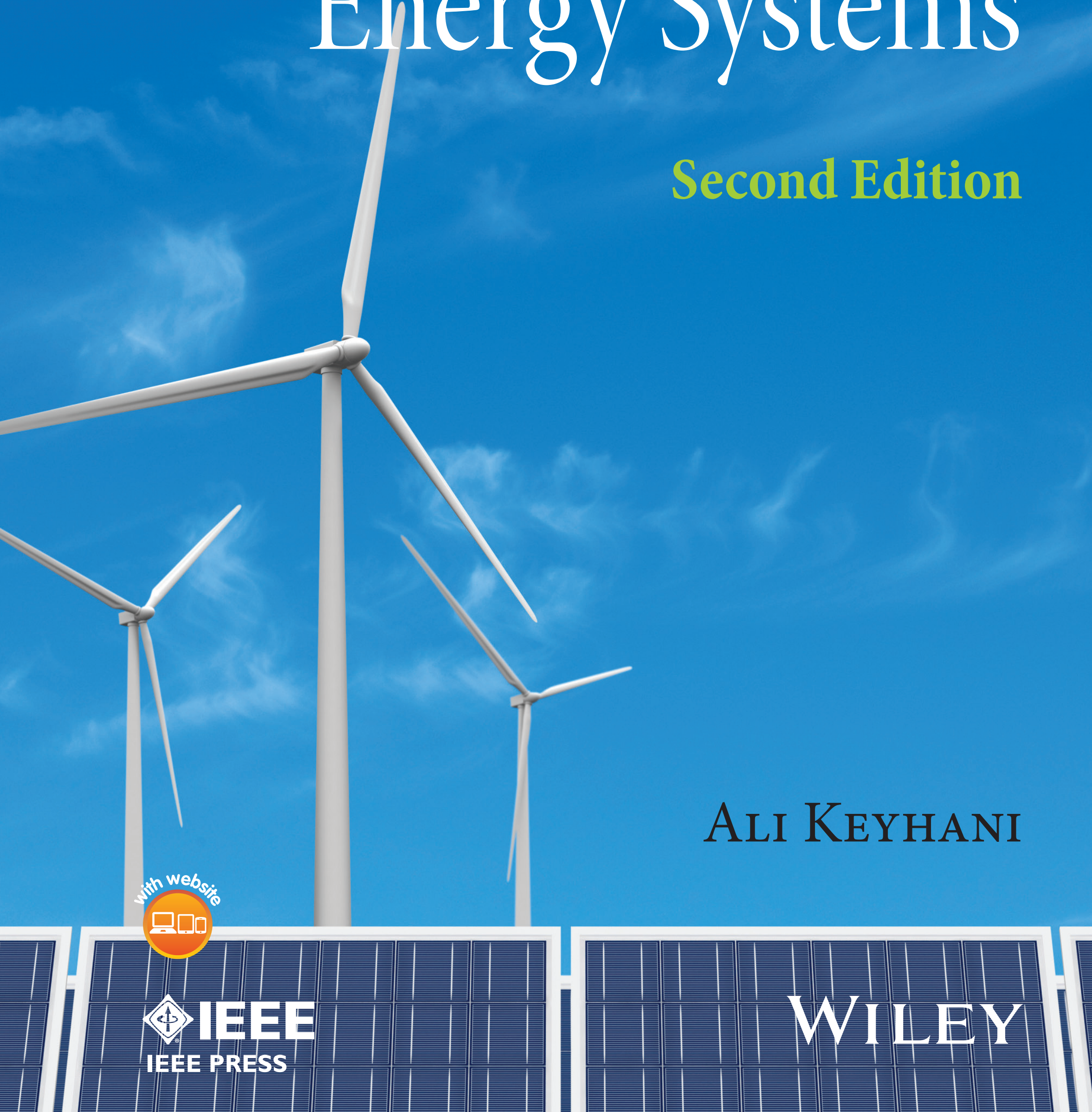
Design of Smart Power Grid Renewable Energy Systems

Second Edition



Ali Keyhani

IEEE
IEEE PRESS

WILEY

DESIGN OF SMART POWER GRID RENEWABLE ENERGY SYSTEMS

DESIGN OF SMART POWER GRID RENEWABLE ENERGY SYSTEMS

Second Edition

ALI KEYHANI

IEEE
IEEE PRESS

WILEY

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

Library of Congress Cataloging-in-Publication Data:

Names: Keyhani, Ali, 1942- editor.
Title: Design of smart power grid renewable energy systems / Ali Keyhani.
Description: Second edition. | Hoboken, New Jersey : John Wiley & Sons, Inc., [2017] | Includes bibliographical references and index.
Identifiers: LCCN 2016009194 | ISBN 9781118978771 (cloth)
Subjects: LCSH: Smart power grids–Design and construction. | Electric power systems–Automatic control. | Distributed generation of electric power–Computer simulation. | Renewable energy sources.
Classification: LCC TK1007 .K49 2016 | DDC 621.319/1–dc23
LC record available at http://lccn.loc.gov/2016009194

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

I dedicate this book to my parents,
Dr. Mohammed Hossein Keyhani
and
Mrs. Batool Haddad

CONTENTS

PREFACE

Sustainable energy production and the efficient utilization of available energy resources, thereby reducing or eliminating our carbon footprint, is one of our greatest challenges in the twenty-first century. This is a particularly perplexing problem for those of us in the discipline of electrical engineering. This book addresses the problem of sustainable energy production as part of the design of microgrid and smart power grid renewable energy systems.

Today, the Internet offers vast resources for engineering students; it is our job as teachers to provide a well-defined learning path for utilizing these resources. We should also challenge our students with problems that attract their imaginations. This book addresses this task by providing a systems approach to the global application of the presented concepts in sustainable green energy production, as well as analytical tools to aid in the design of renewable microgrids.

In each chapter, I present a key engineering problem, and then formulate a mathematical model of the problem, followed by a simulation test bed in MATLAB, highlighting solution steps. A number of solved examples are presented, while problems designed to challenge the student are given at the end of each chapter. Related references are also provided at the end of each chapter.

This book is accompanied by a companion website (www.wiley.com/go/smartpowergrid2e), which includes a Solution Manual and PowerPoint lecture notes with animation that can be adapted and changed as instructors deem necessary for their presentation styles. Solutions to the homework problems presented at the end of each chapter are also included in the Solution Manual. A prerequisite for the book is a basic understanding of electric circuits. The book presents a historical perspective of energy use; an analysis of fossil fuel use is provided through a series of calculations of human's carbon footprints in relation to fossil fuel consumption or that of a single household appliance. The book integrates and presents three areas of electrical engineering:

design of smart, efficient photovoltaic (PV), how to compute the energy yield of photovoltaic modules and the angle of inclination for modules with respect to their position to the sun for maximum energy yields, and wind microgrids. The book builds its foundation on the design of distributed generating system and the design of PV generating plants by introducing design-efficient, smart residential PV microgrid, including energy monitoring systems, smart devices, building load estimation, and load classification and real-time pricing. The book presents basic concepts of phasor systems, three-phase systems, transformers, loads, DC/DC converters, DC/AC inverters, and AC/DC rectifiers, which are all integrated into the design of microgrids for renewable energy as part of bulk interconnected power grids. The focus is on the utilization of DC/AC inverters as a three-terminal element of power systems for the integration of renewable energy sources; MATLAB simulations of PWM inverters are also provided. Topics covered are the basic system concepts of sensing, measurement, integrated communications, and smart meters; real-time pricing; cyber-control of smart grids; high green energy penetration into the bulk interconnected power grids; intermittent generation sources; and the electricity market and the basic modeling and operation of synchronous generator operations, the limit of power flow on transmission lines, power flow problems, load factor calculations and their impact on the operation of smart grids, real-time pricing, and microgrids, power grid bus admittance and bus impedance as well as a power flow analysis of microgrids as part of interconnected bulk power systems. In the final part of the book, the Newton formulation of power flow, the Newton–Raphson solution of a power flow problem, and the fast decoupled solution for power flow studies and short circuit calculations are presented.

This book provides the fundamental concepts of power grid integration with microgrids using green energy sources, which are on the technology road map of virtually all nations. The design of smart microgrids is the driver for the modernization of infrastructure using green energy sources, sensor technology, computer technology, and communication systems.

Ali Keyhani

January 2015
Berkeley, California

ACKNOWLEDGMENTS

Over the years, many graduate and undergraduate students have contributed to the material presented in this book, in particular, the following students: Chris Zuccarelli, an undergraduate student; Abir Chatterjee, Ehsan Dadashnialehi, and Paloma Sodhi of IIT, India; Vefa Karakasli of Istanbul Technical University, Turkey; and Adel El Shahat Lotfy Ahmed, Department of Electrical Power and Machines Engineering, Faculty of Engineering, Zagazig University, Egypt. Finally, I acknowledge the support of Professor Joel Johnson, Chair, and Mr. Edwin Lim of the Department of Electrical and Computer Engineering, Ohio State University, for software assistance.

I would also like to thank Simone Taylor, Director, Editorial Development.

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website:

www.wiley.com/go/smartpowergrid2e

The website includes:

- Solution Manual for instructors
- PowerPoint presentations for instructors

CHAPTER 1

GLOBAL WARMING AND MITIGATION

1.1 INTRODUCTION—MOTIVATION

The world electric energy production is 65% thermal (coal, gas, and oil), 22% hydro, 12% nuclear, and 1% renewable. The 1% renewable energy is produced by 3% solar, 24% wind, 29% geothermal, and 4% biomass.[1] The trend of renewable energy production is alarming low. The United States and China have the largest energy consumption. The two countries' combined energy productions are 31% and consumptions are 41% of the world's total energy in 1999 as reported by International Energy Agency (IEA).[2] Sustainable energy production and the efficient utilization of available energy resources, thereby reducing or eliminating our carbon footprint, is one of our greatest challenges in the twenty-first century. This is a particularly perplexing problem for those of us in the discipline of engineering and sciences. This book addresses the problem of sustainable electric energy production as part of the design of building efficient microgrids and distributed generation and smart power grid renewable energy systems.

1.2 FOSSIL FUEL

It is estimated that fossil fuels—oil, natural gas, and coal—were produced 300–370 million years ago.[1] Over millions of years, the decomposition of the flora and fauna remains that lived in the world's oceans produced the first oil. As the oceans receded, these remains were covered by layers of sand and earth, and were subjected to severe climate changes: the Ice Age, volcanic eruption, and

Design of Smart Power Grid Renewable Energy Systems, Second Edition. Ali Keyhani.

Companion website: www.wiley.com/go/smartpowergrid2e

drought burying them even deeper in the earth's crust and closer to the earth's core. From the earth's core intense heat and pressure, the remains essentially were boiled into oil. If you check the word "petroleum" in a dictionary, you will find it means "rock oil" or "oil from the earth."

The ancient Sumerians, Assyrians, Persians, and Babylonians found oil at the bank of the Karun and Euphrates rivers as it seeped above ground. Historically, humans have used oil for many purposes. The ancient Persians and Egyptians used liquid oil as a medicine for wounds. The Zoroastrians of Iran made their fire temples on top of percolating oil from the ground.[1] Native Americans used oil to seal their canoes.[1]

In fact, although our formally recorded history of humanity's energy use is limited, we can project the impact of energy on early civilizations from artifacts and monuments. The legacy of our oldest societies and their use of wood, wood charcoal, wind, and water power can be seen in the pyramids of Egypt, the Parthenon in Greece, the Persepolis in Iran, the Great Wall of China, and the Taj Mahal in India.[3]

1.3 ENERGY USE AND INDUSTRIALIZATION

The first energy source was wood. Then coal replaced wood, and oil began to replace some of the coal usage to the point that oil now supplies most of the energy needs around the world.

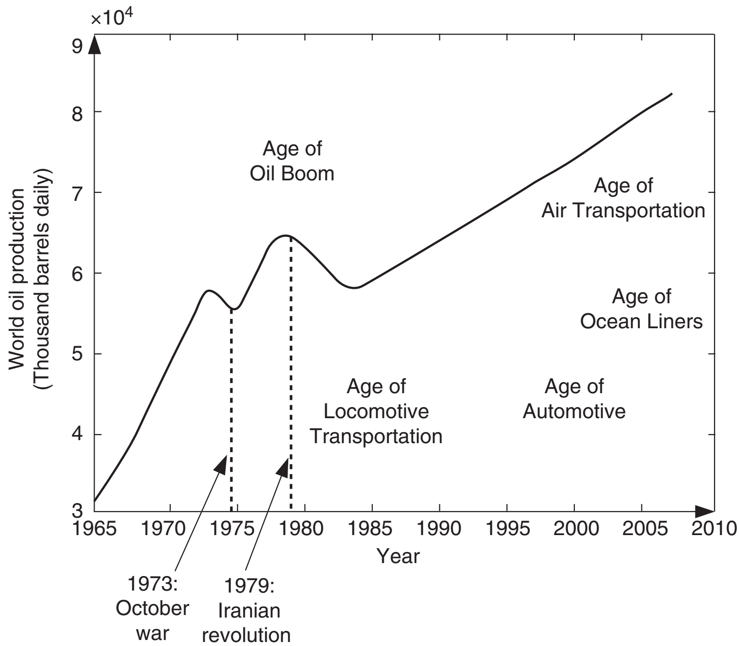


Figure 1.1 The world's oil production (consumption) from 1965–2000 and estimated from 2005–2009.[4,5]

Since the Industrial Revolution, humans have been using coal. Since 1800, for approximately 200 years, humans have been using oil. Sometime in the past, human societies left nomadic way of life, developed agriculture to produce food. Humans used wood and wood charcoal for cooking food. Recorded history shows that human societies have been using wood energy for 5000 years out of 100,000 years living on earth. Similarly, modern human societies have been using oil for 200 years out of 5000 years of recorded history. In the near future, the human societies would exhaust the oil reserve. Oil is not renewable; it cannot be made again. The oil and gas should be conserved. Figure 1.1 depicts the plot of oil production from 1965 to 2000 and estimated from 2005 to 2009[4,5] and the impact of oil on industrialization.

1.4 NEW OIL BOOM–HYDRAULIC FRACTURING (FRACKING)

The new technology in oil and gas extraction from wells deep in the earth rock crust is known as hydraulic fracturing.[6] Fracturing of the rock crust of earth is accomplished by directing pressurized mixture of water with sand and chemicals into crust of earth below the water lines. This technique of oil and gas extraction is known as fracking. Fracking is the method used in wells for shale gas, tight gas, tight oil, and coal seam gas[6] hard rock wells. Fracking has raised environmental concerns. Water contamination, air quality, and migration of chemicals to the ground surface have become a major concern of environmental groups. Fracking has reversed the decline of oil and gas production in United States and has made United States self-sufficient in oil and gas. Fracking methods have become a high charged political issue.[6–9]

1.5 NUCLEAR ENERGY

The US departments of energy estimates worldwide uranium resources are generally considered to be sufficient for at least several decades. The amount of energy contained in a mass of hydrocarbon fuel such as gasoline is substantially lower than in a much less mass of nuclear fuel. This higher density of nuclear fission makes it an important source of energy; however, the fusion process causes additional radioactive waste products. The radioactive products will remain for a long time giving rise to a nuclear waste problem. The counterbalance to a low carbon footprint of fission as an energy source is the concern about radioactive nuclear waste accumulation and the potential for nuclear destruction in a politically unstable world.

1.6 GLOBAL WARMING

Figure 1.2 depicts the process of solar radiation incident energy and reflected energy from the earth's surface and the earth atmosphere. Greenhouse gases in

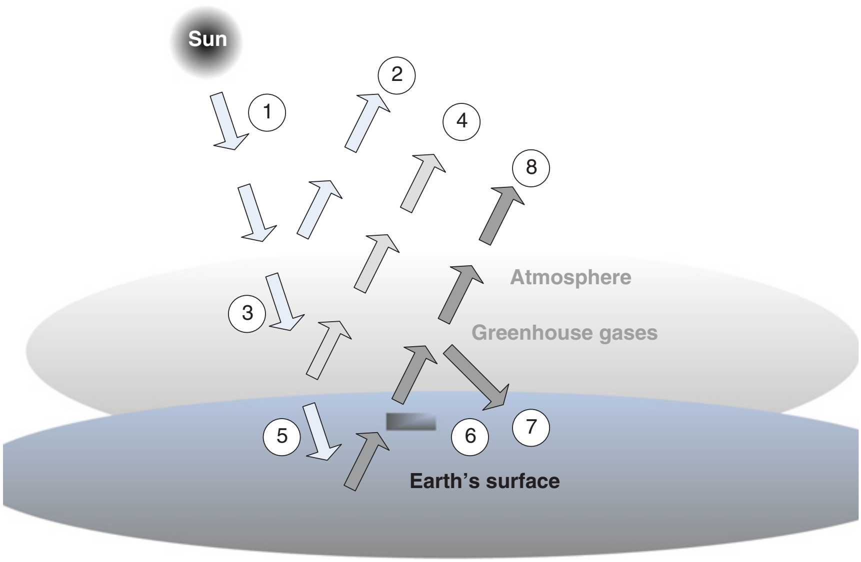


Figure 1.2 The effects of sun radiation on the surface of the earth.

the earth's atmosphere emit and absorb radiation.[10–12] This radiation is within the thermal infrared range. Since the burning of fossil fuel and the start of the Industrial Revolution, the carbon dioxide in the atmosphere has substantially increased as shown in Figures 1.3 and 1.4. The greenhouse gasses are primarily carbon dioxide, carbon monoxide, ozone, a large amount of water vapor, and a number of other gases. Within the atmosphere of earth greenhouse gasses are trapped.

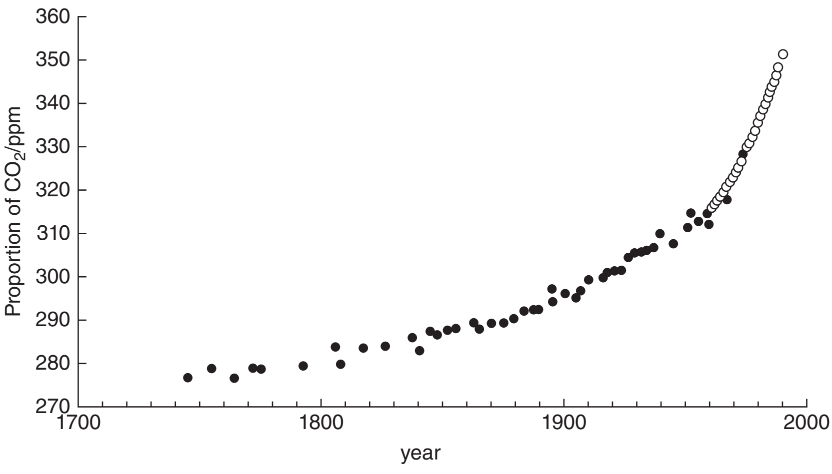


Figure 1.3 The production of CO_2 since 1700.[13]

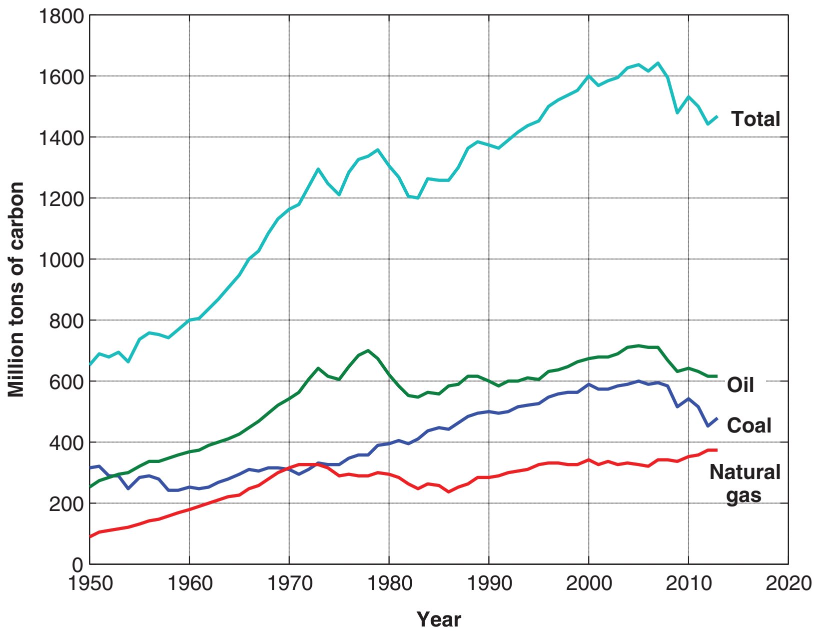


Figure 1.4 The production of CO_2 since 1950.[13]

The solar radiation incident energy as depicted by circle 1 is emitted from the sun and its energy is approximated as 343 W/m^2. Some of the solar radiation, depicted by circles 2 and 4, is reflected from the earth's surface and the earth's atmosphere. The total reflected solar radiation is approximated as 103 W/m^2. Approximately 240 W/m^2 of solar radiation, depicted by circle 3, penetrates through the earth's atmosphere. About half of the solar radiation as depicted by circle 5, approximately 168 W/m^2, is absorbed by the earth's surface. This radiation is depicted by circle 6 and it is converted into heat energy. This process generates infrared radiation in the form of emission of a long wave back to earth. A portion of the infrared radiation is absorbed. Then, it is reemitted by the greenhouse molecules trapped in the earth's atmosphere. Circle 7 represents the infrared radiation. Finally, some of the infrared radiation (circle 8), passes through the atmosphere and into space. As the use of fossil fuel is accelerated, the carbon dioxide in the earth's atmosphere is also accelerated. The growth of carbon dioxide in the atmosphere is shown in parts per million in Figure 1.3.

The World Meteorological Organization (WMO)[13] is the international body for monitoring climate change. The WMO has clearly stated the potential environmental and socioeconomic consequences for the world economy if the current trend continues. In this respect, global warming is an engineering problem, not a moral crusade. Until the world takes serious steps to reduce carbon footprints, pollution and the perilous deterioration of earth's environment will continue.

The CO_2 emission into the atmosphere has peaked during the last 100 years. If concentrated efforts are made to reduce the CO_2 emission and it is reduced over the next few hundred years to a lower level, the earth's temperature will still continue to rise, however, and then stabilize.

Reduction of CO_2 will reduce its impact on the earth's atmosphere; nevertheless, the existing CO_2 in the atmosphere will continue to raise the earth's temperature by a few tenths of a degree. The earth's surface temperature will stabilize over a few centuries.

The rise in temperature due to trapped CO_2 in the earth's atmosphere will impact the thermal expansion of oceans. Consequently, the sea level will rise due to melting of ice.

As the ice sheets continue to melt due to rising temperatures over the next few centuries, the sea level will also continue to rise.

The US contribution is shown in Figure 1.5 which depicts the contributions of various fossil fuel types to CO_2.

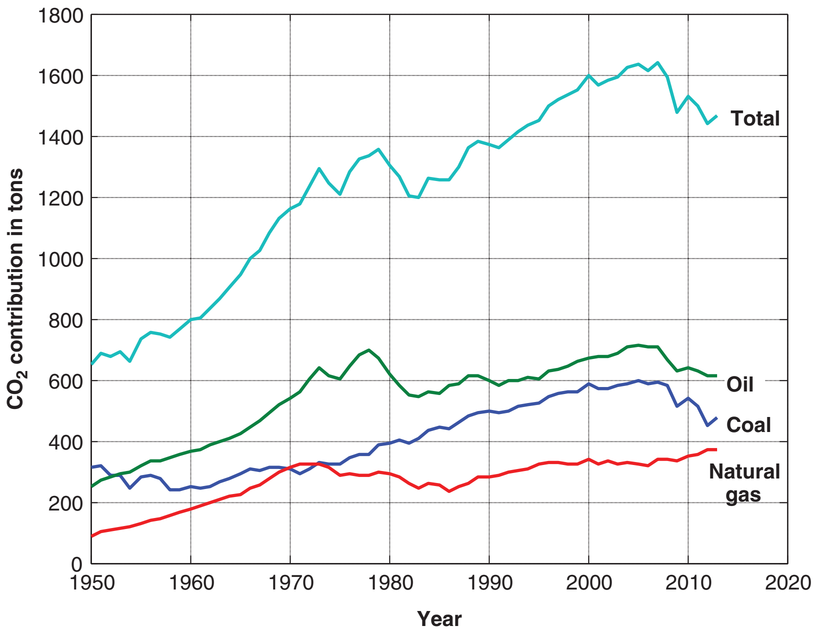


Figure 1.5 US energy-related carbon dioxide emissions by fuel type, 1950–2012, with projection for 2013.[13] Source: Compiled by Earth Policy Institute with 1950–1993 from "Carbon Dioxide Emissions from Energy Consumption by Source, 1949–2011," Table 11.1 in U.S. Department of Energy (DOE), Energy Information Administration (EIA), "Annual Energy Review," available at www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb1101, updated September 27, 2012; 1994–2013 from "U.S. Macroeconomic Indicators and CO_2 Emissions," Table 9a in DOE, EIA, "Short-Term Energy Outlook," available at www.eia.gov/forecasts/steo/tables/?tableNumber=5}, updated September 10, 2013. Note: Emissions figures are in million tons of carbon; for tons of CO_2, multiply by 44/12.

1.7 ESTIMATION OF FUTURE CO_2

The rapidly growing electrification of developing world and their reliance on fossil fuel vehicles increases, the demand for energy has turned developed nations to mass production of fossil fuels for power and energy. The subsequent burning of these resources has increased the amount of carbon dioxide in the earth's atmosphere. Figure 1.3 shows the measured proportion of CO_2 in the atmosphere over the last few centuries. Table 1.1 presents the CO_2

TABLE 1.1 Annual Production of CO_2

Year	CO_2 (ppm)	Year	CO_2 (ppm)
1745	277	1930	306
1754	279	1933	307
1764	277	1937	308
1772	279	1940	310
1774	279	1945	308.5
1793	279	1952	311
1805	284	1954	315
1808	280	1959	312
1817	283	1960	314
1826	284	1961	312
1837	287	1962	316
1840	283	1963	317
1845	288	1964	318
1847	287	1965	320
1850	288	1967	320.5
1854	289	1968	321.5
1860	290	1969	322
1865	288	1970	323
1870	289	1971	324
1875	290	1972	327
1880	291	1974	328.5
1882	292	1976	330
1886	292	1977	330.5
1893	294	1978	332
1894	298	1979	333
1900	296	1980	335
1904	295	1981	337
1906	297	1982	339
1910	299	1983	340
1916	300	1984	341
1917	300	1985	342.5
1919	301	1986	344
1920	301.5	1987	345
1921	301	1988	347
1923	305	1989	349
1926	306	1990	352

measurements for each year recorded in this figure. With the accelerated increase in transportation and electricity generation since the 1900s, the burning of more fossil fuels has caused an exponential rising trend in the carbon dioxide concentration.

Using Table 1.1 data, an exponential equation is used to estimate the carbon dioxide concentration for future years if energy production trends are unaltered. This equation was found by fitting an exponential best fit line to the data in Figure 1.3 and Table 1.1 using Microsoft Excel. The equation is

$$\text{Concentration} = 1.853^{*}\text{e}^{(0.0146^{*}x)} + 277 \tag{1.1}$$

Here, x is the number of years since 1745 and "Concentration" is the proportion of carbon dioxide in parts per million. Equation (1.1) was plotted against the available data in Figure 1.6 and also projected out to the year 2100 to estimate the CO_2 concentration for the year 2100 in future. The estimated carbon dioxide proportion in the year 2100, if current trends continue, is about 610 parts per million, which is nearly double the current proportion of carbon dioxide in the atmosphere. Such data can show the importance of reducing the global carbon footprint by investing in clean energy technologies and more efficient power generation.

If this projection in carbon dioxide concentration would become a reality, the increased amount of CO_2 in the earth's atmosphere would have disastrous effects. More carbon dioxide, as a major greenhouse gas, would trap more of

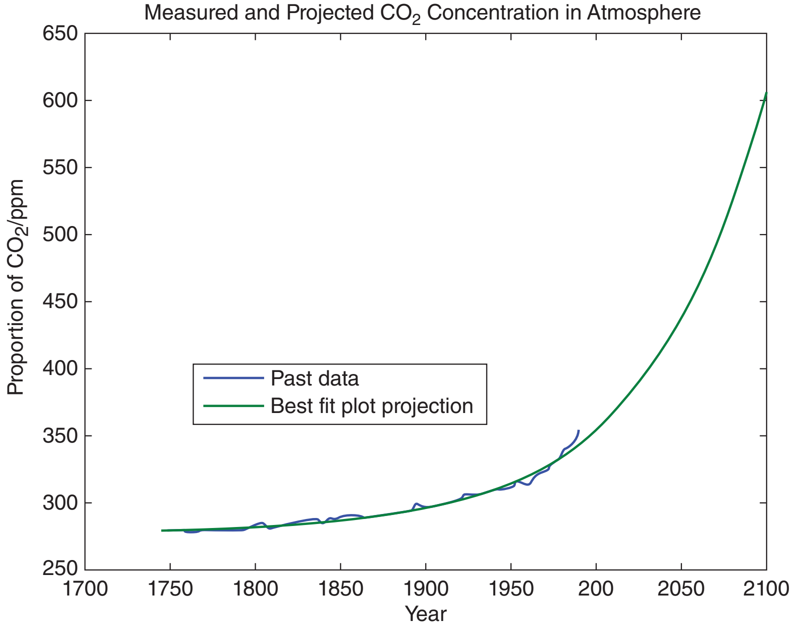


Figure 1.6 Recorded and estimated annual production of CO_2.