Nanotechnology for Sustainability: Environment, Water, Food, Minerals, and Climate*

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The global sustainability challenges facing the world are complex and involve multiple interdependent areas. Chapter "Nanotechnology for Sustainability: Environment, Water, Food, Minerals, and Climate" focuses on sustainable nanotechnology solutions for a clean environment, water resources, food supply, mineral resources, green manufacturing, habitat, transportation, climate change, and biodiversity. It also discusses nanotechnology-based energy solutions in terms of their interdependence with other sustainability target areas such as water, habitat, transportation, and climate change. Chapter "Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation" is dedicated to energy resources.

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1 Vision for the Next Decade

1.1 Changes in the Vision Over the Last 10 Years

Brundtland's Commission placed sustainability at the intersection of social, economic, and environmental factors (Fig. 1) where, "sustainable development is that which meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Sustainability entails considerations of people, the environment, and the economy. To achieve sustainability, it is vital to take into account the complex linkages between the "social system" (i.e., the institutions that support human existence on Earth), the "global system" (i.e., the Earth's ecosystems that support human life) and the "human system" (i.e., all the other factors that impact the health and well being of humans) [2]. Every human being needs food, water, energy, shelter, clothing, healthcare, employment, etc., to live and prosper on Earth. One of the greatest challenges facing the world in the twenty-first century is providing better living conditions to people while minimizing the impact of human activities on Earth's ecosystems and global environment.

In 2000, the nanotechnology research agenda was primarily focused on the discovery, characterization, and modeling of nanoscale materials and phenomena. As nanotechnology continues to advance, the agenda is increasingly focused on addressing two key questions related to sustainability over the next 10 years:

- How can nanotechnology help address the challenges of improving global sustainability?
- Can nanotechnology be developed in a sustainable manner?

Soon after the inception of the National Nanotechnology Initiative (NNI), it was envisioned that nanotechnology could provide more sustainable solutions to the global challenges related to providing and protecting water, energy, food and shelter habitat, mineral resources, clean environment, climate, and biodiversity. Indeed, sustainability has been a goal of the NNI from the outset: "Maintenance of industrial sustainability by significant reductions in materials and energy use, reduced sources of pollution, increased opportunities for recycling" was listed as an

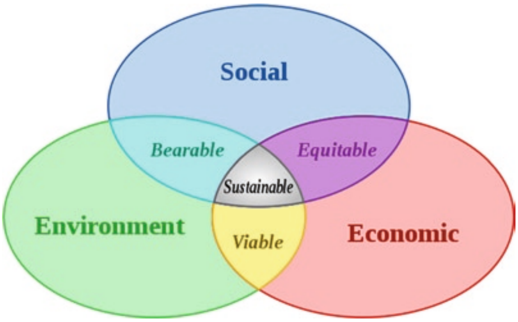


Fig. 1 The three pillars of sustainability [1]

important goal of the NNI in the 1999 Nanotechnology Research Directions Report [85]. Also, in a subsequent address at the Cornell Nanofabrication Center on September 15, 2000, Mike Roco [3] of the National Science Foundation (then co-chair of the Nanoscale Science and Technology Subcommittee of the National Science and Technology Council's Committee on Technology), discussed how nanotechnology could improve agricultural yields for an increased population, provide more cost-efficient and cost-effective water treatment and desalination technologies, and enable the development of renewable energy sources, including highly efficient solar energy conversion systems. Continuing in that vein, he has also noted that nanotechnology promises to "extend the limits of sustainable development… For example, nanoscale manufacturing will provide the means for sustainable development: less materials, less water, less energy, and less manufacturing waste for manufacturing, and new methods to convert energy and filter water …" ([4], pp. 181, 185).

1.2 Vision for the Next 10 Years: A World in Balance

Although Earth has experienced many cycles of significant environmental change, during which civilizations have arisen, developed, and thrived, the planet's environment has been stable during the past 10,000 years [5]. This stability is now threatened as the world's population will reach about seven billion in 2012 [6], and industrial output per capita continues to increase around the world.

Since the Industrial Revolution, human actions have become the main drivers of global environmental change, and could put the "Earth System" (Fig. 2) outside a stable state, with significant or catastrophic consequences. This thesis was proposed by group of investigators from the Resilience Alliance [5]. They defined the Earth System as the set of coupled and interacting physical, chemical, biological, and socioeconomic processes that control the environmental state of Planet Earth. Rockström and colleagues [5] proposed a new conceptual framework, "planetary boundaries," for "estimating a safe operating space for humanity with respect to the functioning of the Earth System." They suggested planetary boundaries in nine areas underlying global sustainability: climate change, rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading (see Fig. 2 and Table 1).

Rockström et al. [5] argue that humanity must stay within defined planetary boundaries for a range of key ecosystem processes to avoid catastrophic environmental changes; they maintain we have already transgressed three of these of nine boundaries: (1) atmospheric CO_2 concentration, (2) rate of biodiversity loss, and (3) input of nitrogen into the biosphere. In the case of global freshwater, they believe that "the remaining safe operating space for water may be largely committed already to cover necessary human water demands in the future"(http://www.ecologyandsociety.org/vol14/iss2/art32/).

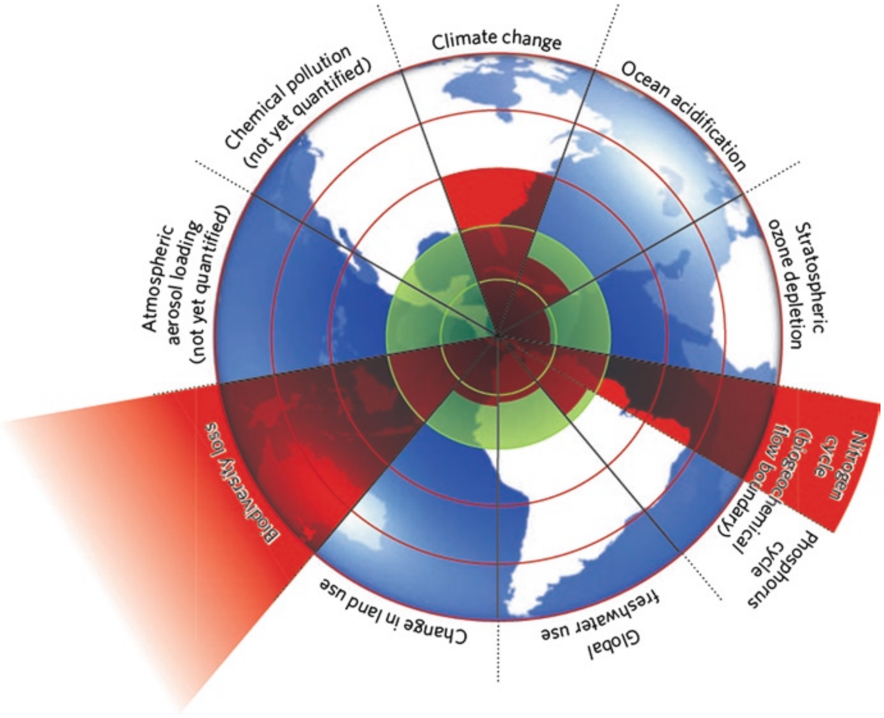


Fig. 2 Planetary boundaries: The inner (*green*) shaded nonagon represents the safe operating space with proposed boundary levels at its outer contour. The extent of the wedges for each boundary shows the estimate of current position of the control variables as highlighted in Table 1 [5]

Arguably, nanotechnology has the potential to address each of these areas of global sustainability, where metrics could be developed to quantify the impact of, for example, the ability of nanotechnology to ameliorate a critical value of one or more control variables for the planetary boundaries, such as carbon dioxide concentration. The following discussion highlights several topical areas in sustainability where nanotechnology is likely to have the greatest impact over the next decade. Efficiency—the amount of energy, water, and natural resources consumed per unit of goods produced or performance achieved—is the most important metric for gauging progress in achieving sustainability.

2 Advances in Last 10 Years and Current Status

To address the two interrelated questions about sustainability raised above, the following subsections provide a background discussion (the status) for each of the nine sustainability goals, an assessment of how nanotechnology may advance the goal, and quantitative metrics against which progress can be measured.

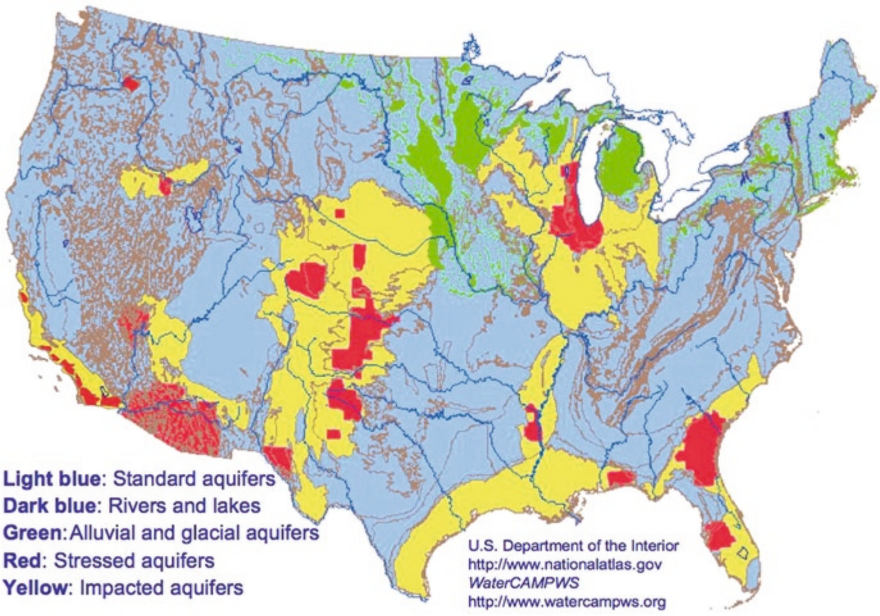
Table 1 Planetary boundaries with proposed boundary and current values of the control variables

Planetary boundaries				
Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	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_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acididfication	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^3 per year)	4,000	2,600	415
Change 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 on ecosystem and functioning of Earth system thereof	To be determined		

Source: Rockström et al. [5]

2.1 Sustainable Water Supply: Provide Clean Water for the Planet

The United States and many regions of the world face multiple challenges in sustainably supplying potable water for human use and clean water for agriculture, food processing, energy generation, mineral extraction, chemical processing, and industrial manufacturing. Demand for water is increasing due to population growth at the same time as water supplies are being stressed by the increasing contamination and salinization of fresh waters, the depletion of groundwater aquifers, and loss of snowpacks and water stored in glaciers, due to climate change. Figure 3 is a map of the sources of freshwater in the United States. The red regions of Fig. 3 correspond to stressed aquifers that experienced declines in water level of more than 60 ft between 1980 and 1999. It should be noted that as aquifers are drawn down to great depths, their salinities increase significantly. Aquifer salinization is a growing problem along the Gulf Coast and the southern Atlantic and Pacific coasts of the United States. The salinization of rivers and lakes also is increasing due to increase discharges of pollutants and nutrients (nitrates and phosphates) from surface runoff.



U.S. Department of the Interior
http://www.nationalatlas.gov
WaterCAMPWS
http://www.watercampws.org

Fig. 3 Sources of freshwater in the United States, including all rivers, lakes, and standard and "fossil" groundwater aquifers. Over-pumping can stress aquifers and can impact water supplies. Estimates are shown of stressed (*red*) and impacted (*yellow*) aquifers throughout the United States [7]

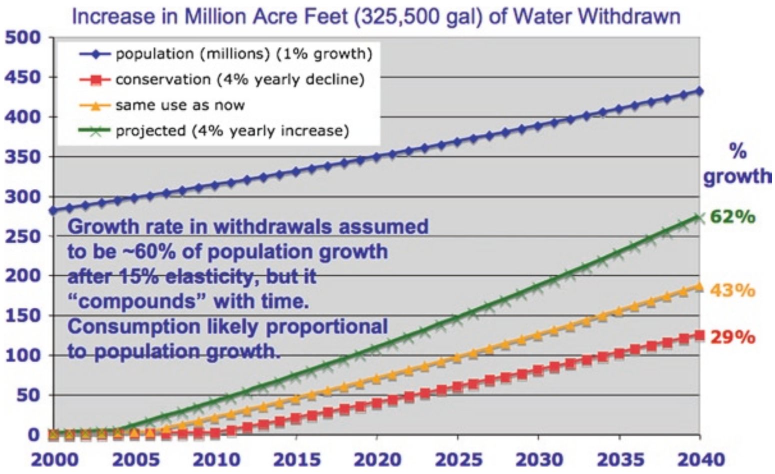


Fig. 4 Predictions of water withdrawals in the United States [7]. (*Top line*) The average overall increase in population of the United States, assuming a 1% increase (between the low and high estimates). Estimates for the growth in water supplies needed to sustain the population growth, assuming projected changes in per capita consumption, as follows: higher use of energy and economic expansion, with current technologies, yielding a 4% per annum increase in per capita use (*62% by 2040, second line from top*); maintenance of current levels (*43% by 2040, third line from top*); and a drop in per capita use of 4% per annum due to increased conservation and efficiency (*20% by 2040, bottom line*) of 20%. The conservation projection for 2040 requires 60% less water in domestic use, 30% less for energy production, and 20% less for agriculture and livestock. Achieving this will require new technologies

As water supplies are decreasing, growth in population, energy use, and economic expansion are driving demand for more water. Figure 4 shows predicted water withdrawals in the United States during the next two decades.

Many other areas of the world also are experiencing water stresses. The United Nations Environment Program (UNEP) predicts that freshwater will become scarcer in many regions of the world by 2020 [8].

Nanotechnology has the potential to provide efficient, cost-effective, and environmentally sustainable solutions for supplying potable water for human use and clean water for agricultural and industrial uses.

2.1.1 Status

During the last 10 years, there has been significant progress in the development and applications of nanotechnology-based solutions in the areas of water treatment, desalination, and reuse ([9–13]). Relevant examples are:

- Nanosorbents with high capacity and selectivity that can remove cations, anions, and organic solutes from contaminated water, including (1) nanoclays; (2) metal oxide nanoparticles; (3) zeolites; (4) nanoporous carbon fibers; and (5) nanoporous polymeric adsorbents

- Nanocatalysts and redox active nanoparticles that can convert toxic organic solutes and oxyanions into harmless byproducts, including (1) titanium dioxide (TiO_2) photocatalysts that can be activated by visible light; (2) redox active zero valent iron (Fe^0) nanoparticles; and (3) catalytic bimetallic particles, including Fe^0/Pd^0, Fe^0/Pt^0, Fe^0/Ag^0, Fe^0/Ni^0 and Fe^0/Co^0
- Nanobiocides that can deactivate bacteria in contaminated water without generating toxic byproducts, including (1) MgO nanoparticles; (2) Ag^0 nanoparticles; and (3) bioactive dendrimers
- Nanostructured filters and reactive membranes for water treatment, desalination, and reuse, including (1) carbon nanotube filters that can remove bacteria/viruses [14]; (2) reverse osmosis (RO) membranes with enhanced water flux, including zeolite nanocomposite membranes [15] and carbon nanotube membranes [16]; and (3) polymeric nanofibrous membranes with enhanced separation efficiency and water flux [86]
- Nanoparticle-based filtration systems and devices, including (1) a dendrimer-enhanced ultrafiltration system that can remove ions from aqueous solutions using low-pressure membrane filtration [17, 18], and (2) a nanofluidic seawater desalination system [19] (see the example in Sect. 8.1)

2.2 *Food Security and Sustainability: Feed the Planet*

In 2008, the total amount spent for all food consumed in the United States was \$1,165 billion [20]. Another food-related cost is that of food-borne illness, estimated at \$152 billion a year in the United States [21]. Godfray and colleagues [22] suggested that the world will face major challenges in meeting the global demand for adequate food over the next 40 years as the world population reaches approximately nine billion by 2050. Viable solutions to this challenge will require a radical transformation of agriculture by growing more food while (1) minimizing the environmental impact of the agriculture and food industries; (2) managing the impact of global climate change; and (3) ensuring the safety and security of the food supply. Advances in nanotechnology could result in major improvements in the technologies used to grow, process, store, and distribute food [23–25].

2.2.1 Status

The application of nanotechnology to agriculture and food systems became part of the U.S. research agenda after a workshop report held in Washington D.C. was published in November 2002 [26]. Several potential applications of nanotechnology to agriculture and food systems were discussed in the report, including:

- Disease diagnosis and treatment delivery systems
- New tools for molecular and cellular breeding
- Development and modification of new food products (smaller, more uniform particles, heat-resistant chocolate, powder suspension, etc.)
- New food packaging materials and systems

To date, a number of significant advances have been made in areas of materials (nanoparticles, nanoemulsions, and nanocomposites), food safety and biosecurity (nanosensors and nanotracers), products (delivery systems and packaging), and processing (nanobiotechnology). Relevant examples include:

- Molecular imprinted polymers to recognize plant and insect viruses
- DNA nanobarcodes to track bacteria in agriculturally important microbial environments
- Nanocomposite materials to detect pore-forming toxins
- Surface-enhanced Raman spectroscopy (SERS) nanosensor array systems to detect food-borne bacteria and toxins
- Edible nanoparticles as sensors of food quality and safety
- “Nutraceutical” nanocomposites utilizing engineered edible films with controlled release morphology
- Nanofluidic arrays for detection of pathogens and bacteria

2.3 Sustainable Habitats: Provide Human Shelter

In the United States, commercial and residential buildings consume 40% of the total energy and account for 39% of the total emissions of CO_2 [27]. Heating, cooling, and lighting are responsible for about 50% of the total energy consumed by commercial and residential buildings [27]. Thus, increases in the energy efficiency of buildings could result in a significant reduction of the environmental footprint of edifices. The U.S. Department of Energy (DOE) has initiated a broad range of research activities to develop and demonstrate zero energy buildings (ZEB) [28]. The underlying premise of the ZEB concept is that buildings can be designed and constructed to achieve zero net energy consumption and zero carbon emissions annually.

2.3.1 Status

Nanotechnology is emerging as a versatile platform technology for producing key ZEB components, including (1) super-insulating aerogels (see chapter “Applications: High-Performance Materials and Emerging Areas”), and (2) more efficient solid-state lighting and heating systems (see chapter “Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation”).

2.4 Sustainable Transportation: Build "Greener" Automobiles and Trucks

In the United States, transportation is responsible for approximately 33% of CO_2 emissions, 66% of oil consumption, and 50% of urban air pollution [29–31]. The United States and many other countries have initiated a broad range of research and development (R&D) programs to build greener (e.g., electric and hybrid) automobiles and heavy-duty trucks and passenger vehicles with 50% improvements in fuel efficiency (e.g., see the DOE $187 Million Super Truck R&D Program website. http://www.energy.gov/8506.htm). Nanotechnology is emerging as an enabling platform technology for producing key components of the next generation of sustainable transportation systems, including automobiles, aircrafts, and ships.

2.4.1 Status

A study by the National Research Council [32] found a linear relationship between vehicle fuel consumption and weight (Fig. 5). The NNI program envisioned very early that nanotechnology could lead to "materials that are ten times stronger than steel, but a fraction of the weight" ([33], p. 14). Subsequent measurements have shown that the density-normalized modulus and strength of single-walled nanotubes (SWNTs) are, respectively, 19 and 56 times greater than that of steel wires [34] and thus SWNTs provide clear opportunities for significantly improved new vehicle materials. Critical technical issues for producing lighter materials with enhanced mechanical properties include achieving uniform dispersions of SWNTs within a

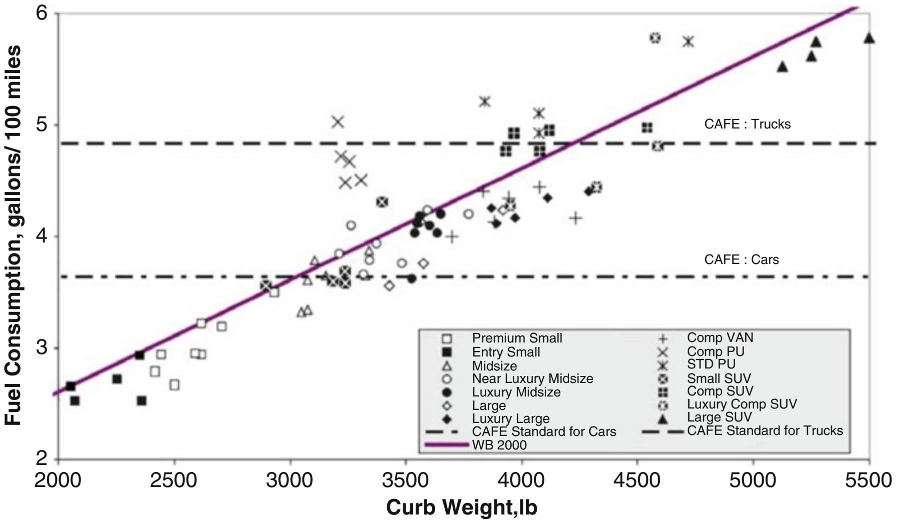


Fig. 5 Relationship between vehicle weight and fuel consumption. For example, by reducing the weight of a vehicle by 20%, fuel consumption also is reduced by 15% [32]

host matrix (e.g., polymer) as well as tailoring interfaces to control adhesion and stress transfer. During the last 10 years, significant advances have been made in the development of carbon nanotube polymer nanocomposites (PNCs) and clay PNCs with enhanced stiffness, strength, and toughness [35–36].

2.5 Mineral Resources: Establish Sustainable Mineral Extraction and Use

Natural resources derived from the Earth's lithosphere, hydrosphere, biosphere, and atmosphere are the key building blocks of a sustainable human society. Like energy and water, the availability of minerals is critical to the United States and the world economy. In 2006, the United States National Research Council (NRC) estimated the added value of processed nonfuel minerals to the U.S. economy to exceed $2.1 trillion [9].

In situ mining (ISM) is emerging as a more efficient and environmentally sound alternative mining technology for valuable metal ions [36]. *In situ* leaching (ISL) is an ISM process that involves extracting a valuable metal/element (e.g., U(VI), Cu(II) and Au(I)) by injection of a leaching solution (commonly referred to as lixiviant) into the ore zone of a subsurface formation (Fig. 6). Because ISL enables

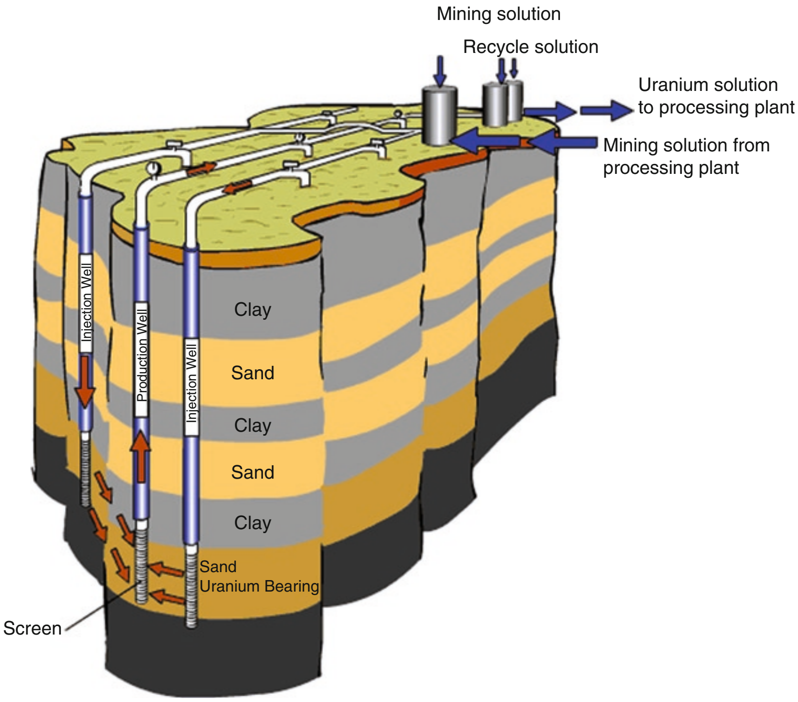


Fig. 6 Uranium mining by ISL (http://www.uraniumsa.org/processing/insitu_leaching.htm)

Table 2 End uses of rare earth elements

End use	Percentage
Automotive catalytic converters	32
Metallurgical additives and alloys	21
Glass polishing and ceramics	14
Phosphors (television, monitors, radar, lighting)	10
Petroleum refining catalysts	89
Permanent magnets	2
Other	13

Source: Committee on Critical Mineral Impacts of the U.S. Economy, Committee on Earth Resources, National Research Council [9]

the mining and recovery of the minerals or elements of interest without excavating the underlying subsurface formation, it has emerged at the technology of choice for mining uranium from permeable subsurface deposits such as sandstones [32]. About 20% of the world uranium production is generated by ISL.

Although the United States is one of the world's largest producers of minerals, it imports more than 70% of its needs for important minerals, many of which have been listed as *critical minerals* by the U.S. National Research Council ([9]). In addition to uranium used in nuclear power generation, many key segments of U.S. industry (Table 2) use significant amounts of minerals such as copper, manganese, lithium, titanium, tungsten, cobalt, nickel, chromium, platinum group metals (e.g., platinum, palladium, and ruthenium), and rare earth elements (e.g., europium, cerium, neodymium, gadolinium, and terbium) ([9]).

Many of these minerals will be required to build nanotechnology-based materials, devices, and systems for sustainable energy generation and storage (Table 3; see also chapter "Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation") [37].

2.5.1 Status

The application of nanotechnology to mineral discovery, mining, extraction, and processing has thus far received little attention. In a white paper published by the Foresight Institute, Gillett [38] surveyed the potential applications of nanotechnology to the extraction and processing of valuable minerals and elements from ores. Although the U.S. Geological Survey has an active nanotechnology research program, most of its current research activities are focused on (1) bacteria-mediated synthesis of nanoparticles; and (2) characterization of the environmental impact of engineered nanomaterials (http://microbiology.usgs.gov/nanotechnology.html). During the last 10 years, significant advances have been made in the development of nanoscale supramolecular hosts that can serve as high-capacity, selective, and recyclable ligands and sorbents for extracting valuable metal ions from solutions and mixtures; advances include the following:

- Dendrimer-based chelating agents for valuable metal ions, such as Cu(II), Ni(II), Zn(II), Fe(III), Co(II), Pd(II), Pt(II), Ag(I), Au(I), Gd(III), or U(VI) ([87]; [18])

Table 3 Selected applications of nanomaterials in power and energy systems

Start-up	Technology	Power segment	Applications	Nanomaterial used
A_{123}Systems	Lithium iron phosphate (LFP)	Utility applications	Frequency regulation	LFP nanoparticles
Altair Nanotechnologies	Lithium titanate (LTO)	Utility applications	Frequency regulation	LTO nanoparticles
GeoBattery	LFP	Utility applications	Grid storage	LFP nanoparticles i
A_{123}Systems	LFP	Portable power applications	Power tools	LFP nanoparticles
American lithium energy	Lithium nickel cobalt oxide (LNCO), LFP	Portable power applications	E-bikes	LFP nanoparticles
Anzode	Nickel zinc	Portable power applications	E-bikes	Nanoporous zinc
CFX battery	Lithium primary	Portable power applications	Military	Carbon nanotubes, nanoporous carbon, graphene
China BAK battery	Lithium ion, including LCO, nickel manganese cobalt (NMC), lithium manganese spinel (LMS), and LFP	Portable power applications	E-bikes, scooters, power tools	LFP nanoparticles
International battery	Lithium ion, including NMC and LFP	Portable power applications	Military portable power	LFP nanoparticles
K_2 energy solutions	LFP	Portable power applications	Power tools, garden tools, e-bikes, scooters	LFP nanoparticles
NanoeXa	LFP and NMC	Portable power applications	Power tools	Nanostructured LFP, Nanostructured NMC
Pihsiang energy technology	LFP, Lithium polymer	Portable power applications	Medical, e-bikes, scooters	Carbon coated LFP nanoparticles
Planar energy devices	Lithium ion	Portable power applications	Military and specialty handsets	Nano-enabled composite

Source: Lux [37]

- Dendrimer-based separation systems for recovering metal ions from aqueous solutions [17, 18] (see Sect. 8.3)
- Nanosorbents based on self-assembled monolayers on mesoporous supports for recovering metal ions, such as Cu(II), Ni(II), Zn(II), Fe(III), Co(II), Pd(II), Pt(II), Ag(I), Au(I), Gd(III), or U(VI) [39]

2.6 Sustainable Manufacturing: Reduce the Environmental Footprint of Industry

Industrial manufacturing has a heavy environmental footprint. First, it requires a significant amount of materials, energy, and water. 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. Thus, many industries spend a significant amount of financial and human resources in waste treatment and environmental remediation. 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)

Nanotechnology is emerging as an enabling platform for green manufacturing in the semiconductor, chemical, petrochemical, materials processing, pharmaceutical, and many other industries [40].

2.6.1 Status

The Semiconductor Research Corporation, through the Engineering Research Center for Environmentally Benign Semiconductor Manufacturing at the University of Arizona, is exploring the use of nanotechnology to reduce the environmental footprint of the semiconductor industry [41]. This includes the development of new methods for layering microchips with nanofilms (e.g., selective deposition). Carbon nanotubes and nanoclays also are being evaluated as flame-retardant additives for polymeric materials. The hope is that these nanoparticles can someday replace toxic brominated fire-retardant additives [42]. Fe-based nanocatalysts are providing new opportunities to synthesize valuable chemicals with high yield (~90%) and reduced waste generation. Zeng and colleagues [43] have developed recyclable Fe_3O_4 magnetic nanoparticles that can catalyze the coupling of aldehydes, alkynes, and amines to produce bioactive intermediates such as propargylamines. They were able to recover the Fe_3O_4 nanocatalysts by magnetic separation and reuse them 12 times without activation.

2.7 Sustain a Clean Environment: Reduce the Impact of Pollution

Green manufacturing is arguably the most efficient way to reduce and (eventually) eliminate the release of toxic pollutants into the soil, water, and air. However, large-scale implementation by industry will take decades. Thus, more efficient and cost-effective technologies are critically needed in the short term to (1) detect and monitor pollutants (environmental monitoring), (2) reduce the release of industrial pollutants (waste treatment), and (3) clean polluted sites (i.e., undertake environmental remediation). The 2010 Deepwater Horizon oil spill in the Gulf of Mexico (http://www.energy.gov/open/oil_spill_updates.htm) suggests that more efficient technologies are needed to monitor and clean up oil spills in marine ecosystems.

2.7.1 Status

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 [44–48]. Nanoscale sensors are less energy-intensive than conventional ones, use fewer material resources, and are often reusable. The devices can combine a variety of sensing and detection modalities, such as chemical (e.g., molecular recognition), optical (e.g., fluorescence), and mechanical (e.g., resonance). Potential applications of engineered nanomaterials for environmental monitoring include detection of various compounds in gaseous, aquatic, or soil media; sampling and detecting in biological media (cells, organs, tissues, etc.), and monitoring of physical parameters (pressure, temperature, distance, etc.). Nanotechnology-enabled sensors can enable rapid and accurate detection of harmful compounds using only minute concentrations of analytes.

Advances in nanotechnology are enabling development of more efficient and cost-effective waste treatment and environmental remediation technologies [12, 49]. Nanoscale zero valent iron (NZVI) particles have proven to be very efficient redox-active media for the degradation of organic contaminants, especially chlorinated hydrocarbons [50–52]. Dendritic nanomaterials, which consist of highly branched nanoscale polymers, have been successfully employed to “encapsulate” environmental pollutants. Dendritic nanomaterials are often recyclable and water-soluble and have demonstrated great potential for removing inorganic pollutants, heavy metals, biological, and radiological compounds [53–56]. Another key advance is the development of nanowire membranes with tunable wettability ranging from superhydrophobic to superhydrophilic [73] these have good potential as oil-spill cleanup media (see Sect. 8.4).

2.8 Sustain Earth's Climate: Reduce and Mitigate the Impacts of Greenhouse Gases

Global climate change has emerged as the most daunting challenge facing the world in the twenty-first century [57]. During the last two decades, a consensus has gradually emerged that increasing emissions of carbon dioxide (CO_2) from the combustion of fossil fuels (e.g., coal and petroleum) are the key drivers of global climate change [57]. Currently, fossil fuels provide approximately 80% of the energy used worldwide [58]. Although many non-CO_2-emitting energy sources are being developed (chapter "Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation"), the world will continue to burn significant amounts of fossil fuels in the foreseeable future. Thus, carbon capture and storage (CCS) is emerging as a viable short- to medium-term alternative for reducing the amounts of anthropogenic CO_2 released into the atmosphere [58].

2.8.1 Status

The efficient and selective separation of CO_2 from gas mixtures is the critical step of any CCS technology. Nanotechnology has the potential to provide efficient, cost-effective, and environmentally acceptable sorbents for CO_2 separation (capture and release) from the flue gases of fossil-fuel-fired power plants and relevant industrial plants (Fig. 7). During the last 5 years, there has been significant progress in

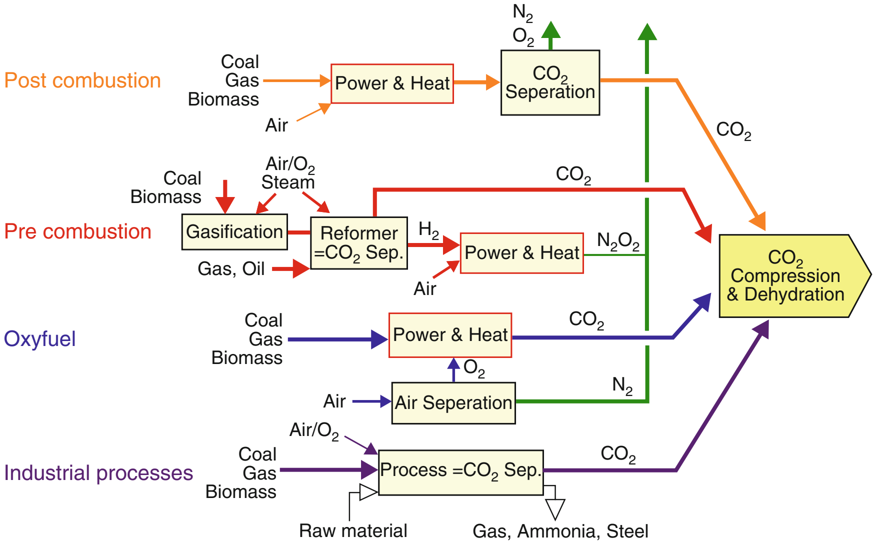


Fig. 7 Gas separation needs for CCS technologies [58]

the development of high-capacity and selective nanosorbents for the CO_2 separation from gaseous mixtures. Relevant examples include:

- Nanoporous silica particles with covalently attached amine groups [59]
- Nanoscale metal organic frameworks (MOFs) [60]
- Nanoscale zeolitic imidazolate frameworks (ZIF) [61, 62] (see Sect. 8.5)

2.9 Sustain Earth's Natural Capital: Preserve the Biodiversity of Earth's Ecosystems

Human beings depend heavily on Earth's natural capital—its biological resources and ecosystems—to live and prosper. Earth's biological resources are extraordinarily diverse. They include a myriad of species of plants, animals, and microorganisms, and they provide a significant fraction of mankind's food, agricultural seeds, pharmaceutical intermediates, and wood products [63]. Earth also possesses a variety of ecosystems (e.g., wetlands, rainforests, oceans, coral reefs, and glaciers) that provide critical services such as (1) water storage and release; (2) CO_2 absorption and storage; (3) nutrient storage and recycling; and (4) pollutant uptake and breakdown. Preservation of the biodiversity of Earth's ecosystems is critical to human life and prosperity.

2.9.1 Status

- The application of nanotechnology to biodiversity has so far received little attention [64]. An integrated research and development program has yet to be formulated.

3 Goals, Barriers, and Solutions for the Next 5–10 Years

3.1 Sustainable Supplies of Clean Water

The availability of clean water has emerged as one of the most critical problems facing society and the global economy in the twenty first century [12, 13]. As previously stated, the United States and many regions of the world are already experiencing higher demands for clean water while freshwater supplies are being stressed. Energy and water issues are strongly coupled (Fig. 8). Energy generation requires reliable and abundant sources of clean water. Conversely, the production and delivery of clean water require a lot of energy. Thus, we expect that increasing demands of clean water for energy generation [65] will cause additional stresses to our freshwater resources globally.

A report published by the Intergovernmental Panel on Climate Change [66] suggests that global climate change will adversely impact the world's freshwater

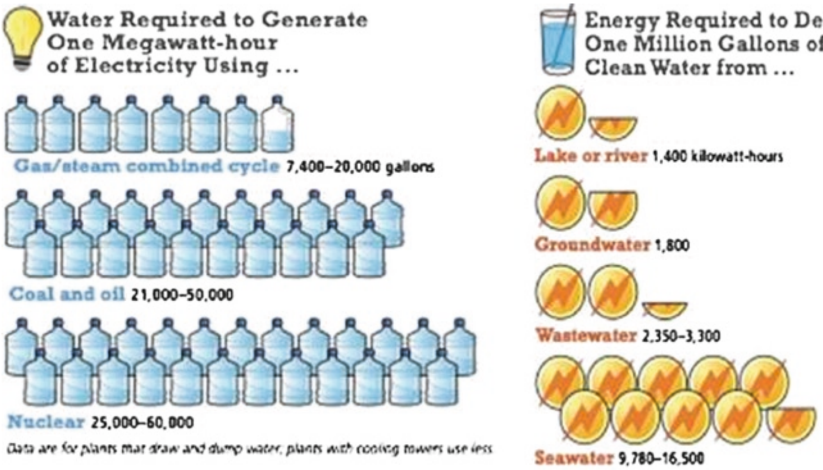


Fig. 8 Energy and water are strongly linked: both energy and water are in short supply; thus, both crises needed to be solved together [65]

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. Thus, a significant increase is needed in the amount of clean water produced from impaired water (e.g., wastewater, brackish water, and seawater) to meet the growing demand throughout the world in the next decade—and beyond.

- Approximately 70–90% of the water used in agriculture and industry and for human consumption is returned to the environment as wastewater [7]. Wastewaters contain 25 MJ/kg of dry weight in organics, including nutrients and compounds with fuel values [7]. Current treatment technologies spend energy to destroy (i.e., mineralize) organic compounds in wastewater; instead, efficient ways must be found to extract clean water, energy, nutrients, and valuable organic compounds from wastewater.
- Seawater and brackish water from saline aquifers constitute ~97% of the water on Earth [13]. Approximately 2.58–4.36 KWh of energy is need to produce 1 m^3 of clean water from saline water [65]. Development of low-energy desalination technologies must be a priority for extracting clean water and valuable minerals (e.g., lithium) from brackish water and seawater.

A convergence between nanotechnology, chemical separations, biotechnology, and membrane technology will lead to revolutionary advances in water desalination and reuse technologies, including the following:

- Solar-powered electrochemical or photo-catalytic systems, which can extract clean water and produce energy (e.g., hydrogen) from wastewater (Sect. 8.2).

- Separation systems (e.g., membranes and sorbents) that can produce clean water and valuable products through selective extraction and release of valuable compounds (e.g., organics and nutrients) from industrial and municipal wastewater.
- Low-energy membranes and filtration systems that selectively reject and reversibly bind and release ions from brackish water and seawater with very high water recovery (>90%) and minimum environmental impact (e.g., reduced brine generation).
- Solar-powered and high-performance deionization systems that can desalinate brackish water and seawater at lower cost and reduced environmental impact (e.g., brine generation).

3.2 Sustainable Agriculture and Food Production

It is envisioned that the convergence between nanotechnology, biotechnology, plant science, animal science, crop, and food science/technology will lead to revolutionary advances in the next 5–10 years, including

- “Reengineering” of crops, animals and microbes at the genetic and cellular level
- Nanobiosensors for identification of pathogens, toxins, and bacteria in foods
- Identification systems for tracking animal and plant materials from origination to consumption
- Development of nanotechnology-based foods with lower calories and with less fat, salt, and sugar while retaining flavor and texture
- Integrated systems for sensing, monitoring, and active response intervention for plant and animal production
- Smart field systems to detect, locate, report and direct application of water
- Precision- and controlled release of fertilizers and pesticides
- Development of plants that exhibit drought resistance and tolerance to salt and excess moisture
- Nanoscale films for food packaging and contact materials that extend shelf life, retain quality and reduce cooling requirements

3.3 Sustainable Human Habitats

During the next 5–10 years, it is expected that nanotechnology will continue to be an enabling technology for zero energy commercial and residential buildings. Anticipated major advances include:

- More efficient organic light-emitting diodes (chapter “Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation”)
- Super-insulating and self-cleaning windows

- More efficient roof-top photovoltaic systems (chapter "Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation")
- More efficient sensors for monitoring and optimizing energy usage in buildings

3.4 Sustainable Transportation

It is envisioned that in the next 5–10 years nanotechnology will become a key enabling platform technology for the next generation of transportation systems. Significant advances are expected in:

- More efficient and lighter materials for automotive and aircraft systems
- High-performance tires for automobiles
- Efficient and non-platinum-based catalytic converters
- Novel and more efficient fuel and power sources (see chapter "Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation")

3.5 Sustainable Raw Mineral Extraction and Use

China had 97% of the market of rare-earth elements (REE) in 2010 and its export limitations [67, 68] have disrupted the sustainable supply of *critical minerals* (Table 2). Nanotechnology is emerging as key platform technology for solving the global challenges in sustainable supply of *critical minerals* such as REE. It is envisioned that in the next 10 years the convergence between nanotechnology, geosciences, synthetic biology, biotechnology, and separations science and technology will lead to major advances and significant improvements in mineral extraction, processing and purification technologies, including:

- Development of non-acidic microbial strains that can selectively leach valuable metal ions including platinum group metals, rare-earth elements and uranium from mineral ores without extensive dissolution of the surrounding rock matrices
- Development of more efficient and environmentally benign leaching solutions for in-situ leach (ISL) mining (Fig. 6) and hydrometallurgical processing of ores containing *critical minerals*
- Development of more efficient, cost-effective, and environmentally acceptable separation systems (e.g., chelating ligands for solvent extraction, ion-exchange media, and affinity membranes) for recovering valuable minerals and elements such as rare earth elements from mine tailings, leaching/hydrometallurgical solutions and wastewater from mineral/metallurgical extraction and processing plants

Nanotechnology could also lead to significant reductions in the consumption of *critical minerals* through the efficient use of mineral resources and the development of nontoxic and cost-effective substitutes to rare-earth elements for the applications listed in applications in Table 2. For example, a group of nanotechnology researchers from the Universities of Delaware and Nebraska have received a $4.5 million grant from the Advanced Research Projects Agency for Energy (ARPA-E) to develop magnetic nanomaterials (20–30 nm) with higher magnetic strength than those of Nd2Fe14B, which is the "world's strongest magnet" [69]. A key goal of this research is the development of "REE-free high anisotropy and high magnetization compounds in doped Fe-, Co- or Mn- rich materials" [69].

3.6 Sustainable Manufacturing

In the next 10 years, a convergence between nanotechnology, green chemistry, and green engineering will enable society to build the sustainable products, processes, and industries of the twenty-first century, including:

- 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 nanotechnology-based consumer products such as nanotechnology-enabled, high performance, and environmentally sustainable "green cars" (Fig. 9)

3.7 Sustaining a Clean Environment

It is envisioned that in the next 5–10 years, small-scale and ubiquitous sensors will be developed and deployed that can be customized to perform "real time" monitoring of environmental systems, including air, water, and soils. For example, "smart" and

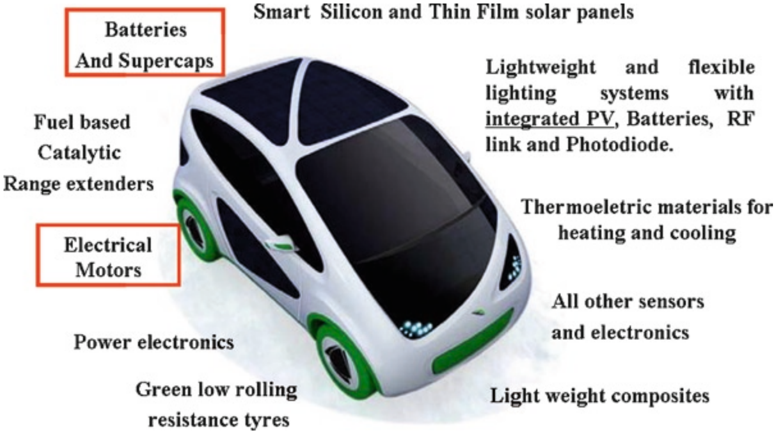


Fig. 9 Nanomaterials as components of the next generation of electric cars (Courtesy of Pietro Perlo, Fiat, http://www.gennesys2010.eu/)

"ubiquitous" nanosensor devices—with the ability to perform a specified action upon detection of a compound—could be placed in surface water systems or subsurface environments to track contaminant migration and implement preventive measures to keep critical compounds from contaminating local water sources. Reduced size coupled with an increase in computational power and speed will make these sensors particularly effective. We also envision the continued development of cost-effective environmental cleanup and remediation technologies for emerging contaminants, including pharmaceuticals, household products, and nanomaterials.

3.8 Sustaining the Climate: Reducing the Impact of Greenhouse Gases

Nanoscale metal organic frameworks (MOFs) and zeolite imidazolate frameworks (ZIFs) are promising CO_2 sorbents with high adsorption capacity, selectivity, and reversibility. However, the first generation of nanoscale MOFs and ZIFs can only perform a single function, i.e., CO_2 separation. Thus, their use alone might not lead to the revolutionary advances needed to significantly decrease the atmospheric release of greenhouse gases by capturing CO_2 and converting it to useable products (e.g., fuels and chemicals). The vision for the 5–10 year timeframe is that convergence between nanotechnology, chemical separations, catalysis, and systems engineering will lead to revolutionary advances in CO_2 capture and conversion technologies, including:

- Nanoscale sorbents containing functionalized size- and shape-selective molecular cages that can capture CO_2 and convert it to useable products
- Nanoporous fibers and/or membranes containing functionalized size- and shape-selective molecular cages that can capture CO_2 and convert it to useable products

In addition to CO_2 capture, transformation, and storage, geoengineering is being considered as a potential climate mitigation technology. The ultimate goal of geoengineering is to reduce global warming by developing and deploying large scale "cooling" systems in the stratosphere. Sect. 8.6 discusses the use of nanotechnology as enabling technology platform for geoengineering.

3.9 Sustaining Biodiversity

In the next 10+ years, it is expected that nanotechnology will contribute significantly to the preservation of biodiversity through the development and implementation of:

- Advanced sensors and devices for monitoring ecosystem health (e.g., soil/water composition, nutrient/pollutant loads, microbial metabolism, and plant health)

- Advanced sensors and devices for monitoring and tracking animal migration in terrestrial and marine ecosystems
- Cost-effective and environmentally acceptable solutions to the global sustainability challenges, including energy, water, environment, and climate change as described in this report

4 Scientific and Technological Infrastructure Needs

During the past 10 years, there has a gradual shift from the discovery, characterization and modeling of nanoscale materials toward the development of nano-enabled systems, devices, and products. In the next 10 years, it will be necessary to harness the power of nanotechnology to develop and commercialize the next generation of sustainable products, processes, and technologies. Key science and technological infrastructure needs and R&D investment needs include:

- Holistic investigations of all interdependent aspects of sustainable development, including cost-benefit environmental risk assessments
- Nanomaterial scale-up and manufacturing facilities/hubs for sustainability applications
- Dedicated nanomaterial characterization facilities for sustainability applications
- Computer-aided nanomaterials modeling and process design tools for sustainability applications
- Test-beds for nanotechnology-enabled sustainability technologies

5 R&D Investment and Implementation Strategies

Because sustainability entails considering social, economic, and environmental factors, it is critical in all cases to integrate fundamental science (e.g., materials synthesis, characterization, and modeling) with engineering research (e.g., system design, fabrication, and testing), commercialization (e.g., new products), and societal benefits (e.g., new jobs and cleaner environment) as scientists and engineers pursue the research priorities outlined in this report. Thus, nanotechnology solutions for sustainable development cannot simply be addressed at the level of small- and single-investigator funded research grants. Sustainability R&D has to be integrated with broader research goals and included from the beginning in large interdisciplinary programs to be carried out by interdisciplinary teams of investigators and/or dedicated Federally funded research and development centers. To achieve these objectives, it will be necessary to:

- Establish centers to develop and implement nanotechnology solutions tied to key aspects of sustainability, as well as to develop suitable open-source databases and partnerships

- 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
- Accelerate knowledge and technology transfer from academic/government laboratories (e.g., academic spin-off companies)

6 Conclusions and Priorities

The global sustainability challenges facing the world are complex and involve multiple interdependent areas. Energy generation/usage, water usage/delivery, CO_2 emissions, and industrial manufacturing are strongly coupled. Nanotechnology has the potential to provide breakthrough solutions for sustainable development, particularly in the areas of energy generation, storage, and usage (See chapter "Nanotechnology for Sustainability: Energy Conversion, Storage, and Conservation"), clean water resources, food/agriculture resources, green manufacturing, and climate change. The following key priorities have been identified for the next decade:

- A comprehensive study of all interdependent factors affecting sustainability and how nanotechnology solutions can extend the limits of sustainable development must be undertaken and updated each year.
- Solar-powered photocatalytic systems and separation systems (e.g., nanoporous membranes with ion-channel mimics) that extract clean water, energy and valuable elements (e.g., nutrients and minerals) from impaired water including wastewater, brackish water and seawater.
- Multifunctional sorbents/membranes that can capture CO_2 from flue gases and transform it into useful products (e.g., chemical feed stocks) must be optimized and then scaled up for industrial scale use.
- Development of more efficient, cost-effective, and environmentally acceptable separation systems (e.g., chelating ligands for solvent extraction, ion-exchange media, and affinity membranes) for recovering *critical minerals* such as rare earth elements (REE) from mine tailings, leaching/hydrometallurgical solutions and wastewater from mineral/metallurgical extraction and processing plants.
- Green manufacturing technologies to (1) develop nontoxic and cost-effective substitutes for REE and (2) reduce and (eventually) eliminate the release of toxic pollutants into the environment (soil, water, and air).

7 Broader Implications for Society

Every human being needs adequate food, water, energy, shelter, clothing, healthcare, and employment to live and prosper on Earth. One of the greatest challenges facing the world in the twenty-first century is continuing to provide better living conditions to people while minimizing the impact of human activities on Earth's ecosystems and the global environment. Nanotechnology offers the potential to expend the limits of sustainability in all critical areas of human development on the Earth. However, it is critical to make sure that any potential adverse effects on humans and the environment are effectively assessed and addressed before the large-scale deployment of nanoscience-enabled sustainability technologies.

8 Examples of Achievements and Paradigm Shifts

8.1 Nanofluidic Water Desalination System

Contact person: Jongyoon Han, Massachusetts Institute of Technology

Figure 10 shows a new promising nanotechnology for desalinating water at the point of use. This nanofluidic device desalinates water with energy consumption that approaches that of a large-scale reverse osmosis desalination system [19]. However, no high pressure is needed to operate the system. Instead, low-pressure and electricity are used to drive seawater through a microchannel containing a nano-junction, consisting of an ion-selective nanoporous Nafion membrane, to connect two microchannels. This causes an ion concentration polarization that separates the seawater stream into an ion "depleted" stream (freshwater) and ion "rich" stream (concentrate).

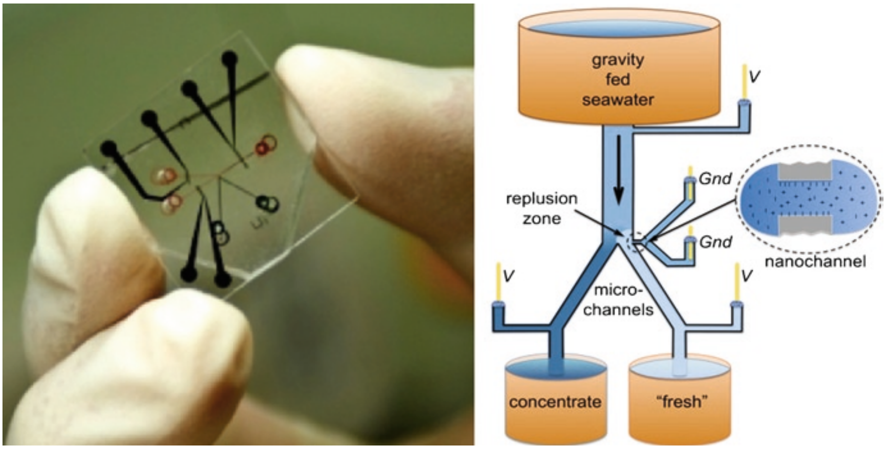


Fig. 10 A chip-sized nanofluidic device (*left*) desalinates water at an energy use approaching that of a large-scale reverse osmosis desalination system Kim et al. [19]

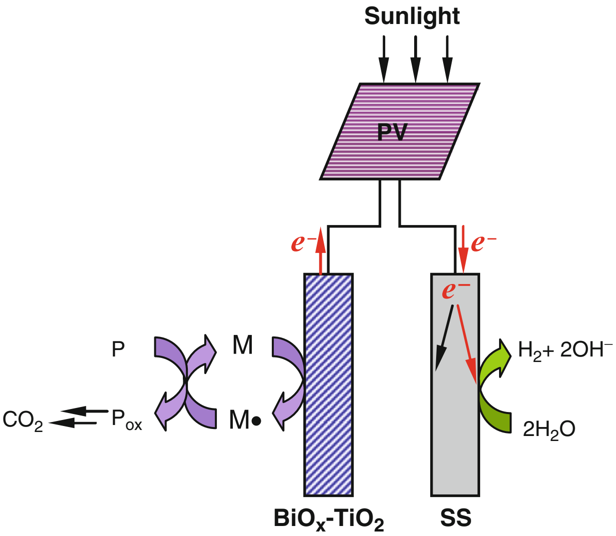


Fig. 11 Solar-powered photocatalytic systems for sustainable water reuse

8.2 Solar-Driven Photocatalytic and Electrochemical Systems for Sustainable Water Reuse

Contact person: Michael Hoffmann, California Institute of Technology

The need for alternative energy sources with reduced carbon footprints is growing. Solar-powered electrochemical or photo-catalytic systems (Fig. 11), which produce hydrogen via water splitting using organic pollutants as sacrificial electron donors, provide a possible solution to achieve two objectives: generation of energy and production of clean water [70–72]. Hybridization of a BiO_x-TiO_2/Ti anode with stainless steel or functionalized metal cathodes, powered by photo-voltaic (PV) arrays, has been shown to achieve simultaneous water purification coupled with H_2 generation. Note that hydrogen generation can be suppressed by purging the reactor system with air. A variety of other hetero-junction, mixed-metal nanooxide semiconductors have also been shown to be highly efficient electro-chemical catalysts for both anodic and cathodic electron transfer.

8.3 Recovery of Metal Ions from Solutions by Dendrimer Filtration

Contact person: Mamadou Diallo, California Institute of Technology

Diallo et al. ([17–18]) have developed a dendrimer-enhanced ultrafiltration (DEF) systems that can remove dissolved cations from aqueous solutions ions using low-pressure membrane filtration (Fig. 12). DEF works by combining dendrimers

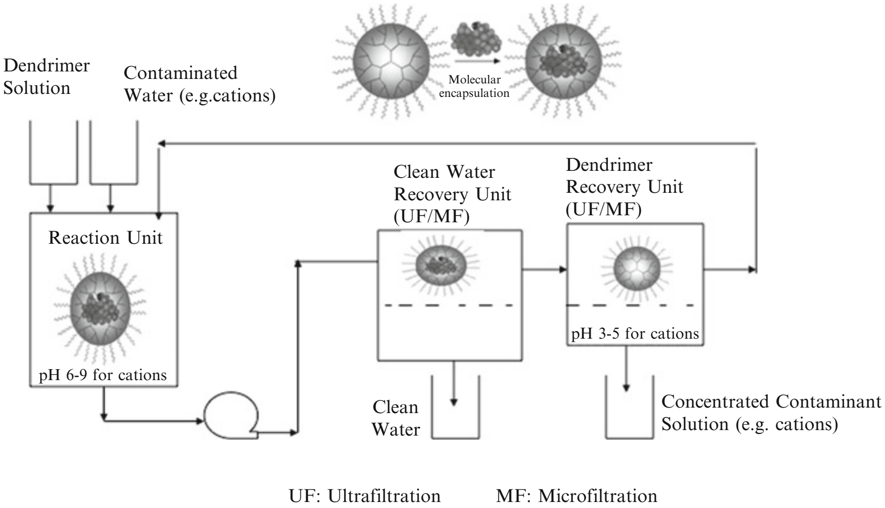


Fig. 12 Recovery of metal ions from aqueous solutions by dendrimer filtration (Adapted from Diallo [18])

with ultrafiltration or microfiltration membranes. Functionalized and water-soluble dendrimers with large molar mass are added to an incoming aqueous solution and bind with the target ions. For most metal ions, a change in solution acidity and/or salinity causes the dendrimers to bind or release the target metal ions. Thus, a two-stage filtration process can be used to recover and concentrate a variety of dissolved ions in water including Cu(II), Ag(I), and U(VI). A key feature of the DEF process is the combination of dendritic polymers with multiple chemical functionalities with the well-established separation technologies of ultrafiltration (UF) and microfiltration (MF). This allows a new generation of metal ion separation processes to be developed that are flexible, reconfigurable, and scalable. The flexibility of DEF is illustrated by its modular design approach. DEF systems will be designed to be "hardware invariant" and thus reconfigurable in most cases by simply changing the "dendrimer formulation" and "dendrimer recovery system" for the targeted metal ions of interest. The DEF process has many applications including the recovery of valuable metal ions including platinum group metals, rare-earth metals and actinides from mineral/hydrometallurgical processing solutions, *in situ* leach mining solutions and industrial wastewater solutions.

8.4 Superhydrophobic Nanowire Membranes for Oil-Water Separation

Contact person: Francesco Stellaci, Massachusetts Institute of Technology

Yuan et al. [73] have developed a new generation of nanoporous membranes with tunable wettability (Fig. 13). These membranes consist of manganese oxide nanowires that self-assemble into an open porous network. By coating the membranes

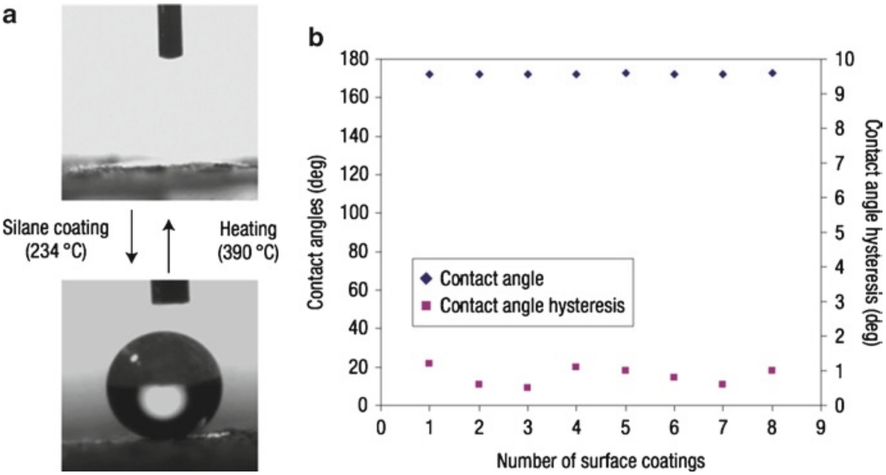


Fig. 13 Nanowire membranes with tunable surface wetting properties [73]. (**a**) Reversible transition between superhydrophilic (*top*) and superhydrophobic (*bottom*); (**b**) contact angles and hysteresis measurements between cycles

Fig. 14 "Seaswarm" is a nanotechnology-enabled oil-spill-cleaning robot developed by a group of MIT engineers (*TechNews Daily*, August 25, 2010). The conveyor belt of the robot is coated with a mesh of superhydrophobic nanowires (Developed by Yuan et al. [73])

with silicone, Yuan et al. [73] were able to fabricate oil-water separation membranes to "selectively absorb oils up to 20 times the material's weight in preference to water, through a combination of superhydrophobicity and capillary action" systems. Recently, a team of MIT engineers used the superhydrophobic nanowires as components to build a robot (Fig. 14) that can clean oil spills in water (*TechNews Daily*, August 25, 2010).

8.5 MOFs and ZIFs for CO_2 Capture and Transformation

Contact person: Omar Yaghi, University of California, Los Angeles

Nanoscale zeolitic imidazolate frameworks (ZIFs; Fig. 15; [61, 62]) and metal organic frameworks (MOFs) with multivariate (MTV) functionalities [74] exhibit

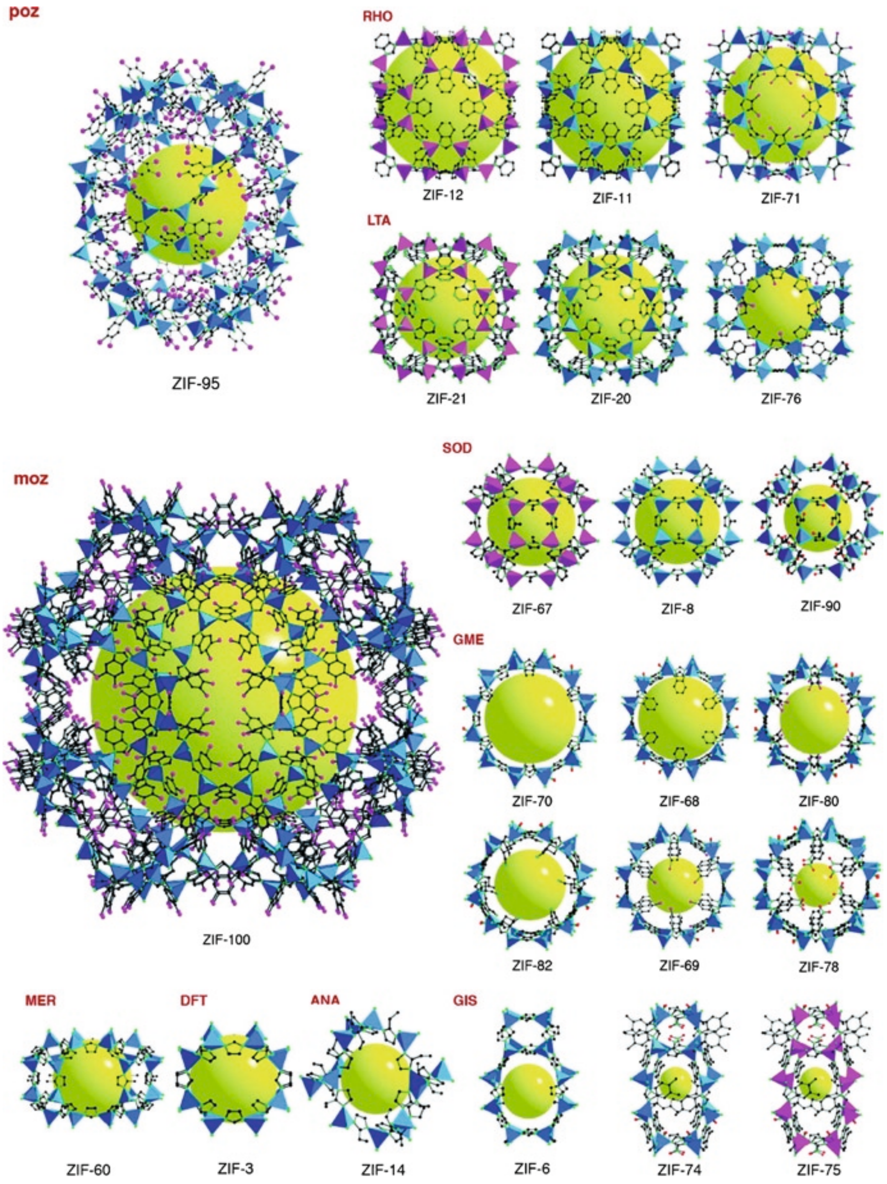


Fig. 15 Crystal structures of zeolitic imidazolate frameworks grouped according to their topology (three-letter symbol). The ball indicates the space within the cage [62]

very large CO_2 sorption capacity, selectivity, and reversibility [62]. ZIFs possess larger pores (2–3 nm) than zeolites and can be processed into adsorbents and gas separation membranes [75]. MTV-MOFs incorporate multiple functionalities on their linking groups. This can lead to a significant enhancement of their CO_2 selectivity. ZIFs and MTV-MOFs have high chemical stability and can be readily reacted with various organic moieties to produce industrial-scale quantities of materials. Thus, nanoscale ZIFs and MTV-MOFs have great potential as building blocks for the next generation of CO_2 capture and transformation media.

8.6 Nanotechnology and Geoengineering

Contact persons: Jason Blackstock and David Guston, Arizona State University

As concerns about climate change continue to mount, "geoengineering" concepts for intentionally altering part of the climate system in order to counteract greenhouse gas–induced changes are receiving rapidly increasing scientific and public attention (*Science Daily* 2010). Among the most prominent concepts is the notion of artificially reducing the amount of sunlight absorbed by the Earth's atmosphere and surface by injecting reflective nanoparticles into the stratosphere. Until recently, the material and design specifications for such reflective nanoparticles for "solar radiation management" (SRM) had only been the subject of speculative discussions and very limited theoretic calculations. But in recent years, calls for developing serious SRM research programs (Fig. 16)—which would include specific focus on the "engineering" of suitable nanoparticles for potential megaton-quantity atmospheric dispersion—have emerged in the scientific [78] and public literature [79]. Recently, the first field-experiment dispersing very small quantities of sulfur-dioxide aerosol particles into the environment were conducted in Russia [80].

The most common reflective nanoparticulates considered for SRM are those of sulfur-dioxide [81, 82], because such particles mimic those naturally produced by volcanoes and could have their dispersed size distribution optimized/engineered for "optimal" radiative properties. However, dielectric and metallic materials predicted to have unique radiation properties or even magnetic or photophoretic levitation characteristics (potentially useful for moderating altitudinal and geographic dispersion of nanoparticulate "mists") have also been seriously proposed in recent literature [83, 84]. Plans for expanded small- to medium-scale field tests of nanoparticle-based climate-modifying technologies are now being discussed seriously and could be underway as soon as 2015. The development of and potential for large-scale atmospheric dispersion of such nanoparticles should be managed under a framework of responsible nanotechnology development.

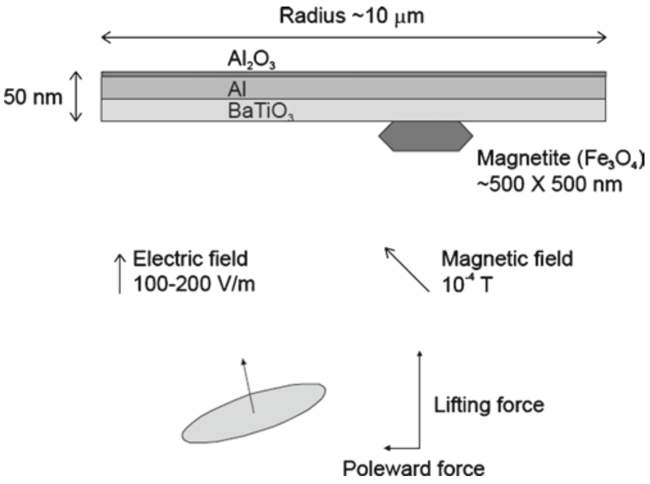


Fig. 16 Conceptual design of a self-levitated nano-disk for SRM geoengineering [76, 77]. This nano-disk configuration is theoretically designed to have three properties: (1) the aluminum layer ~25 nm thick would be reflective in the visible and transparent in the infrared portion of the electromagnetic spectrum; (2) the nano-disks would self-levitate in the stratosphere due to the interaction of the barium titanate ($BaTiO_3$) with the natural electric-field (100–200 V/m) in the stratosphere; and (3) the nano-disks would "tilt" due to the off-center presence of the magnetic iron oxide (Fe_3O_4) interacting with the earth's magnetic field in the stratosphere, leading to the nano-disks being pushed by Brownian forces in the direction of the earth's magnetic poles and concentrating the particles over the Arctic. All of the material layers and size scales indicated in this figure could be produced using existing nanofabrication techniques

9 International Perspectives from Site Visits Abroad

9.1 U.S.–European Union Workshop (Hamburg, Germany)

Panel members/discussants

Antonio Marcomini (co-chair), University of Venice, Italy
Mamadou Diallo (co-chair), California Institute of Technology, USA
C. Jeffrey Brinker, University of New Mexico and Sandia National Laboratory, USA
Inge Genné, VITO, Belgium
Karl-Heinz Haas, Fraunhofer-Institut fuer Silicatforschung, Germany
John Schmitz, NXP,
Udo Weimar, Institut für Physikalische und Theoretische Chemie, University of Tübingen, Germany

During the last 10 years, nanotechnology has emerged as a suitable platform technology for addressing global sustainability challenges, especially in terms of energy, water, food, habitat, transportation, mineral resources, green manufacturing, clean environment, climate change, and biodiversity. Key advances include the development of (1) more efficient renewable energy generation and storage technologies, (2) improved water treatment and desalination membranes, (3) improved food safety (detection and tracking) systems, (4) more efficient separation systems for recovering valuable metals, (5) miniaturized sensors that can detect and monitor pollutants more efficiently, and more effective environmental remediation technologies, (6) more efficient CO_2 capture media, and (7) microchip fabrication processes that use less materials, energy, and water.

In the next 10 years, the power of nanotechnology should be used to develop and commercialize the next generation of sustainable products, processes, and technologies. Priority areas will include (1) water desalination and reuse, (2) CO_2 capture and transformation to useful products and (3) green manufacturing. Current reverse osmosis (RO) desalination membranes have limited water recovery (e.g., 40–70%) and require high pressure (e.g., 10–70 bar) to operate and generate significant amounts of liquid wastes that need to be disposed. Thus, a key priority in water desalination and reuse is to develop the next generation of low-pressure membranes (e.g., 0.5-5 bar) with high water recovery (>95%) and capability to:

- Reject dissolved anions and cations from saline water (e.g., brackish water and seawater)
- Reversibly and selectively bind and release dissolved anions and cations in saline water
- Extract clean water, nutrients, and other valuable compounds from domestic and industrial wastewater

Current CO_2 capture media only perform a single function, i.e., separate CO_2 from flue gases. Thus, a key priority in climate change mitigation and reduction of greenhouse gas emissions is to develop:

- Size- and shape-selective media with nanocages that can capture CO_2 and convert it to useable products
- Membrane reactors with embedded nanocages that can capture CO_2 and convert it to useable products

Green manufacturing is arguably the most efficient way to fabricate high-performance products at lower cost while reducing and (eventually) eliminating the release of toxic pollutants in the environment. Nanotechnology is a key enabling platform technology for green manufacturing. Priority research areas include the development of:

- Nano-enabled, environmentally benign manufacturing processes and products for the semiconductor industry
- High-performance nanocatalysts for the chemical, petroleum and pharmaceutical industries
- More efficient nanotechnology-based consumer products (e.g., nano-enhanced “green” cars)

Potential negative impacts on human health and the environment should not be overlooked. In order to mitigate the potential environmental impact from nanomaterials and products, it is important to design them in a sustainable, life-cycle-oriented way, balancing their environmental performance with technical, cost, cultural, and legal requirements. Suitable design strategies for pollution prevention and resource conservation include product/material life extension, reduced material intensiveness, and process management. In order to achieve this, appropriate environmental analysis tools should be applied.

The sustainable development of nanotechnology also requires the education and training of a new generation of scientists, engineers, entrepreneurs, policymakers, and regulators. This education should not be limited to natural sciences or engineering, but, being more interdisciplinary in nature, it should also develop societal awareness and cover practical communication, entrepreneurial and management skills. Today, there is growing recognition that the field is in urgent need for trained workforce and any delay in launching suitable educational initiatives would ultimately impede innovation.

Finally, although nanotechnology holds great promise for solving global sustainability challenges, there is growing awareness that some nanomaterials could pose environmental and health hazards. Thus, we have to make sure that any potential adverse effects on humans and the environment are effectively assessed and addressed before large-scale deployment of nano-enabled sustainability technologies.

9.2 U.S.–Japan–Korea–Taiwan Workshop (Tokyo/Tsukuba, Japan)

Panel members/discussants

Chul-Jin Choi (co-chair), Korea Institute of Materials and Science, Korea
James Murday (co-chair), University of Southern California, USA
Tomoji Kawai , Osaka University, Japan
Chuen-Jinn Tsai, National Chiao Tung University, Taiwan
Jong Won Kim, Higher Education Research Data Collection Office, Korea
Kohei Uosaki, National Institute for Materials Science , Japan

During the last 10 years, nanotechnology has emerged as an ideal platform technology for solving global sustainability challenges in energy, water (see Fig. 17), food, habitat, transportation, mineral resources, green manufacturing, clean environment, climate change and biodiversity. Key advances in 10 years has been achieved in many areas of sustainability including: (1) new sensing concepts and devices to detect nanomaterials and monitor their toxicity in a workplace environment; (2) smart (self-cleaning) windows and walls; (3) nanoabsorbents, nanocatalysts, nanobiocides, and nanostructured filters/membranes; (4) nanofluidic arrays for detection of pathogens; and (5) more efficient nanostructured building insulation materials.

Fig. 17 Suggested research agenda for nano-enabled sustainability (Courtesy of Tomoji Kawai, Osaka University)

In the next 10 years, priority areas will include (1) CO_2 capture and conversion, (2) water desalination and reuse, e.g., more effective desalination membranes; (3) artificial photosynthesis and (4) green manufacturing, e.g., change in feedstock from petroleum/naphtha to biomass/methane enabled by nano catalysts, and (5) recycling and recovery of limited materials from semiconductor plants and electronic devices (Fig. 17).

9.3 U.S.–Australia–China–India–Saudi Arabia–Singapore Workshop (Singapore)

Panel members/discussants

Murali Sastry (co-chair), Tata Chemicals Innovation Center, India
James Murday (co-chair), University of Southern California, USA
Rose Amal, University of New South Wales, Australia
Calum Drummond, Commonwealth Scientific and Industrial Research Organization, Australia
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During the last 10 years, there has been growing shift from nanoscale science/engineering discovery to nano-enabled processes, technologies, and products. However, the development of nanotechnology solutions and products for sustainability applications has received limited attention. In the next 5–10 years, the emphasis should on the development/commercialization of:

- Green manufacturing and nanotechnologies
- Improved water filtration technologies
- Functional coatings that enable self-healing and wear/ice/bio-fouling resistance
- Solution-based processing of nanostructures (as opposed to vacuum-based processing)
- Nano-enabled recycling with minimal waste, including scavenging

The R&D investment and implementation strategies will continue to evolve toward greater focus on topics of regional and national interest, with collaboration between industry, academia, and research institutes. With the growing emphasis on near-term commercial goals, attention must be paid to a balance with long-term strategic goals and knowledge generation.

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