements have been made toward achieving inclusive economic and societal development (UN System Task Team 2012). Strong economic growth has occurred in many developing countries, thus lifting millions of people out of poverty. One of the most significant developments in the last 10 years is the convergence between ICT (e.g., mobile phones), social media (e.g., Facebook), and social entrepreneurship (Rifkin 2011). This convergence has radically transformed the “way people communicate, organize, network, learn, and participate as national and global citizens” (UN System Task Team 2012, 14). This in turn is enabling major and beneficial changes:

- Participatory sustainable development
- Increased transparency
- Environmental and intergenerational equity/justice
- Public scrutiny and governance of emerging/transformational technologies

Although tangible progress has been made in the implementation of Millennium Development Goals, a great deal remains to be done. Costanza et al. (2012) recently published their report “*Building a Sustainable and Desirable Economy-in-Society-in-Nature*”. In this report, the authors argue that we need a “new vision of the economy” to achieve “inclusive” economic and societal development with minimum environmental impact. More to the point, they argue that such new economic models should be based on the principles of “Ecological Economics,” including:

1. Respect of “planetary boundaries,” i.e., the carrying capacity of the natural environment
2. Recognition of the critical relationships between human development and well-being on societal/cultural values and “fairness”



**Fig. 9.8** An integrated framework for realizing the “future we want for all” in the post-2015 UN development agenda (UN System Task Team 2012, Figure 9.1, p. 24; reuse under stock image license)

3. Acceptance that the ultimate goal of societal development is “real and sustainable human well-being, not merely growth of material consumption”

Costanza et al. (2012) believe that implementation of this new economic vision will be critical to realizing a sustainable, healthy, secure, and peaceful world. Figure 9.8 provides the UN System Task Team’s integrated framework for achieving this goal.

### 9.3 Goals for the Next Decade

The overarching theme of this chapter is that in the next 10 years, progress in CKTS will be critical to achievement of sustainable development in consideration of the factors listed in Fig. 9.1. The UN study “*Realizing the Future We Want for All*” (UN System Task Team 2012) provides an integrated framework for achieving “inclusive” economic and societal development with minimum environmental impact (Fig. 9.8). Given the global environmental challenges and expected increase in population, realizing the UN vision will require transformative advances and the convergence of many fields, including physical/earth sciences, biological sciences, engineering, and social sciences, as outlined below.

### 9.3.1 Sustainable Supply of Energy for All

As previously discussed, solar energy is the most attractive source of non-GHG-emitting source of energy. Solar energy is both abundant and versatile. Concentrating solar power (CSP) can convert solar energy into thermal energy that can be subsequently stored and utilized to produce electricity via a steam turbine or a heat engine. Photovoltaics (PV) convert solar radiation directly into electricity. Both CSP and PV are flexible and modular. They can be incorporated into large centralized power plants as well as into smaller, distributed systems (e.g., rooftop units). Solar radiation could ultimately be combined with CO<sub>2</sub> and water to produce solar fuels (e.g., hydrogen and methanol). Solar energy has the potential to provide “*Sustainable Energy for All*” by 2050 (WWF 2011).

In the next 10 years, we envision that the convergence between physical sciences (e.g., chemistry, physics, materials sciences), nanotechnology, information technology, engineering (e.g., mechanical engineering, electrical engineering, chemical engineering, and systems engineering) and scalable manufacturing (e.g., 3D printing) will lead to transformative advances in solar energy generation, conversion, storage, and distribution. The most significant advances will include:

- High-efficiency solar cells and modules (30–35 %) that produce electricity at a cost of 0.35 per Watt
- Third-generation solar cells that are able to overcome the Shockley-Queisser limit (31–41 % power efficiency) for single band gap PV cells
- Scalable Li-S and Li-Air batteries with high energy density (2,000–3,000 Wh/kg) for storage of solar PV electricity
- More efficient grid-scale energy storage devices for electricity derived from solar energy
- First prototype of a scalable solar fuel generator that produces H<sub>2</sub> by splitting water
- More efficient solid-state materials for storage of H<sub>2</sub> derived from solar power

### 9.3.2 Sustainable Supply of Clean Water for All

As previously stated, water scarcity is expected to grow more acute as the world population increases and the amount of available freshwater decreases due to climate change. Global climate change will adversely impact the world’s freshwater resources in several ways: (1) increase the frequency of droughts and floods; (2) decrease the amount of water stored in snowpack and glaciers; and (3) decrease the overall water quality due to salinity increase and enhanced sediment, nutrient, and pollutant transport in many watersheds throughout the world (Bates et al. 2008). Consequently, transformative advances in water purification technology and major behavioral changes in the ways people use water will be required to alleviate future water shortages. Section 9.8.3 provides a case study showing how the convergence between nanotechnology and microbiology could lead to more efficient and safer water

disinfection strategies. In the next 10 years, we envision that the convergence between earth-systems science, physical sciences (e.g., chemistry and materials sciences), biological sciences (e.g., microbiology and biotechnology), nanotechnology, engineering (e.g., chemical/environmental process engineering), and social sciences will lead to transformative advances in water science, technology, management, and utilization. We expect that these major advances will enable us to:

- Understand, model, and manage the impact of global climate change on freshwater resources
- Develop more sustainable technologies to (1) reuse water, (2) reclaim wastewater and (3) desalinate brackish water and seawater while recovering energy, nutrients (nitrogen and phosphorous), and valuable elements (e.g., lithium and magnesium)
- Develop more efficient and cost-effective decentralized water treatment systems to meet the drinking and clean water needs of population clusters (e.g., residential buildings, villages, and private homes) in developed and developing countries
- Develop more efficient water treatment and reuse technologies to address the special needs and growing water stresses of industry worldwide
- Educate the public and regulators about the value of water, the current water crisis, and the necessity to save and reuse water

### ***9.3.3 Sustainable Supply of Food for All***

Modern agriculture has a heavy environmental footprint. Firstly, it requires significant amounts of land, energy, water, fertilizers, and pesticides. Secondly, it generates significant amounts of GHG and liquid wastes (e.g., run-off) containing nutrients and toxic by-products (e.g., excess pesticides). In the next decades, the world will face the daunting challenging of doubling the amount of food it currently produces to feed around nine billion people in 2050 while reducing energy usage and GHG emissions, as the amount of freshwater available decreases due to global climate change. In the next 10–20 years, we expect that the convergence between nanotechnology, biotechnology, information technology, and social sciences will produce the transformative advances required to meet this formidable challenge. Broad goals for the next decade are to:

- Satisfy human food, feed, and fiber needs, and contribute to biofuel needs
- Enhance environmental quality and the resource base
- Sustain the economic viability of agriculture
- Enhance the quality of life for farmers, farm workers, and society as a whole
- Reduce hunger, malnutrition, and poverty worldwide

More specific goals will be to:

- Freeze agriculture's carbon footprint by slowing agricultural land expansion, in particular, loss of tropical forests

- Reduce yield (production) gaps between existing growth (production) levels and the genetic potential for both plants and animals
- Improve efficiencies of agriculture and natural resources (more output/input resource)
- Reduce “diet” gaps, changing the mix of food products to enhance food availability and reduce environmental impacts
- Reduce food wastes at every level in the agriculture and food system
- Integrate agriculture and food systems into sustainable community thinking, possibly via opportunities for renewable, distributed energy generation, including “vertical” farms in the urban areas

### ***9.3.4 Health and Wellness for All***

The emergence of large urban communities and megacities with more than ten million inhabitants is a formidable challenge to societal sustainability in the twenty-first century (See Sect. 9.2.5 of this report). In addition to their heavy environmental impact (e.g., high GHG emissions, increased air pollution, and huge stresses on freshwater resources), megacities pose significant challenges to achieving health and wellness for the world’s population. Over the course of history “medical access” has been inextricably linked with “distance to doctor”. As we enter into a world with a myriad of advanced/instant communication tools in which satellites and ground-based high-speed fiber optics-based information systems are all connected, the convergence of information and communication technology (e.g., smart phones) with biotechnology (e.g., low-cost and rapid DNA sequencing technologies), and medicine (e.g., molecular diagnostic tools) will lead to transformative advances in the 10–20 years. Relevant and important advances will include:

- Access to best-in-world medical and wellness information, instantly, anywhere, and anytime.
- More effective disease avoidance options/information.
- More personalized and cost-effective medical diagnostics tools.
- More personalized and cost-effective treatment and drugs.

In addition, we expect that some of the new molecular diagnostic tools will be integrated into advanced sensors and detection systems to monitor the presence of flu viruses or emerging pathogens in air, water, and urban living environments. This will provide city managers and first responders with more effective tools to protect public health by early detection of the presence of infectious agents and/or poisonous, toxic, or radioactive substances into urban air, water, soil, and transportation systems.

### ***9.3.5 Sustainable Communities for All***

A key societal goal in the 21st century is to build/establish sustainable communities for all; that is communities that meet the basic needs of food, clean drinking water, energy, healthcare, education, and providing meaningful jobs, affordable homes,



and economical transportation for all people, with minimum impact on Earth's climate and ecosystems. Major and transformative advances and the convergence between many fields (e.g., physical sciences, engineering, information/communication technology, architecture, and social sciences) will be required to achieve this colossal undertaking in the next 10–20 years as global climate change accelerates and the world's population continues to grow. Section 9.8.4 discusses the development of CKTS-based solutions for building sustainable rural communities. Relevant and significant advances for building the sustainable urban communities of the twenty-first century will include smarter cities with:

- More affordable/resilient housing and distributed energy generation, storage, and distribution systems
- Resilient and distributed water/wastewater infrastructure
- More energy-efficient transportation systems
- More efficient food production and delivery systems
- Distributed healthcare infrastructures, employment opportunities for all, and more livable environments

### ***9.3.6 Sustainable Materials Supply and Utilization***

Innovations in materials science/engineering and the sustainable supply/utilization of materials will be critical to developing the next generation of sustainable technologies and products, including high-efficiency solar cells, high-efficiency magnets for electrical cars and wind turbines, high-capacity batteries, low-energy desalination membranes, energy-efficient transportation systems, and high-performance carbon capture and storage technologies. Because our current consumption of critical metals is at an all-time high (Reck and Graedel 2012), there is an urgent need for novel strategies to decrease the utilization of critical materials in energy generation, conversion, and storage, and/or to replace them with earth-abundant elements. New technologies and strategies are also needed to augment the supply of critical materials through recycling and reuse. In the next 10–20 years, we expect that the convergence between nanotechnology, materials science, separations science, and engineering (e.g., chemical, mechanical, and systems engineering) will lead to the transformative advances required to ensure global materials sustainability including:

- Nanocrystalline-silicon thin films for high-efficiency photovoltaics cells
- Nanostructured materials based on earth-abundant elements (e.g., silicon nanowires) for high-capacity energy storage systems (e.g., batteries)
- More efficient magnets for electric vehicles and wind turbines using earth-abundant elements (e.g., iron, nickel, and manganese) as alternatives to rare-earth elements
- Nanostructured catalysts based on earth-abundant elements (e.g., iron, copper, nickel, and manganese) for fuel cells and solar fuel generation

- More efficient and cost-efficient separation materials (e.g., sorbents and membranes) and systems for extracting and recovering critical materials from nontraditional sources, including mine tailings, industrial wastewater, seawater, and brines

### ***9.3.7 Sustainable Climate and Clean Environment***

#### **Sustaining Earth's Climate**

Mitigation of global climate change is among the most urgent tasks facing the world. As previously discussed, the switch to renewable and non-GHG emitting energy sources (e.g., solar energy) is the most effective mean for stabilizing Earth's climate. However, the deployment of terawatt-scale non-GHG-emitting energy sources will require decades. Thus, a consensus has emerged that more efficient mitigation and adaptation strategies will also be needed to stabilize the level of CO<sub>2</sub> in the atmosphere (see Table 9.1) and minimize/manage the impact. In the next 10–20 years, we expect that the convergence between nanotechnology, separations science, catalysis, engineering, earth-systems science, architecture urban/planning, and social sciences will lead to transformative advances in climate mitigation and adaptation technologies/strategies, including:

- Nanoscale sorbents containing functionalized size- and shape-selective molecular cages that can selectively capture carbon dioxide (CO<sub>2</sub>) from flue gases and convert it to useable products
- More efficient and cost-effective systems that can directly extract CO<sub>2</sub> from air and convert it to useable fuels and useable products
- More robust strategies and solutions to increase the resilience and decrease the vulnerability of people, urban/rural communities, and ecosystems to extreme weather events (e.g., drought and flooding) caused by global climate change

#### **Clean Environment for All**

Pollution prevention through green manufacturing is arguably the most efficient way to reduce and/or prevent the release of many toxic pollutants into the soil, water, and air. In the next 10 years, a convergence between nanotechnology, materials science, green chemistry, and green engineering will enable society to build the sustainable products, processes, and industries of the twenty-first century while maintaining a clean environment. Relevant advances will include:

- Environmentally benign building blocks and manufacturing processes for the semiconductor, chemical, petroleum, metal/mineral, and pharmaceutical industries
- High-performance nanocatalysts for the chemical, petroleum, and pharmaceutical industries

- More efficient and environmentally acceptable industrial separation and purification process for the chemical, petroleum, metal/mineral, and pharmaceutical industries

In addition to pollution prevention and green manufacturing, more efficient and cost-effective technologies will continue to be needed to detect and monitor pollutants, reduce the release of industrial pollutants, and clean polluted sites and accidental releases of hazardous materials (e.g., oil spills). Thus, we envision that in the next 10 years, the convergence between nanotechnology, information communication/technology, and engineering will lead to major advances, including:

- Small-scale and ubiquitous sensors capable of performing real-time monitoring of environmental systems, including air, water, and soils
- More cost-effective environmental cleanup and remediation technologies for emerging contaminants, including pharmaceuticals, household products, and nanomaterials
- More efficient and cost-effective oil spill clean-up technologies

### **Human Progress, Societal Values, and Economic Development**

As previously discussed, significant progress has been made toward achieving economic and human development worldwide since the adoption of the Millennium Development Goals by the United Nations (UN System Task Team 2012; UNEP 2011a). However, this progress has been uneven, with great disparities in incomes and access to basic service between the “haves” and “have-nots” (Milanovic 2010). Following the June 2012 Rio Conference on Sustainable Development, the United Nations began developing its post-2015 development agenda to promote and facilitate the implementation of a global development agenda that is inclusive, “people-centered,” and sustainable (UN System Task Team 2012). Three guiding principles of the post-2015 UN development agenda are (1) human rights, (2) equality, and (3) sustainability (Fig. 9.8). The implementation of this development agenda will require transformative changes in the ways we produce and consume goods, manage our natural resources, and govern our society. In addition, the convergence of knowledge and technology from numerous fields (physical/biological sciences, engineering, social sciences) will also be required to produce the transformative advances critical to realizing a sustainable, healthy, secure, and peaceful world. Key goals for the next 10–30 years will include:

- Sustainable energy for all
- Universal access to clean water and sanitation
- Sustainable food and nutrition for all
- Universal access to quality healthcare
- Stable climate and clean environment
- Sustainable urban and rural communities
- Sustainable transportation for all
- Decent and productive employment for all

## 9.4 Infrastructure Needs

To realize the post-2015 UN development agenda (Fig. 9.8), it will also be necessary to merge knowledge with technology and entrepreneurship to develop, scale-up, and commercialize the next generation of sustainable products, processes, and technologies. Key science and technological infrastructure needs in the next 10 years include:

- Holistic investigations of all interdependent aspects of sustainable development, including the strong couplings between energy and water, water and agriculture, and energy and materials
- Dedicated facilities for scale-up and testing of materials/systems for sustainability applications
- Dedicated material characterization facilities for sustainability applications
- Computer-aided modeling and process design tools for sustainability applications
- Supercomputers or supercomputing nodes dedicated to solving sustainability-related grand challenges (e.g., catalyst design for solar water splitting and large-scale modeling of urban systems)
- Test-beds for benchmarking and rapid prototyping of sustainability-enabling products, processes, and technologies

## 9.5 R&D Strategies

The critical Grand Challenge for the post-2015 UN development agenda (Fig. 9.8) is to stabilize Earth's climate while (1) achieving a more equitable and sustainable management of our natural resources and (2) enabling inclusive economic and societal development (UNDPUN System Task Team 2012). Because sustainability entails considering social, economic, and environmental factors, it is critical in all cases to converge knowledge (e.g., materials science, nanotechnology, and multiscale modeling) with engineering (e.g., system design, fabrication, and testing), commercialization (e.g., scale-up and new products/solutions), and societal benefits (e.g., new jobs and cleaner environment) as we address the R&D priorities outlined in this report. Thus, sustainable development cannot simply be addressed at the level of small- and single-investigator research grants. Sustainability R&D needs to be integrated with broader research goals and included from the beginning in large interdisciplinary programs to be carried out by teams of investigators and/or dedicated Federally funded transdisciplinary research and development centers. In addition, partnerships between academia, government (Federal, state, and local), industry, and the venture capital community will be critical to translating R&D advances into innovative products and solutions. To achieve these objectives, it will be necessary to:

- Establish focused centers and networks to develop and implement solutions to our critical sustainability challenges in energy, water, food, materials, climate, and environment

- Develop new funding mechanisms to advance promising early-stage research projects, e.g., automatic supplemental funding for projects with commercial potential
- Involve industry at the outset of programs
- Establish focused innovation hubs and ecosystems to bring sustainable solutions/products into the marketplace for broader societal benefit

## 9.6 Conclusions and Priorities

The convergence of knowledge and technology for societal benefit (CKTS) will be critical to achieving the UN goals discussed above. The global sustainability challenges facing the world are complex and involve multiple interdependent and strongly coupled global problems. We expect CKTS to provide breakthrough and scalable solutions for sustainable development, particularly in the areas of renewable energy (generation, conversion, and storage), clean water resources, food/agriculture resources, materials resources, climate stabilization, and clean environment. The following key priorities have been identified for the next decade:

- Solar energy generation, storage, and distribution. Two priorities are:
  - Development and deployment of terawatt-scale solar energy at a cost comparable to or lower than that of energy derived from fossil fuels
  - Development of efficient and cost-effective technologies to convert solar energy into hydrogen and liquid fuels
- Water science, technology, management, and utilization. Two priorities are:
  - Understanding, modeling, and managing the impact of global climate change on freshwater resources
  - Development of sustainable technologies to (1) reuse water, (2) reclaim wastewater, and (3) desalinate brackish water and seawater while recovering energy, nutrients (nitrogen and phosphorous), and valuable metals (e.g., lithium and magnesium)
- *Sustainable agriculture and food security*. A key priority is to develop and deploy more sustainable agricultural and food production systems with reduced (or zero) greenhouse gas emissions, reduced water/land usage, and increased application of conservation tillage, biotechnology, and information technologies throughout the agricultural and food production chain.
- *Sustainable supply and utilization of critical materials*. Three key priorities are to develop novel technologies/strategies to:
  - Decrease the utilization of critical materials in energy generation, conversion, and storage, and/or to
  - Replace them with earth-abundant alternatives
  - Augment the supply of critical materials through recycling, reuse, and extraction from nontraditional sources such as mine tailings, industrial wastewater, seawater, and brines

- *Sustainable urban communities.* A key priority is to reconfigure existing megacities and configure future ones into smarter cities with:
  - Resilient and distributed energy and water infrastructures
  - Sustainable agriculture/food production and supply systems
  - Energy-efficient transportation systems
  - Distributed healthcare infrastructure, more livable environments, and employment opportunities for all

## 9.7 R&D Impact on Society

CKTS offers the potential to extend the limits of sustainability and enable inclusive human, economic, and societal development on Planet Earth. However, we must ensure that any potentially adverse effect on humans and the environment are effectively assessed and addressed before large-scale deployment of CKTS-enabled sustainability products and solutions.

## 9.8 Examples of Achievements and Convergence Paradigm Shifts

### 9.8.1 *R&D Programs to Support Sustainable Development in the United States*

*Contact persons: Jessica Robin and Bruce Hamilton, NSF*

A number of U.S. Federal agencies are making very substantial investments to support R&D for sustainable development. Examples include the Department of Energy (DOE) for clean energy (see <http://www.eere.energy.gov/>); the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA) for sustainable agriculture (see <http://www.sare.org/Grants>), and in collaboration with DOE, fuels from biomass (see <http://www.usbiomassboard.gov/>); and the U.S. Environmental Protection Agency (EPA) for sustainable materials management (see <http://www.epa.gov/epawaste/conservesmm/vision.htm>). Correspondingly, the President's 2013 budget proposed \$2.3 billion for DOE's Energy Efficiency and Renewable Energy Office and \$292 million for USDA's bio-energy research (OSTP 2012). Concurrently, NSF formulated and implemented an agency-wide investment area, Science, Engineering, and Education for Sustainability (SEES).

SEES is a 10-year initiative with the overall mission to advance science, engineering, and education to inform the societal actions needed for environmental and economic sustainability and sustainable human well-being. Now in its fourth year, the SEES portfolio includes 17 interdisciplinary programs that represent a

significant and growing cross-NSF investment. The first set of SEES programs focused on the environment and the portfolio has expanded to include programs in energy, materials, cyber, and resilience (see SEES program page, <http://www.nsf.gov/sees/>). NSF investment in SEES for FY10 was \$70 million, for FY11 was \$93 million, for FY12 was \$170 million, and the request for FY13 was \$203 million (NSF's budget requests to Congress are available online at <http://www.nsf.gov/about/budget/>). SEES programs give strong attention to incorporating the human sciences in addition to integrating education, partnerships, and networks both domestically and internationally.

A 2012 National Academy of Sciences sustainability symposium stated there lacks a commonly accepted operational framework for how to move forward in addressing sustainability challenges (Saunders 2012). Sustainability efforts must integrate and coordinate government resources and funding. Furthermore, the interface between science and policy needs a more adaptive management structure that allows agencies to learn from their management experiences and incorporate lessons learned into their management structures. In turn, sustainability research requires new knowledge, technologies, and approaches; education and workforce development; more integrative science; partnerships; and linking knowledge to action.

Sustainability science includes a broad range of research domains spanning climate, biodiversity, agriculture, fishery, forestry, energy, water, economic development, health, and lifestyles (Kajikawa 2008; Kajikawa et al. 2007). While the field of sustainability science has grown rapidly since the 1980s, the integration across disciplines into a new field only started in recent years (Bettencourt and Kaur 2011). Collaborative links between researchers accelerated after 1989, but it was not until 2000 that the field became dominated by a unified group of collaborations to which most authors in this field now belong. Bettencourt et al. (2009) argue that such unification is the hallmark of a true field of science. Correspondingly, there are numerous Federal programs that support new knowledge, technologies, and approaches, as well as education and workforce development, in the research domains of sustainability. By and large these programs coincide with the corresponding agencies' missions (e.g., NSF supporting fundamental science and engineering, National Institutes of Health [NIH] enhancing human health, the Department of the Interior (DOI) protecting natural resources). Some agencies' programs focus on generating new knowledge across a spectrum of domains, such as NSF's SEES portfolio, while others such as the NIH Clean Cookstoves initiative (NIH Fogarty International Center 2010) and DOI's WaterSMART Clearinghouse (<http://www.doi.gov/watersmart/>) focus on specific technologies and approaches.

The degree to which the sciences are integrative across these programs also depends on the agencies' mission and their partnerships. The National Science Foundation, which funds basic research across all nonmedical science and engineering disciplines from mathematics to geosciences and social sciences, provides opportunities for supporting integrative science across disciplines through initiatives such as SEES. USDA's mission to provide leadership on food, agriculture, natural resources, rural development, nutrition, and related issues allows for integrative research, extension, and education programs that focus on sustaining all

components of agriculture, including renewable energy, rural communities, and human nutrition. Additionally, partnerships across Federal agencies integrate the sciences even further by coordinating resources and broadening the range of research and services that can be supported. NSF supports agriculture research in its Water Sustainability and Climate (WSC) and Decadal and Regional Climate Prediction using Earth System Models (EaSM) programs through a partnership with USDA. DOE also partners on the latter program. Concurrently, NSF's Arctic SEES program provides space for engaging community stakeholder groups and local, state, and regional governments in research through a partnership with the EPA. Additionally, partnerships with DOI (the Bureau of Ocean Energy Management, U.S. Geological Survey, U.S. Fish and Wildlife Service) and a consortium of French agencies broaden the scope of this program even further.

Such partnerships extend internationally as well. NSF, NIH, and the U.S. Agency for International Development (USAID) collaborate on the Partnerships for Enhanced Engagement in Research (PEER), which provides support to researchers from developing countries in a wide range of sustainability topics from disaster mitigation to renewable energy to child survival. USAID and NSF partner on the PEER Science component, and USAID and NIH partner on the PEER Health component, both managed by The National Academies. Funding resources are also leveraged by partnering with scientific funding agencies from other countries. NASA, NSF-China, and the São Paulo Research Foundation of Brazil (FAPESP) partner with NSF on their Dimensions of Biodiversity program (DoB). Additionally, NSF's Partnerships for International Research and Education (PIRE) program partners with funding agencies from the UK, Japan, and Russia, in addition to the Inter-American Institute for Global Change Research (IAI), USAID, and EPA. In this program, the partner agencies indicate priority sustainability research areas and provide support for their respective researchers collaborating with U.S. researchers funded through the PIRE program in those topics. Priority research areas include materials & engineering (UK), nanotechnology (Russia), energy (Japan and Russia), information technology (Russia), water (Japan and EPA), and global change (IAI and Japan).

Sustainability science, like agricultural and health sciences, is defined by the problems it addresses rather than by the disciplines it employs; it is neither basic nor applied but use-inspired science with a commitment to moving such knowledge into societal action (Clark 2007; Kates 2011). While use-inspired research aligns more closely with USDA and the U.S. Department of Human & Health Services, their mandates limits them to supporting only certain domains of sustainability (e.g., agriculture and health). DOE broadens the portfolio by supporting energy-related research, and NSF, with an even broader research mandate, covers multiple domains. But they lack the expertise, resources, and mandate to link the scientific research they support to action. EPA and DOI are much better suited for that role through their regional offices and partnerships with local and state governments. However, they need the research support of these other agencies. In short, no U.S. Federal agency has the capability, or mandate, to support and manage all the needed requirements for sustainability research.



Partnerships, domestically and internationally, are essential, and the ones above are moving in the right direction but opportunity-specific. What is needed is a comprehensive and coordinated approach that spans across all Federal agencies and research domains of sustainability science. The President's National Science and Technology Council, through its Committee on Environment, Natural Resources, and Sustainability, has taken preliminary steps in that direction. Additionally, an ad hoc National Research Council committee under its Science and Technology for Sustainability Program has been convened to identify priority areas for interagency cooperation among domains such as energy, water, and health that are not routinely considered in decision-making. This project is sponsored by multiple Federal agencies, private foundations, and industry. The task is not an easy one, and much can be learned from the experiences of the U.S. Global Change Research Program (USGCRP; <http://globalchange.gov/>), a consortium of U.S. agencies that coordinate Federal research on changes in the global environment, and the Belmont Forum (<http://igfagcr.org/index.php/belmont-forum>), a scientific council for global change research comprised of 14 countries and the European Union (EU), as well as the International Council for Science (ICSU) and the International Social Science Council (ISSC). In closing, sustainability research inherently requires converging knowledge and technologies. A comprehensive and coordinated U.S. Federal research program would provide the needed space for that to happen and to address the sustainability challenges we now face.

### ***9.8.2 Nuclear Energy as a CKTS Solution for Sustainability***

*Contact persons: Ken Chong, NIST and George Washington University, and Philippe M. Bardet, George Washington University*

Like wind and hydroelectricity, nuclear power has a very low carbon footprint. Nuclear power plant capital costs are about three times more than conventional coal power plant costs. However, the production cost of electricity from nuclear power is 50 % less than from coal. President Obama called for “a new generation of safe, clean nuclear power plants” in his 2010 State of the Union address.<sup>1</sup> As of November 2010, 29 countries worldwide were operating 441 nuclear reactors for electricity generation. After Japan's Fukushima Daiichi nuclear power plant disaster due to the earthquake and following tsunamis on March 11, 2012, new attention has been given to nuclear safety worldwide. Nevertheless by May 2012, 66 new nuclear plants were under construction in 14 countries.

#### **Introduction and Historical Background Since the 1940s**

The development of nuclear energy marks a great accomplishment of human ingenuity and collaboration (Marcus 2010). Driven initially by fundamental physicists

---

<sup>1</sup><http://www.whitehouse.gov/the-press-office/remarks-president-state-union-address>

who uncovered the structure of the atom and how to extract energy from it, it took the twentieth century to transform nuclear energy into a safe and reliable source of electricity. Atomic energy is the densest known source of energy, and it has one of the smallest carbon footprints for electricity production. It is also one of the least expensive sources of baseload electricity. However, high costs of building new plants, the handling of nuclear wastes, and negative public perceptions have all hindered its further deployment in some countries. In 2010, nuclear energy represented 13.5 % of the world electricity production. Despite severe accidents such as at Three-Mile Island, Chernobyl, and Fukushima, this energy source continues to grow: besides the 66 reactors being built now, another 250 are being planned within the next 25 years. Other countries are considering investing in this technology.

The development of nuclear technology is the result of multidisciplinary collaboration among physicists and chemists, as well as chemical, electrical, mechanical, structural, and materials science engineers, working together to create and build revolutionary technologies, ranging from electricity production to medical applications. The introduction of nuclear engineering departments at U.S. universities in the 1950s is an illustration of this phenomenon; professors from established and diverse academic backgrounds created and defined this new field of study.

### **Radioactive Sources for Medical, Energy, Explosive, and Other Purposes**

Many isotopes of chemical elements are radioactive, and we are surrounded by low-level radioactivity. Depending on the application, various isotopes are used in treating cancers, medical imaging, space power systems, food sterilization, and nuclear power, among many other fields.

For nuclear energy production, both fissionable nuclides, i.e., capable of sustaining a chain reaction, and fertile nuclides, which first need to be converted to fissile ones by neutron absorption, have been demonstrated and used. Uranium-235 is the most commonly used fissile nuclide; plutonium-239 is also used in fast reactor and mixed oxide (MOX) fuels. Fertile nuclides such as thorium-232 and uranium-238 are all employed.

Many synthetic isotopes, such as cesium-137 or cobalt-60, are produced in nuclear reactors and employed for medical radiation therapy, food irradiation, or industrial radiography. Plutonium-238 is used for space radioisotope thermoelectric generators. Another alpha-emitter, Americium-241, a by-product of fission, is commonly employed in smoke detectors.

### **Research, Education, and Safety of Nuclear Power Plants**

Continued public and private research has led to better understanding of reactor conditions. As a result, plant safety, operation, and predictability have improved significantly. However, there are still some major challenges and research areas with

respect to nuclear power plants, and CKTS will have a transformative effect on them (Chong 2011). As an example, the broad field of mechanics plays a critical role in nuclear technology, through such subdisciplines as fracture mechanics, multiscale mechanics, new materials, nano-mechanics for high-temperature and extreme-environment applications and assured safety (Glade et al. 2006), nuclear penetration mechanics, and multiphase flow.

Simulation refers to the application of computational models to the study and prediction of physical events or the behavior of engineered systems (Oden et al. 2006). The development of computer simulation has drawn from a deep pool of scientific, mathematical, computational, and engineering knowledge and methodologies. Improvements in performance for large-scale simulations of turbulent magneto hydrodynamics show that advances in simulation algorithms over a period of a couple of decades have tripled the effective performance compared to performance improvements due to advances in processor speed alone. Similar results have been documented in many other domains, such as turbulent combustion and radiation transport.

There has been a significant increase in U.S. DOE R&D funding since 2000 (see section below on R&D investment). Nuclear engineering education has had contributions from many branches of engineering and fundamental sciences, such as chemistry, biology, and physics. Only a fraction of graduating nuclear engineers ends up working in the energy field. Enrollment in nuclear engineering degrees has increased since 2006, from a low in the early 2000s (ORISE 2011). In 2010, the number of undergraduate students getting a degree in nuclear engineering at 32 U.S. academic institutions was 443. This represents a 167 % increase compared to 2003.

### **Next-Generation Nuclear Energy Systems: GEN IV**

The current operating fleet of nuclear power plants is comprised of generation II nuclear reactors, and most of the reactors being currently deployed worldwide are generation II+ systems or above, with nearly half being generation III and III+. The main evolution for generation III+ systems is the introduction of enhanced passive safety systems. Passive safety systems do not require electrical power for the reactor to be cooled down in case of accident.

The next-generation nuclear energy systems, or GEN IV, incorporate transformative technology with new coolants and materials. By design, this next generation of nuclear systems will produce reactors that are sustainable, economical, safe and reliable, and proliferation-resistant. To study the feasibility of alternative designs and initiate R&D, the Generation IV International Forum (GIF) was formed with 13 Members (Argentina, Brazil, Canada, China, Euratom [European Atomic Energy Community], France, Japan, Republic of Korea, Republic of South Africa, Russian Federation, Switzerland, the United Kingdom, and the United States). GIF selected six nuclear energy systems as most promising for future collaborative development and able to meet GIF goals: gas-cooled fast reactors, lead-cooled fast reactors, sodium-cooled fast reactors, molten-salt-cooled reactors, supercritical-water-cooled reactors, and very-high-temperature reactors.

## Transmutation Science and Engineering

Nuclear wastes, or spent fuels, are significantly denser than those of any other energy sources; however, if untreated, they need to be stored for millenniums before their activity reaches non-radiotoxic levels. This makes it a very controversial issue that hinders public acceptance of atomic energy. By bombarding nuclides with neutrons, the nuclear structure can be artificially manipulated, i.e., the number and type of nucleons in a nucleus can be altered, changing “lead into gold” or fissioning large transuranic isotopes (actinides). Actinides are long-lived radioactive isotopes in spent fuels; by transmutation their activity can be reduced from millennia to a few decades. Nuclear wastes thus can become more manageable on a human scale.

A roadmap for the third- and fourth generation nuclear energy systems (NERAC/GIF 2002, 5) anticipates that these will be technically available after 2010 and 2030, respectively.

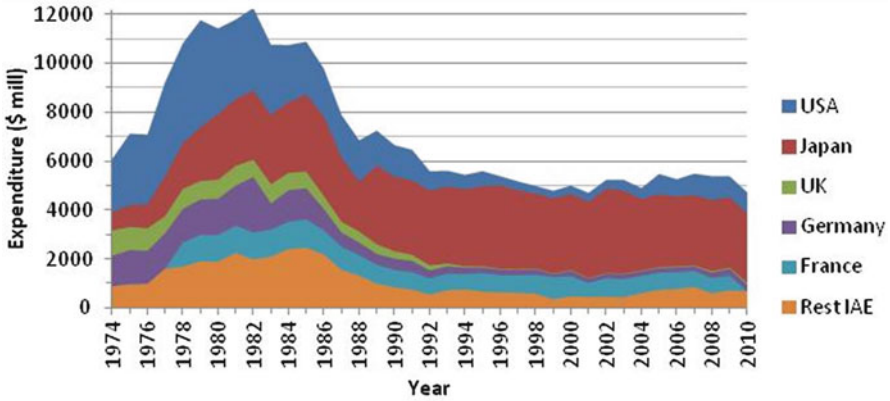
To artificially transmute used nuclear fuels, high-energy particles are necessary. They can be produced by neutrons in fast reactors (in the deep burn fuel cycle), in particle accelerators, or in fusion devices. Accelerator technology coupled with better predictability of composition of spent fuels rods has led to the advancement of the “reactor-driven reactors,” which are becoming a very promising technology.

## Public Investment in R&D Since 1950 for Civilian Nuclear Energy

Energy R&D support has a distinct share between government and industry. Government financing of R&D tends to be focused on long-term new technology development. On the other hand, private R&D financing is focused on further developing and improving existing technology. In the United States from 1950 till 2010, the government provided \$837 billion for all energy development, in 2010 dollars (NEI 2011). Of this, the largest fraction was tax concessions, which mostly benefitted the oil, gas, and coal industries (47 % of the total); the nuclear industry did not receive any tax incentives. Nuclear energy, excluding fusion, received nearly half (\$74 billion of \$153 billion) of all public R&D funding—\$42 billion from 1950 to 1976 and \$31.4 billion from 1976 to 2010—and 9 % of all energy incentives.

## Evolution of Investment in Civilian Nuclear RD&D in the U.S. in Comparison to Other Countries

Since 1950 in the United States, light water reactor technology accounted for only 8 % (\$5.3 billion in 2010 dollars) of the nuclear RD&D (research, development, and demonstration) incentives, though it now provides almost 20 % of U.S. electricity. Many of the alternative reactor concepts studied in the United States served as the baseline for GEN-IV development. Public funding was significantly reduced in 1988 (Fig. 9.9) when the breeder reactor program was cancelled (EIA 2011). Overall,



**Fig. 9.9** IEA countries' expenditure in 2010 dollars from 1974 to 2010 for research development & demonstration on nuclear energy, including fusion (Courtesy of Philippe Barder; created using data from EIA 2011). Data are missing for France prior to 1976 and in 2010, and for South Korea prior to 2002. The main contributors to the "rest of IEA" category of countries have been Canada, Italy, and South Korea

nuclear R&D peaked at \$4.4 billion in 1979: \$0.04 billion for LWR, \$0.90 billion for fuel cycle, \$2.3 billion for breeder and other converter reactors, \$1.2 billion for fusion, \$0.2 billion for nuclear supporting technology. Public R&D funding declined sharply to about \$550 million in 1987 then fell steadily to a low of \$310 million in 1999 (with \$281 million for fusion and only \$29 million for fission). In 2010, funding for fission R&D increased back to \$470 million. Since 1988, public spending on nuclear R&D has been less than for coal, and since 1994 it has been less than that for renewable energies as well.

The peak in public expenditure for nuclear energy R&D in countries associated with the International Energy Agency (IEA; <http://www.iea.org/countries/>), notably excluding China, Russian Federation, and India) was reached around 1979 (\$12 billion, with more than a third of that in the United States) (Fig. 9.9). IEA-reported RD&D expenditures decreased sharply after the Chernobyl accident in 1986. From the late 1980s till 2010, while the United States, the United Kingdom, and Germany significantly decreased their investment in nuclear energy R&D, only Japan, France, and Canada have maintained a steady R&D program at an annual funding, respectively, of about \$3 billion, \$700 million, and \$300 million. In 2010, the U.S. Government-supported nuclear energy R&D represented 0.3 % of total Federal R&D support; the comparative investments were 12 % for Japan and 4 % for France. In 2010, total national R&D funding was \$402 billion for the United States, \$138 billion for Japan, and \$48 billion for France; government contributions were, respectively, 31 %, 18 %, and 39 % of total R&D funding.

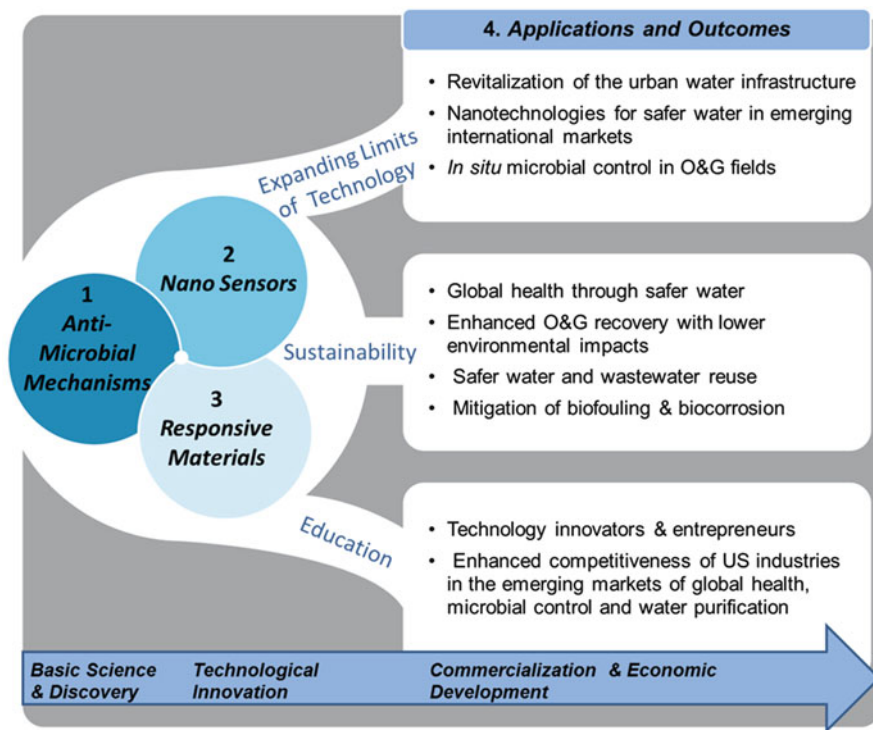
### **9.8.3 *Convergence of Nanotechnology and Microbiology: Emerging Opportunities for Water Disinfection, Microbial Control, and Integrated Urban Water Management***

*Contact person: Pedro Alvarez, Rice University*

No other resource is as universally necessary for life as is water; its safety and availability is a grand challenge inextricably linked to global health and economic competitiveness. While a myriad of water contaminants can cause disease, by far the greatest waterborne threat arises from pathogenic microorganisms. Overcoming this challenge is becoming increasingly difficult as the demand for safer water grows with the world's population and climate change threatens to take away a large fraction of already scarce freshwater. Furthermore, aging water treatment and distribution systems in many cities cannot ensure reliable disinfection; in fact, some systems serve as incidental sources of microbial diseases. Traditional solutions to microbial control have not been able to keep up with the increasing complexity, new barriers, and renewed relevance of this problem. For example, 106 outbreaks and 5,024 recent cases of illness in the United States were attributed to waterborne pathogens in public water systems (Yoder et al. 2008), while each year 39 million Americans suffer infections from waterborne pathogens, leading to productivity losses on the order of \$20 billion (Reynolds et al. 2008). The problem is more pronounced in developing nations. Almost one billion people still lack access to safe water (Hutton and Haller 2004), and diarrhea causes about two million infant deaths every year (UNICEF and WHO 2009). Overall, the importance of enhancing water disinfection and microbial control cannot be overstated. The challenge to efficiently disinfect without forming harmful disinfection byproducts (DBPs) and the growing demand for retrofitting aging water infrastructure and developing distributed point of use (POU) water treatment and reuse systems, underscore the needs for new technologies and water management approaches that provide practical solutions for clean water.

#### **Convergence of Nanotechnology and Microbiology as a Synergistic Interdisciplinary Area**

The most intellectually stimulating and technologically productive areas of research often occur at the interfaces between disciplines. Such interdisciplinary research has great potential to generate new products and services; enhance human capacity, economic competitiveness, and social achievements; and enable sustainable development (Roco and Bainbridge 2003). Nanotechnology has had a transformative impact on numerous disciplines, including surface science, organic chemistry, molecular biology, semiconductor physics, and microfabrication. Similarly, the convergence of nanotechnology with environmental microbiology would likely result in an interdisciplinary field with great potential for meaningful disruptive



**Fig. 9.10** Operational vision and potential outcomes of nanotechnology-enabled water disinfection and microbial control (Courtesy of Pedro Alvarez, Rice University)

innovation. This convergence could expand the limits of water technologies and enhance industrial competitiveness in the emerging markets of global health, microbial control, and water purification, as well as contribute to water security (and thus, energy and food security) and sustainable development (Fig. 9.10).

### How Can Nanotechnology Make a Difference in Water Treatment?

Previous research suggests a great potential for nanotechnology-enabled microbial control (Li et al. 2008). Some nanoparticles interact directly with microbial cells to disrupt the integrity of the cell membrane (e.g., carbon nanotubes) and interrupt respiration and energy transduction (e.g., fullerenes and ceric oxide [CeO<sub>2</sub>]). Other nanoparticles act indirectly by producing secondary products that serve as disinfection agents, e.g., reactive oxygen species generated by titanium dioxide (TiO<sub>2</sub>) or dissolved metal ions released by silver nanoparticles (AgNPs). Nanotechnology can also contribute to integrated urban water and wastewater management by enabling a distributed and differential water treatment and reuse paradigm where water and wastewater are treated locally to the level required by the intended use. This would

minimize water quality degradation within aging distribution networks, alleviate dependence on large and centralized system infrastructure (e.g., use only basic treatment near the source water to enhance distribution, and complement it by tailored POU treatment), exploit alternative water sources (e.g., recycled wastewater or storm water) for potable, agricultural, or industrial use, and decrease energy requirements for treating and moving water (Qu et al. 2012).

### Implementation Barriers

Cost and performance are critical factors for the broad acceptance of novel water treatment nanotechnologies. In developing countries, water treatment often only covers the most basic needs, such as disinfection, when available. In contrast, industrialized nations tend to use more advanced technologies to remove a wider spectrum of emerging pollutants. However, in both scenarios, there is a need to treat increasingly complex pollutant mixtures and supply higher-quality water at lower cost, which is pushing the boundaries of current treatment approaches. The proposed nanotechnology-based treatment options are high performance—enabling more efficient treatment. However, the relatively high costs of nanomaterials represent a significant (but, perhaps, only temporary) implementation barrier.

Nanomaterial costs are unlikely to decrease significantly without an increase in demand to favor economy of scales. Nevertheless, the cost of nanomaterial synthesis is generally small compared to that incurred by separation and purification steps, due to the high energy and chemical requirements of the latter. This suggests an opportunity to decrease costs by using nanomaterials of lower purity. Another cost-reduction strategy is to facilitate nanomaterial reuse, such as immobilizing photocatalysts that retain high activity after multiple reuse cycles, and iron-containing nano-adsorbents (e.g., nano-magnetite for arsenic removal), which can be separated magnetically and regenerated. Reuse decreases nanomaterial costs per volume of water treated, which is a more relevant feasibility metric than the price of nanomaterials per gram. Potential impacts to human or ecosystem health associated with incidental or accidental releases of nanomaterials represent another important barrier from both regulatory and public acceptance perspectives (Alvarez et al. 2009). Therefore, it is important to take a proactive approach to assess the fate and mitigate potential risks associated with nanomaterials used in (or flowing into) water and wastewater treatment processes.

Social acceptability is also a critical consideration that requires balancing economic and human dimensions while adopting a position of proactive responsibility and inclusiveness. An unbalanced focus on technical innovation may pose risks to the human dimension and jeopardize the sustainability of the technology, whereas focusing too much on responsible development may generate too-restrictive regulations and approaches that delay economic and societal benefits (Roco and Bainbridge 2003). Similarly, disregarding the need to include all stakeholders represents a wasted opportunity to integrate social and ethical issues that intersect with pertinent governmental functions (e.g., funding and regulation), and to establish mechanisms



to inform and involve the public about potential impacts of nanotechnology and dispel common misconceptions. This could lead to slower technology implementation and dissemination (and even isolationism). Finally, it is important to resist a tendency to focus on short-term economic feasibility, and rather prioritize a longer-term vision for water security (e.g., nanotechnology-enabled integrated water management) for current and future generations.

### **Outlook for Nanotechnology in the Water Sector**

Despite the aforementioned potential barriers, nanotechnology will likely be increasingly relied upon for needed innovations in water treatment and reuse. The benefits of incorporating nanomaterials have a clear overall benefit when one or more of the following conditions prevails:

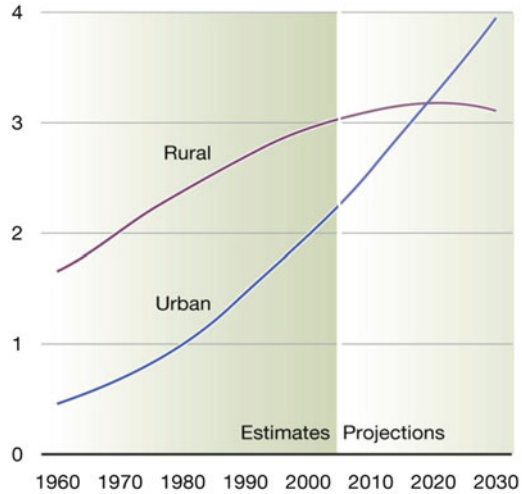
- Current processes fail to meet existing or upcoming requirements
- Wastewater reuse is hindered by hazardous micropollutants that break through the treatment process
- POU approaches are needed because of insufficient infrastructure
- Nanomaterials can improve the cost-effectiveness of the treatment process at low additive ratios

Near-term applications include upgrading and enhancing treatment capabilities without major alterations to existing infrastructure (e.g., more efficient disinfection of resistant microbes, and lower potential for DBP formation, microbial-induced corrosion, and membrane fouling) while possibly enabling the use of nonconventional water sources for different reuse scenarios (Qu et al. 2012). Nanomaterials could also be incorporated in POU systems to differentially treat drinking water to higher standards, obviating concerns about secondary contamination through the distribution system. Distributed and differential treatment approaches enabled by POU devices would also be attractive for rural areas and expanding cities in developing countries that lack extensive water infrastructure, where capital investment for new infrastructure may not be feasible. In such cases, nanotechnology could help develop POU systems that are tailored to site-specific needs with minimal use of electricity or imported chemicals.

### **Conclusions**

The extraordinary size-dependent properties of some nanomaterials (e.g., high specific surface area, photosensitivity, catalytic and antimicrobial activity, electrochemical, optical, and magnetic properties, and/or tunable pore size and surface chemistry) offer leapfrogging opportunities to develop next-generation applications for drinking water disinfection and safer wastewater reuse (e.g., photocatalytically enhanced disinfection, biofouling-resistant membranes, biofilm- and corrosion-resistant surfaces, and sensors for pathogen detection). The convergence of nanotechnology

**Fig. 9.11** Urban and rural populations in less developed regions (billions), estimated projections (Ahlenius 2009, ©UNEP/GRID-Arendal, used by permission)



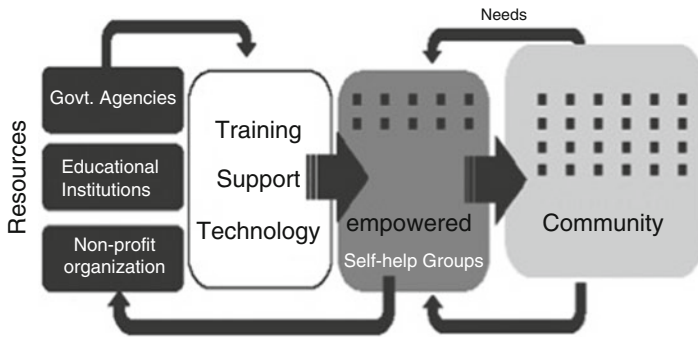
with environmental microbiology is a fertile interdisciplinary research area that could expand the limits of technology, enhance global health through safer water reuse, serve as an innovation ecosystem to nurture intellectual entrepreneurs, and contribute towards sustainable and integrated urban water management.

#### 9.8.4 Sustainable Rural Communities

*Contact person: Roop Mahajan, Virginia Polytechnic Institute and State University*

Rural communities in large swaths of the developing world face an array of poverty-related challenges, including lack of housing, infrastructure, access to quality healthcare, education, and a steady means of income. Despite an historic population shift towards urban areas (Fig. 9.11), global poverty remains a massive and predominantly rural phenomenon. According to the Rural Poverty Report 2011, “of the 1.4 billion people living in extreme poverty [less than US\$1.25/day] in 2005, approximately one billion—around 70 %—lived in rural areas.” With an estimated global population of 8.3 billion in 2030, the rural population in less developed countries, after accounting for the expected migration from rural to urban areas, is estimated to be over three billion (Ahlenius 2009; Cohen 2006).

Lifting this large population out of poverty is a mammoth undertaking, and not surprisingly, one of the top priorities of most governments. However, the implementation of rural development programs over the years has had mixed results, at best, due to political instability, lack of resources, and most important, the absence of a planned approach for sustainable long-term solutions. In many cases where non-profits, philanthropists, and businesses have intervened to supplement the scant resources and fill the gap, many of these efforts remain uncoordinated. Needed are innovative solutions that integrate the best available technologies and practices,



**Fig. 9.12** Role of self-help groups as drivers of positive change at the grass-roots level (Courtesy of Roop Mahajan)

and seek the active involvement of the affected population to achieve sustainable development. The goal is to establish *sustainable rural communities* that meet the basic needs of food, clean drinking water, energy, healthcare, education, and provide meaningful jobs, affordable homes, and economical transportation.

To reach these goals, regions much rely as much as possible on their capabilities and the natural resources of the area. Such self-reliant and vibrant rural communities will help retain and attract young people and thus stem the migration to increasingly unsustainable urban centers that are characterized by sprawl where people live in slums larger than the cities themselves, inefficient energy use resulting in heavy smog, uncontrolled wastewater, and overburdened systems that impede rather than enable human ability. A possible model to identify, develop, and successfully implement solutions for creating sustainable rural communities is to form partnerships among self-help groups (SHGs)—*informal clubs or associations of people who choose to come together to find ways to improve their life situations*, government agencies at the local level, privately supported nonprofits, and local colleges and communities (Fig. 9.12).

At the core of these partnerships are SHGs, which have been shown to be critical in formulating the needs of the community and gaining acceptance of the proposed solutions in education, micro-financing and technology adoption, to name a few (Mayoux 1997). In the words of Kanayo F. Nwanze, the president of the International Fund for Agricultural Development (IFAD), “It is time to look at poor smallholder farmers and rural entrepreneurs in a completely new way—not as charity cases but as people whose innovation, dynamism and hard work will bring prosperity to their communities and greater food security to the world in the decades ahead” (<http://www.un.org/en/globalissues/briefingpapers/ruralpov/progress.shtml>). In these partnerships, institutions of higher learning play multifaceted roles. They serve as interlocutors between the SHGs and other stakeholders. Through their extension and outreach programs, they can provide the curriculum, structure, and in some cases, workforce to implement solutions. Lastly, their student bodies can act as role models for the young people in the community. The other stakeholders—the nonprofits

and government agencies—can bring the resources and the best practices for the partnerships to succeed. Organic in nature, such partnerships can serve as the testing grounds for an appropriate mix of converging knowledge and technology, which could possibly migrate to neighboring communities and beyond.

An example of a portfolio of technologies and practices that can be deployed to marshal a rural community in a developing country to reach self-reliance is shown in Table 9.2. The solutions represent a holistic combination of technological solutions, practices, and principles of self-empowerment targeted specifically for rural communities.

Although not specifically listed in Table 9.2, it is implied that the latest converging and emerging technologies, where feasible, will be part of the solution. In large-scale farming, for example, new farm equipment with GPS and radio signals can be used to tailor planting, fertilizing, and insect-control to the specific strengths and needs of the soil, allowing plants to better withstand severe conditions. Other examples include smart sensors and delivery systems that can help the agriculture industry in early disease detection, combating viruses and other crop pathogens, monitoring environmental conditions, and delivering nutrients or pesticides as appropriate (ETC Group 2004). Nanotechnology can also improve our understanding of the biology of different crops and thus potentially enhance yields or nutritional value. In addition, it can offer routes to added-value crops or environmental remediation (Nanoforum 2006). Nanofibers, electrospun from biodegradable cellulose and scrap material, can be used for air filtration, protective clothing, and possibly as mats to absorb and release fertilizers and pesticides for targeted application (Johnson 2005).

As one of the emerging technologies, additive manufacturing (AM) may offer a novel means for the incorporation of converging technologies into prototype and finished products (Ivanova et al. 2013). Since AM allows products to be designed and printed that are more appropriate for local consumption using local materials, including recycled materials, the rural community could reduce reliance on expensive imports by designing and making their own products and reaping the profits from this production.

Finally, the need for sustainable communities, including rural, is also receiving attention from the developed world. For example, in the United States, the interagency Partnership for Sustainable Communities was established on June 16, 2009, among the Department of Transportation (DOT), Department of Housing and Urban Development (HUD), and U.S. Environmental Protection Agency (EPA) to coordinate investments and policies to support sustainable communities—urban, rural, and suburban. The partnership provided six guiding “living principles”: (1) safe, reliable, and economical transportation choices; (2) equitable and affordable housing; (3) enhanced economic competitiveness; (4) support of existing communities; (5) healthy, safe, and walkable neighborhoods; and (5) coordination of Federal policies and resources. The U.S. Department of Agriculture (USDA) joined this Partnership to form a Rural Work Group to reinforce the initiatives and ensure that the four agencies’ efforts lead to economically vibrant and environmentally sustainable rural communities. In 2003, the British government launched the “Communities

**Table 9.2** Convergence of knowledge and technology to build sustainable communities

Need	Enabling technology/ service	Comments
Energy	Solar technology	Electricity, water purification, and food processing at a community level
	Wind	Low cost, locally built windmills for power generation and/or pump water for irrigation
	Biomass	A user-friendly biogas plant that can be linked to a community kitchen as well as linked to organic farming
	Oil	Oil-based power generation unit that supplements a solar + wind power plant
	Natural gas	Natural gas to supplement the bio gas system to provide fuel for the community
Water for household	Rain water harvesting	Harvested rain water linked to a point of use (POU) purification system to supplement existing drinking water supply
	Waste water treatment POU systems	Use of sustainable filtration system for grey water POU systems installed and run by the community, for safe drinking water (Heierli 2008)
Agriculture	Small-scale farming	Promoted by self-help groups, it can result in jobs in agriculture, food processing and transportation sectors
	Large-scale farming	Industrial-scale farming equipment, a catalyst for subsidiary services, training centers, and fabrication facilities
	Smart sensors	Better communication & efficiency among various system components
	Drip irrigation	A service offered by a local self-help group to small-scale farmers. It can energize food production, jobs
Healthcare	Immunization	Effective immunization to reduce child mortality, promote women's health and community productivity; a cell-phone-based immunization system will simplify the process for the government agencies and users
	Mobile clinics	Mobile clinics with a link up to a regional hospital can serve multiple communities
	Telemedicine	Access to a physician at remote locations using hi-tech communication devices
Women empowerment	Micro entrepreneurship	Micro-finance self-help groups provide opportunities for community-level solutions (Mayoux 1997)
	Skills training	SHGs can be trained in the areas of small scale manufacturing, food processing, and providing support services for education
	Local governance	Role of SHGs expanded to include women in local governments

(continued)

**Table 9.2** (continued)

Need	Enabling technology/ service	Comments
Education	Education	Innovative ways to provide non-formal access to education
	Secondary education	Secondary level education program that is in tune with the local needs and culture
	Community centers	To be run by SHGs after they have been trained in critical areas like small-scale manufacturing
Employment	Cultural/folk art centers	To preserve and promote the artistic expressions of the local community and provide much needed encouragement
	IT centers	Easy access to information in a user-friendly way can catalyze a community in a revolutionary way
	Job opportunities	To educate and inform the community about various employment opportunities

Plan” (Sustainable Communities: Building for the Future) and set out plan of actions for “delivering sustainable communities in both urban and rural areas” (Smith 2008). As expected, there is an overlap between the aspirations of rural communities in the developed and the developing economies. The concept of participatory SHGs and the deployment of CKTS can therefore be easily adapted for rural communities across the world.

### ***9.8.5 Convergence of Knowledge and Technology for Extracting Valuable and Critical Metals from Waste Streams***

**Contact person:** David Allen, *The University of Texas at Austin*

Industrialized economies use large quantities of fuels, minerals, biomass, and other materials. Although material use varies among developed economies, on average, total material use in all industrial economies is greater than 100 lb per person per day, not including water use (Matthews et al. 2000). Each of these materials has a life cycle: they are extracted from the lithosphere or biosphere, processed into commodity materials and products, then recycled or disposed of.

Most industrial systems use materials once, with no engineered recycling systems. It could be argued that the low rates of material reuse in industrialized economies are due to the inherently low value of materials in wastes; however, empirical evidence suggests that much more extensive mining of materials from wastes could be done economically. Doing so will require a convergence of knowledge concerning the flows of materials in industrialized economies and the development of technologies suitable for recovering critical materials.

## Mapping Material Flows

As noted above, per capita material flows in industrialized economies are significant. Characterizing the flows and emissions of these materials over the course of their life cycles requires data on material flows entering the economy, manufacturing processes, and information on wastes, emissions, and recycling structures. Data that enable tracking and optimization of national and global material flows are just emerging, and terminology and data analysis frameworks are still evolving (NRC 2003). Material flow analyses are performed on systems with well-defined boundaries. The system boundary might be the geopolitical boundaries of a nation, the natural boundaries of a river's drainage basin, or the technological boundaries of a cluster of industries.

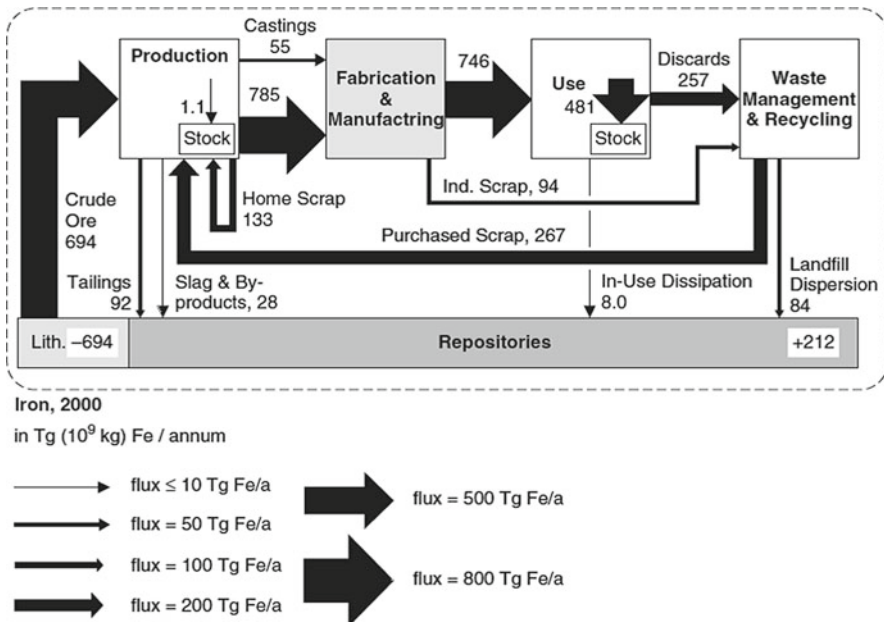
Consider, as an example of material flow analyses, the element lead (Pb). Pb is a neurotoxin, and Pb exposure is associated with developmental delays (<http://www.epa.gov/iris>), so human exposure should be minimized. Historically, some of the principal uses of lead have been as an octane enhancer in gasoline, in batteries, and in paint. The material flows of Pb in the United States in 1970 and in the mid-1990s are shown in a USGS publication (2000, 14). Such a figure can provide details such as in 1970 the fraction of virgin material was 36 % (450 tons recycled/1,250 tons total usage), while in the mid-1990s the fraction had increased to 65 % (910 tons recycled/1,400 tons total usage). The Pb was incorporated into a variety of products. Some products, even when used as designed (such as lead paint applied outdoors or lead additives in gasoline), result in the release of Pb into the environment (dissipative uses). Other products, when used as designed (lead acid batteries), allow Pb to be effectively recovered and recycled at the end of the product's life (nondissipative uses).

Figure 9.13 illustrates another potential structure for the mapping of material flows (Graedel et al. 2011). The figure includes additional types of flows, using global use of iron as a case study. It separates iron flows into production, fabrication/manufacturing, use, and waste management categories. There are flows between these stages of materials processing, for example, as "home" scrap within production operations is reprocessed. The material flow mapping of Fig. 9.13 also shows flows of material from different processing stages into anthropogenic repositories (such as landfills) and the flows of material into durable goods (stock).

Detailed material flow mappings are not available for most materials. Yet, combinations of materials scarcity and geopolitical factors will put increasing pressure on material flows, and this will necessitate better knowledge of material flow patterns in industrialized economies, so that critical materials can more readily be recovered and recycled.

## The Role of Separation Technologies

If materials are to be mined from waste streams, there must not only be the knowledge of the stocks and flows of the materials, but technologies to recover critical materials from wastes. Currently, the range of technologies used to manage waste



**Fig. 9.13** Global flows of iron in 2000 (Graedel et al. 2011; STAF Project, Yale University Center for Industrial Ecology; © *Journal of Industrial Ecology* 2007, <http://dx.doi.org/10.1111/j.1530-9290.2011.00342.x>, used by permission)

streams is relatively limited. Combustion, wastewater treatment, and land disposal dominate, leaving substantial opportunity for technological progress (Allen 1992; Baker et al. 1992; Allen and Behmanesh 1992). A sense of the critical role that new technologies may play in mining materials from wastes is provided by free energies of mixing. A simple calculation reveals that the entropy that needs to be overcome in separating a pound of a critical material from a million pounds of ore or waste is on the order of 1,000 BTU (a gallon of gasoline has a heating value in excess of 100,000 BTU). This amount of energy is negligible relative to the amounts of energy required by technologies employed to perform such separations. Therefore, fundamental physical limitations are not the key limitation in separating critical materials from wastes. Effective and energy-efficient separation technologies are required.

The potential value of critical materials that might be recovered from waste streams can also be illustrated through a simple case study. Allen and Behmanesh (1994) examined the extent to which hazardous wastes in the United States might be mined (cost-effectively recycled) by comparing the degree of dilution of metals in hazardous waste streams to the concentrations at which the materials were mined. Their original analysis, summarized in Table 9.3, found that many hazardous waste streams in the United States had high enough concentrations of metals to merit additional recycling. Hazardous wastes were chosen because detailed data existed on their compositions, flow rates, and fates.



**Table 9.3** Percentage of metals in hazardous wastes in the U.S. that can be recovered economically (as estimated by Allen and Behmanesh 1994)

Metal	Percent theoretically recoverable (%)	Percent recycled in 1986 (%)
Antimony (Sb)	74–87	32
Arsenic (As)	98–99	3
Barium (Ba)	95–98	4
Beryllium (Be)	54–84	31
Cadmium (Cd)	82–97	7
Chromium (Cr)	68–89	8
Cooper (Cu)	85–92	10
Lead (Pb)	84–95	56
Mercury (Hg)	99	41
Nickel (Ni)	100	0.1
Selenium (Se)	93–95	16
Silver (Ag)	99–100	1
Thallium (Tl)	97–99	1
Vanadium (V)	74–98	1
Zinc (Zn)	96–98	13

Surprisingly, many hazardous waste streams contained relatively high concentrations of metals. Approximately 90 % of the copper, 95 % of the zinc, and 100 % of the nickel found in hazardous wastes was, at the time, at a concentration high enough to recover. For every metal for which data existed, recovery occurred at rates well below rates that would be expected to be economically viable. The economic value of these waste streams is significant. For example, the roughly 3.6 million tons per year of Ni identified as unrecovered in the 1994 analysis has a current market value of over \$50 billion (\$7.00/lb).

This focused analysis, initially performed in 1994, led to the conclusion that many opportunities exist for recovering materials from wastes. There are limitations to the analysis, however. The analysis focused only on hazardous wastes, where legal liability concerns may limit the desire to recycle. The identification of “recycleable” streams was simplistic. It ignored issues related to economies of scale (processing geographically dispersed, heterogeneous waste streams may be more expensive than extracting relatively homogeneous ore from a single mine). Nevertheless, the analysis indicated that resources are not effectively recovered from many waste streams.

The United Nations has assembled more recent, global data on metals recycling. That analysis concludes that global recycling rates can continue to be improved. Metals like Pb (along with Fe, Cr, Co, Ni, Cu, Zn, and many precious metals) have post-consumer recycling rates that exceed 50 % globally, but many other metals (e.g., rare earth elements) have post-consumer recycling rates of less than 1 % (UNEP 2011b). Key factors in changing this situation will be knowledge of material flow patterns and separation technologies required to recover critical materials.

## 9.9 International Perspectives

The following are summaries relevant to this chapter of discussions during the international regional WTEC NBIC2 workshops held in Leuven, Belgium, September 20–21, 2012; in Seoul, Korea, October 15–16, 2012; and in Beijing, China, October 18–19, 2012. Further details of those workshops are provided in Appendix A.

### 9.9.1 United States–European Union NIBIC2 Workshop (Leuven, Belgium)

#### *Panel members/discussants*

*Daan Schuurbiens (Chair), Utrecht University (EU)*

*Mamadou Diallo, Caltech (U.S.) and Korea Advanced Institute of Science and Technology (KAIST)*

*Albert Duschl, University of Salzburg (EU)*

*Barbara Harthorn, University of California–Santa Barbara (U.S.)*

*Todd Kuiken, Woodrow Wilson International Center for Scholars (U.S.)*

*Andy Miah, University of the West of Scotland (EU)*

*Alfred Nordmann, Darmstadt University of Technology (EU)*

*Anders Sandberg, Oxford University (EU)*

*Bruce Tonn, University of Tennessee (U.S.)*

The U.S.–EU Working Group 2 consisted of a diverse group of physical scientists, engineers, and social scientists. The group devoted its discussion to the broad areas of sustainable development and human development. The discussion focused on four topics of global sustainability: water (Topic 1), energy and environment (Topic 2), megacities and urban communities (Topic 3), and agriculture and food (Topic 4). For each topic, the U.S.–EU Working Group 2 outlined broad research questions/objectives and discussed how the convergence of knowledge and technology for the benefit of society can help address these questions to achieve concrete outcomes in the next 10, 20, and 50 years. The group also discussed governance-related issues for each topic. Below we give a summary of the discussion for each topic.

#### **Topic 1: Water**

Core Idea: Use wastewater and saline water as sources of clean water, nutrients, and materials.

Concrete outcomes:

- Beyond reverse osmosis—develop biomimetic desalination membranes that work like ion channels and aquaporins
- Solutions of major energy and water problems

Governance:

- Competing technological options: water reuse or desalination
- Public acceptance of water reuse: “purity” and “disgust” issues

## **Topic 2: Energy**

Core Idea: Reduce energy imports; reduce GHG by 80 %: low or no carbon emissions by 2050.

Concrete outcomes:

- Solar energy-develop more efficient and advanced photovoltaic cells
- Fusion energy after 2050.

Governance:

- Energy security as a social concern
- Energy as international development issue
- Energy and society: how does the social system of energy production, distribution, and use have to change to accommodate a shift to a society that consumes less energy?

## **Topic 3: Megacities and Urban Communities**

Core Idea: Design and build the sustainable cities and urban communities of the twenty-first century.

Concrete Outcomes:

- Urban planning for megacities – maximizing positive effects
- Sustainable energy infrastructure (“on-the-spot” generation of energy and smart grids)
- Sustainable materials usages (recycling, urban mining and 3D printing)

Governance:

- Intelligent management systems: information/communication technologies to address social planning questions, harness creativity and tacit knowledge to identify, improve, and share solutions for a sustainable lifestyle in mega cities and urban communities.

## **Topic 4: Agriculture and Food**

Core idea: Build sustainable agriculture and food production systems

Concrete Outcomes:

- Non-genetically modified drought-resistant crops
- More efficient hydroponic agricultural and vertical farming systems
- Precision agriculture systems to optimize the delivery of water, nutrients (nitrogen and phosphorus), and pesticides to crops.

Governance:

- Food quality and taste: “Keep things as they are”
- Necessary condition for the EU debate, otherwise it would jeopardize the acceptance of CKTS as tool in building sustainable agriculture and food production systems

### **9.9.2 United States–Korea–Japan NBIC2 Workshop (Seoul, Korea)**

#### **Panel members/discussants**

*Mamadou Diallo (co-chair), Caltech (U.S.) and KAIST (Korea)*

*Kazuyo Matsubae (co-chair), Tohoku University, Japan*

*Young Hyun Cho, Dongbu Hitek Co., Ltd. (Korea)*

*Bruce Tonn, University of Tennessee (U.S.)*

*Robert Urban, MIT (U.S.)*

The U.S.-Korea-Japan Working Group S9 devoted its discussion to the broad area of sustainable development. The group focused on three topics: renewable energy sources (Topic 1), agriculture, food and natural resources (Topic 2), megacities and urban communities (Topic 3). For each topic, the U.S.-Korea-Japan Working Group S9 outlined broad research questions/objectives and discussed how the convergence of knowledge and technology (CKTS) can help address these questions in the next 10 years. Below we give a summary of the discussion for each topic.

#### **Topic 1: Renewable Energy Sources (Solar and Biomass)**

Core Idea: Develop and deploy more efficient renewable energy sources from solar and biomass.

*CKTS Tools*

##### **A. Solar energy**

- World’s best Si-based solar cell modules have an efficiency of 24.7 %
- Multi-junction concentrators are very expensive but can get up to 42 %.
- Next generation of high-efficiency solar cells: nanocrystalline silicon-quantum dots, thin film solar cells using quantum dots

##### **B. Biomass**

- Korea established the Advanced Biomass R&D Center at KAIST to convert algae biomass to fuels. The program is funded at a level of \$12–15 million per year for 9 years.

## Topic 2: Agriculture, Food, and Natural Resources

Core Idea: Recovery of nutrients (phosphorous) from non-traditional sources

### *CKTS Tools*

- Monitor the global flow of phosphorous using advanced sensor networks
- Develop more efficient separation technologies to recover phosphorous from non-traditional sources including wastewater and slags from steels plant
- Increase public/regulatory acceptance of using recycled phosphorus to grow food crops

## Topic 3: Megacities and Urban Communities

Core Idea: Design and build smart and sustainable cities

### *CKTS Tools*

- New forms of transportation that anticipates destinations and builds routing, timing, clustering, and redistribution
- Balance power usages through on and off grid energy bi-directional transfers
- Wellness-based living: walkable, breathable, community health-centric, safety, stress-minimized, family/education-directed
- Ubiquitous monitoring/sensing of urban systems (environment, diseases, hazards)
- On-demand and local manufacturing (3D printers, auto assemblers, carbon legos)
- Urban agriculture/food production systems (e.g., high-efficiency vertical farms)
- Design efficient closed-loop urban water and wastewater systems
- Develop strategies to retrofit existing megacities into smarter and more sustainable cities

### 9.9.3 *United States–China–Australia–India NBIC2 Workshop (Beijing, China)*

#### *Panel members/discussants*

*Mamadou Diallo (co-chair), Caltech (U.S.) and KAIST (Korea)*

*Ming Liu (co-chair), Chinese Academy of Sciences (China)*

*Ian Lowe (co-chair), Australian Conservation Foundation (Australia)*

*Yajun Guo, National Natural Science Foundation (China)*

*Xiangyu Jiang, National Center for NanoScience and Technology (China)*

*Bruce Tonn, University of Tennessee (U.S.)*

*Robert Urban, MIT (U.S.)*

The U.S.-China-Australia-India Working Group S9 devoted its discussion to the broad area of sustainable development. The group focused on three topics: minerals

and materials (Topic 1), global climate change and environment (Topic 2) and rural and low-income communities (Topic 3). For each topic, the U.S.–China–Australia Working Group S9 outlined broad research questions/objectives and discussed how the convergence of knowledge and technology can help address these questions to achieve concrete outcomes in the next 10 years. Below we give a summary of the discussion for each topic.

### **Topic 1: Minerals and Materials**

Core Idea: Optimize materials usage and supply to reduce the reliance on critical minerals/materials in sustainable energy generation and storage.

#### *CKTS Tools*

- Materials are not the limit, if energy is unlimited, non-critical materials (earth-abundant materials) can be found/used in lower amounts (supply, utilization, substitution)
- Recycling advances (extraction of industrial waste, mine tailings)
- Energy efficient separation technologies using high-capacity and selective ligands/hosts
- High-efficiency supercapacitors using nanostructured materials
- Integrated battery-supercapacitor systems

### **Topic 2: Environment and Global Climate Change**

Core Idea: Develop more efficient strategies to mitigate CO<sub>2</sub> emission and utilize CO<sub>2</sub> as feedstock to produce liquid fuels and useful products

#### *CKTS Tools*

#### A. Mitigation

- Develop and deploy low-CO<sub>2</sub> emitting sources of energy (e.g., solar and wind)
- Develop and deploy carbon capture and storage technologies (e.g., flue gases and ambient air)
- Improve the energy efficiency of existing products and processes

#### B. Utilization

- Conversion of CO<sub>2</sub> to fuels and chemicals by artificial photosynthesis
- Use CO<sub>2</sub> as a raw material in chemical manufacturing to produce polymers and cement

### **Topic 3: Rural and Low-Income Communities**

Core Idea: Sustainable technologies for supporting rural and low income communities

*CKTS Tools*

- Connect every family to “the cloud” to enable access to health and wellness information
- Effective information/communication (ICT) tools to support and empower rural and low-income communities
- Affordable healthcare products (e.g., vaccines, paper-based diagnostics, nano-patches)
- Low-cost energy generation and storage technologies
- Sustainable and distributed water purification and sanitation technologies
- Open source building materials/plans
- Sustainable and affordable food production and storage technologies.

**References**

- Ahlenius, H.: Chart in Nellemann, C, MacDevette, M, Manders, T, Eickhout, B, Svihus, B, Prins, AG, Kaltenborn, BP (eds.) The environmental food crisis—the environment’s role in averting future food crises UNEP/GRID-Arendal. Available online: [http://www.grida.no/graphicslib/detail/trends-in-urban-and-rural-populations-less-developed-regions-1960-2030-estimates-and-projections\\_bd04](http://www.grida.no/graphicslib/detail/trends-in-urban-and-rural-populations-less-developed-regions-1960-2030-estimates-and-projections_bd04) (2009)
- Allen, DT: An overview of industrial waste generation and management practices. *MRS Bull.* **17**(3), 30–33 (1992)
- Allen, DT, Behmanesh, N: Non hazardous waste generation. *Hazard. Waste Hazard. Mater.* **9**, 91–96 (1992)
- Allen, DT, Behmanesh, N: Wastes as raw materials. In: Allenby, BR, Richards, DJ (eds.) *The Greening of Industrial Ecosystems*, pp. 69–89. The National Academies Press, Washington, DC (1994)
- Alvarez, PJ, Colvin, V, Lead, J, Stone, V: Research priorities to advance eco-responsible nanotechnology. *ACS Nano* **3**(7), 1616–1619 (2009)
- Aravinda, CL, Cosnier, S, Chen, W, Myung, NV, Mulchandani, A: Label-free detection of cupric ions and histidine-tagged proteins using single poly(pyrrole)-NTA chelator conducting polymer nanotube chemiresistive sensor. *Biosens. Bioelectron.* **24**, 1451–1455 (2009)
- ARPA-E: Rare earth alternatives in critical technologies (REACT). Available online: <http://arpa-e.energy.gov/programsprojects/react.aspx> (2011)
- Bainbridge, WS: Demographic collapse. *Future* **41**, 738–745 (2009)
- Baker, RD, Warren, JL, Behmanesh, N, Allen, DT: Management of hazardous waste in the United States. *Hazard. Waste Hazard. Mater.* **9**, 37–60 (1992)
- Balogh, L, Swanson, DR, Tomalia, DA, Hagnauer, GL, McManus, ET: Dendrimer-silver complexes and nanocomposites as antimicrobial agents. *Nano Lett.* **1**(1), 18–21 (2001)
- Baochang, G, Feng, W, Zhigang, G, Erli, Z: China’s local and national fertility policies at the end of the twentieth century. *Popul. Dev. Rev.* **33**(1), 129–147 (2007)
- Bates, BC, Kundzewicz, ZW, Wu, S, Palutikof, JP (eds.): *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva (2008). Available online: <http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf>
- Bettencourt, LMA, Kaur, J: Evolution and structure of sustainability science. *PNAS* **108**(49), 19540–19545 (2011)
- Bettencourt, LMA, Kaiser, DI, Kaur, J: Scientific discovery and topological transitions in collaboration networks. *J. Informetr.* **3**(3), 210–221 (2009). <http://dx.doi.org/10.1016/j.joi.2009.03.001>

- Birnbaum, ER, Rau, KC, Sauer, NN: Selective anion binding from water using soluble polymers. *Sep. Sci. Technol.* **38**(2), 389–404 (2003)
- Brinker, JC, Ginger, D: Nanotechnology for sustainability: energy conversion, storage, and conservation. In: Roco, MC, Mirkin, C, Hersham, M (eds.) *Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook*, pp. 261–303. Springer, Dordrecht (2011). *Science Policy Reports*
- Britt, D, Furukawa, H, Wang, B, Glover, TG, Yaghi, OM: Highly efficient separation of carbon dioxide by a metal-organic framework with open metal sites. *PNAS* **106**, 20637–20640 (2009)
- Brundtland, GH: Annex A/42/427 to Report of the World Commission on Environment and Development: Our Common Future. United Nations World Commission on Environment and Development, New York (1987). Available online: [http://www.channelingreality.com/Documents/Brundtland\\_Searchable.pdf](http://www.channelingreality.com/Documents/Brundtland_Searchable.pdf)
- Cáceres-Delpiano, J: Can we still learn something from the relationship between fertility and mother's employment? Evidence from developing countries. *Demography* **49**(1), 151–174 (2012)
- Capper, JL, Cady, RA, Bauman, DE: The environmental impact of dairy production: 1944 compared with 2007. *J. Anim. Sci.* **87**, 2160–2167 (2009)
- Chen, DP, Yu, CJ, Chang, C-Y, Wan, Y, Goddard, WA, Diallo, MS: Branched polymeric media: perchlorate-selective resins from hyperbranched polyethyleneimine. *Environ. Sci. Technol.* **46**, 10718–10726 (2012)
- Chong, K.P.: Nuclear energy: safety, production, mechanics research and challenges. Plenary Lecture IMECE2011-65987, ASME Congress, Denver, CO, November (2011)
- Christensen, K, Doblhammer, G, Rau, R, Vaupel, JW: Aging populations: the challenges ahead. *Lancet* **374**(9696), 1196–1208 (2009)
- Clark, WC: Sustainability science: a room of its own. *PNAS* **104**, 1737–1738 (2007)
- Clive, J.: Global status of commercialized Biotech/GM crops: 2011. ISAAA Brief No. 43. ISAAA, Ithaca: International Service for the Acquisition of Agri-Biotech Applications. Available online: <http://www.isaaa.org/resources/publications/briefs/43/default.asp> (2011)
- Cohen, JE: *How Many People Can the Earth Support?* W. W. Norton, New York (1995)
- Cohen, JE.: Human population: the next half century. In Kennedy, D. (ed.) *Science Magazine's State of the Planet 2006–7*. Island Press, London (2006). Joseph, T., Morrison, M.: Nanotechnology in Food and Agriculture. Institute of Nanotechnology. <http://www.nano-forum.org/dateien/temp/nanotechnology%20in%20agriculture%20and%20food.pdf> (2006)
- Coleman, J.: World's 'seven billionth baby' is born. *The Guardian*. Sunday 30 Oct 2011. Available online: <http://www.guardian.co.uk/world/2011/oct/31/seven-billionth-baby-born-philippines?intcmp=122> (2011)
- Costanza, R., Alperovitz, G., Daly, H., Farley, J., Franco, C., Jackson, T., Kubiszewski, I., Schor, J., Victor, P.: Building a Sustainable and Desirable Economy-in-Society-in-Nature. Report to the United Nations for the 2012 Rio+20 Conference. Division for Sustainable Development, United Nations Department of Economic and Social Affairs, New York (2012)
- Crooks, RM, Zhao, M, Sun, L, Chechik, V, Yeung, LK: Dendrimer-encapsulated metal nanoparticles: synthesis, characterization, and application to catalysis. *Acc. Chem. Res.* **34**, 181–190 (2001)
- Davis, K: The theory of change and response in modern demographic history. *Popul. Index* **29**, 345–366 (1963)
- Davis, SC, Diegel, SW, Boundy, RG: *Transportation Energy Data Book*. ORNL-6981, 27th edn. Oak Ridge National Laboratory, Oak Ridge (2008)
- den Hond, F: Industrial ecology: a review. *Reg. Environ. Chang.* **1**(2), 60–69 (2000)
- Diallo, MS, Brinker, JC: Nanotechnology for sustainability: environment, water, food, minerals and climate. In: Roco, MC, Mirkin, C, Hersham, M (eds.) *Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook*, pp. 221–259. Springer, Dordrecht (2011). *Science Policy Reports*
- Diallo, MS, Christie, S, Swaminathan, P, Balogh, L, Shi, X, Um, W, Papelis, C, Goddard, WA, Johnson, JH: Dendritic chelating agents. 1. Cu(II) binding to ethylene diamine core poly(amidoamine) dendrimers in aqueous solutions. *Langmuir* **20**, 2640–2651 (2004)



- DOE (Department of Energy): Buildings energy data book. Available online: <http://buildingsdata-book.eere.energy.gov> (2009a)
- DOE (Department of Energy): Modern shale gas development in the United States: A primer. Available online: [http://fossil.energy.gov/news/techlines/2009/09024-Shale\\_Gas\\_Primer\\_Released.html](http://fossil.energy.gov/news/techlines/2009/09024-Shale_Gas_Primer_Released.html) (2009b)
- DOE (Department of Energy): Critical materials strategy. Available online: <http://energy.gov/pi/office-policy-and-international-affairs/downloads/2010-critical-materials-strategy> (2011)
- DOE (Department of Energy): Critical materials hub. Available online: <http://energy.gov/articles/ames-laboratory-lead-new-research-effort-address-shortages-rare-earth-and-other-critical> (2013)
- Ehrlich, PR: *The Population Bomb*. Ballantine, New York (1968)
- EIA (U.S. Energy Information Administration): Annual energy outlook 2011. <http://www.eia.gov/oiaf/aeo/gas.html> (2011)
- Elimelech, M, Phillip, WA: The future of seawater desalination: energy, technology and environment. *Science* **333**, 712–717 (2011)
- ETC Group. Down on the Farm: The Impact of Nano-scale Technologies on Food and Agriculture. ETC Group, Ottawa. Available online at <http://www.etcgroup.org/content/down-farm-impact-nano-scale-technologies-food-and-agriculture> (2004)
- Fan, ZY, Wang, DW, Chang, PC, Tseng, WY, Lu, JG: ZnO nanowire field-effect transistor and oxygen sensing property. *Appl. Phys. Lett.* **85**, 5923–5925 (2004)
- Field, L.: Soft geoen지니어ing: Ice 911. Available online: [http://www.wilsoncenter.org/event/considering-soft-geoen지니어ing#field\\_files](http://www.wilsoncenter.org/event/considering-soft-geoen지니어ing#field_files) (2012)
- Fromer, N., Eggert, R.G., Lifton, J. (ed.): *Critical Materials for Sustainable Energy Applications*. Caltech Resnick Institute Report. Available online: <http://resnick.caltech.edu/programs/critical-materials/index.html> (2011)
- Gallezot, P: Conversion of biomass to selected chemical products. *Chem. Soc. Rev.* **41**, 1538–1558 (2012)
- Glade, SC, Wirth, BD, Odette, GR, Asoka-Kumar, P: Positron annihilation spectroscopy and small angle neutron scattering characterization of nanostructural features in high-nickel model reactor pressure vessel steels. *J. Nucl. Mater.* **351**, 197–208 (2006)
- Graedel, TE, Allwood, J, Birat, J-P, Buchert, M, Hagelüken, C, Reck, BK, Sibley, SF, Sonnemann, G: What do we know about metal recycling rates? *J. Ind. Ecol.* **15**(3), 355–366 (2011). <http://dx.doi.org/10.1111/j.1530-9290.2011.00342.x>
- Heidrich, ES, Curtis, TP, Dolfig, J: Determination of the internal chemical energy of wastewater. *Environ. Sci. Technol.* **45**(2), 827–832 (2011)
- Holt, JK, Park, HG, Wang, Y, Stadermann, M, Artyukhin, AB, Grigoropoulos, CP, Noy, A, Bakajin, O: Fast mass transport through sub-2-nanometer carbon nanotubes. *Science* **312**, 1034–1037 (2006)
- Howden, LM, Meyer, JA: Age and Sex Composition: 2010. 2010 Census briefs. U.S. Census Bureau, Washington, DC (2011)
- Hutton, G, Haller, L: Evaluation of the Costs and Benefits of Water and Sanitation Improvements at the Global Level. World Health Organization WHO/SDE/WSH/04.04, Geneva (2004)
- Iceland, C.: Aqueduct and the water–energy–food nexus. Presentation, Bonn Nexus Conference, Bonn, Germany, 17 Nov 2011. Interactive water map available online: <http://insights.wri.org/aqueduct> (2011)
- EIA (International Energy Agency): Energy technology RD&D budgets. Available online: <http://www.iea.org/stats/rd.asp> (2011)
- ILO (International Labour Organization): World Social Security Report 2010/11: Providing Coverage in Times of Crisis and Beyond. ILO, Geneva (2010)
- ILO (International Labour Organization): Global Employment Trends 2011 (Geneva). Available from [http://www.ilo.org/wcmsp5/groups/public/@dgreports/@dcomm/@publ/documents/publication/wcms\\_150440.pdf](http://www.ilo.org/wcmsp5/groups/public/@dgreports/@dcomm/@publ/documents/publication/wcms_150440.pdf) (2011)
- IPCC (Intergovernmental Panel on Climate Change): Carbon Dioxide Capture and Storage. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Eds.

- Metz, B, Davidson, O, de Coninck, H, Loos, M, Meyer, L. Cambridge University Press, Cambridge (2005)
- IPCC (Intergovernmental Panel on Climate Change): Climate change 2007: the physical science basis. In: Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M, Miller, HL (eds.) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge/New York (2007a)
- IPCC (Intergovernmental Panel on Climate Change): Impacts, adaptation, and vulnerability. In: Parry, ML, Canziani, OF, Palutikof, JP, van der Linden, PJ, Hanson, CE (eds.) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York (2007b)
- IPCC: Summary for policymakers. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schloßner, S., von Stechow, C. (eds.) IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge/New York (2011)
- Ivanova, O., Williams, C., Campbell, T.: Additive manufacturing (AM) and nanotechnology: promises and challenges. *Rapid Prototyp. J.* **19**(5), 353–364 (2013)
- Jeong, BH, Hoek, EMV, Yan, Y, Huang, X, Subramani, A, Hurwitz, G, Ghosh, AK, Jawor, A: Interfacial polymerization of thin film nanocomposites: a new concept for reverse osmosis membranes. *J. Membr. Sci.* **294**, 1–7 (2007)
- Johnson, A.: Agriculture and Nanotechnology (University of Wisconsin–Madison Student-Produced Report). Available online at <http://www.tahan.com/charlie/nanosociety/course2011/nanos/AJ.pdf> (2005)
- Kajikawa, Y: Research core and framework of sustainability science. *Sustain. Sci.* **3**(2), 215–239 (2008). <http://dx.doi.org/10.1007/s11625-008-0053-1>
- Kajikawa, Y, Ohno, J, Takeda, Y, Matsushima, K, Komiyama, H: Creating an academic landscape of sustainability science: an analysis of the citation network. *Sustain. Sci.* **2**(2), 221–231 (2007). <http://dx.doi.org/10.1007/s11625-007-0027-8>
- Kates, RW: What kind of a science is sustainability science? *PNAS* **108**(49, 99), 19449–19450 (2011). <http://dx.doi.org/10.1073/pnas.1116097108>
- Keith, DW, Parson, E, Morgan, MG: Research on global sun block needed now. *Nature* **463**, 426–427 (2010)
- King III, SB, Meier, B: Interventional treatment of coronary heart disease and peripheral vascular disease. *Circulation* **102**, Iv-81–Iv-86 (2000)
- Knodel, J, van de Walle, E: Lessons from the past: policy implications of historical fertility studies. *Popul. Dev. Rev.* **5**, 217–245 (1979)
- Lewis, NS: Toward cost-effective solar energy use. *Science* **315**, 798–801 (2007)
- Li, Q, Mahendra, S, Lyon, DY, Brunet, L, Liga, MV, Li, D, Alvarez, PJ: Antimicrobial nanomaterials for water disinfection and microbial control: potential applications and implications. *Water Res.* **42**(18), 4591–4602 (2008)
- Liu, Y, Majetich, SA, Tilton, RD, Sholl, DS, Lowry, GV: TCE dechlorination rates, pathways, and efficiency of nanoscale iron particles with different properties. *Environ. Sci. Technol.* **39**, 1338–1345 (2005)
- Logan, BE, Rabaey, K: Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies. *Science* **337**, 686–690 (2012)
- Lowry, GV, Johnson, KM: Congener-specific dechlorination of dissolved PCBs by microscale and nanoscale zero-valent iron in a water/methanol solution. *Environ. Sci. Technol.* **38**(19), 5208–5216 (2004)
- Malthus, TR: *An Essay on the Principle of Population*. J. Johnson, London (1798)
- Marcus, GH: *Nuclear Firsts: Milestones on the Road to the Nuclear Power Development*. American Nuclear Society, La Grange Park (2010)
- Matthews, E, Amann, C, Bringezu, S, Fischer-Kowalski, M, Hüttler, W, Kleijn, R, Moriguchi, Y, Ottke, C, Rodenburg, E, Rogich, D, Schandl, H, Schütz, H, van der Voet, E, Weisz, H: *The Weight of Nations*. World Resources Institute, Washington, DC (2000)

- Mayoux, L.: Participatory learning for women's empowerment in micro-finance programmes: negotiating complexity, conflict and change, (October 1996), 1–21 (1997)
- McCarty, PL, Bae, J, Kim, J: Domestic wastewater treatment as a net energy producer—can this be achieved? *Environ. Sci. Technol.* **45**(17), 7100–7106 (2011)
- Milanovic, B: *The Haves and the Have-Nots: A Brief and Idiosyncratic History of Global Inequality*. Basic Books, New York (2010)
- Mishra, H, Yu, C, Chen, DP, Dalleska, NF, Hoffmann, MR, Goddard III, WA, Diallo, MS: Branched polymeric media: boron-chelating resins from hyperbranched polyethyleneimine. *Environ. Sci. Technol.* **46**, 8998–9004 (2012)
- Moyo, DF: *Winner Take All. China's Race for Resources and What It Means for the World*. Basic Books, New York (2012)
- Nanoforum Report. Nanotechnology in Agriculture and Food. Available online at [ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/nanotechnology\\_in\\_agriculture\\_and\\_food.pdf](ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/nanotechnology_in_agriculture_and_food.pdf) (2006)
- NEI (Nuclear Energy Institute), prepared by Management Information Services, Inc.: 60 years of energy incentives: analysis of federal expenditures for energy development. NEI, Washington, DC. Available online: <http://www.misi-net.com/publications/NEI-1011.pdf> (2011)
- NERAC (U.S. Nuclear Energy Research Advisory Committee) and the Generation IV International Forum (GIF): A technology roadmap for Generation IV nuclear energy systems. Available online: <http://www.gen-4.org/PDFs/GenIVRoadmap.pdf> (2002)
- NIH Fogarty International Center: NIH partners on clean cookstoves initiative. *Adv. Sci. Glob. Health* **9**(5). <http://www.fic.nih.gov/News/GlobalHealthMatters/Oct2010/Pages/cookstove.aspx> (2010)
- NRC (National Research Council): *Materials Count: The Case for Material Flows Analysis*. The National Academies Press, Washington, DC (2003)
- NRC (National Research Council): *Minerals, Critical Minerals, and the U.S. Economy*. The National Academies Press, Washington, DC (2008)
- NRC (National Research Council): *Toward Sustainable Agricultural Systems in the 21st Century*. Committee on Twenty First Century Systems Agriculture, Board on Agriculture and Natural Resources, Division on Earth and Life Sciences. The National Academies Press, Washington, DC (2010)
- NRCS (National Resources Conservation Service): *National Resource Conservation Handbook*. NRCS, Washington, DC (2012). Available online: <http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/home>
- Oden, J.T., Belytschko, T., Fish, J., Hughes, T.J.R., Johnson, C., Keyes, D, Laub, A., Petzold, L., Srolovitz, D., Yip, S.: *Simulation-Based Engineering Science: Revolutionizing Engineering Science Through Simulation*. Report of the National Science Foundation Blue Ribbon Panel on Simulation-Based Engineering Science. Available online: [http://www.nsf.gov/pubs/reports/sbes\\_final\\_report.pdf](http://www.nsf.gov/pubs/reports/sbes_final_report.pdf) (2006)
- Oeppen, J, Vaupel, JW: Broken limits to life expectancy. *Science* **296**, 1029–1031 (2002)
- Ogburn, WF: *Social Change with Respect to Culture and Original Nature*. B. W. Huebsch, New York (1922)
- Olson, RL: Soft geoengineering: a gentler approach to addressing climate change. *Environ. Sci. Policy Sustain. Dev.* **54**(5), 29–39 (2012)
- ORISE (Oak Ridge Institute for Science and Education): Nuclear engineering enrollments and degrees survey, 2010 Data, June 2011 Update. Available online: <http://orise.ornl.gov/files/sep/NE-Brief-68.1-2011-data.pdf> (2011)
- OSTP (Office of Science and Technology of the Executive Office of the President): *Innovation for America's Economy, America's Energy, and American Skills: Science, Technology, Innovation, and STEM Education in the 2013 Budget*. OSTP, Washington, DC (2012). Summary available online: [http://www.whitehouse.gov/sites/default/files/microsites/ostp/fy2013rd\\_summary.pdf](http://www.whitehouse.gov/sites/default/files/microsites/ostp/fy2013rd_summary.pdf)
- Park, S, Cheedra, RK, Diallo, MS, Kim, CH, Kim, IS, Goddard III, WA: Nanofiltration membranes based on polyvinylidene fluoride nanofibrous scaffolds and crosslinked polyethyleneimine networks. *J. Nanopar. Res.* **14**, 884 (2012)
- Parsons, T, Shils, EA (eds.): *Toward a General Theory of Action*. Harvard University Press, Cambridge (1951)

- Pennisi, E: Water reclamation going green. *Science* **337**, 674–676 (2012)
- Phan, A, Doonan, CJ, Uribe-Romo, FJ, Knobler, CB, O’Keeffe, M, Yaghi, OM: Synthesis, structure, and carbon dioxide capture properties of zeolitic imidazolate frameworks. *Acc. Chem. Res.* **43**, 58–67 (2010)
- Qu, X, Brame, J, Li, Q, Alvarez, PJ: Nanotechnology for a safe and sustainable water supply: enabling integrated water treatment and reuse. *Acc. Chem. Res.* (Jun 27), 834–843 (2012)
- Rapport, DJ: Sustainability science: an ecohealth perspective. *Sustain. Sci.* **2**, 77–84 (2007)
- Reck, BK, Graedel, TE: Challenges in metal recycling. *Science* **337**, 690–695 (2012). <http://dx.doi.org/10.1126/science.1217501>
- Reid, J.F: The impact of mechanization on agriculture. In Fall issue of The Bridge on Agriculture and Information Technology. National Academy of Engineering (NAE) **41**(3), 22–29. Available online: <http://www.nae.edu/Publications/Bridge/52548/52645.aspx> (2011)
- Reynolds, KA, Mena, KD, Gerba, CP: Risk of waterborne illness via drinking water in the United States. *Rev. Environ. Contam. Toxicol.* **192**, 117–158 (2008)
- Rickerby, DG, Morisson, M: Nanotechnology and the environment: a European perspective. *Sci. Technol. Adv. Mater.* **8**, 19–24 (2007)
- Rifkin, J: *The Third Industrial Revolution: How Lateral Power is Transforming Energy, the Economy, and the World*. Palgrave Macmillan, New York (2011)
- Rockström, J, Steffen, W, Noone, K, Persson, Å, Chapin III, FS, Lambin, EF, Lenton, TM, Scheffer, M, Folke, C, Schellnhuber, HJ, Nykvist, B, de Wit, CA, Hughes, T, van der Leeuw, S, Rodhe, H, Sörlin, S, Snyder, PK, Costanza, R, Svedin, U, Falkenmark, M, Karlberg, L, Corell, RW, Fabry, VJ, Hansen, J, Walker, B, Liverman, D, Richardson, K, Crutzen, P, Foley, JA: A safe operating space for humanity. *Nature* **461**, 472–475 (2009a)
- Rockström, J, Steffen, W, Noone, K, Persson, Å, Chapin III, FS, Lambin, EF, Lenton, TM, Scheffer, M, Folke, C, Schellnhuber, HJ, Nykvist, B, de Wit, CA, Hughes, T, van der Leeuw, S, Rodhe, H, Sörlin, S, Snyder, PK, Costanza, R, Svedin, U, Falkenmark, M, Karlberg, L, Corell, RW, Fabry, VJ, Hansen, J, Walker, B, Liverman, D, Richardson, K, Crutzen, P, Foley, JA: Planetary boundaries: exploring the safe operating space for humanity. *Ecol. Soc.* **14**(2), art.32 (2009b)
- Roco, MC, Bainbridge, WS: *Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology, and Cognitive Science*, p. 467. Kluwer Academic Publishers, Dordrecht (2003). xiii
- Satterthwaite, D: Will most people live in cities? *Br. Med. J.* **321**(7269), 1143–1145 (2000). Available online: <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1118907>
- Saunders, J: Meeting Summary: Partnerships, Science, and Innovation for Sustainability Solutions, A Symposium, May 16–18, 2012. The National Academies Press, Washington, DC (2012). Available online: <http://sites.nationalacademies.org/PGA/sustainability/SustainabilitySymposium/>
- Savage, N, Diallo, M: Nanomaterials and water purification: opportunities and challenges. *J. Nanopart. Res.* **7**, 331–342 (2005)
- Schmidt, KF: *Green Nanotechnology: It is Easier Than you Think*. Project on Emerging Nanotechnologies (Pen 8). Woodrow Wilson International Center for Scholars, Washington, DC (2007)
- Service, RF: Save pave the world. *Science* **337**, 676–678 (2012)
- Shannon, MA, Bohn, PW, Elimelech, M, Georgiadis, JG, Mariñas, MJ, Mayes, AM: Science and technology for water purification in the coming decades. *Nature* **452**, 301–310 (2008)
- Smith, M.K.: Sustainable Communities and Neighbourhoods. Theory, Policy and Practice. In the Encyclopaedia of Informal Education. Available online: [http://www.infed.org/community/sustainable\\_communities\\_and\\_neighbourhoods.htm](http://www.infed.org/community/sustainable_communities_and_neighbourhoods.htm) (2008)
- Song, H, Carraway, ER: Reduction of chlorinated ethanes by nanosized zero-valent iron kinetics, pathways, and effects of reaction conditions. *Environ. Sci. Technol.* **39**, 6237–6254 (2005)
- Staff, J, Mortimer, JT: Explaining the motherhood wage penalty during the early occupational career. *Demography* **49**(1), 1–21 (2012)
- Tang, CY, Zhao, Y, Wang, R, Hélix-Nielsen, C, Fane, AG: Desalination by biomimetic aquaporin membranes: review of status and prospects. *Desalination* **308**, 34–40 (2012). <http://dx.doi.org/10.1016/j.desal.2012.07.007>

- Tobert, JA: Lovastatin and beyond: the history of the HMG-CoA reductase inhibitors. *Nat. Rev. Drug Discov.* **2**, 517–526 (2003)
- Tratnyek, PG, Johnson, RL: Nanotechnologies for environmental cleanup. *Nano Today* **1**(2), 44–48 (2006)
- Tuck, CO, Pérez, E, Horváth, I, Sheldon, RA, Poliakoff, M: Valorization of biomass: deriving more value from waste. *Science* **337**, 695–699 (2012)
- UN (United Nations): 2010 Statistical Yearbook. United Nations, New York (2012)
- UN (United Nations): Demographic, economic, and social drivers. Chapter 2 in *World Water Development Report 3*. Paris: World Water Assessment Program, UNESCO Division of Water Sciences, UNESCO Publishing (2009)
- UN Millennium Project: A Practical Plan to Achieve the Millennium Development Goals. United Nations Development Group, New York (2005). Available online (historic site): <http://www.unmillenniumproject.org/reports/fullreport.htm>
- UN System Task Team on the Post-2015 UN Development Agenda: Realizing the Future We Want for All: Report to the Secretary-General. UN System Task Team, New York (2012). Available online: [http://www.un.org/millenniumgoals/pdf/Post\\_2015\\_UNTTreport.pdf](http://www.un.org/millenniumgoals/pdf/Post_2015_UNTTreport.pdf)
- UNEP (United National Environment Programme): Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication. Part I, Investing in Natural Capital: Chapter 1, Agriculture. UNEP, Nairobi (2011a). Available online: <http://www.unep.org/greeneconomy/greeneconomyreport/tabid/29846/default.aspx>
- UNEP (United National Environment Programme): Recycling Rates of Metals: A Status Report, 2011. Available online: <http://www.unep.org/resourcepanel/Publications/Recyclingratesofmetals/tabid/56073/Default.aspx> (2011b). Accessed July 2011
- UNICEF/WHO: Diarrhoea: Why Children Are Still Dying and What Can Be Done, Ed. Jensen. The United Nations Children’s Fund (UNICEF), New York. World Health Organization (WHO), Geneva (2009)
- UNPF (United Nations Population Fund): State of World Population 2007: Unleashing the Potential of Urban Growth. United Nations Population Fund, New York (2007)
- USGS (United States Geological Survey): Materials and Energy Flows in the Earth Science Century: A Summary of a Workshop Held by the USGS in November 1998, USGS Circular 1194. Available online: <http://pubs.usgs.gov/circ/2000/c1194/c1194po.pdf> (2000)
- Vaseashta, A, Dimova-Malinovska, D: Nanostructured and nanoscale devices, sensors, and detectors. *Sci. Technol. Adv. Mater.* **6**, 312–318 (2005)
- Wang, B, Cote, AP, Furukawa, H, O’Keeffe, M, Yaghi, OM: Colossal cages in zeolitic imidazolate frameworks as selective carbon dioxide reservoirs. *Nature* **453**, 207–211 (2008)
- Wang, R., Setiawan, L., Fane, A.G. (eds.): Forward osmosis: Current status and perspectives. *J. Membr. Sci. Virtual Special Issue*. Available online: <http://www.journals.elsevier.com/journal-of-membrane-science/virtual-special-issues/forward-osmosis-current-status-and-perspectives/> (2012)
- Webber, ME: Energy versus water: solving both crises together. *Sci. Am. Earth* **3**, 34–41 (2008)
- Wikimedia Commons: Top 400 “urban areas” with at least 1,000,000 inhabitants in 2006. Available online at <http://commons.wikimedia.org/wiki/File:2006megacities.PNG> (2007)
- Wikipedia Commons: World Population. Available online at <http://en.wikipedia.org/wiki/File:World-Population-1800-2100.svg> (2012)
- WWF (World Wildlife Fund): The Energy Report—100% Renewable Energy by 2050. Available online: [http://wwf.panda.org/what\\_we\\_do/footprint/climate\\_carbon\\_energy/energy\\_solutions/renewable\\_energy/sustainable\\_energy\\_report/](http://wwf.panda.org/what_we_do/footprint/climate_carbon_energy/energy_solutions/renewable_energy/sustainable_energy_report/) (2011)
- Yoder, J, Roberts, V, Craun, GF, Hill, V, Hicks, LA, Alexander, NT, Radke, V, Calderon, RL, Hlavsa, MC, Beach, MJ, Roy, SL: Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking—United States, 2005–2006. *MMWR Surveill. Summ.* **57**(9), 39–62 (2008)
- Zalasiewicz, J, Williams, M, Steffen, W, Crutzen, P: The new world of the anthropocene. *Environ. Sci. Technol.* **44**(7), 2228–2231 (2010)