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Emerging Challenges, Sustainability, Resiliency, and Sustainable and Resilient Engineering

Chapter Goal and Objectives

This chapter aims to introduce the drivers and concepts of sustainability and resilience, highlighting the importance of integrating them into engineering practice. The specific objectives are to (i) provide examples of emerging challenges that necessitate a focus on sustainability and resilience, (ii) explain the definitions of sustainability and resilience and clarify the differences between these two concepts, and (iii) emphasize the importance of sustainable and resilient engineering in promoting sustainable development.

1.1 Introduction

The concepts of *resiliency* and *sustainability* are everywhere. In recent years, ever-growing numbers of people around the world have become more aware of strains placed on the Earth. These strains have been manifested in a variety of ways – accelerated exploitation of natural resources, increased waste generation, pollution of air, soil, and water, and climate change. Not only have private citizens taken notice, but governments and the business world have also taken steps to address sustainability. Numerous intra- and intergovernmental initiatives and agreements have been developed to address the strains on the environment and to identify measures that encourage more sustainable practices. Businesses, too, have realized that sustainability is a good practice for a variety of reasons. New systems and products have been developed that are more protective and less wasteful of resources, and the pursuit of the "triple bottom line" (TBL) of sustainability has been increasingly applied in new projects and products. The TBL is the reference framework in sustainability that accounts for financial as well as social and environmental metrics.

Similarly, the increasing impacts of climate change, along with other uncertainties such as economic instability and social unrest, make it essential for the world to embrace the concept of resilience. In engineering, technical robustness against both expected and unexpected shocks has historically been the primary focus of design and implementation. This approach can be seen as a form of resiliency consideration. However, growing concerns over climate change and other uncertainties necessitate the engineering community to consider other dimensions of resiliency, such as environmental, economic, and social impacts of a failure. Despite the importance of these dimensions of resiliency, they are often overlooked during engineering decision-making processes.

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Companion website: www.wiley.com/go/reddy/sustainableresilientengineering2e

Several key questions have emerged that necessitate contemplation. What emerging challenges are forcing us to think about sustainability and resiliency? What is sustainability? What is resiliency? How do we take action to further these concepts? What are sustainable engineering (SE), resilient engineering (RE), and integrated sustainable and resilient engineering, and what role can they play in sustainable development? Of equal importance, how do we determine success in pursuit of these initiatives, and how do we measure our progress toward these goals? These evolving and increasingly significant concepts are the focus of this book.

This chapter describes the broader emerging challenges that are forcing us to think about sustainability and resiliency. Next, the general definitions and interpretations of the meaning of sustainability and resiliency are presented. Finally, sustainable and resilient engineering and its role in achieving sustainable development are described.

1.2 Emerging Challenges

Before we delve into the concepts, applications, methods, and measures related to sustainability and resiliency, let us examine several acute problems and related examples that are faced worldwide and are increasingly having a measurable, detrimental effect on the planet.

1.2.1 Increased Consumption and Depletion of Natural Resources

A key consideration of sustainability focuses on our ability to preserve resources for future generations. This is extremely important, as many essential resources (e.g. precious metals, fossil fuels) are non-renewable and are limited in quantity. For many of these resources, we are on a current trajectory of utilization/exploitation in which near-total depletion of economically viable reserves is a very realistic possibility. The alarming rates of consumption of a number of resources not only spell trouble for the availability of these resources for future generations but also cause unintended secondary, yet catastrophic, side effects on the environment.

1.2.1.1 Easter Island Example

A classic example of the catastrophic consequences of the primary and secondary effects of natural resource depletion is the collapse of a civilization on *Easter Island*. Located in the southeastern Pacific Ocean and arguably the most remote habitable region on the planet, Easter Island gained its name from the sighting/discovery of the island on Easter Sunday, 1722, by Dutch sailors. It was subsequently annexed by Chile in 1888. Large stone statuary called moai, created by early Rapa Nui peoples, were important monuments to a sophisticated culture and civilization that had once flourished on Easter Island but had devolved into a small, primitive culture at the time of European discovery (DiNapoli et al. 2021).

Although Easter Island is subject to a cold and dry climate, it was at one time heavily forested with palms, conifers, and sandalwood. The first Polynesians arrived at Easter Island in the fifth century and numbered no more than 20 or 30. The harsh climate and nutrient poor soils restricted agricultural activity to the cultivation of sweet potatoes. Nevertheless, a sophisticated and advanced society flourished among the Rapa Nui. To allow for agricultural activity, much of the land was deforested. Trees were also harvested to provide structural materials for housing and boat fabrication and for use as fuel. However, a significant number of trees were also harvested to create a track system to maneuver the large moai from quarry locations to sites where they were erected. As the population grew upward of 7000 persons, these resources were further utilized to meet increasing demand.

By the 1600s, the entire island had been deforested. The lack of timber resources eliminated the ability to construct fishing boats and wooden structures. The elimination of bark materials prevented the fabrication of cloth materials. Furthermore, the deforestation greatly accelerated soil erosion, and the agricultural capacity of the already nutrient-poor soils was again severely reduced. Elaborate rituals centered around the moai statuary diminished, placing even greater strain on the social fabric of the declining society, including the breakdown of social and religious conventions. Because boats could no longer be fabricated without timber, the Rapa Nui were trapped on the remote island. Eventually, they were forced to resort to primitive cultural practices where available shelter had been reduced to available caves. Ongoing turbulent conditions fueled conflict/warfare, slavery, and even reports of cannibalism.

Ultimately, the once great civilization had collapsed. At the time of European discovery, the population had declined precipitously. The collapse of island's agricultural capacity and activity resulted in widespread, ongoing starvation. Subsequent contacts from seafaring groups, such as whalers, introduced sexually transmitted diseases and smallpox. Peruvian slave parties also captured numerous Rapa Nui for use in the slave trade. By 1877, only 111 Rapa Nui remained on Easter Island, and at the time of Chilean annexation, the Chilean government confined the remaining inhabitants to one village.

Rapa Nui remain on Easter Island to this day. Archaeologists brought attention to the island in the mid-twentieth century, which in turn has stimulated tourism and led to the restoration of some of the moai statuary. Conditions have improved for the Rapa Nui, although unemployment remains high and alcoholism and related social strains are quite prevalent. Additionally, they are still dependent on imported food.

Nevertheless, the story of the Rapa Nui has been repeated with other people – the Mayan and Inca people of Central and South America as well as the ancient Greeks and Romans. All of these people offer a cautionary tale – when a society disregards the health of its environment, places excessive strains on vital resources, such as soil and water, can lead to a collapse of agricultural activity and other aspects of economy and culture. When basic necessities such as food, clothing, and shelter become scarce, a disparity between "haves" and "have-nots" is often exacerbated, leading to mistrust and resentment between classes. As the problem grows, conflict is inevitable, and collapse of the underlying civilization will occur.

1.2.1.2 Metallic Ores Consumption Example

Several examples can be presented with respect to unsustainable utilization of natural resources. Let us take the example of the usage of metallic ores, and as an example, let us examine the use of zinc (Graedel and Allenby 2010). Consider zinc use over a sustainability design period of 50 years and a global population of 7.5 billion people. Estimated global zinc reserves consist of 330×10^{12} g (330 Tg) of zinc. Considering a 50-year period (after which all resources will be depleted), 6.6 Tg may be used per year. Assuming an even allocation among 7.5 billion people, each person would be entitled to 0.9 kg/year. Allowing for recycling (assuming a 30% increase in zinc supply), the available per capita allotment may be increased to 1.2 kg/person/year.

Consider these industrial/consumer uses of zinc: zinc alloys – 38% (0.5 kg/person/year); construction coatings – 31% (0.4 kg/person/year); zinc chemicals – 15% (0.15 kg/person/year); vehicle plating – 15% (0.15 kg/person/year); cast, rolled zinc – 4% (0.05 kg/person/year).

However, current automobiles contain approximately 32 kg of zinc (Ortego et al. 2020). Assuming a 1.2 kg/year allocation, this would result in a new car purchase once every 27 years – only if no other uses of zinc were allocated. When compared to the uses listed above, zinc would need to be removed from all other product streams and uses to meet automobile use demand at this rate.

Of course, it is a valid argument that not every person on the planet will consume an equal amount of zinc, allowing for some to consume vastly more than others in this example. Nevertheless, when finite resources are available for use, it is necessary to consider the limits of the resource. A famous example takes this further. Imagine a resource that is finite and is open to use to a finite number of users. Even in this case, the users may be motivated to use more of the resource because the side effects do not offset the gain. This famous example is detailed in a seminal paper, *the Tragedy of the Commons* (Hardin 1968, 2009).

Here is the scenario – 20 farmers use a communal pasture to graze 10 cows each or 200 cows. Each farmer is utilizing 1/20 of the resource – or 5%. Now, let us say one farmer adds an 11th cow. He is increasing his benefit by 10%, but the consequences of the additional cow (let us assume the additional loading begins a process of overgrazing) are borne by all equally, so he suffers 5% of the consequences. He has just increased his marginal benefit of adding one cow by this difference. The farmer has an incentive to act in this manner, but so do all of the farmers. It is reasonable to expect that other farmers will also choose to add cows, increasing their respective marginal benefit, but all of the farmers ultimately will suffer the consequences of overuse together.

The *Tragedy of the Commons* remains a controversial study, and many have pointed out shortcomings or exceptions to the model, but it is a simple illustration that individual parties often have incentives to exploit a resource, even if the consequences will eventually spoil that resource. In other words, it remains difficult to get multiple parties to act together to preserve resources. This is vividly illustrated in Figure 1.1, which shows the effect of overfishing on the population of sardines near the Pacific coast of North America. Sardine populations have dramatically declined since their peak in 2006. This led to a fishing ban enacted to protect the collapsing population. The fishing ban is not expected to be lifted in the short or mid-term, until the sardine population reaches acceptable levels to support fishing again.

1.2.2 Growing Environmental Pollution

The growth in consumption of natural resources has led to increasingly problematic side effects – one in particular is increased environmental pollution. Air, soil, and water are being

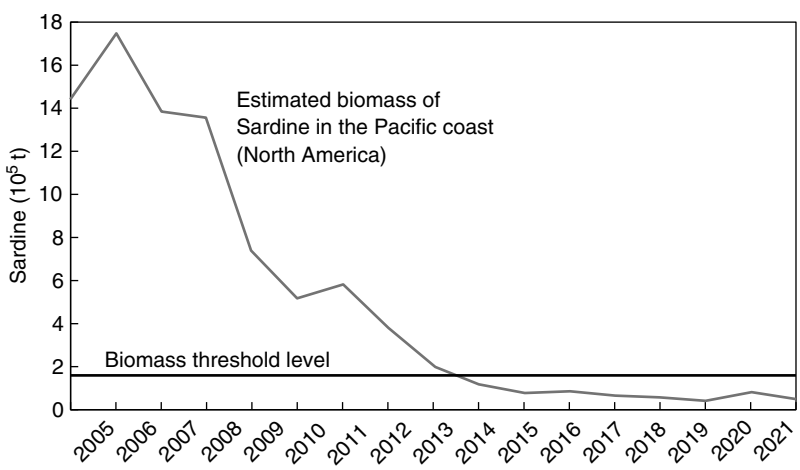

Figure 1.1 Sardine population declining up to below the threshold level. *Source:* Kuriyama et al. (2022)/The National Oceanic and Atmospheric Administration (NOAA)/Public domain.

increasingly polluted from human development and activities. Control and remediation of the effects of pollution are crucial in order to protect the environment and public health, and a movement toward sustainability is not possible without control or prevention.

Water pollution can have many effects. Pollutant loading can directly affect domestic water sources, such as surface water or groundwater resources. Sediment runoff can affect water flow in navigable waterways. In addition to direct deposition of toxic materials to surface water, pollution sources can also have a long-term detrimental effect on surface water bodies (Schweitzer and Noblet 2018).

Soil impacts are also increasing. In the form of mining, waste products are often landfilled at or near the extraction point. Noxious by-product chemicals capable of leaching are often disposed of as well, and when mixed with tailings and rainwater, the resulting toxic "soup" can significantly pollute soil as well as groundwater. Not only can mining practices affect soil, but also other practices such as deforestation, overgrazing, timber harvesting, and agricultural management can lead to releases of potentially toxic materials or otherwise exacerbate environmental impacts such as erosion of topsoil. Further, landfilling practices used in waste management can also affect soil. Older landfills often do not have protective measures in place, such as liners or leachate collection systems, and authorized or unauthorized hazardous waste disposal facilities accept acutely toxic or recalcitrant compounds, such as aromatic and aliphatic hydrocarbons, chlorinated solvents, PCBs, pesticides, and heavy metals, which can be released into the environment (Li et al. 2019).

In addition to water and soil, air is also increasingly polluted by human activities. Combustion of wood and fossil fuels leads to emissions of gases and particulate matter, many of which can affect health or even climate. Evaporated volatile organic compounds (VOCs), carbon monoxide, heavy metals, and particulates can lead to harmful impacts on public health, including elevated asthma or cancer rates. Some emission constituents are subject to secondary reactions in the atmosphere, leading to increased smog, near-surface ozone, or depletion of higher atmospheric ozone (Mannucci et al. 2015).

1.2.3 Increasing Population

Much of the strain placed on the planet is associated with ever-increasing uses of natural resources, the unintended side effects, and pollution that results from their use of land, air, and water. However, even if measures were taken to curtail these uses and mitigate the effects of pollution, a third problem leading to strains that may not be as easy to curtail, is the rapid increase in the total human population as well as increasing acceleration in population growth.

The statistics are staggering – over 8 billion humans are currently alive on Earth. This number has increased by approximately 2 billion in only 25 years and has doubled from approximately 4 billion in the past 50 years (Figure 1.2). Currently, the world population grows by 75 million on an annual basis. If current growth rate predictions prove to be true, the world population will exceed 9.1 billion by the year 2050. Figure 1.2 demonstrates the rapid acceleration in population growth over the past millennium. It also demonstrates how population totals may grow, level off, or contract by the year 2200 assuming worldwide average female fertility rates over this period of time (Wakabayashi 2020).

With additional people added at such an accelerating pace, goods and resources become scarcer. Of course, the growing population will need to use resources for food, clothing, and shelter, as well as participate in a meaningful way in local, national, and/or international economies. Yet, challenges are already faced by a significant portion of the world's population in even trying to meet the most basic human needs. Approximately 985 million people experience extreme poverty (defined as income of less than or equal to US $1 per day). Over 800 million people face severe

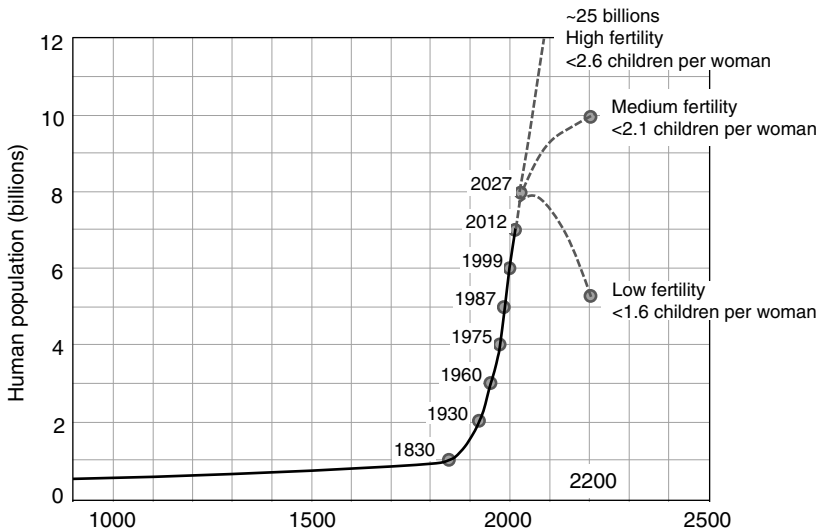

Figure 1.2 World's population explosion and projection to the year 2200. *Source:* Data from United Nations.

malnutrition. A startling number of preschool children, over 6 million, die from hunger/malnutrition-related maladies per year (Dasandi 2014).

With the rapid increase in world population, similar appreciable growth in world economic output has occurred. Global economic production has doubled in the past 25 years, a rate that even exceeds the rapid rate in population growth. This development has led to a great benefit for many millions of people, as the growth has indeed lifted millions out of poverty. Gross domestic products in numerous developing countries have grown significantly over this time period, and scores of nations throughout the world have grown into world economic powers from modest economic positions within a generation. Nevertheless, economic development in many of these countries has proven to be uneven at best; large inequalities in wealth have developed within these countries as well as compared to the positions of larger, more developed countries, such as those in Europe or North America. As a result, real income in many developing countries is actually falling. Countries with high birth rates are especially susceptible to this growing inequity; stabilization of birth rates will be essential in assuring more equitable economic growth for a given population in the future.

Example 1.1

The city of Beijing has a recorded population of 21.7 million people in the year 2017. The annual population growth rate has been recorded at 2.1% per year. China's average birthrate has declined swiftly over the past five years, from 12.4 births for every 1000 citizens in 2017 to 7.52 births for every 1000 citizens in 2021. At the same time, the average death rate in China was recorded at a constant value of 7 deaths for every 1000 citizens over the five-year period. Assuming that Beijing's birth and death rate are consistent with that of China's average, calculate the following:

a) Assuming the decrease in birth rates is linear between 2017 and 2021, determine the population increase due to newborns each year in Beijing.
b) Assuming birth, death, and migrant influx/outflux as the only reasons for population change, calculate the population growth due to migrant influx each year, comment on the observed trends.

Solution:

a) Considering a linear decrease in birth rates between 2017 and 2021, the birth rates for the years 2017, 2018, 2019, 2020, and 2021 are 12.4, 11.18, 9.96, 8.74, and 7.52 births for every 1000 citizens, respectively.
Population increase = (birth rate × population in the corresponding **year)**
Population increase In 2017 = $21.7 \times (12.4/1000) = 0.269$ million people
Population increase in 2018 = $[21.7 \times (1 + 2.1\%)] \times (11.18/1000) = 0.2477$ million people
Population increase in 2019 = $[22.1557 \times (1 + 2.1\%)] \times (9.96/1000) = 0.2253$ million people
Population increase in 2020 = $[22.62 \times (1 + 2.1\%)] \times (8.74/1000) = 0.2018$ million people
Population increase in 2021 = $[23.096 \times (1 + 2.1\%)] \times (7.52/1000) = 0.1774$ million people

b) **Natural growth = growth due to birth-decrease due to death**
Natural growth in 2017 = $0.269 - 21.7 \times (7/1000) = 0.11718$ million people
Natural growth in 2018 = $0.24771 - 22.1557 \times (7/1000) = 0.09262$ million people
Natural growth in 2019 = $0.2253 - 22.62 \times (7/1000) = 0.06696$ million people
Natural growth in 2020 = $0.2018 - 23.096 \times (7/1000) = 0.0402$ million people
Natural growth in 2021 = $0.17733 - 23.581 \times (7/1000) = 0.01226$ million people

Migrant growth = total growth-natural growth
Migrant growth in 2017 = $21.25 \times 2.1\% - 0.11718 = 0.329$ million people
Migrant growth in 2018 = $21.7 \times 2.1\% - 0.09262 = 0.36$ million people
Migrant growth in 2019 = $22.1557 \times 2.1\% - 0.06696 = 0.4$ million people
Migrant growth in 2020 = $22.62 \times 2.1\% - 0.04 = 0.43$ million people
Migrant growth in 2021 = $23.096 \times 2.1\% - 0.01226 = 0.47$ million people

This trend suggests that despite the birth rate decrease, the overall population of Beijing continued to grow steadily, primarily driven by migrants.

1.2.4 Increasing Waste Generation

As the population continues to grow at an accelerating rate and is coupled with increasing use of natural resources, an additional by-product of these factors is also placing strain on the environment of the planet – increased waste generation. Enormous quantities of waste are being generated every year, and this growth continues unabated. It is especially troubling and detrimental to the environment because much of this waste generation growth is occurring in the developing world, where waste management and disposal practices are very basic and not protective of the environment. Much of the developed world has placed an increased focus on waste minimization and diversion, such as reuse and/or recycling; however, large quantities of waste materials cannot be practicably repurposed and therefore require disposal or incineration. As a result, the detrimental environmental effects of both proper and improper waste management continue to grow, further spoiling the environment. Collectively, countries around the world must find ways to reduce this increasing trend of waste generation, as these practices cannot be considered sustainable.

The framework to reduce waste generation and the pollution effects that lead to fouling of the environment is straightforward, and it is a necessary undertaking such that we do not jeopardize the quality of life for present or future generations. Ultimately, we need to identify waste products that have the greatest impact on the environment. Once these materials have been identified, the activities acting as a source of waste materials can be identified, and steps can be taken to reduce or minimize the activity through alterations in generation practices or by identifying more protective

alternative activities. Measures may also be taken to prevent the introduction of unavoidable waste products into the environment in such a way that environmental impacts may occur. Further, pollution impacts that have already occurred may be identified and remedied through a variety of traditional or innovative environmental remediation techniques. Ultimately, in order to achieve sustainability, civilization will need to identify technologically feasible means to transition from polluting activities to environmentally protective activities.

Before techniques and alternatives to reduce waste generation can be identified, it is important to discuss types of waste. In 1976, the Resource Conservation and Recovery Act (RCRA) was enacted into law in the United States. While this was not the first attempt to regulate waste disposal practices, it was the first comprehensive legal framework that reached nearly all facets of waste generation, storage, and disposal for a wide range of waste classifications. Generally speaking, solid waste is generated in a variety of residential, commercial, and industrial settings. Much of this material is not considered hazardous and thus falls into a general category of municipal solid waste (MSW). Figure 1.3 shows the MSW production by type in the United States. Much of this material can be recycled and reused or repurposed. Figure 1.4 shows the end fate of the MSW waste stream in the United States. Notable progress in recycling programs has greatly expanded the percentage of waste that is recycled. However, two-thirds of MSW are still not being repurposed and are either being landfilled or incinerated.

As an example of MSW management, consider landfills. Landfills have been used for countless generations in waste management; however, only in the past century have advances been made to help mitigate the environmental side effects of landfilling. Sanitary landfills have been constructed to manage odors, protect underlying soil and groundwater, and facilitate the collection and management of generated landfill gas and leachate. Leachate is a liquid by-product of landfill operation. It consists of infiltrated water (often from rainfall) as well as liquid and "leached" solid wastes from waste materials. Leachate often contains elevated concentrations of a variety of organic and

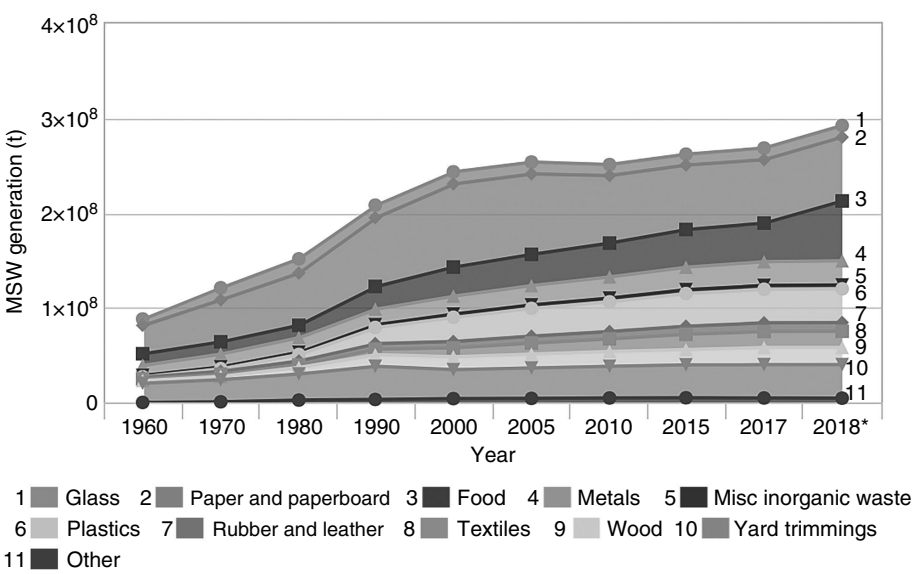

Figure 1.3 Total municipal solid waste (MSW) generated in the United States. *Source:* USEPA (2023)/United States Environmental Protection Agency.

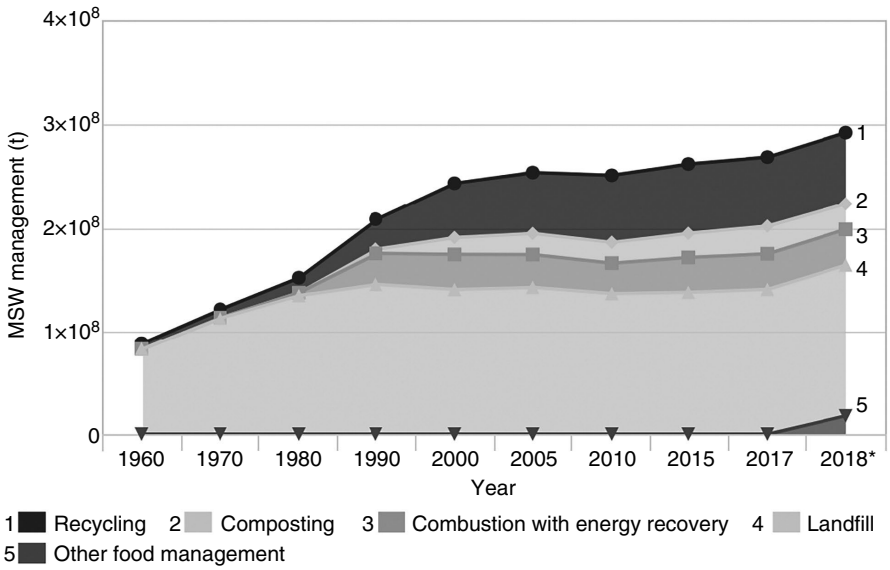

Figure 1.4 Municipal solid waste (MSW) recovery by material and MSW management in the United States. *Source:* USEPA (2023)/United States Environmental Protection Agency.

inorganic chemical compounds, heavy metals, and other potentially deleterious materials. If not controlled properly, it can enter groundwater, where it can adversely affect aquifer sources (Ozbay et al. 2021). Landfill-induced groundwater contamination is a serious problem throughout all 50 states, not only from recently constructed landfills but more often from old uncontrolled or abandoned landfill sites.

Landfills also generate copious amounts of gases that need to be controlled. Buried wastes commonly undergo anaerobic decomposition, resulting in the production of biogas. This biogas primarily contains methane, carbon dioxide, and hydrogen-containing compounds. If not controlled, this can be a significant health and explosion hazard, both at the landfill site and off-site due to horizontal and vertical migration into nearby structures. However, when properly captured and treated, biogas is a valuable resource that can be used as a fuel for power generation. As an example, in 2008, commercial landfill gas produced electricity and natural gas for 1.4 million homes (Sadasivam and Reddy 2014). Because it burns relatively clean, its capture and use can displace the use of dirtier fossil fuels, leading to a relative reduction in greenhouse gas emissions and air pollutants.

1.2.5 Increasing Greenhouse Gas Emissions

Increased resource generation and utilization leads not only to increased solid/liquid waste generation but also to increased gas emissions. Gas emissions, particularly those from agriculture and combustion processes in the industrial, transportation, and energy generation sectors, can lead to serious air pollution consequences, but they can also facilitate climate change. Although climate change occurs due to a variety of natural physical processes, overwhelming evidence suggests that anthropogenic sources also contribute to climate change. The magnitude of this contribution and the resulting effects of climate change are still being debated, but very little scientific basis exists that objectively refutes contributions to these effects from anthropogenic sources.

Much of the anthropogenic portion comes from the emission of greenhouse gases. Greenhouse gases, such as carbon dioxide, methane, nitrous oxide, and water vapor, as well as a range of fluorocarbons, act to trap heat from the earth's surface that would normally radiate to space harmlessly (Figure 1.5). This effect, similar to the trapping of heat generated by sunlight within a greenhouse (commonly known as the Greenhouse Effect), warms the lower atmosphere. Higher temperatures result in increased generation of water vapor, which can act to trap more heat. However, higher temperatures also accelerate plant metabolism, which leads to utilization (and removal) of carbon dioxide from the atmosphere. These phenomena are still being studied (Rae et al. 2021).

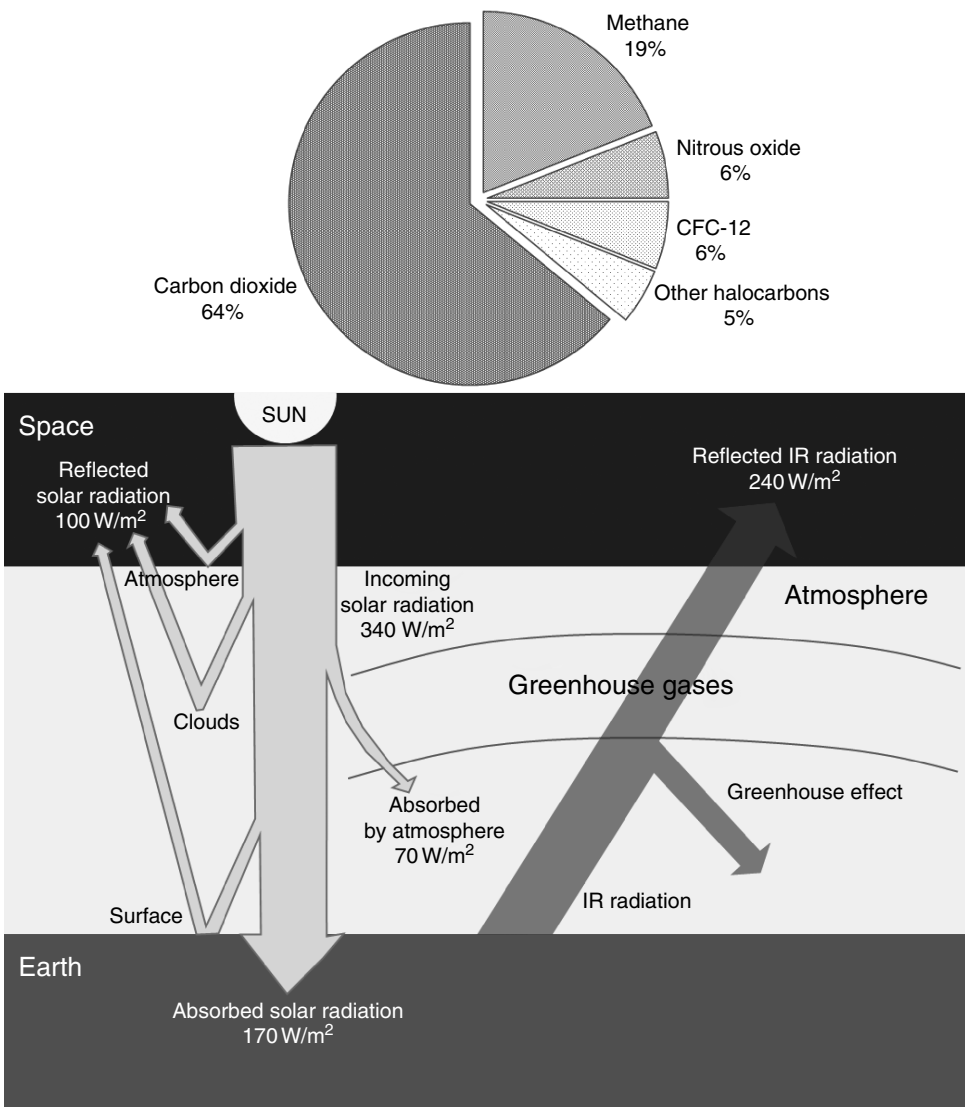

Figure 1.5 Greenhouse gas effect on the atmosphere and the estimated relative contribution of main greenhouse gases.

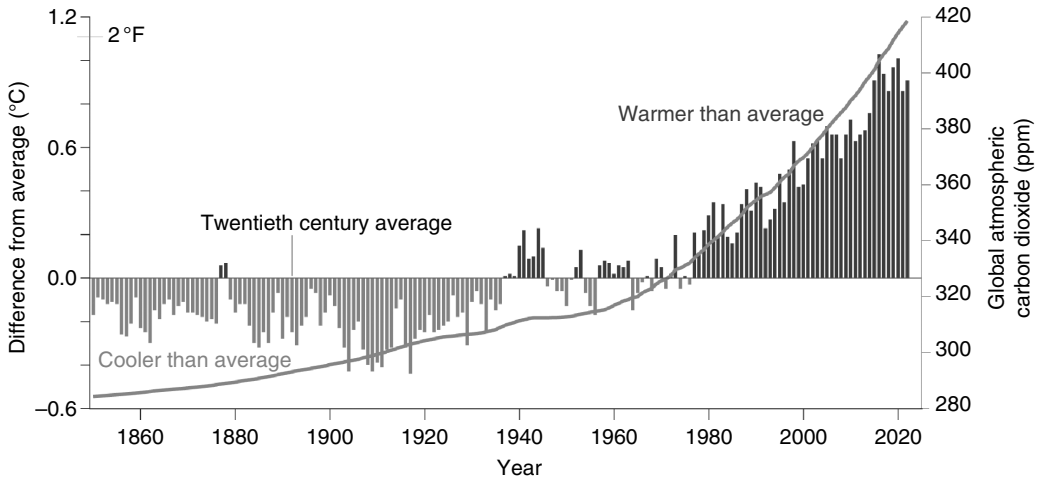

Figure 1.6 Average global temperature change (bars) and atmospheric carbon dioxide (line). *Source:* NOAA (2023)/Public domain.

Nevertheless, substantial increases in greenhouse gases have been generated during the industrial era, contributing to a rapid increase in global temperatures. Figure 1.6 depicts the correlation between global temperature and atmospheric carbon dioxide concentrations over the past 180 years.

Predictions of further impact are difficult to make and offer wide ranges due to variations in mathematical models. By 2100, global temperatures are predicted to increase between 2.5 and 10.4 °F (1.4–5.8 °C), with temperatures expected to increase even more in the United States (IPCC 2023). Increased global temperatures can lead to drastic shifts in weather patterns, with more precipitation in some areas, less in others, and more intense storm events. These effects can drastically affect agricultural activities and induce strains on ecosystems and biodiversity. Furthermore, increased temperatures are expected to accelerate the melting of polar ice and alpine glaciers, leading to increases in sea elevation, which in turn can inundate coastal areas.

As a short example of the current impact and sustainability of greenhouse gas emissions, consider carbon dioxide and a sustainability period of 50 years as well as a representative world population of 7.5 billion people. If global emissions were limited to a doubling of atmospheric carbon dioxide concentrations, this would be 7–8 pg (picograms) of carbon ($7–8 \times 10^{-15}$ kg). Based on an allocation to 7.5 billion people, this would result in 1 Mg (megagram) of carbon per year per person. Assuming a 40/25/35% breakdown of transportation, energy, and general society emissions, this would translate to 400, 250, and 350 kg of carbon dioxide per year, respectively.

With respect to generation, a typical automobile emits 62 g of carbon/km, and coal-fired power generates 89 kg of carbon/GJ. This translates to 6450 km/year of automobile transport and 2.8 GJ/year/person in terms of allowable carbon emissions. However, in Germany, the current per capita distance of auto travel is 15 000 km/year, and per capita use of energy is 270 GJ/year (EUROSTAT 2024a, 2024b, 2024c). The current rates are way above an allocated level of emissions that would only lead to a doubling of carbon atmospheric concentrations.

If these levels of consumption and emission generation continue, current predictions for these inputs are for a 3–5 °C increase in global temperature. To put it in perspective, a 5 °C difference in global temperature represents the difference between a warm period and an ice age. As indicated above, such a temperature will have a significant effect on sea level, agricultural practices, and numerous other activities that can adversely affect coastal and inland populations alike.

Example 1.2

The United States has been monitoring its greenhouse gas (GHG) emissions over the years. In 2021, the total GHG emissions were recorded at 6340 million metric tons of CO_2-equivalent. Due to the new environmental policies taken up by the government to reduce GHG emissions, the annual GHG emissions are expected to decrease by 2% each year.

Questions:

a) Calculate the total GHG emissions for the US for the year 2025, assuming the annual decrease rate remains constant.
b) Determine the total decrease in GHG emissions from 2020 to 2025.
c) Compare the total GHG emissions for 2025 with and without the implementation of the new environmental policies. How much emissions reduction is achieved due to the policy change?

Solution:

a) Assuming an annual decrease of 2%, starting in the following year of 2022, we can calculate the estimated total GHG emissions for the year 2025 with the following formula:

$$E_{2025} = E_{2021}(1-r)^t$$

where r is the targeted annual decrease of 2% and t is the time period between 2021 and 2025 of four years. Calculating for E2025, we have:

$$E_{2025} = 6340(1-0.02)^4 = 5848 \text{ million metric tons } CO_2e$$

If the US maintains their new environmental policies, it is estimated that the total GHG emissions for 2025 is 5848 million tons of CO_2e.

b) The US Environmental Protection Agency (EPA) generates the annual report Inventory of US Greenhouse Gas Emissions and Sinks. The 2023 report (which inventories 1990–2021) notes that in 2020, the US generated 6026 million tons of CO_2e. Therefore, the total decrease in GHG emissions from 2020 to 2025 is:

$$6026 - 5848 = 168 \text{ million metric tons } CO_2e$$

c) Using the recorded GHG emissions in the years 2020 and 2021, we can calculate the annual growth rate of GHG emissions, r', and prior to the enactment of new environmental policies:

$$E_{2021} = E_{2020}(1-r')^t$$
$$r' = \frac{E_{2021}}{E_{2020}} - 1 = \frac{6340}{6026} - 1 = 0.052 \ (i.e., 5.2\%)$$

We can now calculate estimated GHG emissions in the year 2025, assuming the growth rate stays similar without implementation of the new environmental policies, and compare it to the emissions for 2025 with enactment of the proposed environmental policies that were calculated earlier.

Emissions without enactment of environmental policies:

$$6340 \times (1 + 0.052)^4 = 7768 \text{ million metric tons of } CO_2\, e$$

Emission reduction achieved due to this policy change is therefore:

$$7768 - 5848 = 1920 \text{ million metric tons } CO_2e.$$

1.2.5.1 Climate Change and Extreme Weather Impacts: Hurricane Sandy Example

On the evening of October 29, 2012, Hurricane Sandy unleashed its full force upon New York City, bringing with it a storm surge that the city's infrastructure was ill-prepared to handle. At Consolidated Edison's 13th Street substation in lower Manhattan, the waters began to rise ominously. Though the substation had been engineered to withstand water levels up to 12.5 ft, the storm surge from Sandy reached up to 14 ft. As the water overwhelmed the system, the transformer exploded, plunging lower Manhattan into darkness. Power outages spread to surrounding neighborhoods as officials pre-emptively disconnected areas to prevent overloading the already-strained power grid. Critical facilities across the city, including hospitals, had to be evacuated due to the lack of electricity. At New York University's Medical Center, two backup generators failed, leaving the facility without power.

Hurricane Sandy was not only notable for the destruction it caused but also for its unprecedented scale. It was the largest Atlantic hurricane ever recorded in terms of diameter, with tropical storm-force winds extending across a staggering 1150 miles (Gutner 2012). The storm wreaked havoc across multiple countries, causing nearly $70 billion USD in damages, an amount that, when adjusted for inflation, equals approximately $93 billion in 2023. Tragically, it also claimed the lives of 254 people across eight countries, from the Caribbean to Canada.

Sandy's destruction stands as a stark reminder of the growing threat posed by climate change. As the planet continues to warm, the frequency and intensity of extreme weather events are on the rise. These events, which used to be rare occurrences, are increasing in frequency and intensity. Globally, dozens of extreme weather events are reported every year, with increasingly severe impacts on communities and infrastructure. In the United States alone, since 1980, there have been 395 weather and climate disasters in which damages exceeded $1 billion, resulting in a staggering total loss of $2.77 trillion and claiming 16 449 lives (NOAA 2024). The increasing frequency of such events in recent years, as depicted in Figure 1.7, raises critical concerns about the safety, reliability, and future resilience of public infrastructure systems.

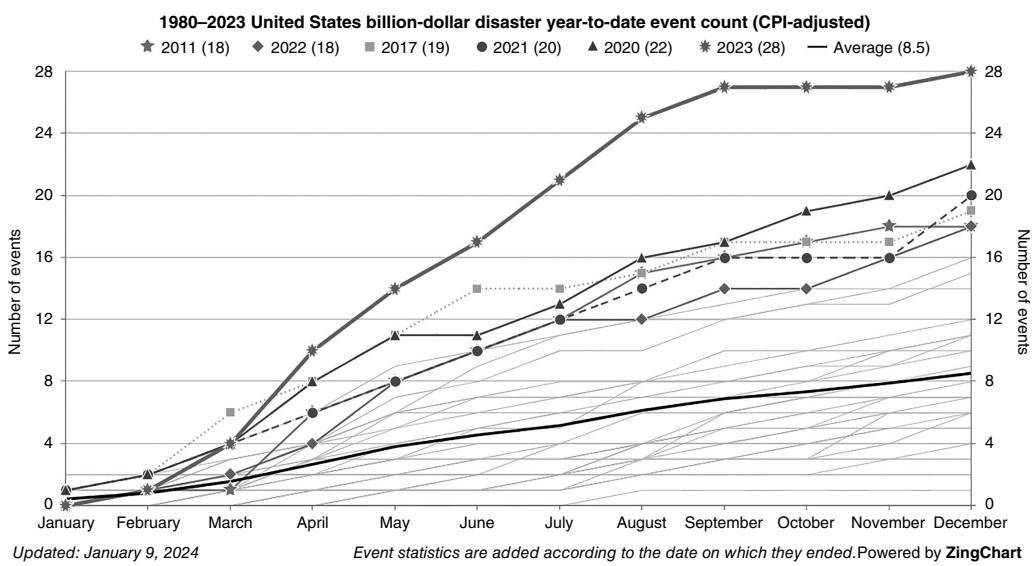

Figure 1.7 Month-by-month accumulation of billion-dollar disasters for each year on record. The colored lines represent the top six years for most billion-dollar disasters. All other years are colored light gray. *Source:* NOAA (2024)/The National Oceanic and Atmospheric Administration (NOAA)/Public domain.

These alarming statistics are not unique to the United States; nations across the world face similar, if not worse, consequences from climate-induced disasters. Traditional engineering design standards, which were developed under more predictable climate patterns, are now being revised to address the heightened risks posed by climate change. It is no longer sufficient to design infrastructure merely to meet historical weather conditions. Instead, engineers have to prioritize the resilience of systems to ensure that they can withstand and adapt to the unpredictable, often severe impacts of climate change. This concept is increasingly referred to as climate resiliency – essential for safeguarding public infrastructure and mitigating the effects of future climate disasters.

1.2.6 Decline of Ecosystems

The ongoing harm and destruction of natural environments resulting from waste generation and emissions lead to an additional problem – the decline of ecosystems. Healthy ecosystems are critical to human civilization – of primary importance; they support human life and economies by providing a supply of materials to be used in goods and services. However, these resources are not being managed in a healthy or sustainable manner. Human populations and consumption, commercial activity, and industrial activity are leading to the depletion and contamination of groundwater, topsoil, forests, and fisheries.

The global economy is highly dependent on natural, renewable resources that are provided by the wide range of ecosystems on the planet. The primary, direct products available in these ecosystems include fresh water, food, fuel, wood/timber, leather, wool, furs, and other products. Secondary and/or refined/synthesized products include raw materials for fabrics, oils, chemicals, and many others. Furthermore, the utilization of these materials in industries such as agriculture, forestry, and fishing is responsible for 50% of jobs worldwide (Vallecillo et al. 2019).

Ecosystems are also a primary source for service-based economic roles. Some services that derive directly from ecosystem management include waste management, climate regulation, erosion control, water treatment, and vector management. These combined goods and services form "ecosystem capital" – economic development, income, and overall human well-being are strongly based on the effective management of this capital. These goods and services are available and feasible as long as the ecosystems from which they are derived are healthy and protected. Therefore, the ecosystem capital in a particular nation and its income-generating capacity represent a critical component of a particular nation's wealth.

As the new millennium dawned, an assessment was performed to evaluate overall ecosystem health. The assessment focused on the services that are provided by ecosystems and provided an agenda for ecosystem restoration. Further, the *Millennium Ecosystem Assessment* gathered information on the world's ecosystems. This study, which included the work of 1360 scientists in 95 countries, gathered, analyzed, and synthesized ecosystem-related information to focus on the links between ecosystem goods/services and the well-being of human civilization (Marzec 2018).

The conclusions of the *Millennium Ecosystem Assessment* were sobering: it found that humans have altered the world's ecosystems more rapidly and profoundly over the past 50 years than at any time in the human history. Further, over 60% of ecosystem goods and services are being degraded or not being utilized in a sustainable manner. In the absence of a reversal of these trends, there will soon be critical consequences to human civilization. Ideally, the *Assessment* will serve as a knowledge base for sound decisions and management that can be undertaken by policymakers and managers in both the private and public sectors.

1.2.7 Loss of Biodiversity

With the ongoing decline of ecosystems comes another related problem – the loss of biodiversity. Biodiversity is generally defined as the variability among living organisms and the greater ecological complexes to which they belong. Millions of species exist on the planet, and many have not been studied or assessed. Of an estimated 5–30 million organisms, only approximately 2 million have been described. Many of these have been adversely affected. Since 1970, vertebrate species have reportedly declined by 27% (Butchart et al. 2010).

Stresses and impacts on biodiversity come from several causes. Many are linked to strains on host ecosystems, including pollution, introduction of invasive species that "crowd out" native species or are predatory on native species, and conversion of natural lands into developed land use, such as agriculture, timber harvesting, commercial/industrial uses, or residential uses. Additionally, species may be exploited for commercial values, either legally or illegally. For instance, many species continue to be hunted, killed, and marketed even after national or international prohibitions have been enacted.

The loss of biodiversity can have substantial negative effects on the environment and human civilization. Diverse species play a critical role in agriculture, the overall food chain, as well as in advances in pharmaceuticals and medicine. Further, a robust, diverse range of flora and fauna are critical in an ecosystem's self-healing mechanisms after major natural or artificial disruptions, such as hurricanes, forest fires, or flooding.

As a counterpoint to overexploitation, the protection of biodiversity can provide short-term and long-term economic benefits. Land and resource stewardship performed in a sustainable manner can have significant economic benefits. These resources can be a source of economic wealth through their incorporation into goods and services, especially among the poor. Further, many argue there are aesthetic and, even more powerfully, moral obligations to protect biodiversity and the range of flora and fauna present on the planet (Vellend 2017).

1.2.8 Social Injustice

Effective stewardship of resources, ecosystems, and their side effects on biodiversity requires some relative form of intervention, both economically and politically. Yet the means and degree of intervention are continuously subject to debate, both locally and globally. Figure 1.8 shows a matrix outlining political and economic systems. On the vertical axis is a depiction of political systems – moving upward along the axis indicates an increasing libertarian view, which espouses that justice is based on the equality of opportunity toward inputs or events. Moving downward along the axis indicates a more egalitarian view, which defines justice as the equality of an outcome based on inputs or events. The horizontal axis depicts different types of economic values. To the left indicates a greater degree of communitarianism, in which welfare is optimized by the absorption of individual economic activity into the community. A position to the right of the access indicates a greater focus on corporatism, in which welfare is optimized by the free economic activity of individuals.

With respect to many other nations, the economic and political system of the United States has long been positioned toward the upper right-hand corner of the matrix – indicating a greater focus on libertarian political and corporate economic policies. At first glance, some would argue that this is at the opposite end of the matrix from where a sustainable-inducing position would be located. However, there are many points to refute this. First, many of the worst environmental atrocities and catastrophes have occurred in nations of totalitarian government regimes and communal economic

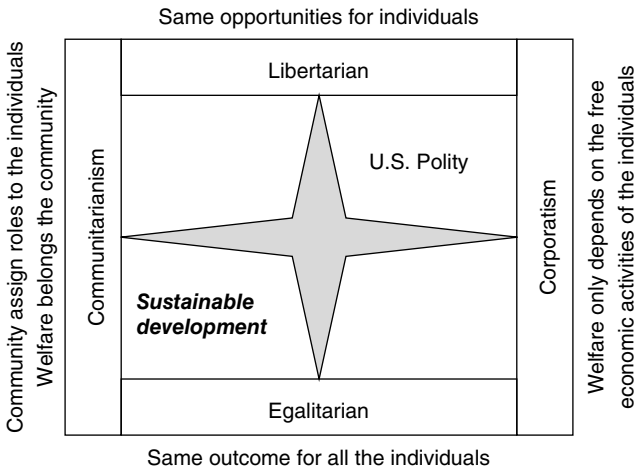

Figure 1.8 Relations between political and economic systems.

principles – no individual or group could challenge the will of these governments and a lack of economic competition diminished innovations or better alternatives to practices that led to these outcomes. Second, less regulation and more enterprise can lead to market-based solutions to address sustainability. When financial gain is to be made, many economic participants will pursue these gains. The goal should be to find a way to align sustainability goals and financial goals. This is increasingly being applied with the "triple bottom line" – where emphasis is placed on financial, social, and environmental metrics for a particular economic activity.

When it comes to environmental and resource stewardship, it is also important to facilitate just relationships within both economic and political systems. An increasing focus is being placed on environmental justice – a concept that addresses the increased notoriety of environmental racism. The concept of environmental racism is better defined in terms of socioeconomic status, although sadly, this range in status often follows along racial or ethnic lines. Environmental racism postulates that waste sites and harmful industries are often placed in areas of lower economic status residents – which often include substantial portions of minority or historically disadvantaged residents. This is further exacerbated by the perception of greater infrastructure expenditures and facility improvements, including institutional buildings and facilities, roads, and utility conveyance projects, in areas of greater political activity or economic clout, which often includes greater percentages of white residents. Whether the racial component in specific cases is coincidental or a real influencing factor is irrelevant, the perception is that these decisions are made along racial lines, and this leads to greater perceptions of environmental racism.

The concept of environmental justice has received greater focus in recent years throughout the developed world. Citizens of all racial/ethnic and economic backgrounds have coalesced into groups to pursue environmental justice issues. Citizen and "watchdog" groups increasingly bring effective action toward environmental justice goals and to monitor progress toward effective, desirable outcomes (Figueroa 2022).

Increased focus on social and environmental justice is also critical in the developing world. In many instances, this has not occurred in areas with rapid economic growth, leading to an alarming disparity between the wealthy and poor. The economic developments in developing countries are often driven by natural resource utilization or low-tech industries. In this process, people often lose

their land or their ability to utilize it, leading to strains on their individual economic prospects. Decreased access to food, shelter, and other basic needs in turn often leads to increased health problems. These factors tend to repeat, and more people are trapped in poverty. In fact, over a billion people face extreme poverty from economic and environmental injustice that stems from this pattern. This is exacerbated in developing countries, as they often have weak or immature governing institutions. Corruption between politicians, wealthy individuals, and other officials who are intermediaries between these groups leads to the inappropriate diversion or outright theft of vast sums of money. Reforms, strengthened institutions, and accountability for governments, corporations, and their respective individuals are necessary to reverse these trends.

Wealthy, industrialized nations also have a role to play in combating these forms of injustice. Many industrialized nations or large developing countries engage in unfair trade practices that prevent others from participating fairly. Tax and tariff systems and quotas often restrict imports that may emanate from other developing countries. Some countries (especially those with heavy mass production-focused manufacturers) will flood markets with products at depressed prices (often for less than the cost to manufacture the products) with the aim to damage competition from other competing countries. These practices destroy competitors and create too many barriers in developing countries from competing in a fair environment. In addition to providing forms of political, advisory, and economic aid to developing countries, wealthy, developed nations can play a role in eliminating these unfair practices. By forming and enforcing free trade agreements as well as educating the marketplace, these unethical and often illegal destructive trade practices can be limited when meaningful sanctions are put in place toward offending nations.

1.2.9 Urban Sprawl

Governments and their institutions not only have a role in facilitating economic and social justice but they also play a greater role in advancing humans to preserve their built environment. Urban sprawl is causing an adverse impact on the environment in many developed and developing worlds. Urban sprawl is difficult to define, but it can be described as the pursuit of a built environment that focuses more on low-density residential areas, retail areas (such as low-rise shopping malls), industrial facilities, and other facilities. These features often are polynuclear in nature (areas of intense activities are often situated at relatively large distances from each other) and need to be connected by transportation linkages, such as multilane highways (Artmann et al. 2019).

Urban sprawl leads to an ever-expanding boundary for cities into the surrounding countryside. In areas without or with weak planning codes/regulations or traditions, sprawl can occur without due consideration of side effects or a defined limit of where growth will be fostered or controlled. Expansion of the built environment with respect to land uses (residential, commercial, and industrial) and transportation linkages often leads to the destruction of open areas and natural lands. Explosive development around traditional city centers often happened when cheap land was available for development without any forethought to planning principles. Eventually, this development extended out toward existing entities (towns and villages) that had their own jurisdictional authority or, in cases where planning regulations existed, their own land use plans and codes; in many cases, keeping residential and commercial uses separate in manners that make sense within the specific jurisdiction but are incongruous when considered from a regional standpoint. In the absence of land use regulatory frameworks or where conflicting approaches existed, growth has often occurred without undertaking a regional approach to planning or infrastructure development, leading to inefficiency, as well as areas overserved or underserved by infrastructure.

Uncontrolled urban sprawl can lead to significant side effects that can affect sustainability principles. A polynuclear land use approach emanating from unchecked sprawl that requires relatively intensive transportation systems drives up the energy requirements for transportation. Increased needs from transportation affect the environment – approximately 28% of greenhouse gas emissions are related to transportation-based activity (Rode et al. 2017). Much of this is due to intensive automobile use – cars are responsible for approximately 80% of these emissions – and numerous cities in the United States (many lacking a robust mass transit infrastructure) cannot meet air quality standards.

Greater sprawl takes up a greater footprint of the landscape. Impervious materials – paving for roads and parking, roofs, etc. – increasingly replace natural pervious ground surfaces, leading to increased water runoff, erosion, and flooding. This runoff also picks up pollutants – sediments, oils, and agricultural chemicals – leading to a general degradation in water quality.

Increased land development resulting from low-density sprawl also takes already productive land out of use. Sprawl leads to the removal of an estimated 1.3 million acres of productive agricultural land per year. As a result, there is a greater reliance on food products from increasingly distant locales – local sources have been replaced by sources often hundreds or thousands of miles away. This, in turn, leads to greater emissions from the requisite transportation activity to deliver these products. Further, 1.8 million acres per year of natural lands are lost due to development. This can affect the habitats of species, either through direct reduction or fragmentation of wild areas that can affect species which need large areas to thrive (Lawler et al. 2014).

Sprawl also can generate several secondary effects that can affect the quality of life of people and communities as a whole. A greater reliance on automobile trips in lower-density areas results in higher mileage trips, leading to more energy consumption and wear and tear on roads. A greater number of trips per capita also lead to a greater absolute number of accidents, injuries, and fatalities. When infrastructure cannot keep up with population growth or when constraints are in place (e.g. existing land uses or natural landforms like water bodies or mountains) to limit expansion of existing systems, traffic congestion is inevitable, leading to lost productivity, increased transit times, and a greater waste of energy to power idling vehicles. Building additional roadways to increase transportation capacity requires greater expenditure, which may lead to an increased rate of taxes. The greater trip distances that result from sprawl lead to greater reliance on automobile transportation and a like reduction in physically active transportation, such as biking or walking. As a result, reduced physical activity, increased obesity, and related health effects tend to rise.

1.3 The Master Equation or IPAT Equation

To assess the combined impacts of resource use, environmental impact, and population, the "*Master Equation*" may be used to assess the overall impact of these inputs. The equation is defined as follows:

$$\begin{aligned}\text{Overall impact} = \text{Population} &\times (\text{Resource use/person}) \\ &\times (\text{Environmental impact/unit of resource use})\end{aligned} \tag{1.1}$$

This equation is also known as the IPAT equation (Chertow 2000) first proposed by Ehrlich and Holdren (1971), where I = Impact, P = Population, A = Affluence, and T = Technology. As for measurements of inputs, resource use can be set to gross domestic power (GDP) and converted

to a per capita value to account for a person-by-person basis. As can be seen, with increased population and resource use (which are relatively easy to measure), a reduction in environmental impact per unit of resource use is necessary and must be of sufficient magnitude if overall impact is to be minimized.

Example 1.3
Given:

- A country has a population of 50 million people.
- The affluence level, measured as GDP per capita, is $30 000.
- The technology factor, which represents the environmental impact per unit of GDP, is 0.25 units of impact per $1000 of GDP.

Calculate the total environmental impact of the country using the IPAT equation.

Solution:

$$\begin{aligned}\text{Total environmental impact} &= \text{population} \times \text{affluence (GDP per capita)} \times \text{technology factor} \\ &= 50\ \text{M people} \times \$30\,000/\text{person} \times (0.25\ \text{units}/\$1000) \\ &= 375\ \text{M units}\end{aligned}$$

1.4 What Is Sustainability?

Several problems faced on a global scale that could severely affect the environment and ultimately human civilizations have been presented in preceding sections. There is a growing desire to pursue sustainable solutions to address these growing problems, but what exactly is sustainability? There is no universally accepted definition, but several common definitions convey similar concepts. The most commonly used definition comes from one presented by the 1987 United Nations World Commission on Environment and Development (commonly known as the Brundtland Commission, named after the commission chair, Gro Harlem Brundtland, former Prime Minister of Norway). In the Commission's report, *Our Common Future*, sustainability was defined as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN 1987). This definition is succinct and powerful in conveying the need to act responsibly so that the current and future generations can have a high quality of life while protecting the planet. This definition, however, does not inform on how this can be accomplished. The term 'sustainability' has since been defined differently by different organizations. However, it is essential to note that any definition of sustainability is incomplete without considering all the TBL aspects: environment, society, and the economy.

The United Nations (UN) adopted the 2030 Agenda (Transforming our World: the 2030 Agenda for Sustainable Development) in September 2015 with effective date 1 January 2016 (UN 2015). The agenda is a commitment to achieve sustainable development by 2030 world-wide. It consists of 17 global goals (known as Sustainability Development Goals or simply SDGs) with associated 169 specific targets. The SDGs cover multiple social, economic, and environmental development issues, including no poverty, quality education, clean water and sanitation, affordable and clean energy, sustainable cities and communities, and others. These goals are vital and ambitious but necessary to shift the world onto a sustainable and resilient path.

The concept of sustainability and sustainable development supersedes the concept of "environmentalism" that has been in existence for several years. In addition to protection of the

environment, sustainability incorporates the concept of equity – the needs of the present shall be met, but of equal importance is the preservation of resources for equally deserving future generations. The incorporation of sustainability means different things to different people, too. Economists typically consider sustainability and its aspects with respect to growth, efficiency, and resource use. Sociologists focus on human needs, including equity, empowerment, social cohesion, and cultural identity. Environmentalists tend to focus on the preservation of the integrity of the environment, living within the limits, means, and carrying capacity of the planet, and exploring ways to minimize environmental impacts while remediating existing impacts from past and present pollution occurrences.

The pursuit and achievement of sustainable solutions presents several challenges, not the least of which is that development and economic activity often have goals that, at first glance, can be in direct conflict with environmental stewardship or resource preservation. However, sustainable solutions are increasingly desired, and the concept of the TBL has been a valuable framework in which to consider the relative efficacy of these solutions. The TBL (Figure 1.9) consists of three measurement schemes to consider these solutions (Halpern et al. 2013):

- *Environmental* – Diversity and interdependence within living systems, the goods and services produced by the world's ecosystems, and the impacts of human-generated wastes (the planet).
- *Economic* – Flow of financial capital and the facilitation of commerce (prosperity).
- *Social* – The interactions between institutions/firms and people, functions expressive of human values, aspirations, and well-being, and ethical issues (people).

Sustainable solutions are those that maximize the relative return to these three categories and their representative metrics. More sustainable solutions lead to a greater intersection of these metrics.

A collective transition to more sustainable practices may be hard to imagine, but it is necessary. A stable human population must recognize that the earth has a finite set of resources as well as a finite ability to accept and absorb waste products. If sustainable practices are not incorporated,

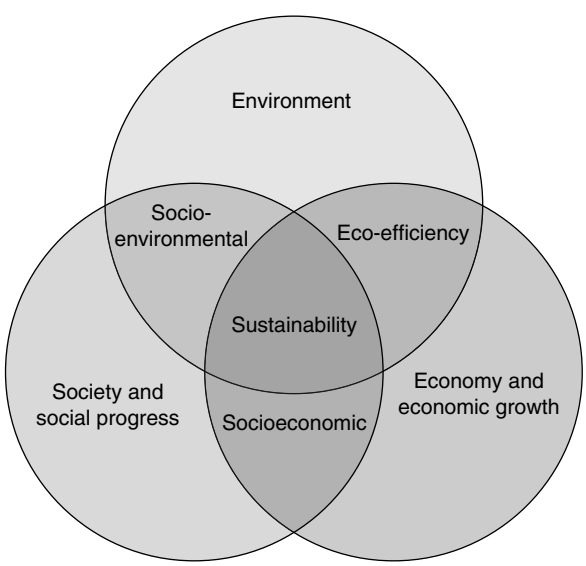

Figure 1.9 The triple bottom line: environment, economic, and social aspects, in sustainability.

catastrophic consequences may result. A pursuit of greater sustainability requires care and dedication to the preservation of the natural world and a commitment to justice and equity among various sections of people on the planet.

Several actions or characteristics are vital for the transformation to more sustainable practices. First, population growth must slow down to a more stable, sustained pace. Political and social institutions need to increasingly embrace environmental stewardship and approaches to reduce poverty and inequity. Resource utilization needs to progress from a sole focus on short-term economic benefit and output to one that incorporates a long-term view with due consideration for the protection of ecosystems and natural resources. Technology needs to play a role in the reduction of greenhouse gases and transition from pollution and waste-intensive processes to more environmentally protective activities. Finally, land use and planning should increasingly focus on community development practices that discourage sprawl-causing development and encourage higher-density uses, including more livable cities.

In summary, the sustainability concept, if not the specific definitions, is relatively easy to comprehend. However, the ability to measure sustainability remains a work in progress. Nevertheless, efforts have been made, and sustainability measuring tools are beginning to evolve. As an example, in 2007, the United Nations Commission on Sustainable Development listed 96 indicators under 14 themes to measure sustainability or sustainability in a particular country. Some examples are presented in Table 1.1. However, sustainability at project level requires a new set of sustainability indicators, which are addressed in Section II of this book.

1.4.1 United Nations Sustainable Development Goals (SDGs)

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, serves as a universal blueprint for fostering peace and prosperity for both people and the planet, both now and in the years to come. Central to this agenda are the 17 Sustainable Development Goals (SDGs), representing a compelling call to action for all nations, whether developed or developing, to collaborate in a worldwide partnership. These goals are:

- *Goal 1*. End poverty in all its forms everywhere (No Poverty)
- *Goal 2*. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture (Zero Hunger)
- *Goal 3*. Ensure healthy lives and promote well-being for all at all ages (Good Health and Well-being)
- *Goal 4*. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all (Quality Education)
- *Goal 5*. Achieve gender equality and empower all women and girls (Gender Equality)
- *Goal 6*. Ensure availability and sustainable management of water and sanitation for all (Clean Water and Sanitation)
- *Goal 7*. Ensure access to affordable, reliable, sustainable, and modern energy for all (Affordable and Clean Energy)
- *Goal 8*. Promote sustained, inclusive and sustainable economic growth, full and productive employment, and decent work for all (Decent Work and Economic Growth)
- *Goal 9*. Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation (Industry, Innovation, and Infrastructure)
- *Goal 10*. Reduce inequality within and among countries (Reduced Inequalities)
- *Goal 11*. Make cities and human settlements inclusive, safe, resilient, and sustainable (Sustainable Cities and Communities)

Table 1.1 Indicators for measuring sustainability.

Theme	Subtheme	Indicator (example)
Poverty	Income poverty	Proportion of population living below national poverty line
	Income inequality	Ratio of share in national income of highest to lowest quintile
	Sanitation	Proportion of population using an improved sanitation facility
	Drinking water	Proportion of population using an improved water source
	Access to energy	Share of households without electricity or other modern energy services
	Living conditions	Proportion of urban population living in slums
Governance	Corruption	Percentage of population having paid bribes
	Crime	Number of intentional homicides per 100 000 population
Health	Mortality	Under-five mortality rate
	Health care delivery	Percentage of population with access to primary health-care facilities
	Nutritional status	Nutritional status of children
	Health status and risks	Morbidity of major diseases such as HIV/AIDS, malaria, tuberculosis
Education	Education level	Net enrolment rate in primary education
	Literacy	Adult literacy rate
Demographics	Population	Population growth rate
	Tourism	Ratio of local residents to tourists in major tourist regions and destinations
Natural hazards	Vulnerability to natural hazards	Percentage of population living in hazard-prone areas
	Disaster preparedness and response	Human and economic loss due to natural disasters
Atmosphere	Climate change	Carbon dioxide emissions
	Ozone layer depletion	Consumption of ozone depleting substances
	Air quality	Ambient concentration of air pollutants in urban areas
Land	Land use and status	Land degradation
	Desertification	Land affected by desertification
	Agriculture	Arable and permanent cropland area
	Forests	Proportion of land area covered by forests
Oceans, seas, and coasts	Coastal zone	Percentage of total population living in coastal areas
	Fisheries	Proportion of fish stocks within safe biological limits
	Marine environment	Proportion of marine area protected

Table 1.1 (Continued)

Theme	Subtheme	Indicator (example)
Freshwater	Water quantity	Water use intensity by economic activity
	Water quality	Presence of fecal coliforms in freshwater
Biodiversity	Ecosystem	Proportion of terrestrial area protected, total and by ecological region
	Species	Change in threat status of species
Economic development	Macroeconomic performance	Gross domestic product (GDP) per capita
	Sustainable public finance	Debt to GNI (Gross National Income) ratio
	Employment	Labor productivity and unit labor costs
	Information and communication technologies	Internet users per 100 population
	Research and development	Gross domestic expenditure on R&D as a percentage of GDP
	Tourism	Tourism contribution to GDP
Global economic partnership	Trade	Current account deficit as percentage of GDP
	External financing	Net Official Development Assistance (ODA) given or received as a percentage of GNI
Consumption and production patterns	Material consumption	Material intensity of the economy
	Energy use	Annual energy consumption, total and by main user category
	Waste generation and management	Generation of hazardous waste
	Transportation	Modal split of passenger transportation

Source: UN (2007)/United Nations.

- *Goal 12*. Ensure sustainable consumption and production patterns (Responsible Consumption and Production)
- *Goal 13*. Take urgent action to combat climate change and its impacts (Climate Action)
- *Goal 14*. Conserve and sustainably use the oceans, seas, and marine resources for sustainable development (Life Below Water)
- *Goal 15*. Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss (Life on Land)
- *Goal 16*. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels (Peace, Justice and Strong Institutions)
- *Goal 17*. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development (Partnerships for the Goals).

These 17 Goals specify a total of 169 targets, which in turn are monitored using 247 Indicators. Figure 1.10 illustrates the most common graphical representation of these SDGs. These goals acknowledge the necessity of simultaneously addressing poverty and other forms of deprivation, alongside implementing strategies that enhance health and education, diminish inequality, and stimulate economic growth. This approach is also integral to addressing climate change and conserving our oceans and forests (https://sdgs.un.org/goals).

The Division for Sustainable Development Goals (DSDG) within the United Nations Department of Economic and Social Affairs (UNDESA) offers essential support and builds capacity for the SDGs and their associated themes, such as water, energy, climate, oceans, urbanization, transport, science, and technology.

Annually, the UN Secretary-General delivers a report on the progress of the SDGs. This report is prepared in collaboration with the UN System, drawing on the global indicator framework. It utilizes data from national statistical systems and regional information. Details about SDG indicators and reports can be found at https://unstats.un.org/sdgs. Furthermore, the Global Sustainable Development Report is published every four years to support the quadrennial review of the SDGs at the General Assembly. Authored by an Independent Group of Scientists selected by the Secretary-General, the most recent edition was *The Sustainable Development Goals Report* released in 2024 (https://unstats.un.org/sdgs/report/2024/).

The SDGs are relevant to every country and sector, including cities, businesses, schools, and organizations, all of which are encouraged to take action (Universality). These goals are interconnected within a system, meaning we cannot focus on achieving just one; we need to work toward all of

Figure 1.10 United Nations Sustainable Development Goals (UN SDGs). *Source:* United Nations Development Programme.

them (Integration). Realizing these goals requires significant, fundamental changes in our lifestyle on Earth (Transformation).

The ASCE Policy statement 517 endorses the civil engineering components of the United Nations' SDGs. ASCE collaborates with both domestic and international organizations to involve engineers in helping disadvantaged communities. This involves building capacity and creating sustainable, appropriate solutions to combat poverty. There is a growing demand for resources and services like energy, food, land, water, transportation, materials, waste disposal, construction, health care, environmental cleanup, telecommunications, and infrastructure. Engineers play a vital role in meeting these needs across different scales, especially in the developing world, from small remote communities to large urban areas. It is essential to educate a new generation of engineers who are equipped to tackle the challenges in the developing world and cater to the needs of disadvantaged communities. Engineers are key to building a more sustainable, stable, and secure world.

The latest report on the SDGs published in 2024 provides a status update on the progress toward achieving the 17 Sustainable Development Goals. The individual data by country and SDG is available in the report. Figure 1.11 shows the results by groups of countries, categorized by regions or economic levels. As seen in Figure 1.11, the highest index corresponds to OECD countries and high-income countries. The lowest index values correspond to Sub-Saharan Africa, Oceania, and low-income countries. The detailed analysis of the individual results for each SDG shows that only a few of these goals have been achieved in specific countries or regions, while other goals are facing significant challenges in many regions of the world. Notably, SDGs 2, 14, 15, and 16 show serious difficulties in being achieved globally and by region according to current data, indicating that additional efforts are still needed to change the trend and ensure these SDGs can be met by the 2030, target set by the United Nations in the design of this program.

1.4.2 What Is Sustainable Engineering?

With a definition or at least a general idea of sustainability in place, it is time to discuss how sustainability principles and goals can be applied to the world around us. Of course, for centuries, engineers have applied scientific principles to devise solutions in nearly all aspects of our lives, including water, sanitation, mobility, energy, information management and propagation, food, health care, shelter, and communications. For much of this time, engineers have developed solutions with an implicit notion of limitless resources and little concern with respect to the management of waste or by-products or at least solutions independent of these factors. Additionally, engineers have commonly sought solutions that have not fully considered the social implications of their solutions.

With an understanding that, in fact, resources, waste management, and social implications are indeed critical factors, the concepts of sustainable engineering have begun to emerge. Sustainable engineering is the development of engineering solutions to advance human life to maximize benefits and minimize adverse impacts on the environment, the economy, and society ("the triple bottom line") throughout the life cycle of a project. Sustainable engineering can be applied regardless of value chain position or the magnitude of a project – it is scalable and applied across molecular, product, process, and system design.

The goals of sustainable engineering are shared among many specific disciplines. As presented in the American Academy of Environmental Engineers (AAEE) Environmental Engineering Body of Knowledge (2008), a joint declaration was issued with the American Association of Engineering

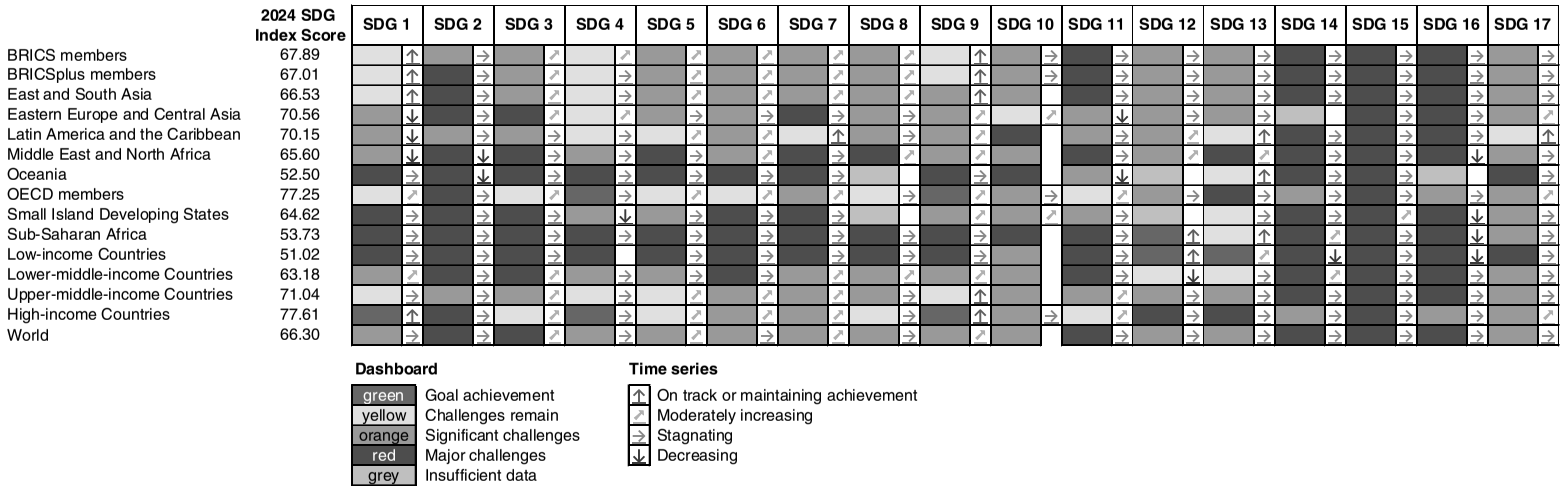

Figure 1.11 Performance scores and trends of individual Sustainable Development Goals (SDGs) in 2024 for different groups of countries categorized by regions or economic levels.

Societies (AAES), American Institute of Chemical Engineers (AIChE), the American Society of Mechanical Engineers (ASME), and the National Academy of Engineering (NAE) that stated the following: "Creating a sustainable world that provides a safe, secure, healthy life for all the people is a priority for the US engineering community. Engineers must deliver technically viable, commercially feasible, and environmentally and socially sustainable solutions." The American Society of Civil Engineers (ASCE) addresses sustainable development in its Policy statement 418 by stating, "Sustainability is a set of environmental, social, and economic conditions (aka "The Triple Bottom Line") in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely without degrading the quantity, quality, or the availability of environmental, social, and economic resources" (ASCE 2023a).

Lately, the concept of green engineering (GE) has begun to emerge, but there are important, clear distinctions between green engineering and sustainable engineering. Generally stated, green engineering is the development of engineering solutions that are protective of human and environmental health throughout the life cycle of a project. Sustainable engineering is broader than green engineering in that it aims to develop engineering solutions that are not only protective of human and environmental health but are also economically and socially responsible throughout the life cycle of a project. In other words, green engineering is a subset of sustainable engineering with a focus on minimizing environmental impacts. Table 1.2 and Figure 1.12 summarize key principles of green engineering and sustainable engineering, respectively.

Table 1.2 Principles of green engineering.

Inherent rather than circumstantial	Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible
Prevention instead of treatment	It is better to prevent waste than to treat or clean up waste after it is formed
Design for separation	Separation and purification operations should be designed to minimize energy consumption and materials use
Maximize efficiency	Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency
Output-pulled versus input-pushed	Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials
Conserve complexity	Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition
Durability rather than immortality	Targeted durability, not immortality, should be a design goal
Meet need, minimize excess	Design for unnecessary capacity or capability (e.g. "one size fits all") solutions should be considered a design flaw
Minimize material diversity	Material diversity in multicomponent products should be minimized to promote disassembly and value retention
Integrate material and energy flows	Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows
Design for commercial "afterlife"	Products, processes, and systems should be designed for performance in a commercial "afterlife"
Renewable rather than depleting	Material and energy inputs should be renewable rather than depleting

Source: Anastas and Zimmerman (2003). Reproduced with permission of American Chemical Society.

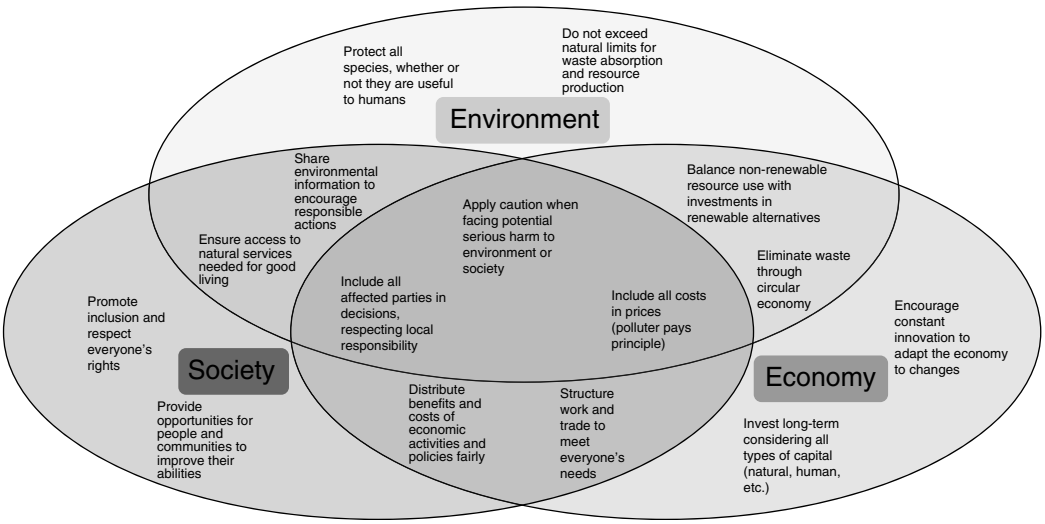

Figure 1.12 Classification of sustainable engineering principles across environmental, social, and economic criteria.

Of equal importance to environmentally protective green concepts and financial considerations are several socially focused dimensions. In helping to maximize the benefit within the context of these dimensions, it is important to identify to the extent possible the social issues and values that a particular activity or project will affect, and it is equally important to consider both the positive and the negative social consequences. For many reasons, perhaps due to practice, cultural, or social traditions, it is important that the social context even be considered, as it has not been incorporated in the past for countless projects or activities. To the extent possible, it is important to provide a culture/environment around a project or activity such that dialogue with respect to socially related aspects can occur. In such an environment, social values that may not have been seriously considered or even identified can be integrated into the project-related, decision-making process. Once this culture and dialogue are in place, decisions with respect to important social dimensions may be thoughtfully considered. Some important dimensions that may be considered include effects on population factors, such as birth rate, literacy, life span, cultural acceptance/openness (art, religion, etc.), and gender roles and degree of equity.

Aspects of a project can be designed or re-designed to maximize social or cultural benefits to the maximum extent feasible, while at the same time maximizing relative benefit with respect to traditional financially driven metrics, including costs, rate of return, and consumer demand. Of course, this is an iterative process, and it is rare, if not impossible, to maximize return or benefit to all three triple bottom line aspects. However, with iterations and thoughtful consideration of these three frames of reference, the goal is to maximize the relative benefit of each frame, incorporate into design, execution, and management, and carry out the action to attain the desired result.

Although the framework and the nomenclature of sustainable engineering are relatively new, some concepts have been around for a long time, and there has been a steady progression for decades toward its current state. Figure 1.13 shows how this trend has evolved over the past 40–50 years. For instance, prior to 1970, very little thought was given to social or environmental aspects. However, with significant environmental issues and related government regulation

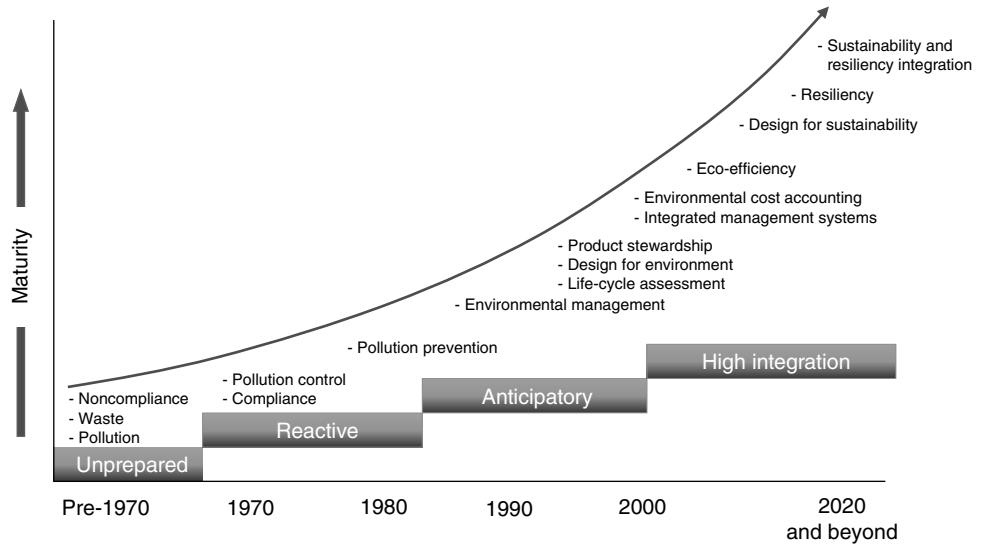

Figure 1.13 Evolution of concepts in sustainable and resilient engineering.

increasingly becoming part of the public consciousness in the 1970s, projects began to react and comply, then anticipate, and later even guide evolving environmental attitudes. As this evolution progressed, increased attention was paid to socially responsible and culturally aware practices, with an increased incorporation into design phases of projects and activities.

As we have introduced and discussed the aspects of sustainable engineering, there are several emerging general strategies or goals that are increasingly being considered core to sustainable engineering. Ultimately, there is a goal to pursue a full integration of engineered systems within the overall natural system of which it is a part. Additionally, it is important to seek flexible, scalable solutions that may be adapted from a micro- to macrolevel or a local-to-global scale. Further, thoughtful designs are based on a system approach that incorporates green chemistry, processes, and material use with comprehensive considerations of life cycle impacts with respect to energy and material inputs as well as emissions and other waste outputs. Finally, these designs should consider socially responsible outcomes as well as traditional economic metrics, including revenue, profit, profit margin, return on investment (ROI), and return on equity (ROE), among many others.

As mentioned, sustainable engineering operates at various scales. From a local standpoint, concepts and principles may be incorporated by individual firms as they attempt to design projects or products that are protective of the environment, aim to reduce pollution or waste generation, and utilize resources efficiently. On the next larger scale, firms or other entities may cooperate on larger initiatives, such as intra or intersector initiatives, standards of practice, joint ventures, collaborative studies, or facility development. Finally, on a regional or global scale, larger multinational firms, entire industries, or government entities may participate in even large initiatives, such as budget and cycle studies, materials and energy flow studies, research initiatives, and modeling scenarios that can ultimately lead to practice regulations.

An example of this scalability comes from the automotive industry. Imagine a single firm that fabricates a component of an automobile, such as axles. At the firm level, they can find sustainable designs or implement systems that eliminate waste or add efficiency to the design. At the next scale, they can participate with their client (one of the large automobile companies, such as General

Motors or Toyota) as well as with the company's other subcontractors to develop eco-friendly integrated systems for overall design or for manufacturing principles. At the next larger scale, they may work within the industry to find larger-scale sustainable solutions, such as those that may affect the design of roads and infrastructure, refining of traditional motor fuels and transitions to alternative fuels. Finally, at the global scale, they may work with several intra-industry groups as well as those from other industries or from governments to look for other initiatives that directly look to solve society's needs, such as alternative transportation modes, or land use that may optimize trip length and density.

A concrete example of this concept is the design and manufacture of Sertraline by Pfizer, a large pharmaceutical company (USEPA 2002; Nameroff et al. 2004). Sertraline is the active ingredient in Zoloft, a market-leading drug for the treatment of depression. Hundreds of millions of prescriptions have been written for Zoloft in the United States alone. By applying some of the sustainable engineering principles described in this chapter, Pfizer was able to eliminate the use of 140 metric tons per year of titanium tetrachloride and eliminate the generation of 440 metric tons of titanium dioxide waste per year. In addition, 150 metric tons of hydrochloric acid waste and 100 metric tons of sodium hydroxide needed for production were eliminated on a yearly basis. Other raw materials were also eliminated. These reductions saved Pfizer substantial money with respect to raw materials purchases and waste management. Corresponding resources were preserved, and Pfizer's financial metrics improved.

When designing products or projects that aim to be sustainable, it is important to measure the degree of sustainability involved in the fabrication, use, and disposal of the product. Not only should this study span the project or product itself, but it should also consider all inputs and activities associated with the final disposition of the product or project. Such a study may include a life cycle assessment (LCA). An LCA includes an inventory of inputs (e.g. raw materials and energy) and outputs (e.g. products, emissions, and solid waste) of the product over its entire life. The inventories that are assembled are converted into categories of impact; some of these may include emissions-related effects on climate change, acidification, aquatic toxicity, or human health. The LCA can further assign a quantitative weighting system of the individual categories to compute a single impact number.

LCAs can be incredibly powerful and useful in assessing sustainability. They consider the entire cycle of a project or product and related effects. It allows for the consideration and incorporation of several value-based assessment criteria, as well as latitude with respect to the weighting of these criteria. Their use also promotes comparison between project/product alternatives as well as individual components. Unfortunately, there are some limitations associated with LCAs. They are costly and time-consuming to perform. There is an inherent imprecision of some data associated with the attempt to quantify qualitative aspects or virtues. Additionally, it is difficult to incorporate and/or measure all relevant data, and some impacts may be inadvertently overlooked. Nevertheless, they are useful tools in working to achieve more sustainable designs with respect to material and energy inputs as well as waste management/reduction.

One of the concepts, whether with respect to the degree of sustainability, the TBL, or applications of LCAs, is the effect of globalization. Increasingly, virtually all aspects of economic activity are moving toward a global approach and participation. Very little economic activity of any importance occurs without some form of global impact. The global aspects of economic activity need to be carefully considered when assessing sustainability. Trade policies and regulations, the interaction of design and manufacturing in distant locations, transportation, and the flow of inputs, outputs, and waste by-products (such as emissions) are important factors to consider when assessing sustainable alternatives.

1.5 What Is Resiliency?

The impacts of climate change, such as extreme weather events discussed in the previous section, along with other shocks and stressors that may affect a system throughout its life cycle, motivate the adoption of resilience in the design and implementation of engineering systems. The term resilience originates from the Latin word "*resilire*", meaning "to jump back" or "to recoil." This traditional concept of resilience, emphasizing recovery from stressors, has been recognized for decades. The term is used across various domains, including psychology, biology, ecology, sociology, and engineering. Since the scope of this book is limited to engineering systems' resilience, our discussion will focus accordingly.

While resilience is interpreted differently across fields, most definitions share a consensus (Hosseini et al. 2016). Many intersect with concepts like robustness, fault tolerance, flexibility, survivability, and agility. In general, resilience is understood as the ability of a system to sustain its operations despite sudden shocks, stresses, changing conditions, or disturbances. In the modern-day engineering practice, resiliency encompasses four main concepts: rebound capability, robustness, flexibility, and sustained adaptability (Woods 2015). Rebound capability refers to a system's ability to recover from catastrophic failure or performance deterioration due to stress. Robustness denotes the system's capacity to absorb recurring disturbances. Flexibility contrasts brittleness, referring to a system's ability to avoid sudden failure in the face of unexpected or unprecedented challenges. In the context of climate change, adaptability – the system's capacity to adjust to continuous changes in conditions – has become increasingly relevant.

Another dimension of resilience concerns its scope, whether referring to the technical resilience of a single project or the resilience of a socio-technical system as a whole. A holistic perspective of resilience reflects the ability of communities to cope with external stresses resulting from social, political, or environmental changes. This view – that resilience is a socio-technical system's potential to achieve desirable performance – implies that resilience itself is not the end goal but rather a formal concept tied to the overarching aims of engineering, such as ecological safety and human well-being (Doorn et al. 2019).

1.5.1 What Is Resilient Engineering?

Resilient engineering focuses on developing solutions that can withstand and recover from unexpected shocks or stressors. For example, climate-resilient engineering involves designing and constructing projects that address climate-related impacts such as sea level rise, heavy rainfall, droughts, storms, and cyclones. Traditionally, engineering aims to design systems with a certain level of resilience so that they can endure expected stressors or weather events over the project's life cycle. However, this conventional understanding of resilience is becoming outdated as challenges continue to evolve.

Modern, resilient engineering requires building systems that can maintain functionality despite sudden shocks, stresses, changing conditions, or disturbances. Climate effects, like natural disasters, cause variations in system loads and often influence a project's overall performance. Designing a technically resilient system can lead to overconsumption of environmental, human, and economic resources, making such designs unsustainable in the long term. On the other hand, compromising technical performance can result in catastrophic system failures during extreme events, causing environmental, social, and economic losses. Therefore, there is a trade-off between these two aspects, with the TBL elements impacted either way. It is crucial to balance technical resilience with the TBL aspects to ensure sustained resiliency.

Many professional engineering organizations are actively promoting resilient engineering. For example, the American Society of Civil Engineers (ASCE) is encouraging resilient engineering through its newly released toolkit, which centralizes resources to help civil engineers and community leaders adopt modern building codes and standards. The toolkit highlights hazard-specific standards for climate-resilient engineering like ASCE 7-22: "Minimum design loads and associated criteria for buildings and other structures" (ASCE 2021). The toolkit also features the Envision program, which supports sustainable and resilient infrastructure design. ASCE's efforts also focus on educating policymakers and local communities to build infrastructure capable of withstanding climate-related and other hazards. Similarly, to ensure the resilient design of power grid systems, the ASME made several recommendations: accelerating the replacement of aging infrastructure, shortening supply chains to reduce replacement times for key components, hardening the power supply at the national level against threats from weather and cyber/physical attacks, deploying new technologies, encouraging diverse clean energy technologies, supporting deployment of energy storage, and updating the operating systems for the electric grid. Similarly, recommendations were made by AIChE for water resiliency and the Interstate Technology Regulatory Council (ITRC) for resilient remediation of contaminated sites.

1.5.2 Difference Between Resiliency and Sustainability

The concepts of sustainability and resilience share many similarities and are often used interchangeably across various applications, though their meanings and purposes are distinct. It is important to note that both sustainability and resilience serve as descriptors of systems, rather than being independent entities. These systems can range from the global economy to an individual's physical or mental well-being. Both concepts emphasize the state of a system over time, focusing on its persistence under normal conditions and its ability to withstand disruptions. This common focus on system survivability leads to the use of similar research methodologies, such as similar time scales (life cycle). Sustainability and resilience are both influenced by global political trends, with frameworks and agendas promoting both concepts in areas such as urbanization. The overlap in their goals has led to the creation of integrated sustainability and resilience departments within government agencies, universities, and nonprofit organizations.

However, despite their similarities, sustainability and resilience are two distinct entities. They operate on different spatial and temporal scales, with sustainability often focusing on broader spatial areas and longer timeframes than resilience. "Resiliency refers to the ability of a system to withstand and recover from unexpected shocks or stressors, such as extreme weather events resulting from climate change. Sustainability represents a holistic approach that encompasses environmental, economic, and social considerations. It aims to continuously improve the quality of life and infrastructure without compromising the needs of future generations" (Reddy et al. 2024). Particularly with respect to climate change, resilience is the ability to adapt, withstand, and recover from climate impacts, whereas sustainability is an approach adopted to reduce the rate and extent of climate change. In some cases, resilience may be achieved at one scale or timeframe but compromised at another, which is not the case with sustainability.

A lack of understanding of the similarities and differences between sustainability and resiliency can create challenges in implementation, leading to missed opportunities for synergy and the potential for conflicting objectives. Hence, it is important to clearly understand the differences and similarities between the concepts of resilient and sustainable engineering.

1.6 Integrated Sustainable and Resilient Engineering

Both sustainability and resilience of engineered systems are important for human existence and survival; these terms cannot be viewed separately because having resilient systems that are not sustainable may exacerbate the climate change and other impacts making the built environment nonresilient in the future. Conversely, sustainable systems that are not resilient to extreme events defy the primary purpose of building such systems, thus making them inherently unsustainable. Integrated sustainable and resilient engineering refers to the practice of developing solutions that not only endure extreme shocks and stressors but do so sustainably by minimizing resource consumption and environmental impact as well as maximizing the environmental and social benefits. In other words, the solution ensures resilience while minimizing the impacts on the environment, economy, and society.

In order to properly integrate these concepts, one needs clearly to understand such similarities and differences and try to maintain a balance between the conflicting objectives of sustainability and resiliency. Traditional engineering might be inadequate in such cases, and this paradigm shift to integrated resilient and sustainable engineering necessitates innovative engineering practices. Examples of such innovations in the field of infrastructure include the adoption of green infrastructure instead of gray infrastructure for urban stormwater management, and the adoption of nature-based solutions such as floodable parks instead of concrete seawalls, among others (Reddy et al. 2024). The paradigm shift toward integrated sustainable and resilient engineering represents a vital step for future engineering practices, prioritizing a balanced approach to infrastructure development that can effectively respond to climate change and other global challenges. Some professional engineering organizations such as ASCE and ITRC have also recognized the importance of integrating these concepts and stipulated guidelines on integrating these aspects into the design and implementation of engineering projects (ASCE 2023b, 2023c; ITRC 2021).

1.7 Summary

When defining sustainability, it is important to remember that it is a concept that transcends and supersedes familiar topics associated with environmentalism. Sustainability entails that the human development or activity currently should not jeopardize the needs and the development of future generations. Sustainability is measured across several factors, and the concept of the TBL assesses sustainability within a framework that considers the overall effects of a project or product with respect to the environment, economics, and the society. Sustainable practices, especially to be applied in the future, must be applied in such a way that several emerging challenges (as described in this chapter) are addressed and incorporated.

Sustainable engineering is the means by which sustainable concepts can be applied to systems, projects, and products. Sustainable engineering is defined as a tool for engineering responsibly and professionally by integrating environmental, social, and economic considerations during the life cycle of a project. Finally, the strategies of sustainable engineering aim to engineer systems that can be integrated into natural systems, are flexible enough to adapt to a range of scales from a local to global basis, incorporate design based on a systems approach, and incorporate judicious resource use while minimizing waste generation.

Resilience, on the other hand, differs from sustainability in that it focuses on the ability of systems to withstand and recover from shocks or stressors, such as extreme weather events. A resilient system may not always be sustainable, as it could require significant resource use that contradicts sustainability goals. Conversely, a sustainable system may not be resilient if it cannot endure unexpected challenges. Both concepts must work together to create effective long-term solutions. Integrated sustainable and resilient engineering combines both principles, promoting innovative solutions that balance resource efficiency with the ability to endure unexpected shocks and stressors. Achieving this requires a paradigm shift in traditional engineering, embracing innovative engineering practices to ensure long-term viability and adaptability in engineered systems.

1.8 Questions

1.1 Describe briefly the case of Easter Island, Chile. Based on this case, explain how and why sustainability is important.

1.2 Explain environmental impacts and other emerging challenges in the context of sustainability.

1.3 Outline three strategies you would recommend to lessen/abate waste generation.

1.4 Discuss how impacts on rainforest ecosystems could affect human populations that live in other areas.

1.5 Explain the "Master Equation." Discuss the validity of this equation.

1.6 Explain the "Tragedy of Commons." How is it relevant in a sustainability context?

1.7 Define "Sustainability" and "Triple Bottom Line." How does it fit into the current regulatory framework?

1.8 Name three specific metrics that can be used to assess the degree of sustainability from within the environmental dimension.

1.9 Name three specific metrics that can be used to assess the degree of sustainability from within the economic dimension.

1.10 Name three specific metrics that can be used to assess the degree of sustainability from within the social dimension.

1.11 Explain a simple approach to quantify sustainability. Give some examples.

1.12 How can one evaluate sustainability under complex and dynamic conditions?

1.13 Explain the "grand objectives" of sustainability. How can they be related to environmental concerns and targeted activities and specific actions?

1.14 What is sustainability (or sustainable) engineering? Why is it becoming more critical in current engineering practice?

1.15 What are the general strategies for sustainable engineering? Explain them.

1.16 Discuss a consumer product of your choosing, listing five raw material inputs and five emissions/outputs that could be included in an LCA analysis.

1.17 Explain the concept of resiliency as defined in various domains.

1.18 Why is resiliency of engineered systems important?

1.19 List potential similarities and differences between sustainability and resiliency.

1.20 What are the main objectives of integrating resiliency and sustainability?

1.21 Explain integrated resilient and sustainable engineering concept with examples.

1.9 Problems

1.1 The country of Indonesia has a forest that covers almost 95 million ha (hectares). The forest is shrinking due to increased logging activities, forest clearance for palm oil and pulpwood in addition to mining activities. The current rate of deforestation is 650 000 hectares per year. However, the government plans to implement conservation measures that will reduce the rate of deforestation by 2% each year. Indonesia is one of the major sources of greenhouse gas emissions resulting from land use. In the last 2 decades, the country has lost forest area approximately 27 million ha, equivalent to 20 Gt of CO_2-equivalent emissions.

a) Calculate the area of the forest that will be left after five years if the conservation measures are implemented.
b) Determine the total area of the forest that will be lost due to deforestation over these five years.
c) If the government introduces a reforestation program that plants trees over 150 000 hectares each year starting from the first year, what will be the net change in the forest area after 5 years?
d) Analyze how the situation would differ if the rate of deforestation did not decrease each year. What would be the forest area after five years in this scenario?
e) Calculate the annual amount of CO_2-equivalent emissions that would result from Indonesia's land use activities after 10 years, considering that the target rates of deforestation and reforestation are met by the government, and compare it with the case if the rate of deforestation continues at current rate without any reforestation. Comment on the results.

1.2 The city of Delhi has been experiencing increasing levels of air pollution due to vehicle emissions (38.8%), road dust (18.1%), power plants (10.9%), construction activities (8.4%), residential (6.3%), landfill fires (4.6%), open burning (3.8%), industries (3.4%), agricultural burning (1.3%), and other sources (4.3%). The percentage contributions given are contributors to daily PM2.5 concentration levels. (PM2.5 refers to fine particulate matter that is 2.5 μm or smaller in diameter).

In an effort to reduce air pollution, the city implements a policy that reduces the on-road traffic to half of what it is now. The air quality index (AQI) due to a pollutant (I_p) is determined using the following equation:

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{HI} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + I_{Lo}.$$

where I_p = the index for pollutant p
C_p = the truncated concentration of pollutant p
BP_{Hi} = the concentration breakpoint that is greater than or equal to C_p
BP_{Lo} = the concentration breakpoint that is less than or equal to C_p
I_{Hi} = the AQI value corresponding to BP_{Hi}
I_{Lo} = the AQI value corresponding to BP_{Lo}

The values corresponding to I_{Hi}, I_{Lo}, BP_{Hi}, BP_{Lo} for PM2.5 are given in the following table.

I_{Hi}	I_{Lo}	BP_{Hi} (μg/m^3)	BP_{Lo} (μg/m^3)	Category
0	50	0.0	12.0	Good
51	100	12.1	35.4	Moderate
101	150	35.5	55.4	Unhealthy for sensitive groups
151	200	55.5	150.4	Unhealthy
201	300	150.5	250.4	Very unhealthy
301	400	250.5	350.4	Hazardous
401	500	350.5	500.4	Hazardous

On a given day, the truncated concentration of PM2.5 (C_p) was recorded to be 226 μg/m^3.

a) Determine the PM2.5 concentrations resulting from different sources on the given day.
b) Calculate the AQI corresponding to existing PM2.5 concentrations on the given day.
c) If the city's goal to reduce traffic by half was a success, what would the reduced PM2.5 concentration and the corresponding AQI be?
d) If the government suspends agricultural burning, construction activities, and open burning activities owing to the worsening air quality, what would the reduced PM2.5 concentration and the corresponding AQI be?

Note: Refer to EPA's Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index for examples on calculating the AQI.

USEPA (2018). Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI). US Environmental Protection Agency. Available at: https://document.airnow.gov/technical-assistance-document-for-the-reporting-of-daily-air-quailty.pdf (accessed 10 December 2024).

1.3 The concentration levels of different pollutants are recorded as follows in Delhi, India on a given day:

Pollutant	Concentration ($\mu g/m^3$)
PM2.5	154.5
PM10	257
O_3	9.1
NO_2	13.3
SO_2	1.3
CO	900

Calculate the air quality index corresponding to each pollutant, and determine the overall air quality index (AQI) of Delhi on the given day.

Note: Refer to EPA's Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index for examples on calculating the AQI.

1.4 The city of New York generates an average of 1.6 kg of municipal solid waste (MSW) per person per day. The current population of the city is 8.65 million people, growing at an average 0.5% per year. Percentage of waste managed though different methods and the corresponding GHG emissions for New York are given below:

Management technique	Fraction of MSW	Greenhouse gas emissions
Recycled	19%	100 kg CO_2e per tonne of recycled waste
Incinerated	15%	415 kg CO_2e per tonne of MSW incinerated
Landfilled	66%	781.05 kg CO_2e per tonne of MSW landfilled

Average composition of MSW collected in New York is as follows:

Organic	47%
Paper	23%
Plastic	14%
Construction debris	7%
Metals	4%
Glass	3%
Appliances and electronics	1%
Household hazardous waste	0%
Miscellaneous	1%

a) Calculate the total amount of waste generated by the city in one year at the current rate.
b) Determine the total amount of waste that will be generated in the next year, considering the 5% increase in waste generation per person.

c) Calculate the greenhouse gas emissions from each management method and the total greenhouse gas emissions from MSW management in New York city at current generation rates.
d) Identify the recyclables in the MSW matrix, and what is their fraction of the total MSW generated.
e) NYC aims to reduce the landfilling rate of MSW by 75%. Assuming that the city meets its target of reducing the landfilling rate and all the recyclables in the MSW matrix are recycled, determine the percentage of GHG emissions reduced.

1.5 The city of Beijing generates an average of 0.22 kg of municipal solid waste (MSW) per person per day. The current population of the city is 21.5 million people, growing at an average 2% per year. Percentage of waste managed though different methods and the corresponding GHG emissions for Beijing are given below:

Management technique	Fraction of MSW	Greenhouse gas emissions
Recycled	20%	100 kg CO_2e per tonne of recycled waste
Composted	15%	400 kg CO_2e per tonne of MSW composted
Incinerated	15%	415 kg CO_2e per tonne of MSW incinerated
Landfilled	50%	781.05 kg CO_2e per tonne of MSW landfilled

Average composition of MSW collected in Beijing is as follows:

Waste component	Composition (%)
Kitchen waste	71.71
Paper (non-recyclable/recyclable)	6.30/5.87
Plastics (non-recyclable/recyclable)	2.75/7.09
Metals	0.15
Glass	3.92
Textile	0.60
Others	1.20

a) Calculate the total amount of waste generated by the city in one year at the current rate.
b) Determine the total amount of waste that will be generated in the next year, considering the 2.5% increase in waste generation per person.
c) Calculate the greenhouse gas emissions from each management method and the total greenhouse gas emissions from MSW management in Beijing city at current generation rates
d) Identify the recyclables in the MSW matrix, and what is their fraction of the total MSW generated
e) Beijing aims to increase the recycling and composting rate of MSW. Assuming that the city can increase the recycling rate by 10% in the next one year, and composting rate by 5%, determine the percentage of GHG emissions reduced due to the diversion of these waste streams from landfilling.

1.6 Scientists have discovered and identified 8.7 million different species of animals and plants on the Earth until now. However, due to deforestation alone Earth is losing approximately 50 000 species each year. Annual deforestation rate stands as 25 million ha currently. Assume the global deforestation rate reduces by 2% each year for the next 10 years due to various national and international policies.

a) Calculate the number of species that the Earth is expected to lose due to deforestation in the next 10 years.
b) Determine the total number of species remaining on the Earth after 20 years, considering the annual reduction in the loss is only due to deforestation.
c) If the policies are more successful and reduces the deforestation rate by 3.5% each year instead of 2%, how many species will be lost in the next 10 years?
d) Apart from deforestation, list other possible reasons for loss of biodiversity, and briefly explain some conservation efforts that can be undertaken to avoid the loss of biodiversity.

1.7 In India, the income distribution is highly skewed. A latest survey shows that the richest 10% of the population earns 57% of the total national income, while the poorest 50% earns only 13% of the total income; the income distribution is as shown in the table below:

Population (%)	National income (%)
Top 10	57
Next 40	28
Next 10	3
Bottom 40	10

The per capita national income of India is $2400 USD, and the population of India is approximately 1.4 billion.

a) Calculate the total income earned by the richest 10% of the population.
b) Determine the total income earned by the poorest 40% of the population.
c) If the government of India decides to implement a policy to redistribute 5% of the total income from the richest 10% to the poorest 40%, calculate the new total income for both groups after redistribution.
d) Calculate the Gini coefficient of income inequality based on the given data. Compare it with the Gini coefficients of other countries and comment on the results.
e) Discuss the potential impacts of this income redistribution on reducing income inequality. What are some other measures that could be taken to address social injustice in India?

Note:

- Search on the internet for information about Gini coefficients of different nations.
- Method to calculate Gini coefficients can be obtained at Hasell (2023).

Hasell, J. (2023). Measuring inequality: what is the Gini coefficient?". Available at: OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/what-is-the-gini-coefficient' (accessed 10 December 2024).

1.8 The city of Bangalore, India, has been expanding rapidly due to urban sprawl. In 2000, the city had a built-up area of 200 km^2 and had a population of 5 561 000. By 2015, the city's built-up area had increased to 275 km^2, while the population grew to 10 000 000. The city is planning further expansion, and the projected growth rate of the built-up area is 3% per year, while the population is expected to grow at a rate of 3% per year.

a) Determine the projected built-up area of Bangalore in 2025.
b) Calculate the projected population of Bangalore in 2025.
c) If the increase in built-up area leads to GHG emissions of 75 kg CO_2e/m^2 area, what would be the increase in GHG emissions after 10 years due to the increase in the built-up area?
d) If the per capita waste generation rate of Bangalore stands at 500 g/day, what would be the total waste generated in the year 2025?
e) Discuss the potential impacts of urban sprawl on Bangalore's infrastructure, environment, and quality of life. What strategies could be employed to manage urban sprawl effectively?

1.9 Given:

- Country A: Population = 10 million, Affluence (GDP per capita) = $20 000, Technology factor = 0.2 units/$1000 GDP.
- Country B: Population = 20 million, Affluence (GDP per capita) = $15 000, Technology factor = 0.3 units/$1000 GDP.

Using IPAT equation,

a) Calculate the total GDP for each country.
b) Calculate the total environmental impact for each country.
c) Compare the impacts of Country A and Country B.

1.10 The data regarding car ownership in the metropolitan cities of Chicago and New York are given below:

City	Total number of households	Number of cars owned per household	Manufacturing emissions (kg CO_2e/car)
Chicago	1.08M	1.12	5000
New York	3.2M	0.63	5000

Assuming the all the cars have similar rate of emissions per manufactured car, calculate the following using the IPAT equation.

a) Calculate the total GHG emissions due to manufacturing the existing cars in Chicago and New York. Comment on the results.
b) Assuming that each car travels 37 miles a day on an average and each car emits 400 g CO_2e emissions per mile, calculate the daily greenhouse gas emissions from Chicago and New York. Compare and comment on the results.

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