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THE ANTHROPOCENE

We, the *Homo sapiens sapiens*, have enjoyed a relatively short but illustrious history of about 100,000 years on Earth, adapting remarkably well to its diverse range of geographical conditions and proliferating at an impressive pace across the globe. Easily displacing the competing relatives of the genus, we emerged the sole human species to claim the planet. It is a commendable feat indeed, considering the relatively low fertility and the high incidence of reproductive failures in humans compared to other mammals. A good metric of this success is the current world population that has increased exponentially over the decades and now standing at slightly over seven billion. It is estimated to grow to about 10 billion by 2100, given the increasing longevity worldwide. At this growth rate, the number of people added to the global community next year will now be equal to about the population of a small country (such as England or France) (Steck et al., 2013). The world population increased[1] by 26% just in the past two decades! The plethora of environmental issues we face today and the more severe ones yet to be encountered tomorrow are a direct consequence of this dominant human monoculture striving to survive on a limited base of resources on the planet. As we approach the carrying capacity[2] of the planet, competition for space and scarce resources, as well as rampant pollution, will increase to

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[1] The increase was mostly in West Asia and in Africa according to UNEP estimates (United Nations Environment Programme, 2011a).

[2] Carrying capacity is the theoretical limit of population that the (Earth) system can sustain.

Plastics and Environmental Sustainability, First Edition. Anthony L. Andrady.

unmanageable levels, unless the human race carefully plans for its future.[3] However, no global planning strategies have been agreed upon even at this late hour when irrefutable evidence of anthropogenic climate change, deforestation, and ocean pollution is steadily accumulating. Incredibly, no clear agreements are there on whether the looming major environmental problems are real or imaginary.

Though it did happen on Earth, the simultaneous occurrence of the conditions that support life as we know it is a very unlikely event, and even here, it is certainly a transient phenomenon. Life on Earth exists over the brief respite (in geological timeline) thanks to a cooling trend between the cauldron of molten metal the Earth was a few billion years back and the sun-scorched inhospitable terrain will turn into a few billion years from now. Even so, life spluttered on intermittently with a series of ice ages, geological upheavals, and mysterious mass extinctions regularly taking their toll on biodiversity. The last of these that occurred some 200 million years ago wiped out over 75% of the species! The resilient barren earth fought back for tens of millions of years to repopulate and reach the present level of biodiversity. Thankfully, the conditions are again just right to sustain life on Earth, with ample liquid water, enough solar energy to allow autotrophs to spin out a food web, a stratospheric ozone layer that shields life from harmful solar UV radiation, enough CO_2 to ensure a warm climate, and oxygen to keep the biota alive. We owe life on Earth to these natural cycles in complex equilibrium. However, the apparent resilience of the biosphere to human interference can often be misleading as the dire consequences of human abuse of the ecosystem might only be realized in the long term. Figure 1.1 shows the growth in world population along with 10-year population increments.

Clearly, human populations have already taken liberties with the ecosystem leaving deep footprints on the pristine fabric of nature. Biodiversity, a key metric of the health of the biosphere, is in serious decline; biodiversity fell by 30% globally within the last two decades alone (WWF, 2012). The current extinction rate is two to three orders of magnitude higher than the natural or background rate typical of Earth's history (Mace et al., 2005). Arable land for agriculture is shrinking (on a per capita basis) as more of the fertile land is urbanized.[4] Millions of hectares of land are lost to erosion and degradation; each year, a land area as large as Greece is estimated to be lost to desertification. Increasing global affluence also shifts food preferences into higher levels of the food pyramid. Though Earth is a watery planet, only 3% of the water on Earth is freshwater, most of that too remains frozen in icecaps and glaciers. Freshwater is a finite critical resource, and 70% of it is used globally for agriculture to produce food. Future possible shortage of freshwater is already speculated to spark off conflicts in arid regions of Africa. Evidence of global warming is mounting, there is growing urban air pollution where most live, and the oceans are clearly increasing

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[3] There is a regional dimension for the argument as well. In the US, the birth rates are on the decrease, which will in the future result in lower productivity. Adding to the population in a resource-poor region (say, Sub-Saharan Africa) will result in lower standards of living as the available meager resources have to be now distributed over a larger population.

[4] In 2007, for the first time, global urban population outnumbers the rural populations. The figures for land area degradation are quoted from the World Business Council for Sustainable Development (2008).

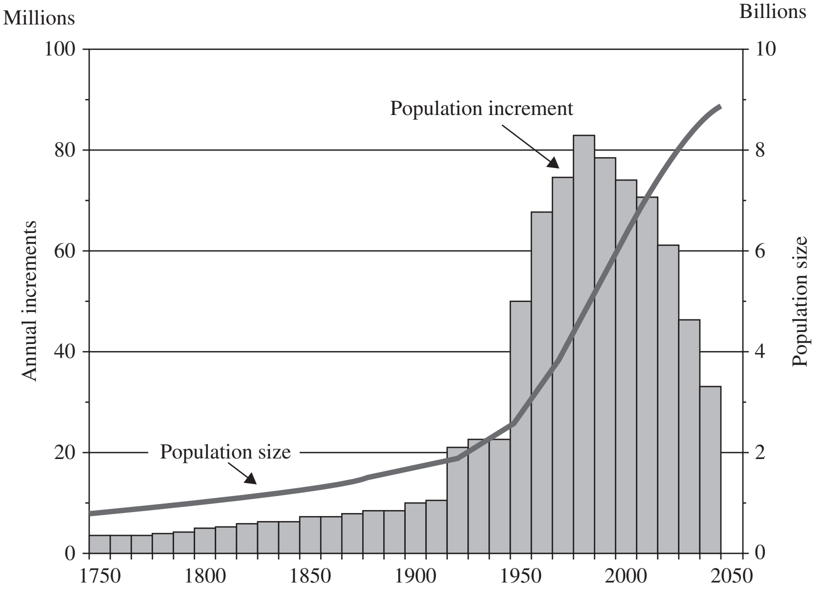

FIGURE 1.1 Projected world population and population increments. Source: Published with permission from UN Population Division. Reproduced with permission from World at Six Billion. UN Populations Division. ESA/P/WP.154 1999.

in acidity due to CO_2 absorption. Phytoplankton and marine biota are particularly sensitive to changes in the pH of seawater (Riebesell et al., 2000), and both the ocean productivity as well as its carbon-sink function might be seriously compromised by acidification. Some have suggested this is in fact the next mass extinction since the dinosaurs' die-off, poised to wipe out the species all over again.[5] Is it too late for the human organism to revert back to a sustainable mode of living to save itself from extinction in time before the geological life of the planet ends?

A driving force behind human success as a species is innovation. Starting with Bronze Age toolmaking, humans have steadily advanced their skills to achieve engineering in outer space, building supercomputers and now have arrived at the frontier of human cloning. Human innovative zest has grown exponentially and is now at an all-time high based on the number of patents filed worldwide. Recent inventions such as the incandescent light bulb, printing press, internal combustion engine, antibiotics, stem-cell manipulation, and the microchip have radically redefined human lifestyle.

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[5] Major catastrophes that lead to mass extinction of species occurred five times in Earth's history during the last 540 million years; the last one was 65 million years back (end of the Mesozoic) when the dinosaurs disappeared. The high rate at which species are disappearing has led scientists to suggest that the sixth mass extinction is already under way; Barnosky estimates that in 330 years, 75% of mammalian species will be extinct! (Barnosky et al., 2011).

FIGURE 1.2 Rio Tinto (Red River) in Southwestern Spain devastated and tinted red from copper mining over several thousand years.

A singularly important development in recent years is the invention of the ubiquitous plastic material. It was about 60 years back when science yielded the first commodity thermoplastic material. It was an immediate and astounding success with increasing quantities of plastics manufactured each subsequent year to meet the demands of an expanding base of practical applications. There is no argument that plastics have made our lives interesting, convenient, and safe. But like any other material or technology, the use of plastics comes with a very definite price tag.

Mining anything out of the earth creates enormous amounts of waste; about 30% of waste produced globally is in fact attributed to mining for materials. In 2008, 43% of the toxic material released to the environment was due to mining (US Environmental Protection Agency, 2009). For instance, the mining waste generated in producing a ton of aluminum metal is about 10 metric tons (MT) of rock and about 3 MT of highly polluted mud. The gold in a single wedding band generates about 18 MT of such waste ore left over after cyanide leaching (Earthworks, 2004)! The complex global engine of human social and economic progress relies on a continuing supply of engineering materials that are mined out of the earth and fabricated into diverse market products. At the end of the product "life cycle" (often defined merely in terms of its unacceptable esthetics rather than its functionality), it is reclassified as waste that has to be disposed of to make room for the next batch of improved replacements. The mining of raw materials and their preprocessing, whether it be oil, metal ore, or a fuel gas, are also as a rule energy intensive operations. Air and water resources used are "commons resources" available at no cost to the miners (Fig. 1.2). With no legal ownership, the users tend to overexploit these resources (or pollute it) to maximize

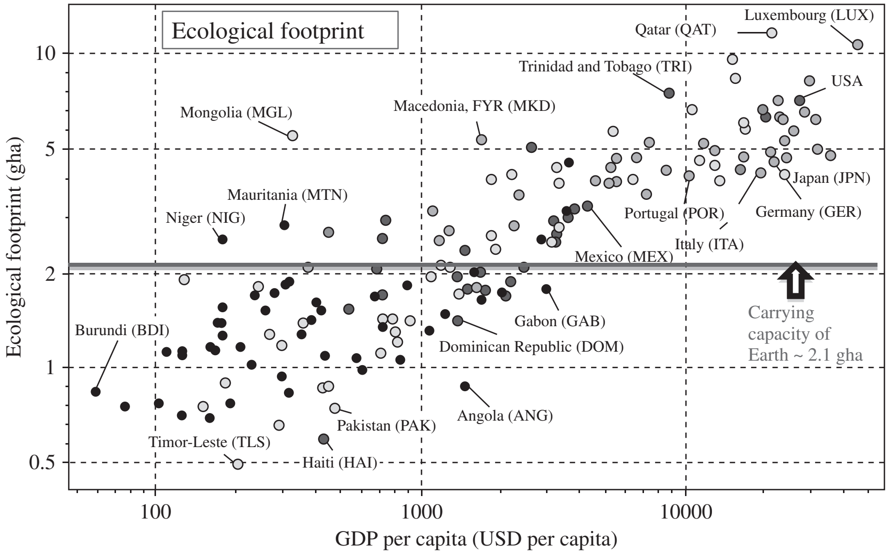

FIGURE 1.3 The ecological footprint of nations (hectares required per person) versus the per capita GDP of the nation. Source: Reproduced with permission from Granta Design, Cambridge, UK. www.grantadesign.com

individual gain. Naturally, in time, the resource will be compromised.[6] Externalities[7] associated with mining or other industrial processes, however, are not fully reflected in what the users pay for in a given product. Often, a community, a region, or even the entire global population is left to deal with the environmental effects of the disposal of waste generated during manufacture. The use of these ever-expanding lines of products, made available in increasing quantities each year to serve a growing population, presents an enormous demand on the Earth's resource base.

The notion of "ecological footprint (EF)" (Reese, 1996, 1997) illustrates the problem faced by the world at large. EF is defined as the hectares of productive land and water theoretically required to produce on a continuing basis all the resources consumed and to assimilate all the wastes produced by a person living at a given geographic location. For instance, it is around 0.8 global hectares (gha) in India and greater than 10 gha in the United States. By most estimates, the footprint of the population has already exceeded the capacity of the planet to support it. In 2008, the EF of the 6 billion people was estimated at 2.7 gha/person, already well over the global biocapacity of approximately 1.8 gha/person in the same year (Grooten, 2013)! In North America, Scandinavia, and Australia, the footprint is already much larger (5–8 gha/capita) (Fig. 1.3). The largest

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[6] A good example of this "tragedy of the commons" is the state of the global fishing industry. The deep-sea fishery is a common property available to all nation players. Rampant overfishing by different nations without regard to agreed-upon quotas and ecologically safe practices has seriously depleted the fishery.

[7] An externality is a cost or benefit resulting from a transaction that is experienced by a party who did not choose to incur that cost/benefit. Air pollution from burning fossil fuel, for instance, is a negative externality. Selecting renewable materials in building can in some instances be cheaper and delivers the positive externality of conserving fossil fuel reserves.

component of the footprint is availability of sufficient vegetation to sequester carbon emissions from burning fossil fuels.

Plastics, being a material largely derived from nonrenewable resources such as oil, are not immune from these same considerations. Their production, use, and disposal involve both energy costs and material costs. The process also invariably yields emissions and waste into the environment that can have local or global consequences. Plastics industry is intricately connected and embedded in the various sectors that comprise the global economy. Its growth, sustainability, and impact on the environment ultimately depend on what the future world will look like. Therefore, to better understand the impacts of the use of plastic on the environment, it is first necessary to appreciate the anthropogenic constraints that will craft and restrict the future world. The following sections will discuss these in terms of the future energy demand, the material availability, and the pollution load spawned by increasing global population and industrial productivity.

1.1 ENERGY FUTURES

Rapid growth in population accompanies an inevitable corresponding increase in the demand for food, freshwater, shelter, and energy. Supporting rapid growth of a single dominant species occupying the highest level of the food chain must invariably compromise global biodiversity. Humans naturally appropriate most of the Earth's resources, and to exacerbate the situation, the notion of what constitutes "comfortable living" is also continually upgraded in terms of increasingly energy- and material-intensive lifestyles. Invariably, this will mean an even higher per capita demand on materials and energy, disproportionate to the anticipated increase in population. An increasing population demanding the same set of resources at progressively higher per capita levels cannot continue to survive for too long on a pool of limited resources.

Energy for the world in 2012 was mainly derived from fossil fuels: 36.1% from oil, 25.7% from natural gas, and 19.5% from coal, with 9.7% from nuclear power and about 9% from renewable resources (Fig. 1.4). The global demand is projected by the Energy Information Administration (EIA) to rise from the present 525 quads/year[8] in 2010 to 820 quads/year by 2040; over half of this energy will continue to be used for transportation[9] (Chow et al., 2003). Even this estimate is likely an underestimate given the rate of growth in China and the developing world. In the developing countries, residential heating/cooling demands most of the energy followed by industrial uses. The pattern is different in the developed world where transportation is often the leading sector for energy use. How will this large annual energy deficit of about over 295 quads of energy be covered in the near future? Given our singular penchant for

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[8] A "quad" is a quadrillion (10^{15}) BTUs of energy and is the energy in 172 million barrels of oil, 51 million tons of coal or in 1 trillion cubic feet of dry natural gas.

[9] Internal combustion engine is a particularly inefficient converter of fuel into useful energy. About 75% of energy input into an automobile is lost as heat. Only about 12% is translated to energy at the wheels!

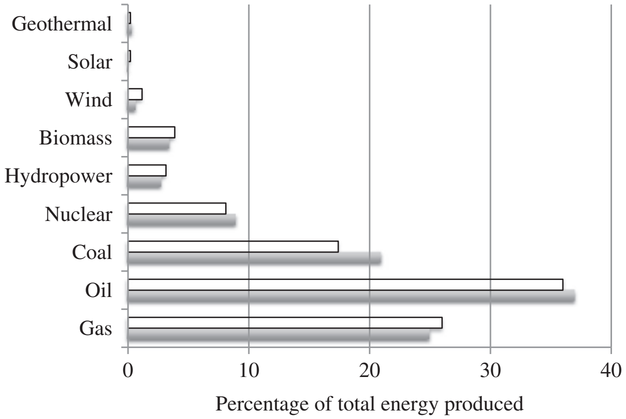

FIGURE 1.4 Global energy use (open bars) and US energy use (filled bars) by source. Source: US 2011 data based on US Energy Information Administration. Web: www.eia.gov. World 2011 data based on International Energy Agency 2012 Report, www.iea.org.

energy, this presents a particularly vexing problem. The most pressing problem will be the huge demand for electricity, the world's fastest growing form of high-grade energy. About 40% of our primary energy (more than half of it from fossil fuel) is spent on generating electricity in an inefficient process that captures only about half their energy content as useful electrical energy. Satisfying electricity demand in next 20 yrs will use as much energy as from bringing on line a 1000 MW power station every 3.5 days during that period (Lior, 2010).

The United States was the leading consumer of energy in the world (~95 quads in 2012) until recently. Since 2008, however, China has emerged in that role with the United States in the second place. Naturally, the same ranking also holds for national carbon emissions into the atmosphere. By 2035, China alone is expected to account for 31% of the world consumption of energy (US EIA, 2010). Around 2020, India will replace China as the main driver of the global energy demand. On a per capita basis, however, the United States leads the world in energy use; 4.6% of the world population in United States consume approximately 19% of the energy, while 7% in the European Union consume 15%. While most of this (~78%) is from fossil fuels approximately 9% of the energy is from renewable sources. But in the medium term, the United States is forecasted to have ample energy and will in fact be an exporter of energy, thanks to the exploitation of natural gas reserves.

Increased reliance on conventional fossil fuel reserves appears to be the most likely medium-term strategy to address the energy deficit, assuming no dramatic technology breakthrough (such as low-temperature fusion or splitting water with solar energy) is made. But it is becoming increasingly apparent that any form of future energy needs to be far less polluting and carbon intensive relative to fossil fuel burning. If not, there is a real possibility that humankind will "run out of livable environment" long before they run out of energy sources! About 26% of the global greenhouse gas (GHG) emissions (mostly CO_2) is already from energy production.

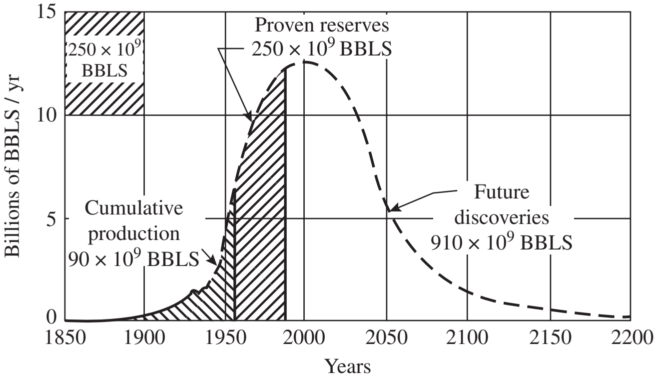

FIGURE 1.5 Hubbert's original sketch of his curve on world oil production. Source: Reprinted with permission from Smith (2012).

1.1.1 Fossil Fuel Energy

Fossil fuels, such as coal, oil, and natural gas, were created millions of years ago by natural geothermal processing of primitive biomass that flourished at the time. Thus, fossil fuel reserves are in essence a huge savings account of sequestered solar energy. Since the industrial revolution, we have steadily depleted this resource to support human activity, relying on it heavily for heating and generating power. About 88% of the global energy used today is still derived from fossil fuels,[10] and that translates primarily into burning 87 million barrels of oil a day (bbl/d) in 2010 (estimated to rise to nearly 90 bbl/d in 2012).[11]

1.1.1.1 Oil Since Edwin Drake drilled the first oil well at the Allegheny River (PA) in 1859, we have in the United States ravenously consumed the resource also importing half of our oil needs. Global reserves of oil presently stand only at about 1.3 trillion barrels, over half of it in the Middle East and Venezuela. The US oil reserves that stand only at 25 billion barrels (2010) are continuing to be very aggressively extracted at the rate of 5.5 million (bbl/d) and can therefore only last for less than a decade. Hubbert (1956)[12] proposed a bell-shaped Gaussian curve (see Fig. 1.5) to model US oil production and predicted it to peak in 1970 (and ~2005 for the world). Estimating the future oil supplies is complicated as new reserves are discovered all the time, improvements are made to extraction technologies, more oils being classified as proven resources, and due to fluctuating demands for oil in the future.

[10] The data are from the Statistical Review of World Energy (British Petroleum, 2007). The remaining 12% is from nuclear and hydroelectric power plants. The estimates of global oil reserves are also from the same source.

[11] Based on figures published in 2011 by the US Energy Information Administration.

[12] As with Malthus's famous predictions, Hubbert's timing was off by decades, but his arguments were sound. Estimates of new reserves are upgraded each year, but we may have finally reached peak production.

In the United States, we likely have already reached the peak production rate for oil [or the Hubbert's peak] and are fast reaching the same for world oil production (see Fig. 1.5); thereafter, we can expect escalating prices. As prices rise, the recovery of heavy crudes in unconventional oil sand reserves will become increasingly economical. As expected, price increases driven by scarcity may result in both the lowering of the minimum acceptable quality of product and exploitation of poor reservoirs hitherto considered unprofitable to work on. Burning lower quality oil will result in emissions with an adverse effect on the environment. Our addiction to oil in the United States is such that we have seriously considered drilling for oil in the Arctic National Wildlife Refuge off the Northern Alaskan coast, the largest protected wilderness in the United States.

However, fossil fuel will likely be in good supply in the United States in the immediate future because of aggressive policies in place to exploit shale oil and gas reserves. These include particularly the shale gas (within layers of rock) and "tight oil and gas" trapped in low-permeability rock formations. Hydraulic fracturing or "fracking" might be the only way to exploit these presently inaccessible resources. The potential for "tight oil" and "tight gas" is so high locally that within the next few years, the United States could well be the leading oil producer in the world (replacing Saudi Arabia) and soon thereafter a net energy exporter. In spite of its attractiveness, however, hydrofracking is associated with serious environmental risks. Some of these are its link to earthquakes, the relatively high water demand for the process, limitations of environmentally acceptable disposal choices for spent process wastewater, risk of groundwater contamination, and high potential for GHG release. Despite the opposition from environmental groups, fracking is gaining pace in the United States.

Thankfully, the world still has considerable coal and shale gas reserves; the United States is believed to have 261 billion tons of coal and around 827 trillion cubic feet of shale gas. The United States is presently the second largest producer of coal, and at the present rate of consumption, reserves of coal should last the United States about another 500 years. Not only can coal be burnt to derive power but can also be converted to oil via the Fischer–Tropsch chemistry. Developed in the 1920s, the Fischer–Tropsch process converts CO and H_2 (called syngas) into liquid paraffin hydrocarbons using transition metal catalysts. Syngas is obtained from coal:

$$\mathrm{C} + \mathrm{H_2O} \longrightarrow \mathrm{CO} + \mathrm{H_2}$$
$$n\mathrm{CO} + (2n+1)H_2 \longrightarrow \mathrm{C}_n\mathrm{H}_{2n+1} + \mathrm{H_2O}$$

The paraffin produced is upgraded into fuel by hydrocracking into smaller molecules.

1.1.1.2 ***Coal*** Already, by the mid-decade, 43% of the world's electricity supply was derived from burning coal.[13] In the United States, 21% (and globally close to 30%) of the energy consumed in 2010 was derived from coal. At some future higher

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[13] UNEP/GRID Arendal.

level of oil prices, the use of coal to produce synthetic oil may become cost-effective, and the relevant Hubbert's curve would have been pushed back a few years or decades into the future. Coal is a cheap direct energy source for the United States, but this reassurance of a few more centuries of fossil fuel comes with a forbidding environmental price tag. Coal plants are more polluting and less costeffective compared to state-of-the-art natural gas plants. At least 49 GW of existing coal power plants in the United States can be retired and replaced with natural gas plants or even with wind-power plants with significant cost savings as well as improved environmental emissions (UCS, 2012).

There is a good justification for closely examining large-scale coal burning, especially without capture or sequestration of CO_2 as a future strategy for generating energy. Coal-fired power plant emissions include particulate matter, sulfur dioxide (SO_2), and nitrogen oxides (NOx) as well as mercury. They are already the largest source of mercury (Hg) pollution in the United States; the emissions from US plants in 2009 exceeded 134,000 lbs. Organic mercury is already present in human blood though at levels below those associated with health effects. Ingestion of mercury-contaminated food can result in serious neurological damage in humans especially children (Counter and Buchanan, 2009). A national standard on limiting mercury emissions from power plants is presently being drawn up by the USEPA; it is already being challenged by the power industry.[14]

1.1.1.3 Gas About a quarter of the domestic as well as global energy consumed is derived from natural gas where the proven global reserves have been estimated to meet about 64 years of production. In recent years, the domestic production of natural gas has increased, and in 2011, the United States was the leading producer of natural gas in the world. The dramatic growth of natural gas industry has been even more apparent in China with investment in upscale technologies for its cost-effective exploitation. Reserves are the largest in these two countries. Interestingly, in the first half of the twentieth century, natural gas was thought of as a virtually useless by-product of oil production! Natural gas is often hailed as an example of cheap "green energy," but methane (the primary component of natural gas) that escapes during the drilling process is a potent global warming gas.

Extraction of shale gas by fracturing the porous rock (fracking) involves pumping a slurry of water, sand, and chemicals into the rock to crack them to release the trapped gas. The process requires drilling vertically, often through aquifers, and horizontally below them. The slurry pumped into the ground has additive chemicals (such as acids, surfactants, and methanol) that can leak into aquifers creating a very serious, regrettably underestimated water pollution problem (Cooley and Donnelly, 2012). The water demand for fracking is high (2–5 million gallons/well),

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[14] In October of 2011, 25 states urged a federal court to require that the USEPA delay implementing the rule on emission of Mercury and other pollutants from (coal-fired) power plants by at least a year, as the changes will be too costly. Gardnery, T. Reuters. Monday, October 10, 2011. Available at http://www.reuters.com/article/2011/10/11/us-25-states-urge-court-to-make-us-epa-d-idUSTRE79A0E520111011. Accessed July 1, 2013.

and wastewater management can also be an issue. The slickwater is collected in lined ponds and disposed of away from aquifers of potable water. Scientific data on the costs of fracking to the environment are sparse as large-scale fracking is just starting. But the potential damage is serious enough (Boudet et al., 2014; Mackie et al., 2013) to adopt a precautionary attitude and closely observe the development of this technology.

Perhaps a bright spot in the energy future is the huge untapped fossil fuel resource of methane hydrate (or clathrate) trapped in icy marine sediments in places such as the outer continental shelf of the United States (Chatti et al., 2005). These reserves are larger than all fossil fuel reserves combined (Collett, 2002). The US reserves alone are estimated to be sufficient to replace the current global natural gas demand for a century. Global warming is slowly disrupting under sea clathrate supplies and releasing methane, a GHG, into the atmosphere. Harvesting the methane therefore serves two purposes: producing energy and avoiding global warming. The technology to use the methane hydrate as an energy source is being aggressively developed; for the first time in the world, Japan successfully extracted methane from clathrate fields off the central coast (Nankai Trough) in mid-2013. However, methane too is a fossil fuel that when burnt will add to the carbon load in the atmosphere of an uncontrollably warming earth.

1.1.1.4 Nuclear Energy Increased use of nuclear energy (a nonrenewable source) might be a potential short-term solution especially if the penalty cost of carbon emission (under Kyoto Protocol) increases. Decommissioning of nuclear weapons can of course be a low-cost short-term source for enriched uranium that can be diluted and used as reactor fuel. It is an option being aggressively pursued in China, India, and Russia. In the United States, 104 nuclear plants are presently operational. However, like with oil reserves, the known U_{235} reserves are not adequate to meet the projected global energy demand (world uranium resources are estimated to be only ~5 million tons). As already discussed, mining is particularly damaging to the earth and results in the release of particulates carrying heavy metal residues into air and acid mine drainage into groundwater. The overwhelming negative effects of these on native wildlife and plant populations cannot be overstated.

A majority of the plants in operation today (over 200 worldwide) are 20–30 years old and have a residual lifetime of only 10–20 more years. Uranium ore is presently used to generate nearly 15% of the world's electricity (and ~20% of US electricity) and will likely last only a few more decades. Even if more ore becomes available, nuclear energy can be an environmentally high-risk technology as illustrated by the nuclear accidents in Russia's Chernobyl plant in 1986 and Japan's Fukushima Daiichi power plant in 2011. The ecological devastation and the cost of cleanup of inevitable spills of radioactive material are far greater and more complicated compared to managing oil spills. Alternative reactors (such as those based on thorium[15]) might be used in the future despite the safety risks they pose. Nuclear waste disposal is another

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[15] Thorium-232 can be used in specially designed nuclear reactors that use U_{235} or Pu_{239}. But the World Thorium reserves also stand around 6 million tons.

daunting problem. Nuclear plants are shut down every 12–24 months to replace "spent" fuel with fresh uranium. The still radioactive spent fuel has to be stored safely for thousands of years in robust underground storage facilities (1000 ft deep site within in Yucca Mountain, NV, is being considered for the purpose).[16] The plutonium waste, for instance, has a half-life of 24,000 years!

1.1.2 Renewable Energy

The only route to sustainable development is via renewable energy technolgies that are generally carbon-neutral. In the United States, hydroelectric power is used to generate approximately 7.9% of the electricity. A significant amount of our energy already comes from renewable sources (19% of the energy used globally in 2011) primarily as hydroelectric power. The new 22.5 GW plant at the Three Gorges Dam in China is a remarkable example of the technology, which also illustrates the socioeconomic costs of displacement of people and loss of land use associated with such projects. Worldwide, however, the best hydroresources are already exploited, and a natural limit to growth in hydroelectric power generation might be anticipated. Yet, at this time, the highest growth rate in electricity generation worldwide is with hydropower. In the United States and in the West, the water resources are nearly fully tapped already and the growth will be much slower.

1.1.2.1 Wind Energy Wind energy that accounts for a respectable 2% of the worldwide electricity generation (and ~1.2% of US energy) has the potential to grow and be deployed rapidly. It is an economical option; cost/MWh compares well with that of conventional coal or hydropower installations. Several small countries generate 10–20% of their power needs from wind energy. The present technology can be relied upon to deliver about 2 W/m^2 of wind farm. It is a fundamentally attractive option with the potential power proportional to the third power of wind speed. A recent report (Hansen et al., 2013) finds wind energy to be the leading or renewable energy source for electricity production until 2035. The main constraint will be availability of land in windy areas to locate such farms. In regions with adequate wind resources, the technology holds promise as a supplementary power source. Offshore wind farms, especially in deep-sea areas, might be more efficient than land-based facilities.

A potential environmental problem with wind farms is their negative impact on migrating bird populations. A recent estimate suggests the mortality to be about 0.27 deaths/GWh generated (Marris and Fairless, 2007). Given that the bird deaths by fossil fuel plants are greater than 5 per GWh and that for nuclear power plants are 0.42 per GWh (Sovacool, 2012), the cost is modest compared to energy derived.

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[16] This one facility designed for 77,000 tons of waste will not be enough even for our present needs. Furthermore, the area is seismically active, and one needs to worry about the buried canisters of waste being compromised in an earthquake.

1.1.2.2 Solar Energy

All of the Earth's processes are ultimately energized by solar energy (excluding chemosynthesis in the seabed). Solar energy reaching the Earth's surface in a single hour is estimated to be more than the annual global energy demand (US Department of Energy, 2005). Presently, only a paltry 0.01% of the global energy demand (0.1% of the US demand in 2011) is met by solar energy. The sunlit half of the globe receives a solar flux of 680 $\mathrm{W/m^2}$ of radiation and is for the most part captured by plants that very inefficiently (typically <2%) convert it into biomass. (Interestingly, the incandescent lamp also converts only 5–10% of the input energy into light!) Biomass generated in turn serves as food to herbivores with the food energy transferred up the complex food chain to the human consumer. The energy transfer across trophic levels (say, herbivores to predator carnivore) is particularly inefficient, approximately only 10%. The rest (~90%) of solar energy captured by plants is dissipated as low-value heat. The efficiency of using installed[17] solar cells converting sunlight into useful energy as electricity is at least an order of magnitude higher in efficiency compared to photosynthesis.

Solar energy can be harvested either using photovoltaic (PV) cells that convert the light directly into electricity or using solar thermal collectors. The latter is much lower in capital cost and is far more efficient in that they convert nearly half the impinging solar radiation into heat. Heat, however, is a low-grade energy not as convenient to store or use as electricity. Commercial efficiency of PV modules based on polycrystalline silicon (over 70% of modules produced in 2010) is approximately 14% (and 7–11% for the newer thin-film modules) (U.S. Department of Energy (US DOE, 2011)). Research cells under development show higher efficiencies, as much as 42% in a multijunction concentrator. The 3D solar PV panels still under development can generate 20 times more energy compared to conventional flat panels and are claimed to push the efficiencies close to the theoretical maximum for silicon. Emerging printed electronic technologies are also likely to soon deliver roll-to-roll production of flexible, fully printed solar cells on plastics substrate.

The global installed PV capacity in 2010 stood at 40 GW with Europe, the market leader, and the United States, a minor producer, with a capacity of only 2.5 GW. The world's largest facility in Bavaria, Germany, produces 10 MW of electricity from its 3 acre solar farm. The capital cost of installed PV cannot as yet effectively compete with fossil fuel energy; a robust PV farm installed over less than 0.05% of Earth's surface should be able to generate the annual fossil fuel energy budget of the world. Despite the low cost of energy in the near future, solar energy technology is likely to grow into a very significant player in the future energy markets around the world (Fig. 1.6).

1.1.2.3 Solar Biomass Energy

Indirect harvesting of solar energy via biomass (ineffective as the conversion might be as pointed out already) is a growing renewable energy strategy. The best-known example is the use of corn-based alcohol as fuel. In the United States, up to 10% ethanol is typically blended into gasoline, and in 2010,

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[17] The capital cost of growing corn is very different from that of installing a field of solar cells. The comparison is therefore based on installed solar cells versus growing corn.

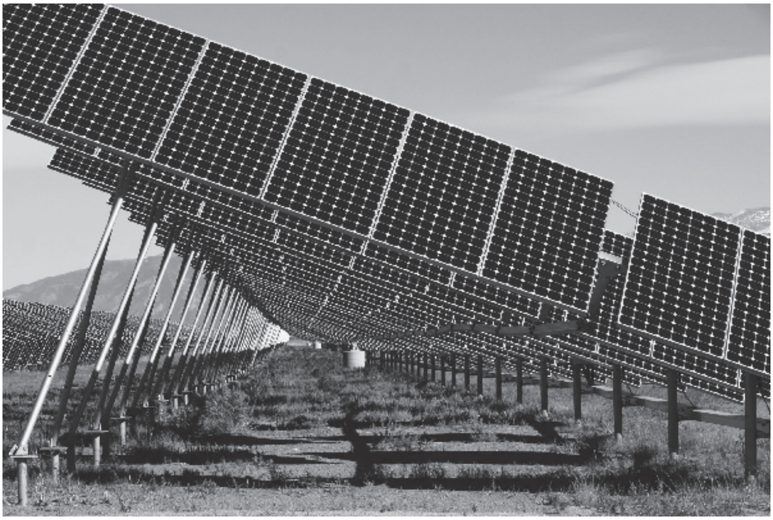

FIGURE 1.6 Sprawling solar energy complex in San Luis Valley, CO.

40% of the US corn production was diverted from feed/food uses to make about 13 billion gallons of fuel-grade ethanol.[18] While biomass technologies can be scaled up and implemented quickly, an approach that converts agricultural food-producing land into fuel-producing acreage has obvious drawbacks. In 2007, 47% of vegetable oil in the EU was used for biodiesel production but still contributed only to 0.36% of the global energy supply (UNESCO, 2009)! Biomass such as marine algae, cellulosic waste, or rapidly growing nonfood land species (switchgrass) can also be converted into fuel. Using these in place of corn biomass will make far better economic sense in the future. Available crop varieties presently yield less than 1 W/m^2 of land used.

1.2 MATERIALS DEMAND IN THE FUTURE

Thomas Malthus (Cambridge University) in 1798 predicted a catastrophic fate for the human race due to a growing population outrunning its subsistence. More recently, Paul Ehrlich (1974) predicted materials shortages worldwide that will result in skyrocketing prices even for basic commodities. However, his timing has been proven to be inaccurate; population has grown, but the austere times of severe shortages they envisioned had thankfully not materialized. Except in some remote regions of Asia and Africa, adequate food supplies are still available. Then was Malthus wrong? What Malthus did not fully take into account and what effectively countered the predicted shortages thus far is technology or human ingenuity. The same winning trait that outwitted the *Neanderthals*, tamed fire, and developed tools to conquer nature in the dawn of human civilization has continued on, unabated, in modern times.

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[18] US total installed capacity of fuel-grade ethanol to 15.0 billion US gallons.

Great strides have been made in high-yield agricultural technology, in post-harvest management of produce, as well as in packaging and distribution of food. This has allowed the inconceivable achievement of producing increasingly more food despite the depleting acreage of arable agricultural land. Science and technology has thus far allowed humankind to be a step ahead of Malthus's ominous prediction. Material consumption too has become increasingly efficient across the board, with substitution for scarce materials, design improvements to use less of the more expensive materials, and learning to better locate new ore reserves. But can we always count on technology to keep us a step ahead of a Malthusian catastrophe? In the short term, it is probably so. But it cannot be assured over long periods of time as there are inherent limits to improving a system using progressively better technologies (Brown, 2009; Evans, 2009). The limit will probably be due to either the shortage of nonrenewable resources needed to fuel the industrial machinery or the pollution load associated with more sophisticated technologies that have to be practiced at high intensity.

1.2.1 Materials of Construction

The dominant materials in demand worldwide are materials of construction including wood, gravel, clay, and aggregate, followed by of course the fossil fuel materials. Several metals are in high-volume use; iron is the most important of these followed by aluminum, copper, zinc, manganese, chromium, nickel, titanium, and lead. As opposed to these, there are metals that are used in very small quantities but are nevertheless indispensable in high-technology applications, especially in the energy industry.

Being a renewable material, the availability of hardwood for construction can be relied on as long as enough acreage is available for forestry development. Other materials such as sand, steel, cement, aluminum, and plastics that rely on mineral supplies need to be mined out of the ground. As long as extractible resources are available and the energy expenditure in tapping/processing of these is affordable, these too are likely to be in good supply. Based on today's conditions and technology, the embodied energy and CO_2 footprint for representative materials are given in Figure 1.7. Plastics are only moderately energy intensive to use, though not as economical as materials such as concrete or wood.

Industry requires a continuing supply of raw material to produce goods and services. In effect, the purpose of the complex industrial machinery is to use materials (some renewable and other not) to continuously produce goods and services for consumers. With renewables, managed harvesting or use should not present a special problem. But with scarce materials such as rare earth oxides, a problem that parallels that of fossil fuels exists. Metals occur as concentrated ores; their use entails extracting them and using them often in minute quantities in various products and then dispersing them as waste into the environment. Post-use metals are very expensive and tedious to recover. The global and US consumption of selected materials of construction in 2011 is given in Table 1.1.

It is interesting to calculate the total embodied energy (GJ) in different types of building materials based on the data in Table 1.1. The bar diagrams in Figure 1.8 compares the global materials-use energy and carbon emissions for selected materials based on 2011 data. In numerous applications, the functionality demands of the

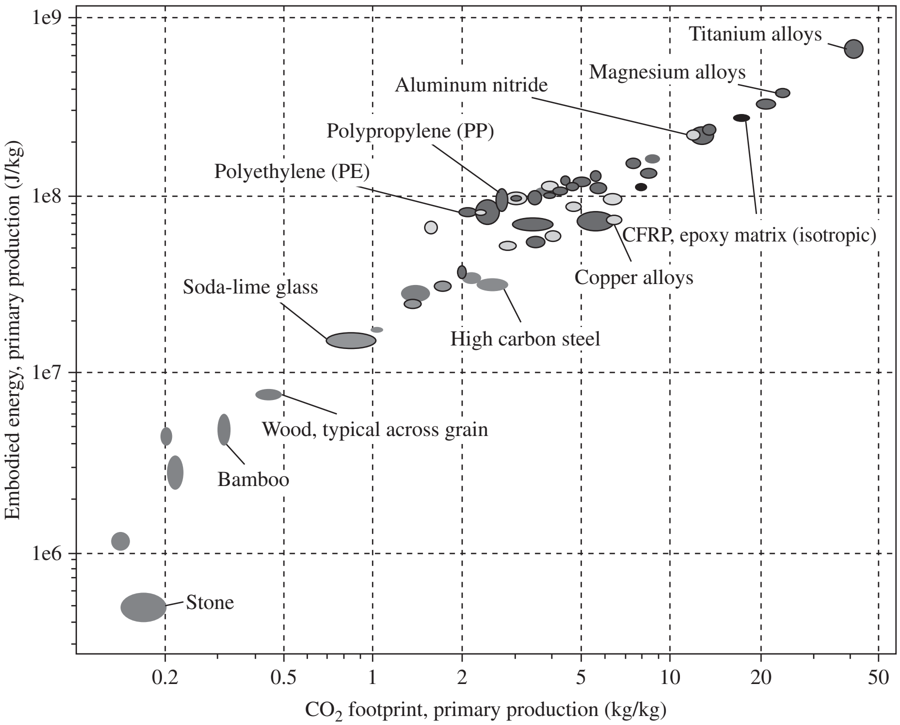

FIGURE 1.7 Comparison of the embodied energy (J/kg) and CO$_2$ footprint for different materials. Source: Reprinted with permission from Ghenai (2012).

TABLE 1.1 Approximate Global Use of Selected Building Materials (2011 Data)

Region	Cement	Roundwood	Steel	Plastic	Aluminum
World (BMT)	3.6	1.74	1.52	0.28	0.04
United States (MMT)	72	145	90	47.5	3.6

The table is based on data from “Materials and the Environment” (www.forestinfo.org)

product can be delivered using less-scarce and lower energy-intensive substitutes such as plastics. In Chapter 3, the advantage of using plastics as a substitute material will be discussed in greater detail.

1.2.2 Metal Resources

Metal resources are nonrenewable and their long-term availability depends on the known reserves and the cost of extraction. With some metals such as uranium, the fraction of the oxide present in earth is approximately 0.1–0.2%. This means that a large area of earth has to be processed to extract the metal. This would result in relatively larger environmental impact compared to producing a metal such as aluminum

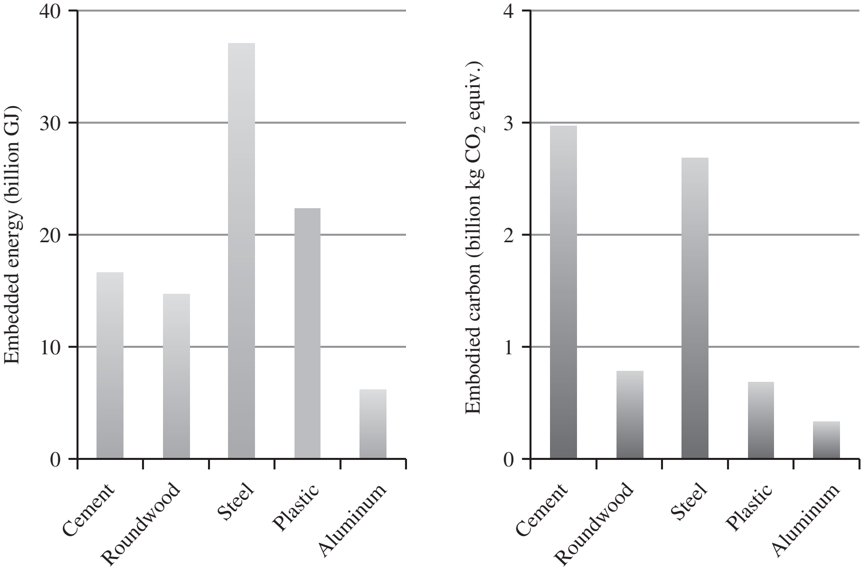

FIGURE 1.8 Estimated embodied energy (left) and carbon emissions (right) of classes of building materials globally consumed in 2011. Source: Calculations based on data in Hammond and Jones (2011). See http://www.circularecology.com/ice-database.html.

TABLE 1.2 Estimated Future Global Supply of Some Common Metals

Metal	Estimated supply (years)	Metal	Estimated supply (years)
Iron ore	178	Lead	19
Aluminum	219	Copper	35
Zinc	19	Nickel	51
Manganese	43	Uranium	65

Source: Data from Richards (2009).

where the ore is 30–50% oxide. Richards (2009) reported the world reserves of selected industrially important metals. These numbers (Table 1.2) are based on the current rate of use and can change in the future because of accelerated use and the discovery of new reserves.

Hubbert's theory of diminishing reserves on exploiting a finite resource beyond a certain level might also be used to estimate how long rare metal resources might last. Unlike base metals such as iron and copper, the rare metals show a peak in the production versus time curves. Some, such as mercury, zircon, selenium, and gallium, have already peaked by year 2000. Metals such as indium, hafnium, gallium, germanium, and arsenic are estimated to deplete within two decades! Indium is used in solar panels as well as in liquid crystal displays, while hafnium is used in computer chips and in nuclear engineering. A majority of the metals in short supply are expected to deplete within the next 100 years (Rhodes, 2008).

However, such estimates will be approximations for a variety of reasons. First, the resource base is not constant as new supplies are being added to the reserve base each year and the annual demand for metals also changes with time. Secondly, the rate of exploitation being demand-sensitive is highly variable. Physically running out of these materials is unlikely in the medium term; more intensive and increasingly polluting new technologies will ensure their supply. The United States is heavily dependent on foreign sources[19] of these materials; this suggests that, as with oil political realities may also play a role in their future supply. Despite these observations, the next century is unlikely to be an austere metal resource-strapped world as more of the Earth's crustal reserves will probably be exploited more intensively and with even better technology. Learning to use less of the scarce materials and substituting for them will be a slower process, and changes in technology may ultimately shift the demand away from the scarce metals.

Generally, the base metals used in high volume are not "consumed" in the sense that they are at the end of use converted into an irrecoverable state. Thus, metals such as iron or aluminum used in construction or packaging can be recovered and recycled extending the lifetime of the resource. While there are inevitable losses in reuse or recycling operations, it can save energy and reduce the pollution load on the environment (Gordon et al., 2006). Energy savings in recycling of steel, aluminum, copper, and lead are estimated to be 74, 95, 85, and 65%, respectively (Steinbach and Wellmer, 2010).

1.2.3 Critical Materials

A class of materials increasingly used in a variety of high-technology and emerging energy applications is the rare earth and platinum group metals.[20] However, future technologies such as electric vehicles, displays, next-generation solar panels, and advances in wind power rely on the availability of these metals. For instance, the world demand for neodymium used in magnets and laser applications will be 40,000 tons/year by 2030; this compares with the demand of only 7000 tons in 2006 (European Environment Agency, 2010). The US DOE has identified several critical materials in this category that will be in short supply in the United States within the next couple of decades. A strong growth in short-term demand is expected at the very least for Te, In, and Ge. The periodic table in Figure 1.9 highlights these and also indicates those regarded as being critical materials in the European Union.

Applications of critical metals are dissipative, and post-use recovery is either impractical or impossible. In theory, the low-volume, high-value critical metals can also be recycled effectively. Often, these are used in complex constructs such as thin layers used in solar panels. The processes to separate out the components in recycling

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[19] Over 95% of mineral commodities used in the US is imported from China.

[20] Communication services, such as the operation of satellites, GPS, computers, and even cellphones, all depend on the availability of specialized materials such as semiconductor materials, phosphorus, and battery technology.

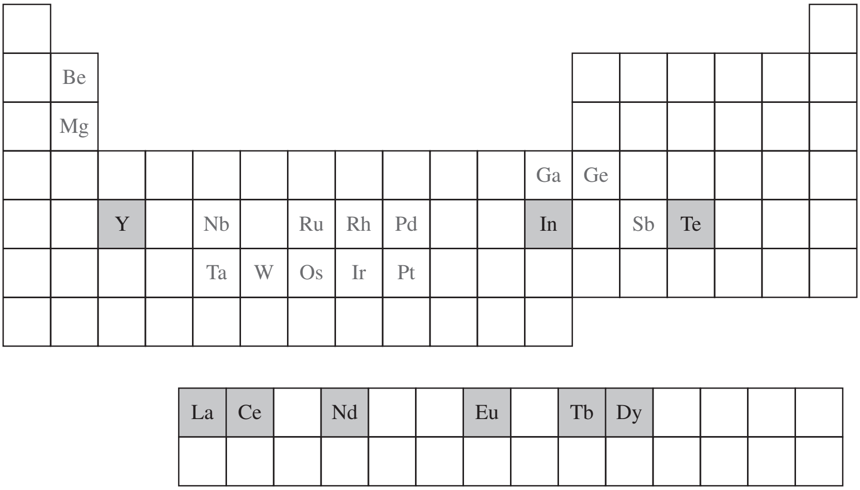

FIGURE 1.9 Critical elements likely to be in short supply in the near future. The shaded boxes are those identified by the US DOE study (2010). The others are additional critical elements identified by a European Commission (2010).

are complicated and costly. A recent UNEP report (UNEP, 2011b) suggests global rates of post-use recycling of these to be less than 1% (1.35% for tantalum). Table 1.3 summarizes some typical exemplary uses of critical metals.

With future shortages anticipated, a strategy for using these scarce resources prudently and an aggressive plan to recover/recycle these are needed. Inevitably, recovery and reuse of the higher-value materials will be an attractive propositions. With those materials beyond Hubbert's type peak recycling will be the only way to ensure a continuing supply in the near future. For instance, rhenium (Hubbert's peak in the late 1990s) is already being extracted and recycled. In the West with an ingrained "disposable" consumer culture, reuse–recycle will be a difficult task. But at some cost point, it will be cost-effective and even be very lucrative to recycle these than to process fresh ore.[21] Figure 1.9 shows the critical elements that are likely to be in short supply in the near future.

1.2.4 Plastic Materials

Though commercially introduced into the market as a commodity material some 60 years ago, the design versatility, low cost, formability, and bio-inertness of plastics have made it the material of choice in a broad range of applications. The demand for plastics is linked to economic development of nations. With some conventional materials such as cement or steel, the demand on materials is decoupled with economic development and is decreasing on a per capita basis in developed countries. This can

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[21] Already, the Pt content derived from automobile catalytic converters in road dust has reached the levels it is present in South African Platinum ore! (Cohen, 2007).

TABLE 1.3 The Use Sectors, Global Reserves, and Production of Selected Critical Materials

Electrical and electronic	E	P	Ba	Cat	Reserves 1000 MT	Annual production 1000 MT	Main uses
Tantalum	X				130	1.4	Capacitors, carbide tools, and alloys
Indium	X	X			11	0.6	LCD and OLEDs, alloys, and solder
Ruthenium	X				5	0.04	Magnetic (hard drive) media
Gallium	X	X			6.5 (in Zn ore)	0.08	LEDs, cell phone displays
Germanium	X	X			0.45	0.11	
Palladium	X						
Tellurium		X			21	0.45	Alloys, solar energy
Cobalt			X		7,000	55.5	Superalloys and cemented carbide
Lithium			X		4,100	25	Batteries, ceramics, and lubricants
Platinum				X	27	0.20	Cat converters, jewelry
Palladium				X	26	0.37	Cat converters, jewelry
Rare earth oxides			X	X	88,000	124	Cat converters, refineries, and alloys

Source: Data compiled from UNEP (2009).
Primary sectors of application.
Ba, batteries; Cat, catalysts; E, electrical and electronic uses; P, photovoltaic.

occur when the gross domestic product (GDP) of the country becomes dominated by the service sector (vonWeizsäcker et al., 1997). However, this is not the case with plastic materials that continue to grow coupled and in tandem with regional or national economic growth. The future supply of commodity plastics is generally tied closely to that of fossil fuels. This need not necessarily be the case as plastics can also be manufactured from renewable resources, but the processes are as of yet not cost competitive. As petroleum resources continue to dwindle, the cost of plastics will undoubtedly increase, and recycling of some of these may become cost-effective.

Historically, the rate of growth of material consumption has outpaced that of population. During the period (1961–2012) that saw a population increase of about 230%, that of wood, steel, and cement consumption grew by 160, 426, and 1100%, respectively. Plastics consumption in the same period grew by over 4800%.[22] Plastics are so common a material that today it is difficult to imagine living in a world with no plastics. If all plastics were instantaneously removed from modern lifestyle, we would certainly miss the material. Most of our clothing including footwear, consumer goods and building products (plumbing, siding, some glazing, and

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[22] Data quoted from www.forestinfo.org by Dovetail Partners Inc., Minneapolis, MN.

electrical components), parts of vehicles (some bodywork, all seat covers, lamps), critical residential services (electricity, water/sewer, gas, telephone), most packaging and healthcare products will fade away. Of course, some of these can be substituted with other materials such as glass, metal, wood, or paper but generally at a higher materials and life cycle energy costs.

There are several key characteristics of plastics that make them highly competitive as a material in the marketplace and will guarantee its continued growth:

1. Strength and low density
   Plastics, though lightweight, are exceptionally strong materials. Some specialty plastics such as Kevlar are stronger than steel and are used in bulletproof vests. Carbon-fiber and other composite materials (including nanocomposites) are used in transportation applications that require lightweight and high strength. As will be elaborated in Chapter 5, reducing weight, especially in vehicles, is particularly profitable because of savings in fossil fuel use and related GHG emissions.
2. Moldability into complex shapes
   Advanced molding techniques allow both thermoplastic and thermoset materials to be fabricated into complex 3D objects. This has the engineering advantage where, unlike with materials such as steel (used in aircraft construction, for instance), individual pieces need not be fastened together to create such shapes. Large objects like hot tubs, shower stalls, or marine vessels can be fabricated easily as a single piece with no joints that can fail during use. These can be colored in any hue desired and in some instances even coated with a protective surface layer.
3. Durability can be designed into the material
   Depending on the specific application, the plastic material can be compounded with antioxidants, light stabilizers, and flame retardants to ensure that the service requirements of products are met. For instance, the same plastic can be compounded for durability or long service lifetimes as well as degradability or controlled loss of properties (as with enhanced photodegradable plastics) using appropriate additives.
4. Biological and chemical inertness
   Common plastics are not affected by aggressive chemicals, and some (such as bleach, lubricant oils, solvents, and acids) are even safely packaged in plastic bottles. It is their bio-inertness that allows them to be extensively used in food packaging and medical devices. Common plastics do not support the growth of microorganisms. In cases where this sometimes is seen to occur (such as in PVC shower curtains), it is the additive plasticizer that supports the growth, rather than the PVC plastic material.
5. Electrical and thermal insulators
   Plastics do not conduct electricity[23] and are used to make electrical hardware such as switches and household power outlets. However, where needed,

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[23] A special group of plastics that include examples such as polyaniline and polythiophene are inherently electrically conducting and are used in electronic applications.

conductive fillers such as metal whiskers or carbon nanotubes can be used as fillers in the plastic to impart electrical conductivity at the desired level. As they are good thermal insulators as well, plastics are used for retort packaging and microwavable cookware. The inherent low thermal conductivity can be improved further by making the plastic into a closed-cell foam that traps air or other gas to make it an excellent insulation material. Again, where needed, a desired level of thermal conductivity can be imparted into the plastics using a conductive filler.

From sustainability considerations, all materials are not created equal. A distinction needs to be made between materials derived from:

1. fossil fuel;
2. other limited resources such as critical metal and oxide ores;
3. raw materials available in abundant or renewable supply (e.g., wood, sand, sodium chloride); and
4. waste or residues from the use or consumption of the three other categories earlier.

Wagner and Wellmer (2009) have formalized this classification into a hierarchy, suggesting that substituting for materials placed higher in the hierarchy with those at a lower level constitutes a sustainable change. This included recycling a material or reusing within its own class within the hierarchy. The hierarchy is based on the valuation of the materials alone and lacks the dimension of environmental and human safety that should also be important considerations in material selection and use. The use of a material or a product that contains a potentially toxic residue/leachate or does not have a means of recovery is certainly not a sustainable practice.

1.3 ENVIRONMENTAL POLLUTION

Emissions that pollute the environment, particularly the air and water resources, are inextricably linked with the life cycle of a generic product especially where the raw material has to be extracted from the earth's crust as shown in the generalized diagram in Figure 1.10. Each step involves the use of energy and some emissions into the environment and generates a residue that invariably needs to be disposed of. These costs are neither immediately evident or are fully accounted for in the cost of the product or reflected in assessing the GDP of the producer nations. It is this shortcoming of GDP as a measure of development that helped the popularity of the better[24] index, Genuine Progress Indicator, used in full cost accounting.

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[24] It is indeed a better index compared to GDP. For instance, GDP counts pollution as income from the abatement and cleanup of pollution is a business activity in the economy. GPI, however, counts it correctly as a cost. Cut down a thriving forest into lumber; the GDP counts this as income, while GPI counts it as cost.

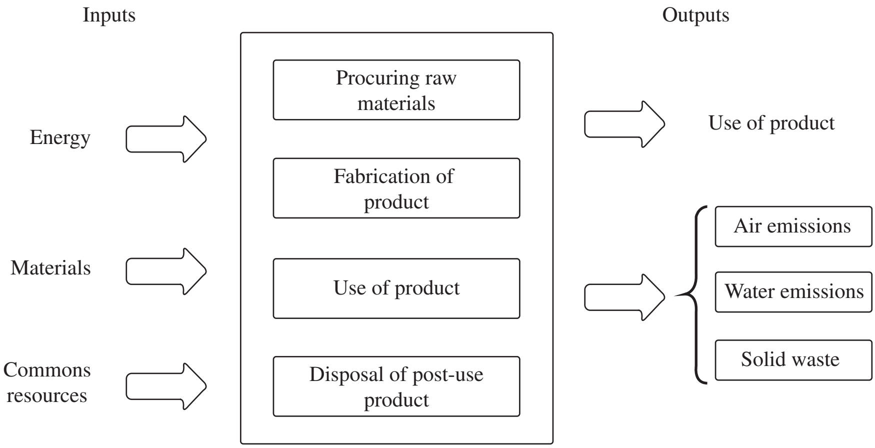

FIGURE 1.10 Illustration of the life cycle of a product showing different steps. Residues are the externalities associated with each phase. Each phase also requires the input of energy.

1.3.1 Classifying Pollution Impacts

In assessing the significance of different types of pollution, it is useful to classify them in terms of their spatio-temporal impacts. The spatial dimension defines the extent of the ecosystem impacted (and therefore also the population affected) by the pollutant in question, while the temporal aspect takes into account the kinetics of the impact. Spatial effects are easier to estimate and where needed, weighted to take into account any effects on human health. Temporal impacts are far more difficult to quantify as the impacts are felt by different populations or even different generations. The fact that the polluter and the affected can be so markedly separated in space and time introduces an ethical dimension to environmental issues. Generally, consumers tend to pay more attention to the needs of the present generation compared to future generations.

An attempt is made to capture this distinction in the following four-group classification of environmental impacts (Table 1.4) of (i) short-term local impacts, (ii) short-term global impacts, (iii) long-term local impacts, and (iv) long-term global impacts.

Local effects as well as the effectiveness of remedial strategies implemented are fairly easy to monitor and validate. For instance, when 700 oil wells in Kuwait were set ablaze by the retreating Iraqi forces in 1991, it spawned a severe local short-term environmental catastrophe. But the extent of damage and the success of control measure used by the fire control teams could be easily monitored. The same was not true of long-term effects of mercury waste being dumped into Minamata Bay in Japan; the more serious impacts occurred in the future, while there was no immediate recognition of a threat to local community.[25]

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[25] But the pollutant may affect other localities in the general region. For instance, the release of Mercury from coal-fired power plants in the Upper Ohio River basin resulted in high blood Mercury levels in Eagles (especially eaglets) in Catskill area of New York. The pollutant was transferred, biomagnified, via contaminated fish that the eaglets consumed. The report is reminiscent of the Minamata Bay incident in Japan in 1960s (Nearing, 2008).

TABLE 1.4 Classification of Environmental Pollution Events

	Local impact	Global impact
Short term	Eutrophication of lakes due to fertilizer pollution	Oil or chemical spills during ocean transport of materials
	Deterioration of indoor air quality by VOC[a]	Nuclear fallout or the release of active or waste nuclear material into air or sea
	Strip mining for metal ore releasing aerosols	Accidental release of genetically modified cultivars or animal species into the environment
	Destruction of coral reefs by fishing	
Long term	Discharge of organic Hg into the Minamata Bay (Japan) leading to neurological disease	Stratospheric ozone depletion resulting in increased solar UV-B radiation at the ground level
	Overfishing resulting in the depletion of preferred fish stocks	Global warming and climate change
	Deforestation and loss of biodiversity	Mercury pollution of air and water from coal-powered plants

[a] Volatile organic compounds.

Despite any classification adopted for convenience of the discussion, it is still a single interconnected global environment that needs to be protected. Pollution reduction that entails the removal of a pollutant from one part of the environment (say, air) only to increase its concentration in another (say, the ocean) is of no practical benefit. For instance, remediation of groundwater contaminated with fuel (perhaps from a leaking fuel tank) by air stripping to volatilize the hydrocarbons merely shifts the problem from one medium to another. The argument that in an alternative medium the pollutant will have a reduced risk is not a robust one. Emphasis needs to be on pollution prevention in industrial processes to make sure that less waste is generated, emitted, and waste does poses the minimum damage to the environment.

1.3.2 Climate Change and Global Warming

The temperature at the Earth's surface depends on how much solar radiation reaches the surface and how much of it is reemitted back into space. Only about half the incoming solar radiation reaches Earth's surface due to scattering by clouds and absorption by atmosphere. A fraction of the incoming radiation absorbed by the Earth is emitted back as longer-wavelength heat into the atmosphere. Some of this is reflected back into space. It is the delicate balance between the incoming radiation absorbed by Earth and that emitted back into space that maintains the average temperature at Earth's surface within a hospitable range. How well the emitted heat can traverse the atmosphere and escape into space depends on the composition of the

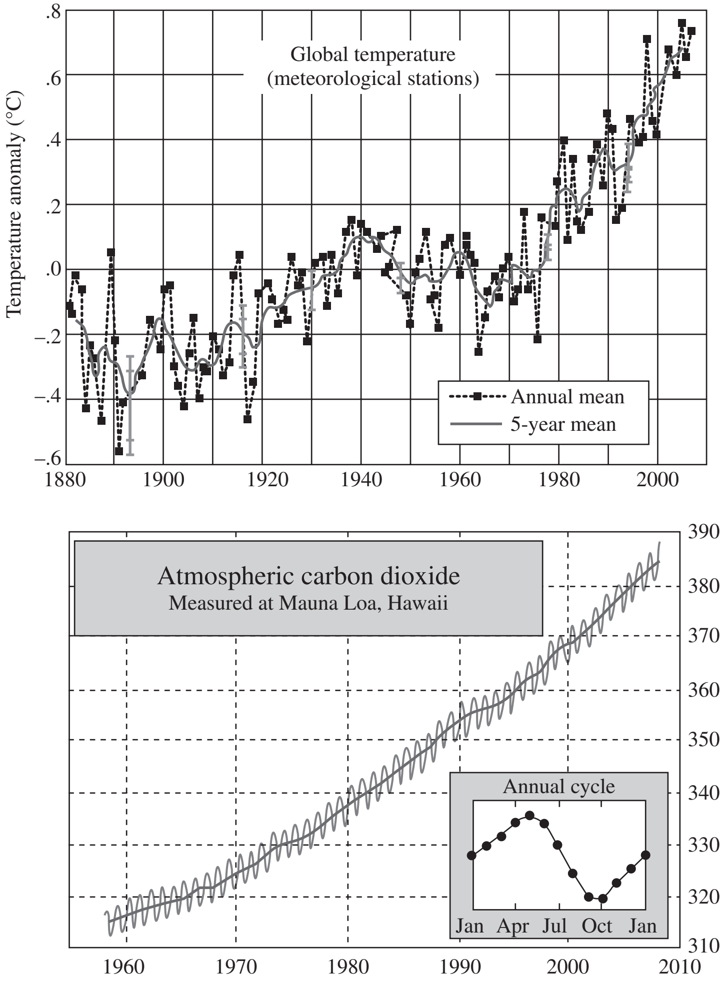

FIGURE 1.11 Global average temperature variation and global CO_2 emissions over time. Source: Reproduced with permission from Akorede et al. (2012).

atmosphere. Molecules such as water vapor, CO_2, and CH_4, the GHGs, are in the upper atmosphere, impair this process, and the heat is reflected back toward the Earth's surface. It is this natural "greenhouse effect" that maintains the temperatures at Earth's surface within a range that supports life.[26]

However, the levels of these contaminants in the environment, especially that of CO_2 and methane emissions from human activity, have steadily increased by about 40%, from 280 ppm, at the time of industrial revolution, to about 337 ppm today (see Fig. 1.11). Higher levels of CO_2 have not been seen in Earth's atmosphere for nearly

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[26] Without the greenhouse effect, the temperature on Earth's surface will plummet to 0°F (−18°C), and all water on Earth, including the oceans, will freeze! Life as we know it will not be possible.

the last one million years! In response, the average global temperature rose by 0.8°C over the last century. In the twenty-first century, it can increase by a further 1.5–6.1°C, depending on how well we control the emission of these gases (Solomon et al., 2007). The potential of a gas to cause global warming (GWP) depends on its lifetime in the atmosphere and how well it absorbs the infrared radiation (especially in a wavelength window where the atmosphere itself does not absorb such radiation). For instance, CO_2, CH_4, NO_2, and the Freon HFC-23 have 100-year GWP values of 125, 298, and 14,800, respectively (IPCC, 2010). The same mass of these different gases released into the atmosphere can contribute to dramatically different extents of warming.

Despite the best concerted effort the world can muster, the average global temperatures will still likely be at least 2°C higher than the pre-industrial level by 2100 (this is an agreed-upon climate goal[27]). There is no assurance that being under this limit of warming (<2°C) will avoid serious deleterious impacts (Hansen et al., 2013; Richardson et al., 2009). Severe and sustained climate change will probably occur with that much, or even smaller, increases in the average temperature. These include changes in weather patterns across the globe, melting glaciers (Arctic sea ice dropped to its lowest levels in 2011 (Kinnard et al., 2011)), sea level rise (now at ~2.1 mm/year), changes in precipitation patterns, increase in average ocean temperatures, and increases in UV flux reaching earth. The 10 warmest years on record have all been within the last two decades. Effects of warming are readily apparent in the melting of snow and ice masses (especially in Greenland and the Arctic), higher incidence of heat waves as well as droughts, tropical storms, changes in sea level, and flooding. These changes are expected to reduce the hydroelectric power output, decrease agricultural productivity, increase incidence of disease, and disrupt freight transportation in the coming decades. But international commitment to hold the goal of warming lesser to less than 2°C is essential for the well-being of the planet and, very likely, the survival of the human race.

Both globally and in the United States, man-made GHGs are dominated by CO_2 from combustion of fossil fuels (reaching a record of 31.6 Gt in 2012),[28] mainly for production of energy. However, much larger loads of carbon dioxide are emitted by natural processes that have been around for millions of years. The respiratory emissions of biota alone amount to over 750 Gt of CO_2 a year, but at least until the industrial revolution, the carbon cycle efficiently removed the gas, allowing only about 290 ppm of it to remain in the atmosphere. The issue is with the *additional* 34 Gt CO_2 equiv./year[29] of the gas from anthropogenic activity. The carbon cycle cannot easily accommodate this added load placed on it in the short period of less than a quarter century. With the cycle overwhelmed, the concentration of CO_2 in the atmosphere is on the rise. Globally, about a fifth of the CO_2 emitted is from

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[27] Governments agreed at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties in Cancun, Mexico in 2010 (COP-16) on this level.

[28] A ton of CO_2 gas has the volume inside a typical two-story US home.

[29] Carbon dioxide is the dominant greenhouse gas, but others such as methane and oxides of nitrogen also contribute to the greenhouse effect. For convenience, the total effect is quantified in terms of CO_2 equivalents.

industrial and manufacturing activity. Most of it is derived from burning oil, while the contributions from coal and natural gas fuels are also significant. The annual US emissions of about 30 MMT of CO_2 (2007 data) presently amount to about 20% of the global emissions. In order to be under the <2°C limit, by 2050, the global GHG emissions must be reduced to 80% of that in 1990. This can only be achieved if conventional energy used today is replaced substantially by renewable energy. If we continue business as usual, the limit will be surpassed within the next 50 years (Joshi et al., 2011).

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