Preface

Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.

– Marie Skłodowska Curie

Academic research scientists tend to have a reputation for being socially and politically disengaged. Somehow, even in 2019, the myth of the solitary, disheveled professor locked up in an office, drowning among stacks of dusty books, and scribbling incoherent notes on pads of paper still pervades our notion of academic research. Those of us at universities know that this stereotype could not be further from the truth and that strong collaboration and effective communication are fundamental to the success of the modern research scientist. What is true, however, is that the obligations of both professors and graduate students in the present day are certainly demanding: grant writing, teaching, research, and administrative duties can easily fill the better part of the week. Wandering away from one's focused research program is not trivial and often not condoned within the community.

The research, writing, and consulting that culminated in this text certainly proved to be an exercise in wandering. We carry scientific expertise in nanochemistry and materials science. Our research involves studying the catalytic processes that might enable carbon

dioxide (CO_2) to react chemically and form other compounds. However, like everyone else, we are living in the time of the existential threat of climate change. Halting the release of carbon dioxide into the atmosphere has become imperative if we are to cap global temperature rise to maintain a livable environment on Earth. Naturally, we became curious as to how our research on carbon dioxide fit into the big picture of a global climate-change-mitigation strategy. As it turns out, although our lab benches are a far cry from the scale of industrial chemical plants, fundamental research in nanochemistry and materials science is an essential part of improving on current carbon-related technologies and industrial processes.

Since the release in the 1960s of the first cautionary reports predicting global warming, climate change has slowly disseminated its way to the public consciousness and become what is arguably the biggest issue of our time. While opinions will always vary, many people, irrespective of political leaning or economic conviction, recognize that climate change is associated with anthropogenic carbon emissions and that there is the need for definitive action. At the time of writing this study, in September 2019, no less than seven million people took part in a global climate strike. With an ever-growing youth-led movement and an increasing number of countries and municipalities declaring a state of climate emergency, the urgency of the matter could not have been more evident. The Green New Deal, conceived in the spirit of Franklin D. Roosevelt's New Deal in response to the Great Depression, to enable a just and equitable transition toward an emissions-free economy is now a proposed legislation in the United States, and other countries are quickly following suit in developing their own version. At present, the social and political forces surrounding climate change are shifting daily, and we recognize that, by the time of reading, some of our content will already be outdated.

While the urgency to mitigate emissions has finally become apparent in mainstream media, the feasibility of breaking away

entirely from our current fossil fuel–based economy remains continuously called into question. Electric vehicles provide a clear substitute for combustion-fuel-engine cars, but no such tangible solution seems to yet exist for air travel. From fertilizer in our fields to rubber in our bicycle tires, most chemicals and materials used today are still derived from fossil products. The ideas presented herein aim to make the case that it is technologically possible for all our modern industries – from power generation to transportation to agriculture to manufacturing – to operate without releasing further carbon dioxide into the atmosphere. Renewably generated electricity, hydrogen fuel, and carbon dioxide itself all have an important role to play in the transition toward an emissions-free economy. At the heart of this story, however, is the notion that carbon dioxide can be not only captured and sequestered but also *transformed* into a myriad of products, from feedstock chemicals to polymers to cement to drugs to synthetic fuels. Through these pages we attempt to shine light on the latest scientific research and technologies that will hopefully leave you with a clearer picture of what a future emissions-free world might look like.

Before proceeding any further, we should emphasize that while science can explain the origins and effects of climate change, it alone cannot resolve the problem. Climate change is a complex environmental, economic, and social issue that requires comprehensive, systems-level solutions. While science and technology inevitably play an important role in reducing our emissions, solutions are only as effective as their implementation. As we shall see, we are already too advanced to expect that good engineering and market signaling alone can eradicate our carbon emissions. Informed policy, strong public support, grassroots leadership, and unwavering political will are just as, if not more, crucial than technological know-how in achieving the systemic changes required to transition our planet toward a just, equitable, and low-carbon future.

So, although we try our best to outline strategies, we cannot offer a comprehensive plan to address climate change. This said, much has already been written on the topic, and we refer the reader to a list of recommended reading in appendix B. Instead, this story seeks to inspire a scientifically inclined audience as well as the general-interest reader on the latest carbon dioxide technologies and how they fit within the broader context of carbon-emission-mitigation strategies.

The Story of CO_2: Big Ideas for a Small Molecule is a seven-chapter account of all aspects of carbon dioxide, from the atomic to the universal. Rather than assuming a strictly technical viewpoint, the story interweaves fundamental scientific concepts with economics, engineering, and technology. Each chapter is followed by a bullet-point summary of the key concepts to take away. Chapter 1, "The Good, the Bad, and the Oily," provides an overview of the world's changing energy economy, highlighting our ongoing dependence on fossil-based energy sources. The chapter starts by introducing the Paris Agreement, then explores in greater depth the current global energy mix and the projected global energy trends. The state of both our primary energy sources and our trends in energy consumption are discussed. The chapter concludes that, despite the increasing market share of renewable-energy suppliers and technologies, our growing population's heavy dependency on fossil fuels means that these numbers are forecasted to grow in the immediate future.

Chapter 2, "From Space to Earth and Back Again," begins with the CO_2 molecule's origins in the big bang and its distribution throughout the planetary atmospheres of the solar system. We then address the role of CO_2 in the creation of life on Earth, the process of biomineralization, and the earth's natural carbon cycle. The exchange of carbon between the four main carbon reservoirs is described in greater detail, supplemented by a discussion on the use of carbon-isotope-tracing technology for tracking the source of carbon on our planet. We then offer a detailed explanation of the greenhouse

effect and walk the reader through a simple mathematical model from which one can predict the expected rise in temperature given a small change in atmospheric conditions. The chapter concludes by discussing the effects of rising levels of atmospheric CO_2 on our climate and our health.

In contrast to the first two chapters, chapter 3, "Confronting Climate Change," addresses the social, political, and ethical aspects of addressing climate change. It begins by identifying four attitudes that pose a barrier to action on climate change and goes into further detail on how income, lifestyle, and identity help to shape our perspective on the environment and climate. It briefly covers the topic of climate justice and the need to work toward solutions that are effective, equitable, and just.

Chapter 4, "Stubborn Emissions," details the reasons that certain industrial processes are more challenging to decarbonize than others. It introduces the concept of carbon capture and storage and explains how capturing, recycling, and repurposing CO_2 can help to enable a faster energy transition.

Chapter 5, "Power to the CO_2," covers the technical challenges of recycling CO_2 and introduces the various ways in which energy, in the form of heat, electricity, or sunlight, can help to convert it into useful products. It goes on to address the other key aspects of CO_2 technologies – namely, hydrogen, water, and renewable electricity – and how they might be sourced in a sustainable manner.

Chapter 6, "It Is a CO_2 World," uses the information presented in the previous chapters to illustrate more concrete examples of the CO_2 capture, storage, and utilization technologies that might be integrated into our industries. It covers everything from fertilizer production to concrete manufacturing to air-conditioning.

Finally, chapter 7, "Bringing It All Together," illustrates the big-picture requirements of bringing these technologies to market and shares a vision of what CO_2 refineries might look like in the future. It also provides a list summary of the key chemicals and

materials needed to sustain the manufacturing of critical commodities, and how they can be obtained without fossil resources. The chapter concludes by offering a practical list of ways in which the individual reader can make a difference.

Provided in appendix A is an exhaustive (though not complete) list of existing companies whose products and processes are based on CO_2 utilization technologies. Appendix B recommends further reading. By the end of this book, the reader should have a solid understanding of how carbon-dioxide-conversion technologies can offer significant benefits for the economy, environment, and society.

Short vignettes are sprinkled throughout the text as optional asides for the more curious reader who wishes to delve deeper into certain topics. Given the highly interdisciplinary spirit of this book, all technical terms are defined in the margins to assist readers with new jargon. The text includes schematics and illustrations to enrich the reader's experience and to make the text as engaging as possible, especially to non-experts. We have provided citations for those who wish to explore further any point or to refer to original sources; the references presented at the end of the book are numbered sequentially as they first appear in the text. Still, we recognize that some of the material covered in these chapters may be very new to readers with little or no background in science. Most of the technical detail can be overlooked without compromising the key message of each chapter. So, although we encourage the readers to challenge themselves in learning new material, we fully endorse a selective reading of the book to guarantee a joyful and satisfactory experience for individuals of all educational backgrounds.

As scientists, we are excited to share some of the latest emerging science that is transforming the capacity for carbon dioxide to be recycled. We believe this story to be critical to today's current political and cultural climate, in which the public receives conflicting messages about effective solutions to combating climate change. We also think that scientists owe a responsibility to the wider

community to inform it of the potential impact of new technologies. Evidence-based decision-making is our only viable guide to navigate effectively the changing energy landscape, and the key instigator of political action on carbon mitigation and climate change will ultimately be an informed public.

In the spirit of Marie Curie's statement, we hope that *The Story of* CO_2 will inspire in you a newfound appreciation of and optimism for the non-fossil CO_2 molecule and all it can offer.