DRAWDOWN
THE MOST COMPREHENSIVE PLAN *EVER PROPOSED* TO REVERSE GLOBAL WARMING

NEW YORK TIMES BESTSELLER

EDITED BY PAUL HAWKEN

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We accumulated more than 5,000 references, citations, and sources in the process of researching and writing . Although they are too numerous to be published in the book, they may be found at www.drawdown.org/references.

FOREWORD

CLARENCE HOUSE

In January 2017, Penguin U.K. published my "Ladybird Expert Book on Climate Change", written in partnership with Dr. Tony Juniper and Dr. Emily Shuckburgh. The Ladybird book is a brief exposition of the latest peer-reviewed climate change science, written for the lay reader. It also points, very briefly, to some of the most important solutions to the climate change challenge: renewable energy, forest protection, better management of soil and marine conservation, to name but a few.

It was therefore a great pleasure to read "Drawdown"; a magisterial and detailed exposition, in detail, of one hundred of the best and most promising solutions to climate change. Some eighty of those solutions are 'tried and tested', already being put in place around the world; a further twenty are described, intriguingly, as 'coming attractions' – in other words, technologies and approaches currently under review, which pose great promise.

The results of this comprehensive effort are surprising, fascinating and inspiring in equal measure. I was pleased, although not surprised, to see to what extent forest protection, restoration and improved soil management would contribute to creating a better climate for our and future generations. Ensuring and safeguarding the rights of indigenous peoples is another solution in the same vein. Furthermore, I was equally struck by the weight given to the need to support better access to modem, voluntary family planning, women's and girls' education and reproductive health care throughout the world, which is not only intrinsically the right thing to do, but a potentially significant contribution to reducing our collective climate footprint. Often, the solutions put forward in the book reaffirm compelling truths that for some inexplicable reason have not yet been taken forward effectively. Equally often, however, "Drawdown's" methodology and approach shed new insights and prompt innovative thinking.

"Drawdown's" focus on reversing, rather than simply reducing, climate change is a compelling and urgent narrative that surely needs to be widely adopted? I also much appreciate its focus on regenerative and restorative development, as well as its references to the circular economy. These approaches are particularly close to my heart.

"Drawdown" has already been read widely around the world and used as a tool to stimulate thinking and new approaches to development and planning within many countries. In these uncertain times, in which it so often feels that the climate is already running out of control, through both our actions and inaction, this book is resolutely focused on a positive response to our current predicament and therefore deserves the widest possible readership.

INTRODUCTION

As a climate scientist, it's disheartening to witness world events unfold as they have over the past few decades. The clear and precise warnings we scientists have made about our planet's changing climate are materializing as predicted. Greenhouse gases are trapping heat in the earth's atmosphere, producing warmer seasons and an amped-up water cycle.

Warmer air holds more moisture, allowing for higher rates of evaporation and precipitation. Record heat waves, coupled with intense droughts, spark the perfect conditions for massive wildfires. Warming oceans trigger supercharged storms, with greater rainfall and higher storm surges. We can expect a steady rise in extreme weather events in the coming decades, potentially causing countless lost lives and significant financial losses.

Whether we like it or not—whether we choose to "believe" the science or not—the reality of climate change is upon us. It's affecting everything: not just weather patterns, ecosystems, ice sheets, islands, coastlines, and cities across the planet, but the health, safety, and security of every person alive and the generations to come. Worldwide, we're seeing related symptoms like the acidification of our oceans, which could devastate coral reefs and marine life, and the changing biochemistry of plants, including staple crops.

We know exactly why this is happening. We've known for more than a hundred years.

When we burn fossil fuels (coal, oil, and natural gas), manufacture cement, plow rich soils, and destroy forests, we release heat-trapping carbon dioxide into the air. Our cattle, rice fields, landfills, and natural gas operations release methane, warming the planet even more. Other greenhouse gases, including nitrous oxide and fluorinated gases, are seeping out of our agricultural lands, industrial sites, refrigeration systems, and urban areas, compounding the greenhouse effect. It's important to remember that climate change stems from many sources such as energy production, agriculture, forestry, cement, and chemical manufacturing; thus, the solutions must arise from those same many sources.

Beyond the damage to our planet, climate change threatens to undermine our social fabric and the foundations of democracy. We see the impacts of this in the United States in particular, where key parts of the federal government are denying the science, and are closely aligned with fossil fuel industries. While most people continue to move through their day as if nothing is wrong, others who are aware of the science are fearful, if not in despair. The climate change narrative has become a doom and gloom story, causing people to experience denial, anger, or resignation.

At times, I have been one of those people.

Thanks to *Drawdown*, I have a different perspective. Paul Hawken and his colleagues have researched and modeled the one hundred most substantive ways we can reverse global warming. These solutions reside in energy, agriculture, forests, industries, buildings, transportation, and more. They also highlight critical social and cultural solutions, such as empowering girls, reducing population growth, and changing our diets and consumption patterns. Together, these solutions not only slow climate change, they can reverse it.

Drawdown goes beyond solar panels and energy-efficient light bulbs to show that the needed solutions are far more diverse than just those associated with clean energy, and that there are many effective means to address global warming. *Drawdown* illustrates how we can make dramatic strides by reducing the emissions of more exotic greenhouse gases, like refrigerants and black carbon, lowering nitrous oxide emissions from agriculture, cutting methane emissions from cattle production, and reducing carbon dioxide emissions from deforestation. Moreover, *Drawdown* demonstrates the potential for removing carbon dioxide from the atmosphere through innovative land use practices, regenerative agriculture, and agroforestry.

But, more importantly to me, *Drawdown* illuminates ways we can overcome the fear, confusion, and apathy surrounding climate change, and take action as individuals, neighborhoods, towns and cities, states, provinces, businesses, investment firms, and non-profits. This book should become the blueprint for building a climate-safe world. By modeling solutions that are hands-on, well understood, and already scaling, *Drawdown* points to a future where we can reverse global warming and leave a better world for new generations.

We think that our climate future is harsh because news and reports have focused on what will happen if we do not act. *Drawdown* shows us what we can do. Because of that, I think this is the single most important book ever written about climate change.

Drawdown has helped restore my faith in the future, and in the capacity of human beings to solve incredible challenges. We have all the tools we need to combat climate change, and thanks to Paul and his colleagues, we now have a plan showing us how to use them.

Now let's get to work and do it.

Dr. Jonathan Foley
Executive Director, California Academy of Sciences
San Francisco

ORIGINS

The genesis of Project Drawdown was curiosity, not fear. In 2001 I began asking experts in climate and environmental fields a question: Do we know what we need to do in order to arrest and reverse global warming? I thought they could provide a shopping list. I wanted to know the most effective solutions that were already in place, and the impact they could have if scaled. I also wanted to know the price tag. My contacts replied that such an inventory did not exist, but all agreed it would be a great checklist to have, though creating one was not within their individual expertise. After several years, I stopped asking because it was not within my expertise either.

Then came 2013. Several articles were published that were so alarming that one began to hear whispers of the unthinkable: It was game over. But was that true, or might it possibly be game on? Where did we actually stand? It was then that I decided to create Project Drawdown. In atmospheric terms drawdown is that point in time at which greenhouse gases peak and begin to decline on a year-to-year basis. I decided that the goal of the project would be to identify, measure, and model one hundred substantive solutions to determine how much we could accomplish within three decades towards that end.

The subtitle of this book—the most comprehensive plan ever proposed to reverse global warming—may sound a bit brash. We have chosen that description because no detailed plan to reverse warming has been proposed. There have been agreements and proposals on how to slow, cap, and arrest emissions, and there are international commitments to prevent global temperature increases from exceeding two degrees centigrade over preindustrial levels. One hundred and ninety-five nations have made extraordinary progress in coming together to acknowledge that we have a momentous civilizational crisis on our earthly doorstep and have created national plans of action. The UN's Intergovernmental Panel on Climate Change (IPCC) has completed the most significant scientific study in the history of humankind, and continues to refine the science, expand the research, and extend our grasp of one of the most complex systems imaginable. However, there is, as yet, no road map that goes beyond slowing or stopping emissions.

To be clear, our organization did not create or devise a plan. We do not have that capability or self-appointed mandate. In conducting our research, we found a plan, a blueprint that already exists in the world in the form of humanity's collective wisdom, made manifest in applied, hands-on practices and technologies that are commonly available, economically viable, and scientifically valid. Individual farmers, communities, cities, companies, and governments have shown that they care about this planet, its people, and its places. Engaged citizens the world over are doing something extraordinary. This is their story.

In order for Project Drawdown to be credible, a coalition of researchers and scientists needed to be at its foundation. We had a tiny budget and oversized ambitions, so we sent out appeals inviting students and scholars from around the world to become research fellows. We were inundated with responses from some of the finest women and men in science and public policy. Today, the Drawdown Fellows comprise seventy individuals from twenty-two countries. Forty percent are women, nearly half have PhDs, and others have at least one advanced degree. They have extensive academic and professional experience at some of the world's most respected institutions.

Together we gathered comprehensive lists of climate solutions and winnowed them down to those that had the greatest potential to reduce emissions or sequester carbon from the atmosphere. We then compiled literature reviews and devised detailed climate and financial models for each of the solutions. The analyses informing this book were then put through a three-stage process including review by outside experts who evaluated the inputs, sources, and calculations. We brought together a 120-person Advisory Board, a prominent and diverse community of geologists, engineers, agronomists, politicians, writers, climatologists, biologists, botanists, economists, financial analysts, architects, and activists who reviewed and validated the text.

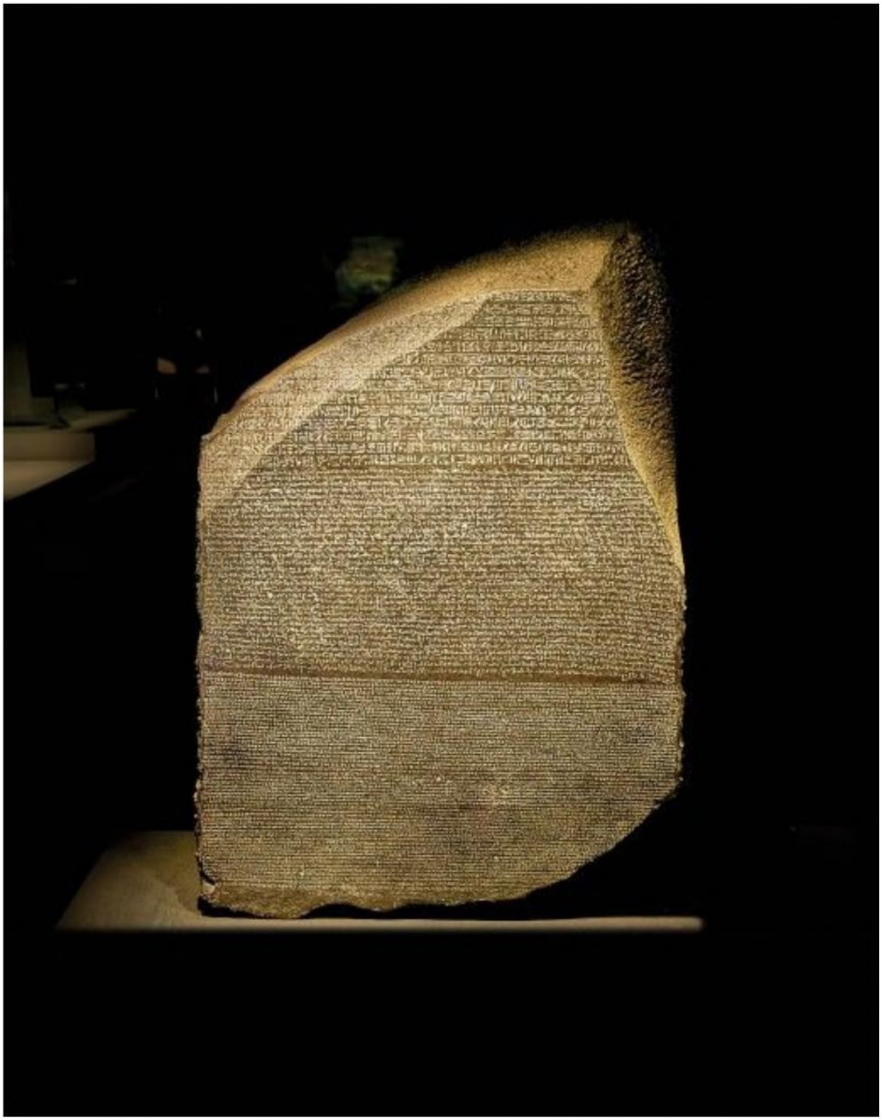
Almost all of the solutions compiled and analyzed here lead to regenerative economic outcomes that create security, produce jobs, improve health, save money, facilitate mobility, eliminate hunger, prevent pollution, restore soil, clean rivers, and more. That these are substantive solutions does not mean that they are all the best ones. There are a small handful of entries in this book whose spillover effects are clearly detrimental to human and planetary health, and we try to make that clear in our descriptions. The overwhelming majority, however, are no-regrets solutions, initiatives we would want to achieve regardless of their ultimate impact on emissions and climate, as they are practices that benefit society and the environment in multiple ways.

The final section of the main part of *Drawdown* is called "Coming Attractions" and features twenty solutions that are nascent or on the horizon. Some may succeed, while others may fail. Notwithstanding, they provide a demonstration of the ingenuity and gumption that committed individuals have brought to address climate change. Additionally, you will find essays from prominent journalists, writers, and scientists—narratives, histories, and vignettes—that offer a rich and varied context to the specifics of the book.

Three-week-old spotted owl hatchlings on a mossy hemlock branch in northern Oregon.

We remain a learning organization. Our role is to collect information, organize it in ways that are helpful, distribute it to any and all, and provide the means for anyone to add, amend, correct, and extend the information you find here and on the drawdown.org website. Technical reports and expanded model results are available there. Any model that projects out thirty years is going to be highly speculative. However, we believe the numbers are approximately right and welcome your comments and input.

Unquestionably, distress signals are flashing throughout nature and society, from drought, sea level rise, and unrelenting increases in temperatures to expanded refugee crises, conflict, and dislocation. This is not the whole story. We have endeavored in *Drawdown* to show that many people are staunchly and unwaveringly on the case. Although carbon emissions from fossil fuel combustion and land use have a two-century head start on these solutions, we will take those odds. The buildup of greenhouse gases we experience today occurred in the absence of human understanding; our ancestors were innocent of the damage they were doing. That can tempt us to believe that global warming is something that is happening *to* us—that we are victims of a fate that was determined by actions that precede us. If we change the preposition, and consider that global warming is happening *for* us—an atmospheric transformation that inspires us to change and reimagine everything we make and do—we begin to live in a different world. We take 100 percent responsibility and stop blaming others. We see global warming not as an inevitability but as an invitation to build, innovate, and effect change, a pathway that awakens creativity, compassion, and genius. This is not a liberal agenda, nor is it a conservative one. This is the human agenda. —Paul Hawken



The decree carved into the Rosetta Stone in Egypt in 196 B.C. is known less for its content—an affirmation of the rule of King Ptolemy V—than for its unique combination of scripts. The same text repeats in Greek, Egyptian hieroglyphics, and Egyptian demotic, respectively royal, sacred, and common languages of the time. In the 19th century, European scholars used the Rosetta Stone to crack the code of hieroglyphics, opening up understanding of Ancient Egypt. Today, the Rosetta Stone is what Richard Parkinson, professor of Egyptology at Oxford, calls “an icon of … decipherment” and “a symbol of our desire to understand each other.” To convey and comprehend through language is at the heart of the human endeavor.

LANGUAGE

Confucius wrote that calling things by their proper name is the beginning of wisdom. In the world of climate change, names can sometimes be the beginning of confusion. Climate science contains its own specialized vocabulary, acronyms, lingo, and jargon. It is a language derived by scientists and policy makers that is succinct, specific, and useful. However, as a means of communication to the broader public, it can create separation and distance.

I remember my economics professor asking for a definition of Gresham's law and how I rattled off the answer mechanically. He looked at me—none too pleased, though the answer was correct—and said, now explain it to your grandmother. That was much more difficult. The answer I gave the professor would have made no sense to her. It was lingo. So it is with climate and global warming. Very few people actually understand climate science, yet the basic mechanism of global warming is pretty straightforward.

We have sought to make *Drawdown* understandable to people from all backgrounds and points of view. We endeavored to bridge the climate communication gap by the words we choose, the analogies we avoid, the jargon we stay away from, and the metaphors we employ. As much as possible, we refrain from acronyms and lesser-known climate terminology. We generally spell out *carbon dioxide* instead of abbreviating it. We write *methane*, not CH4.

Let's consider an example. In November 2016, the White House released its strategy for achieving deep decarbonization by mid-century. From our perspective, *decarbonization* is a word that describes the problem, not the goal: we decarbonized the earth by removing carbon in the form of combusted coal, gas, and oil, as well as through deforestation and poor farming practices, and releasing it into the atmosphere. When the word *decarbonization* is used, as it was by the White House, it refers to replacing fossil fuel energy with clean, renewable sources. However, the term is often employed as the overarching goal of climate action—one that is unlikely to inspire and more likely to confuse.

Another term used by scientists is "negative emissions." This term has no meaning in any language. Imagine a negative house, or a negative tree. The absence of something is nothing. The phrase refers to sequestering or drawing down carbon from the atmosphere. We call that sequestration. It is carbon positive, not negative. This is another example where climate-speak removes itself from common parlance and common sense. Our goal is to present climate science and solutions in language that is accessible and compelling to the broadest audience, from ninth graders to pipe fitters, from graduate students to farmers.

We also avoid using military language. Much of the rhetoric and writing about climate change is violent: the war on carbon, the fight against global warming, and frontline battles against fossil fuels. Articles refer to slashing emissions as if we had machetes. We understand the use of these terms because they convey the gravity of what we face and the tightening window of time to address global warming. Yet, terms such as "combat," "battle," and "crusade" imply that climate change is the enemy and it needs to be slain. Climate is a function of biological activity on earth, and physics and chemistry in the sky. It is the prevalent weather conditions over time. Climate changes because it always has and will, and variations of climate produce everything from seasons to evolution. The goal is to come into alignment with the impact we are having on climate by addressing the human causes of global warming and bringing carbon back home.

The term “drawdown” needs explanation as well. The word is conventionally used to describe the reduction of military forces, capital accounts, or water from wells. We use it to refer to reducing the amount of carbon in the atmosphere. However, there is an even more important reason for the use of the word: drawdown names a goal that has been hitherto absent in most conversations about climate. Addressing, slowing, or arresting emissions is necessary, but insufficient. If you are traveling down the wrong road, you are still on the wrong road if you slow down. The only goal that makes sense for humanity is to reverse global warming, and if parents, scientists, young people, leaders, and we citizens do not name the goal, there is little chance it will be achieved.

Last, there is the term “global warming.” The history of the concept goes back to the nineteenth century when Eunice Foote (1856) and John Tyndall (1859) independently described how gases trap heat in the atmosphere and how changes in the concentration of gases would alter the climate. The term *global warming* was first used by geochemist Wallace Broecker in a 1975 *Science* article entitled “Climatic Change: Are We on the Brink of a Pronounced Global Warming?” Before that article, the term used was *inadvertent climate modification*. Global warming refers to the surface temperature of the earth. Climate change refers to the many changes that will occur with increases in temperature and greenhouse gases. That is why the U.N. climate agency is called the Intergovernmental Panel on Climate Change—the IPCC, and not the IPGW. It studies the comprehensive impacts of climate change on all living systems. What we measure and model in *Drawdown* is how to begin the reduction of greenhouse gases in order to reverse global warming. —Paul Hawken

NUMBERS

WHAT YOU WILL SEE ON THE PAGE

Behind every one of the solutions in *Drawdown* are hundreds of pages of research and rigorous mathematical models developed by some very bright minds. Each solution includes an introduction that draws on history, science, key examples, and the most current information available. Every description is supported by a detailed technical assessment available on our website for further exploration. Each entry also features a summary of output from the models, including a ranking of the solution by its emissions-reduction potential. We enumerate how many gigatons of greenhouse gases are avoided or removed from the atmosphere, as well as the total incremental cost to implement the solution, and the net cost or—in most cases—savings. In the models, we rely on peer-reviewed science for inputs. In some areas, such as land use and farming, there is a plethora of anecdotal facts and figures, some of which we refer to but we do not use in our calculations.

At the end of the book, you will find a summary table presenting the combined impact of solutions, grouped by sector.

RANKING OF SOLUTIONS

There are several ways one can rank solutions: how cost-effective they are; how quickly they can be implemented; or how beneficial they are to society. All are interesting and useful methods with which to interpret the results. For our purposes, we rank solutions based on the total amount of greenhouse gases they can potentially avoid or remove from the atmosphere. The rankings are global. The relative importance of one solution may differ depending on geography, economic conditions, or sector.

GIGATONS OF CARBON DIOXIDE REDUCED

Carbon dioxide may get the most press, but it is not the only greenhouse gas. Other heat-trapping gases include methane, nitrous oxide, fluorinated gases, and water vapor. Each has long-term impacts on global temperatures, depending on how much of it is in the atmosphere, how long it remains there, and how much heat it absorbs or radiates back out during its lifetime. Based on these factors, scientists can calculate their global warming potential, which makes it possible to have a "common currency" for greenhouse gases, translating any given gas into its equivalent in carbon dioxide.

Each solution in *Drawdown* reduces greenhouse gases by avoiding emissions and/or by sequestering carbon dioxide already in the atmosphere. The degree to which a given solution has a bearing on greenhouse gases is translated into gigatons of carbon dioxide removed between 2020 and 2050. Taken together, they represent the total reduction of greenhouse gases that could be achieved by 2050, compared to a fixed reference case, a world where very little changes.

But what is a gigaton? To appreciate its magnitude, imagine 400,000 Olympic-sized pools. That is about a billion metric tons of water, or 1 gigaton. Now multiply that by 36, yielding 14,400,000 pools. Thirty-six gigatons is the amount of carbon dioxide emitted in 2016.

TOTAL NET COST AND OPERATIONAL SAVINGS

The total cost of each solution in this book is the amount needed to purchase, install, and operate it over thirty years. By comparing this to what we typically would spend on food, fuel for cars, heating and cooling for our homes, etc., we determined the net costs or savings from investing in a given solution.

We err on the side of being conservative. That means assuming costs associated with the solution that are on the high end, and then keeping them relatively constant from 2020 to 2050. Because technologies are changing rapidly and will vary in different parts of the world, we expect the actual cost to be less and the amount of savings higher. Even taking a conservative approach, however, the solutions tend to offer an overwhelming net savings. For some solutions though, the costs and savings are incalculable, as in the cost to save a specific rainforest or support girls' education.

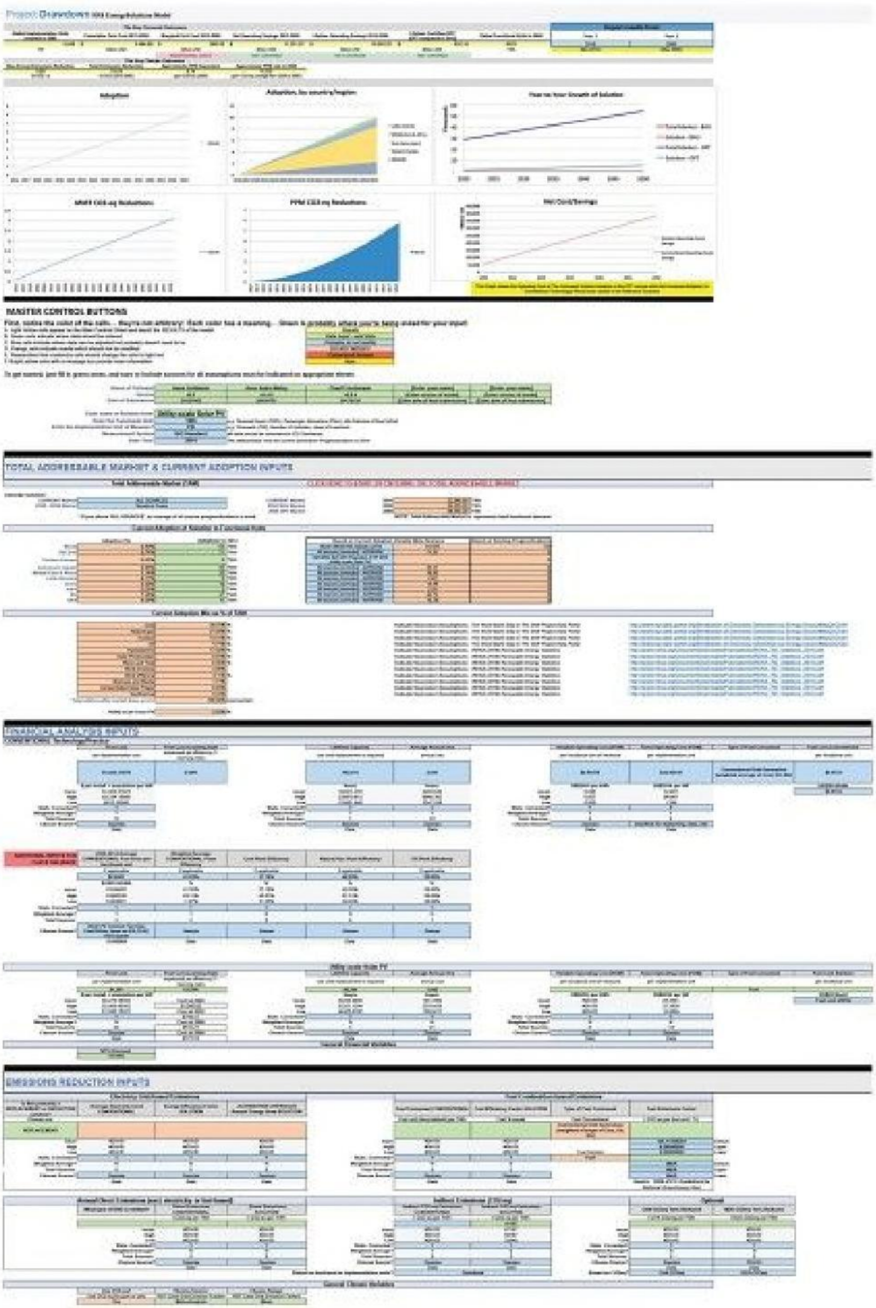
How much are we willing to spend to achieve results that benefit all of humanity? In the back of the book, we summarize the net cost and savings solution-by-solution for comparison. Net savings are based on the operating costs of solutions after implementation from 2020 to 2050. This calculation reveals the cost-effectiveness of the solutions presented. When considering the scale of benefits, the potential profits and savings, and the investments needed if conditions remain the same, the costs become negligible. The payback period for most solutions is relatively short in time.

TO LEARN MORE

The solutions presented in *Drawdown* are only a summary of the full research conducted to support our findings. A more detailed outline of our approach and assumptions can be found in the section

"Methodology." We also provide a full description of our research at drawdown.org—how all the data were generated, sources used, and assumptions made.

As you read the book, what will become apparent is how sensible and empowering these solutions are. Rather than a lengthy technical manual, impenetrable to all save experts who have spent their lives immersed in the science behind these technologies, *Drawdown* aims to be accessible to anyone who wants to know what we, collectively, can do and the role each one of us might play. —Chad Frischmann


Project Drawdown
Adoption
Adoption, by country/region
Year on Year Growth of Solution
PPM CO2-eq Reductions
Net Cost/Savings
MASTER CONTROL BUTTONS
Utility-scale Solar PV
TOTAL ADDRESSABLE MARKET & CURRENT ADOPTION INPUTS
FINANCIAL ANALYSIS INPUTS
EMISSIONS REDUCTION INPUTS

transition in history. The era of fossil fuels is over, and the only question now is when the new era will be fully upon us. Economics make its arrival inevitable: Clean energy is less expensive.

ENERGY

WIND TURBINES

RANKING AND RESULTS BY 2050 (ONSHORE) #2

84.6 GIGATONS	$1.23 TRILLION	$7.4 TRILLION
REDUCED CO_2	NET COST	NET SAVINGS

RANKING AND RESULTS BY 2050 (OFFSHORE) #22

15.2 GIGATONS	$545.3 BILLION	$762.5 BILLION
REDUCED CO_2	NET COST	NET SAVINGS

An athlete swims past the Sheringham Shoal Offshore Wind Farm off the coast of Norfolk, England. The wind farm consists of 88 Siemens 3.6-megawatt turbines placed over a 14-square-mile area, 11 miles from shore.

Wind never blows. Because of uneven heating of the earth's surface and the planet's rotation, it is drawn from areas of higher pressure to lower, undulating over and above the landscape like an incoming tide of air. Change is riding on that tide: Wind energy is at the crest of initiatives to address global warming in the coming three decades, second only to refrigeration in total impact.

Take the thirty-two offshore wind turbines—each double the height of the Statue of Liberty—that have been installed off the coast of Liverpool, England, at the Burbo Bank Extension. Owned by a surprising entry into the energy business—Lego, the toy maker—Burbo is an international effort: The blades are made on the Isle of Wight in the United Kingdom by a Japanese company for its Danish client, Vestas. Each turbine generates 8 megawatts of electricity. Their 269-foot blades have a sweep diameter nearly twice the length of a football field, and weigh 33 tons. A single rotation of the blades generates the electricity for one household's daily use. Altogether, the project will supply power for all 466,000 inhabitants of Liverpool.

Today, 314,000 wind turbines supply 3.7 percent of global electricity. And it will soon be much more. Ten million homes in Spain alone are powered by wind. Investment in offshore wind was $29.9 billion in 2016, 40 percent greater than the prior year.

Human beings have harnessed the power of wind for millennia, capturing breezes, gusts, and gales to send mariners and their cargo down rivers and across seas or to pump water and grind grain. The earliest recorded windmills were created around 500 to 900 AD in Persia. The technology spread to Europe during the Middle Ages, and for centuries the Dutch fostered most windmill innovation. By the late 1800s, inventors around the world were successfully converting the kinetic energy of wind into electricity. Prototypical turbines popped up in Glasgow, Scotland, Ohio, and Denmark, and the 1893 World's Columbian Exposition in Chicago featured a variety of manufacturers and their designs. In the 1920s and '30s, farms across the midwestern United States were dotted with wind turbines as a dominant energy source. In 1931, Russia launched utility-scale wind production, and the world's first megawatt turbine went online in Vermont in 1941.

Fossil fuels sidelined wind energy during the mid-twentieth century. The oil crisis of the 1970s reignited interest, investment, and invention. This modern resurgence paved the way for where the wind industry is today with its proliferation of turbines, dropping costs, and heightened performance. In 2015, a record 63 gigawatts of wind power were installed around the world, despite a dramatic drop in fossil fuel prices. China alone brought nearly 31 gigawatts of new capacity online. Denmark now supplies more than 40 percent of its electricity needs with wind power, and in Uruguay, wind satisfies more than 15 percent of demand. In many locales, wind is either competitive with or less expensive than coal-generated electricity.

In the United States, the wind energy potential of just three states—Kansas, North Dakota, and Texas—would be sufficient to meet electricity demand from coast to coast. Wind farms have small footprints, typically using no more than 1 percent of the land they sit on, so grazing, farming, recreation, or conservation can happen simultaneously with power generation. Turbines can harvest electricity while farmers harvest alfalfa and corn. What's more, it takes one year or less to build a wind farm, quickly producing energy and a return on investment.

Wind energy has its challenges. The weather is not the same everywhere. The variable nature of wind means there are times when turbines are not turning. Where the intermittent production of wind (and solar) power can span a broader geography, however, it is easier to overcome fluctuations in supply and demand. Interconnected grids can shuttle power to where it is needed. Critics argue that turbines are noisy, aesthetically unpleasant, and at times deadly to bats and migrating birds. Newer designs address these concerns with slower turning blades and siting practices that avoid migration paths. Yet, not-in-my-backyard sentiment—from the British countryside to the shores of Massachusetts—remains an obstacle.

Another impediment to wind power is inequitable government subsidies. The International Monetary Fund estimates that the fossil fuel industry received more than $5.3 trillion in direct and indirect subsidies in 2015; that is $10 million a minute, or about 6.5 percent of global GDP. Indirect fossil fuel subsidies include health costs due to air pollution, environmental damage, congestion, and global warming—none of which are factors with wind turbines. In comparison, the U.S. wind-energy industry has received $12.3 billion in direct subsidies since 2000. Outsize subsidies make fossil fuels look less expensive, obscuring wind power's cost competitiveness, and they give fossil fuels an incumbent advantage, making investment more attractive.

Ongoing cost reduction will soon make wind energy the least expensive source of installed electricity capacity, perhaps within a decade. Current costs are 2.9 cents per kilowatt-hour for wind, 3.8 cents per kilowatt-hour for natural gas combined-cycle plants, and 5.7 cents per kllowatt-hour for utility-scale solar. A Goldman Sachs research paper published in June 2016 stated simply, "wind provides the lowest cost source of new capacity." The cost of both wind and solar includes

Wind energy, like other sources of energy, is part of a system. Investment in energy storage, transmission infrastructure, and distributed generation is essential to its growth. Technologies and infrastructure to store excess power are developing quickly now. Power lines to connect remote wind farms to areas of high demand are being built. For the world, the decision is simple: Invest in the future or in the past. ●

IMPACT: *An increase in onshore wind from 3 to 4 percent of world electricity use to 21.6 percent by 2050 could reduce emissions by 84.6 gigatons of carbon dioxide. For offshore wind, growing from .1 percent to 4 percent could avoid 15.2 gigatons of emissions. At a combined cost of $1.8 trillion, wind turbines can deliver net savings of $8.2 trillion over three decades of operation. These are conservative estimates, however. Costs are falling annually and new technological improvements are already being installed, increasing capacity to generate more electricity at the same or lower cost.*

Blades for a wind farm prior to assembly in Stylida, Greece.

ENERGY

MICROGRIDS

#78

RANKING AND RESULTS BY 2050

AN ENABLING TECHNOLOGY—COST AND SAVINGS ARE EMBEDDED IN RENEWABLE ENERGY

This is the Solar Settlement in Freiburg, Germany. A 59-home community, it is the first in the world to have a positive energy balance, with each home producing $5,600 per year in solar energy profits. The way to positive energy is designing homes that are extraordinarily energy efficient, what designer Rolf Disch calls PlusEnergy.

The "macro" grid is a massive electrical network of energy sources that connects utilities, energy generators, storage, and 24-7 control centers monitoring supply and demand. Anything that is plugged in taps into the grid's centralized power—electricity that is available from large fossil-fuel plants, day or night and rain or shine. This setup made sense when power generation was concentrated. Today, it hinders society's transition from dirty energy produced in a few places to clean energy produced everywhere.

Enter microgrids. A microgrid is a localized grouping of distributed energy sources, such as solar, wind, in-stream hydro, and biomass, together with energy storage or backup generation and load management tools. This system can operate as a stand-alone entity or its users can plug into the larger grid as needed. Microgrids are nimble, efficient microcosms of the big grid, designed for smaller, diverse energy sources. By bringing together renewables and storage, microgrids provide reliable power that can augment the centralized model or operate independently in an emergency situation.

Microgrids will play a critical role in the advancement of a flexible and efficient electric grid. The use of local supply to serve local demand reduces energy lost in transmission and distribution, increasing efficiency of delivery compared to a centralized grid. When coal is burned to boil water to turn a turbine to generate electricity, two-thirds of the energy is dispersed as waste heat and in-line losses.

Microgrid installations in grid-connected regions offer several key advantages. Civilization is dependent on electricity; losing access due to outages or blackouts is a critical risk. In developed countries, economic losses from such events can be many billions of dollars per year. Associated social costs include increased crime, transportation failures, and food wastage, in addition to the environmental cost of diesel-fueled backup power. Studies indicate that as overall demand for electricity increases, owing in part to use of air conditioning and electric vehicles, existing power systems become more frail and blackouts more frequent. By virtue of being localized systems, microgrids are more resilient and can be more responsive to local demand. In the event of disruption, a microgrid can focus on critical loads that require uninterrupted service, such as hospitals, and shed noncritical loads until adequate supply is restored.

In low-income countries, the advantages are greater. Globally, 1.1 billion people do not have access to a grid or electricity. More than 95 percent of them live in sub-Saharan Africa and Asia, a majority in rural areas where highly polluting kerosene lamps are still the main source of lighting and meals are cooked on rudimentary stoves. While the connection between electrification and human development has been clear, progress has remained slow due to the high cost of extending the grid to remote regions. In rural parts of Asia and Africa, populations are best supplied with electricity from microgrids (and in remote locations by stand-alone solar).

Establishing microgrids in low-income rural areas is easier than operating them in energy-rich high-income locales. In many places, the business models of large utilities are not compatible with distributed energy and storage. They have sunk costs in a system of generation and delivery that is becoming outmoded. Where utilities are resistant, monopoly, not technology, is the biggest challenge for microgrids. Lessons could cross-pollinate: large grids need to be less rigid and adapt to a changing world; microgrids need to adopt robust technical standards for long-term success. In the age of technological disruption, working out a partnership of technologies makes good sense. ●

IMPACT: *We model the growth of microgrids in areas that currently do not have access to electricity, using renewable energy alternatives such as in-stream hydro, micro wind, rooftop solar, and biomass energy, paired with distributed energy storage. It is assumed that these systems replace what would otherwise be the extension of a dirty grid or the continued use of off-grid oil or diesel generators. Emissions impacts are accounted for in the individual solutions themselves, preventing double counting. For higher-income countries the benefits of microgrid systems fall under "Grid Flexibility."*

than 10 percent of the planet, new technologies dramatically expand production potential in areas where useful resources were previously unknown. Conventionally, locating hydrothermal pools is the first step; however, pinpointing subsurface resources has been a challenge and limitation for geothermal power. It is difficult to know where reservoirs are and expensive to drill wells to find out. But new exploration techniques are opening up larger territories.

Maintenance engineer with protective clothing repairs a pipe connection that is leaking 221° Fahrenheit steam.

One of these new approaches is enhanced geothermal systems (EGS), which typically targets deep underground cavities and creates hydrothermal pools where they do not currently exist. EGS uses engineering to make use of areas that contain ample heat but little or no water, adding it in rather than relying on nature's supply. By injecting high-pressure water into the earth, EGS techniques fracture and break up hot rock, making it more permeable and accessible. Once the rock is porous, water can be pumped in via one borehole, heated underground, then returned to the surface via another. After using it for electricity production, injection wells pump spent water back down into the reservoir. Or, in the case of Iceland's Blue Lagoon geothermal spa, the Svartsengi power plant's wastewater becomes bathwater for residents and tourists alike. With recirculation, the cycle repeats.

These innovations could dramatically increase the geographic reach of geothermal energy and, in certain locales, help address a critical challenge for renewables: providing baseload or readily dispatchable power. Wind power dwindles when winds are not blowing. Solar power takes the night off. With subterranean resources flowing 24-7, without interlude, geothermal production can take place at all hours and under almost any weather conditions. Geothermal is reliable, efficient, and the heat source itself is free.

In the process of pursuing its potential, geothermal's negatives need to be managed. Whether naturally occurring or pumped in, water and steam can be laced with dissolved gases, including carbon dioxide, and toxic substances such as mercury, arsenic, and boric acid. Though its emissions per megawatt hour are just 5 to 10 percent of a coal plant's, geothermal is not without greenhouse impact. In addition, depleting hydrothermal pools can cause soil subsidence, while hydrofracturing can produce microearthquakes. Additional concerns include land-use change that can cause noise pollution, foul smells, and impacts on viewsheds.

In twenty-four countries around the world, tackling these drawbacks is proving worthwhile because geothermal power can provide reliable, abundant, and affordable electricity, with low operational costs over its lifetime. In El Salvador and the Philippines, geothermal accounts for a quarter of national electric capacity. In volcanic Iceland, it is one-third.

In Kenya, thanks to the activity beneath Africa's Great Rift Valley, fully half of the country's electricity generation is geothermal—and growing. Though less than .5 percent of national electricity production, U.S. geothermal plants lead the world with 3.7 gigawatts of installed capacity.

There is opportunity to pursue geothermal with greater steam and in more places. According to the Geothermal Energy Association, 39 countries could supply 100 percent of their electricity needs from geothermal energy, yet only 6 to 7 percent of the world's potential geothermal power has been tapped. Theoretical projections based on geologic surveys of Iceland and the United States indicate that undiscovered geothermal resources could supply 1 to 2 terawatts of power or 7 to 13 percent of current human consumption. However, that number is significantly lower when capital requirements and other costs and constraints are factored in.

The world's geothermal vanguards point the way forward. They also underscore the importance of government involvement in growing generation. Even with a viable location in hand, geothermal plants can be expensive to bring online. The up-front costs of drilling are especially steep, particularly in less certain, more complex environments. That is why public investment, national targets for its production, and agreements that guarantee power will be purchased from companies that develop it have a crucial role to play in expansion. These measures all help to rein in the level of risk for investing. While hot new technologies such as enhanced geothermal systems advance, continued development of traditional geothermal generation remains indispensable, especially in Indonesia, Central America, and East Africa—places where the planet is most active and "earth heat" is abundant. ●

IMPACT: *Our calculations assume geothermal grows from .66 percent of global electricity generation to 4.9 percent by 2050. That growth could reduce emissions by 16.6 gigatons of carbon dioxide and save $1 trillion in energy costs over thirty years and $2.1 trillion over the lifetime of the infrastructure. By providing baseload electricity, geothermal also supports expansion of variable renewables.*

ENERGY

SOLAR FARMS

RANKING AND RESULTS BY 2050 #8

36.9 GIGATONS	-$80.6 BILLION	$5.02 TRILLION
REDUCED CO2	NET COST	NET SAVINGS

Any scenario for reversing global warming includes a massive ramp-up of solar power by mid-century. It simply makes sense; the sun shines every day, providing a virtually unlimited, clean, and free fuel at a price that never changes. Small, distributed clusters of rooftop panels are the most conspicuous evidence of the renewables revolution powered by solar photovoltaics (PV). The other, less obvious iteration of the PV phenomenon is large-scale arrays of hundreds, thousands, or in some cases millions of panels that achieve generating capacity in the tens or hundreds of megawatts. These solar farms operate at a utility scale, more like conventional power plants in the amount of electricity they produce, but dramatically different in their emissions. When their entire life cycle is taken into account, solar farms curtail 94 percent of the carbon emissions that coal plants emit and completely eliminate emissions of sulfur and nitrous oxides, mercury, and particulates. Beyond the ecosystem damage those pollutants do, they are major contributors to outdoor air pollution, responsible for 3.7 million premature deaths in 2012.

The first solar PV farms went up in the early 1980s. Now, these utility-scale installations account for 65 percent of additions to solar PV capacity around the world. They can be found in deserts, on military bases, atop closed landfills, and even floating on reservoirs, where they perform the additional benefit of reducing evaporation. If Ukrainian officials have their way, Chernobyl, the site of a mass nuclear meltdown in 1986, will house a 1-gigawatt solar farm, which would be one of the world's largest. Whatever the site, *farm* is an appropriate term for these expansive solar arrays because photovoltaics are literally a means of energy harvesting. The silicon panels that make up a solar farm harvest the photons streaming to earth from the sun. Inside a panel's hermetically sealed environment, photons energize electrons and create electrical current—from light to voltage, precisely as the name suggests. Beyond particles, no moving parts are required.

Silicon PV technology was discovered by accident in the 1950s, alongside the invention of the silicon transistor that is present in almost every electronic device used today. That work happened under the auspices of the United States' Bell Labs, accelerated by a search for sources of distributed power that could work in hot, humid, remote locations, where batteries might fail and the grid would not reach. Silicon, the Bell scientists found, was a major improvement over the selenium that had been standard for experimental solar panels since the late 1800s. It achieved more than a tenfold rise in efficiency of converting light to electricity. In the 1954 debut of the Bell "solar battery," a tiny panel of silicon cells powered a twenty-one-inch Ferris wheel and then a radio transmitter. Small as they were, the demos duly impressed the press. The *New York Times* proclaimed it might mark "the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams—the harnessing of the almost limitless energy of the sun for the uses of civilization."

At that time, photovoltaics were so expensive (more than $1,900 per watt in today's currency), their only sensible use was in satellites. Up to space they went, but almost nowhere else. Ironically, the first major purchaser of solar cells for use on earth was the oil industry, which needed a distributed energy source for its rigs and extraction operations. Since then, public investment, tax incentives, technology evolution, and brute manufacturing force have chipped away at the cost of creating PV, bringing it down to sixty-five cents per watt today. The decline in price has always outpaced predictions, and drops will continue. Informed predictions about the cost and growth of solar PV indicate that it will soon become the least expensive energy in the world. It is already the fastest growing. Solar power is a solution, but it might be fair to say it is a revolution as well. Constructing a solar farm is also getting cheaper, and it is faster than creating a new coal, natural gas, or nuclear plant. In many parts of the world, solar PV is now cost competitive with or less costly than conventional power generation. Developers are bidding select projects at pennies per kilowatt-hour, which would have been unthinkable a few years ago. Thanks to plunging hard and soft costs, alongside zero fuel use and modest maintenance requirements over time, the growth of large-scale solar has outpaced the most bullish expectations.

Compared to rooftop solar, solar farms enjoy lower installation costs per watt, and their efficacy in translating sunlight into electricity (known as efficiency rating) is higher. When their panels rotate to make the most of the sun's rays, generation can improve by 40 percent or more. At the same time, no matter where solar panels are placed, they are subject to the diurnal and variable nature of solar radiation and its misalignment with electricity use, peaking midday while demand peaks a few hours later. That is why as solar generation continues to grow, so should complementary renewables that are constant, such as geothermal, and that have rhythms different from the sun, such as wind, which tends to pick up at night. Energy storage and more flexible, intelligent grids that can manage the variability of production from PV farms will also be integral to solar's success.

The International Renewable Energy Agency already credits 220 million to 330 million tons of annual carbon dioxide savings to solar photovoltaics, and they are less than 2 percent of the global electricity mix at present. Could solar meet 20 percent of global energy needs by 2027, as some University of Oxford researchers calculate? Thanks to complementary government interventions and market progress, there are many promising signs: costs reaching “grid parity” with fossil fuel generation and dropping, the typical solar panel factory churning out hundreds of megawatts of solar capacity each year, and panels lasting easily for twenty-five years, if not decades more. In 2015, solar PV met almost 8 percent of electricity demand in Italy and more than 6 percent in Germany and Greece, leaders in the solar revolution. PV has had a long history of surpassing expectations and taking unexpected leaps forward. Hand in hand with distributed solar and supported by the right enabling technologies, the “new era” cited by the *New York Times* in 1954 is becoming reality. ●

IMPACT: *Currently .4 percent of global electricity generation, utility-scale solar PV grows to 10 percent in our analysis. We assume an implementation cost of $1,445 per kilowatt and a learning rate of 19.2 percent, resulting in implementation savings of $81 billion when compared to fossil fuel plants. That increase could avoid 36.9 gigatons of carbon dioxide emissions, while saving $5 trillion in operational costs by 2050—the financial impact of producing energy without fuel.*

ENERGY

ROOFTOP SOLAR

RANKING AND RESULTS BY 2050		#10
24.6 GIGATONS	$453.1 BILLION	$3.46 TRILLION
REDUCED CO2	NET COST	NET SAVINGS

An Uros mother and her two daughters live on one of the 42 floating islands made of totora reeds on Lake Titicaca. Their delight upon receiving their first solar panel is infectious. Installed at an elevation of 12,507 feet, the panel will replace kerosene and provide electricity to her family for the first time. As high tech as solar may be, it is a perfect cultural match: The Uru People know

Roof modules are spreading around the world because of their affordability. Solar PV has benefited from a virtuous cycle of falling costs, driven by incentives to accelerate its development and implementation, economies of scale in manufacturing, advances in panel technology, and innovative approaches for end-user financing—such as the third-party ownership arrangements that have helped mainstream solar in the United States. As demand has grown and production has risen to meet it, prices have dropped; as prices have dropped, demand has grown further. A PV manufacturing boom in China has helped unleash a torrent of inexpensive panels around the world. But hard costs are only one side of the expense equation. The soft costs of financing, acquisition, permitting, and installation can be half the cost of a rooftop system and have not seen the same dip as panels themselves. That is part of the reason rooftop solar is more expensive than its utility-scale kin. Nonetheless, small-scale PV already generates electricity more cheaply than it can be brought from the grid in some parts of the United States, in many small island states, and in countries including Australia, Denmark, Germany, Italy, and Spain.

The advantages of rooftop solar extend far beyond price. While the production of PV panels, like any manufacturing process, involves emissions, they generate electricity without emitting greenhouse gases or air pollution—with the infinite resource of sunlight as their sole input. When placed on a grid-connected roof, they produce energy at the site of consumption, avoiding the inevitable losses of grid transmission. They can help utilities meet broader demand by feeding unused electricity into the grid, especially in summer, when solar is humming and electricity needs run high. This "net metering" arrangement, selling excess electricity back to the grid, can make solar panels financially feasible for homeowners, offsetting the electricity they buy at night or when the sun is not shining.

Numerous studies show that the financial benefit of rooftop PV runs both ways. By having it as part of an energy-generation portfolio, utilities can avoid the capital costs of additional coal or gas plants, for which their customers would otherwise have to pay, and broader society is spared the environmental and public health impacts. Added PV supply at times of highest electricity demand can also curb the use of expensive and polluting peak generators. Some utilities reject this proposition and posit contradictory claims of rooftop PV being a “free rider,” as they aim to block the rise of distributed solar and its impact on their revenue and profitability. Others accept its inevitability and are trying to shift their business models accordingly. For all involved, the need for a grid “commons” continues, so utilities, regulators, and stakeholders of all stripes are evolving approaches to cover that cost.

Off the grid, rooftop panels can bring electricity to rural parts of low-income countries. Just as mobile phones leapfrogged installation of landlines and made communication more democratic, solar systems eliminate the need for large-scale, centralized power grids. High-income countries dominated investment in distributed solar until 2014, but now countries such as Chile, China, India, and South Africa have joined in. It means rooftop PV is accelerating access to affordable, clean electricity and thereby becoming a powerful tool for eliminating poverty. It is also creating jobs and energizing local economies. In Bangladesh alone, those 3.6 million home solar systems have generated 115,000 direct jobs and 50,000 more downstream.

Since the late nineteenth century, human beings in many places have relied on centralized plants that burn fossil fuels and send electricity out to a system of cables, towers, and poles. As households adopt rooftop solar (increasingly accompanied and enabled by distributed energy storage), they transform generation and its ownership, shifting away from utility monopolies and making power production their own. As electric vehicles also spread, "gassing up" can be done at home, supplanting oil companies. With producer and user as one, energy gets democratized. Charles Fritts had this vision in the 1880s, as he looked out over the roofscape of New York City. Today, that vision is increasingly coming to fruition. ●

IMPACT: *Our analysis assumes rooftop solar PV can grow from .4 percent of electricity generation globally to 7 percent by 2050. That growth can avoid 24.6 gigatons of emissions. We assume an implementation cost of $1,883 per kilowatt, dropping to $627 per kilowatt by 2050. Over three decades, the technology could save $3.4 trillion in home energy costs.*

ENERGY

WAVE AND TIDAL

RANKING AND RESULTS BY 2050		#29
9.2 GIGATONS	$411.8 BILLION	-$1 TRILLION
REDUCED CO2	NET COST	NET SAVINGS

The oceans are in constant motion, rippling, swirling, swelling, retreating. As wind blows across the surface, waves are formed. As the gravitational forces of earth, moon, and sun interact, tides are created.

These are among the most powerful and constant dynamics on earth.

Wave- and tidal-energy systems harness natural oceanic flows to generate electricity. A variety of companies, utilities, universities, and governments are working to realize the promise of consistent and predictable ocean energy, which currently accounts for a fraction of global electricity generation. Early technologies date back more than two centuries, with modern designs emerging in the 1960s, thanks especially to the work of Japanese naval commander Yoshio Masuda and his 1947 invention of the oscillating water column (OWC). As a wave or tide rises within an OWC, air is displaced and pushed through a turbine, creating electricity. With the ongoing movement of ocean waters, air is compressed and decompressed continuously. It is the same principle used in whistling buoys, which draw on compressed air to create noise near treacherous shoals or outcroppings. Today, there are several OWC power plants in the world.

The appeal of wave and tidal energy is its constancy: No energy storage is required. And while communities often resist the presence of wind turbines along ridges or shorelines for violating viewsheds, the idea of underwater, out-of-sight wave and tidal systems has proven to be more acceptable to coastal citizens. (Though they can pose concerns for local fishermen, whose livelihoods depend on the same waters.)

When it comes to energy generation, not all waves and tides are created equal. East-west trade winds blow at 30 to 60 degrees latitude, giving the west coasts of all continents the greatest wave activity. Surfing destinations are often wave-energy hot spots. Key locations for vigorous tidal energy are the northeastern coast of the United States, the western coast of the United Kingdom, and the shoreline of South Korea. Many experts also point to smaller islands as candidates for wave and tidal energy, given isolated geographies and limited energy resources.

dropping rapidly, that gap will likely widen. However, as this technology evolves and policy comes into place to support implementation, marine renewables may follow a similar path, attracting private capital investment and the interest of large companies such as General Electric and Siemens. On a trajectory like that, wave and tidal energy could also become cost competitive with fossil fuels. ●

IMPACT: *There are not many projections of wave and tidal energy to 2050. Building on those few, we estimate that wave and tidal energy can grow from .0004 percent of global electricity production to .28 percent by 2050. The result: reducing carbon dioxide emissions by 9.2 gigatons over thirty years. Cost to implement would be $412 billion, with net losses of $1 trillion over three decades, but the investment would pave the way for longer-term expansion and emissions reductions.*

ENERGY
CONCENTRATED SOLAR

RANKING AND RESULTS BY 2050 #25

10.9 GIGATONS	$1.32 TRILLION	$413.9 BILLION
REDUCED CO2	NET COST	NET SAVINGS

The Crescent Dunes Solar Energy Project is a 110-megawatt solar thermal plant located near Tonopah, Nevada. It also is a molten salt storage plant, capable of holding 1.1 billion kilowatt-hours of energy. 10,347 heliostats circle a 640-foot tower at the center and have a combined surface area of 1.28 million square feet. The $1 billion plant produces electricity at 13.5 cents per kilowatt-hour, higher than wind and solar farms to be sure. However, Tonopah provides steady baseload power, which in turn enables intermittent energy from renewable wind and solar to be seamlessly integrated into the grid.

So far, concentrated solar power (CSP) "has been a tale of two countries, Spain vs. the U.S." That is how the International Energy Agency sums up the beginning of the story of CSP, also known as solar thermal electricity. The first plants came online in California in the 1980s, and still run today. Instead of capturing energy from the sun's light and converting it directly into electricity like photovoltaics do, they rely on the core technology of conventional fossil fuel generation: steam turbines. The difference is that rather than using coal or natural gas, CSP uses solar radiation as its primary fuel—free and clear of carbon. Mirrors, the essential component of any CSP plant, are curved or angled in specific ways to concentrate incoming solar rays to heat a fluid, produce steam, and turn turbines. As of 2014, this technology was limited to just 4 gigawatts worldwide. Roughly half was in Spain, the one country where CSP is significant enough to show up in national generation statistics, at about 2 percent. Because of CSP's unique advantages, it will grow and those stats will shift. Morocco's giant Noor Ouarzazate Solar Complex, on the edge of the Sahara, is already changing the solar thermal landscape and will be the world's largest when complete.

CSP plants rely on immense amounts of direct sunshine—direct normal irradiance (DNI). DNI is highest in hot, dry regions where skies are clear, typically between latitudes of 15 and 40 degrees. Optimal locales range from the Middle East to Mexico, Chile to Western China, India to Australia. According to a 2014 study in the journal *Nature Climate Change*, the Mediterranean basin and the Kalahari Desert of Southern Africa have the greatest potential for large, interconnected networks of CSP, with the potential to supply power at a cost comparable to that of fossil fuels. In many regions best suited to making solar thermal power, technical generation capacity (the electricity they could be capable of producing) far surpasses demand. With advances in transmission lines, they could supply local populations *and* export power to places where CSP is more constrained.

Rather ironically, the recent success of solar photovoltaic (PV) has limited the growth of solar thermal electricity. PV panels have become so cheap with such speed that CSP has been sidelined; steel and mirrors have not seen the same price plunge. But as PV comes to comprise a greater fraction of the generation mix, it may shift from a damper to a boost. That is because CSP has the very advantage photovoltaics struggle with and need: energy storage. Unlike PV panels and wind turbines, CSP makes heat before it makes electricity, and the former is much easier and more efficient to store. Indeed, heat can be stored twenty to one hundred times more cheaply than electricity. In the past decade, it has become relatively standard to build CSP plants with storage in the form of molten salt tanks. Warmed with excess heat during the day, molten salt can be kept hot for five to ten hours, depending on the DNI of a particular site, then used to generate electricity when the sun's rays soften. That capacity is crucial for the hours when people remain awake, consuming electricity, but the sun has gone down. Even without molten salt, CSP plants can store heat for shorter periods of time, giving them the ability to buffer variations in irradiance, as can happen on cloudy days—something PV panels cannot do. More flexible and less intermittent than other renewables, CSP is easier to integrate into the conventional grid and can be a powerful complement to solar PV. Some plants pair the two technologies, strengthening the value of both.

Compared to wind and PV generation, the major downside of CSP, to date, is that it is less efficient, in terms of both energy and economics. Solar thermal plants convert a smaller percentage of the sun's energy to electricity than PV panels do, and they are highly capital intensive, particularly because of the mirrors used. Experts anticipate that the reliability of CSP will hasten its growth, however, and as the technology scales, costs could fall quickly. Efficiency of energy conversion is also projected to improve. (Technologies currently under development are already proving it.)

Other downsides require attention as well. Solar thermal typically relies on natural gas as a production backup or, in some cases, a consistent production boost, with accompanying carbon dioxide emissions. The use of heat often implies the use of water for cooling, which can be a scarce resource in the hot, dry places ideal for CSP. Dry cooling is possible, but it is less efficient and more expensive. Lastly, by concentrating channels of intense heat, CSP plants have killed bats and birds, which literally combust in midair. One company, Solar Reserve, has developed an effective strategy to stop bird deaths; spreading that practice for mirror operation will be critical as more plants come online.

Human beings have long used mirrors to start fires. The Chinese, Greeks, and Romans all developed "burning mirrors"—curved mirrors that could concentrate the sun's rays onto an object, causing it to combust. Three thousand years ago, solar igniters were mass-produced in Bronze Age China. They're how the ancient Greeks lit the Olympic flame. In the sixteenth century, Leonardo da Vinci designed a giant parabolic mirror to boil water for industry and to warm swimming pools. Like so many technologies, using mirrors to harness the sun's energy has been lost and found repeatedly, enchanting experimentalists and tinkerers through the ages—and once again today. ●

IMPACT: *CSP comprised .04 percent of world electricity generation in 2014. Despite slow adoption in recent years, this analysis assumes CSP could rise to 4.3 percent of world electricity generation by 2050, avoiding 10.9 gigatons of carbon dioxide emissions. Implementation costs are high at $1.3 trillion, but* turnaround." Germany currently produces 7 percent of its energy from biomass. When the total cost of harvesting and processing wood is calculated, it is not carbon neutral. The industry exists because of significant government subsidies.

How does the world get from one powered by fossil fuels to one that runs entirely on energy from the wind, sun, earth's heat, and water's movement? Part of the answer is biomass energy generation. It is a "bridge" solution from status quo to desired state—imperfect, riddled with caveats, and probably necessary. Necessary because biomass energy can produce electricity on demand, helping the grid meet predictable changes in load and complementing variable sources of power, like wind and solar. Biomass can aid the shift away from fossil fuels and buy time for flexible grid solutions to come online, while utilizing wastes that might otherwise become environmental problems. In the near-term, substituting biomass for fossil fuels can prevent carbon stocks in the atmosphere from rising.

Photosynthesis is an energy conversion and storage process; solar energy is captured and stored as carbohydrates in biomass. Under the right conditions and over millions of years, biomass left intact would become coal, oil, or natural gas—the carbon-dense fossil fuels that, at present, dominate electricity production and transportation. Or, it can be harvested to produce heat, create steam for electricity production, or be processed into oil or gas. Rather than releasing fossil-fuel carbon that has been stored for eons far belowground, biomass energy generation trades in carbon that is already in circulation, cycling from atmosphere to plants and back again. Grow plants and sequester carbon. Process and burn biomass. Emit carbon. Repeat. It is a continuous, neutral exchange, so long as use and replenishment remain in balance. Energy efficiency and cogeneration are integral to ensure that, in any given year, carbon from biomass combustion is equal to or less than the carbon uptake of replanted vegetation. When this balance is achieved, the atmosphere sees net zero new emissions.

There is an if: Biomass energy is a viable solution *if* it uses appropriate feedstock, such as waste products or sustainably grown, appropriate energy crops. Optimally, it also uses a low-emission conversion technology such as gasification or digestion. Using annual grain crops such as corn and sorghum for energy production depletes groundwater, causes erosion, and requires high inputs of energy in the form of fertilizer and equipment operation. The sustainable alternative is perennial crops or so-called short-rotation woody crops. Perennial herbaceous grasses such as switchgrass and *Miscanthus* can be harvested for fifteen years before replanting becomes necessary, and they require fewer inputs of water, and labor. Woody crops such as shrub willow, eucalyptus, and poplar are able to grow on "marginal" land not suited to food production. Because they grow back after being cut close to the ground, they can be harvested repeatedly for ten to twenty years. These woody crops circumvent the deforestation that comes with using forests as fuel and sequester carbon more rapidly than most other trees can, but not if they replace already forested lands. Care needs to be taken with both *Miscanthus* and eucalyptus, however, as they are invasive.

Another important feedstock is waste from wood and agricultural processing. Scraps from saw mills and paper mills are valuable biomass. So are discarded stalks, husks, leaves, and cobs from crops grown for food or animal feed. While it is important to leave crop residues on fields to promote soil health, a portion of those agricultural wastes can be diverted for biomass energy production. Many such organic residues would either decompose on-site or get burned in slash piles, thus releasing their stored carbon regardless (albeit perhaps over longer periods of time). When organic matter decomposes, it often releases

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not
available