Chapter 2
Environmental and Ecological Effects of Energy Production and Consumption

Abstract The exponential increase of energy consumption, since the beginning of the industrial revolution, has produced significant changes in the global environment, chief among which is the increase of the average concentration of carbon dioxide in the atmosphere from 280 ppm in 1750 to more than 390 ppm in 2011. Climatologists predict that this change will cause an increase of the average temperature of the planet as well as regional and global and climatic changes. Other significant environmental effects of energy consumption are: the several ecological problems caused by acid rain, which has threatened in the past the ecosystems of several lakes and rivers; lead contamination of the atmosphere; nuclear waste, which is produced by the more than 430 nuclear power plants in continuous operation worldwide; and, the waste heat rejection by all thermal power plants, which is accompanied by fresh-water consumption. Environmental threats are neutralized by public policy, either national policy or concerted international efforts and protocols that are ratified by several countries. Despite the efforts of the environmental community, there is not yet a global agreement for the mitigation of the effects of high carbon dioxide concentration, which poses the principal environmental threat of the twenty-first century. The problem of nuclear waste is being addressed at several national and regional levels and it appears that solutions for the long term storage of radionuclides will become available in the near future. National public policies and international collaboration has almost solved the acid rain and lead contamination problems. The two are viewed as success stories stemming from international collaboration and successful public policy. This chapter starts with a short section on the environment and ecosystems, continues with descriptions of the most significant environmental problems that are caused by energy consumption and delineates adopted and proposed suggestions on the mitigation of environmental threats.

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2.1 Environment, Ecology and Ecosystems

The *environment* is everything that surrounds the humans and where all the economic activity occurs. The lithosphere, the atmosphere and the hydrosphere are the three distinct components of the environment. Processes and events interact in different ways with the environment. For example, a hurricane is formed in the atmosphere and encompasses water that comes from the hydrosphere. When the hurricane washes over land, it dumps to the ground very high quantities of water as rain, which causes local flooding, erodes the soil and caries it into the sea. These types of interactions produce *environmental changes,* most of which are undesirable.

Ecology is the study of the relationships of organisms with one another and the relationship of organisms to their environment. This subject incorporates principles from the scientific disciplines of biological sciences, physics, physiology, and chemistry.

The *ecosystem* is a rather loose concept that refers to a subdivision of the landscape or a geographic region that is relatively homogeneous. An ecosystem is made up of organisms, environmental factors, and physical or ecological processes. Hence, the concept of ecosystem comprises organisms, species and populations; soil and water; climate and other physical factors; and processes, such as nutrient cycles, energy flow, water flow, freezing, and thawing.

Although the two are related and are often confused, there is a clear distinction between environmental and ecological processes as well as between the environmental and ecological concerns: The ecological concerns always involve effects on ecosystems. For example, a hurricane will wash a great deal of soil into the sea and will change the coastline of an entire region. If we are only concerned with the physical process of soil erosion, the suspension sediment in the water, and its subsequent deposition on the bottom of the sea, three purely physical processes, then we have an *environmental concern*. If we are concerned about the effect of the erosion on the crops, the loss of habitat of subsurface organisms, or about the effect of the increased concentration of pesticides that accompanies soil erosion on the aquatic life, then we have an *ecological concern.*

Because ecosystems are closely connected to their environment, every environmental change has ecological consequences. The observed increase in carbon dioxide concentration and the expected global and regional climate changes are related environmental changes. Their consequences in the ecosystems include altered patterns of crop production as well as migration or disappearance of species from several regions. Similarly, the discharge of pollutants, such as dioxin or lead, on dump sites is an environmental event that has ecological consequences.[1] When one considers the effects of the pollutants on the subsurface organisms, the effects of the leaching of the pollutants in nearby aquifers, streams, or lakes and its ultimate effects on animals and humans that drink the water, then the concern is

[1] In most countries it is illegal to discharge pollutants in the environment.

ecological. Another example on the distinction of environmental and ecological effects and concerns may be made in relation to the Chernobyl nuclear power plant accident, which occurred in 1986. The steam explosions in the reactor released into the environment a great deal of radionuclides, which were accumulated in the region or were transported to other areas by atmospheric currents. As a result of run-off from the rainfall, a great deal of radioactive cesium and strontium is now physically buried in the bottom of rivers and lakes or in the subsurface of the land. These are environmental changes. The ecological effects that are consequences of these environmental changes include the mutations in the cells of living species that absorbed radionuclides via the food chain; the decimation of herds of reindeer in Lapland, which consumed grass contaminated with radionuclides; the forests with trees that have radioactive bark; and the significant increase of childhood leukemia and cancer incidents in the human populations, which were severely affected by the release of the radioactivity.

2.2 Global Climate Change

The most pressing environmental issue of the early twenty-first century is the accumulation of carbon dioxide (CO_2) and the expected global warming. Global warming has become an urgent political issue in many countries. The issue is often debated, frequently divides the experts and has affected several national elections. By the term *global warming* we define all the effects of the expected increase of the average temperature of the planet, which are due to the increase of the atmospheric concentration of CO_2 and other similar gases. The main cause of the CO_2 accumulation is the anthropogenic activities related to the fossil fuel combustion processes. All fossil fuels—coal, petroleum and natural gas—are composed of carbon and other atoms, typically hydrogen. The carbon atoms form CO_2 upon combustion, as for example in the following complete combustions of coal and methane:

$$C + O_2 \rightarrow CO_2 \quad ; \quad CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O. \tag{2.1}$$

Since humans have increasingly used the fossil fuels for their energy needs, the amount of fossil fuels that are burned annually has increased exponentially and, as a result, the average concentration of CO_2 has reached very high, almost alarming levels and is expected to increase in the near future. Figure 2.1 shows the average concentration by volume of the CO_2 in the Earth's atmosphere since the beginning of the industrial revolution. While the concentration of this gas was almost constant for centuries before 1750, at approximately 280 ppm, the concentration started rising with the increased use of fossil fuels and reached the level 391 ppm in April 2010, a 40 % increase from its historical level. It is also apparent in this figure that the rate of increase of the CO_2 concentration has accelerated in the last sixty years. The increased CO_2 concentration and its rate of growth show a very

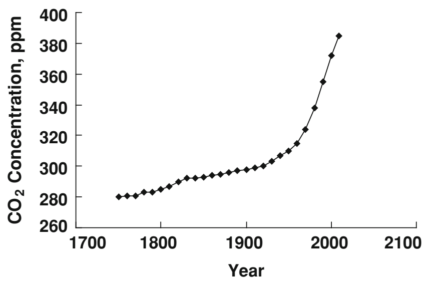

Fig. 2.1 Average atmospheric concentration of CO_2, since the beginning of the industrial revolution (data from Mauna Loa Observatory)

high correlation with the increased energy consumption by humans and, especially, with the significant increase of the combustion of fossil fuels since the 1950s, which is mainly due to the widespread adoption of personal transportation by automobile in the developed countries.

The 40 % increase of the CO_2 concentration represents a significant change in the composition of the planet's atmosphere, which is the outer "blanket" of the planet. The Earth is a complex, highly nonlinear, dynamic system, where small changes have the potential to cause significant local and global effects. Most climatologists and the vast majority of the scientific community expect that this significant change in the planet's outer "blanket" will also have a significant impact on the Earth's climate, globally and regionally as well as on human economic activities.

2.2.1 The Energy Balance of the Earth

We may consider that the atmosphere of the planet Earth is a thermodynamic system, the *system Earth,* which receives a rate of heat, $\dot{Q}_S$, primarily from the Sun, and simultaneously radiates heat, $\dot{Q}_E$ in all directions. In addition, because of the nuclear reactions that continuously occur inside the core of the planet, an additional quantity of heat power, $\dot{Q}_{\text{int}}$, is convected by magma to the surface of the planet. For this analysis, we may identify the atmospheric layer around the surface of the planet of total mass m_E, with average specific heat capacity, c_E, and average temperature T_E. For this thermodynamic system, which is schematically depicted in Fig. 2.2, one may write the energy balance equation as follows:

$$m_E c_E \frac{dT_E}{dt} = \sum_i \dot{Q}_i = \dot{Q}_S - \dot{Q}_E + \dot{Q}_{\text{int}}. \tag{2.2}$$

The Sun may be approximated as a black body, with absolute temperature, T_S, while the Earth is better approximated as a grey body with a radiation emissivity, ε_E, and absorbtivity, α_E. In a similar manner, one may approximate the conduction heat transfer from the interior in terms of an effective conductivity, k_E. Since the thickness of the atmosphere, H, is very small in comparison to the radius of the

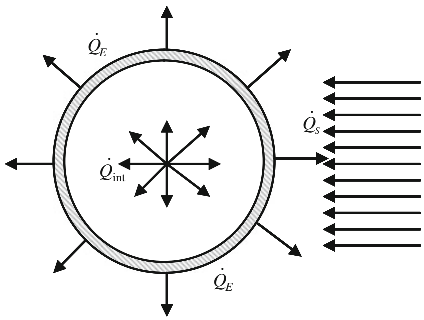

Fig. 2.2 The Earth's surface layer as a closed system and its heat balance

Earth R, that is $H<<R$, one may treat this layer as a thin layer on a sphere and then use the closure equations of radiation and conduction to write Eq. (2.2) in terms of the average Earth's surface temperature, T_E, as follows:

$$4\pi R^2 H\rho c_E \frac{dT_E}{dt} = \pi R^2 \sigma \alpha_E T_S^4 - 4\pi R^2 \sigma \varepsilon_E T_E^4 + 4\pi R^2 k_E (T_{\rm int} - T_E)/H, \qquad (2.3)$$

where all temperatures are absolute temperatures, ρ is the average density of the atmosphere, σ is the Boltzmann constant $5.67{*}10^{-8}$ W/m^2K^4, and T_{int} is the interior temperature of the Earth. It must be pointed out that Eqs. (2.2) and (2.3) are approximations. Climatologists use less restrictive assumptions, better defined averages and more complex models that include geographic regions to derive quantitative predictions for the Earth's regional temperature and climate. The above approximation is sufficient to qualitatively demonstrate the global warming, to perform simple calculations for the average atmospheric temperature, T_E, and to elucidate the climate trends associated with global environmental change.

It is apparent from the last two equations that if the three rates of heat are constant over a long period of time, the surface temperature, T_E, will reach a constant value. Then the "Earth system" will be at steady state and the temperature T_E, will not vary. However, if any parameter of the system is perturbed, one or more of the three heat rates will change, the non-linear system will undergo a transient process and will reach a new equilibrium state with a different temperature T_E'. For example, if the radiation emissivity were to decrease, the rate of heat loss of the Earth, $\dot{Q}_E$, would also decrease. If the other parameters did not change at the same time, Eq. (2.3) shows that the surface layer's temperature T_E would gradually increase until it reached a new equilibrium temperature, $T_E' > T_E$, where the sum of the three rates of heat as shown in Eq. (2.2) is again zero. In a similar manner, an increase in the Earth's average radiative absorptivity, α_E, would cause an average temperature increase, while a decrease of α_E, would cause an average temperature decrease. Such variations of the average atmospheric temperature will inevitably result in regional and global climatic changes with significant and, probably, adverse effects on the environment, the ecosystems and the human population.

It must be emphasized that, because of the very high thermal inertia of the surface layer ($m_E c_E$) the characteristic time of these changes is on the order of centuries. Therefore, the permanent changes in the average temperature, T_E, will take decades until they are accurately measured. As a consequence any warming or cooling trends that may be predicted from Eq. (2.3) and more accurate climate models will take decades to be experimentally verified and confirmed. Similarly, and because of this high thermal inertia, the effects of any corrective action humans may wish to undertake, in order to influence the Earth's surface temperature and their climate, will also take several decades or centuries to be realized.

2.2.2 The Greenhouse Effect

The Sun's light is transmitted to the Earth in a wide spectrum as will be explained in more detail in Chap. 7. A very high percentage of the energy from the Sun lies in the high frequency and short wavelength part of the spectrum (Fig. 7.2) which has a maximum at 490 nm (0.49 μm). The Sun's radiation supplies the rate of heat $\dot{Q}_S$ which provides needed energy to the planet and enables the photosynthesis and other life-supporting processes on the surface of the planet. CO_2, and other similar gases allow this high frequency part of the spectrum to pass almost unimpeded. According to the laws of radiation, the Earth also radiates energy to the universe. A qualitative difference between the radiative spectra of the Sun and the Earth is in the wavelengths or frequencies of the bulk of the spectra. This difference is explained in terms of *Wien's Law*, which relates the wavelength at the maximum radiation density, λ_m, to the absolute temperature of the radiative black body, T:

$$\lambda_m T = 0.0029 \quad mK, \tag{2.4}$$

where the temperature T is in Kelvin (K). The Sun's surface temperature is approximately 5,900 K, which corresponds to a maximum wavelength of 490 nm. The Earth's average surface temperature is close to 300 K, which corresponds to a 9,700 nm wavelength. The consequence of this is that most of the Earth's radiation is in the infrared part of the spectrum and invisible to human eye.

There are several atmospheric gases, most notably H_2O vapor, CO_2, CH_4, N_2O, and O_3, whose molecules freely absorb infrared radiation. These gases are frequently called *greenhouse gases (GHG's).* By absorbing the infrared radiation, the molecules of these gases reach higher, non-equilibrium energy states. Because individual atoms and molecules cannot exist for long at non-equilibrium states, the molecules of these gases reach equilibrium with their surroundings by imparting their excess energy to other atmospheric molecules. This is accomplished by molecular collisions or by radiating the excess energy to neighboring molecules. The net effect of this energy transfer is the warming of the other atmospheric gases and the reflection of part of the Earth's infrared radiation back to the surface of the Earth. Figure 2.3 shows in a schematic diagram this exchange of radiation between

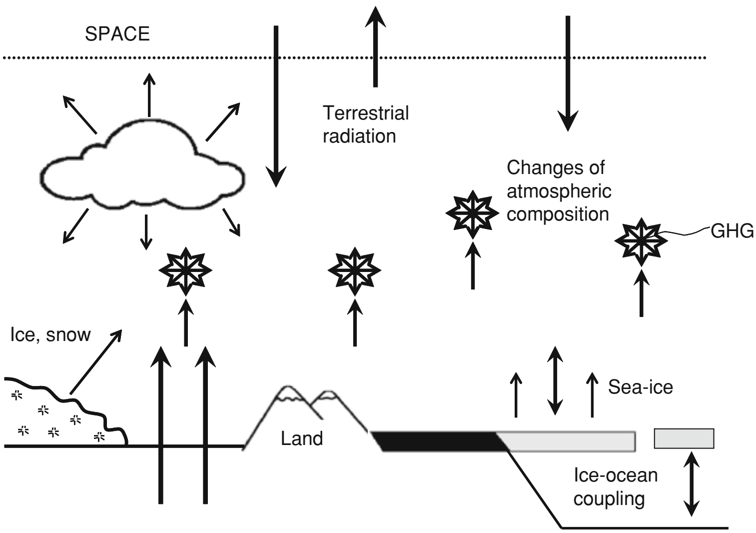

Fig. 2.3 Radiation exchange between the surface of the Earth, the atmosphere and the outer space

the greenhouse gases, the atmosphere and the surface of the Earth. The GHG's are depicted in the figure as absorbing preferentially the Earth's radiation and subsequently re-radiating it in all directions. This process results in the radiation of part of the energy back to the surface of the Earth and the atmosphere.

In terms of the simplified model described by Eqs. (2.2) and (2.3), the net effect of the presence of the GHG's is a decrease of the Earth's radiation emissivity, ε_E. This reflects a fraction of the heat rate $\dot{Q}_E$back to the surface layer of the Earth. The immediate consequence of this reflection is that the current temperature of the surface layer is higher than what would have been in the complete absence of the GHG's.

Actually, if the GHG's were entirely absent from the atmosphere, the rate of heat $\dot{Q}_E$ would have been significantly higher because the average emissivity of the Earth, ε_E, would have been much higher than its present value. Hence, Eq. (2.3) would predict a lower surface temperature T_E than the current average temperature. Accurate climatic models show that, in the absence of any GHG's, the average temperature of the atmosphere would have been approximately 33°C (59°F) lower than what it is at present. The beneficial effects of the current concentration level of the GHG's in the atmosphere are immediately apparent: without the GHG's (at their historical levels) most of the oceans and the surface waters would have frozen and the climate of the Earth would have been inhospitable to life in its current forms. Without the benign warming effect of the GHG's it is doubtful that human life would have evolved in this planet.

While the low concentration of the GHG's is necessary for the life on the planet Earth, significantly higher concentrations of these gases will have a detrimental effect to the ecology and the economic activities of the human society. The GHG's may be likened to a "blanket" around the Earth that keeps the planet warm. If this "blanket" becomes too thick, the inside temperature will increase and will cause several regional and global long-term effects that are unwanted and detrimental. The 40% increase of the CO_2 concentration in the last three centuries and, especially, the highly accelerated increase of this parameter in the last fifty years, as seen in Fig. 2.1, are causing the Earth's "blanket" to become significantly "thicker." Many climatologists and scientists as well as the Intergovernmental Panel on Climate Change (IPCC) of the United Nations have issued warnings about the uncontrolled increase of the CO_2 concentration and its consequences for the economic activity and life in our planet.

It must be noted that the term *Greenhouse Effect* is neither new nor a product of the twentieth century environmentalists. The effect was first predicted analytically by Jean-Batiste Jaques Fourier, the founder of the modern heat transfer theory, in 1824. The Greenhouse Effect was verified experimentally in the laboratory by the British physicist John Tyndall in the 1850s and was quantitatively validated for the atmospheric temperature in the 1890s by S. Arrhenius, a Nobel laureate and one of the founders of Physical Chemistry. Modern scientists and climatologists have developed sophisticated and accurate climate models to study quantitatively the Greenhouse Effect and its consequences on the planet Earth. While not all the climate models agree on the exact value of the average temperature rise, all the reliable models converge in predicting a significant average global temperature rise accompanied by significant regional changes of the temperature and severe weather changes that have the potential to disrupt the human economic activities.

2.2.3 Major Consequences of the Greenhouse Effect

The Greenhouse Effect threatens to change the entire global climate. Before we discuss the climate and its impending changes it is advisable to distinguish between weather and climate: The *weather* is the short-term product of all the complex interactions between the Sun, the atmosphere, the hydrosphere, the continents and their features, such as mountains, vegetation, and ice sheets. Weather is a short-term phenomenon that results from the temporary thermal interactions between the solar radiation, the atmosphere and the hydrosphere. The weather may be predictable over short times, e.g. a few days, but is unpredictable over long periods of time, e.g. months or years. The *climate* is the long-term result of the weather. It may be said that climate is the average weather, taken over a period of several years and decades.

The economic activities of humans have developed over the centuries based on the fact that the regional and global climate has been unaltered for millennia: For centuries one could rely on the fact that the January days in Hanover, Germany, will be exceptionally cold; the month of March in London will carry a significant amount of rain; and that July in Fort Worth, Texas, will be hot and dry. Weather may bring rain on a particular October day in the Sahara desert, but one can rely on the climatic fact that, during a given year or a given season, the rainfall in the Sahara will be significantly lower than the rainfall in the Amazon basin. Weather changes frequently, but the weather phenomena are brief and do not impact significantly the environment and the human activities. On the contrary, climate changes, whether regional or global, will affect significantly the environment, the ecosystems and the human economic activities. For example, a 2–3°C temperature increase in the American Midwest accompanied by drought will convert that area to a desert and will deprive the USA of its breadbasket. An increase of the average temperature of the Earth's surface is a *de facto* global climate change that will significantly impact all human activities and the global economy. This section enumerates some of the most important consequences of global climate change, several of which will be detrimental to the environment, the ecosystems and the lives of humans.

A. Melting of the polar ice caps: An increase of the average atmospheric temperature will result in an increase of the temperature of the Polar Regions. Actually, Global Circulation Models (GCM's) predict a higher temperature rise in the polar zones than in the equatorial and temporal zones. An immediate effect of the polar temperature rise will be the melting of part or the entire ice caps in the Polar Regions. Ice reflects 92% of the incident sunlight and the polar ice caps reflect a high percentage of the incident solar radiation. The disappearance or simply the size reduction of the polar ice caps will effectively increase the average global absorbtivity, α_E. A glance at Eq. (2.3) will prove that this will further increase T_E and will thus, accelerate the rate of global warming.

B. Sea level rise: The total or partial melting of the polar ice caps will free enormous masses of liquid water. Following the hydrological cycle, a very large fraction of the mass of this additional fresh water will eventually end in the oceans. Because water is incompressible, the volume conservation principle implies that the level of the oceans will rise to accommodate this additional mass of water. It is estimated that, if only the West Antarctic sheet ice melted, the average sea level would rise by 5 m (16.6 ft) and that if all the ice on the surface of the Earth melted, the sea-level rise would be approximately 60 m (200 ft). This will bring under water very large parts of the continents and will threaten other coastal parts with significant floods. Since, 76% of the planets population lives within 50 km from the coasts, even a moderate rise of the seal level will have catastrophic consequences on large parts of the human population and its economic activities: With a 5–10 m rise in the average sea level, not only cities such as Venice and New Orleans, which have been historically vulnerable to floods, will be underwater, but also modern and thriving economic hubs, such as New York, Shanghai, Los Angeles, Karachi and London, will be severely threatened. Large parts of the planet will become uninhabitable and close to one billion humans will need to be relocated with a 5–10 m rise of the average sea-level rise.

C. Regional climate change: The average temperature rise will be accompanied by regional temperature rises, some more significant than others. As a consequence, the climate of several regions will change. The GCM's are not sufficiently validated to make accurate predictions on regional climate changes and, for this reason, these predictions exhibit high variability. For example, model predictions, such as the development of a desert in the Midwestern and the Great Plains of the United States or of a significant rainfall in the Sahara, are not verified and may or may not materialize. However, scientific reasoning, common sense, and all the models agree that the global average temperature will increase and the regional climate will change. This will have unwelcome consequences in the agricultural and economic activities of the population, which depend on constant climate, predictable seasons and predictable rainfall.

Changes in the regional climate in combination with a sea level rise of any magnitude will disrupt the entire economic life of the planet, will necessitate the displacement of populations and will create severe socioeconomic problems. In 2005, following the hurricane Katrina, the entire world watched with horror the hardship of approximately 1 million persons who were displaced temporarily from the coastal area of the northern Gulf of Mexico. Global warming consequences may necessitate the permanent displacement of 1–2 billion inhabitants. Most of the contemporary nations and societies are not ready to respond to such dramatic consequences of global warming. There is a danger that several of today's societies and nations will crumble under the socioeconomic pressures that follow human displacements of this magnitude and that the human bonds that form the society and the nations will break and will be replaced by anarchy and destruction.

2.2.4 Remedial Actions for Global Warming

Even though all the scientific models predicted the temperature rise of the planet Earth since the time of Fourier in 1824, until the end of the twentieth century there have not been accurate measurements, independent and reliable confirmations of global warming. Reliable, scientific confirmations of the global average temperature rise came in the early twenty-first century. Most notable among them, the United Nations Intergovernmental Panel on Climate Change (IPCC) confirmed in 2007 that the average global temperature has increased during the Twentieth century by $0.74 \pm 0.18°C$ ($1.33 \pm 0.32°F$). This is a rate that is much higher than that of previous centuries. The pertinent IPCC[2] report also attributed most of the measured temperature rise to the observed increase of the GHG concentrations. These reliable and independent scientific confirmations of the global warming effect have alarmed the scientific community, which has called the global scientists and political leaders to action.

Since global warming is caused by the increased anthropogenic emissions of the GHG's, it is apparent that any mitigation of the problem is centered on the reduction of the rate of these emissions. Because CO_2 is the most abundant of the

[2] The members of the IPCC shared the 2008 Nobel Peace Prize.

greenhouse gases and because the atmospheric increase of CO_2 is the main reason for the acceleration of the global climate change in the last years, the reduction of the anthropogenic creation of this gas appears prominently in the set of remedial actions that humans will have to take. In any concerted action for the reduction of the anthropogenic emissions of CO_2, one must take into account that this is a global, not a national problem. A CO_2 molecule produced in Rome or Dallas has the same adverse effect as a molecule produced in Madras or in Beijing. For this reason the collaboration and the coordinated action of all nations is required to avert the potential adverse environmental effects of the global warming.

The *Kyoto protocol,* which was created within the *United Nations Framework Convention on Climate Change*, is an agreement reached between several nations, both developed and developing, for the reduction of the CO_2 global emissions. The protocol calls for the industrialized countries to reduce their collective greenhouse gas emissions by 5.2% from the level in 1990 and also has provisions for the transfer of energy conservation technology to the developing nations. The Kyoto protocol asked for a CO_2 reduction of 8% for the European Union countries, a reduction of 7% for the USA, 6% for Japan and 0% for Russia. The protocol has been signed and ratified by most countries, with two most notable exceptions: the U.S.A. and the People's Republic of China (PRC). While most of the signatories, and especially the European Union countries, have taken meaningful steps for the reduction of their GHG emissions, between 1997 and 2010, the USA has actually increased its emissions by 16% and the PRC by 130%. Because according to the provisions of the protocol, most developing countries did not have to reduce their own GHG emissions, this international agreement has only had a symbolic and not a real impact on the anthropogenic CO_2 and GHG global emissions. Simply, the Kyoto protocol was ineffective and the GHG concentration in the atmosphere has continued to increase at an alarming rate.

Since the beginning of the twenty-first century it has become apparent to the scientific community that a more concerted, stringent and inclusive global effort is necessary for the actual and meaningful reduction of GHG global emissions. The following list includes some of the actions individual nations and the global community may take to, first, reduce the growth of CO_2 emissions and, secondly, to reduce the actual concentration of the gas in the atmosphere.

1. **Reduction of energy consumption per capita**: this is the first of the actions the global community may take to at least reduce the growth of the CO_2 emission, especially in the wealthier, developed nations. This is the best, most inexpensive and most feasible alternative to counteracting global warming and may be simply accomplished with energy conservation and higher efficiency.
2. **Sequestration of CO_2 at the production sites, that is at the power plants, and subsequent storage**: while there is current technology and several proven and reliable methods for CO_2 sequestration, most sequestration methods involve the liquefaction of this gas, all the methods necessitate the use of large amounts of energy and, hence, are intrinsically very expensive. The cost of carbon sequestration on the price of the produced electric energy is significant:

estimates for coal power plants range from 130 to 230% higher electricity prices and those for natural gas power plants are in the range 40–90%. In addition, the safe, long-term storage of the produced CO_2, in liquid or superctitical form, may not be feasible with today's technology. Reliable, long-term CO_2 storage in the deep ocean, in depleted oil fields and in coal seams has not been demonstrated to be feasible during the time-frame required for the effective carbon sequestration, which is in the range of 1,000 to 5,000 years. It would be an environmental calamity if the CO_2 that is stored in 2015 starts leaking in 2020 through cracks in the geological formation that will be called "CO_2 Geysers."

3. **Substitution of coal with nuclear fuel for the production of electricity**[3]: While this is technologically feasible, nuclear energy has its own environmental problems, most notably the long-term storage of nuclear waste. At present, lack of nuclear reactor know-how and lack of safety standards in some developing countries make this option a very risky solution for the global environment. A concerted international program that would involve nuclear technology transfer to developing nations as well as international oversight of the nuclear reactors on a global scale would be a viable long-term solution for the reduction of the GHG emissions as well as for the reduction of other pollutants that emanate from the combustion of fossil fuels.
4. **Reforestation**: this process always removes some of the CO_2 from the atmosphere. While reforestation is always good for the regional and global environment, its impact on the atmospheric CO_2 concentration is very weak, because of the large magnitude of the daily CO_2 emissions. For example, it will take 8,900 fully grown pine trees to remove the CO_2 produced by a single 400 MW coal power plant during a single day. This plant requires 1,000 MW of heat input or $8.64 * 10^{10}$ kJ of heat per day. The latter is produced by the consumption of 2,637 tons of carbon and is accompanied by the production of 9,669 tons of CO_2. Similarly, it will take 8 fully grown eucalyptus trees to remove the CO_2 emissions caused by the engine of a single sport utility vehicle (SUV) which runs for 15,000 miles. Clearly, while reforestation is a desired activity and beneficial to the environment, it does not substitute for all the fossil fuels our society currently uses.
5. **Seeding large ocean regions with iron and nitrogen-rich fertilizer:** this will promote the rate of CO_2 absorption by biological organisms that form more complex organic compounds. While this may be an option on paper, the alteration of the ecological function of large tracts of the ocean will also produce many undesirable effects, such as eutrophication (abundance of organic food for all organisms), which leads to water hypoxia (low dissolved oxygen levels) that cause the death of fish and larger sea life.

[3] The USA would have been in compliance of the Kyoto protocol, in the first decade of the twenty-first century, if it simply diverted 15% of its electricity production from coal producing units to nuclear power plants. This would have been achieved with the construction of approximately 56 new nuclear power plants.

6. **Higher use of renewable energy sources:** such as solar, wind, hydraulic and geothermal energy not only for the production of electricity but also for other societal tasks, such as the heating of buildings, clothes drying, etc. Most of these energy sources are abundant in the developed as well as the developing countries and their increased use will alleviate the consumption of fossil fuels for energy production. Reliable and economical methods for energy storage will benefit significantly the increased use of these energy sources, which are to a great extend benign to the environment.

2.2.5 The Failure of the Copenhagen Summit

A very much advertised United Nations environmental summit took place in Copenhagen, Denmark during December 2009.[4] In the years leading to the summit, the environmental community developed the noble hope that the world leaders will finally adopt environmental principles and will take formal and legally binding measures to implement some of the actions, which were enumerated in the previous subsection and which are needed for the aversion of a major global environmental catastrophe. It is unfortunate that the entire world population became spectators of a well-orchestrated, politically-driven and acrimonious spectacle, where nothing of substance for the environment was achieved. Several reasons contributed to this, among which are the following:

1. The debate on global warming has been framed in many countries, including the EU and the USA, as a debate of "personal belief" rather than as an indisputable effect of well-researched scientific causes, supported by long-term scientific observations. There is still a great deal of dispute on the dependability of scientific predictions on global warming among many in the political circles and the news media. The immediate result is that several global powers do not espouse the idea that hard decisions and strict measures need to be taken for the "beliefs" of other people or nations.[5]
2. The 2008–09 severe global economic recession has diverted a great deal of the attention from remedies for the global warming to the economic realities of high unemployment and lower GDP in most nations. At the national levels, global environmental concerns were relegated to secondary issues in favor of

[4] A subsequent summit that took place in Cancun, Mexico in December 2010 was not attended by any world leaders. Its activities were largely symbolic and did not result in anything definitive, substantial or committing for the climate change.

[5] The scandal, which erupted from the unfortunate revelation of hundreds of "tongue in cheek" e-mail messages from environmental scientists at the East Anglia University, England three weeks before the summit, created confusion and doubts on the immediate need for action among many political leaders and citizens. It also fueled the objections of the opposition to remediation efforts.

national economic stimulus packages, which usually result in increased economic activity and higher levels of GHG emissions.

3. During the three months leading to the summit, it became apparent that the preliminary multilateral environmental negotiations, which were taking place for a couple of years, have failed to produce the political framework of a solution that would be acceptable to even a simple majority of the participating nations. The restrained tone of national announcements and press communiqués and the downplaying of the expectations set the eventual tone of the summit's failure.
4. On the OECD side, the leaders of the European Union and the North American countries came to the summit with other more important issues at home among which were the consequences of the global recession, high unemployment rates and overall citizenry dissatisfaction. Especially in the USA, during the summit, the attention of the government was at the economy and the impending passage of a health care legislation on which the national administration had spent a great deal of its influence and political capital.
5. On the side of the developing nations, there was an obvious linkage between economic aid, economic development and environmental action. With daily statements in the press and a short-duration walkout during the last days of the summit, the delegates of several African countries made it clear that, as a result of any agreement on the environment and global climate change, they expected increased economic aid from the developed nations, which was not apparently forthcoming.
6. China and India, two developing nations that have made great strides towards industrialization in the first decade of the twenty-first century and account for most of the growth rate in carbon emissions have refused to make any binding concessions for the long-term reduction of CO_2 emissions. In the absence of realistic concessions from these two countries with the highest growth rates of CO_2 emissions, the leaders of other nations were reluctant to make commitments that would appear to be unilateral.

The failure of the Copenhagen summit notwithstanding, the environmental threat from increased carbon dioxide concentration and the impending global climate changes are realistic and imminent. What is at stake here may be the continuation of human civilization as we know it. Action in national and international fora is needed and taking remedial measures is essential before changes become irreversible. The scientific and engineering community must play a leading role in the arena of global change by doing the following:

(a) Continuing to make accurate global measurements;
(b) Communicating these measurements and the pertinent conclusions to the public in an unbiased and honest (that is, scientific) manner;
(c) Developing reliable measures of accountability for GHG emissions;
(d) Developing methods and building meaningful engineering projects for the mitigation of the adverse effects of the global climate change;

(e) Improving the efficiency of power production plants and internal combustion engines; and
(f) Continuing the research and development efforts on alternative sources for energy that would reduce and would finally nullify the global GHG emissions.

2.3 Acid Rain

Acid rain or acid precipitation is the return to the terrestrial aquatic environment of the oxides of carbon, nitrogen and sulfur in an acidic form. Acid rain is closely related to the combustion of fossil fuels. Fossil fuels, and especially coal, contain large quantities of sulfur which forms SO_2 upon combustion. In addition CO_2 and a series of nitrogen oxides with the general formula NO_x (or, commonly, NOX) are formed during coal combustion. These oxides combine with water vapor in the atmosphere to form mild acids. For example the hypo-sulfuric and the carbonic acid, two weak acids, are formed in the atmosphere by the following reactions:

$$\begin{aligned} &SO_2 + H_2O \rightarrow H_2SO_3 \text{ and} \\ &CO_2 + H_2O \rightarrow H_2CO_3. \end{aligned} \tag{2.5}$$

Atmospheric SO_2 may also combine with ozone first and then with water vapor, to form the much stronger sulfuric acid:

$$SO_2 + O_3 \rightarrow SO_3 + O_2 \text{ and } SO_3 + H_2O \rightarrow H_2SO_4. \tag{2.6}$$

In addition, the several NO_x compounds that are formed during the combustion processes may also combine with water vapor in the atmosphere and finally form the weaker nitrous acid (HNO_2) or the stronger nitric acid (HNO_3) thus making NOX a contributor to acid precipitation.

Typically the acidic chemicals in the atmosphere are formed within small droplets or on the side of very fine particles, which are called aerosol particles. The sizes of these droplets and particles are in the submicron range. This implies that they settle extremely slowly and, may remain airborne in the atmosphere for weeks or months following the air currents and turbulence. During rain or snow precipitation, the aerosols combine with the larger rain drops or snow flakes, precipitate faster on the ground and, thus, are removed from the atmosphere. The rain or snow runoff, which eventually feeds rivers and lakes, contains higher concentration of the acids and for this reason it has been called *acid rain, acid snow* or in general, *acid precipitation.* In the aquatic environments, H^+ ions are released from these acids according to the following chemical reactions:

$$\begin{aligned} &H_2CO_3 \rightarrow H^+ + HCO_3^- \\ &H_2SO_3 \rightarrow H^+ + HSO_3^- \\ &\text{and} \quad H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}. \end{aligned} \tag{2.7}$$

As a consequence of acid precipitation, the concentration of the H^+ increases significantly and the pH of these bodies of water drops from its natural range of 6.8–7.4 to significantly lower values. Some of the more dramatic acid precipitation observations are listed below [1]:

1. A storm in Scotland in 1974 dropped rain with pH 2.4.
2. The pH of rain in Kane, Pennsylvania on September 19 1978 was 2.32. This is lower than the pH of vinegar.
3. For the entire year of 1975, rains in Norway and Sweden recorded pH less than 4.6.
4. During the 1970s the pH of 80% of drizzles in Holland was less than 3.5, and sometimes as low as 2.5. This is the pH of common vinegar.

The drop of the pH has significant adverse effects on the ecosystems of the rivers and lakes, because many animal species cannot survive at these low (as well as very high) pH levels. As a result, several of the species may disappear, either because of the direct effect of a lower pH or because of lack of nutrients. The low pH resulting from acid deposition decimated the fish population in several lakes in the 1970s and 1980s. In addition, high acidity precipitation rendered the soil acidic with a significantly adverse effect on crops as well as on forests. Some of the environmental and ecological effects of acid precipitation are:

1. As the water of the streams becomes more acidic, a shift to acid-tolerant plants occurs, such as green algae.
2. Acid sensitive species, such as snails, clams and amphipods disappear.
3. Higher concentrations of Al^{3+} and other metal ions are observed. These ions damage the gills of fish and also enhance the precipitation of dissolved organic matter in the water, which is a source of food for fish. With decreased food supply, fish become emaciated or die.

These causes had a catastrophic effect on the aquatic populations of most rivers and lakes in northern Europe and North America. For example, salmon in several Norwegian rivers did not reproduce for years and became almost extinct. Also the fish disappeared from 190 lakes in the Adirondacks, Canada and more than 2,000 lakes in southern Norway.

What accentuated the environmental problems of acid deposition is that, in most cases, the production of SO_2 and the other oxides actually occurred in other, neighboring countries. The oxides or the acid laden aerosols are carried by the air currents over international boundaries and affect neighboring nations. Given that most of the economic activity of the world is produced in the northern latitudes between the 30th and the 60th parallels, where the predominant winds are south-easterlies—directed from southeast to northwest—acid rain produced in countries to the South was deposited in countries to the North. Thus, the acid oxides produced in Ohio and Michigan affected the lakes in the Ontario Province, Canada, while acid oxides produced in the industrial Ruhr of Germany affected the aquatic environment of Holland and Scandinavia. Pollution does not respect national boundaries and, when it occurs it becomes an international issue.

A concerted international effort to mitigate acid rain started in the 1970s and continued in the 1980s and 1990s with great success. Despite the protests of the coal industry and several electricity generating corporations, one after another, national governments enacted regulations to limit the emissions of SO_2. In the United States a goal was set to reduce the SO_2 emissions to less than 9 million tons per year by 2010. The Environmental Protection Agency (EPA) incorporated this program in an amendment to the *Clean Air Act*[6] and developed a market-based initiative to achieve the reduction of SO_2 emissions. This amendment sets annual upper limits (caps) for the emissions of SO_2 for all polluters and issues permits to these companies, which are called *annual allowances.* The *allowances* are consistent with the overall goals for the national reduction of the emissions. Corporations that exceed their targets may trade their *allowances* to others that do not meet their own goals. This is the so-called *cap and trade program*. It creates a market incentive for corporations to exceed their own goals and trade the differences of their annual allowances to others for a profit. The sulfur cap and trade programs have been immensely successful in Europe and North America, where the 2010 reduction goals were met before 2007. As a result, in the beginning of the twenty-first century, acid deposition has dropped by two-thirds from its peak and it is not any more the environmental and ecological threat that was in the 1980s. Because of this resolute international action, the ecosystems in most of the affected lakes, rivers and forests have recovered.

The strategies for compliance with the reduced SO_2 emission standards varied among countries and corporations. These strategies affected the choice of fuel for the production of electricity, implementation of new technologies for the removal of SO_2 and the location for the construction of new power plants. In the USA and the European Union the principal technical approach that was used to reduce the SO_2 emissions has been flue gas desulphurization (FGD) that removes SO_2 from the stack gases by scrubbers before they are discharged to the atmosphere. A FGD process is shown in Fig. 2.4. SO_2 laden gas enters the scrubber, where it is "showered" by a basic water solution, typically a limestone-water solution that contains the basis chemical of calcium hydroxide, $Ca(OH)_2$. The SO_2 is absorbed by the water to first form hypo-sulphuric acid as in Eq. (2.5) and then the weak acid reacts with the basis in the water solution to form calcium carbonate:

$$\begin{aligned} &SO_2 + H_2O \rightarrow H_2SO_3 \text{ and} \\ &H_2SO_3 + Ca(OH)_2 \rightarrow 2H_2O + CaSO_3. \end{aligned} \tag{2.8}$$

$CaSO_3$ is a solid that precipitates. It is subsequently removed from the water and, since it is not a pollutant, it is buried or disposed of.

[6] The Clean Air Act of the U.S.A. was enacted in 1963 and significantly amended in 1970 and 1990. The NO_x emissions problem was tackled by the 1990 amendment.

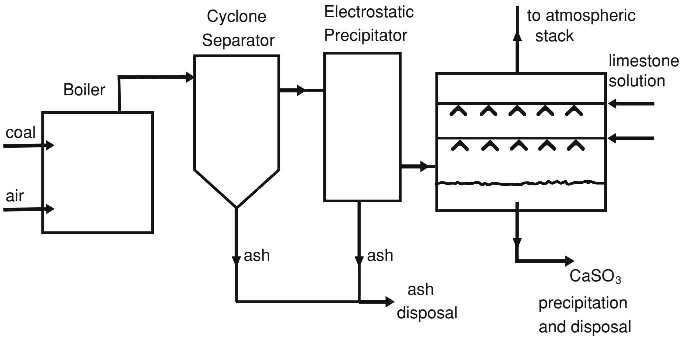

Fig. 2.4 The flue-gas desulfurization process

Some of the other methods that have resulted in the significant reduction of the SO_2 emissions are:

1. Using Fluidized Bed Reactors (FBR) in new plants, which employ limestone particles *in situ* to remove SO_2 during the combustion by converting it to solid $CaSO_3$.[7] The latter is removed with the solid materials of the ash.
2. Blending high-sulfur coal with low-sulfur coal.
3. Switching coal fuel to natural gas, or a mixture of coal and natural gas.
4. Retiring old electricity generation units and replacing them with FBR's or units with SO_2 scrubbers.
5. Purchasing or transferring emissions allowances from other units.
6. Increasing the demand-side management and conservation efforts to reduce the electric power consumption.
7. Power purchases from other utilities or non-utility generators that use low-sulfur coal or other fuels.

The acid-rain reduction programs that were implemented in Europe and North America have been an overwhelming environmental success. Figure 2.5 shows the dramatic drop of the emissions of SO_2 and NO_x in the U.S.A. as a result of the implementation of the Clean Air Act. It is apparent in this figure that the SO_2 emissions dropped to one-third of their values in the 1970. The significant reduction of the NO_x started after the 1990 amendment to the Clean Air Act and the emissions of this pollutant dropped to 60% of their values in 1990. More encouraging is the fact that the recent slope of the two curves is significantly negative, which implies that the emission reduction of the two pollutants will continue in the near future. Not only the long-term goals of the programs were achieved ahead of the deadlines, but also the costs of the programs' implementations to the businesses and the consumers were significantly lower than the

[7] In a FBR the SO_2 comes in direct contact with particles of $Ca(OH)_2$ and reacts as: $SO_2+Ca(OH)_2 \rightarrow CaSO_3+H_2O$. The solid $CaSO_3$ is removed with the ash.

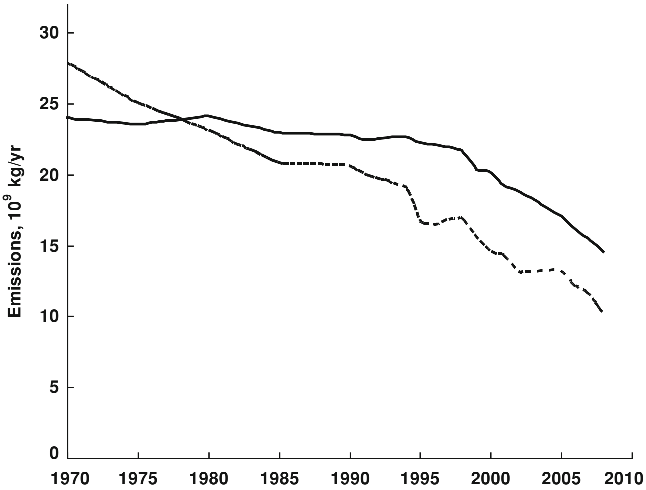

Fig. 2.5 Emission reductions of SO_2 (dashed line) and NO_x (solid line) in the USA

original predictions. It is estimated that, in the USA, the total cost of the SO_2 emissions reduction implementation strategies was in the range \$1 billion to \$2 billion. This is only one fourth of the original estimates by the coal industry and, most important, it did not cause any disruptions in the electric power production. By the concerted efforts of the international community, the detrimental environmental effects of acid rain have been mitigated and remediated in a short time at a very small cost to the electricity generation industry and the population.

2.4 Lead Abatement

Gasoline and diesel are mixtures of liquid hydrocarbons. While the diesel-air mixture in the diesel engines is designed to ignite by itself at the end of the compression stage, when high temperature is reached, the gasoline-air mixture is designed to ignite during the ignition stage by a spark. Because high temperatures are achieved during the compression stage, several of the hydrocarbons in the gasoline liquid mixture reach their own ignition point, auto-ignite and release heat prematurely. This has led to the "knocking" problem in gasoline engines where auto-ignition has caused premature engine detonation, severe vibrations, low cycle efficiency and subsequent engine damage.

Auto-ignition in gasoline engines may be prevented by chemical additives, the most common of which is tetra-ethyl lead, $Pb(C_2H_5)_4$. Tetra-ethyl lead, when added to the gasoline, prevents engine knocking and engine damage. The use of this chemical compound was widely adopted by the refining and automobile industries as an "anti-knock" additive to the gasoline in the early twentieth century. However, the $Pb(C_2H_5)_4$ burns with the fuel and its combustion releases lead oxides, primarily PbO and Pb_2O, as well as atomic Pb, to the environment. These chemicals were proven to be harmful to the health of the population. Lead compounds affect the synapses in brain cells, especially those of children. Prolonged exposure to lead has been proven to cause mental retardation and brain disorders.

The lead compounds are also incompatible with several types of catalytic converters and reduce significantly the useful life of these converters. For this reason, during the 1970s, regulations were enacted in all OECD countries to phase out the use of $Pb(C_2H_5)_4$ from gasoline additives. In addition other lead compounds were phased out from other commonly used materials, such as paints. In the USA and the countries of the European Union the sale of leaded fuel for automobiles has been completely banned since the 1990s, but it is still allowed for marine engines, racing cars and certain farm equipment. Most of the other countries have followed suit by 1990 and $Pb(C_2H_5)_4$ has now been replaced by other additives, typically made by aromatic hydrocarbons. Only in a few countries of South America, Asia, some of the countries of the former Soviet Union and the Middle East, leaded gasoline is still in use. Even in these countries emerging environmental regulations significantly restrict its use. It is anticipated that by 2020 the use of leaded gasoline will be banned globally. The restriction and ban on leaded gasoline, as well as leaded paint, resulted in millions of tons of lead not being released in the environment. The immediate effect was the lowering of lead in the human bloodstream, especially in children. This is expected to become the means to better public health, lesser neurological disorders and significant improvements of the quality of life.

The vast reduction of the acid rain environmental effects and the reduction of the lead concentration in the blood stream of humans are two significant environmental developments of the late twentieth century. Both took a great deal of effort by various citizen and scientific groups to bring to the attention of the public and, finally, to translate this attention to regulations and national legislation. Several years after their implementation, there is no doubt that their effects have been beneficial to the environment and to the public health and that there are very few individuals who would like to see these measures reversed. While at the start, the affected industries resisted the adoption and implementation of the measures to curb Pb and acid rain using the argument that the cost of energy and gasoline would rise significantly and that the general population would suffer economically, both measures were implemented at a fraction of the cost that was originally predicted by the industry. Furthermore, this cost was absorbed very well by the market and the consumers with no apparent regional and global economic effects. For example, SO_2 abatement methods only reduced the overall efficiency of modern coal-fired power plants by only 1–1.2%. This was counteracted by the use of new materials and processes that resulted in an actual increase of the overall efficiency of the modern electric power plants.

Similar arguments are currently used against measures to curb the global warming by reducing the GHG emissions. The success stories of lead and acid reduction convey optimism that, despite the resistance of the fossil fuel industry and some electric utilities, a significant reduction of GHG emissions will be achieved in the near future without an undue economic disruption.

2.5 Thermal Pollution and Fresh-Water Use

Thermal power plants reject a great deal of energy to the environment in the form of low-temperature heat. All processes in these power plants are subjected to the Second Law of Thermodynamics and, as a consequence, the power plants must reject a great deal of heat to their condensers and through their cooling system to their surroundings (Sect. 3.5). A typical 1,000 MW fossil fuel plant has an overall efficiency close to 40%. It receives 2,500 MW of heat power, of which 1,000 MW are converted to electric power and the remaining 1,500 MW are rejected to the environment. These numbers are slightly different for a typical nuclear power plant, which has an overall efficiency close to 33%. The reactor of this plant would produce approximately 3,000 MW of heat, of which 1,000 MW are typically converted to electricity and 2,000 MW are rejected as waste heat to the environment. These vast amounts of heat power are rejected at low temperatures, typically in the range 30–45°C and may not be used for any practical applications.

A common misconception, even among engineers, is that the waste heat from a power plant may be somehow used for the production of more power. This is impossible: The power plant is designed to produce the maximum possible amount of energy and any heat that needs to be rejected is a consequence of the Second Law of Thermodynamics. The waste heat is at such a low temperature that it is not possible to be of further use for the production of power. Small quantities of this waste heat may be used for heating buildings, for aquaculture or for agricultural purposes (heating of the soil to produce a higher yield). However, economic considerations limit significantly the amount of waste heat that is utilized. Several possible uses of the waste heat from power plants and the overall potential of waste heat utilization are discussed in Sect. 13.2.4.

The annual global electricity production from thermal power plants is approximately 17,500 TWh, which is equivalent to $63*10^{15}$ kJ. At an average efficiency of 35% these power plants reject $117*10^{15}$ kJ to the environment. The rejection of this quantity of heat to the environment is the total *thermal pollution* due to the power plants. An additional part of the thermal pollution is produced from the transportation industry as exhaust heat from automobiles, ships and airplanes. The thermal pollution energy is by all means a vast amount of energy that is released to the environment and causes concerns among some environmentalists. However, it must be noted that the waste heat is only a minor fraction of the total energy that enters the earth's atmosphere from the sun or the energy that is radiated from the earth itself. The annual energy received from the sun is equal to $5.46*10^{24}$ kJ and the annual amount of heat radiated by the earth is of a comparable magnitude. Both of these quantities by far surpass the total waste heat rejected annually by all the power plants on the planet. For this reason, the waste

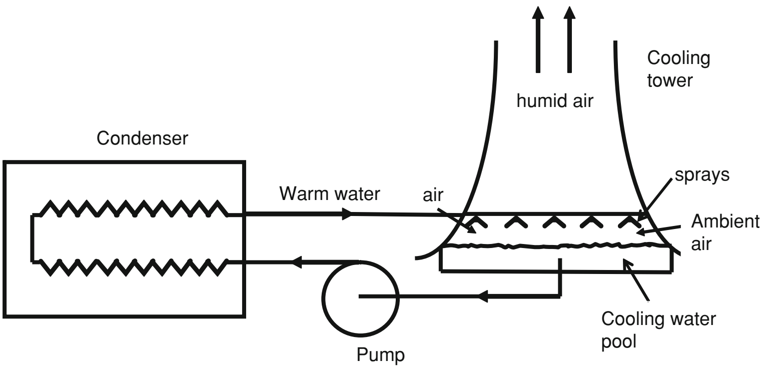

Fig. 2.6 The cooling system of a thermal power plant

heat rejection by power plants does not contribute in any sizable measure to the global warming and does not pose a threat to be such a contributor in the near future. Actually, the calculated rate of heat that is absorbed and diffused in the atmosphere by the GHG's is higher than the entire waste heat production caused by anthropogenic activities by several orders of magnitude.

Their insignificant contributions to global warming notwithstanding, thermal power plants and the environmental heat rejection processes make a significant claim on the fresh water resources of the planet. Heat is rejected primarily from the condensers of power plants, which are cooled by a closed or open circuit of *cooling water*. The process is shown schematically in Fig. 2.6. Relatively cold water enters the condenser, removes the waste heat and then enters a wet cooling tower, where part of it evaporates and cools the rest. The colder water from the cooling tower is directed back to the condenser (Chap. 3). The cooling process uses very high amounts of fresh water, because the temperature rise, ΔT, between the colder and the warmer is typically of the order of 5°C. A heat balance in the condenser yields the following equation for the rate of waste heat rejection $\dot{Q}_{wh}$:

$$\dot{Q}_{wh} = \dot{m}_{cw} c_p \Delta T, \tag{2.9}$$

where $\dot{m}_{cw}$ is the mass flow rate of the cooling water that is needed and c_p is the specific heat capacity of water, 4.18 kJ/kgK. A quick computation proves that a typical nuclear power plant, which rejects 2,000 MW of heat through a cooling tower, would need close to 95,000 kg/s of water. If instead of a cooling tower the nuclear power plant rejected this rate of heat to a river or a lake, the maximum ΔT would be 2.7°C and the actual need for cooling water would be close to 176,000 kg/s.[8]

[8] This is the reason why large thermal power plants are usually built close to a natural source of fresh water, a river or a lake. In the USA, 42 of the 103 nuclear power plants in operation are located near the banks of the Mississippi river or one if its larger tributaries. 85% of the nuclear power plants in France are located at the banks of the Seine, the Loire and the Rhone rivers.

It must be emphasized that only a small fraction of the water used in the cooling system evaporates. The latent heat of evaporation, h_{fg}, of the water is approximately 2,400 kJ/kg. Assuming that all the waste heat, $\dot{Q}_{wh}$, is released to the environment solely by evaporation, the amount of water that evaporates, $\dot{m}_{ev}$, is given by the expression:

$$\dot{Q}_{wh} = \dot{m}_{ev} h_{fg}. \tag{2.10}$$

Therefore, a nuclear power plant that rejects 2,000 MW of heat will also cause the evaporation of approximately 833 kg/s of water in its cooling tower. This is equivalent to 72,000 tons per day, by all means a significant amount. Even the power plants that do not use cooling towers, but instead draw their cooling water directly from rivers and lakes in the "once-through" cooling systems, will cause significant water evaporation: The evaporation occurs because the water, which is returned to the river or the lake, is at an elevated temperature, typically 2–3°C higher. The partial pressure of warmer water is higher and, therefore, it evaporates faster. In the long run, the river or the lake will attain their equilibrium temperature by the evaporation of additional amounts of water. On average, approximately 1 kg/s of water is evaporated for every 1 MW of electric power produced by a thermal power plant. This is equivalent to 1 gallon of water per kWh produced.

Fresh water availability for the production of electric power is fast becoming an environmental issue in the twenty-first century. Even though 71% of the surface of the planet is covered by water, only 3% of the water on the planet is fresh water and 90% of it, or 2.7% of the total, is in the form of ice glaciers and underground water aquifers. The remaining 0.3% of the total water of the planet is fresh water in lakes (87%) swamps (11%) and rivers (2%). While the availability of fresh water was not a significant issue in the previous centuries, it is becoming a significant environmental and political issue in the twenty-first century. With the rise of the planet's population and the desired increase of the standard of living in all countries, there is a higher demand of fresh water for agricultural and domestic uses. Large water consumers, such as large thermal power plants, must compete for this resource, which is becoming scarce in several parts of the planet, as for example in the southwestern part of the USA and several regions of Asia and northern Africa. In the near future, the human society will have to make hard decisions on how to better allocate this precious resource among nations and among competing users. Alternative energy sources for the production of electricity are very promising in this regard, either because they do not need cooling (photovoltaics, wind, hydroelectric, tidal, etc.) or because they produce sufficient water for the needs of their own cooling systems (geothermal).

2.6 Nuclear Waste

The transportation and storage of the waste materials produced in the nuclear power plants around the world is a significant global environmental threat because the uncontrolled release of radioactive compounds is harmful to all living animals

Table 2.1 Nuclear waste isotopes and their characteristics

Isotope	Half-life (yrs)	Radioactivity (Bq)
Americium-231	433	$11.84*10^{10}$
Americium-234	7,900	$0.7*10^{10}$
Iodine-129	17,000,000	$5.9*10^{6}$
Plutonium-239	24,400	$0.23*10^{10}$
Plutonium-240	6,600	$0.81*10^{10}$
Technetium-99	210,000	$6.29*10^{8}$

on the planet. In 2009 there were 439 operating nuclear power plants in the world, 103 of which operated in the USA. Heat in a nuclear power plant is typically produced by the fission of the nuclear fuel, primarily uranium-235 and plutonium-239. The fission of the radioactive materials produces other isotopes, some of which are radioactive. Since the typical reactor is a closed system, the entire radioactivity remains inside the reactor until the next refueling period. During refueling, the spent fuel and fission products are removed from the reactor and stored temporarily, within the confines of the nuclear power plant. These materials constitute the *nuclear waste* from the reactor. Similar nuclear waste materials are produced in fuel reprocessing and fuel enrichment facilities. Table 2.1 shows some of the isotopes that are present in nuclear waste, their half-lives, in years, and the level of radioactivity in Becquerel, Bq, or disintegrations per gram per second. More details on the half-lives of isotopes and the theory of nuclear reactions and nuclear power plants are given in Chaps. 4 and 5.

It is apparent from Table 2.1 that nuclear waste will continue to be radioactive and will pose a health threat to the human population for millennia. For this reason permanent storage facilities must be constructed that will be capable to store the radioactive waste for thousands of years, until the eventual residue does not pose a public health threat. This presents a significant scientific and engineering problem, simply because of the timescale of the storage. There is not a proven and reliable method for the storage of such materials during the thousands or tens of thousands of years required for remediation of the nuclear waste materials. Any accidental or intentional (e.g. by an act of terrorism) release of radioactive materials from these sites may render whole regions uninhabitable.

The safe and permanent storage of nuclear waste is an environmental issue of paramount importance to the nuclear industry. However, the populations and governments of several countries, including the USA, have not come to grips with the magnitude of this problem and have not prepared permanent storage facilities for the nuclear waste that has been produced since the 1950s. At present, the nuclear waste is typically stored in temporary facilities in the vicinity of the power plant that produced the waste. A typical temporary storage facility is a water pool, where the nuclear waste is immersed. The heat produced by nuclear disintegrations is convected to the water of the pool, which is maintained at almost constant temperature by evaporation. Make-up water replenishes the evaporated water in the pool. These storage arrangements are temporary, mostly unsecured and pose a threat to the surrounding communities.[9] Permanent disposal of nuclear waste in safe and controlled sites will reduce significantly this environmental concern.

An environmental concern that needs to be addressed before the public accepts the reliability of sites for the long-term storage of radionuclides is the long-term structural integrity of the containers and compartments, where the nuclear waste is stored. Metal or composite tanks corrode, develop cracks from where leakage may occur and, in general deteriorate to the point that they are unsuitable to contain the nuclear waste. The release of heat from the decaying radionuclides only accelerates the deterioration of the containers. The further decay of the radionuclides in the nuclear waste and the reduction of radioactivity to natural levels occur after 10,000 to 1,000,000 years. At present, there is no known storage material that may be reasonably expected to preserve its structural integrity and keep the nuclear waste confined for such long periods of time. For this reason, the proposed nuclear waste management processes involves several stages and processes, of which the most important are summarized in the following sections.

2.6.1 Initial Treatment of the Waste

An initial treatment helps reduce the volume and radioactivity of the waste, while the waste is located in a controlled environment and the heat generated is removed in a controlled manner. Methods for the initial treatment are:

1. *Vitrification*, or *glassification* of the waste. The nuclear waste is mixed with sugar and heated until all the water and nitrates in it are evaporated. The mixture is then combined with glass and further heated until the glass melts. This melt is poured into stainless steel containers, where it solidifies and forms a glass-like substance, that is, "it vitrifies." The vitrified substance is then stored in a steel cylinder. Vitrified materials are very stable. They are hard, water resistant, have very low erosion or chipping and are believed that they are capable to last unaltered for thousands of years.
2. *Concentration* of the waste. The volume of the nuclear waste may be reduced by concentrating it into a smaller volume, which may be disposed of or stored better and more economically. Flocculation (concentration of fine particles) with ferric hydroxide is often used to remove highly radioactive metals from aqueous solutions. After the removal of these isotopes, the resulting low-level radioactive materials are stabilized and immobilized by mixing with ash and cement to form concrete. The low radiation levels of this concrete do not pose any threats to the environment or the population and may be stored anywhere.

[9] The 2011 nuclear power plant accident in Fukushima Dai-ichi, where the stored nuclear waste was exposed and contributed significantly to the environmental pollution underscores this environmental problem.

3. *Synrock* is a complex chemical material of nuclear waste stabilization. Synrock consists of hollandite ($BaAl_2Ti_6O_{16}$), zirconolite ($CaZrTi_2O_7$) and perovskite ($CaTiO_3$). The zirconolite and perovskite become hosts and immobilize the actinide elements, that is elements with atomic number higher than 89, such as uranium and plutonium. The radioactive strontium and barium, which are produced in nuclear reactors, are also trapped and immobilized in the perovskite, while the hollandite immobilizes the caesium and similar lighter metals.

2.6.2 Long-Term Disposal

Immobilization stabilization or simply immobilization is the first stage in nuclear waste management. The long-term disposal of the nuclear waste includes the following suggestions:

1. *Geologic disposal,* either in deep and stable formations on the earth or in the deep sea. The proposed *Yucca Mountain* repository in the United States and the *Schacht Asse* repository in Germany, which operated briefly in the 1990s, are two examples of such ground disposal sites. These repositories are typically in stable, arid geological formations, where water leakage will not be a problem in the future. One of the impediments for permanent geologic disposal is the legal problem of *stewardship cessation* of the materials. This legal term implies the shifting of the burden for the safe maintenance and perpetual management of nuclear waste from the producer to the one who undertakes the storage. The latter is typically the government or a smaller receiver corporation, which does not have the financial resources to guarantee stewardship in the long term and to compensate for damages that may potentially be incurred. Several environmentalists do not believe this is prudent and recommend perpetual management and monitoring of the waste by the producer.
2. *Transmutation* implies the transformation of radionuclides to other materials that are not radioactive. Special nuclear reactors will be needed for the transmutation processes. In the United States research activity on the transmutation has ceased since the late 1970s because plutonium is a byproduct of the process. Since plutonium is used in atomic bombs, its production raises concerns of atomic weapon proliferation. Relevant research work has continued in the European Union, where the reactor *Myrrha* has been built and may be used for transmutation purposes along with other high technology applications.
3. *Waste re-use* usually accompanies the concentration process which was described in the previous section. The produced high-radioactivity materials may be re-used in a nuclear reactor for the production of additional power. Because a great deal of the current nuclear waste is the isotope uranium-238, it is envisioned that this isotope will be separated from the waste and will be used in the breeder reactors of the future.

4. *Space disposal* is a possible alternative that has been advocated by a few non-experts. Given that it costs more than $25,000 to lift a kg of mass to the space, this is extremely expensive and has not been proven to be a reliable way of nuclear waste storage. Considerations of the adverse effects of "space debris" to satellite communications make this a prohibited option.

It must be noted that, in many countries, the long-term or permanent storage of nuclear waste has become a political problem, because local and regional governments resist nuclear materials storage within the boundaries of their jurisdictions. A prime example in the United States is the permanent repository in the Yucca Mountain, Nevada, which was identified as a permanent storage site in the 1970s. A multitude of engineering and scientific studies showed that nuclear waste storage in the Yucca Mountain does not pose significant risks for the local population. Despite of this and the spending of billions of dollars for the studies, local population resistance and political and legal maneuvering delayed the construction of a permanent nuclear waste storage facility. After several years of studies and many legislation acts, in March 2009, the U.S. Department of Energy announced that the Yucca Mountain "…is not considered as an option for storing nuclear waste," without specifying an alternative location for nuclear waste storage. As a result, and for the foreseeable future, the tons of nuclear waste that have been generated since the 1950s and continue to be generated in the USA will be temporarily stored in makeshift pools next to the more than 100 power reactors that produced them. In the absence of a centralized facility to receive the produced nuclear waste, these poorly planned and "temporary" facilities have become a significant environmental threat to the surrounding area and its population.

2.7 Sustainable Development

Sustainable development or simply *sustainability,* is an all-encompassing concept, which basically advocates that the global economic development must be pursued without causing irreparable damage to the ecology and the environment. Sustainability includes all the global economic activities from the production of goods and services to the transportation and energy production. Measures of sustainability include the calculation of pollutant emissions per unit of the desired product or service. Most notable among these measures is the *carbon footprint*, which is defined as the amount of CO_2 produced for the completion of an economic activity. For example, the carbon footprint of driving 1,000 km in a small car with mileage 30 km/l (kilometers per liter) of gasoline (at the consumption of 23.3 kg of gasoline) is 9.0 kg of CO_2 while the carbon footprint of the same trip with a 5 km/l in a SUV is 54.0 kg of CO_2. Similar metrics have been adopted for other pollutants as well as for the use of scarce resources, such as water.

The concept of sustainability treats the pollutant emissions and reductions of emissions as a global economic phenomenon. Its advocates maintain that, for the long term environmental health, the economic activities must be re-engineered to ensure that their net effect on the environment is neutral. It must be pointed out that the sustainability concept does not necessarily advocate the banning of pollutants. Rather, it supports a pollution reduction counteraction for every pollution emission action. A simple example of the application of the sustainability concept is the removal of the 54.0 kg of CO_2 produced from the 1,000 km trip in the SUV of the previous paragraph: the owner of the SUV may plant a tree that will absorb this amount of CO_2 from the atmosphere. Actually, and if the tree grows to become a mature tree of approximately 500 kg, it would have removed enough CO_2 from the atmosphere to counteract the equivalent of 17 trips of 1,000 km. Therefore, one may drive for 17,000 km in an SUV and all the CO_2 that is emitted would be counteracted by the planting and growth of this tree. Similar counteraction measures may be taken in every field to remove the environmental effects of all economic activities. The subject of sustainability advocates that carbon sequestration and storage on a large, global scale is necessary to remove the adverse environmental effects of fossil fuel combustion.

The subject of sustainability is a product of the late twentieth century reaction to the environmental effects that are caused by anthropogenic activities and the realization that if these activities are continued unchecked and unmitigated, the planet may become uninhabitable to the vast majority of the population. Sustainability encompasses ideas and concepts from several disciplines including engineering, environmental science, ecology, economics, sociology, anthropology, political science, and public policy. Central to this subject is the realization that significant global threats, such as global warming and pollution prevention, may only be tackled by a combination of technological advances, social awareness, and public policy.

It has become apparent that the continuation of the current practices on energy consumption and the *laissez faire* or *market* energy policies in all countries are not sustainable for long and that, if continued unchecked, they will inevitably bring environmental disaster that may be followed by agricultural crop failures. This may lead to socio-economic, security, and cultural disruptions in the long run. The long-term sustainability of human economic activities is a subject that needs careful consideration. The subject of sustainability is still undergoing evolution, its definitions are mainly subjective, and its metrics are still debated among the scientists and policy makers. However, the adoption of at least some of the sustainability principles in the energy field appears to be a reasonable and realistic way for global economic expansion and equitability as well as for the long-term continuation of our current standards of living.

It must be noted that several sustainability promoters of the twenty-first century have advocated a "return to the fundamentals," where individuals become farmers and herders, withdraw in simple farms from urban centers, grow their own food and produce their own energy. These advocates often withdraw from urban centers and live in farms or rural communities. While a small fraction of the world population may be able to live such lives, the entire population reverting back to a farming society is not a solution to the global environmental problems. Simply, the finite surface of the Earth cannot support so many small, independent and inefficient farming enterprises. A small, family farm that would grow food as well as fuel for the needs of a family of four persons is approximately 150 acres (60 hectares). In most of the countries there is simply not enough arable land for each family to have such a small farm. For example, in the United States—one of the least densely populated countries of the world—such a societal system would only support 21% of its current population, even assuming that the entire land in the country is arable. In China it would support less than 5% of the current population and in Belgium—the most densely populated country in the world—a mere 1.9% of its current population. Clearly, the entire Earth is too small for all the humans living in the twenty-first century to return to a simple, agrarian and sustainable economy.

A more realistic alternative for sustainability, which may encompass the entire, current population of the planet, is the wider use of alternative energy sources combined with increased efficiency and energy conservation. The use of alternative energy sources, including the nuclear option, is fundamental to tackling several pollution problems, most important of which is the increased global CO_2 concentration. The substitution of a single 400 MW base-load coal-fired plant by twenty 20 MW geothermal plants will have the net effect of removing 3,530,000 tons of CO_2 annually from the atmosphere. Similarly, the substitution of a 60 MW gas turbine for peak power generation that operates for 20% of the year with solar power will have the effect of removing 20,400 tons of CO_2 annually. Permanent reforestation, not simply for biomass-based fuel production, removes tons of CO_2 and other pollutants from the atmosphere for several decades. Extensive use of the hydroelectric potential, tidal and wind power and a more widespread use of electric cars avert the further emissions of CO_2, SO_2, NO_x and other pollutants from an environment that 7 billion humans inhabit. Therefore, energy production from alternative sources, energy conservation and higher efficiency are the principal long-term solutions to achieving global and sustainable development.

Problems

1. A type of anthracite contains 90% carbon by weight. How much CO_2 is produced from the combustion of 1 metric ton of this anthracite? How much CO_2 is produced from the combustion of 1 Mcf (1,000,000 ft^3 at standard conditions) of propane?
2. A 400 MW electric power plant with an overall efficiency 38% uses bituminous coal, which contains 70% carbon, 2% sulfur with the rest being volatile matter and ash. The heating value of this coal is 26,500 kJ/kg. Determine: (a) how much heat the plant needs annually, if it operates continuously; (b) how much of this coal the power plant uses daily and annually; and (c) how much CO_2 and SO_2 the power plant produces annually.
3. Three coal power plants with a total power producing capacity of 1,000 MW and average thermal efficiency 36%, are substituted by one nuclear power plant with 33% thermal efficiency. What is the annual amount of CO_2 that is not emitted to the atmosphere? What is the increase of the waste heat produced? The heating value of the coal that was used is 28,000 kJ/kg and contains 80% carbon.

4. Three coal power plants with a total capacity of 1,000 MW and average thermal efficiency 36%, are substituted by ten smaller gas units that use methane. The new units have an average thermal efficiency 43%. What is the annual amount of CO_2 that is not emitted to the atmosphere because of this substitution? Assume that the heating value of coal is 30,000 kJ/kg and contains 90% carbon, and that of methane is 50,020 kJ/kg.
5. The coal power plant of problem 2 is fitted with a sulfur abatement system that has 99.6% efficiency. How much of the SO_2 mass is removed by the abatement system and how much is released in the atmosphere?
6. What effect the following parameters would have on the long-term temperature of the atmosphere? Write a short statement to explain your reasons.

   (a) A decrease of the earth's core temperature.
   (b) An increase of the average cloudiness.
   (c) A decrease of the earth's reflectance.
   (d) An increase of the amount of atmospheric methane.
   (e) An increase of the surface temperature of Venus.
   (f) Producing 10% of the total electric power from solar cells.

7. "The melting of the polar ice caps will be a major environmental calamity because it will increase the average temperature by 10.41°C." Comment by writing a short (250–300 word) essay.
8. A lake has a surface area of 18 square kilometers and an average depth of 6 m. The average pH of the lake is 6.9. How many tons of acid rain—in the form of H_2SO_3—would reduce the pH of the lake from 6.9 to 3.2?
9. Three Fluidized Bed Reactors (FBR's) consume bituminous coal with 65% carbon, 2.3% sulfur by weight and heating value $24{*}10^3$ kJ/kg. The FBR's supply with heat power a 600 MW coal power plant with 42% overall thermal efficiency. Determine: (a) How much heat the set of FBR's produce annually; (b) how much coal they consume; and (c) how much $Ca(OH)_2$ must be supplied to the FBR's in order to remove the SO_2 produced?
10. A certain type of leaded gasoline contains 1.2% of tetra-ethyl lead by weight. How much lead oxide, PbO, is released in the environment with every litter and with every gallon of this gasoline? Assume that all Pb is converted to PbO.
11. Calculate the amount of heat, in TJ (10^{12} J), rejected annually from the following types of electric power plants assuming that they operate continuously.

   (a) A 400 MW coal plant with thermal efficiency of 40%.
   (b) A 1,000 MW nuclear power plant with thermal efficiency of 33%.
   (c) A 35 MW geothermal power plant with 14% thermal efficiency.
   (d) A 10 MW thermal solar plant with 18% thermal efficiency.
   (e) An 80 MW natural gas power plant with 46% thermal efficiency.

12. The wet cooling towers of power plants use air and water for the cooling of the condensers. Air enters the cooling tower of such a plant at 22°C, 50% relative humidity and exits at 34°C, 90% relative humidity. Determine: (a) the amount of heat removed by 1 kg of (dry) air from this cooling system; and (b) the

amount of water (in kg) consumed for every kg of air that passes through the cooling tower.

13. The cooling tower of a 200 MW coal power plant with 40% thermal efficiency admits air at 15°C, 70% relative humidity and rejects it at 32°C, 95% relative humidity. Determine: (a) How much cooling air passes through the cooling system of this plant per minute? (b) How much water is used annually?
14. It is recommended that ten small geothermal power plants of 20 MW each (total 200 MW) substitute a coal power plant. If the average thermal efficiency of the geothermal power plants is 14%, how much water will be used annually?[10]
15. A 1,000 MW nuclear power plant with a 32% thermal efficiency discharges its waste heat in a lake with 22 km^2 surface and 3 m depth. If there is no other cooling effect for the lake, what would be the average increase of the water temperature annually? What other factors would nullify this temperature increase?
16. What is the Carbon footprint of the following activities? For all, you will need to find the wattage of the pertinent appliances in your residence. In the case of electric appliances, you may assume that 70% of the electricity comes from coal power plants with an overall thermal efficiency 38%.

    (a) Watching television for 1 hour.
    (b) Using a microwave oven for 10 minutes.
    (c) Forgetting to switch off a 100 W light bulb for 12 hours.
    (d) Driving for 2,000 miles in a SUV, which consumes 12 miles per gallon.
    (e) Driving for 2,000 miles in a compact car, which consumes 40 miles per gallon.

17. "The human society in its current form has failed to create a sustainable future for us and the next generations. Humans should abandon the cities and urban life and create a sustainable future for themselves and their children by producing their own food and fuel from products they have grown for millennia and can depend on in the future." Comment by writing a short (250–300 word) essay.

Reference

Gates DM (1985) Energy and Ecology. Sinauer, Sunderland Massachusetts

[10] This is not an environmental burden, because geothermal wells produce fresh water that may be used for the cooling of the geothermal power plant.