MARK Z. JACOBSON

Foreword by BILL MCKIBBEN

‘Pollution, climate catastrophe and energy security can all be addressed with his simple plan... This book is a godsend.’
MARK RUFFALO

# No Miracles Needed

## How Today's Technology Can Save Our Climate and Clean Our Air

# No Miracles Needed

The world needs to switch away from using fossil fuels to using clean, renewable sources of energy as soon as possible. Failure to do so will lead to accelerated and catastrophic climate damage, loss of biodiversity, and economic, social, and political instability. This book describes how to solve the climate crisis, and at the same time eliminate air pollution and safely secure energy supplies for all – without using "miracle" technologies. It explains how to use existing technologies to harness, store, and transmit energy from wind, water, and solar sources to ensure reliable electricity and heat supplies. It also discusses which technologies are not needed, including natural gas, carbon capture, direct air capture, blue hydrogen, bioenergy, and nuclear energy. Written for everyone, *No Miracles Needed* advises individuals, communities, and nations on what they can do to solve the problems, including the economic, health, climate, and land benefits of the solutions.

**Mark Z. Jacobson** is a professor of Civil and Environmental Engineering and Director of the Atmosphere/Energy Program at Stanford University. He has published six books and over 175 peer-reviewed papers. His work forms the scientific basis of the Green New Deal and many laws and commitments for cities, states, and countries to transition to 100 percent renewable electricity and heat generation. He received the 2018 Judi Friedman Lifetime Achievement Award, and in 2019 was selected as "one of the world's 100 most influential people in climate policy" by Apolitical. In 2022, he was chosen as the World Visionary CleanTech Influencer of the Year. He has served on an advisory committee to the U.S. Secretary of Energy, appeared in a TED talk, appeared on the David Letterman Show, and cofounded The Solutions Project.

"To those who wrongly insist we lack the tools to decarbonize our economy today, I say: read energy systems expert Mark Jacobson's amazing new book. In *No Miracles Needed*, Jacobson presents a comprehensive and detailed, yet highly accessible and readable blueprint for the options we have right now to address the climate crisis by taking advantage of existing renewable energy, storage, and smart grid technology combined with electrification of transportation systems, and efficiency measures. Read this book and be informed and engaged to help tackle the defining challenge of our time."

Michael Mann, Distinguished Professor of Atmospheric Science at
Penn State University and author of
*The New Climate War*

"Many people believe or fear that we can't solve the climate crisis, because we just don't have the technologies in hand to do so. This book should lay that fear to rest, once and for all."

Naomi Oreskes, co-author (with Erik M Conway) of
*The Big Myth: How American Business Taught Us to Loathe Government and Love the Free Market*

"… shows impressively that numerous crises can be killed with one stone, without us having to wait for miracles: the energy, economic, health, and biodiversity crises can be solved by transitioning to a smart and complete supply of renewable energies. Let's not wait for miracles: let's simply implement it as soon as possible. Well worth reading!"

Claudia Kemfert, German Institute for Economic Research and
Professor of Energy Economics and Energy Policy at
Leuphana University

"… a highly compelling and accessible book laying out the best path for [our] energy future, one that is achievable with currently available technologies, with no need for some new miraculous breakthrough. This is a must read for all who care about the future of our society and our planet, written by the world's premier thinker on energy futures."

Bob Howarth, Cornell University

"… blends science, engineering and history into a readable cornucopia of information … Mark's style is to present approachable depth on dozens of major topics: everything you need to understand, and to join the fight against, the peril of our time."

Anthony R. Ingraffea, Cornell University

"Forget future miracle technologies promised by snake oil salespeople. This book offers a practical and real-world solution today. It is a must read for everyone concerned about climate change and air pollution and interested in the transition to a more sustainable all-purpose renewable energy future. It is sure to be one of the most important books that you will read this decade."

Peter Strachan, Aberdeen Business School,
Robert Gordon University

"Mark Jacobson's essential book, *No Miracles Needed,* offers clean, safe, and efficient solutions for our energy needs in this time of ever-growing climate chaos and disaster … The tools for producing, storing, and transmitting affordable and safe clean energy exist here and now with wind, water, and solar. *No miracles are needed.* A tireless and brilliant advocate for the environment, Professor Mark Jacobson's voice must be read, heard, and acted upon —now."

Heidi Hutner, Stony Brook University

# No Miracles Needed

## How Today's Technology Can Save Our Climate and Clean Our Air

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**To the young people of today, who will take us to the finish line tomorrow**

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# FOREWORD

This is among the most important books you'll ever read, because it lays out in clear and frank terms the great problem of our age, and the great solution.

Burning things – coal, gas, oil, and biomass – has produced the prosperous world that we in the West inhabit. It has allowed us to heat and cool our buildings when the temperature is not to our liking, to light our spaces so as to extend our days, and to move ourselves and our stuff great distances with great ease. It has liberated us, that is, from many of the constraints that had traditionally governed human life.

But we now know that those liberations have come with unbearable cost. Breathing the smoky byproducts of all that burning kills more than 7 million of our brothers and sisters each year, far more than Covid, or HIV/AIDS, or malaria, or war. And that combustion has filled the air with invisible greenhouse gases that now threaten the very stability of our civilizations by raising the temperature and in the process melting the icecaps, destabilizing the jet stream and the Gulf Stream, raising the sea level, and sundry other catastrophes on a scale of destruction we'd previously imagined only in connection with atomic weapons.

So replace them we must – but with what? Mark Jacobson and his team have provided, after two decades of work, all the answers we need. Wind power, hydropower, and solar power – wind, water, and sun, or WWS to use his formulation – are sufficient to give us more than enough energy for our needs, and to do it at a cost that should allow for quick transition. This book lays out those essential facts in interesting, accessible, and readable fashion: it is a user's manual for a planet in transition, and one that should settle the panic in anyone who thinks we lack the resources to do what needs doing.

To state it plainly: there is no longer any technical or economic obstacle to the swift transition of our energy system to something far cleaner, cheaper, and more rational. We have the miracle technologies we require firmly in hand. You can point a sheet of glass at the sun and out the back will come light, air conditioning, information, mobility: all the requirements of modernity. Jacobson dutifully considers the possible drawbacks – will it use up minerals we don't possess in sufficient quantity, or occupy too much land – and comes back with mathematical assurances. He has the data.

But of course winning the argument is not the same as winning the fight. Shifting in the short time that climate science requires will mean overcoming both inertia and vested interest, which means that all of us, even if we are not engineers, have a role to play in getting the job done. Indeed, some of the most interesting sections of this volume describe Jacobson's own evolution into an activist of sorts, or at least someone trying to make the case for change. If he can overcome the sweaty panic that overtook him in the seconds before his nationwide interview with David Letterman, the rest of us can learn to make this case in letters to the editor and to our elected leaders.

In fact, it would be a dereliction of intellectual duty to read this book and then not take some actions to change the debate. If we had no readily available answer to the twin crises of climate change and air pollution, then I suppose we could in conscience ignore them. But the solutions are readily at hand. This book should empower you – and with not a moment to spare!

**Bill McKibben**

# PREFACE

On July 11, 2011, I was invited to a dinner at the Axis Café and Gallery in San Francisco to discuss the potential of renewable energy as an alternative to natural gas hydrofracking in New York State. Little did I know it at the time, but that dinner would set off a chain reaction of events that turned a scientific theory, that the world has the technical and economic ability to run on 100 percent clean, renewable energy and storage for all purposes, into a mass popular movement to do just that. The movement catalyzed an explosion of worldwide country, state, and city laws and proposed laws, including the Green New Deal, and business commitments. Ten years after that meeting, critics were no longer mocking our ideas as pie-in-the-sky and tooth-fairy-esque. They were no longer claiming that transitioning to more than 20 percent renewables would cripple power grids. Instead, the discussion had changed to what is the cost of 100 percent renewables, how fast can we get there, and should we leave a few percent for non-renewables?

Why do we want to transition our worldwide energy system entirely to clean, renewable energy and storage for everything? This book first explores the three main reasons: to eliminate air pollution, global warming, and energy insecurity. Air pollution kills about 7 million people and injures hundreds of millions more each year worldwide. It is the second-leading cause of death. The impacts of global warming are accelerating as greenhouse gases and dark pollution particles in our atmosphere continue to increase. Such impacts include melting of glaciers and sea ice, rising sea levels, more droughts and floods, more intense hurricanes and wildfires, more air pollution and heat-related deaths and illnesses, agricultural shifts and famine, climate migration, species extinction, coral reef damage, and more. Lastly, fossil fuels are limited resources. As they run out, economic, social, and political instability will ensue. These three problems require an immediate and drastic solution.

Do we need *miracle technologies*? No. Then what is the solution? It is to transition the world's current combustion-based energy to 100 percent clean, renewable **wind, water, and solar** (**WWS**) and storage for all energy purposes and to eliminate non-energy emissions. The main idea behind the solution comes from the fact that air pollution health and climate problems arise from the same cause: combustion of fossil fuels, bioenergy fuels, and open biomass. **Fossil fuels** include coal, oil, natural gas, and all their derivatives, such as gasoline, diesel, kerosene, jet fuel, and liquefied natural gas. **Bioenergy fuels** include liquid biofuels, such as ethanol, biodiesel, and bio jet fuel, for transportation, and solid biomass, such as wood, wood pellets, dung, and vegetation, for electricity and heat. **Open biomass** includes forests, woodland, grassland, savannah, agricultural crops, and agricultural residues. Burning any of these leads to pollution that affects both health and climate.

To solve the problems, it is necessary to move away from combustion by electrifying and providing direct heat without combustion. For the electricity and heat to remain clean and available for millennia to come while not creating other risks, they need to originate from clean, renewable, and sustainable sources, namely WWS.

WWS includes energy from **wind** (onshore and offshore wind electricity), **water** (hydroelectricity, tidal and ocean current electricity, wave electricity, geothermal electricity, and geothermal heat), and **sunlight** (solar photovoltaic (PV) electricity, concentrated solar power (CSP) electricity and heat, and direct solar heat). WWS electricity and heat need to power all current energy sectors, which include the electricity, transportation, building heating and cooling, industrial, agriculture/forestry/fishing, and military sectors. Although human-designed energy systems cause about 90 to 95 percent of **anthropogenic** (human-produced) air pollution and 75 percent of anthropogenic greenhouse gas emissions, this book also discusses methods of eliminating non-energy anthropogenic emissions that damage air quality and warm the planet.

Many solutions to date that have focused on the climate problem have included some technologies that are less helpful than WWS technologies. This book describes such technologies, which raise costs to consumers and society, increase emissions relative to WWS sources, create substantial risks that WWS sources do not have, and/or delay the solution to pollution and global warming because of the long time they take to come online. Given our limited time and funding available to solve the pollution, climate, and energy security problems we face, it is essential to focus on known, effective solutions that can be implemented rapidly. Money spent on less-useful options will permit more health, climate, and energy insecurity damage to occur.

In fact, to solve the three problems posed here, we have 95 percent of the technologies that we need already commercially available. We also know how to build the rest, which include primarily long-distance aircraft and ships, powered by hydrogen fuel cells, and some industrial technologies. As such, we do not need *miracle technologies* to solve these problems. We need the collective willpower of people around the world to solve them.

Why 100 percent clean, renewable energy and storage for everything? Why not 50 percent, 80 percent, or 99 percent? First, the health plus climate damage of every bit of pollution that we allow to remain in the air is so enormous that it is important both morally and economically to eliminate 100 percent of emissions. Second, 99 percent is not an ambitious goal to shoot for. Did Magellan aspire to circumnavigate 99 percent of his way around the Earth? Did the Apollo 11 crew aspire to reach 99 percent of its way to the moon? No. One hundred percent is the goal because that is the best society can do and will result in the cleanest air and most stable climate possible for future generations. Societies often strive for the best and safest.

How fast do we need to transition? In order to avoid more than 1.5 degrees Celsius global warming compared with temperatures between 1850 and 1900, we need to eliminate at least 80 percent of all emissions by 2030 and 100 percent no later than 2050, but ideally by 2035. In order to avoid tens of millions more air pollution deaths, we need to eliminate all emissions even faster.

Can we reach the goal of 100 percent WWS across all energy sectors and eliminate non-energy emissions at that speed? This book examines this question, including the data and scientific studies that say we can. It concludes that a transition among all energy and non-energy sectors worldwide is economically possible with technology that is almost all existing. The main obstacles are social and political.

This book is for lay-readers concerned about the massive air pollution, climate, and energy security problems the world faces. To summarize, it discusses why no *miracle technologies* are needed to solve these problems in the short period we have left to do so. The solution is to use existing and known technologies to harness, store, and transmit energy in the wind, the water, and the sun, and to ensure reliable electricity and heat supplies worldwide. The book also discusses what technologies are not helpful or needed but are being pursued vigorously. "Transition highlights" throughout the text offer examples of changes to renewable energy somewhere in the world. Finally, the book gives information about what individuals, communities, and nations can do to solve the problems, as well as the cost, health, climate, and land benefits of the solution.

# 1 WHAT PROBLEMS ARE WE TRYING TO SOLVE?

Why do we want to transition all of our energy to clean, renewable energy? Why don't we just continue burning fossil fuels until they run out, which may be in 50 to 150 years? For three major reasons. Namely, fossil fuels today cause massive air-pollution health damage, climate damage, and risks to our energy security. These three problems, which have the same root cause, require immediate and drastic solutions. The longer we wait to solve these problems, the more the accumulated damage. This chapter examines each problem, in turn.

## 1.1 The Air Pollution Tragedy

Today, air pollution is the second-leading cause of human death and illness worldwide. It also kills and injures animals; impedes visibility; and harms plants, trees, crops, structures, tires, and art. Because air pollution causes such enormous loss and cost, controlling it is one of the greatest challenges of our time.

What is air pollution? **Air pollution** occurs when

> *gases or aerosol particles in the air build up in concentration sufficiently high to cause direct or indirect damage to humans, plants, animals, other life forms, ecosystems, structures, or works of art.*

What are gases and aerosol particles? A **gas** is a group of atoms or molecules that are not bonded to each other. Whereas a liquid occupies a fixed volume and a solid has a fixed shape, a gas is unconfined and freely expands with no fixed volume or shape.

An **aerosol particle** consists of 15 or more gas atoms or molecules, suspended in the air, that have bonded together and changed phase to become a liquid or solid. An aerosol particle can contain one chemical or a mixture of many different chemicals. An **aerosol** is an ensemble, or cloud, of aerosol particles.[1] Aerosol particles are distinguished from cloud drops, drizzle drops, raindrops, ice crystals, snowflakes, and hailstones, in that the latter all start as an aerosol particle but grow far more water on them than the former.

Gases and aerosol particles may be emitted into the air naturally or by humans (**anthropogenically**). They may also be produced chemically in the air from other gases or aerosol particles. Natural air pollution problems on the Earth are as old as the planet itself. Volcanos, natural fires, lightning, desert dust, sea spray, plant debris, pollen, spores, viruses, bacteria, and bacterial metabolism have all contributed to natural air pollution.

Humans first emitted air pollutants when we burned wood for heating and cooking. Today, anthropogenic air pollution arises primarily from the burning of fossil fuels and bioenergy fuels used for energy, and from the burning of open biomass for land clearing or ritual, or due to arson or carelessness. Air pollutants also arise from the release of chemicals to the air, such as from industrial processes or leaks.

The main **fossil fuels** burned today are coal, natural gas, and crude oil. Crude oil is refined into multiple products, including gasoline, diesel, kerosene, heating oil, naphtha, liquefied petroleum gas, jet fuel, and bunker fuel. **Bioenergy** fuels burned are either solid fuels, such as wood, vegetation, or dung, or liquid fuels, such as ethanol or biodiesel. **Open biomass** includes forests, woodland, grassland, savannah, and agricultural residues. Anthropogenic emissions have contributed not only to indoor and outdoor air pollution, but also to acid rain, the Antarctic ozone hole, global stratospheric ozone loss, and global warming.

In 2019, 55.4 million people died from all causes worldwide.[2] Air pollution enabled about 7 million (12.6 percent) of the deaths, making it the second-leading cause of death after heart disease.[3] Of the air pollution deaths, about 4.4 million were due to outdoor air pollution and about 2.6 million were due to indoor air pollution.[3] Indoor air pollution arises because 2.6 billion people burn solid fuels (wood, dung, crop waste, coal) and kerosene indoors for cooking and heating.[4] Air pollution also causes hundreds of millions of illnesses each year.

The deaths and illnesses arise when air pollution particles (mostly) and gases trigger or exacerbate heart disease, stroke, chronic obstruction pulmonary disease (chronic bronchitis and emphysema), lower respiratory tract infection (flu, bronchitis, and pneumonia), lung cancer, and asthma.

Almost half of all pneumonia deaths worldwide among children aged five and younger are due to air pollution.[4] Many children who die live in homes in which solid fuel or kerosene is burned for home heating and cooking. Their little lungs absorb a high concentration of aerosol particles in the air that result from fuel burning. They die of pneumonia because their immune systems weaken owing to the assault of air pollutants on their respiratory systems. Most of the casualties are in developing countries, where indoor burning often still occurs on a large scale. These deaths and illnesses not only devastate families, but also incur tremendous cost. The worldwide cost of all air pollution death and illness is estimated to be over US$30 trillion per year today.[5]

**Transition highlight**

In 2019, 7 million people died from air pollution worldwide. China and India absorbed the brunt of mortalities, with a combined total of 3.6 million deaths (52 percent of the total). Nigeria, Pakistan, Indonesia, Bangladesh, the Philippines, and Russia all suffered more than 100,000 air pollution deaths that year. The highest per capita air pollution death rates were in North Korea, Georgia, Chad, Nigeria, Bosnia and Herzegovina, and Somalia, respectively.

Around half the mass of aerosol particles emitted worldwide is in natural particles. However, natural particles are mostly large and thus do not penetrate deep into people's lungs. On the other hand, combustion particles, which are almost all from human sources today, are mostly small and penetrate deep into the lungs. Most combustion particles are also emitted near where people live, so people breathe in these particles. As a result, about 90 to 95 percent of air pollution deaths today are caused by anthropogenic air pollution. Of these deaths, about 90 percent are due to air pollution particles; the rest are due to air pollution gases, primarily ozone.

Because combustion during energy production is the world's major source of air pollution, changing the world's energy infrastructure to eliminate combustion will largely eliminate air pollution death and illness worldwide. This goal can be accomplished by transitioning to 100 percent clean, renewable energy and storage for everything.

## 1.2 Global Warming

### 1.2.1 The Natural Greenhouse Effect

**Global warming** is the human-caused increase in the average temperature of the Earth's lower atmosphere since the Industrial Revolution above and beyond the temperature due to the natural greenhouse effect. The **natural greenhouse effect** is the increase in the Earth's average temperature above its temperature without an atmosphere. The natural greenhouse effect is due to the build-up of natural greenhouse gases in the atmosphere since the formation of the Earth. **Greenhouse gases** are gases that are mostly transparent to sunlight but that absorb some of the heat emitted by the surface of the Earth. All objects in the universe, including the Earth, emit heat.

The Earth has three main sources of heat. The first and, by far, the most important, is sunlight, also called **solar radiation**. The Earth absorbs sunlight and converts it to heat, also called **infrared radiation**. About 99.97 percent of the heat emitted by the surface of the Earth originates from sunlight. The remaining 0.03 percent of heat originates from the interior of the Earth from two sources, each in relatively equal proportions. One is heat left over from the formation of the Earth, called **primordial heat**. Owing to gravitational compression of the Earth's interior during its formation, and despite heat loss over time, the temperature at the center of the Earth is still about 4,300 degrees Celsius. This heat transfers slowly to the surface of the Earth by **conduction**, which is the process by which molecules transfer energy to each other when they collide. Primordial heat also gets to the surface by volcanic activity. The other source of interior heat is heat released during the decay of radioactive elements in the Earth's interior. The main elements that decay are uranium, thorium, and a small fraction of potassium. The decay products of these elements decay further as well. The resulting heat transfers slowly to the surface, also by conduction.

Greenhouse gases in the Earth's atmosphere are transparent to sunlight, allowing it to penetrate to the Earth's surface. However, the same gases trap a portion of the Earth's outgoing heat, warming the ground and air near the ground. The more greenhouse gases present, the greater the trapping of heat and warming of the air. When the greenhouse gases are natural, the resulting warming is called the natural greenhouse effect.

The primary natural greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide ($CO_2$), ozone, nitrous oxide, methane, and oxygen gas. Oxygen gas is a weak greenhouse gas, but it is so abundant in the air (20.95 percent of all air molecules) that it has a non-trivial natural warning impact. Nitrogen gas, which comprises 78.08 percent of the molecules in the Earth's atmosphere, is not a greenhouse gas.

If the Earth had no atmosphere, thus no natural greenhouse effect, its average surface temperature would be about minus 18 degrees Celsius (zero degrees Celsius is the freezing temperature of water). At that temperature, little life would exist on Earth's surface.

During Earth's 4.6-billion-year history, several processes released to the air all of the Earth's natural greenhouse gases, except for ozone. These processes included emissions (through volcanos, fumaroles, and geysers) of greenhouse gases from the Earth's interior, bacterial metabolism, bacterial photosynthesis, and green-plant photosynthesis. Ultraviolet sunlight cooked some oxygen to produce ozone, most of which formed high above the ground, in what is now called the stratospheric ozone layer. The formation of the ozone layer was critical for protecting the surface of the Earth from harmful ultraviolet sunlight, permitting life to move from underwater and underground to above the ground.

Natural greenhouse gases raised the temperature of the Earth substantially compared with the Earth without an atmosphere, permitting life to flourish on the Earth. Just before the start of the Industrial Revolution, around 1760, Earth's average temperature was about 15 degrees Celsius. That is 33 degrees Celsius higher than Earth's temperature without greenhouse gases (minus 18 degrees Celsius). This warming was due to the natural greenhouse effect. Of this temperature rise, about 66 percent was due to water vapor, about 25 percent was due to background carbon dioxide, and about 6.2 percent was due to background ozone, most of which is in the upper atmosphere.[6]

### 1.2.2 Global Warming

**Global warming** is the rise in the Earth's globally averaged ground and near-surface air temperature above and beyond that due to the natural greenhouse effect, due to human activity. The Earth's average global warming in the period 2011 to 2020 compared with the period 1850 to 1900 was about 1.09 degrees Celsius.[7] Since this is an average value, some places on Earth have warmed more, whereas others have warmed less or cooled. For example, the Arctic has warmed by over 5 degrees Celsius. Many other high-latitude locations (parts of Canada, Northern Europe, and Russia) have warmed by 2 to 5 degrees Celsius. The North Atlantic Ocean has cooled slightly.

### 1.2.3 Causes of Global Warming

Global warming is due to four major warming processes partially offset by one major cooling process (Figure 1.1). The four major warming processes are anthropogenic greenhouse gas emissions, anthropogenic warming particle emissions, anthropogenic heat emissions, and the urban heat island effect. The cooling process is anthropogenic cooling particle emissions.

#### 1.2.3.1 Anthropogenic Greenhouse Gas Emissions

The primary anthropogenic greenhouse gases contributing to global warming are carbon dioxide, methane, halogens, ozone, nitrous oxide, and anthropogenic water vapor.

The primary anthropogenic sources of **carbon dioxide** are fossil-fuel combustion, bioenergy combustion, open biomass burning, and chemical reaction during industrial processes, such as cement manufacturing, steel production, and silicon extraction. Owing to these emissions, carbon dioxide in the air has increased from about 275 parts per million (ppm) to 420 ppm, or by 53 percent, between 1750 and 2021. One part per million of carbon dioxide means that, for every million molecules of total air, one molecule is carbon dioxide. Carbon dioxide has been increasing in the air, not only owing to its emissions from human activity, but also because it stays in the air a long time. The major removal methods of carbon dioxide from the air are its dissolution into the oceans and other water bodies and green-plant

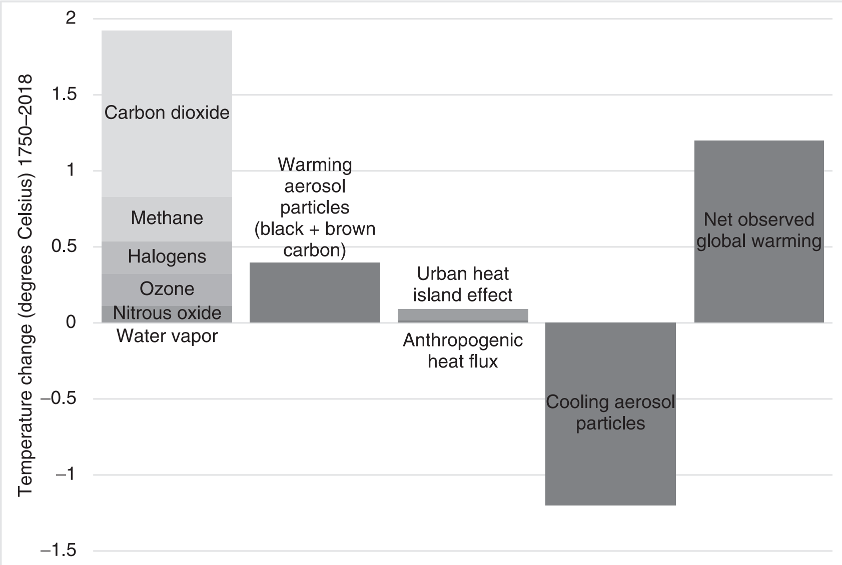


**Figure 1.1** Estimated primary contributors to net observed global warming from 1750 to 2018. Warming aerosol particles include black and brown carbon from fossil-fuel burning, biofuel burning, and open biomass burning. Cooling aerosol particle components include sulfate, nitrate, chloride, ammonium, sodium, potassium, calcium, magnesium, non-brown organic carbon, and water. Of the gross warming (warming before cooling is subtracted out), 45.7 percent is due to carbon dioxide, 16.3 percent is due to black plus brown carbon, 12 percent is due to methane, 9 percent is due to halogens, 8.8 percent is due to ozone, 4.3 percent is due to nitrous oxide, 3 percent is due to the urban heat island effect, 0.7 percent is due to anthropogenic heat flux, and 0.23 percent is due to anthropogenic water vapor. Source: Jacobson, *100% Clean, Renewable Energy*.[8]

photosynthesis (the conversion of carbon dioxide and water vapor into oxygen and cell material by plants and trees). However, these sinks remove carbon dioxide very slowly over many decades.

The primary anthropogenic sources of **methane** are natural gas, coal, and oil mining leakage; fossil-fuel combustion, bioenergy combustion; open biomass burning; and leakage from landfills, rice paddies, livestock, and manure. Methane is removed from the air primarily by chemical reaction in the air itself and by bacterial metabolism at the surface of the Earth.

**Halogens** are a series of synthetic chemicals whose main uses are as refrigerants, solvents, degreasing agents, blowing agents, fire extinguishants, and fumigants. The first halogen was invented in 1928. Halogens enter the atmosphere when appliances or tubes sealing them in liquid form leak or are drained, and the liquid evaporates.

Most halogens are **halocarbons**, which are chemicals that contain carbon and possibly hydrogen, but also either chlorine, bromine, fluorine, or iodine. The main types of halocarbons are the following. **Chlorofluorocarbons** (CFCs) are halocarbons containing carbon, chlorine, and fluorine. **Halons** are halocarbons containing carbon and bromine. **Perfluorocarbons** are halocarbons containing carbon and fluorine. **Hydrofluorocarbons** are halocarbons containing carbon, fluorine, and hydrogen. Some halogens, such as sulfur hexafluoride, have no carbon, so are not halocarbons.

Because chlorofluorocarbons and halons contain stratospheric-ozone-destroying chlorine and bromine, most countries outlawed them through international agreement starting with the 1987 Montreal Protocol. Hydrofluorocarbons and perfluorocarbons were developed as ozone-layer-friendly replacements. However, because many of them are greenhouse gases with long lifetimes in the air, such chemicals, while not directly damaging to the ozone layer, have the unintended consequence of enhancing global warming.

**Ozone** is the only greenhouse gas with no emission source. It forms chemically in the air. About 90 percent of ozone resides in the upper atmosphere (stratosphere), and the rest resides in the lower atmosphere (troposphere). The troposphere is the layer of air between the ground and 8 kilometers above sea level at the North and South Poles and between the ground and 18 kilometers above sea level at the equator. The stratosphere is the layer of air just above the troposphere and extends to about 48 kilometers above sea level. Because of the substantial abundance of ozone in the stratosphere, the stratosphere is also called the ozone layer.

In the stratosphere, ozone (which has three oxygen atoms) forms chemically following the breakdown of oxygen gas (made of two oxygen atoms bonded together) into two unbonded oxygen atoms, by ultraviolet sunlight. Atomic oxygen then combines with oxygen gas to form ozone.

In the troposphere, ozone is produced chemically following the breakdown, by ultraviolet sunlight, of nitrogen dioxide into atomic oxygen. The atomic oxygen then combines with the oxygen gas that we breathe (molecular oxygen) to form ozone. The nitrogen dioxide comes either from direct emissions or from chemical reaction between nitric oxide and certain reactive organic gases. Most emissions of nitric oxide, nitrogen dioxide, and reactive organic gases result from the burning of fuels by humans. Some comes from natural forest burning and bacterial metabolism. Some nitric oxide comes from lightning.

Since the Industrial Revolution, the mass of tropospheric ozone has increased by about 43 percent because of the worldwide increase in air pollution (the anthropogenic emissions of nitric oxide, nitrogen dioxide, and reactive organic gases). Since the late 1970s, stratospheric ozone has declined by about 5 percent owing to the increased presence of chlorofluorocarbons and halons within the stratosphere.

Ozone has a relatively short lifetime in the air. Most of its loss is due to chemical reaction. Just as its concentration has grown rapidly in the troposphere owing to increases in air pollution, its tropospheric concentration and warming impact can decrease rapidly if air pollution levels decrease. This is one reason that a strategy to eliminate air pollution can help to decrease global warming as well.

**Nitrous oxide (laughing gas)** is a colorless gas emitted naturally by bacteria in soils and in the oceans. Because it is long-lived, nitrous oxide stays in the air for up to hundreds of years once emitted. It is a powerful greenhouse gas, so it causes substantial warming per molecule during this period. Humans have increased the abundance of nitrous oxide in the air through fertilizer use, agricultural waste, sewage, legumes (plants in the pea family), bioenergy burning, biomass burning, jet-fuel burning, nylon manufacturing, and aerosol spray can manufacturing. Agriculture (fertilizers, agricultural waste, and legumes) is the largest source of human-emitted nitrous oxide today.

**Anthropogenic water vapor** comes from two main sources. The first is evaporation of water that is used to cool power plants and industrial facilities that run on coal, natural gas, oil, biomass, or uranium. The second is emission of water vapor during the burning of fuels for energy. Water vapor emitted annually from these sources is only about 1/8,800 of the 500 million metric tonnes of water vapor emitted per year from natural sources. Nevertheless, this relatively small anthropogenic emission rate of water vapor contributes a modest 0.23 percent of global warming.[6]

#### 1.2.3.2 Anthropogenic Warming Particle Emissions

Dark aerosol particles may contribute more to today's global warming than any other chemical aside from carbon dioxide (Figure 1.1).[9,10,11,12,13] Dark particles, also called **warming particles**, contain primarily black and brown carbon.

**Black carbon** is an agglomerate of solid spherules made of pure carbon and attached to each other in an amorphous shape. The source of black carbon is incomplete combustion of diesel, gasoline, jet fuel, bunker fuel, kerosene, natural gas, biogas, solid biomass, and liquid biofuels. Black carbon is often visible to the eye and appears black because it absorbs all wavelengths of sunlight, transmitting none to the eye. Black carbon particles convert the absorbed light to heat, raising the temperature of the particles and causing them to re-radiate some of the heat to the surrounding air.

Black carbon and greenhouse gases warm the air in different ways from each other. Greenhouse gases are mostly transparent to sunlight. They warm the air by absorbing heat emitted by the surface of the Earth. They then re-emit half of that heat upward and half downward, raising the ground and near-surface air temperatures.

Black carbon particles, on the other hand, heat the air primarily by absorbing sunlight, converting the sunlight to heat, then re-emitting the heat upward and downward, like with greenhouse gases. Black carbon particles also absorb and re-emit heat itself, but that process is important for them only at night and when black carbon concentrations are high.

When other aerosol material, such as sulfuric acid, nitric acid, water, or brown carbon, coats the outside of a black carbon particle, the black carbon heats the air 2 to 3 times faster than without a coating because more light hits the larger particle, thus more light bends (refracts) into the particle. Inside the particle, this light bounces around until it hits and is absorbed by the black carbon core.

Black carbon not only warms the air but also evaporates clouds and melts snow. When black carbon enters a cloud, it absorbs sunlight that bounces around in the cloud, converts the sunlight to heat, then emits the heat to the cloud, warming the cloud. If a sufficient number of black carbon particles is present, this warming can cause the cloud to evaporate completely. When black carbon falls on snow or sea ice, it similarly absorbs sunlight, converts the sunlight to heat, then emits the heat to the ice or snow, melting it.

Thus, for four reasons (its strong absorption when pure, its stronger absorption when coated, its ability to evaporate clouds, and its ability to melt snow and sea ice), black carbon is the second-leading cause of global warming after carbon dioxide. In fact, per molecule in the air, black carbon causes over a million times more warming than does carbon dioxide.[11] However, because black carbon particles last only days to weeks in the air, their concentrations are much lower than are those of carbon dioxide, which lasts decades in the air. Nevertheless, because black carbon is continuously emitted, it always causes a strong warming.

**Brown carbon** is also a particle component that increases global warming and causes health problems. Whereas brown carbon is generally more abundant than is black carbon, brown carbon is much less effective per unit mass at causing warming than is black carbon. As such, black carbon causes more overall warming than does brown carbon.

Whereas black carbon contains pure carbon, brown carbon contains carbon, hydrogen, and possibly oxygen, nitrogen, and or other atoms. In other words, brown carbon is a type of **organic carbon** (which is a chemical containing carbon, hydrogen, and other atoms). Not all organic carbon is brown carbon. Brown carbon is the subset of organic carbon that absorbs short (blue) and some medium (green) wavelengths of visible light. The remaining long wavelengths (red) and some of the green are transmitted to the viewer's eye, making the particle haze appear brown. The more green light that is transmitted (the less that is absorbed), the more yellow the particles appear. Other organic carbon particles are often white or grey because they do not absorb much or any visible light.

The sources of brown carbon, the combustion of fossil fuels, bioenergy, and biomass, are also the sources of black carbon. However, the relative amount of brown or black carbon from a combustion source depends largely on the temperature of the flame. Hotter flames favor black carbon, whereas cooler flames favor brown carbon. For example, in smoldering biomass (a low-temperature flame), the ratio of brown to black carbon is about 8 to 1. In diesel combustion (a high-temperature flame), the ratio is about 1 to 1.

Because black and brown carbon particles together cause such a large warming per molecule and have such short lifetimes in the air, reducing their emissions is the fastest way of slowing global warming.[11]

Because such particles both cause substantial human death and illness, reducing their emissions not only slows global warming but also immediately improves human health. Thus, two major reasons exist to eliminate black and brown carbon particle emissions: to slow global warming rapidly and to improve human health rapidly.

#### 1.2.3.3 Anthropogenic Heat Emissions

**Anthropogenic heat emissions** are emissions of heat from the use of electricity; friction created by vehicle tires on the road; the combustion of fossil fuels, biofuels, and biomass for energy; nuclear reaction; and anthropogenic biomass burning. Such heat emissions warm the air directly. Much of the hot air eventually rises, converting the heat energy into **gravitational potential energy**, which is energy embodied in air lifted to a certain height against gravity. Differences in gravitational potential energy between one location and another create winds, which carry with them kinetic energy. Thus, some anthropogenic heat emissions are converted to energy in the wind. The increases in both temperature and wind speeds due to heat emissions cause liquid water to evaporate. Since water vapor is a greenhouse gas, the production of water vapor accelerates the impact of the original heat emissions.

In sum, much of the heat from anthropogenic heat emissions converts to other forms of energy. Since energy is conserved, the different forms of energy persist in the atmosphere (or oceans and land). Overall, though, the impacts of anthropogenic heat emissions are much less than are those of greenhouse gases, which persist for decades to centuries and cause greater overall warming than do anthropogenic heat emissions. Anthropogenic heat may contribute to about 0.7 percent of global warming to date (Figure 1.1).[6] As such, eliminating combustion and nuclear reaction, which a WWS system does, substantially reduces anthropogenic heat emissions as well as the emissions of air pollutants, greenhouse gases, and warming particles.

#### 1.2.3.4 The Urban Heat Island Effect

**The urban heat island effect** is the temperature increase in urban areas due to the covering of soil and replacing of vegetation with impervious surfaces, such as concrete and asphalt. Covering surfaces reduces evaporation of water from soil and plants. Because evaporation is a cooling process, eliminating it warms the surface. Built-up areas also have sufficiently different properties of construction materials that they enhance urban warming relative to surrounding vegetated areas. Worldwide, the urban heat island effect may be responsible for about 3 percent of gross global warming (warming before cooling is subtracted out) (Figure 1.1).

#### 1.2.3.5 Cooling Particle Emissions

**Cooling particles** are light-colored aerosol particles that cool the Earth's surface by reflecting sunlight to space and by thickening clouds, which are largely reflective. Cooling particles contain primarily sulfate, nitrate, chloride, ammonium, sodium, potassium, calcium, magnesium, non-brown organic carbon, and water. Because cooling particles tend to be more soluble in water than are warming particles, cooling particles allow water vapor to condense readily on them, enhancing cloudiness, thereby cooling the climate. Warming particles, on the other hand, tend to heat clouds, helping to burn them off. Like with warming particles, cooling particles last only days to weeks in the air and cause major air pollution health damage. Like with warming particles, eliminating cooling particle emissions will improve human health dramatically. However, eliminating cooling particles will raise global temperatures. This is why a strategy of eliminating all greenhouse gases, warming particles, and cooling particles simultaneously through a transition to WWS is necessary to solve both air pollution and global warming problems together.

### 1.2.4 Impacts of Global Warming

Global warming has already caused the world significant financial loss, and the cost is expected to grow to over $30 trillion per year by 2050.[5] Losses arise due to coastline erosion (from sea level rise); fishery and coral reef damage; species extinction; illness and death due to heat stress and heat stroke; agricultural loss; more famine and drought; more wildfires and air pollution; increased climate migration; and more severe weather and storminess (e.g., hurricanes, tornados, and hot spells).

Higher temperatures increase air pollution in cities where the pollution is already severe.[14,15] Higher temperatures also increase the risk of wildfires, which themselves cause air pollution, loss of life, and structural damage. For example, during November 2018, three major wildfires in California, enhanced by drought and unusually high November temperatures, killed dozens of people, displaced hundreds of thousands more, rendered several thousand people homeless, and produced dangerous levels of air pollution throughout the state for over 2 weeks.

Similarly, global warming has already caused a lot of damage by increasing hurricane duration, size, wind speed, and storm surge. Global warming has also caused agriculture crops to fail in many parts of the world, triggering mass migrations. Such migrations are already occurring from the Middle East and North Africa to Europe, and from Central America to the United States, for example.

### 1.2.5 Strategies for Reducing Air Pollution and Global Warming Together

Because all aerosol particles together are the leading cause of air pollution mortality, reducing both cooling and warming particles is desirable from a public health perspective. However, Figure 1.1 indicates that cooling particles cause more cooling than warming particles cause warming globally. As such, if emissions of all warming and cooling particles are eliminated together without eliminating other sources of heat, global warming will worsen.

Similarly, since cooling particles mask half of global warming, eliminating only cooling particles will roughly double net global warming.

One strategy to address global warming and human health simultaneously is to eliminate only warming particles. The downside of this strategy is that it permits most global warming and air pollution to continue.

Thus, Figure 1.1 suggests that the best strategy for addressing human health and climate simultaneously is to eliminate greenhouse gases, cooling particles, and warming particles simultaneously. This will also reduce most anthropogenic heat and water vapor emissions.

This book is about understanding and implementing that strategy – eliminating all anthropogenic emissions of greenhouse gases, warming particles, and cooling particles at the same time. This strategy will be accomplished by transitioning the world's energy to 100 percent wind, water, and solar plus storage for all energy and by eliminating non-energy emissions.

## 1.3 Energy Insecurity

Energy insecurity is a third major problem that needs to be addressed on a global scale. Several types of energy insecurity are of concern.

### 1.3.1 Energy Insecurity Due to Diminishing Availability of Fossil Fuels and Uranium

One type of energy insecurity is the economic, social, and political instability that results from the long-term depletion of non-renewable energy supplies. Fossil fuels and uranium are limited resources and will run out at some point. As fossil-fuel supplies dwindle, their prices will rise. Such price increases will first hit people who can least afford them – those with little or no income. These people will suffer, since they cannot warm their homes sufficiently during the winter, cool their homes sufficiently during the summer, or pay for vehicle fuel easily.

Higher energy prices will also increase the cost of food and ultimately lead to economic, social, and political instability. The end result may be chaos and civil war.

A solution to this problem is to transition to an energy system that is sustainable – one in which energy is at less risk of being in long-term short supply. Such a system is one that consists of **clean, renewable energy**, which is energy that is replenished by the wind, the water, and the sun. Solutions that do not solve this problem are fossil-fuel power plants, with or without carbon capture, and almost all nuclear power plants, because they rely on fuels that will disappear over time.

### 1.3.2 Energy Insecurity Due to Reliance on Centralized Power Plants and Oil Refineries

A second type of energy insecurity is the risk of power loss due to a reliance on large, centralized electric power plants and oil refineries. If a city or an island relies on centralized power plants, and one or more plants or the transmission system goes down, power to a large portion of the city or island may be unavailable for an indeterminate period. Such an event can result from severe weather, a power-plant failure, or terrorism. An accidental fire or act of terrorism at an oil refinery or gas storage facility can similarly cause a disruption in local and regional oil and gas supplies.

For example, a September 14, 2019, terrorist attack on two Saudi Arabian oil processing facilities knocked out the production of 5 million barrels of oil per day, or 5 percent of the world's and half of Saudi Arabia's daily oil production. Oil and gas refineries and storage facilities worldwide are continuously at risk of being attacked, and many become targets during conflict. Although decentralized power generation and storage facilities provided by WWS do not decrease the risk of attack to zero, they decrease the risk significantly because of the difficulty in taking down hundreds to thousands of smaller individual units rather than one or two larger ones.

**Transition highlight**

On September 18, 2017, Hurricane Maria hit Puerto Rico and knocked out power to its 1.5 million people for almost 11 months. The hurricane toppled 80 percent of the island's utility poles and transmission lines. With ten oil-fired power plants, two natural gas plants, and one coal plant, the island's energy supply was all but wiped out by the loss of transmission. The long delay in restoring power to individual homes and businesses occurred because of the need to rebuild most of the transmission system. A more distributed energy system with rooftop solar photovoltaics (PV), distributed onshore and offshore wind turbines, and local battery storage would have allowed hospitals, fire stations, and homes to maintain at least partial power during the entire blackout period and would have reduced the time required to restore power to most customers. In fact, in early 2019, the main utility in Puerto Rico proposed to divide the island into eight interconnected microgrids dominated by solar and batteries. If one microgrid goes down, the other seven will still function. On April 11, 2019, Puerto Rico went even further and passed a law to go to 100 percent renewable electricity by 2050.

Another problem with large, centralized power plants is that they do not serve the 940 million people worldwide without access to electricity,[16] and they poorly serve another 2.6 billion people who have access to only dirty solid fuels (dung, wood, crop residues, charcoal, and coal) for home cooking and heating.[3] Burning solid fuels fills homes with smoke that causes short- and long-term illness to hundreds of millions of people and death to 2.6 million people worldwide each year.[3] Similarly, centralized power plants cannot provide power to remote military bases. Those bases obtain their electricity from diesel transported long distance and used in diesel generators. For example, in 2009, 7 liters of diesel fuel were burned during the transport of each liter of diesel used to produce electricity in U.S. military bases in Afghanistan.[17] Many soldiers died during the transport of the fuel.

Because WWS technologies are largely **distributed** (decentralized), it is possible to use them in microgrids to reduce this lack of access to electricity. A **microgrid** is an isolated grid that provides power to an individual building, hospital complex, community, or military base. A microgrid may either be far from a larger grid or wired to a larger grid but disconnected from it. A WWS microgrid consists of any combination of solar PV panels, wind turbines, batteries, other types of electricity storage, heat pumps, hydrogen fuel cells for electricity and heat, vehicle chargers, and energy-efficient appliances. Electricity in a microgrid may also be used to purify wastewater, desalinate salty water, and/or grow food in a container farm or a greenhouse.[18] When used in a microgrid, WWS can bring electricity to people without previous access to it.

In sum, a transition to WWS facilitates the creation of microgrids and results in the use of more distributed energy sources. Both factors reduce the chance that severe weather, power-plant failure, or terrorism will deny people energy. Fossil-fuel power plants, with or without carbon capture, and nuclear power plants do not solve this insecurity problem because these plants are large and centralized. In addition, fossil fuels almost always require the import of fuel to a region. With a clean, renewable energy microgrid, this problem is eliminated since all energy is produced locally from natural sources, namely wind, water, and sunlight.

### 1.3.3 Energy Insecurity Due to Reliance on Fuel Supplies Subject to Human Intervention

A third type of energy insecurity is the risk associated with fuel supplies that can be manipulated or fluctuate substantially in price. Such risks often arise when one country relies on another country to supply its energy. For example, many countries, particularly island countries, must import coal, oil, and/or natural gas to run their energy system. Similarly, prior to the 2022 war in the

Ukraine, over 40 percent of the European Union's natural gas was imported from Russia. During the war, bans placed on Russian fuel decreased the flow substantially. Japan imports over 75 percent of its oil, primarily from the Middle East. Israel imports over 90 percent of its oil, primarily from Azerbaijan and Kazakhstan. Importing fuel not only results in higher fuel prices, but also creates reliance of one country on another. This reliance may be tested in times of international conflict. In some cases, a country that controls the energy may withhold it through a ban, an embargo, or price manipulation, or just may not be able to supply it anymore. Similarly, fossil-fuel and uranium fuel supplies, even within a country, can be held up by a labor dispute or civil war.[19]

Fossil-fuel power plants, with or without carbon capture, and nuclear power plants are particularly prone to this problem because they rely on fuels that must be supplied continuously, either from across country borders or from within the country. In many cases, especially for island countries, the fuels must be transported long distance.

A clean, renewable WWS energy system built within a country avoids this type of energy insecurity. This is mainly because WWS requires no mined fuels (oil, natural gas, coal, or uranium) to run. Instead, WWS relies only on natural energy sources. Eliminating mined fuels eliminates the energy insecurity associated with them.

Although a country that supplies 100 percent of its own energy with WWS minimizes the risk of energy insecurity due to international conflict and price manipulation, a benefit arises when adjacent countries trade WWS electricity between each other. Such trading, in the absence of conflict, reduces the overall cost of energy and improves the reliability of the overall energy system.

### 1.3.4 Energy Insecurity Due to Fuels That Have Mining, Pollution, or Catastrophic Risk

A fourth type of energy insecurity is the risk associated with byproducts of energy use. The perpetual mining of fossil fuels and uranium causes health damage to miners and major environmental degradation. For example, underground coal mining results in black lung disease to many miners. Underground uranium mining results in high cancer rates from the decay products of radon. In addition, plants and vehicles that burn fossil fuels produce air pollution that kills millions of people worldwide each year. Nuclear power plants produce radioactive waste that must be stored for hundreds of thousands of years. Nuclear plants also run the risk of a reactor core meltdown. The historic spread of nuclear energy to dozens of countries has also contributed to the proliferation of nuclear weapons in several of these countries.

A transition to clean, renewable energy avoids these risks to health, the environment, and public safety. The continued use of fossil fuels, with or without carbon capture, and of nuclear power, prolongs these energy security problems.

# 2 WWS SOLUTIONS FOR ELECTRICITY GENERATION

The solution to air pollution, global warming, and energy insecurity is, in theory, simple and straightforward: Electrify or provide direct heat for all energy; obtain the electricity and heat from only wind, water, and solar sources; store energy, transmit electricity over long distance; and reduce energy use. This chapter first explores the main components of a wind–water–solar system, then focuses on the WWS electricity-generating technologies that will replace traditional energy sources, thereby eliminating all global anthropogenic emissions from such energy sources.

## 2.1 Components of a WWS System

Figure 2.1 summarizes the main components of a 100 percent wind–water–solar energy, storage, transmission, and equipment system that maintains grid stability. It includes WWS electricity and heat generation; hydrogen generation; electricity, heat, cold, and hydrogen storage; transmission and distribution; energy efficiency; and appliances and machines that use WWS electricity.

What is meant by electrifying or providing direct heat for everything? Most all energy worldwide is currently used for electricity, transportation, heating and cooling of buildings, and industry. In a 100 percent WWS world, all modes of transportation will be converted

**WWS Generation**

*WWS electricity generation*
- Onshore/offshore wind
- Rooftop/utility photovoltaics
- Concentrated solar power
- Geothermal electricity
- Hydroelectricity
- Tidal and wave electricity

*WWS heat generation*
- Solar heat/CSP steam
- Geothermal heat

**WWS Grid**

*Transmission/distribution*
- AC/HVAC/HVDC lines
- Distribution lines
- Grid management
  - Software
  - Demand response

**WWS Storage**

*Electricity storage*
- Batteries
- CSP storage
- Pumped hydro storage
- Hydropower reservoirs
- Flywheels
- Compressed air
- Gravitational storage

*District heat storage*
- Water tanks
- Boreholes
- Water pits
- Aquifers

*District cold storage*
- Water tanks
- Ice
- Aquifers

*Building heat storage*
- Water tanks
- Thermal mass

*Hydrogen storage*
- Hydrogen storage tanks

**WWS Equipment**

*Building and district air/water heating*
- Electric heat pumps

*Building and district cooling*
- Electric heat pumps

*Industrial heat*
- Arc/induction/resistance furnaces
- Dielectric and electron beam heaters
- Heat pumps/CSP steam

*Hydrogen generation/compression*
- Electrolyzers/compressors

*Transportation vehicles*
- Battery-electric
- Hydrogen fuel-cell

*Some appliances/machines*
- Induction cooktops
- Electric leaf blowers/lawnmowers
- Heat pump dryers

*Efficiency/reduced energy use*
- Insulate/weatherize buildings
- LED lights/efficient appliances
- Telecommute/public transport

**Figure 2.1** Main generation, transmission, storage, and use components of a 100 percent WWS system to power the world for all purposes. CSP is concentrated solar power, AC is alternating current electricity, HVAC is high-voltage alternating current electricity, HVDC is high-voltage direct current electricity, and LED is light-emitting diode.

to either battery-electric vehicles or hydrogen fuel-cell vehicles, where the hydrogen is produced from WWS electricity (green hydrogen). Electric heat pumps will be used for most air and water heating and air conditioning in buildings. Heat from geothermal reservoirs and sunlight will provide additional air and water heat for buildings. A portion of heating and cooling will come from centralized facilities and be distributed through water pipes to buildings. The remaining heating and cooling will be produced in buildings themselves.

For high-temperature industrial processes, existing electricity-based technologies, such as arc furnaces, induction furnaces, resistance furnaces, and dielectric heaters, will be used to create high-temperature heat.

Energy use in general will be reduced by capturing and recycling waste heat and cold, improving insulation, using more energy-efficient appliances, and creating more pedestrian- and bike-friendly cities.

All the electricity and direct heat in this new paradigm will be powered with WWS sources. Energy not used right away will be stored as electricity, heat, cold, or hydrogen. Electricity will also be transmitted from where it is produced to where it is needed through short- and long-distance electricity transmission lines. In cities, some heat and cold will be transported by hot and cold water pipes. The WWS energy generation technologies for each city, state, and country will include a combination of onshore and offshore wind turbines, solar photovoltaics on rooftops and in power plants, concentrated solar power plants, geothermal plants, conventional and run-of-the-river hydroelectric power plants, tidal and ocean current devices, and wave devices.

Types of storage will include electricity, heat, cold, and hydrogen storage. Major electricity storage options include pumped hydropower storage, existing hydroelectric dams, CSP coupled with thermal energy storage, batteries, flywheels, compressed air storage, and gravitational storage with solid masses. Major heat storage media will include water, soil, and heat-absorbing materials. Major cold storage media will include water and ice. Hydrogen, a form of electricity storage, will be used primarily for long-distance, heavy transport; steel production; and microgrids. Hydrogen will be produced by splitting water with WWS electricity (electrolysis). In some systems, storage will be co-located with energy generation to reduce cost. For example, batteries will often be co-located with residential rooftop solar PV systems to reduce the use of grid electricity when electricity prices are high. Reducing the use of grid electricity also reduces the occurrence of wildfires, which are often caused by transmission line sparks.

WWS electricity-generating technologies are generally defined in terms of their nameplate capacity. **Nameplate capacity** (also called rated capacity, generating capacity, or plant capacity) is the maximum instantaneous discharge rate of electricity from an electricity-producing machine's generator, as determined by the manufacturer of the machine. Whereas a **motor** converts electricity to mechanical motion, a **generator** is just a motor running in reverse, converting mechanical motion to electricity. Nameplate capacities are given in units of power. The base unit of power is the **watt**. When 1 watt of power is produced, 1 **joule** of energy is created (discharged) by an electricity generator per second. Thus, the nameplate capacity of a wind turbine is the rate of energy discharge from the turbine's generator. In other words, a wind turbine that has a nameplate capacity of 1 kilowatt (1,000 watts), can discharge no more than 1,000 joules of energy per second in the form of electricity from its generator.

Energy storage is similarly defined in terms of power and energy. The **peak charge or discharge rate of storage** is the maximum power (rate of change of energy) into or out of storage, respectively. The **peak storage capacity** is the maximum energy that can be stored and equals the peak discharge rate multiplied by the number of hours of storage at the peak discharge rate. Thus, energy stored in a battery is akin to water stored in a reservoir.

## 2.2 Onshore and Offshore Wind Electricity

**Wind turbines** convert the energy in the wind into electricity. The energy that arises due to the movement of air or water is **kinetic energy**. In most wind turbines, a slow-turning turbine blade spins a shaft connected to a gearbox. Progressively smaller gears in the gearbox convert the slow-spinning motion (3 to 20 rotations per minute for modern turbines) to faster-spinning motion (750 to 3,600 rotations per minute), just like shifting from the big gear to smaller gears on a bicycle allows one to pedal faster. A fast spinning motion is needed to convert mechanical energy to electrical energy in a wind turbine's generator.

Some modern wind turbines, called **direct-drive** turbines, are gearless, with the shaft connected directly to the generator. To compensate for the slow spin rate of a gearless turbine's shaft within the generator, the generator must be larger and heavier than it is with a geared turbine. However, because direct-drive turbines avoid the use of a gearbox, they are simpler, require less maintenance, and produce less noise than do geared turbines. Because each has advantages, both direct-drive and geared turbines are still manufactured today.

The **hub height** of a wind turbine is the height above the ground or ocean surface of the axis that the turbine spins around. The power output of a wind turbine increases with increasing turbine hub height because wind speeds generally increase with increasing height above the ground or ocean surface in the lower atmosphere. As such, taller turbines capture faster winds.

Wind farms are often located on flat open land, within mountain passes, on ridges, and offshore. Individual turbines to date have ranged in nameplate capacity from less than 1 kilowatt (1,000 watts) to 15 megawatts (million watts).

Small individual wind turbines, with nameplate capacities of 1 to 10 kilowatts, are often used to produce electricity in the backyard of an individual home or within a city street canyon. These local turbines do not produce much total electricity but, depending on wind speed, the amount is often sufficient to offset much of a homeowner's electricity usage.

**Onshore wind** farms usually contain a few to dozens of mid-sized wind turbines (1 to 8 megawatts in size) to power a part of a town or a city.

**Offshore wind** farms usually contain a few to dozens of mid- to large-sized turbines (3 to 15 megawatts in size). One particular 12-megawatt turbine, for example, designed for offshore use, has a 150-meter hub height above the ocean surface. Its blade diameter is 220 meters. Thus, the height of its furthest vertical extent is 260 meters, or 80 percent of the height of the Eiffel Tower. It can provide electricity for up to 16,000 households.[20]

Offshore wind turbines have either bottom-fixed foundations or floating foundations. Bottom-fixed foundations are used primarily in water depths down to 50 meters. However, a new design allows bottom-fixed foundations down to a depth of 90 meters.[21] Floating wind turbines avoid the need for a foundation that extends from the water surface to the ocean floor. They have a floating platform secured to the sea floor by cables and can be placed in water of any depth.

High-altitude wind energy capture has also been pursued, although it has not been commercialized to date.

Because the wind does not always blow and, when it does blow, its speed changes uncontrollably over time, winds are variable in nature. As such, wind turbine electricity output also varies with time, and wind is called a **variable WWS resource**. Another term commonly used to describe variability is **intermittency**. However, all energy resources are intermittent owing to scheduled and unscheduled maintenance. Variable resources are those whose energy outputs vary with the weather in addition to being affected by maintenance. Because wind output is variable, combining wind with batteries and other types of electricity storage helps to match variable demand for electricity with supply. This is particularly necessary when wind produces a high percentage of the total electricity on the grid but less so when it produces a low percentage.

## 2.3 Wave Electricity

Winds passing over water create surface waves. The faster the average wind speed, the longer the wave is sustained, the greater the distance the wave travels, and the taller the wave becomes. **Wave power devices** capture energy from ocean waves and convert that energy into electricity.

Because wave power output varies with time, wave power is also considered a variable energy source. However, wave power output is less variable than is offshore wind power output, even at the same location. The reason is that waves form from winds dragging the water over a long distance. The variability in wind speed at a given location along a wave's path has little impact on the wave, which already has momentum due to upstream winds. As such, waves at a given point represent the impact of winds accumulated over a long distance, whereas winds at the same point are instantaneous and more variable.

One type of wave power device is a free-floating device that bobs up and down with a wave, creating mechanical energy that is converted to electricity in a generator housed inside the device. The electricity is then sent through an underwater transmission cable to shore. Most of the body of the device is submerged under water. With some designs, the entire device is just below the water line so that it cannot be seen from the coast.

Another type of wave device has arms connected to a pier, jetty, breakwater, floating platform, or fixed platform. The other ends of the arms are connected to floaters that rise and fall with the motion of a wave. Because the device is connected to a structure, it is not free-floating in the open ocean. The pumping motion due to the rising and falling motion of the floaters is transmitted, through fluid pressure, to a power station on the platform that it is connected to. The fluid pressure is used to spin a hydraulic turbine, whose rotating motion is converted to electricity in a generator. Because the turbine and generator are on land, this type of wave device is easier to maintain than one completely offshore. However, a shore-based wave device can be placed in fewer locations than can a free-floating device, which can be placed anywhere over the ocean where waves occur.

Despite the development of a variety of wave energy technologies, the wave energy industry is still less mature, in 2022, than are other WWS industries. As a result, wave energy costs are still higher than are costs of other WWS technologies. Nevertheless, like with solar and wind costs, wave energy costs are expected to decline as some prototypes are deployed in increasing quantities.

## 2.4 Geothermal Electricity and Heat

**Geothermal energy** is energy extracted from hot water or steam residing below the Earth's surface. In both cases, the heat originates from hot rocks or soil. Rocks and soil are both heated in four ways: by the **conductive** (atom-by-atom or molecule-by-molecule) transfer of energy from the center of the Earth (which has a temperature of 4,300 degrees Celsius); the conduction of heat from volcanos; the decay of radioactive elements in the Earth's crust; and the downward conduction of sunlight that hits the Earth's surface. Most high-temperature rocks are found near volcanic activity, which generally occurs near tectonic plates. Low-temperature warm rocks and soil can be found anywhere underground. Even in locations where the ground surface is frozen, the soil temperature 6 meters deep is still high enough to warm buildings.

Depending on the temperature of the heat, geothermal energy is used to provide heat for buildings or electricity. Low-temperature heat (below 120 degrees Celsius) is used to heat buildings. It is extracted by ground-source heat pumps; pipes that capture native (naturally occurring) steam or hot water from hot springs; and absorption of soil heat by pipes circulating water or air.

High-temperature heat (120 to 400 degrees Celsius) is used to generate electricity. Geothermal electricity generating plants produce a steady supply of electricity over time. As such, they are **baseload** plants, which are electricity-generating plants that produce a constant supply of electricity for an extended period to meet loads on the grid. **Loads** are demands for electricity, such as for powering light bulbs or refrigerators.

Prior to the 1900s, steam and hot water from the Earth were used only to provide heat for buildings, industrial processes, and domestic water. The first use of geothermal heat to produce electricity was by **Prince Piero Conti** of **Larderello**, Tuscany, Italy. In 1904, he lit four light bulbs by using high-temperature steam from a geothermal field near his palace to drive a steam engine attached to a generator. A **steam engine** uses steam to push and pull a piston up and down. This piston is attached to a rotating cylinder. A generator converts the rotating motion to electricity.

In 1911, Conti installed the first geothermal power plant, which had a nameplate capacity of 250 kilowatts. This plant grew to 405 megawatts by 1975. The second electricity-producing plant was built at the Geysers Resort Hotel, California, in 1922. This plant was originally used only to generate electricity for the resort, but it has since been developed to produce a portion of electricity for the state of California.

Today, the three major types of geothermal plants for electricity production are dry steam, flash steam, and binary. Dry and flash steam geothermal plants operate when the geothermal reservoir temperature is 180 to 370 degrees Celsius or higher. In both cases, two boreholes are drilled – one for steam alone (in the case of dry steam) or liquid water plus steam (in the case of flash steam) to flow up, and the second for cool, liquid water to return after it passes through the plant.

In a **dry steam plant**, the pressure of the steam rising up the first borehole powers a turbine, which drives a generator to produce electricity. About 70 percent of the steam recondenses after it passes through a condenser, and the rest is released to the air as water vapor. Because several chemicals, including carbon dioxide, nitric oxide, sulfur dioxide, and hydrogen sulfide, in the geothermal reservoir steam do not recondense along with water vapor, these gases are emitted to the air as well.

In a **flash steam plant**, the liquid water plus steam from the geothermal reservoir enters a water tank held at low pressure, causing some of the water to vaporize ("flash"). The vapor then drives a turbine. About 70 percent of this vapor is recondensed. Again, the remainder escapes with carbon dioxide and other gases. The liquid water is injected back into the ground.

**Binary geothermal plants** are developed when the geothermal reservoir temperature is 120 to 180 degrees Celsius. Water rising up a borehole is enclosed in a pipe and heats, through a heat exchanger, a low-boiling-point organic fluid, such as isobutane or isopentane. The evaporated organic turns a turbine that powers a generator to produce electricity. Because the water from the reservoir remains in an enclosed pipe when it passes through the power plant, and is reinjected to the reservoir, binary systems emit virtually no carbon dioxide or other pollutants. About 15 percent of geothermal plants today are binary plants.

## 2.5 Hydroelectricity

**Hydroelectricity** (**hydropower**) is produced by water flowing downhill through a water turbine connected to a generator. Most hydropower is produced from water held in a reservoir behind a large dam. This type of hydropower is referred to as large, or conventional, hydropower. Hydropower dams require a reservoir behind them, which results in the flooding of large areas of land. The largest conventional hydropower plant in the world is the Three Gorges Dam on the Yangtze River in China. Its nameplate capacity is 22.5 gigawatts (billion watts). Some other large hydropower plants include the 14-gigawatt Itaipu plant on the Parana River bordering Brazil and Paraguay, and the 10.2-gigawatt Guri plant on the Caroni River in Venezuela.

A growing portion of hydroelectricity is produced by water flowing down a river directly through a turbine or by water that is diverted through pipes and a turbine near the edge of a river before returning to the river. This type of hydroelectricity is **run-of-the-river hydropower**. The advantage of run-of-the-river hydropower over conventional hydropower is that large amounts of land are not flooded behind a dam with the former. As a result, run-of-the-river hydropower is less useful for storage. However, run-of-the river hydro, with a modest storage pond behind it, like with conventional hydropower, can provide electricity within 15 to 30 seconds of a need. The largest run-of-the-river hydropower dam worldwide is the 11.2-gigawatt Belo Monte Dam in Brazil.

A conventional hydropower plant consists of a dam, a water storage reservoir behind the dam, penstocks, sluice gates, a powerhouse, and a downstream water outlet. A **penstock** is a pipe, channel, or tunnel through which water flows from the storage reservoir to a water turbine. A **sluice gate** is a gate to stop or control water flow between the storage reservoir and the penstock. A **powerhouse** is a building containing water turbines, generators, and power transmission cables. When water passes through a **water turbine** in the powerhouse, the turbine's blades spin, rotating a metal shaft connected to the generator, which converts the mechanical rotating motion into electricity.

A run-of-the-river hydropower facility consists of a water turbine and generator, but no reservoir, except for a small holding pond in some cases, and no pipes, except when the water is diverted a short distance away from the river, through the turbine, and back to the river.