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

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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

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.

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

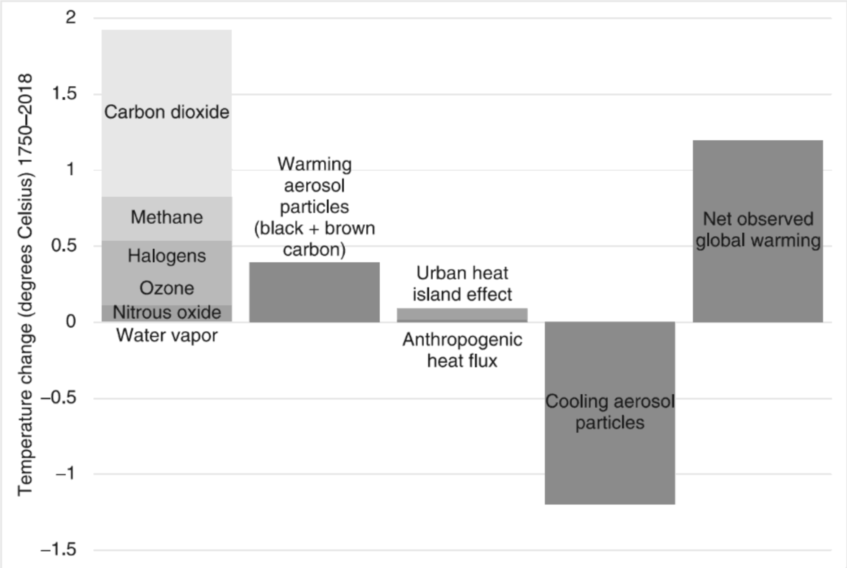

Figure 1.1 Estimated primary contributors to net observed global warming from 1750 to 2018. Warming aerosol particles include black and brown carbon from fossil-fuel burning, biofuel burning, and open biomass burning. Cooling aerosol particle components include sulfate, nitrate, chloride, ammonium, sodium, 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.

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

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.

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.

Only a fraction of the many dams with reservoirs worldwide contain hydroelectric equipment. For example, the United States has about 84,000 dams, but only 2,500 (about 3 percent) of these have hydroelectric power associated with them.

A hydropower plant can be run as a baseload plant, a load-following plant, or a peaking power plant. Whereas a baseload power plant produces a constant supply of electricity for an extended time, a **load-following plant** runs continuously but ramps its power production up and down to meet 5- to 15-minute average changes in demand on the grid. Hydropower plants, when run as load-following plants, run continuously and adjust their output every 5 to 15 minutes to meet such changes. A **peaking power plant** generates electricity within seconds to a few minutes to meet specific peaks in electricity demand that other electricity sources, such as wind turbines and solar panels, cannot meet immediately. Some power plants, such as some natural gas plants, serve no other purpose but to meet peaks in demand. A hydropower plant, on the other hand, is flexible enough that it can run as a baseload, load-following, or peaking plant as needed. However, a hydropower plant's output is often limited by competing uses for the water that it holds and by how much water it can release downstream at a given time.

In a hydropower plant, neither the powerhouse nor the penstock needs to be located inside the dam. The penstock can be built to channel water around the dam to a powerhouse in front of or to the side of the dam. This may be desirable in cases where turbines are added to a hydropower plant, years after the dam is built, in order to increase the plant's peak discharge rate (nameplate capacity) while keeping the annual average water stored in the reservoir constant. Adding turbines is useful for plants that are run in load-following or peaking mode. The addition of turbines to a hydropower plant is called **uprating.** Uprating a hydropower plant may be "*one of the most immediate, cost-effective, and environmentally acceptable means of developing additional electric power*".[22]

The average power output from a hydropower facility is limited not only by the nameplate capacity of its generators but also by the annual average amount of water available in the reservoir to run through the turbines. A measure of the practical average power output of a hydropower facility that accounts for both the water availability and the turbine nameplate capacity is the installed capacity.

Installed capacity for hydropower is the smaller of the average power produced by available water in a hydropower reservoir and the nameplate capacity of turbines in the hydropower plant itself.[23,24] For other types of power-producing technologies, such as wind turbines and solar panels, the installed capacity equals the nameplate capacity of the technology.

2.6 Tidal and Ocean Current Electricity

Tidal currents (**tides**) are back-and-forth currents in the ocean caused by the rise and fall of the ocean surface due to the gravitational attraction among the Earth, the moon, and the sun. The rising and sinking motion of the ocean surface forces water below the surface to move horizontally as a current. Because tides run about 6 hours in one direction before switching directions for another 6 hours, they are fairly predictable.

An **ocean current** is a continuous flow (in one direction) of seawater driven primarily by winds or by temperature and salinity gradients in the ocean. The Gulf Stream current, for example, is a warm, fast-flowing current driven by winds. It runs from the Gulf of Mexico, past the tip of Florida, up the U.S. coast, to the Newfoundland coast, then to the North Atlantic ocean, where it splits into two other currents. Ocean currents, in fact, run along all major ocean coastlines in the North and South Pacific Oceans, the North and South Atlantic Oceans, and the Indian Ocean. For example, the current running along the west coast of North America from Washington State down to Southern California is the California Current. The current running northward along the west coast of South America is the Humboldt (Peru) Current.

A **tidal turbine** captures the kinetic energy of an ebbing and flowing tidal current in the ocean, the continuous flow of an ocean current, or a river current. Because both tidal and ocean currents are steady, tidal turbines usually supply baseload (constant) electricity to the grid when they are not undergoing maintenance.

Tidal turbines can be mounted on the sea floor or hang under a floating platform. They can also be placed in rivers to capture the energy of continuously flowing river water or of tidal water that ebbs and flows in a river. For example, tides from the Atlantic Ocean flow through Chesapeake Bay, near Virginia, then up the Potomac River, past Washington D.C. and Maryland, all the way up to Harper's Ferry, West Virginia, a land-locked U.S. state.

Like a wind turbine, a tidal turbine consists of a blade that spins a turbine, which provides rotational energy to a generator. The generator converts the rotational energy to electrical energy that is transmitted to shore. A tidal turbine's rotor, which lies under water, may be fully exposed to the water or placed within a narrowing duct that directs water toward it.

One type of tidal turbine, called a tidal kite, has 12-meter-wide wings and is shaped like an airplane. It is tethered to the sea floor and steered autonomously in a predetermined pattern. Water passes through its blades 40 meters underwater, causing the blades to spin. The rotation produces up to 1.5 megawatts of electricity in a generator housed in the device. The electricity is sent through a cable to shore, where its first use will be to power part of the Faroe Islands.[25]

2.7 Solar Photovoltaic Electricity

A **solar photovoltaic** panel consists of an array of cells containing a material that converts sunlight into direct current (DC) electricity. An inverter then converts the DC electricity into alternating current (AC) electricity, which may be used immediately in a building, or put in local storage, or sent to the electricity grid for others to use. Photovoltaics are often mounted just above the ground in large (utility-scale) power plants. They are also mounted on or built into the structure of roofs or walls of buildings. They can further be mounted on carports, parking lots, and parking structures, and built into the sides of cars, trucks, and buses. Transparent PVs have been developed to cover windows, but these have not yet been commercialized.[26] Solar PV arrays that are thin and flexible enough to be rolled up and transported have been commercialized.[27] Such panels are useful for disaster relief, for when grid electricity is not available, for remote military bases that must be moved regularly, and for communities that need a rapid but non-permanent source of electricity. Flexible panels can also be installed on a vehicle and used to provide electricity for it.[28] In utility-scale plants, PV panels are mounted either at a fixed tilt or on trackers that rotate to follow the sun. For most other applications, they are mounted at a fixed tilt relative to the ground.

"cold" holding tank until it is recirculated to the central tower. Thus, the molten salt also circulates, but in a separate closed loop.

In many parabolic trough and central tower CSP plants, some of the hot fluid (oil or molten salt mix) is stored in an insulated thermal storage tank before it is used to boil water in the heat exchanger. The purpose is to delay the boiling of water, and thus electricity production, until nighttime, when no immediate solar electricity from the plant is available.

A third type of CSP technology is a **parabolic dish-shaped** (like a satellite dish) reflector that reflects light onto a receiver while rotating to track the sun. The receiver transfers the heat to hydrogen in a closed loop. The expansion of hydrogen against a piston or turbine produces mechanical power used to run a generator to produce electricity. The power conversion unit is air-cooled; thus, water-cooling is not needed. Parabolic dish CSP is not coupled with thermal energy storage.

CSP plants require either air- or water-cooling. The use of air-cooling, which is desirable in water-constrained locations, reduces overall CSP plant water requirements by 90 percent at a cost of only about 1 to 5 percent less electric power production.[31]

Because the components of CSP plants are made of abundant raw materials, material shortages are not expected to limit the mass production of CSP plants. For example, CSP plants consist primarily of mirrors, receivers, and thermal storage fluid. Mirrors are made mostly of glass with a reflective silver layer on the back of the glass. Receivers are stainless steel tubes with an outer surface that absorbs sunlight and that is surrounded by an outer antireflective glass tube. None of these materials has limited availability.

3 WWS SOLUTIONS FOR ELECTRICITY STORAGE

Hydropower, geothermal, and tidal electricity generators can serve as baseload (constant-output) generators because their output can be held steady for long periods. However, wind, solar PV, and wave outputs vary during a day and seasonally. As such, these electricity sources provide variable output. Given that solar and wind may end up supplying 90 percent or more of all WWS energy generation worldwide, on average, it is important to have electricity storage technologies available to provide backup power when both solar and wind are unavailable. Major electricity storage options include existing hydroelectric dams, pumped hydroelectric storage, batteries, concentrated solar power coupled with thermal energy storage, flywheels, compressed air energy storage, and gravitational storage with solid masses. These technologies are discussed herein.

3.1 Hydroelectric Power Reservoir Storage

Conventional hydroelectric power (hydropower) plants have built-in storage since the water that generates the electricity for them is stored in a reservoir behind a dam. Whereas the water can be drained through a turbine to create electricity as needed, the reservoir can only be charged naturally through rainfall and runoff. Thus, the electricity storage associated with a conventional hydropower plant differs from that of battery storage. A battery can be charged when excess electricity is available and discharged when electricity is needed. A hydropower plant can produce electricity precisely when it is needed, but it cannot control when rain and runoff will refill the reservoir. The only option for controlling recharge is to turn the hydropower plant into a pumped hydropower storage facility.

Hydropower plants can be run as baseload plants, load-following plants, or peaking plants. When they are used for load following and peaking, hydropower plants can meet minute-by-minute changes in electricity demand on the grid faster than can natural gas, coal, or nuclear power plants. The **ramp rate** of a power plant is the speed at which it ramps up from zero to maximum power. The ramp rate of a hydropower plant is fast. For example, a hydropower turbine can generate full power from no power within 15 to 30 seconds. That is the time required for the water to flow from the sluice gate, after it opens, through the penstock, and to the turbine. Once the water reaches the turbine, the turbine spins and immediately produces electricity in an attached generator. As such, the ramp rate of a hydropower plant is 100 percent in 15 to 30 seconds. In comparison, the ramp rate of a natural gas open cycle turbine is 100 percent in 5 minutes; that of a natural gas combined cycle turbine is 100 percent in 10 to 20 minutes; and those of coal and nuclear plants are both 100 percent in 20 to 100 minutes.[32]

Because hydropower plants can produce electricity within 15 to 30 seconds of a need, they are often used to provide peaking power when no other electricity is available to match power demand with supply on the electricity grid. At a high continuous electricity discharge rate, hydropower plants can meet a high continuous demand for hours to days, depending on the size of the reservoir and the nameplate capacity of installed turbines in the plant. When used only to meet gaps in supply, such plants may sit idle for days to weeks before being used several days in a row for 2 to 3 hours per day.

3.2 Pumped Hydropower Storage

A related type of storage that can discharge its electricity quickly is **pumped hydropower storage**. Pumped hydropower storage is used primarily to fill in short-term gaps in electricity supply, usually on the order of minutes to a day.

Pumped hydropower storage consists of two reservoirs – an upper one and a lower one. The lower one can be the ocean, a natural lake, a human-made lake or reservoir, or a continuously running river. The upper one can be a natural lake or a human-made lake or reservoir. One newly proposed pumped hydropower storage system consists of Lake Mead, the reservoir behind Hoover Dam, and a pumping station 32 kilometers downstream along the Colorado River.[33]

The idea behind pumped hydropower storage is that, when excess electricity is available or when electricity prices are low, a motor pumps water uphill through pipes, from a pumping station in the lower reservoir to the upper reservoir. When electricity is needed, water drains downhill through a water turbine connected to the motor running in reverse as a generator, producing electricity.

The overall efficiency of a pumped hydropower storage system (ratio of electricity delivered to the sum of electricity delivered and electricity used to pump the water uphill) is around 80 percent. The ramp rate for pumped hydropower storage is the same as for conventional hydropower, from zero to 100 percent power in 15 to 30 seconds. As such, pumped hydropower storage ramps up faster than do natural gas plants, which ramp to 100 percent power in 5 to 20 minutes, or nuclear plants, which ramp to 100 percent power in 20 to 100 minutes.

Transition highlight

Excluding hydropower reservoirs, 97 percent of all electricity storage built on Earth prior to 2021 was pumped hydropower storage. Worldwide, about 530,000 potential pumped hydropower sites exist. These sites can store an estimated 22 million gigawatt-hours of energy for the electricity grid. This represents 100 times the energy needed to back up a 100 percent renewable electricity system worldwide.[34]

The largest pumped hydropower facility in the world is the 3.6-gigawatt facility in China's Hebei province. It can store up to 50 gigawatt-hours of producible electricity. At the peak discharge rate of 3.6 gigawatts, that stored electricity can be extracted continuously for about 14 hours.

3.3 Stationary Batteries

Batteries in a 100 percent WWS world will be used primarily for vehicles; electronic devices (e.g., phones, watches, computers, flashlights), moveable equipment (e.g., leaf blowers, lawnmowers, chainsaws), and stationary electricity storage. Batteries are useful because they generate electricity almost immediately on demand. As such, an electric vehicle accelerates to a high speed faster than does an internal combustion engine vehicle. Similarly, batteries can provide needed electricity to the grid much faster than can coal, natural gas, nuclear, or even hydroelectric facilities. Stationary batteries can provide load-following or peaking power for a large electricity grid or an isolated microgrid. Wall-mounted or floor-mounted battery packs are commercially available for homes, commercial buildings, microgrids, and city electric grids.

A **battery** is an electrochemical cell that converts chemical energy into electricity. A **battery pack** is a collection of such cells. Each cell consists of two half-cells divided by a separator. Each half-cell consists of a current collector, an electrode, and an electrolyte solution.

The **current collector** is a metal cap in each half-cell through which electrons move either forward or backward. In both cells, the current collector is attached to an **electrode**. The current collector in one cell is called the positive current collector. In a **lithium battery**, the electrode attached to the positive current collector is often made of lithium cobalt oxide, which is the source of lithium ions (Li^+) that move back and forth between the half-cells. The current collector in the other cell is called the negative current collector, and the electrode attached to it is often made of pure carbon (graphite). The purpose of the graphite is to receive and bond to lithium ions and electrons.

The **electrolyte solution** contains a lithium salt dissolved in an organic solvent. The liquid solution facilitates the passage of lithium ions between the two half-cells. The **separator** allows lithium ions, but not electrons, to pass between the two half-cells.

During battery charging, a charger plugged into the wall is wired to both current collectors. Electrons first flow from the charger to the negative current collector. The build-up of negative charges there induces lithium cobalt oxide in the other half-cell to break apart into a lithium ion, an electron, and cobalt oxide. The lithium ion is then drawn like a magnet from the positive current collector, through the electrolyte solution, and through the separator, to the electrons accumulating at the negative current collector, neutralizing the charge there.

Electrons released at the positive current collector cannot pass through the separator. Instead, they take the path of least resistance by discharge efficiencies, and long cycle lives. Because they are made of inexpensive material, such batteries are also economical at large sizes, which makes them ideal for stationary electricity storage. They can also be used for vehicles. In fact, one of the first applications of the sodium sulfur battery was in the 1991 Ford Ecostar demonstration electric vehicle, which never went into commercial production. Sodium sulfur batteries operate at high temperature (300 to 350 degrees Celsius). Research is currently being carried out to allow the batteries to be used at medium temperatures (120 to 300 degrees Celsius) and room temperature.[39,40]

Aluminum-ion batteries. These batteries use aluminum instead of lithium to flow between cells. An aluminum ion, Al^{3+}, carries 3 times as much the charge as does a lithium ion, Li^{+}. This allows aluminum-ion batteries to be smaller than lithium-ion batteries. However, the higher charge also results in greater interaction of aluminum ions than lithium ions with other chemicals in the battery, reducing the efficiency of aluminum-ion versus lithium-ion batteries. Aluminum-ion batteries are less flammable than are lithium-ion batteries. Recently, an aluminum-ion battery paired with a graphene electrode was found to charge up to 60 times faster than a lithium-ion battery and hold up to 3 times the charge of other aluminum-based battery cells.[41]

Salt water batteries. In these batteries, a concentrated saline solution (salt water or sodium sulfate mixed with water) is used as the electrolyte to conduct ions. These batteries are similar to lithium-ion batteries, except that with salt water batteries, the sodium ion instead of the lithium ion migrates. However, the voltages are one-third those in lithium-ion batteries. Salt water batteries are suitable for stationary power storage and can be run for 10,000 cycles or more. Salt water batteries are also non-flammable, non-explosive, and have no toxic chemicals, so they are easily recycled.

Vanadium flow batteries. These batteries consist of two separated tanks of vanadium dissolved in a liquid electrolyte. The fluid in each tank is pumped through a pipe, past a membrane that separates the pipes. Ions are exchanged from one side of the membrane to the other, and a current simultaneously flows between the two tanks through an external wire. During electricity charging, ions flow in one direction through the pipe. During discharging, they flow in the opposite direction. A flow battery is much larger than is a lithium-ion battery. As such, flow batteries are used only for stationary electric power storage.

3.4 Concentrated Solar Power with Storage

Parabolic trough and central tower CSP plants work by heating a fluid (either oil for a parabolic trough or a molten salt mixture for a central tower), which passes by water in a heat exchanger to boil the water. The resulting steam runs a steam turbine to generate electricity. For both the parabolic trough and central tower plants, the hot fluid can first be stored in an insulated tank before it is sent to the heat exchanger. This allows electricity production to be delayed until nighttime, or when heavy clouds are present, electricity demand is high, or no other WWS electricity source is available. After the steam passes through the turbine, it is routed to a condenser, which liquefies the steam and sends it back to the heat exchanger in a closed loop to be reheated. After the molten salt exchanges its heat with water in the heat exchanger, the molten salt is also cold and is sent to a holding tank before it is passed through either the parabolic trough or the central tower receiver again to reheat.

Although CSP heat can be stored in a tank containing molten salt, the heat can alternatively be stored in a phase-change material. A phase-change material is a material that absorbs a large amount of heat when it melts and releases a large amount of heat when it solidifies. Phase-change materials require less volume, thus they cost less to store heat, than does molten salt.[42]

The storage associated with CSP is usually sized to last up to 15 hours at the peak discharge rate (nameplate capacity) of the CSP generator before the storage is depleted. Storage of up to 15 hours allows for 24 hours per day of electricity production from CSP plus storage.

> **Transition highlight**
> The Gemasolar CSP plant in Seville, Spain, first demonstrated 24 hours per day of CSP-with-storage electricity production during July of 2011. The plant has provided electricity continuously (24 hours per day) for stretches of up to 36 days. During cloudy and winter days, a CSP-with-storage plant also produces electricity at night, but for fewer hours.

The **capacity factor** of a CSP plant is the actual annually averaged power produced by the generator in the plant divided by the maximum possible power produced by the generator (its nameplate capacity). With no storage, the capacity factor of a CSP plant is limited by the instantaneous electricity generated, averaged over a year. Excess heat not used immediately is wasted because the generator can produce only a limited amount of electricity. A typical capacity factor of a CSP plant without storage in a sunny location is around 25 percent. With storage, however, the capacity factor increases to around 65 percent or higher. This is accomplished first by adding more mirrors and molten salt (for a central tower CSP plant) and storing the excess salt after it is heated. During the night, or when sunlight is weak, the stored hot salt is used to boil water. The additional steam is used to produce electricity in the absence of sunlight, increasing the plant's annual electricity output, thus its annual average capacity factor.

The capacity factor of a CSP plant can be increased even further if wasted heat that is not turned into electricity is captured and used to produce heat for industrial processes or used as a source of heat for heat pumps.

Finally, CSP plants with storage can help to keep the electric grid stable. With storage, CSP plants can ramp from zero to 100 percent power production in about 10 minutes,[43] which is faster than the ramp rate of a coal or nuclear plant (20 to 100 minutes) and similar to that of natural gas plants (5 to 20 minutes).[32] As such, CSP with storage can help meet peaks in electricity demand with 100 percent WWS.

3.5 Flywheels

A **flywheel** is a spinning wheel or disk, usually made of steel or carbon fiber, that rotates around an axis. The axis is perpendicular to the ground, like with a spinning top, so that gravity acts equally on all sides of the spinning wheel.

A flywheel stores energy as rotational energy, then converts that energy to electricity as needed. A flywheel is an electric motor, an energy storage device, and a generator, all in one. When excess electricity is available, it powers an electric motor to rotate the flywheel up to a high speed. Of the energy added to a flywheel, a small portion is used to keep the flywheel rotating. The rest is maintained as stored energy. If the flywheel is run in a vacuum, air resistance is zero, so frictional losses are minimized. Another way to minimize frictional loss is to use an electromagnetic bearing or permanent magnet. This allows the spinning rotor to float.

When electricity is needed, the motor turns into a generator, which converts rotational energy into electricity, with built-in electronics. When electricity is produced, the flywheel slows down but does not stop.

A flywheel can store more and more rotational energy until its rotor shatters. Steel flywheels are limited to around 3,000 rotations per minute. High-energy-density carbon fiber flywheels can spin up to 60,000 rotations per minute. Aside from possible breakage, flywheels require little maintenance and have a long lifetime (about 20 years) with no impact on the environment past the use of materials to build them.

A flywheel accumulates and stores kinetic energy produced by either steady or intermittent electricity over any period of time and releases that energy as electricity at a fast rate over a short period. As such, flywheels are ideal for storing excess electricity from intermittent solar and wind energy on the electric power grid. However, flywheels developed to date have stored only small amounts of energy (e.g., 3 to 25 kilowatt-hours) and have relatively high loss rates (3 percent per hour). As such, the stored electricity must be used quickly.

On the other hand, flywheels can begin to discharge quickly (within 4 milliseconds) and can discharge at a high rate (10 to 100 kilowatts). Thus, two useful applications of a flywheel are to provide short-term peaking power for the electric grid and to charge electric vehicles quickly.[44] For example, a flywheel that has a peak discharge rate of 100 kilowatts can add 20 kilowatt-hours to an electric vehicle in 12 minutes.

3.6 Compressed Air Energy Storage

Compressed air energy storage (CAES) is another technology that can be used to accumulate intermittent renewable electricity in storage over a long period, then to resupply that electricity to the grid when needed. With compressed air storage, excess intermittent electricity is used to compress air. When electricity is needed, the compressed air is expanded in an expansion turbine. The turbine's rotating shaft is connected to a generator, which converts the rotational energy to electricity.

Compressed air can be stored in an underground cavern, a salt dome, an aquifer, or a closed vessel. Although compressed air storage has been studied extensively, only a few large-scale facilities have been built, including one in Germany and two in the United States (Alabama and Texas). The locations for large-scale underground storage facilities are limited geographically.

However, a small, compressed air storage system can be connected to an electricity-producing device, such as a wind turbine. The wind turbine operates normally to produce electricity in a generator. Electricity from the generator at hub height is then used to power a motor that compresses air that is stored in a storage tank. When electricity is needed for the grid, the compressed air is expanded and converted back to electricity in an expander-driven generator. The motor, storage vessel, and second generator are all housed at ground level, below the turbine.[45]

Transition highlight
Another variation of compressed air storage is the use of excess renewable electricity to cool, then compress, air until it condenses as a liquid. The high-pressure, cold liquid is then stored in a container until electricity is needed. At that point, the air is warmed until it re-evaporates. The expanding air then drives a turbine to generate electricity. The process is made efficient by storing the heat released during condensation and using that heat to help re-evaporate the air. The process does not require special materials, such as lithium used in batteries. A 50-megawatt (million watts) storage facility based on this concept, which was developed by inventor Peter Dearman, is being built in the north of England.[46]

3.7 Gravitational Storage with Solid Masses

A form of electricity storage similar to pumped hydropower storage, except that it uses solid material instead of water, is **gravitational storage with solid masses**. In one version of this storage, excess electricity from the grid is used to power an electric motor in a crane to lift cement blocks against the force of gravity and stack them, one at a time, on a tower. When electricity is needed, the crane grabs each block and slowly drops the block toward the ground. The downward motion uncoils the hoist chain holding the block. The rotating motion during the uncoiling is translated to a rotating motion inside the same electric motor that lifted the block, turning the motor into an electric generator.[47] The electricity produced by the generator is sent to the grid.

many countries today, a good portion of electricity used for battery-electric vehicles comes from fossil-fuel power plants. In a 100 percent WWS world, though, all electricity for battery-electric vehicles will come from zero-emission sources.

Some argue that if electricity for a battery-electric vehicle comes from a polluting source, then the battery-electric vehicle is just as bad for health as a fossil-fuel vehicle, which emits pollution continuously from its tailpipe. However, that is not the case. The reason is that the intake fraction of pollution from street traffic is 15 to 30 times that of pollution from power plants.[52] The **intake fraction** is the ratio of the mass of pollutant inhaled by a population to the mass of pollutant emitted by a source. In other words, people breathe in a much greater fraction of vehicle exhaust than they do of power-plant exhaust. As a result, taking pollution off the street and moving it to a power plant reduces health impacts significantly. With 100 percent WWS, though, all power-plant emissions will also be eliminated.

In addition to producing tailpipe emissions, fossil-fuel vehicles produce emissions from the mining, transporting, and processing of oil to produce gasoline, diesel, jet fuel, and bunker fuel. In a WWS world, all such emissions are eliminated.

Fossil-fuel and biofuel vehicles also emit particles during the use of brake pads. In such vehicles, the car slows when a brake pedal is pushed. This pushes a brake against a turning tire disc, reducing the rotation rate of the tire and slowing the vehicle. The resulting friction creates heat and causes some particles to break off the brake pads and float into the air. Electric vehicles eliminate most brake pad emissions because they use mostly regenerative braking rather than brake pads, although drivers still occasionally apply brake pads.

Regenerative braking works as follows: to slow a car, the driver's foot is taken off the accelerator pedal. Doing so causes rotational energy from the rotating wheels to be fed into a generator (the motor running in reverse) to "regenerate" electricity, which is then stored in the vehicle's batteries. Thus, regenerative braking, which converts rotational energy into electricity, slows the car, avoiding the need for the use of brake pads and thus avoiding brake pad particle emissions.

Regenerative braking was invented in 1886 by the Sprague Electric Railway & Motor Company, founded in 1884 by **Frank Sprague** (1857 to 1934). Sprague had worked for Thomas Edison starting in 1883, but because Sprague wanted to develop motors, which Edison was less interested in, he left Edison's company in 1884 to start his own. Sprague's first application of regenerative braking was in electric streetcars that his company put in place in Richmond, Virginia, in 1888. Sprague's company also developed regenerative braking for elevators.

All vehicles require energy for mining materials for the vehicle, manufacturing the vehicle, and recycling the vehicle at the end of its life. In a WWS world, such energy will come from clean, renewable sources with zero emissions.

Also, all vehicles today emit particles due to tire wear. However, such particles are mostly larger and fewer in number than are fossil-fuel combustion particles. Because tire particles are generally large, most drop out of the air faster and do not penetrate so deep into people's lungs as combustion particles do.

In sum, transitioning to battery-electric vehicles substantially reduces air pollution and its health problems. Providing the electricity needed to manufacture the car with WWS reduces pollution even more.

4.1.1 Efficiency of Battery-Electric Vehicles

Another advantage of today's battery-electric vehicles compared with fossil-fuel vehicles is that battery-electric vehicles can travel 3 to 5 times further per unit energy input obtained from the plug outlet than a fossil-fuel vehicle can travel per unit energy in gasoline.

For example, only 17 to 20 percent of the energy in gasoline goes toward moving a gasoline passenger vehicle. This is the **tank-to-wheel efficiency** of the vehicle. The rest of the energy (80 to 83 percent) is lost as waste heat.

On the other hand, 64 to 89 percent of the electricity from a plug outlet moves a battery-electric passenger vehicle, and the rest is waste heat. This is the **plug-to-wheel efficiency** of a battery-electric vehicle. This efficiency accounts for the efficiency loss of charging the vehicle.

As such, a battery-electric vehicle requires much less energy input than does a fossil-fuel vehicle. Alternatively, a conversion from fossil-fuel vehicles to battery-electric vehicles reduces energy demand for transportation fuel by a factor of 3 to 5.

The plug-to-wheel efficiency of a battery-electric vehicle is determined as follows. First, a permanent magnet electric motor has an efficiency of 89 to 96 percent. An induction electric motor has an efficiency of 84 to 94 percent.[53] Thus, the range of efficiencies of electric car motors is 84 to 96 percent. Whereas the Tesla Model S and Model X use an induction motor, for example, the Tesla Model 3 uses a permanent magnet motor.

In addition, efficiency losses occur due to converting electricity from the grid to chemical energy in a battery. Such vehicle charging losses can range from 4 percent to 20 percent of the electricity going into the battery, depending on the current and voltage used to charge the vehicle. Another 1 to 2 percent of energy is lost during conversion of the battery's chemical energy to DC electricity. In addition, 2 to 3 percent is lost with the combination of converting DC to AC electricity in an inverter, adjusting the voltage for use in the motor, and using power electronic controls in the vehicle. Inverter losses are only 1 percent of energy when the inverter uses silicon carbide as the semiconductor material.[54]

Accounting for all losses gives the overall plug-to-wheel efficiency of a battery-electric passenger vehicle as 64 to 89 percent, with an average of 77 percent.

A battery-electric vehicle can increase its efficiency, thus range, by using regenerative braking. As discussed, regenerative braking converts rotational energy into electricity, slowing the vehicle.

Transition highlight

Regenerative braking can not only extend battery-electric vehicle range substantially, but it can also eliminate, in at least one special case, the need to recharge an electric vehicle entirely. The largest stand-alone electric vehicle in the world in 2019 was an enormous electric dump truck operating in a quarry in Biel, Switzerland. The empty truck used electricity to climb from the bottom to the top of the quarry. At the top, it was filled with ore, more than doubling the truck's weight compared with its uphill trip. The additional weight created so much kinetic energy that the electricity produced from regenerative braking during the downhill trip exceeded the electricity consumed during the uphill trip. As such, the truck did not need recharging during its daily operation.[55]

In a WWS world, battery electricity will be used not only to power light-duty vehicles, but also short- and medium-range semi-trucks, short-range aircraft, some military vehicles, and short-distance boats and ships. The history of battery-electric transportation is discussed next.

4.1.2 History of Battery-Electric Transportation

Today, battery-electric vehicles are being developed for ground, water, and air transport. Here, the evolution of battery-electric vehicles is explored for each of these transport types.

4.1.2.1 Ground Vehicles

Passenger Vehicles, Pickup Trucks, Semi-trucks, and Buses

Scotland's **Robert Anderson** built the world's first battery-electric vehicle, which was also the world's first horseless carriage, sometime between 1832 and 1839. To accomplish this feat, he affixed a battery and a motor to a carriage. At the time, batteries were not chargeable, so the carriage's battery needed to be replaced after each use. Thus, Anderson also developed the first swappable battery system. Rechargeable battery-electric vehicles were not possible until 1859 when the French physicist Gaston Planté (1834 to 1889) invented the first chargeable battery, which was made of lead.

Around 1884 in England, Thomas Parker invented several prototype electric cars with chargeable batteries. In 1888, William Morrison of Des Moines, Iowa, showed off an electric carriage in the city parade. The carriage had 24 batteries, a top speed of 32.2 kilometers per hour, and an overall range of 81 kilometers.[56]

In 1894, Pedro Salom and Henry G. Morris of Philadelphia patented several battery-electric streetcars and boats. One battery-electric carriage they developed, called the Electrobat, travelled 40 kilometers at a top speed of 32 kilometers per hour. Salom and Morris turned this idea into a startup, which they sold to Isaac L. Rice, who then started the Electric Vehicle Company in New Jersey. By the early 1900s, the company had produced more than 600 electric taxi cabs used in New York City, Boston, Baltimore, and other cities. In New York City, the cab batteries were replaced at a battery-swapping station. Conflicts among investors caused the company to fold in 1907.

In 1898, Ransom Olds, who had founded the Olds Motor Vehicle Company in 1897, decided to manufacture electric cars, which were less complicated and more reliable than were gasoline cars of the day that he was also producing. Olds retrofitted a part of his Detroit, Michigan, factory to mass produce battery-electric vehicles. However, on March 9, 1901, a worker's mistake caused a fire that destroyed the entire factory and Olds' electric car dream. Only one electric car survived the blaze.

Nevertheless, by 1900, about one-third of all vehicles on the road were battery-electric.[57] The public wanted electric vehicles because they were quiet, easy to drive, required few repairs, and did not produce pollution. Unfortunately, once Henry Ford started producing, in 1908, the Model T, which cost one-third as much as a battery-electric vehicle, the electric vehicle market collapsed. The expansion of gas stations and the greater range and top speed of gasoline vehicles through the 1920s sealed the fate of battery-electric vehicles for the next several decades.

It was not until 1973 that General Motors developed a new-generation tiny two-seat urban electric car prototype. The car was never sold commercially. Only following the Arab Oil Embargo of October 1973 to March 1974 did interest in funding the research and development of battery-electric vehicles revive. This resulted in the American Motor Company producing electric delivery jeeps for a U.S. Postal Service test program in 1975. These vehicles, though, were still limited in their range (64 kilometers) and top speed (72 kilometers per hour). More work was needed. In 1976, the U.S. Department of Energy began to research and develop electric and hybrid vehicles.

In the early 1990s, interest in battery-electric vehicles rose again owing to tougher emission standards for internal combustion engine vehicles enacted under the 1990 U.S. Clean Air Act Amendment and by the California Air Resources Board. As a consequence, General Motors developed the EV1 electric car, which had a range of 129 kilometers and good acceleration. Because the cost to produce it was high, the EV1 was never made available commercially, and General Motors scrapped its development in 2001.

In 1997, Toyota produced the first mass-produced hybrid gasoline-electric vehicle, the Prius. The vehicle was released worldwide in 2000. In 1999, Honda also released a gasoline–electric hybrid, the Insight. The commercial availability of both vehicles motivated the research and development of a new generation of pure battery-electric vehicles.

Arguably the most important event in the history of battery-electric transportation was the announcement in 2006 by a startup company in California's Silicon Valley, **Tesla Motors**, that it would

K9, also known as the BYD ebus. It uses a lithium iron phosphate battery and has a range of 250 kilometers (155 miles) on a single charge under typical urban street conditions.

Trains, Funiculars, Cable Cars, Trams, Streetcars, Trolleys, and Light Rail

Another area of progress is with electric trains. Electric trains eliminate the iconic belching smoke from trains that once ran on coal. Electric trains use an electric motor, which is very efficient, converting 84 to 96 percent of input electricity into motion. They also use regenerative braking, thereby generating electricity when they slow and reducing emissions of pollution particles that arise when brake pads or brake blocks are applied to a train's wheels. An electric train obtains its electricity from either overhead lines, a third rail, or onboard batteries.

Built in 1802, in Shropshire, United Kingdom, the first railway locomotive worldwide ran on coal. Only in 1837 did Scottish inventor **Robert Davidson** (1804 to 1894) built a prototype electric locomotive, which ran on non-rechargeable batteries. He then built an improved version in 1841, a train that could travel at a speed of 6.4 kilometers per hour for 2.4 kilometers while towing 5.4 tonnes. Unfortunately, coal-locomotive workers destroyed the train out of fear that they would lose their jobs to this new technology.

Possibly the first non-polluting (both at the vehicle and at the energy source) non-animal-powered, non-sailboat commercial public transportation vehicle in history was the funicular. A **funicular** is a railway on a steep slope with two parallel tracks and one car on each track. The two cars are connected by a cable that loops over a pulley at the top of the track. The cars move in concert. As one slides down, it pulls the other up. The word funicular derives from the Latin word *funis*, which means rope.

Transition highlight

The first known funicular in the world was the Prospect Park Incline Railway on the United States side of Niagara Falls. It was built in 1845 but closed in 1907 following a deadly accident that killed one person. Each car carried 15 to 20 passengers from the top to the bottom of the falls. The whole system was covered. Water was originally used to make one car heavier than the other. Enough water was added to a water tank under the floor