CLIMATE CHANGE: A WICKED PROBLEM

Under one cover, Frank Incropera provides a comprehensive, objective, and critical assessment of all issues germane to the climate change debate: science, technology options, economic ramifications, cultural and behavioral issues, the influence of special interests and public policy, geopolitics, and ethical dimensions. The underlying science is treated in depth, but in an approachable and accessible manner. A strong case is made for the reality of anthropogenic climate change, while confronting the range of issues that remain uncertain and deconstructing opposing views. Incropera assesses the strengths and weaknesses of technology options for mitigating the effects of climate change, analyzes nontechnical factors – economic, cultural, and political – and provides an in-depth treatment of ethical implications. This book is intended for those wishing to become fully informed about climate change and is designed to provide the reader with a firm foundation for drawing his or her own conclusions.

Frank P. Incropera is Clifford and Evelyn Brosey Professor of Mechanical Engineering at the University of Notre Dame, where he also served as Dean of Engineering from 1998 until 2006. He spent a majority of his career at Purdue University, and among his many honors he has received the American Society of Engineering Education (ASEE) Ralph Coats Roe Award for excellence in teaching (1982), the ASEE George Westinghouse Award for contributions to education (1983), the American Society of Mechanical Engineers (ASME) Heat Transfer Memorial Award (1988), the Melville Medal for the best original paper published by ASME (1988), and the Worcester Reed Warner Medal of ASME (1995). He received the Senior Scientist Award from the Alexander von Humboldt Foundation of the Federal Republic of Germany in 1988 and in 1996 was elected to the U.S. National Academy of Engineering. In 2001, he was named by the Institute for Scientific Information as one of the 100 most frequently cited engineering researchers in the world. He is a Fellow of ASME and the American Association for the Advancement of Science (AAAS). Professor Incropera has had a long-standing interest in transport phenomena and in recent years has turned his attention to the broad range of technical and nontechnical issues associated with transition to a sustainable energy future.

Climate Change: A Wicked Problem

Complexity and Uncertainty at the Intersection of Science, Economics, Politics, and Human Behavior

FRANK P. INCROPERA

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To Andrea, who would rather I had spent my time in other ways, and to our grandchildren, Wally, Michael, Mallory, Brandon, and Kyle. May they have the wisdom and resilience to meet the challenges that await them.

Contents

Foreword

Frank Incropera has done a masterful job of making the case for taking action now to reduce the impact of greenhouse gases attributable to human activity. He does it in a way that even the most ardent skeptics will have to acknowledge is a persuasive and balanced case that respects counterarguments but engages them thoroughly and convincingly.

I have had the pleasure of knowing Dr. Incropera for almost twenty years. I first met him when he agreed to leave Purdue University and move north to take the helm as Dean of the College of Engineering at the University of Notre Dame. As a member of the Advisory Council of the College, I watched as Dr. Incropera put in place the building blocks of a great engineering school. And while many of those building blocks – nanotechnology, bioengineering, advanced control systems, supersonic wind tunnels, and the like – were beyond the ken of this nuclear submarine engineer, I was delighted to discover that the dean and I shared a passion for all facets of the production and use of energy for the benefit of society.

Over the years, I and several other members of the Advisory Council were asked to speak to his classes about the practical aspects of the energy system in America and around the world. You see, Dr. Incropera is more than just a superb engineer. As is amply demonstrated in his book, he has a gift for taking the most complex of technical subjects and making them understandable to casual readers. As one who almost flunked quantum mechanics, I can attest that this is a real gift. Beyond the technical, Dr. Incropera is always interested in the whole range of considerations for any complex energy system. Obviously, a sustainable system must be founded on good science. That is just the starting point. Economics, the environment, history, politics, tax policy, and socioeconomic issues all have roles to play in understanding why we have the energy mix we have today. More importantly, he believes that unless you clearly understand the role each of these

dimensions plays, it will be impossible to craft a solution to this "wicked problem."

As a teacher, Dr. Incropera's approach was to expose his students to multiple points of view to allow them to understand that there is no silver bullet. He would seek out executives from large energy companies, oil companies, venture capitalist firms, research organizations, and equipment manufacturers so his class could complement the sound technical base he was giving them with the real-world context in which they would have to operate. That philosophy is reflected in this book.

Let me illustrate his approach by using my own experience as a lecturer in his classes. I have been a senior executive at a company that was almost bankrupted building a nuclear power plant (GHG emissions free, I might add), a company that was one of the largest coal burners in the United States in a region where manufacturing demanded vast quantities of cheap electricity, and a company that has one of the cleanest generation footprints in the United States. Dr. Incropera had great intellectual curiosity about the driving forces behind the decisions that the companies, policy makers, and investors made in crafting the various regional energy mixes. And he relentlessly tried to extract from each of his guests the essence of what drove the decisions we made in hopes of imparting that knowledge to his students. In many ways, this book does what he did in his classes, and it works.

Dr. Incropera's intellectual curiosity is manifest throughout this book. In the early chapters, he provides that sound technical base he provided to his students. By cataloging a clear compilation of the growing body of climate change science, he lays out an indisputable case for action. What distinguishes his work is that he is refreshingly honest where the evidence is contradictory. He acknowledges that some theories are unprovable in our lifetimes or even in the lifetime of several generations. But he brings that common sense that we come to admire in our everyday lives that at some point the evidence points us in the direction of doing something. That sense of urgency is enhanced by his discussions of the consequences of inaction.

His research doesn't stop there. He proceeds to do a deep dive into all of the other factors that either got us to where we are or will make it difficult to get us out. His book thoughtfully covers potential mitigation strategies, public policy options, and the history of efforts to craft national and international solutions.

Several aspects of this book should make it required reading for every public policy student, legislator, regulator, and business decision maker in

the energy space. By acknowledging the legitimate economic and reliability benefits of fossil fuels, he makes the dialogue less of a personal attack. His discussion in Chapter 9 of the complex human behavioral issues suggests he believes that people generally don't engage in irrational activities. Today's energy mix was developed to address real human needs. In fact, the reason that demand for fossil fuels continues to grow in developing nations is that they are effective at addressing those fundamental needs. And while acknowledging that goes a long way in getting people to focus on less harmful alternatives to accomplish the same goals, he doesn't let people off the hook for sloppy intellectual analysis.

The other insight in the book is that just because we can't fix all of the problems doesn't mean we should do nothing. I was involved in the efforts from 2008 through 2010 to craft comprehensive climate change legislation. The Waxman-Markey Bill passed the U.S. House in 2009 with a razor-thin margin. Its complexities, however, doomed it in the Senate, where a bipartisan effort to make the legislation more palatable stalled long enough to allow unrelated intervening developments to torpedo the initiative. Since then, Congress has been unable to accomplish anything on climate change. I believe part of that is the legacy of an overly complex Waxman-Markey Bill that no one wants to revisit. Dr. Incropera's solution would be to not give up, just because a coordinated national or global effort is highly unlikely. His recommendation is to work hard on what we can do now – conversion to natural gas, battery storage to advance solar and wind resources, more nuclear, and more electric vehicles. In one sense, that is exactly what is happening. Many states are working those edges with renewable mandates, energy efficiency programs, electric vehicle incentives, and the like. The federal government's regulators continue to make their mark through their regulatory push to enact more aggressive vehicle fuel efficiency standards and greenhouse gas rules that will likely keep the states as our incubators for thoughtful solutions.

This state of play leaves much national policy work undone. But Dr. Incropera thoughtfully addresses what policy paths would enhance existing greenhouse gas reduction strategies. For all who are taking his advice not to wait until it is too late, I would recommend that they read this book to strengthen their resolve and give them insights into the issues they must engage in order to succeed.

Anthony F. Earley Jr.
Chairman, CEO, and President
PG&E Corporation

Foreword

I have known Frank Incropera for more than thirty years. We both served as the chair of our respective mechanical engineering departments and then later in other leadership positions. In our respective roles, we often discussed both scientific and academic issues. While we did not always agree, I always found him to be an incredibly insightful individual who has a unique way in which he views the world and the environment around us.

As the author of what is perhaps the most highly regarded textbook on the subject of heat and mass transfer, he is an internationally renowned authority and someone whose opinion I greatly respect and friendship I greatly value. As the Clifford and Evelyn Brosey Professor of Mechanical Engineering at the University of Notre Dame, Professor Incropera continues to address important problems from a unique "problem-solving" perspective and has a deep knowledge and passion for trying to understand the fundamental basis of issues from an engineering perspective. In keeping with his past record, this is exactly what he has done in this latest publication, *Climate Change: A Wicked Problem*.

Who is this book written for? For anyone who is earnestly seeking to increase the breadth of his or her knowledge and understanding of one of the twenty-first century's most contentious issues. Professor Incropera expresses his views and opinions forthrightly throughout, yet his work addresses the issue from the perspective of an engineer, a scientist, an educator, and a pragmatist. As a fair-minded arbiter, he wades deep into the science, but his book also covers numerous related aspects of the issue from the perspective that most interested non-scientists will find accessible.

Professor Incropera dons several hats in his latest book; whether he's momentarily discussing climate change from the standpoint of business, history, ethics, politics, or economics, the scientist/engineer is always standing nearby, ready to lay down facts and figures as the foundation for

potential solutions. Throughout, he changes hats seamlessly, looking at challenges through the eyes of different stakeholders, but always returning to his engineering and scientific base, where he has a standing that few have in this often fevered discussion. He has reached a conclusion, summarized succinctly at the end of Chapter 5: "With regard to scientific matters, the debate is all but over. The Earth will continue to warm due to human forcings, and manifestations of warming will become more pronounced." Whether the reader agrees or disagrees, there is much to recommend in the chapters that follow.

In Chapter 6, for example, Professor Incropera offers potential solutions in a discussion of "Mitigation, Adaptation, and Geoengineering." By Chapter 11, he posits a call to action that resonates strongly at the Georgia Institute of Technology, a world-class technological university where sustainability has long been part of our ethos. Ever the pragmatist, Professor Incropera makes a practical, compelling case for what can be done in a time when what perhaps should be done has too many hurdles to clear.

"Mitigation is not an option; it is a necessity, a cornerstone of efforts to deal with global warming," Professor Incropera writes, before going on to say, "Simply put, energy efficiency must be driven into every facet of human activity." The goal is achievable. Forward-thinking businesses have already incorporated that credo into their operations because they understand that it's wise from both economic and environmental perspectives.

At Georgia Tech, sustainability, of which energy efficiency is a vital part, is woven throughout our curriculum and drives a good deal of the research conducted by our faculty, staff, and students. From my personal perspective, I have to ask, "What happens if we are wrong and climate change is not the result of human activity? What is the resulting penalty for the actions proposed in this book?" I recognize that trade-offs, some controversial, will be necessary to bring Professor Incropera's recommendations to fruition, but the long-term payoffs will be significant economically and environmentally, and will accrue to the generations that follow.

Whether the reader is a climate change novice or an experienced hand, a scientist or an interested layman, *Climate Change: A Wicked Problem* provides invaluable information and insights with which to intelligently engage in shaping the future of this monumental challenge. It will challenge your thinking regardless of your starting point.

G.P. "Bud" Peterson, President
Georgia Institute of Technology
Atlanta, Georgia

Foreword

There is something innately human about caring for other humans and caring for our planet as a whole. Yet, on an issue such as climate change, which arguably could affect all humans and the planet, we are surrounded by controversies, conflicts, and debates in our social discourse. Why? It is because among the many issues that we all face today, climate change spans perhaps the most number of dimensions: scientific, economic, social, ethical, religious, and political. Confronted with this magnitude of complexity, we often grasp only a few facets that we can individually fathom and ignore the other dimensions, epitomizing the story of the blind men and an elephant. It is, therefore, not surprising to find people from different (and even similar) backgrounds talking past each other. Clarity is elusive. In such moments of confusion we need someone to simplify, distill, and connect the dots for us. This remarkable book by Frank Incropera does exactly that – it offers the most balanced, unbiased, and holistic view of this highly complex landscape.

The book starts with energy, which is the lifeblood of our modern life and our economy. When we flip a light switch, drive to our neighborhood grocery store, or do a Google search, we unwittingly receive the benefits of 250 years of industrial revolution that started with the steam engine running on coal to modern computers powered increasingly by natural gas. And this industrial revolution has been largely about how we sourced, distributed, and used energy. It was and continues to be predominantly based on fossil energy. Burning fossil fuels emits carbon dioxide in the atmosphere, which has been claimed to be the key culprit behind global warming.

Dr. Incropera explains with utmost clarity what we know, what is the uncertainty in our knowledge, and what we don't know from the scientific viewpoint. How does our climate work? How much carbon dioxide have we emitted so far? How long does it last in the atmosphere? Are there other

sources of carbon dioxide? Are there other greenhouse gases and what influence do they have compared to carbon dioxide? What are the feedback mechanisms and what are the tipping points? How close are we to them? Dr. Incropera systematically helps the reader navigate through these difficult topics in the most uncomplicated and undemanding manner. He explains the difference between global warming and climate change, and why we are much more certain about the former and know much less about the latter. He addresses the issue of whether extreme weather events are connected to global warming and what the uncertainties are in our knowledge, what we can claim and what we cannot claim.

While it is important to understand the root causes, Dr. Incropera devotes a large section of the book to what we can do about it. A piece of this focuses on what we can do to mitigate global warming, how we ought to adapt to it, and what the risks are associated with geoengineering. But this is not just a technical issue, because technology is connected to economics; after all, energy is a commodity that all citizens in a modern economy use. It needs public policy because our choices of energy affect everyone else. Should there be financial incentives, should there be regulation, and if so, how much? Dr. Incropera even takes on the politics of climate change in the most nonpartisan manner, first delving into global politics and then into the debates in federal, state, and local governments. He extracts for the reader the underlying gist of the political debates and why the politics have come to the present state of affairs. Energy and climate invariably involve industry and the corporate world. Dr. Incropera describes how sound business policies can be mutually inclusive to environmental protection, and what the corporate world has (and has not) done so far to address climate change.

It is well known that the debate on climate change has dissenting opinions, and most books present either one side or the other. What is unique about Dr. Incropera's book is that in addition to the conventional wisdom on climate change, he devotes time to present the dissenting opinions as well. With unusual clarity and balance, he offers the arguments and distills them for the reader and dissects the knowns, unknowns, and uncertainties in these arguments, respecting the reader's prerogative to make up their own mind. There is a certain human element to this debate that becomes emotional and personal, which Dr. Incorpera presents with extraordinary clarity.

If the predictions of global warming turn out to be correct, it will affect the world as a whole: the close to 10 billion people, businesses, nations, and ecosystems. This makes it a human issue of extraordinary proportion,

warranting critical understanding of topics such as ethics, social justice, and religion. The world is replete with diversity of thought and philosophies on such matters, with deep cultural and historical underpinnings. Unlike science, there is no right or wrong answer. It is, therefore, rare to find books that deal with both science and such aspects of human nature and connect the dots between them. Dr. Incropera dares to take this on, tapping into the innate humanity among us, and does exceptionally well in confronting this difficult juxtaposition of science and humanities. He characteristically ends the book with an action plan that not only touches on technology and public policy but also integrates personal and social values.

As we enter a period of intense global and national discourse on this important topic, the timing of this book could not be better. People worldwide need to read Dr. Incropera's book to map out for themselves the panoramic view of this multidimensional complex issue.

Arun Majumdar
Jay Precourt Professor, Stanford University
Former Vice President for Energy, Google
Founding Director, US Advanced Research Projects Agency – Energy (ARPA-E)
Former U.S. Acting Undersecretary of Energy, Department of Energy

Preface

To state the obvious, climate change is an environmental problem. But it has features that distinguish it from other well-publicized problems. For one, competing agents create uncertainty in linkages between cause and effect. With other environmental problems, deleterious effects are due solely to anthropogenic activities. There are no other agents. It is well known that automotive and power plant emissions such as carbon monoxide, sulfur dioxide, and particulates adversely affect human health and the environment. The same can be said of refrigerants that deplete stratospheric ozone. However, for climate change, anthropogenic agents associated with emissions of greenhouse gases such as carbon dioxide are superimposed on natural causes, and distinguishing between their effects is not a trivial matter.

Another distinguishing feature deals with time scales. For other environmental problems, adverse effects are near-term, if not immediate. In contrast, significant inertia is associated with the long residence time of atmospheric greenhouse gases and the slow rate at which equilibrium is achieved between the Earth's atmosphere and oceans. The effects of today's emissions are not felt today but over time, and it may be decades before they are unequivocally revealed. Lastly, unlike many environmental problems, climate change is not a regional or national problem. It is global.

The foregoing features make climate change a uniquely challenging environmental problem. But there's more. Four decades ago, Rittel and Webber (1973) introduced the notion of a *wicked problem*. Wicked problems are inherently societal problems, and in pluralistic societies with diverse interests and traditions there is seldom consensus on the nature of the problem, much less its solution. A wicked problem has many stakeholders, and any attempt at a solution has multiple consequences as its

implications ripple across the many affected parties. Whether the solution is *right* or *wrong* is not judged by absolute or objective standards but by the interests and values of the stakeholders. Climate change, or more specifically anthropogenic climate change, is a prototypical wicked problem.

By integrating a comprehensive set of relevant factors, this book is intended to inform the climate change debate in ways that recognize existing uncertainties and tensions, as well as limitations to achieving timely and meaningful solutions. Drawing on the most recent literature, the underlying science is treated in depth. A strong case is made for the reality of anthropogenic climate change, but not without confronting the range of issues that remain uncertain and deconstructing opposing views. A pragmatic approach is taken on options for mitigating the effects of climate change. Strengths and weaknesses of the options are identified, including limitations that render some options problematic and measures that must be taken to facilitate substantive contributions by others. Assessments include economic considerations, targets of opportunity for innovation, and barriers imposed by special interests, politics, and human behavior.

Although climate change is a comparatively new aspect of a longer-standing relationship between energy and the environment, the two are inextricable. In the 1950s and 1960s there was growing concern for the effects of fossil and nuclear fuels on air, water, and soil pollution, but it was not until the 1990s that climate change began to receive serious attention. Since then, there has been growing recognition that the issue is central to any assessment of energy options. Linkages between energy and climate change are addressed throughout this book, with the view that multiple options must be pursued to reduce the use of fossil fuels, but that economic realities preclude an abrupt withdrawal. Like it or not, the world is awash in fossil fuels, and they will continue to be used, possibly throughout the century. The challenge is to reduce consumption in ways that do not impair the global economy while significantly reducing the threat of climate change.

Issues contributing to the complexity of climate change are treated in eleven chapters. Because global warming is strongly tied to energy utilization, Chapter 1 provides an introduction to the different forms and uses of energy, the importance of energy to economic development, and the impact of energy utilization on the environment. Energy, Economics, and Environment (three big Es) are joined at the hip. It is not good enough to judge an energy portfolio exclusively in terms of its environmental impact, nor is it sufficient to judge it solely on the basis of economic considerations. The need for integration, by its very nature, mandates compromise.

Chapters 2 through 5 consider the scientific origins of global warming. A 2011 poll of the American public revealed that only 44% believed in the scientific basis for anthropogenic warming, down from 75% in 2001 (Harris, 2011). The remaining 56% were evenly divided between nonbelievers and those who simply weren't sure. A more recent survey of twenty nations – developed and developing – revealed that the United States is not alone in questioning the anthropogenic origins of climate change (IPSOS, 2014). Respondents were asked the following question: *To what extent do you agree or disagree* (that) *the climate change we are currently seeing is a* ***natural*** *phenomenon that happens from time to time?* Among Americans, Indians, and Chinese, approximately 50% agreed with the statement, and even in Great Britain (48%) and Germany (39%) there was significant agreement. Recognition that there is in fact a problem begins with the underlying science. What can we say with certainty about natural and anthropogenic agents of warming? What don't we know?

Chapter 2 deals with *natural drivers* of climate change, features of the global energy balance, and aspects of radiation propagation in the Earth's atmosphere that can alter the balance. Chapter 3 deals with *anthropogenic drivers* of warming and climate change. Greenhouse gases are identified and characterized in terms of relevant parameters, and emission trajectories – past and future – are provided. Chapter 4 deals with the extent to which warming has occurred, the contribution of anthropogenic agents, and prospects for future warming. Uncertainties and contentious issues are examined, including the most recent hiatus in the temperature record. Chapter 5 considers the effects of warming and climate change on humankind and the natural world. From rising sea levels to extreme weather events, evidence points to significant effects on the built and natural environments, water resources, food production, and human health and security.

A cautionary note! This book provides a comprehensive assessment of global warming and climate change, one that addresses all relevant factors – scientific and otherwise. It is also written with readers of varied backgrounds – scientific and nonscientific – in mind. That said, Chapters 3 and 4 and portions of Chapter 5 may be tough sledding for those disinclined to deal with scientific details. If you fit that description, I encourage you to make the effort. It will provide you with the *state of the science* circa 2014, including results that deconstruct efforts to dismiss the science. If you wish, the chapter footnotes can be ignored without loss of key material and arguments.

Three lines of defense against the effects of climate change are assessed in Chapter 6. The first line is to *mitigate* the effects by reducing factors that contribute to warming. Chapter 6 provides a comprehensive and critical assessment of technology options. What can be done to reduce greenhouse gas emissions and stabilize atmospheric concentrations at acceptable levels by transitioning to carbon-free sources of energy? Attention is focused on important and problematic issues such as the transition from coal to natural gas for power generation, implementation of carbon capture and sequestration, the role of nuclear power, and the pace at which the use of renewables can be increased. However, economic factors loom large in choosing policy options for decarbonizing the world's energy portfolio, and it is likely that the adverse effects of climate change will not be sufficiently dampened by mitigation measures. Enter the second line of defense – *adaptation* – which involves measures taken to increase the *resilience* of humans, their artifacts, and the environment to climate change. But such measures may also prove insufficient if greenhouse gas emissions continue on their current trajectory. That leaves *geoengineering*, measures of last resort designed to alter the climate system in ways that negate the effects of greenhouse gas emissions.

By focusing on technological options for dealing with climate change, Chapter 6 plays a central role in the book's narrative. That said, even as an engineer, I am not sanguine about prospects for technology doing it alone. It is a necessary part of the solution, but it may not be sufficient. Governments – national, state, and local – must play a role, and public policy options are discussed in Chapter 7. Other chapters of the book, particularly 1, 10, and 11, consider the need for a sea change in cultural norms.

Since climate change is a global problem, a critical question is whether consensus and cooperation can be reached on appropriate solutions. Achieving cooperation on a global scale is the most important requirement for dealing with the problem. Chapter 8 deals with the politics of climate change. From the United Nations to the governing bodies of the world's nations to legislative groups within states of each nation and to cities and towns within the states, politics strongly influences what is, or isn't, done to address the problem. In effect, Chapter 8 is a history lesson on the politics of climate change and, moving forward, a primer on difficulties associated with achieving consensus.

Discussion of climate politics continues in Chapter 9 with consideration of the strategies used by special interests in the United States to thwart mitigation measures. But barriers to dealing with climate change are not entirely technical, economic, or political, and Chapter 9 also considers

cultural conditions that influence decisions. In the face of scientific complexity and uncertainty, what cultural and behavioral factors cause some to dismiss the problem and others to push for solutions?

To this point, climate change is treated as a juxtaposition of the three *E*s (energy, economy and the environment). But there remains one more *E*, namely the *ethics* of climate change. If there are ethical implications to ignoring warming and climate change, what are the moral frameworks and religious traditions that inform these implications? In Chapter 10 these dimensions are explored in search of moral guidance. Although ethical theories are not without ambiguity, Aristotelian (virtue) ethics provides moral clarity consistent with a significant body of religious doctrine.

In a final analysis, what can be said about the problem of climate change and possible solutions? Chapter 11 makes it clear that the problem is real, serious, and must be addressed. It calls for an aggressive approach to reducing greenhouse gas emissions by amplifying public education and accelerating implementation of energy efficiency and conservation measures along with the use of carbon-free sources of energy and lifestyle changes. However, recognizing economic, social, and political realities, the reduction of atmospheric greenhouse gas concentrations to acceptable levels is highly unlikely. Adaptation must therefore combine with mitigation as integral pieces of the world's climate change strategy.

In recent years, I have had many opportunities to speak on climate change, often to nonscientific or technical audiences. I have also engaged in less formal conversations with friends and colleagues. These interactions have left me with several perceptions: (1) there is general (public) awareness of climate change; (2) to the extent that they exist, opinions on whether it is or is not a problem are often strongly held; and (3) many people, well educated or not, have a limited knowledge of the matter, despite many articles and books on the subject. It is these perceptions that provided the impetus for this book.

The book has several distinguishing features, beginning with its comprehensive and critical assessment of all issues germane to the climate change debate – the underlying science, technology options for mitigating the effects of climate change, economic ramifications of the options, cultural and behavioral issues, the influence of special interests and public policy, geopolitical issues, and the ethical implications of climate change. Contents of the book are true to the title labeling climate change as a *wicked problem*. The book also reflects what I bring to the table as an engineer. As well as extensive involvement with energy sciences and technologies in education and research, I have had many opportunities

to engage with thought leaders in energy sectors of the business community, including electric utilities; producers of fossil, nuclear, and renewable energy; and the transportation sector. These industries play a significant role in shaping energy policy – in the United States and elsewhere – and determining what actually gets done to reduce emissions. Their views on climate change span a broad spectrum, but a common thread is their sensitivity to costs and returns on capital investments. This sensitivity has sharpened my perspective on differences between what should be done and what can be done and has no doubt contributed to pragmatic elements of the book.

By integrating the many facets of climate change that inform debate on the subject, my goal is to provide the reader a foundation for shaping personal views, assessing new findings, and contributing to future discourse. The science will continue to evolve, as new data emerge and more is learned about energy exchange between and within the Earth's oceans, land, and atmosphere. Technologies that lend themselves to mitigating or dealing with the effects of climate change will advance, affecting the economic viability of specific measures. New knowledge and technologies will influence our perceptions of risk and our sense of urgency. Actions taken or not taken will continue to be influenced by the shifting sands of public opinion and geopolitics. *Your engagement with the issues matters.*

Acknowledgments

The broad scope of this book presented several challenges. Although my background as an engineer specializing in energy sciences and technologies equipped me to deal with the scientific and technological aspects of climate change, could I do justice to other relevant issues, from economics and public policy to ethics and human behavior? Could all issues be integrated in a readable and compelling manner? To whatever extent I've succeeded, I'm indebted to the assistance of others: To Steve Batill and Bill Colonis, who read early versions of the manuscript and identified weaknesses. To Marjorie Pfeill, who read what I thought was a satisfactory version of the chapter on ethics and suggested ways to make it better. To Anthony F. Earley Jr., Michael O'Sullivan, and Pat Eilers, who broadened and deepened my understanding of corporate perspectives on energy options, particularly economic implications. To my colleagues in Notre Dame's Mendoza College of Business – especially Leo Burke, Tom Frecka, and Jessica McManus – who provided many opportunities for me to engage them and their students in discussions of energy and climate change. To the book's editor, Matt Lloyd, whose involvement during the final stages of writing added value to the end product. And, to the many students – especially Felipe Witchger and Michael Della Penna – who have taken my course on Energy Technology and Policy and have stretched my thinking on the subject.

Abbreviations

ACC	Abrupt climate change
ACESA	American Clean Energy and Security Act
AIS	Antarctic ice sheet
ALEC	American Legislative Exchange Council
AMOC	Atlantic Meridional Overturning Circulation
AOGCM	Atmosphere-Ocean General Circulation Model
API	American Petroleum Institute
AR 3,4,5	Third, Fourth, and Fifth Assessment Reports of the IPCC
CAA	U.S. Clean Air Act
CAFE	Corporate average fuel economy standards
CC	Carbon content of a fuel (mass of carbon per mass of fuel, kg-C/kg-fuel)
CCOC	Cost of carbon capture ($/t-$CO_2$)
CCS	Carbon capture and sequestration
CCSP	Climate Change Science Program
CDM	Clean development mechanism of the Kyoto Protocol
CDR	A form of geoengineering involving carbon dioxide removal from the atmosphere to reduce its contribution to global warming
CEI	Competitive Enterprise Institute
CFC	Chlorofluorocarbon
CI	Carbon intensity of a fuel (carbon emissions per energy consumption, kg-C/GJ-fuel or kg-CO_2/MWh_e)
CIA	U.S. Central Intelligence Agency
COEJL	Coalition on the Environment and Jewish Life
COP	(United Nations) Conference of Parties
CPP	EPA Clean Power Plan

CRU	Climate Research Unit of the University of East Anglia
DOD	U.S. Department of Defense
DOT	U.S. Department of Transportation
EAIS	East Antarctic Ice Sheet
EC	European Commission
EI	Energy intensity (ratio of a nation's energy consumption to its GDP, MJ/$)
EIA	U.S. Energy Information Administration
ENSO	El Niño Southern Oscillation
EOR	Enhanced oil recovery
EOS	Earth orbiting system
EP	European Parliament
EPA	U.S. Environmental Protection Agency
ETS	EU emissions trading scheme
EU	European Union
EV	Electric vehicle
EWE	Extreme weather event
FCCC	(United Nations) Framework Convention on Climate Change
FEMA	U.S. Federal Emergency Management Administration
FIT	Feed-in tariff
GAO	U.S. Government Accountability Office
GCC	Global climate change; Global Climate Coalition
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Greenland ice sheet
GISS	NASA Goddard Institute of Space Sciences
GWP	Gross world product or global warming potential
HadCRU	UK Hadley Centre and Climate Research Unit of the University of East Anglia
HCFC	Hydrochlorofluorocarbon
HDI	Human development index
HFC	Hydrofluorocarbon
HHV	Higher heating value (energy per unit mass, kJ/kg) of a fuel
HV	Heating value (energy per unit mass, kJ/kg) of a fuel
ICE	Internal combustion engine
IEA	International Energy Agency
IGCC	Integrated gasification and combined cycle
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change