Cambridge University Press
978-1-108-47837-3 — Energy Conversion Engineering
Ahmed F. Ghoniem
Excerpt
More Information

1 Low-Carbon Energy, Why?

1.1 Introduction

Energy is one of the most important needs of humanity. Mobility, lighting, communications, heating, and air conditioning are all energy-intensive functions that are indispensable in modern life. Industrial production, food production, and clean water require energy.

Energy consumption correlates strongly with standards of living. The developed world has become accustomed to cheap and plentiful supplies, and recently more of the developing world is striving for the same. Competition over supplies of conventional resources is intensifying, and more challenging environmental problems, especially those related to carbon dioxide (CO_2), are looming. The evidence that atmospheric CO_2 concentration is correlated with the global temperature is strong, and models indicate that the century-old trend of rising temperatures could accelerate. Given the potential danger of such a scenario, steps must be taken to curb energy-related CO_2 emissions. Solutions include substantial improvements in conversion and utilization efficiencies, carbon capture and storage (CCS), and expanding use of zero-carbon sources, namely nuclear energy and renewable sources.

Recent energy consumption rates – total and per source – are summarized in Section 1.2. Nearly 80% of our energy is supplied from fossil resources. Global climate change has been shown to correlate with greenhouse gases. Evidence and trends are discussed in Section 1.3 [1]. In Section 1.4, CO_2 emissions by sector and fuel are reviewed. International agreements and targets for CO_2 reduction are summarized in Section 1.5. Technologies to address resources depletion and CO_2/climate change are discussed in Section 1.6. Conversion efficiency is at the forefront of the effort to conserve resources and reduce the environmental impacts, and is discussed in Section 1.7. Fossil fuels will remain as a major source of electricity generation for decades, and approaches to “decarbonize” power generation plants – including CO_2 capture – are discussed here. Zero-carbon energy includes nuclear energy and renewable sources, such as geothermal, wind, solar, and biomass. Transportation consumes a significant fraction of the total

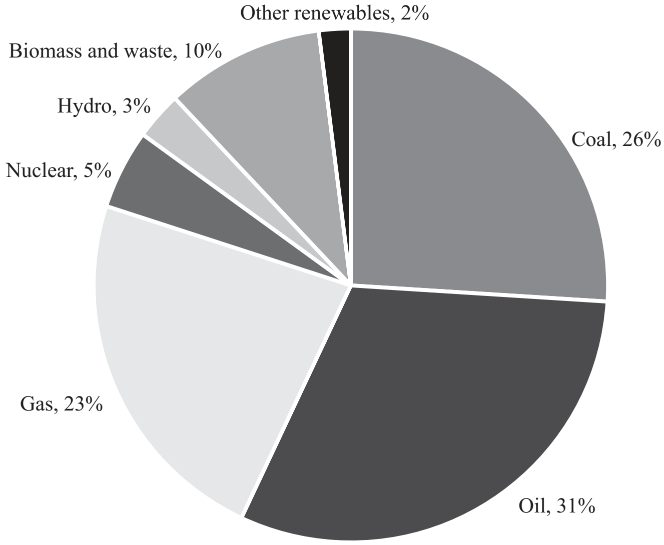

Figure 1.1 The breakdown of the world primary energy consumption in 2018. Except for hydropower, primary energy measures the thermal energy equivalent in the fuel that was used to produce a useful form of energy; e.g., thermal energy (heat), mechanical energy, electrical energy. When energy is obtained directly in the form of electricity, efficiency is used to convert it to equivalent thermal energy. 1 toe = ~42 GJ. IEA World Energy Outlook.

energy used worldwide. While heavily dependent on oil products,[1] the number of electrified and electric vehicles is growing, adding to the need for electricity production.

1.2 Consumption

The world consumed ~570 EJ (exajoule) in 2014 (up from ~440 EJ in 2004). According to the International Energy Agency (IEA), the world power capacity then was close to 18 TW, of which 6.1 TW was for electricity generation. The total capacity is expected to reach beyond 50 TW by the end of the twenty-first century, driven by population growth and rising living standards in developing countries. This is despite the anticipated improvement in energy intensity, defined as the energy used per gross domestic product (GDP), or J/GDP.

Figure 1.1 shows the breakdown of the world *primary* energy consumption in 2018.[2] Fossil-fuel use, measured by the total thermal energy equivalent, is dominated by oil, followed by coal and natural gas. Oil is used mostly in transportation. Coal is used mostly in electricity generation, where the consumption of natural gas has also been rising (in conventional energy units, 1 Mtoe = 41,868 TJ).[3] The total energy consumption in 2014 was 13,558 Mtoe (million tonne oil equivalent), up from 11,059 Mtoe in 2006. The contributions of nuclear and renewable sources such as hydropower, which produce electricity, are converted to thermal energy using First Law efficiencies (the First Law efficiency varies by source – for instance, for geothermal energy it is ~10%). The IEA uses 100% efficiency to

[1] According to the DoE/EIA, in 2007 the breakdown of transportation fuel in the USA was: petroleum 96.3%, natural gas 2.1%, biomass 1.2%, and electricity 0.3% (www.eia.doe.gov/oiaf/1605/gg04rpt/carbon.html).

[2] EJ is an exajoule, or 10^{18} J, and 1 TWh = 0.086 Mtoe.

[3] A megaton = 1×10^6 (metric) ton = 1×10^9 kg.

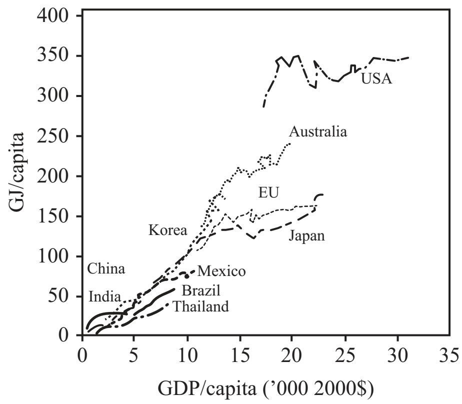

Figure 1.2 The per-capita energy consumption and the per-capita GDP for a number of developed and developing countries (1 BTU = 1.055 kJ). Energy use per capita is for the year 2003; GDP per capita is given for the year 2004 expressed in 2000 US dollars. Data downloaded from the United Nations Development Programme, Human Development Report (HDR) 2006, Table 1, pages 283–286, and Table 21, pages 353–356 (http://hdr.undo.org/hdr2006/report.cfm).

represent the energy content of electricity and 33% efficiency to convert nuclear electricity to thermal energy. Biomass sources[4] are used mostly in rural communities.

Our welfare depends on continuous and guaranteed supplies of energy at affordable rates. Per-capita GDP correlates well with per-capita energy consumption, with developed countries consuming energy at orders of magnitude greater than developing and poorer nations. One can in fact define an affluence index based on the per-capita energy consumption.

Increasing the per-capita GDP of a country goes hand-in-hand with rises in its per-capita energy consumption, especially during the early stages of development. This trend slows down as the economy matures and becomes more energy efficient. Figure 1.2 shows the rise of per-capita energy consumption against per-capita GDP for some developed and developing countries, and others undergoing rapid transition. Developed countries show significant improvement in energy efficiency as the per-capita energy use stabilizes while GDP continues to rise. This trend is enabled by investing in energy efficiency, adopting advances in technology that lead to energy savings, and citizens becoming more aware of their environmental impact. Rising energy prices often promote lower consumption, enabled primarily by switching to higher-efficiency systems, but the impact often persists even after energy prices fall back to more affordable levels. Some developing countries have started to take steps toward improving their economic conditions through industrialization, agricultural mechanization, and large-scale infrastructure improvement, causing their energy consumption to grow more rapidly.

Higher quality of life in developing countries could be achieved at energy intensity lower than the current standard in developed nations. For instance, it has been shown that the UN Human Development Index (HDI), which includes data that reflect the physical, social, and economic health and wellbeing of a population, such as per-capita GDP, education, longevity, use of technology, and gender development, rises steeply during the early stages of growth, alongside per-capita electricity consumption, before it levels

[4] Renewable sources are also non-exhaustable sources.

Cambridge University Press
978-1-108-47837-3 — Energy Conversion Engineering
Ahmed F. Ghoniem
Excerpt
More Information

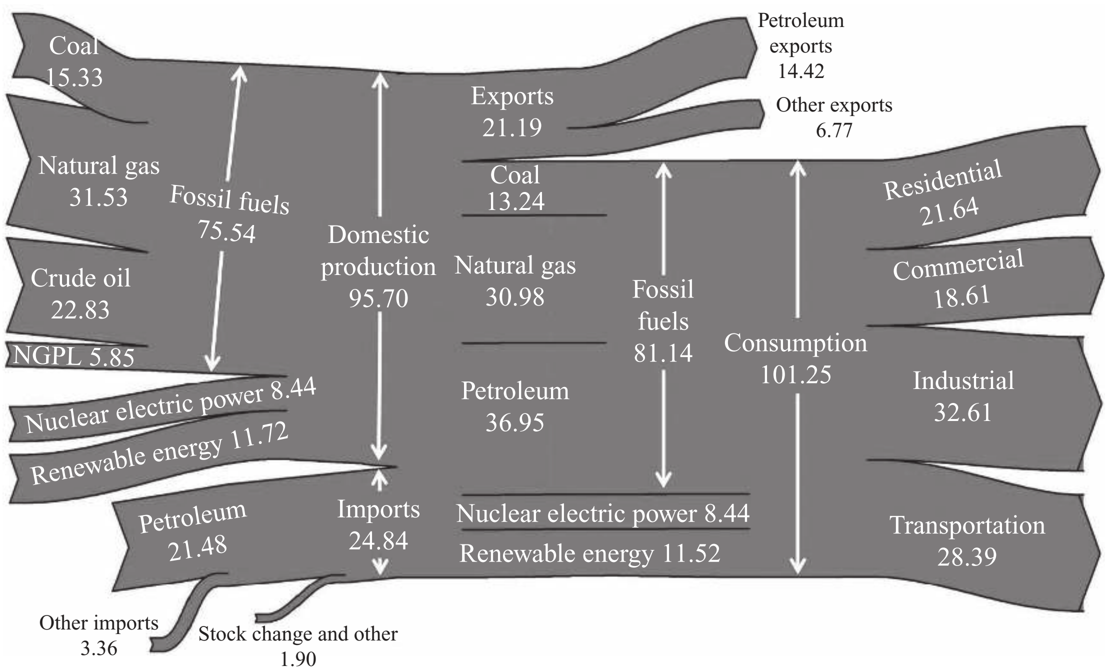

Figure 1.3 Energy sources and consumption patterns in the USA (2018 data), measured in quadrillion BTU (quad BTU or QBTU = 1.055 EJ = 1.055×10^{18} J). The units used here represent the thermal energy content of the fuel. In the case of nuclear and renewable energy, the latter of which is dominated by hydropower, where the energy output is electricity, an assumed First Law efficiency is used to convert the electricity to thermal energy. The efficiency used in assembling these data is an average over fossil-fuel power plants. Please note that some of the conversion factors used in the IEA and the EIA are different (www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf).

off [2]. That is, a "point saturation" of energy consumption is reached beyond which more energy use does not necessarily translate to a better standard of living. Meanwhile, nearly 20% of the world population does not have adequate access to electricity and rely on biomass as their primary source of energy.

Consumption patterns vary widely and depend on the economy, local weather, and population density, among other factors. The USA's energy consumption was ~100 EJ in 2018. The share of different sources and the utilization in different sectors is shown in Figure 1.3.[5] Currently, consumption is projected to rise over the next 25 years, with the fossil-fuel share being ~70%.

The share of different sources in energy production worldwide over the last 40 years is shown in Figure 1.4, along with the projection for the next 20 years. Continued growth in

[5] www.eia.doe.gov/cneaf/alternate/page/renew_energy_consump/rea_prereport.html.

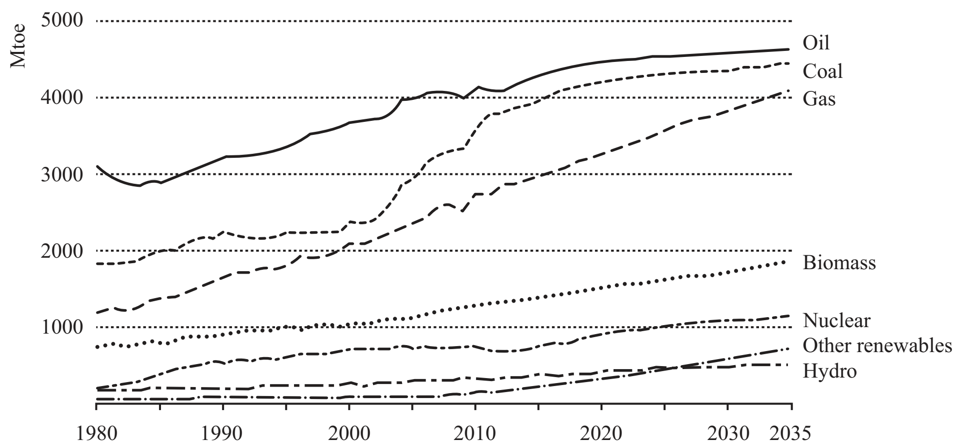

Figure 1.4 World primary energy consumption by fuel. Predicted based on the continuation of existing policies and measures as well as implementation of policies that have been announced by governments but are yet to be given effect (mid-2013). IEA World Energy Outlook 2013, p. 63.

natural gas, as more of its unconventional resources are tapped, will likely reduce the reliance on coal. Biomass contributes to heat and electricity, as well as biofuels such as ethanol. Its fast growth may contribute to slowing down oil consumption. Electricity from wind, solar, and geothermal (and other renewables) will continue to grow as their prices drop, satisfying a rising fraction of new demand. Nuclear energy must address waste storage, safety, and security in order to continue its expansion.

One challenge that energy production faces is related to possible limited supplies of fossil-fuel reserves (those that have been discovered and can be extracted economically using existing technologies) and resources (defined as those thought to exist but whose extraction may require advanced technologies and may not be presently economical), which some have estimated would last for only 100–300 years, depending on the fuel type and recovery.[6] Unconventional sources, such as oil shale and tar sands, could extend this period. For instance, it is estimated that while the proven reserves of oil are nearly 1 trillion barrels, Canadian oil sands could produce 1.7 trillion barrels, and oil shale in the USA could produce 2 trillion barrels. The environmental impact of producing light hydrocarbons from these resources could be significant. Other hydrocarbon resources include deep ocean methane hydrates. A case for the existence of abiogenic (non-organic) methane in deep, underground formations has been made, and if proven would be another vast resource.

A more serious challenge is global warming.

[6] For more on the subject, see [3], [4], and the ASPO website www.peakoil.net.

Cambridge University Press
978-1-108-47837-3 — Energy Conversion Engineering
Ahmed F. Ghoniem
Excerpt
More Information

1.3 Global Warming

Data suggest that current temperatures are close to the highest ever reached in the past 400,000 years, and that CO_2 concentration is even higher than the highest level estimated during this same period. The records of temperature, CO_2 concentration, methane concentration, and solar insolation are shown in Figure 1.5. The temperature (in this case the temperature at Lake Vostok over the Antarctic) and atmospheric concentrations of CO_2 and CH_4 varied cyclically during this period. However, they remained well correlated. It is interesting to note that the time scales for the rise and fall of the quantities of interest are different. The figure shows that cyclic variation over geologic time scales is the norm. On the other hand, current CO_2 levels are higher than the peaks reached previously. Prior to the onset of the Industrial Revolution in the mid-1800s, natural causes were responsible for CO_2 concentration variation.

The correlation between the global temperature and CO_2 atmospheric concentration during the past 1000 years is shown in Figure 1.6. While reasonably stable at around

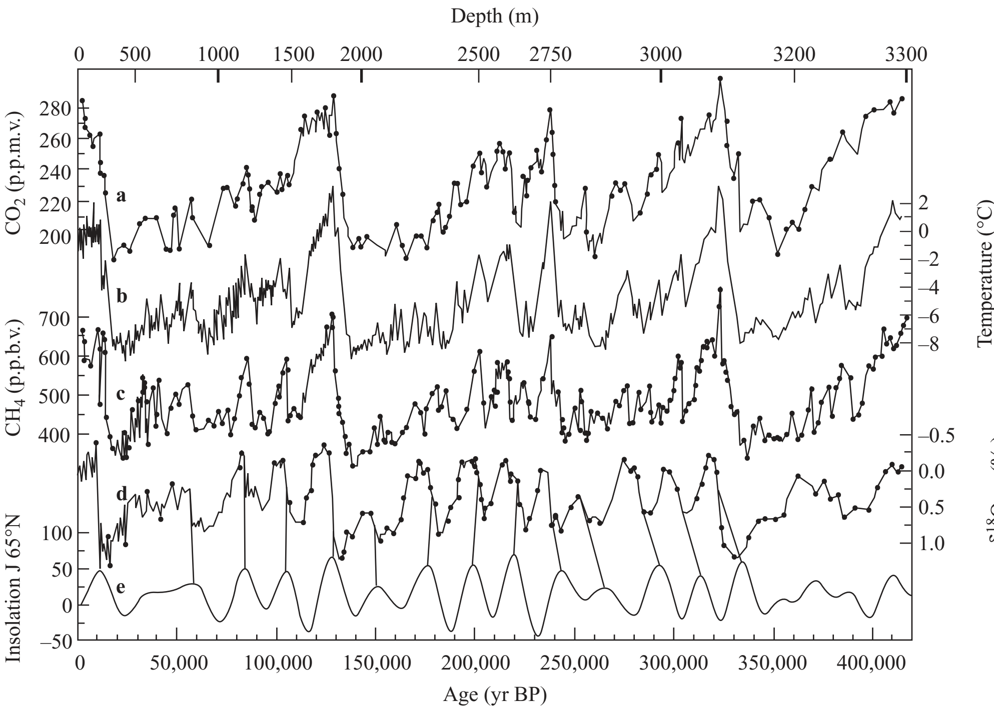

Figure 1.5 Time series of: (a) CO_2 concentration; (b) isotopic temperature of the atmosphere; (c) CH_4 concentration; (d) $\delta^{18}O$ atm (‰); and (e) mid-June insolation at the given location in W/m^2. The top axis shows the depth of the ice sample and the bottom axis shows the age. BP, before present. J.R. Petit, J. Jouzel, D. Raynaud, et al. “Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica,” *Nature*, vol. 399, pp. 429–436, 1999; figure 3, p. 431.

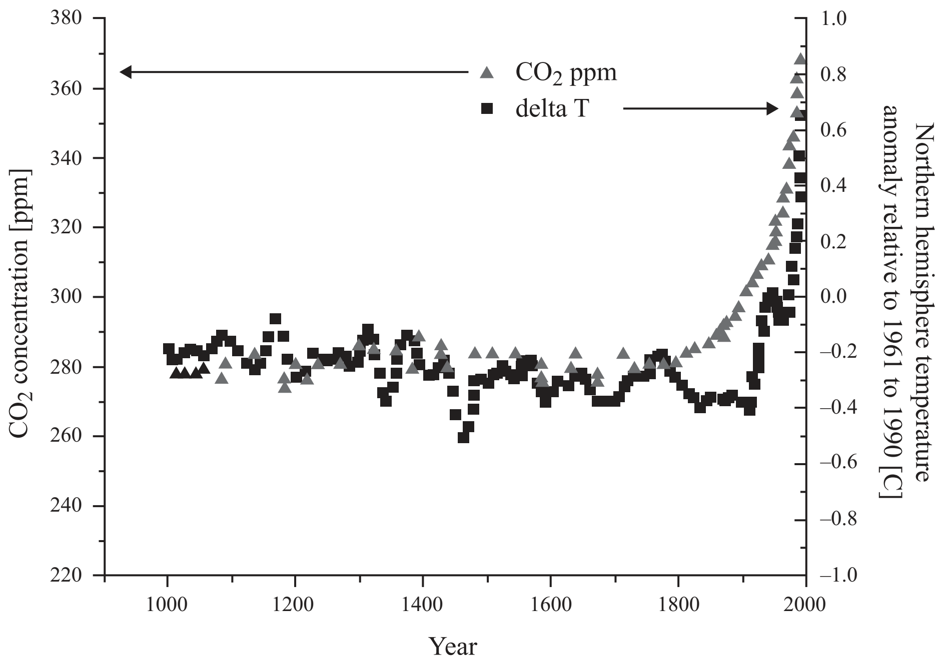

Figure 1.6 The rise in atmospheric concentration of CO_2 and temperature in the Northern Hemisphere over the past 1000 years. Data taken from the *IPCC Third Assessment Report 2001, Working Group I, Technical Summary*. The figure is a combination of data from figure 5, p. 29 (Millennial Northern Hemisphere (NH) temperature reconstruction) and figure 10b, p. 40 (CO_2 concentration in Antarctic ice cores for the past millennium). Recent atmospheric measurements (Mauna Loa) are shown for comparison. Triangles show CO_2 in ppm and squares show delta T in °C.

285 ppm before 1850, its rise around the onset of the Industrial Revolution, followed by a rise in the temperature, is evidence of "man-made" global warming.[7] The trend has intensified over the past ~50 years, as shown in Figure 1.7.[8] Recent measurements show CO_2 concentrations exceeding 400 ppm.

Greenhouse gases include water (H_2O), CO_2, methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and aerosols. The greenhouse potentials of CO_2, CH_4, N_2O, and CFCs (taken as averages among different estimates) are 1:11:270:1300–7000. Because of

[7] For more data on the global mean temperature, the surface temperature anomaly (the difference from historical means), and the impact of solar irradiance variation on global mean temperature, see http://data.giss.nasa.gov/gistemp/2007. On a yearly average basis, the solar insolation (total energy received by an area perpendicular to a beam) at the outer edge of Earth's atmosphere is 1366 W/m^2. Despite a small decrease in solar irradiance recently, global temperature continues to rise, providing further evidence to the greenhouse gas mechanism.

[8] Arrhenius predicted an increase of the Earth surface temperature by 5–6 °C due to the doubling of CO_2 concentration in the atmosphere, more than 100 years ago.

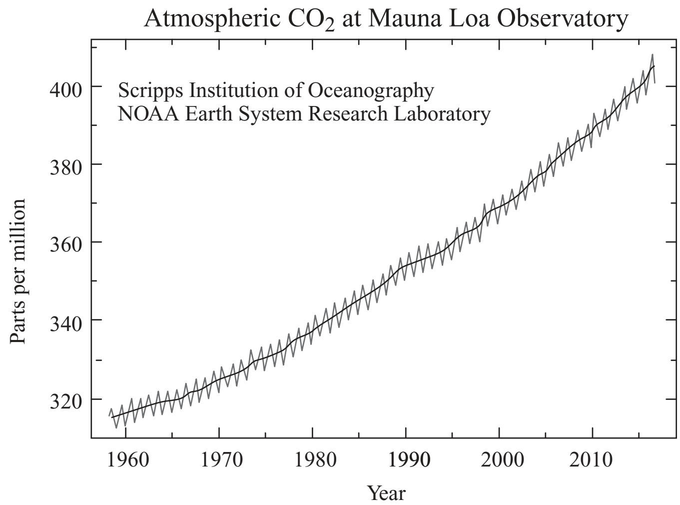

Figure 1.7 Close up of CO_2 concentration and temperature change over a 70-year period.

its much higher concentration, CO_2 is the most impactful. Most CO_2 anthropogenic emissions result from fossil-fuel combustion, with a smaller fraction from industrial processes.

1.3.1 Global Energy Balance

The energy fluxes to and from the Earth's atmosphere, and their change as radiation passes through the atmosphere, are shown in Figure 1.8. Solar radiation is concentrated at short wavelengths, within the visible range of 0.4–0.7 μm, because of the high temperature of the surface of the Sun, estimated to be ~6000 °C. Only a small fraction of solar radiation lies in the ultraviolet range, down to 0.1 μm, and in the infrared range, up to 3 μm. On average, 30% of the incoming solar radiation is reflected back by Earth's atmosphere and its surface (the albedo), 20% is scattered by the atmosphere at different altitudes, and the remaining 50% reaches the surface and is absorbed by the ground and the water. The fraction of the incoming radiation that is either absorbed or scattered while penetrating the atmosphere does so in a spectrally selective way, with the ultraviolet radiation absorbed by stratospheric ozone and oxygen, and infrared radiation absorbed by water, CO_2, ozone (O_3), N_2O, and CH_4 in the troposphere (lower atmosphere). Much of the radiation that reaches the ground goes into evaporating water from the oceans. Outgoing radiation from the cooler Earth's surface is concentrated at the longer wavelengths, in the range 4–100 μm [5].

Greenhouse gases in the atmosphere absorb part of the outgoing radiation, with water molecules absorbing in the 4–7 μm wavelength as well as at 15 μm, and CO_2 absorbing in the range 13–19 μm. A fraction of this energy is radiated back to Earth's surface and the remainder is radiated to outer space. The change of the energy balance due to this greenhouse gas radiation is known as the radiation forcing of these gases, and its contribution to Earth's energy balance depends on the concentration of greenhouse gases in the atmosphere. The net effect of absorption, radiation, and reabsorption is to keep Earth's surface warm, at

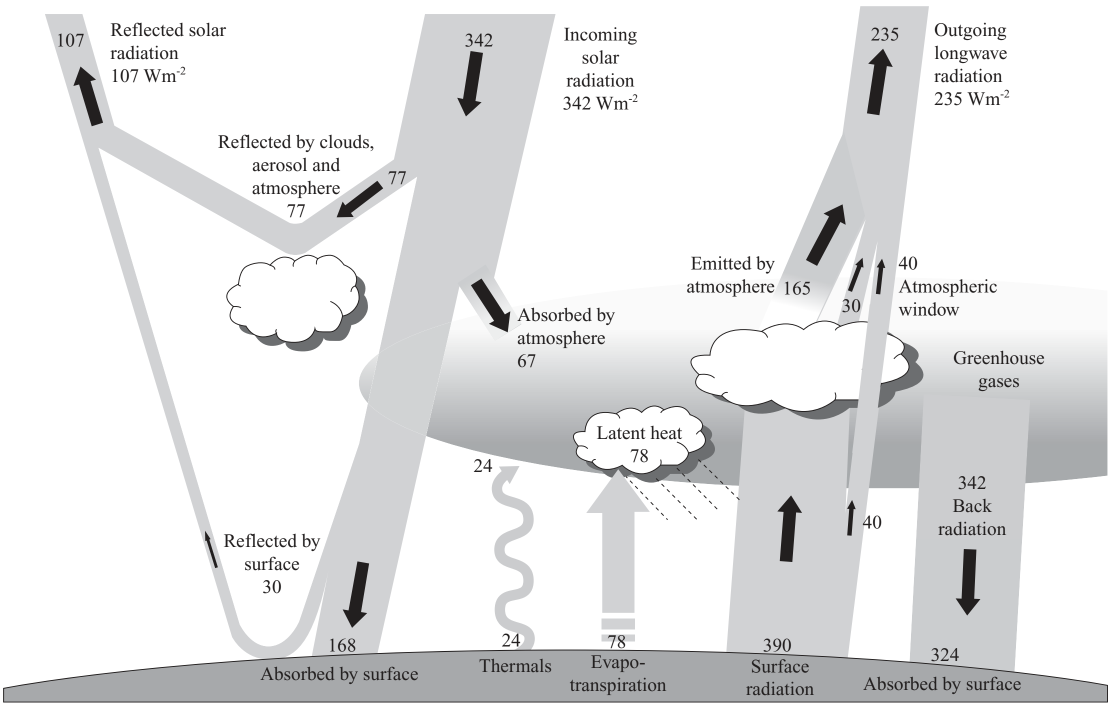

Figure 1.8 Solar energy flux and how much of it reaches Earth's surface; the radiation emitted by the ground and the balance that is re-radiated back to the surface. All numbers are given as averages over Earth's surface in units of Wm^{-2}. Adapted from Intergovernmental Panel on Climate Change, Working Group 1, *The Physical Basis of Climate Change*, p. 96, FAQ 1.1, figure 1 (2007) (http//ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_Ch01.pdf).

average temperature close to 15 °C. In essence, Earth's atmosphere acts as a blanket; without it the surface temperature could fall to values as low as −19 °C. Because of its concentration CO_2 has the strongest radiation forcing among known greenhouse gases, except for water. However, water concentration in the atmosphere is the least controlled by human activities.

Increasing the concentration of greenhouse gases enhances the radiation forcing effect. Moreover, a number of feedback mechanisms, such as the melting of the polar ice (which reflects more of the incident radiation back to space) and the increase of water vapor in the atmosphere (due to the enhanced evaporation resulting from higher temperatures) are expected to accelerate the greenhouse contribution to the rise of the mean atmospheric temperature.

1.3.2 Carbon Balance

Current estimates indicate that fossil-fuel combustion produces ~6 GtC/y. This unit, gigaton carbon per year, is used to account for all forms of carbon injected into the atmosphere, with

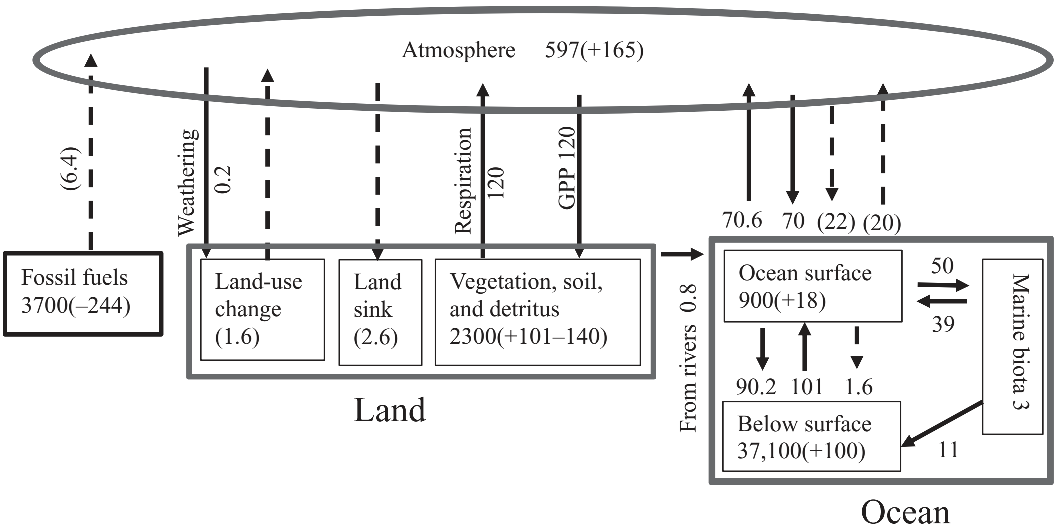

Figure 1.9 The global carbon cycle (in the 1990s), showing the primary annual fluxes in GtC/y: pre-industrial "natural" fluxes and added "anthropogenic" fluxes. Continuous arrows show natural fluxes and broken arrows show fluxes due to anthropogenic activity. Also shown are the reservoirs in GtC; numbers without brackets for natural reservoirs and numbers in brackets added to these reservoirs. Gross fluxes have uncertainty of more than ±20%. GPP is gross primary production during photosynthesis. Adapted from Intergovernmental Panel on Climate Change, Working Group 1, *The Physical Basis of Climate Change*, p. 514, Figure 7.3 (2007) (http//ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_Ch07.pdf).

carbon accounting for 12/44 of CO_2 – that is, 1 GtC is equivalent to 44/12 = 3.667 $GtCO_2$. This should be compared with other sources/sinks that contribute to CO_2 concentration in the atmosphere, as shown in Figure 1.9. Carbon dioxide is injected into the atmosphere through respiration and the decomposition of waste and dead biomatter, and is removed by absorption during photosynthesis and by the phytoplankton living in the oceans. Respiration produces nearly 60 GtC/y, while photosynthesis removes nearly 61.7 GtC/y, with a balance of a sink of 1.7 GtC/y. The surfaces of the oceans act as a sink, contributing a net uptake of 2.2 GtC/y, a source–sink balance between production of 90 and consumption of 92.2 GtC/y. Changing land use (deforestation) and ecosystem exchange adds/removes 1.4/1.7 GtC/y, for a net balance of a sink of 0.3 GtC/y. The overall net gain of CO_2 in the atmosphere is estimated to be around 3.5 GtC/y. It is relative to these balances that the contribution of fossil-fuel combustion and related man-made sources appears significant. These numbers are somewhat uncertain, and there is 1–2 GtC/y unaccounted for in the overall balance, when all the uncertainties are traced. The uncertainty in the numbers is reflected in the different sources, and is demonstrated here by the different numbers.[9]

[9] It is estimated that for each 2.1 GtC introduced into the atmosphere, CO_2 concentration rises by 1 ppm, and that the average lifetime of CO_2 in the atmosphere is 100–200 years.