PLASTICS AND ENVIRONMENTAL SUSTAINABILITY

ANTHONY L. ANDRADY

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Andrady, A. L. (Anthony L.)
Plastics and environmental sustainability / Anthony L. Andrady, PhD.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-31260-5 (cloth)
1. Plastics–Environmental aspects. 2. Plastics–Health aspects. 3. Plastics–Biodegradation. I. Title.
TD798.A53 2015
628.4′4–dc23

2014042233

Cover image courtesy of iStockphoto©Devonyu

Set in 10/12pt Times by SPi Publisher Services, Pondicherry, India

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

1 2015

This book is dedicated to my children
and my grandchildren.

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PREFACE

How quickly a concept is grasped, adopted, and assimilated into the general culture is indicative of how germane a human need it addresses. If that is indeed the case, the notion of sustainable development seemed to have struck a vibrant sympathetic chord with the contemporary society. Since its emergence in the 1980s, the general tenet of sustainability has gained rapid worldwide salience and broad global appeal in some form or the other. Though it is easy to identify with and even subscribe to it in general terms, the goal of sustainability and how to achieve it remain unclear. In addition to being a dictionary term, "sustainability"[1] has also become a buzzword in the business world. Today's message of sustainability reaches way beyond that of the early environmental movements of the 1960s and 1970s in that it includes an ethical component based on social justice for future generations.

With the global carrying capacity already exceeded, energy/materials shortages looming in the medium term, and the climate already compromised by anthropogenic impacts, many believe that we have arrived at decisive crossroads with no time to spare. The only way out of the quagmire is a radical change in thinking that encompasses the core values of sustainable growth. The message of sustainable growth has also reached chemical industry at large including the plastics industry. In a recent global survey of consumer packaged goods companies by DuPont in 2011, a majority (40%) of the respondents identified attaining sustainability (not costs or profits) as the leading challenge facing their industry today. Environmental movements including the call for sustainability have hitherto evolved along strict conservationist pathways over the decades that saw economic development inextricably linked with polluting externalities and tragedy of the commons. This invariably pitted business

[1] The word is derived from the Latin root *sustinere*, which means to uphold.

enterprise against the health of global environment. Industry was still identified a significant polluter and generator of waste. This has lead to the plethora of environmental regulations promulgated in the United States during those decades aiming to "regulate" their operations. The knee-jerk response has been greenwashing, a mere defensive stance by industry, seeking to make small visible changes to nudge existing practices and products into a form that might be construed as being sustainable.

The entrenched belief that business and technological development must necessarily adversely impact the environment remained entrenched in the 1970s and 1980s. In 1992, at the UN Conference in Rio, this notion was finally challenged and the dictum that economic development (so badly needed to eradicate world poverty) can occur alongside environmental preservation was finally proposed. But preservation means maintaining the environmental quality and services at least in its current state for the future generations to enjoy. Without a clearly articulated mechanism of how to achieve this rather dubious goal or the metrics to monitor the progress along the path to sustainability, the notion blossomed out into a popular sociopolitical ideal. Consumers appear to have accepted the notion and are demanding sustainable goods and services from the marketplace.

The allure of sustainable development is that it promises to somehow disengage the market growth from environmental damage. It frees up businesses from having to continually defend and justify their manufacturing practices to the consumer and the environmentalists who continually criticize them. Industry and trade associations still continue under this old paradigm perhaps by the force of habit but the rhetoric and dialogue with environmentalists are slowly changing. Accepting in principal that the need for a certain metamorphosis in their operation that reshuffles their priorities is a prerequisite to fruitful collaboration with environmental interests. The effort toward sustainability is one where industry, the consumer, and the regulators work together, ideally in a nonadversarial relationship. In this awkward allegiance, the business will move beyond meeting the regulatory minima or "room to operate" in terms of environmental compliance and respond positively to burgeoning "green consciousness" in their marketplace. It frees up the environmental movements to do what it does best, and facilitates stewardship of the ecosystem in collaboration with business interest, rather than be a watchdog. This is not an easy transformation in attitudes to envision. Yet it is a change that needs to be achieved to ensure not only continued growth and profitability but the very survivability of the planet and life as we know it.

The Consumer

Primarily, it is the mindset of traditional consumption that determines the demand for market goods, that needs to change. Businesses do not exist to preserve the environment; they exist to make profit for their owners. But to do so, they must meet the demands in the marketplace. With the rich supply of easily-accessible (albeit sometimes erroneous) information via the internet, interested consumers are rapidly becoming knowledgeable. The consumer demand for sustainable goods will grow rapidly, automatically driving business into sustainable modes of operation. Consumers need to be well informed and educated so that they are aware of the need and know what exactly to change.

In such a future scenario, the industry will be called upon to justify not only their economic objectives but also explicitly consider environmental (and social) objectives. This shift from the solely fiscally-driven business plans to the triple bottom-line business plan will propel the marked shift in corporate function. To be successful, the change in corporate orientation must encompass the entire value chain with free flow of communication across the traditional boundaries and interphases with suppliers, customers, and waste managers. This cannot be achieved by a few analysts embedded within a single department but requires champions that represent all aspects of the value chain.

Plastics Industry and Change

Why would a growing, robust, and profitable industry providing a unique class of material that is of great societal value want to change? The plastic industry certainly is not an inordinate energy user (such as cement production or livestock management) and does not place a significant demand on nonrenewable resources. The benefits provided by plastics justify the 4% fossil fuel raw materials and another 3–4% energy resources devoted to manufacturing it. In building applications, plastics save more energy that they use. In packaging (where the energy/material cost can be high), plastics reduce wastage and afford protection from spoilage to the packaged material with savings in healthcare costs. Plastics are a very desirable invention in general. However, the customer base and operating environment are changing rapidly; responding to the challenge posed by these changes is a good business strategy.

The plastics industry has its share of environmental issues. It is based on a linear flow of nonrenewable fossil fuel resources via useful consumer goods into the landfills. Lack of cradle-to-cradle corporate responsibility and design innovations to allow conservation of resources is responsible for this deficiency. For instance, there is not enough emphasis on design options for recovery of post-use waste. The move toward bio-based plastics, an essential component of sustainability, is too slow with not enough incentive to fully implement even what little has been achieved. Though good progress has been made, over-packaging and over-gauging are still seen across the plastics product range. While the plastics litter problem is at its root a social-behavioral issue, the industry is still held at least partially accountable. The issue of endocrine disruptors and other chemicals in plastics potentially contaminating human food still remains a controversial issue. Complaints on plastics in litter, microplastics in the ocean, endocrine disruptors in plastic products, and emissions from unsafe combustion have been highlighted in popular press as well as in research literature. Proactive stance by industry to design the next generation production systems is clearly the need of the day.

Any effort toward sustainability must reach well beyond mere greening of processes and products. Not that greening is bad (unless it is "greenwashing" which is unethical) but because it alone will not be enough to save the day. Sustainability starts at the design stage. Visionaries in the industry need to reassess the supply of energy, materials, and operational demands of the products. Can the present products still remain competitive, profitable, and acceptable despite perhaps more stringent regulatory scrutiny in a future world? What are the ways to increase the efficiency of energy use, materials use, and processes for the leading products? What potential health hazards (perceived as well as real) can the product pose? What technologies are missing that need to be adapted to achieve sustainability? Sustainable growth is a process (not a goal) that has a high level of uncertainty as we are planning for the present as well as for a clouded undefined future. This uncertainty has forced it to be grounded on precautionary strategies.

This Volume

This work is an attempt to survey the issues typically raised in discussions of sustainability and plastics. The author has attempted to separate scientific fact from overstatement and bias in popular discussions on the topics, based on research literature. Strong minority claims have also been presented. Understandably, there are those where plastics have been unfairly portrayed in the media and those where sections of the industry in aggressively protecting their domain have understated the adverse environmental impacts of plastics. The author has attempted to remain neutral in this exercise and he was not funded either by the plastics industry or by any environmental organization in writing this volume.

A work of this nature can never expect to satisfy all stakeholders on all topics covered. Depending on his or her affiliation, the reader will either feel environmental impacts of plastics are exaggerated or that they are too conservatively portrayed and do not capture their full adverse impact. Despite this anticipated criticism, a discussion of the science behind personal judgments and public policy is critical to the cause of sustainability. If the work serves as a catalyst for engagement between industrial and environmental interests or at least generates enough interest in either party to dig deeper into the science behind the claims, the author's objective would have been served.

Raleigh, NC ANTHONY L. ANDRADY
2014

We did not inherit the Earth from our fathers; we merely borrowed it from our children.

ACKNOWLEDGMENTS

I would like to acknowledge the help and support of many people in preparing this manuscript. Without their help and encouragement, the book would have not been possible. Special thanks to the many scientists who read through parts of the manuscript or offered helpful suggestions on the content. These include Professor Michelle A. Mendez (Department of Nutrition), University of North Carolina at Chapel Hill, Chapel Hill, NC; Professor Braden Allenby (School of Sustainable Engineering), Arizona State University, Tempe, AZ; Professor Linda Zettler (The Josephine Bay Paul Center for Comparative Molecular Biology and Evolution), Woods Hole, MA; Professor Kara Lavendar Law (Sea Education Association), Falthom, MA; Professor Halim Hamid (University of Petroleum and Minerals), Dhahran, Saudi Arabia; Professors Saad Khan (Chemical and Biomolecular Engineering); Richard A. Venditti (Pulp and Paper Science); Steven Sexton (Agricultural and Resource Economics) all of NCSU, Raleigh, NC; and Ted Siegler (DSM Environmental Services, Inc.), Windsor, VT.

I would especially like to thank my wife Lalitha Andrady who did not complain of my many solitary long hours at the laptop preparing this manuscript!

LIST OF PLASTIC MATERIALS

LDPE—Low density polyethylene
HDPE—High density polyethylene
PP—Polypropylene
PS—Polystyrene
PVC—Poly(vinyl chloride)
CPVC—Chlorinated poly(vinyl chloride)
PB—Polybutene
GPPS—General purpose polystyrene
HIPS—High impact polystyrene
EPS—Expendable polystyrene
PMMA—Poly(methyl methacrylate)
PET—Poly(ethylene terephthalate)
PBT—Poly(butylene terephthalate)
PC—Polycarbonate
PA—Polyamide
PA-6—Polyamide 6
PA-66—Nylon 66 or polyamide 66
CA—Cellulose acetate
EVA—(Ethylene-vinyl acetate) copolymer
SAN—(Styrene-acrylonitrile) copolymer
ABS—(Acrylonitrile-butadiene-styrene) copolymer
SBS—(Styrene-butadiene-styrene) copolymer

1

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

[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

[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).

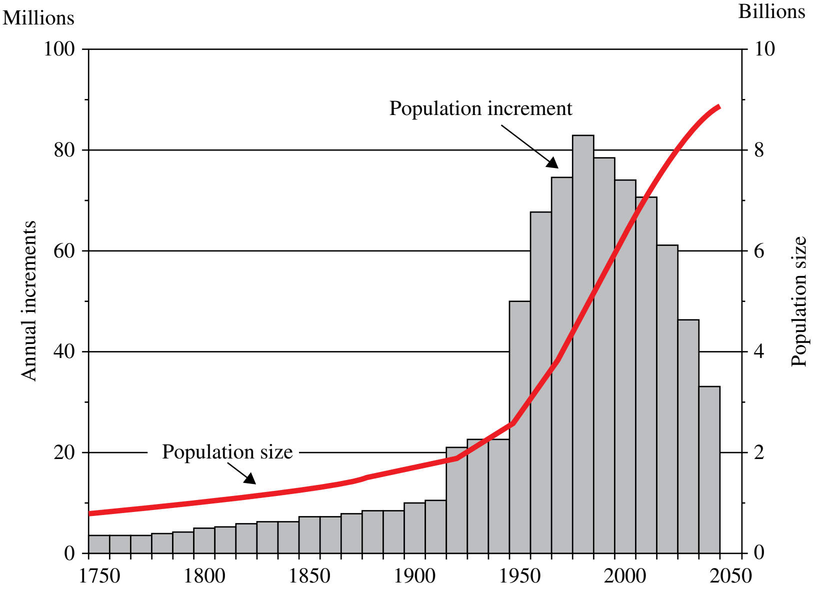

FIGURE 1.1 Projected world population and population increments. Source: Published with permission from UN Population Division. Reproduced with permission from World at Six Billion. UN Populations Division. ESA/P/WP.154 1999.

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.

[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

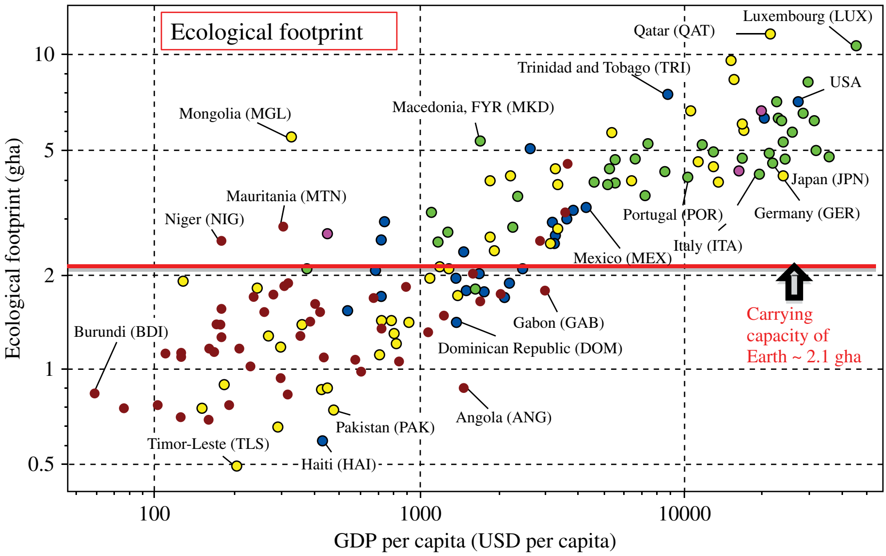

FIGURE 1.3 The ecological footprint of nations (hectares required per person) versus the per capita GDP of the nation. Source: Reproduced with permission from Granta Design, Cambridge, UK. www.grantadesign.com

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

[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

[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!

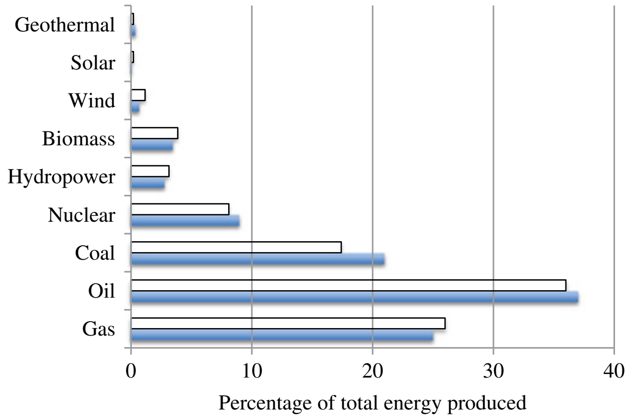

FIGURE 1.4 Global energy use (open bars) and US energy use (filled bars) by source. Source: US 2011 data based on US Energy Information Administration. Web: www.eia.gov. World 2011 data based on International Energy Agency 2012 Report, www.iea.org.

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.

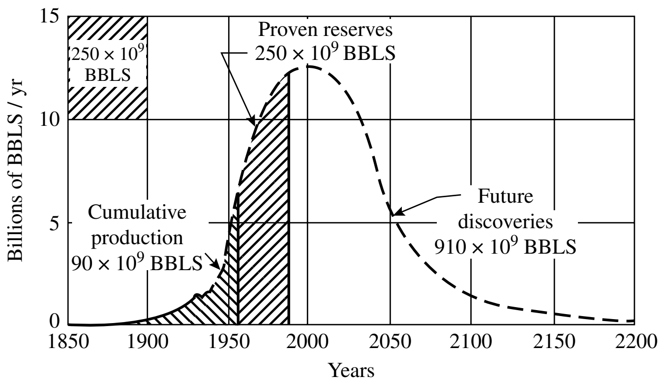

FIGURE 1.5 Hubbert's original sketch of his curve on world oil production. Source: Reprinted with permission from Smith (2012).

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.