DESIGN OF SMART POWER GRID RENEWABLE ENERGY SYSTEMS

ALI KEYHANI

IEEE

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I dedicate this book to my father,
Dr. Mohammed Hossein Keyhani

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FOREWORD

It is an honor for me to add my comments to a very important book by Professor Ali Keyhani, *Design of Smart Grid Renewable Energy Systems*.

The restructuring of the electric power industry was a critical step for individual stakeholders, facilitating their wide participation in the production, delivery, and utilization of energy. The "smart grid" has further offered alternatives to participants looking to enhance the reliability, sustainability, and capability for customer choices in energy systems. The smart grid has made it possible to set up microgrids that could be operated as stand-alone islands in critical operating conditions. Such small installations can enhance the reliability of regional electric power systems when the larger grid is faced with major contingencies. There are several practical examples of microgid installations which have demonstrated that the use of smart switches in distributed power grids could reduce the number and the duration of outages.

In addition, the smart grid allows microgrids to optimize the use of volatile and intermittent renewable energy resources and enhance the sustainability of regional power systems. The applications of solar photovoltaics, which mostly follow the daily load profile for power generation, on-site or local wind energy, along with storage devices for microgrid installations could provide an inexpensive and sustainable means of supplying microgrid loads. The principles of widespread utilization of energy storage can also be found in the emerging market of plug-in electric vehicles, which would utilize wind energy at off-peak hours. Such microgid applications could also eliminate the need for extensive additions of high voltage lines for the transmission of renewable energy across densely populated regions of the world.

However, the evolutions in the electric power industry that I believe will truly revolutionize the way we deliver electricity to individual consumers are smart grid applications related to real-time pricing, hourly demand response, and the expansion of customer choices for promoting energy efficiency. The use of new smart grid innovations would make it possible for consumers to prioritize their energy use according to their daily schedules, needs, and preferences, taking into account a variable cost of electricity to save money. Smart grid advancements would also enable automated control systems to optimize energy use at home or for businesses, identifying the most appropriate times for device operation to reduce the cost of electricity.

Customer participation will offer a number of incentives for the optimization of electric power operations, including lower operation costs by eliminating the commitment of costly generating units at peak hours, mitigating mandatory system upgrades that are required for responding to a few hundred hours of annual peak loads, and reducing the chance of transmission congestion, which could otherwise operate the power system at a state close to its critical point of collapse. Demand response could also offer a less fluctuating daily profile, which would make it possible to forecast the daily load profile and schedule fuel and hydro consumption more comprehensively and efficiently for power generation.

I believe the content of this book will expose readers to subjects that could potentially alter the paradigm for energy generation, delivery, and utilization in the foreseeable future. I would like to congratulate Professor Keyhani for his keen interest in electric power system innovations and thank him for his efforts on introducing such topics to all of us.

MOHAMMAD SHAHIDEHPOUR

Bodine Chair Professor and Director
Center for Electricity Innovation
Illinois Institute of Technology
Chicago, Illinois, USA
January 2011

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 21st 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 imagination. 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 practical design of renewable microgrids. In each chapter, I present a key engineering problem, then formulate a mathematical model of the problem followed by a simulation testbed 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.

The book provides an Instructor's *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*.

The concepts presented in this book integrate three areas of electrical engineering: power systems, power electronics, and electric energy conversion systems. The book also addresses the fundamental design of wind and photovoltaic (PV) energy microgrids as part of smart bulk power-grid systems. A prerequisite for the book is a basic understanding of electric circuits. The book builds its foundation by introducing 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.

In the first chapter, in addition to a historical perspective of energy use, an analysis of fossil fuel use is provided through a series of calculations of our carbon footprint in relation to an entire country's fossil fuel consumption or that of a single household appliance. In Chapter 2, we review the basic principles underlying power systems, single-phase loads, three-phase loads, single- and three-phase transformers, distribution systems, transmission lines, and power system modeling. The generalized per unit system of power system analysis is also introduced. In Chapter 3, the topics include AC/DC rectifiers, DC/AC inverters, DC/DC converters, and pulse width modulation (PWM) methods. The focus is on the utilization of inverters as a three-terminal element of power systems for the integration of wind and PV energy sources; MATLAB simulations of PWM inverters are also provided. In Chapter 4, the fundamental concepts in the design and operation of smart grid power grids are described. The chapter introduces the smart grid elements and their functions from a systems approach, and provides an overview of the complexity of smart power grid operations. Topics covered in the chapter include 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. We are also introduced to 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. These concepts set the stage for the integration of renewable energy in electric power systems. In Chapter 5, we study PV energy sources. We learn 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. The chapter also presents the modeling of PV modules, the microgrid design of PV power plants, and the maximum power point tracking of PV systems. Chapter 6 introduces wind power generation by describing the modeling of induction generators as part of a microgrid of renewable energy systems. In this chapter, we also study the utilization of doubly-fed induction generators, variable speed permanent magnet generators, brushless generators, and variable-speed wind power conversion from a system's perspective. In Chapter 7, the modeling bus admittance and bus impedance for power grids are presented, as well as a power flow analysis of microgrids as part of interconnected bulk power systems. In Chapter 8, we study the Newton formulation of power flow, the Newton-Raphson solution of a power flow problem, and the fast decoupled solution for power flow studies.

This book provides the fundamental concepts of power grid and microgrid integration using green energy sources, which is a goal of virtually all nations. The design of microgrids is key to the modernization of our infrastructure using green energy sources, power electronics, control and sensor technology, computer technology, and communication systems.

Ali Keyhani

January 2011
Sanibel Island, Florida

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I thank my wife Maureen Keyhani for her understanding and support.

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CHAPTER 1

ENERGY AND CIVILIZATION

1.1 INTRODUCTION

Energy technology plays a central role in societal economic and social development. Fossil fuel-based technologies have advanced our quality of life, but at the same time, these advancements have come at a very high price. Fossil fuel sources of energy are the primary cause of environmental pollution and degradation; they have irreversibly destroyed aspects of our environment. Global warming is a result of our fossil fuel consumption. For example, the fish in our lakes and rivers are contaminated with mercury, a byproduct of rapid industrialization. The processing and use of fossil fuels has escalated public health costs: Our health care dollars have been and are being spent to treat environmental pollution-related health problems, such as black lung disease in coal miners. Our relentless search for and need to control these valuable resources have promoted political strife. We are now dependent on an energy source that is unsustainable as our energy needs grow and we deplete our limited resources. As petroleum supplies dwindle, it will become increasingly urgent to find energy alternatives that are sustainable as well as safe for the environment and humanity.

1.2 FOSSIL FUEL

It is estimated that fossil fuels—oil, natural gas, and coal—were produced 300 to 370 million years ago.[1] Over millions of years, the decomposition of the flora

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

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 drought burying them even deeper in the earth's crust and closer to the earth's core. From such 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 on the banks 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.[2]

1.3 DEPLETION OF ENERGY RESOURCES

Figure 1.1 depicts the time needed to develop various energy sources. Coal, oil, and natural gas take millions of years to form. The oil that was made more

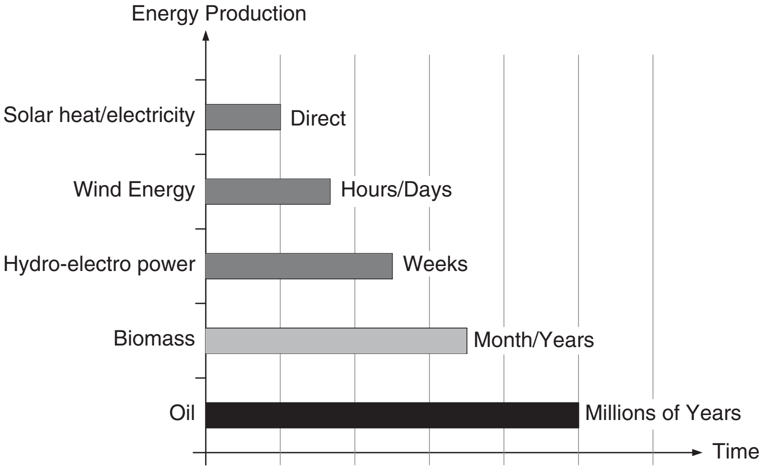

Figure 1.1 The Approximate Time Required for the Production of Various Energy Sources.

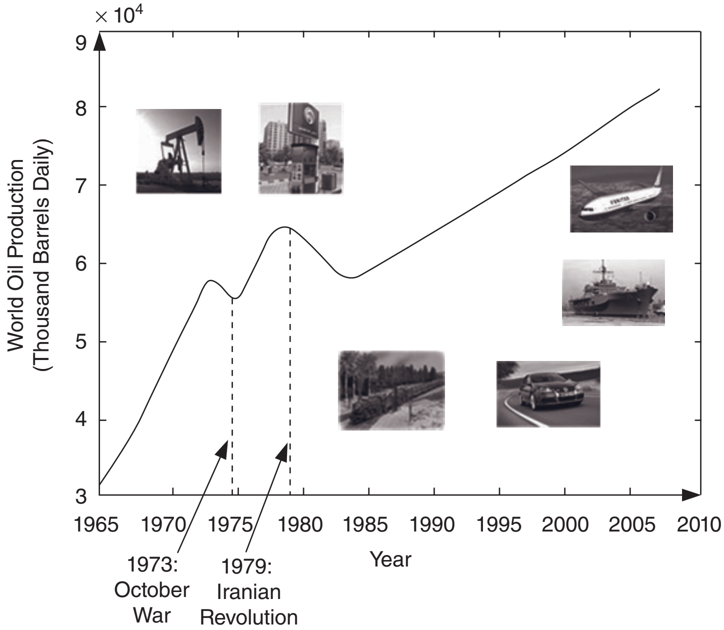

Figure 1.2 The World's Oil Production (Consumption) from 1965–2000 and Estimated from 2005–2009.[3]

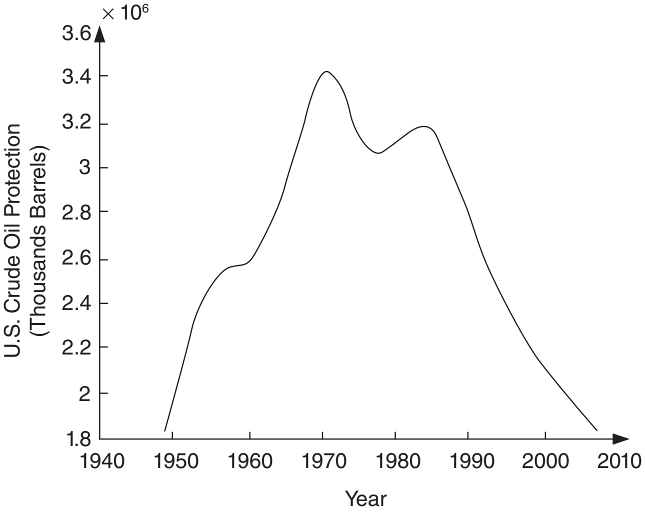

Figure 1.3 U.S. Oil Production/Consumption from 1940–2009.[3]

than a million years ago is being used today.[1] As we look at our energy use over the ages, it becomes clear that our new energy resources are substituting for old resources. Our first energy source was wood. Then coal replaced wood, and oil began to replace some of our coal usage to the point that oil now supplies most of our energy needs.

Since the Industrial Revolution, we have used coal. Since 1800, for approximately 200 years, we have used oil. However, our first energy source was wood and wood charcoal, which we used to cook food. Recorded history shows that humanity has been using wood energy for 5000 of the 100,000 years living on earth. Similarly, we have been using oil for 200 years of the 5000 years of recorded history. In the near future, we will exhaust our oil reserves. Oil is not renewable: we must conserve energy and save our oil—and gas as well.

The Middle East provides more than 50% of the oil imported to the United States. The United States' own oil production peaked around 1970. Europe's oil production is limited except for the North Sea oil reserve; it depends entirely on oil production from other parts of world. In Asia, China, India, Japan, and Korea depend on imported oil. The rapid economic expansion of China, India, and Brazil are also rapidly depleting the world oil reserves.

A closer look at Table 1.1 reveals that if the world reserves are used at the same rate as we do today, oil will run out in 40 years, our natural gas reserves will be depleted in less than 60 years, and our coal reserves will be exhausted in 200 years. No one can predict the future. However, we can empower every

TABLE 1.1 Proven Energy Resources around the World.[3,4]

	Petroleum		Natural Gas		Coal	
Region	2002 Preserved Resources (10^9 bbls)	R/P (Years)	2002 Proved Reserves (10^{12} SCF)	R/P (years)	2002 Preserved Reserves (10^9 tons)	R/P (years)
North America	49.9	10.3	52.4	9.4	257.8	240
South & Central America	98.6	42	250.2	68.8	21.8	404
Europe & Eurasia	97.5	17	2155.8	58.9	355.4	306
Middle East	685.6	92	1979.7	>100	????	>500
Africa	77.4	27.3	418.1	88.9	55.3	247
Asia-Pacific	38.7	13.7	445.3	41.8	292.5	126
World	1047.7	40.6	5501.5	60.7	984.5	204

Note: R/P = Reserves-to-production; bbls = billion barrels; SCF = standard cubic foot. R/P ratios represent the length of time that the remaining reserves would last if production were to continue at the previous year's rate. R/P is calculated by dividing remaining reserves at the end of the year by the production in that year.[4] (Reprinted with permission from the BP Statistical Review of World Energy 2009.)

energy user in a new energy economy based on renewable sources to become an energy producer by conserving energy, reducing carbon footprints, and installing distributed renewable energy sources.

1.4 AN ALTERNATIVE ENERGY SOURCE: NUCLEAR ENERGY

In 1789, Martin Heinrich Klaproth,[5] a German chemist, discovered uranium in the mineral pitchblende. Eugène-Melchior Péligot,[6] a French chemist, was the first person to isolate the metal, but it was Antoine Becquerel,[7] a French physicist, who recognized its radioactive properties almost 100 years later. In 1934, Enrico Fermi[8] used the nuclear fuel to produce steam for the power industry. Later, he participated in building the first nuclear weapon used in World War II. The U.S. Department of Energy[9] 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 in 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.

1.5 GLOBAL WARMING

Figure 1.4 depicts the process of solar radiation incident energy and reflected energy from the earth's surface and the earth atmosphere. Greenhouse gases in the earth's atmosphere emit and absorb radiation. 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 1.5 and 1.6. The greenhouse gasses are primarily water vapor, carbon dioxide, carbon monoxide, ozone, and a number of other gases. Within the atmosphere of earth, greenhouse gasses are trapped.

The solar radiation incident energy as depicted by circle 1 emitted from the sun and its energy is approximated as 343 W/m^2. Some of the solar radiation, depicted by circle 2 and circle 4, is reflected from the earth's surface and the earth's atmosphere. The total reflected solar radiation is approximated as 103 W per m^2. Approximately 240 W per m^2 of solar radiation, depicted by circle 3, penetrates through the earth's atmosphere. About half of the solar radiation (circle 5), approximately 168 W per m^2, is absorbed by the earth's surface. This radiation (circle 6) is converted into heat energy. This process generates infrared radiation in the form of the emission of a long wave back to earth. A portion of the infrared radiation is absorbed. Then, it is re-emitted

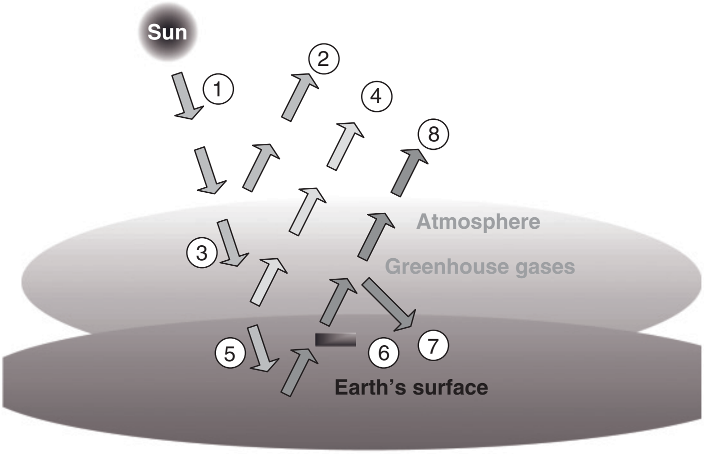

Figure 1.4 The Effects of Sun Radiation on the Surface of the Earth.

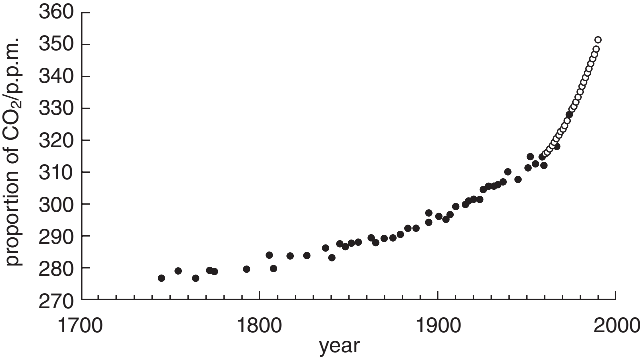

Figure 1.5 The Production of CO_2 since 1700. (Data from the Intergovernmental Panel on Climate Change, IPCC Third Annual Report.[11])

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 our atmosphere is shown in parts per million in Figure 1.5.

The World Meteorological Organization (WMO)[10] is the international body for the monitoring of 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 we take serious steps to reduce our carbon footprints, pollution and the perilous deterioration of our environment will continue.

Figure 1.6 depicts the condition of CO_2 in the upper atmosphere. The Y axis represents the magnitude of response. The X axis is plotted showing the years into future. The Y axis, showing response efforts, does not have units. 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 temperature will still continue to rise, however, then stabilize. Figure 1.7 depicts the stabilization of CO_2 over the subsequent centuries.

The reduction of CO_2 will reduce its impact on the earth 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 as shown in Fig. 1.8.

The rise in the 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 sheets as shown in Fig. 1.10.

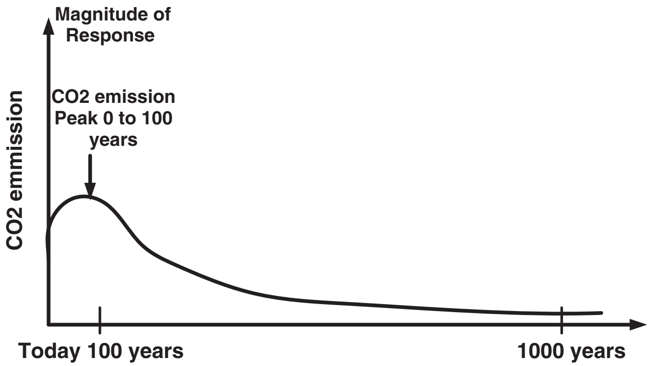

Figure 1.6 The Effect of Carbon Dioxide Concentration on Temperature and Sea Level. (Data from the Intergovernmental Panel on Climate Change, IPCC Third Annual Report.[11])

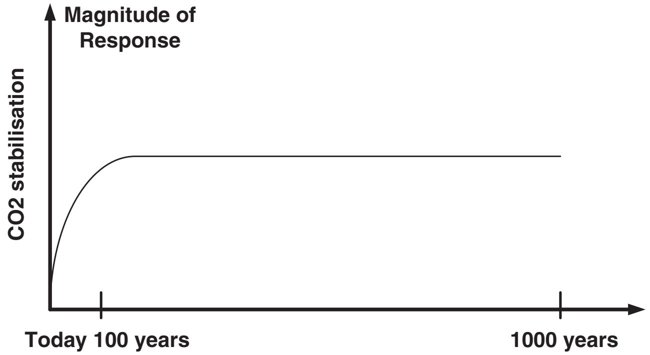

Figure 1.7 CO_2 Stabilization after CO_2 Has Been Reduced. (Data from the Intergovernmental Panel on Climate Change, IPCC Third Annual Report.[11])

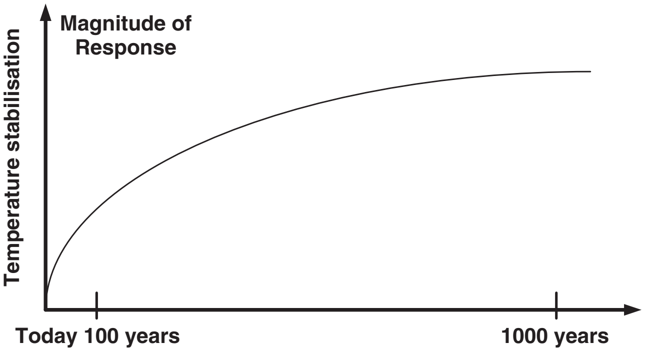

Figure 1.8 Temperature Stabilization after Reduction of CO_2 Emission.

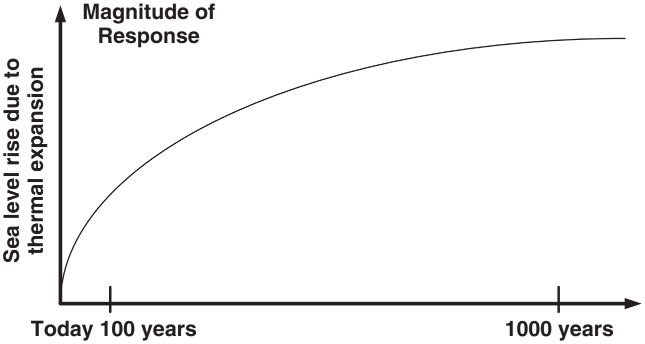

Figure 1.9 The Sea Level Rise after the Reduction of CO_2.

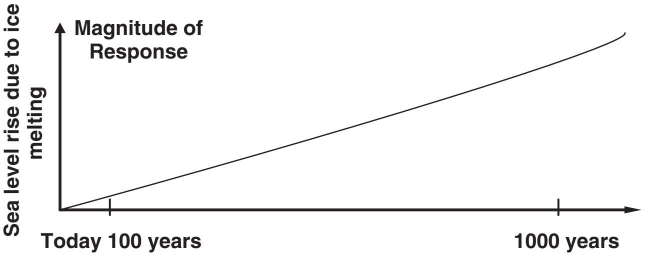

Figure 1.10 The Sea Level Rise after the Reduction of CO_2 in the Atmosphere.

As the ice sheets continue to melt due to rising temperatures over the next few centuries, the sea level will also continue to rise. Figures 1.6 through 1.10 depict the earth's conditions as a function of our level of response. As a direct consequence of trapped CO_2 in the atmosphere, with its melting of the polar ice caps causing increased sea levels that bring coastal flooding, our pattern of life on earth will be changed forever.