ENERGY

This section highlights the technologies and strategies supplanting energy production from fossil fuels. What were once fools' errands in the energy business, particularly wind and solar, have relentlessly defied predictions and are now competitive with coal, gas, and oil. Renewable costs are continuing to fall on a year-to-year basis, while oil, gas, and coal from new sources are significantly more difficult to extract, which will cause carbon-based fuels to rise in cost. Canada, Finland, and four other countries have banned coal, and more are preparing to. Political leadership is a wonderful thing, but its absence does not slow the renewable transition. The United States pulled out of the Kyoto Protocol in 2001, and that act had virtually no impact on the growth of the renewable energy industry. If you spend a year immersed in the economic data about energy, as we did, there is only one plausible conclusion: We are, in writer Jeremy Leggett's words, squarely in the middle of the greatest energy transition in history. The era of fossil fuels is over, and the only question now is when the new era will be fully upon us. Economics make its arrival inevitable: Clean energy is less expensive.

ENERGY

WIND TURBINES

RANKING AND RESULTS BY 2050 (ONSHORE) #2

84.6 GIGATONS	$1.23 TRILLION	$7.4 TRILLION
REDUCED CO2	NET COST	NET SAVINGS

RANKING AND RESULTS BY 2050 (OFFSHORE) #22

14.1 GIGATONS	$572.4 BILLION	$274.6 BILLION
REDUCED CO2	NET COST	NET SAVINGS

An athlete swims past the Sheringham Shoal Offshore Wind Farm off the coast of Norfolk, England. The wind farm consists of 88 Siemens 3.6-megawatt turbines placed over a 35-square-kilometer area, 11 miles from shore.

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

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

Today, 314,000 wind turbines supply nearly 4 percent of global electricity. And it will soon be much more. Ten million homes in Spain alone are powered by wind. Investment in offshore wind was $29.9 billion in 2016, 40 percent greater than the prior year.

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

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

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

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

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

Ongoing cost reduction will soon make wind energy the least expensive source of installed electricity capacity, perhaps within a decade. Current costs are 2.9 cents per kilowatt-hour for wind, 3.8 cents per kilowatt-hour for natural gas combined-cycle plants, and 5.7 cents per kllowatt-hour for utility-scale solar. A Goldman Sachs research paper published in June 2016 stated simply, "wind provides the lowest cost source of new capacity.” The cost of both wind and solar includes production tax credits; however, Goldman Sachs believes that the continuing decline in wind turbine costs will make up for the phasing out of tax credits in 2023. Wind projects built in 2016 are coming in at 2.3 cents per kilowatt-hour. A Morgan Stanley analysis shows that new wind energy production in the Midwest is one-third of the cost of natural gas combined-cycle plants. And finally, Bloomberg New Energy Finance has calculated that “the lifetime cost of wind and solar is less than the cost of building new fossil fuel plants.” Bloomberg predicts that wind energy will be the lowest-cost energy globally by 2030. (This accounting does not include the cost of fossil fuels with respect to air quality, health, pollution, damage to the environment, and global warming.)

Costs are going down because turbines are being built at higher elevations—meaning longer blades in locations that have more wind, a combination that has more than doubled the capacity of a given turbine to generate electricity. Onshore turbines can be made larger because assembly is far easier than on water. Turbines that generate 20 megawatts of power with tip heights taller than the Empire State Building are on the drawing boards.

Could the United States power itself with wind? The National Renewable Energy Laboratory calculates that nearly 775,000 square miles of land area is suited to 40 to 50 percent capacity factors, more than twice the average capacity factor a decade ago. (A wind turbine is rated to be able to produce a stated amount of power at a constant given wind speed, however the capacity factor takes into consideration the variability of wind speed in the actual location.) The ways and means for the United States to be fossil fuel and energy independent are here. What is often missing is political will and leadership.

Critics in Congress disparage wind power because it is subsidized, implying that the federal government is pouring money down a hole. Coal is a freeloader when it comes to the costs borne by society for environmental impacts. Putting aside the difference in emissions costs—none for wind, high for fossil fuels—the subsidy arguments do not include the difference in water usage between wind and fossil fuels. Wind power uses 98 to 99 percent less water than fossil fuel–generated electricity. Coal, gas, and nuclear power require massive amounts of water for cooling, withdrawing more water than agriculture—22 trillion to 62 trillion gallons per year. Water for many fossil fuel and nuclear plants is “free,” bestowed by the federal government or the states, but it is hardly free and instead represents another unacknowledged subsidy. Who else besides the fossil fuel and nuclear power industries can take trillions of gallons of water in the United States and not pay for it?

China’s rise as the world’s wind leader demonstrates that consistent government commitment to scaling wind energy can accelerate a declining cost curve, especially if government support remains constant regardless of shifting political winds. A predictable environment is key to the industry’s development. On the policy side, portfolio standards can mandate a share of renewable generation. Grants, loans, and tax incentives can encourage construction of more wind capacity and ongoing innovation, on such technologies as vertical-axis turbines and offshore systems. Where governments do support wind energy, such as in the European Union, political action is failing to keep up with the growth of renewable wind energy. Bottlenecks in the grid caused 4,100 gigawatt-hours of wind electricity to be wasted in 2015—enough energy to power 1.2 million homes. Concerns that wind would be unable to supply enough energy for Europe are being replaced by worries that grid integration and utility and distributed energy storage systems will not keep up with demand.

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

IMPACT: *An increase in onshore wind from 2.9 percent of world electricity use to 21.6 percent by 2050 could reduce emissions by 84.6 gigatons of carbon dioxide. For offshore wind, growing from .1 percent to 4 percent could avoid 14.1 gigatons of emissions. At a combined cost of $1.8 trillion, wind turbines can deliver net savings of $7.7 trillion over three decades of operation. These are conservative estimates, however. Costs are falling annually and new technological improvements are already being installed, increasing capacity to generate more electricity at the same or lower cost.*

ENERGY
MICROGRIDS

RANKING AND RESULTS BY 2050

#78

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

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

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

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

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

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

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

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

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

ENERGY
GEOTHERMAL

RANKING AND RESULTS BY 2050

#18

16.6 GIGATONS	-$155.5 BILLION	$1.02 TRILLION
REDUCED CO2	NET COST	NET SAVINGS

Ours is an active planet. A constant flow of heat moves up toward the earth's crust, generating tectonic plate movement, earthquakes, volcanoes, and mountain making. About a fifth of the earth's internal heat is primordial, lingering from the planet's formation 4.6 billion years ago. The balance is generated by ongoing radioactive decay of potassium, thorium, and uranium isotopes in the crust and mantle. The heat energy generated is about 100 billion times more than current world energy consumption. Geothermal energy—literally "earth heat"—creates underground reservoirs of steamy hot water. The geysers of Yellowstone National Park are iconic evidence of a geothermal hot pot simmering beneath us, which occasionally gushes *en plein air*. The hot springs scattered across Iceland's fire-and-ice landscape are another.

Hot water and steam within hydrothermal reservoirs can be piped to the surface and drive turbines to produce electricity—a feat first accomplished in Larderello, Italy, on July 15, 1904, when five lightbulbs were lit by a mechanical device powered by geothermal steam, the invention of Prince Piero Ginori Conti. More than a century later, the Larderello plant still runs, and most of the world's 13 gigawatts of geothermal electricity generation are located along boundaries between tectonic plates, where liquid bodies made themselves apparent on the surface in some way. Another 22 gigawatts of direct geothermal supplies heat for district heating, spas, greenhouses, industrial processes, and other uses.

Geothermal energy is earth energy and depends on heat, an underground reservoir, and water or steam to carry that heat up to the earth's surface. Although prime geothermal conditions are found on less than 10 percent of the planet, new technologies dramatically expand production potential in areas where useful resources were previously unknown. Conventionally, locating hydrothermal pools is the first step; however, pinpointing subsurface resources has been a challenge and limitation for geothermal power. It is difficult to know where reservoirs are and expensive to drill wells to find out. But new exploration techniques are opening up larger territories.

Iceland's Svartsengi ("Black Meadow") geothermal power plant, located on the Reykjanes Peninsula in Iceland, was the first geothermal plant designed to both create electricity and provide hot water for district heating. With six different plants, it generates 75 megawatts of electricity, enough to supply 25,000 homes. Its "waste" hot water is piped to the Blue Lagoon Geothermal Spa, visited by 400,000 guests annually.

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

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

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

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

In twenty-four countries around the world, tackling these drawbacks is proving worthwhile because geothermal power can provide reliable, abundant, and affordable electricity, with low operational costs over its lifetime. In El Salvador and the Philippines, geothermal accounts for a quarter of national electric capacity. In volcanic Iceland, it is one-third. In Kenya, thanks to the activity beneath Africa’s Great Rift Valley, fully half of the country’s electricity generation is geothermal—and growing. Though less than .5 percent of national electricity production, U.S. geothermal plants lead the world with 3.7 gigawatts of installed capacity.

There is opportunity to pursue geothermal with greater steam and in more places. According to the Geothermal Energy Association, 39 countries could supply 100 percent of their electricity needs from geothermal energy, yet only 6 to

7 percent of the world’s potential geothermal power has been tapped. Theoretical projections based on geologic surveys of Iceland and the United States indicate that undiscovered geothermal resources could supply 1 to 2 terawatts of power or 7 to 13 percent of current human consumption. However, that number is significantly lower when capital requirements and other costs and constraints are factored in.

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

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

ENERGY
SOLAR FARMS

RANKING AND RESULTS BY 2050

#8

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

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

A solar farm owned by the Sacramento Municipal Utility District in California, the first municipal district to meet the state's mandated renewable energy standards. The utility sells SolarShares in the solar farms to its ratepayers so that they may harvest a monetary return from the renewable energy revolution in California.

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

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

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

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

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

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

ENERGY
ROOFTOP SOLAR

RANKING AND RESULTS BY 2050 #10

24.6 GIGATONS	$453.1 BILLION	$3.46 TRILLION
REDUCED CO2	NET COST	NET SAVINGS

The year was 1884, when the first solar array appeared on a rooftop in New York City. Experimentalist Charles Fritts installed it after discovering that a thin layer of selenium on a metal plate could produce a current of electricity when exposed to light. How light could turn on lights, he and his solar-pioneering contemporaries did not know, for the mechanics were not understood until the early twentieth century when, among other breakthroughs, Albert Einstein published his revolutionary work on what are now called photons. Though the scientific establishment of Fritts's day believed power generation depended on heat, Fritts was convinced that "photoelectric" modules would wind up competing with coal-fired power plants. The first such plant had been brought online by Thomas Edison just two years earlier, also in New York City.

Today, solar is replacing electricity generated from coal as well as from natural gas. It is replacing kerosene lamps and diesel generators in places where people lack access to the power grid, true for more than a billion people around the world. While society grapples with electricity's pollution in some places and its absence in others, the mysterious waves and particles of the sun's light continuously strike the surface of the planet with an energy more than ten thousand times the world's total use. Small-scale photovoltaic systems, typically sited on rooftops, are playing a significant role in harnessing that light, the most abundant resource on earth. When photons strike the thin wafers of silicon crystal within a vacuum-sealed solar panel, they knock electrons loose and produce an electrical circuit. These subatomic particles are the only moving parts in a solar panel, which requires no fuel.

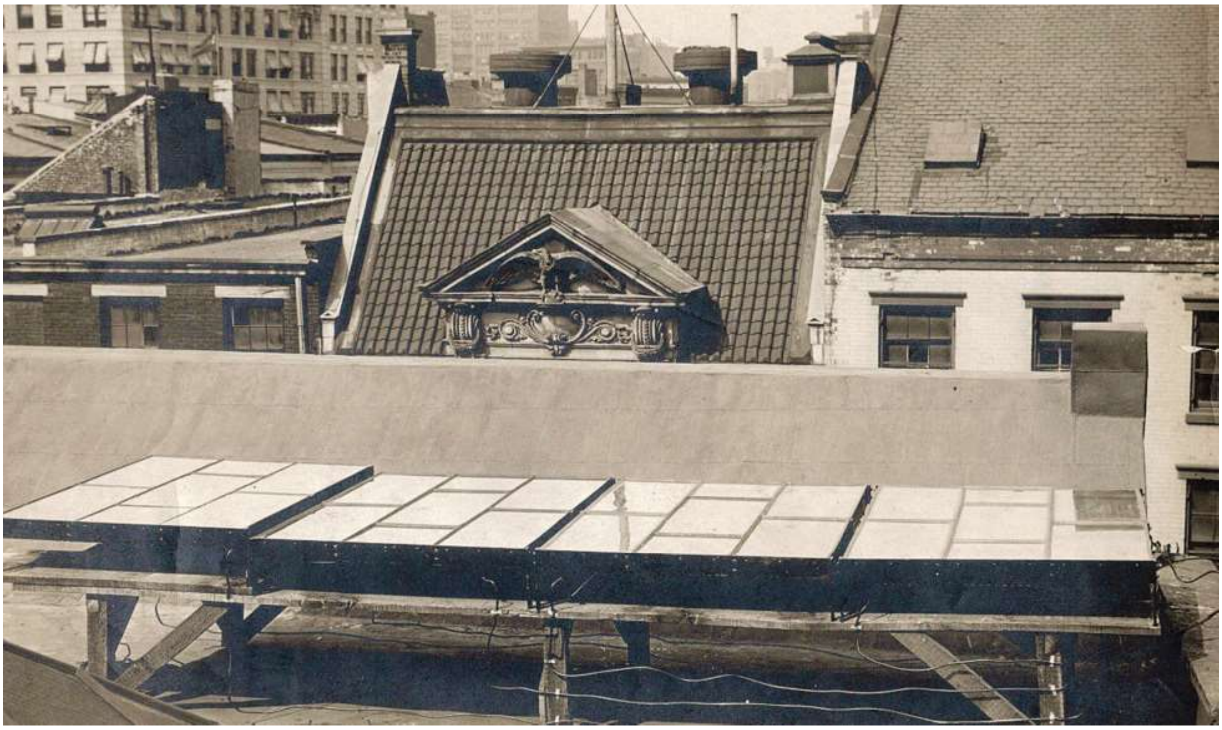
While solar photovoltaics (PV) provide less than 2 percent of the world's electricity at present, PV has seen exponential growth over the past decade. In 2015 distributed systems of less than 100 kilowatts accounted for roughly 30 percent of solar PV capacity installed worldwide. In Germany, one of the world's solar leaders, the majority of photovoltaic capacity is on rooftops, which don 1.5 million systems. In Bangladesh, population 157 million, more than 3.6 million home solar systems have been installed. Fully 16 percent of Australian homes have them. Transforming a square meter of rooftop into a miniature power station is proving irresistible.

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

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

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

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



The first solar array installed by Charles Fritts in 1884 in New York City. Fritts built the first solar panels in 1881, reporting that the current was “continuous, constant and of considerable force not only by exposure to sunlight but also to dim, diffused daylight, and even to lamplight.”

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

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

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

ENERGY

WAVE AND TIDAL

RANKING AND RESULTS BY 2050 #29

9.2 GIGATONS	$411.8 BILLION	-$1 TRILLION
REDUCED CO2	NET COST	NET SAVINGS

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

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

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

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

While the ocean’s perpetual power makes wave and tidal energy possible, it also creates obstacles. Operating in harsh and complex marine environments is a challenge—from designing the most effective systems to building installations for their implementation to maintaining them over time. Salt water corrodes equipment, and waves are more multidimensional than a gust of wind—moving up, down, and in all other directions when there are turbulent conditions. It is also critical to ensure marine ecosystems are not harmed by discharges of sound or substance, or by trapping or killing sea life. All told, these dynamics make operating in salt water more exacting and expensive than operating on solid ground.

Marine technologies are still in early development, lagging decades behind solar and wind. Tidal energy is more established than wave, with more projects in operation today. They are ideally suited for natural bays, inlets, or lagoons—places where ocean water enters and exits in circadian cycles—harnessing the incoming and outgoing tides to generate electricity. Some resemble dams, inside which rising or retreating tides drive turbines. More experimental in-stream systems function like underwater wind turbines, with tides moving blades to produce electricity.

Across the world, a variety of wave-energy technologies are being tested and honed, in pursuit of the ideal design for converting waves' kinetic energy into electricity. Some look like yellow buoys bobbing up and down on the ocean's surface. Others resemble large red snakes riding the waves, or long arms waving back and forth. Still others are fully submerged floating discs that incorporate electricity generation right there in the sea. It is not yet clear which technology is most effective. But whatever their shape and form, these systems tap into the upward and downward, the incoming and outgoing movement of waves to power generation. Oscillation is the key, so the higher the wave, the greater its power potential tends to be.

The Annapolis Royal Generating Station is a 20-megawatt power station located on the Annapolis River in Nova Scotia. Built in 1984, it remains the only tidal generating station in North America and takes advantage of the highest tidal range in the world. The difference in height between high and low tides can be over 50 feet. Currently in-stream turbines are being tested nearby, a simpler design with far less environmental impact.

The opportunity of marine-based energy is massive, but realizing it will require substantial investment and expanded research. Proponents believe wave power could provide up to 25 percent of U.S. electricity and 30 percent or more in Australia. In Scotland, that number may be upwards of 70 percent. Wave and tidal energy is currently the most expensive of all renewables, and with the price of wind and solar dropping rapidly, that gap will likely widen. However, as this technology evolves and policy comes into place to support implementation, marine renewables may follow a similar path, attracting private capital investment and the interest of large companies such as General Electric and Siemens. On a trajectory like that, wave and tidal energy could also become cost competitive with fossil fuels. •

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

ENERGY
CONCENTRATED SOLAR

RANKING AND RESULTS BY 2050 #25

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

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

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

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

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

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

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

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

IMPACT: *CSP comprised .04 percent of world electricity generation in 2014. Despite slow adoption in recent years, this analysis assumes CSP could rise to 4.3 percent of world electricity generation by 2050, avoiding 10.9 gigatons of carbon dioxide emissions. Implementation costs are high at $1.3 trillion, but net savings could be $414 billion by 2050 and $1.2 trillion over the lifetime of the technology. An additional benefit of CSP is that it can easily integrate energy storage, allowing for extended use after dark.*

ENERGY
BIOMASS

RANKING AND RESULTS BY 2050

#34

7.5 GIGATONS	$402.3 BILLION	$519.4 BILLION
REDUCED CO2	NET COST	NET SAVINGS

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

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

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

This is a single-pass, cut-and-chip harvester reaping fast-growing willow for a carbon-neutral biomass plant, part of Germany’s *Energiewende* or “energy turnaround.” Germany currently produces over 30 percent of its energy from wood, but when the total cost of harvesting and processing wood is calculated, it is not carbon neutral. The industry exists because of significant government subsidies.

Another important feedstock is waste from wood and agricultural processing. Scraps from saw mills and paper mills are valuable biomass. So are discarded stalks, husks, leaves, and cobs from crops grown for food or animal feed. While it is important to leave crop residues on fields to promote soil health, a portion of those agricultural wastes can be diverted for biomass energy production. Many such organic residues would either decompose on-site or get burned in slash piles, thus releasing their stored carbon regardless (albeit perhaps over longer periods of time). When organic matter decomposes, it often releases methane and when it is burned in piles, it releases black carbon (soot). Both methane and soot increase global warming faster than carbon dioxide; simply preventing them from being emitted can yield a significant benefit, beyond putting the embodied energy of biomass to productive use.

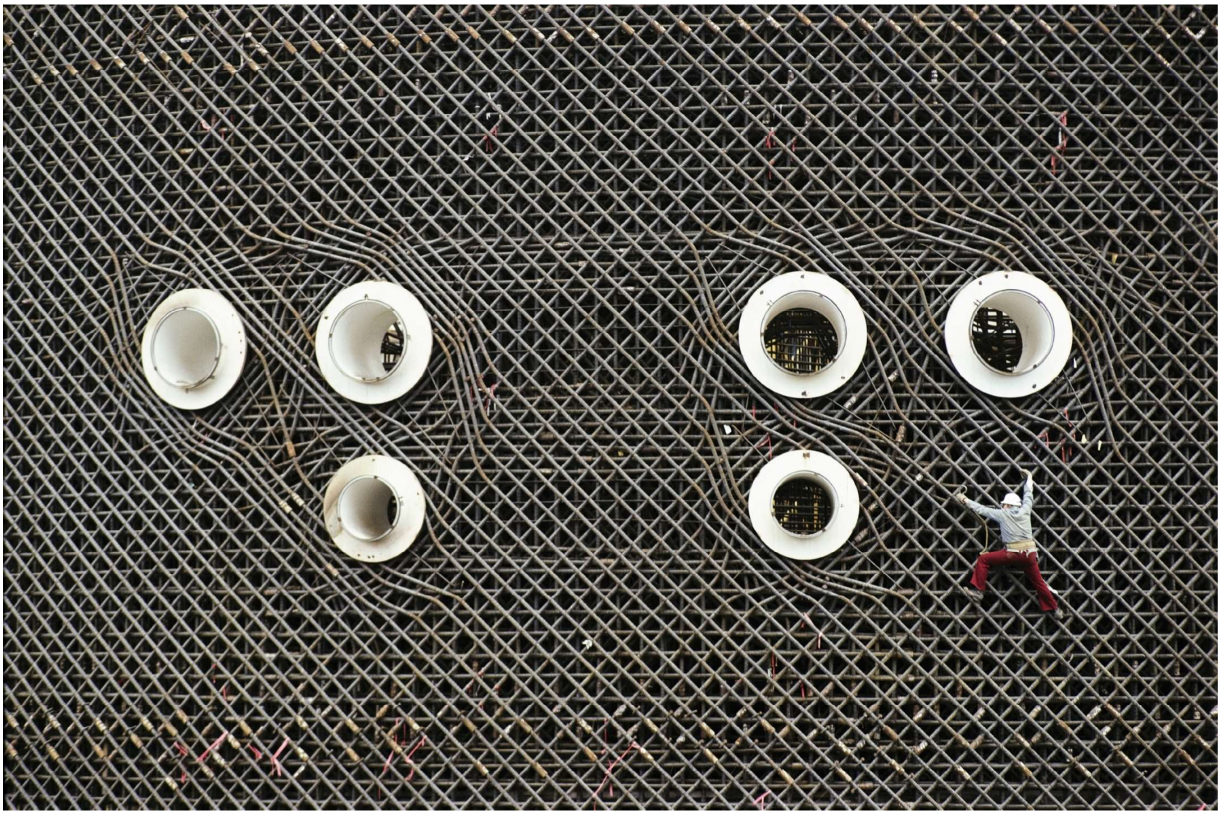
In the United States, a majority of the more than 115 biomass electricity generation plants under construction or in the permitting process plan on burning wood as fuel. Proponents state that these plants will be powered by branches and treetops left over from commercial logging operations, but these claims do not stand up to scrutiny. In the states of Washington, Vermont, Massachusetts, Wisconsin, and New York, the amount of slash generated by logging operations falls far short of the amount needed to feed the proposed biomass burners. In Ohio and North Carolina, utilities have been more forthright and admit that biomass electricity generation means cutting and burning trees. The trees will grow back, but over decades—a lengthy and uncertain lag time to achieve carbon neutrality. When biomass energy relies on trees, it is not a true solution.

Biomass is controversial. To some, biomass is a friend; to others, a foe. A considerable academic effort is under way to more accurately assess its environmental and social impacts. Debates center around three main issues: life-cycle carbon emissions (as previously described), indirect land-use change and deforestation, and impacts on food security. Often, the latter two debates are constructed as forests versus fuel and food versus fuel. In reality, managing land, cultivating food, and producing biomass feedstock interact dynamically—and not always in line with conventional wisdom. The three can be mutually reinforcing or play out to one another's detriment, so *how* biomass feedstocks are approached within a given local context matters enormously. At present, biomass fuels 2 percent of global electricity production, more than any other renewable. In some countries—Sweden, Finland, and Latvia among them—bioenergy is 20 to 30 percent of the national generation mix, almost entirely provided for by trees. Biomass energy is on the rise in China, India, Japan, South Korea, and Brazil. Reaching greater scale in more places requires investment in biomass production facilities and infrastructure for collection, transport, and storage. It is crucial to manage, through regulation, the drawbacks of biomass energy. Pelletizing native forests for biomass continues to be a giant step backward. However, extracting invasive species from forests accompanied with appropriate ecological safeguards can be a good source of biomass energy. That approach is being tested in India by the government of the state of Sikkim, which is making "bio-briquettes" for clean cookstoves. Additionally, smallholder farmers need to be protected from displacement by industrial-scale approaches to biomass generation. Most important to bear in mind is that biomass—carefully regulated and managed—is a bridge to reach a clean energy future, not the destination itself. •

IMPACT: *Biomass is a "bridge" solution, phased out over time in favor of cleaner energy sources. This analysis assumes all biomass is derived from perennial bioenergy feedstock—not forests, annuals, or waste—and replaces coal and natural gas in electricity production. By 2050, biomass energy could reduce 7.5 gigatons of carbon dioxide emissions. As clean wind and solar power become more available in a flexible grid, the need for biomass energy will decline.*

ENERGY
NUCLEAR

RANKING AND RESULTS BY 2050		#20
16.09 GIGATONS	$.88 BILLION	$1.7 TRILLION
REDUCED CO2	NET COST	NET SAVINGS



To give a sense of the scale of a nuclear power plant, this image shows a worker climbing a lattice of steel rods at one of the original Hanford Site nuclear reactors.

In effect, nuclear power plants boil water. Nuclear fission splits atomic nuclei and releases the energy that binds the protons and neutrons together. The energy released by radioactivity is used to heat water, which in turn is used to power turbines. It is the most complex process ever invented to create steam. However, nuclear power has a low carbon footprint, which is why it is seen by some people to be a critical global warming solution; many others believe that it is not now, nor will it ever be, cost-effective compared with other low-carbon options. The almost-universal method used to power steam turbines is gas- or coal-fired power. Greenhouse gases emitted to generate electricity are calculated to be ten to a hundred times higher for coal than for nuclear.

Currently, nuclear power generates about 11 percent of the world's electricity and contributes about 4.8 percent to the world's total energy supply. There are 444 operating nuclear reactors in 29 countries, and 63 more are under construction. Of the 29 countries with operative nuclear power plants, France has the highest nuclear contribution to its electrical energy supply, at 76 percent.

Nuclear reactors are broadly classified by generation. The oldest, Generation 1, first came online in the 1950s and are now almost entirely decommissioned. The majority of current nuclear capacity falls into the Generation 2 category. (Chernobyl consisted of both Gen 1 and Gen 2. The four Fukushima Daiichi reactors are Gen 2, as are all of the reactors in the United States and France.) Generation 2 distinguishes itself from its predecessor by the use of water (as opposed to graphite) to slow down nuclear chain reactions and the use of enriched, as opposed to natural, uranium for fuel. The Generation 3 reactors, five of which are in operation worldwide and several more under construction, along with Generation 4 reactors, which are currently being researched, constitute what is called "advanced nuclear." In theory, advanced nuclear has standardized designs that reduce construction time and achieve longer operating lifetimes, improved safety features, greater fuel efficiency, and less waste.

What makes the future of nuclear energy difficult to predict is its cost. While the cost of virtually every other form of energy has gone down over time, a nuclear power plant's is four to eight times higher than it was four decades ago. According to the U.S. Department of Energy, advanced nuclear is the most expensive form of energy besides conventional gas turbines, which are comparatively inefficient. Onshore wind is a quarter of the cost of nuclear power.

For those who argue against nuclear because of cost, timing, and safety reasons, the counterargument at one time was the unremitting pace of new coal-fired plant construction. Hundreds of coal-fired plants were being built or planned, primarily in south and east Asia, with three-fourths of them slated to be built by China, India, Vietnam, and Indonesia. If the coal boom is not stopped, global warming will increase far beyond any reasonable limit. This is why climate reporting focuses primarily on energy, and it is why proponents of nuclear are frustrated at the sluggish pace of new plant construction. Licensing, permitting, and financing have brought nuclear plants to a near standstill in the United States, while Germany is shutting its plants down and decommissioning. On the other hand, China has thirty-three nuclear plants operative and twenty-two under construction. It is committed to peak carbon dioxide in 2030 with a reduction of its carbon footprint from that date forward.

Discussion of nuclear power goes right to the heart of the climate dilemma with respect to carbon emissions: Is an increase in the number of nuclear power plants, with all their flaws and inherent risks, worth the risk? Or, as some proponents insist, will there be a total meltdown of climate by limiting their use? Nuclear power has been the subject of contentious disagreements by proponents and critics. The arguments for and against are fascinating, complex, and polarized. Take the following three scientists, widely respected in the environmental community, who do not agree:

According to physicist Amory Lovins, “Nuclear power is the only energy source where mishap or malice can destroy so much value or kill many faraway people; the only one whose materials, technologies, and skills can help make and hide nuclear weapons; the only proposed climate solution that [creates] proliferation, major accidents, and radioactive-waste dangers. . . . [N]uclear power is continuing its decades-long collapse in the global marketplace because it’s grossly uncompetitive, unneeded, and obsolete—so hopelessly uneconomic that one need not debate whether it is clean and safe; it weakens electric reliability and national security; and it worsens climate change compared with devoting the same money and time to more effective options.”

James Hansen, the NASA scientist who put the United States on notice in his 1988 congressional testimony on climate change, takes another perspective. He authored an open letter with three other climate leaders stating, “Renewables like wind and solar and biomass will certainly play roles in a future energy economy, but those energy sources cannot expand fast enough to deliver cheap and reliable power at the scale the global economy requires. While it may be theoretically possible to stabilize the climate without nuclear power, in the real world there is no credible path to climate stabilization that does not include a substantial role for nuclear power.” Their proposal would require building 115 reactors per year for thirty-five years.

Joseph Romm, one of the most respected climate writers and bloggers, does not buy it. Nuclear reactors are too expensive and unwieldy and, given the still-plummeting cost of wind and solar, have priced themselves out of the market. The International Energy Agency (IEA) has said nuclear can play “an important but limited role.” In the IEA’s estimation, nuclear can grow from its current 11 percent of generated electricity to 17 percent by 2050.

There seem to be two different worlds here, not one. Nuclear is expensive, and the highly regulated industry in the European Union and the United States may continue to be overbudget and slow. The French company Areva is ten years behind schedule and $5.4 billion over budget on the Olkiluoto reactor in Finland. In Normandy, a $3.4 billion pressurized-water reactor slated for start-up in 2012 will not commence construction until 2018, at a revised cost of $11.3 billion. On the other side of the globe, the largest emitter of carbon in the world is building nuclear reactors more rapidly, motivated in no small part because its cities are extraordinarily polluted from cars and coal-fired power plants. The Chinese nuclear power industry is self-sufficient, in a position to export, and able to complete new plants within two to three years. Yet even where nuclear seems to be “working,” there is a dramatic shift to renewables. China currently leads the world in installed renewable energy capacity, has canceled plans for dozens of coal-fired plants, and is committing to a combined wind and solar capacity of 400 gigawatts by 2020.

Steam rises from the Grafenrheinfeld nuclear power plant in Germany. The plant had been in operation since 1981 and ceased operation in June 2015. Germany is withdrawing from nuclear energy and hopes to cease all nuclear power generation by 2022.

Or maybe there is another possibility. Can nuclear power plants be redesigned to be smaller, lighter, safer, and cheaper? That is a question dozens of start-ups are working on. Generation 3 reactors notwithstanding, the nuclear reactor world is stuck on large, expensive, hugely complex systems that are better than those in the past, but that repeat the past. Do large, centralized power plants of any sort make sense in a world of inexpensive renewables, distributed storage, and advanced batteries? Nearly fifty companies are competing to solve the nuclear problem, creating what could be called Generation 4 reactors. These technologies include molten-salt reactors, high-temperature gas reactors, pebble-bed modular reactors, and fusion reactors (hydrogen-boron reactors). There are new reactor designs that address some of the main criticisms and concerns about nuclear energy. These reactors are being designed to shut down quickly and safely with no one in attendance ("walk-away safety"). They employ better coolants and can scale down to plants one five-hundredth the size of conventional nuclear. They reduce construction time to one or two years. The world may soon have better choices when it comes to nuclear energy than it has had in the past, but it may be too late given the accelerating cost and construction advantages of renewable energy technologies. •

IMPACT: *Nuclear's complicated dynamics around safety and public acceptance will influence its future direction—of expansion or contraction. We assume its share of global electricity generation will grow to 13.6 percent by 2030, but slowly decline to 12 percent by 2050. With a longer lifetime than fossil fuel plants resulting in fewer facilities overall, installation of nuclear power plants could cost an additional $900 million, despite the high implementation cost of $4,457 per kilowatt. Net operating savings over thirty years could reach $1.7 trillion. This scenario could result in 16.1 gigatons of carbon dioxide emissions avoided.*

EDITOR'S NOTE: *One hundred solutions are featured in* Drawdown*. Of those, almost all are no-regrets solutions society would want to pursue regardless of their carbon impact because they have many beneficial social, environmental, and economic effects. Nuclear is a regrets solution, and regrets have already occurred at Chernobyl, Three Mile Island, Rocky Flats, Kyshtym, Browns Ferry, Idaho Falls, Mihama, Lucens, Fukushima Daiichi, Tokaimura, Marcoule, Windscale, Bohunice, and Church Rock. Regrets include tritium releases, abandoned uranium mines, mine-tailings pollution, spent nuclear waste disposal, illicit plutonium trafficking, thefts of fissile material, destruction of aquatic organisms sucked into cooling systems, and the need to heavily guard nuclear waste for hundreds of thousands of years.*

ENERGY
COGENERATION

RANKING AND RESULTS BY 2050 #50

3.97 GIGATONS	$279.3 BILLION	$567 BILLION
REDUCED CO2	NET COST	NET SAVINGS

U.S. coal-fired or nuclear power plants are about 34 percent efficient in terms of producing electricity, which means two-thirds of the energy goes up the flue and heats the sky. All told, the U.S. power-generation sector throws away an amount of heat equivalent to the entire energy budget of Japan. Put your hand behind the tailpipe of your car when the engine is running. It is the same principle, only worse—75 to 80 percent of the energy generated by an internal combustion engine is wasted heat. Coal and single-cycle gas generating plants are the best candidates for capturing wasted energy through cogeneration.

Cogeneration puts otherwise-forfeited energy to work, heating and cooling homes and offices or creating additional electricity. Cogeneration systems, also known as combined heat and power (CHP), capture excess heat generated during electricity production and use that thermal energy at or near the site for district heating and other purposes. The opportunity to reduce emissions and save money through cogeneration is significant because of the inherent low efficiency of electrical generation.

Many of the cogeneration systems currently online are found in the industrial sector. In the United States, 87 percent of them are used in energy-intensive industries such as chemical, paper, and metal manufacturing and food processing. In countries such as Denmark and Finland, cogeneration makes up a significant part of electricity production largely because of its use in district heating systems.

In countries with a high-CHP share in total generation, such as Denmark and Finland, the need to address energy security played a decisive role. Denmark's progress came in large part from specific government policies, while Finland's was more market driven. Finland's large paper and forestry industries are naturally motivated to utilize biomass-based cogeneration given the on-site availability of this wood energy resource. Moreover, the cold climate in the country has provided a basis for a healthy return on investment in heat supply infrastructure. As of 2013, 69 percent of Finland's district heating is provided by cogeneration systems.

Denmark's approach to energy supply is policy driven. Although the use of CHP in the country dates back to 1903, it was the 1970s oil crisis that spurred the use of this technology. Since that time, policies have compelled local authorities to identify opportunities for energy-efficient heat production, helped to move power generation from centralized plants to a decentralized network, and incentivized the use of cogeneration generally, and renewable-based systems particularly, through tax policy. Additionally, Denmark has actively participated in United Nations climate change negotiations and made advances to reduce greenhouse gas emissions. Currently around 80 percent of district heating and more than 60 percent of electricity demand is met by CHP, and there are now microcogeneration units available to households. Usually fueled by natural gas, they can be a fuel cell or heat generator that provides electricity, heating, ventilation, and air-conditioning. They are very efficient, but their price and other factors inhibit adoption.

The United States has long lagged behind Europe on cogeneration, in part because of pushback from utilities— notoriously so twenty years ago, when CHP plans at the Massachusetts Institute of Technology were challenged by the local utility. Litigation followed, with the university finally winning in the courts. Such obstruction is rare in today's energy-conscious environment, and MIT's state-of-the-art cogeneration system is nearing completion.

From a financial viewpoint, the adoption of cogeneration systems makes sense for many industrial and commercial uses, as well as for some residential uses. Cogeneration makes it possible for users that do not have access to renewable energy to produce more energy with the same amount, and cost, of fuel. In addition to clear financial benefits, adoption will reduce greenhouse gas emissions to the extent cogeneration reduces reliance on fossil fuels for heating and electricity. Moreover, it will play a substantial role in the ushering in of smart, distributed, and renewable-based energy networks. Because distributed systems are necessarily placed close to the site of generation, they reduce the need for transmission lines. Cogeneration systems are easily adaptable to user preference and thus allow for a variety of energy sources. Additionally, cogeneration systems can help to reduce water usage and thermal water pollution when compared to separate combustion-based heat and power systems, decreasing demand pressure on another vital natural resource. •

IMPACT: *In our analysis cogeneration refers to on-site CHP from natural gas in commercial, industrial, and transportation sectors. In 2014, industrial cogeneration using natural gas comprised approximately 3.2 percent of global power generation and 1.7 percent of heat generation. If adoption grows to 5.4 percent of power and 3.3 percent of heat by 2050, 4 gigatons of carbon dioxide emissions can be avoided. At an average installation cost of $1,851 per kilowatt, total installation would cost $279 billion. By replacing grid-based electricity and on-site heat generation with more efficient and less costly technology, the growth in cogeneration could produce operational savings of $567 billion over thirty years and lifetime savings of $1.7 trillion.*

ENERGY
MICRO WIND

RANKING AND RESULTS BY 2050 #76

0.2 GIGATONS	$36.1 BILLION	$19.9 BILLION
REDUCED CO2	NET COST	NET SAVINGS

With capacity of 100 kilowatts or less, micro wind turbines are akin to the windmills of yore— standing solo in a Kansas cornfield, meeting the electricity needs of a family or small farm or business. They are often used to pump water, charge batteries, and provide electrification in rural locations. Typically, only one is installed at a particular location, on as little as an acre of land, in contrast to the large, sweeping groupings found at commercial wind farms.

When the electric grid was still sparse in many rural U.S. states, on-site wind energy was often used to fill the gap. It is playing a similar role in developing countries today, where these small-scale systems can bring power to the 1.1 billion people around the world without access to electricity, predominantly in rural parts of sub-Saharan Africa and developing Asia. Micro wind turbines are a notable technology for expanding electrification, giving people a way to light their homes or cook their evening meals, which has wide-ranging benefits for well-being and economic development. At the same time, micro wind in high-income countries can be paired with utility-scale renewables, augmenting production. Though the locations may vary widely, micro wind turbines achieve the same climate benefit: energy production without creating greenhouse gases.

Depending on its speed, wind contains a certain amount of kinetic energy. The efficiency with which a turbine extracts power from the wind is called its capacity factor. For small-scale wind turbines, real-world capacity is typically 25 percent or lower. Siting is critical to maximizing their output, but the technology for doing so is in its infancy compared to that for the commercial wind industry. At the same time, micro wind turbines are able to avoid challenges that plague their utility-scale brethren. Being smaller in scale means they avoid aesthetic issues—claims of ruining bucolic views along ridgelines or off coasts—and noise grievances, as many are nearly inaudible.

At present, the major demand for micro wind turbines is for off-grid use. That means they are often installed with a diesel generator to supply electricity when the breeze does not blow. From a carbon perspective, relying on a fossil fuel complement is not ideal. There are already some combined solar photovoltaic and micro wind systems on the market, which is one fruitful alternative. Improved battery storage technology could also boost the viability of small-scale wind. Where these turbines *are* linked up to the grid, owners may be able to send their unneeded electrons out to the larger network for financial return through net metering.

Experts estimate that a million or more micro wind turbines are currently in use around the world, with the majority whirling in China, the United States, and the United Kingdom. The key factor for growing that number is cost in both low- and high-income countries alike. Currently, the price per kilowatt of small-scale wind is much higher than that of utility-scale turbines, and payback periods can be long, in part because they are installed individually. Acquiring micro-wind technology is beyond the reach of many. Public-support schemes, such as feed-in-tariffs, tax credits, capital subsidies, and net metering, can shift that equation—and have in places where it is thriving. Until small-scale turbine manufacturers can reach economies of scale, end-user cost is likely to remain a challenge. Continued evolution of turbine technology itself also will play an important role in reducing price.

This is a VisionAIR5 vertical axis wind turbine that is quieter than a human whisper at low speeds. The turbine is 10.5 feet high and is rated at 3.2 kilowatts of power. The minimum wind speed required is 9 miles per hour and it can withstand speeds up to 110 miles per hour.

Integrating micro turbines into large structures within the built environment is showing unique promise. Structures that enable turbine placement at high elevation, such as skyscrapers, can take advantage of stronger, steadier breezes. That is one reason visitors to the Eiffel Tower can now find vertical axis turbines on its second level, four hundred feet above the ground, overlooking the Champ de Mars. Their design enables them to utilize wind coming from any direction, producing electricity to power the tower’s restaurants, shop, and exhibits. A symbol of engineering innovation, the Eiffel Tower is an appropriate perch for technologies that can help propel a clean energy future. •

IMPACT: *Increase micro wind fivefold to 1 percent of global electricity generation by 2050, and it can deliver .2 gigatons of emissions reductions. Like in-stream hydro, micro wind turbines allow for the extension of clean, renewable electricity in areas without grid access.*

Human-induced climate change was first identified in 1800 and again in 1831 by the same scientist, Alexander von Humboldt.

Alexander von Humboldt

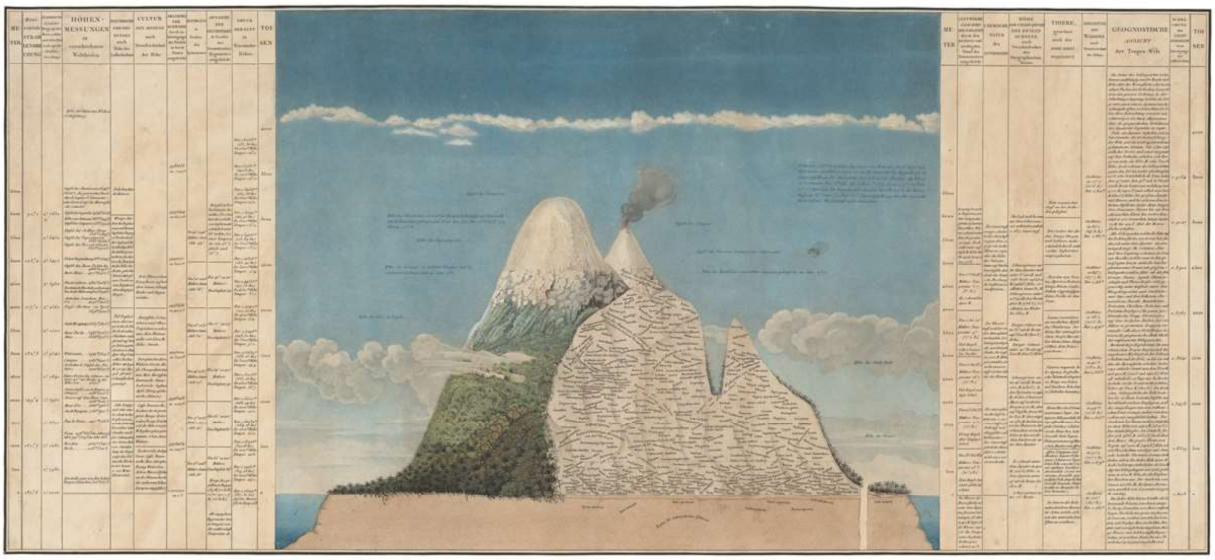
ANDREA WULF

Though little known or studied today, Alexander von Humboldt (b. September 14, 1769) was a legend in his lifetime, and remains one of the most important scientists in history. More places and species are named after Humboldt than after any other human being. His one hundredth birthday was celebrated all over the world with festivities and parades. More than 25,000 people gathered in Central Park to pay homage, 10,000 in Pittsburgh, 15,000 in Syracuse, 80,000 in Berlin, with thousands more in Buenos Aires, Mexico City, London, and Sydney. As people around the world become more aware of how vulnerable living systems are to global warming, Humboldt's insights and writings seem more than prescient. He was the first person to describe the phenomenon and cause of human-induced climate change, in 1800 and again in 1831, based on observations generated during his travels.

Humboldt's first journey, in 1799, took him on a five-year odyssey through Latin America—an expedition that transformed his thinking and that of the rest of the world. It was here that Humboldt created the idea of isotherms, the lines delineating changes in barometric pressure and temperature on weather maps. His concept of climatic zones came about from his near ascent of Chimborazo, a 20,564-foot inactive volcano in Ecuador. He had taken a trunk full of instruments and measured, described, scrutinized, and drawn the plants, animals, forests, people, and lands encountered with an almost perfect recall, *giving him an encyclopedic ability to compare any species with another he had previously seen. During his five-year immersion in largely unspoiled wilderness, Humboldt realized that nature is intricately interconnected in ways that surpass human knowledge. And he saw that living systems, and indeed the whole of the planet, are highly vulnerable to disturbances by human beings. The principles of the web of life variously described by Darwin, Muir, Emerson, and Thoreau arose directly from Humboldt's Latin America expedition and his subsequent writings.*

In 1829, the sixty-year-old Humboldt set off on his last journey, a wide-ranging expedition to Russia arranged after receiving welcoming invitations from Czar Nicholas I and foreign minister Count Georg von Cancrin. In twenty-five weeks, his party traveled 9,614 miles. When he returned, he described precisely and prophetically what could happen to a civilization if it did not recognize how sensitive our atmosphere is to changes on the ground. In this wonderful excerpt from Andrea Wulf's brilliant biography, she describes his return to Moscow and St. Petersburg at the end of his journey. —PH

It was now the end of October and the Russian winter was almost upon them. Humboldt was expected first in Moscow and then in St. Petersburg to report on his expedition. He was happy. He had seen deep mines and snow-capped mountains as well as the largest dry steppe in the world and the Caspian Sea. He had drunk tea with the Chinese commanders at the Mongolian border as well as fermented mare's milk with the Kyrgyz. Between Astrakhan and Volgograd, the learned khan of the Kalmyk choir sang Mozart overtures. Humboldt had watched Saiga antelopes chasing across the Kazakh Steppe, snakes sunbathing on a Volga island and a naked Indian fakir in Astrakhan. He had correctly predicted the presence of diamonds in Siberia, had against his instructions talked to political exiles, and had even met a Polish man who had been deported to Orenburg and who proudly showed Humboldt his copy of *Political Essay of New Spain*. During the previous months Humboldt had survived an anthrax epidemic and had lost weight because he found the Siberian food indigestible. He had plunged his thermometer into deep wells, carried his instruments across the Russian Empire, and taken thousands of measurements. He and his team returned with rocks, pressed plants, fish in vials, and stuffed animals, as well as ancient manuscripts and books for Wilhelm.



Humboldt's first and most stunning depiction of nature as an interconnected whole was his so-called *Naturgemälde*, a German term that can mean "painting of nature" but that also implies a sense of unity or wholeness. It was, as Humboldt later explained, a "microcosm on one page." In today's parlance, this is probably the first infographic ever created, another first by Humboldt.

As before, Humboldt was not just interested in botany, zoology, or geology but also in agriculture and forestry. Noting the rapid disappearance of the forests around the mining centers, he had written to Cancrin about the "lack of timber" and advised him against using steam engines to drain flooded mines because doing so would consume too many trees. In the Baraba Steppe, where the anthrax epidemic had raged, Humboldt had noted the environmental impact of intense husbandry. The region was (and is) an important agriculture center of Siberia, and the farmers there had drained swamps and lakes to turn the land into fields and pastures. This had caused a considerable desiccation of the marshy plains which would continue to increase, Humboldt concluded.

Humboldt was searching for the "connections which linked all phenomena and all forces of nature." Russia was the final chapter in his understanding of nature—he consolidated, confirmed, and set into relation all the data he had collected over the past decades. Comparison not discovery was his guiding theme. Later, when he published the results of the Russian expedition in two books, Humboldt wrote about the destruction of forests and of humankind's long-term changes to the environment. When he listed the three ways in which the human species was affecting the climate, he named deforestation, ruthless irrigation, and, perhaps most prophetically, the “great masses of steam and gas” produced in the industrial centers. No one but Humboldt had looked at the relationship between humankind and nature like this before. •

ENERGY
METHANE DIGESTERS

RANKING AND RESULTS BY 2050 (LARGE)		#30
8.4 GIGATONS REDUCED CO2	$201.4 BILLION NET COST	$148.8 BILLION NET SAVINGS

RANKING AND RESULTS BY 2050 (SMALL)		#64
1.9 GIGATONS REDUCED CO2	$15.5 BILLION NET COST	$13.9 BILLION NET SAVINGS

The same year Thomas Jefferson penned the U.S. Declaration of Independence, Italian physicist Alessandro Volta discovered methane gas. Intrigued by the flammable air rising up from muddy waters along Lake Maggiore, he captured some and recorded his findings from ensuing experiments in a series of letters to friend and fellow curious mind Carlo Campi. “No, sir, no air is more combustible than the air from marshy soil,” Volta wrote on November 21, 1776, beginning to fathom the connection between the gas and decaying vegetation. He went on to engage the fiery power of methane in a pistol of his own design. But it was not until a century later that scientists came to understand that microbes were responsible for the creation of Volta’s combustible air. That microbial wisdom is now being used to manage the planet-warming methane emissions that arise from organic waste—creating clean energy in the process.

Agricultural, industrial, and human digestion processes create an ongoing (and growing) stream of organic waste. Around the world, people grow crops, raise animals, make foodstuffs, and nourish themselves. Every one of those activities creates by-products, from residues to excrement. Even with best efforts to reduce, there is no way around waste. Some spoilage, for instance, is inevitable. And, as the saying goes, shit happens. Without thoughtful management, organic wastes can emit fugitive methane gases as they decompose. Molecules of methane that make their way into the atmosphere create a warming effect thirty-four times stronger than carbon dioxide over a one-hundred-year time horizon. But that need not be the case. One option is to control their decomposition in sealed tanks called anaerobic digesters, which facilitate the natural processes Volta found along Maggiore's marshy shores. They harness the power of microbes to transform scraps and sludge and produce two main products: biogas, an energy source, and solids called digestate, a nutrient-rich fertilizer.

Harnessing organic waste as an energy resource has a long history. Just before the turn of the twentieth century, sewage-gas lamps illuminated the streets of Exeter, England. A full millennium before, biogas warmed Assyrian bathwater. During his years in ancient China, Venetian explorer Marco Polo encountered covered sewage tanks that produced cooking fuel. An asylum for lepers near Mumbai installed a biogas system in 1859, also for lighting. Today, anaerobic digestion is used around the world at backyard, farmyard, and industrial scales, and is on the rise. Thanks to a supportive regulatory environment, Germany leads the way among established economies with nearly eight thousand methane digesters as of 2014—almost 4,000 megawatts of installed capacity in total. Their adoption is increasing in the United States as well, particularly as attention to methane emissions grows. Small-scale digesters dominate in Asia. More than 100 million people in rural China have access to digester gas.

Whatever size or shape digesters take, the dynamics within are the same. As organic wastes are mixed within an airtight, oxygen-less tank, bacteria and other microbes break them down into their component parts, step by step. Over the course of days or weeks, biogas wafts off the top, while solid digestate falls to the bottom, concentrating nutrients such as nitrogen. Biogas is a blend of methane and carbon dioxide that can be used raw or further purified into biomethane, akin to natural gas. The digestion process unfolds continuously, so long as feedstock supplies are sustained and the microorganisms remain happy.

Additional emissions savings result from how a digester's versatile outputs are put to use. Those end uses tend to depend on the scale of production. At the household level, largely in rural and unelectrified areas in Asia and Africa, biogas is utilized for cooking, lighting, and heating, while digestate enriches home gardens and small agricultural plots. Importantly, biogas can reduce demand for wood, charcoal, and dung as fuel sources and therefore their noxious fumes, which impact both planetary and human health. When produced at industrial scales, biogas can displace dirty fossil fuels for heating and electricity generation. When cleaned of contaminants, it also can be used in vehicles that would otherwise rely on natural gas. On the solids side, digestate supplants fossil fuel–based fertilizers while improving soil health. In addition to reducing greenhouse gases, methane digesters reduce landfill volumes and water-polluting effluent, and eradicate odors and pathogens.

Around the same time Volta was combusting gas, the phrase “Waste not, want not” came into fashion. The Latin root of the word waste, *vastus*, means “uncultivated.” The opportunity for digesting organic wastes is, indeed, largely uncultivated. In the face of an ongoing stream of animal and human excrement and organic waste from food production and consumption—and a tandem surge of energy demand—we would do well to take the opportunity to waste not, want not to heart. •

IMPACT: *Our analysis includes both small and large methane digesters. We project that by 2050, small digesters can replace 57.5 million inefficient cookstoves in low-income economies, while large digesters can grow to 69.8 gigawatts of installed capacity. The cumulative result: 10.3 gigatons of carbon dioxide emissions avoided at a cost of $186 billion.*

ENERGY
IN-STREAM HYDRO

RANKING AND RESULTS BY 2050

#48

4 GIGATONS	$202.5 BILLION	$568.4 BILLION
REDUCED CO2	NET COST	NET SAVINGS

Kinetic energy is energy in motion. The world’s waterways brim with it, as gravity draws water across watersheds, through rivulets and creeks, down larger tributaries, and into rivers flowing seaward. For millennia we have harnessed that energy, first to turn waterwheels and power machinery, then, in the nineteenth century, to generate electricity. Today, hydropower conjures images of massive, landscape-shattering dams: the Three Gorges on upper tributaries of the Yangtze River in China, the Hoover on the Colorado River in the United States, and the Itaipu on the Paraná River, between Paraguay and Brazil. To maximize the kinetic energy available for electricity generation, dams use the vertical distance or “head”—water falls from the top of their structures to their base, rushing over turbine blades with high volume and velocity. Hydroelectric dams produce enormous amounts of electricity. But they also swallow up vast swaths of natural and human habitat—the Three Gorges alone displaced 1.2 million people—while impacting water movement and quality, sediment patterns, and fish migration.

These drawbacks have shifted attention from grand dams to smaller, in-stream turbines that are akin to an updated waterwheel. Placed within a free-flowing river or stream, in-stream turbines can capture hydrokinetic energy without creating a reservoir and its repercussions. The underwater analogue to wind turbines activated by the breeze, their blades rotate as water moves past. No barriers, diversions, or storage are required, only limited structural support, and no emissions ensue. In-stream hydro can produce renewable energy that is ecologically sound. The presence of a submerged apparatus with moving parts will always have some impact on the life of a river or stream, and concerns persist about harming fish populations and impeding their migration. Careful design and installation are of utmost importance.

Though water flows can shift season-to-season and year-to-year, hydrokinetic turbines offer a relatively continuous supply of energy. They must be kept free of debris, but upkeep is minimal and initial costs are low. Because in-stream hydro can function in smaller waterways, where currents' powerful, concentrated energy is often untapped, it is a strong candidate for providing electrification in remote areas. From native communities in rural Alaska to rice fields needing irrigation, this technology is being tested and adopted where expensive and dirty diesel generators have been the conventional source of power. Waterways fed by Himalayan snowmelt are hotbeds of in-stream activity, with the potential to propel rural economic development. In urban environments, in-stream turbines target another hydrokinetic resource: city water mains. In Portland, Oregon, 3.5-foot-wide turbines fit perfectly inside underground pipes. As water rushes down from the Cascade Range to the city, it also generates power for the local utility—without harming flow. This subcategory of in-stream technologies is called conduit hydropower.

According to a national assessment of U.S. hydrokinetic resources, the in-stream energy that is technically recoverable is more than 100 terawatt-hours per year. Roughly 95 percent of it is located in the Mississippi, Alaska, Pacific Northwest, Ohio, and Missouri hydrologic regions. The technology needed to seize that opportunity is fairly new and rare, likened by some to the status of wind power fifteen years ago. Small players populate the industry, but their efforts benefit from the similarities between in-stream and tidal energy and the surge of research and investment in the latter. As entrepreneurs and engineers develop in-stream technologies and governments support those efforts, it is important to bear in mind that not all "run-of-river" projects actually let the river run. Some have diverted waterways' currents, impairing their vitality; others have been stacked up so closely that flooding results when waters run high. If potential missteps are managed and in-stream hydro harnesses river power properly, an ancient form of energy could well be important for our future. •

Mini hydroelectric power station with 12 kilowatts of installed power produces around 33,000 kilowatt-hours of electricity per year in Bruton, Somerset, England.

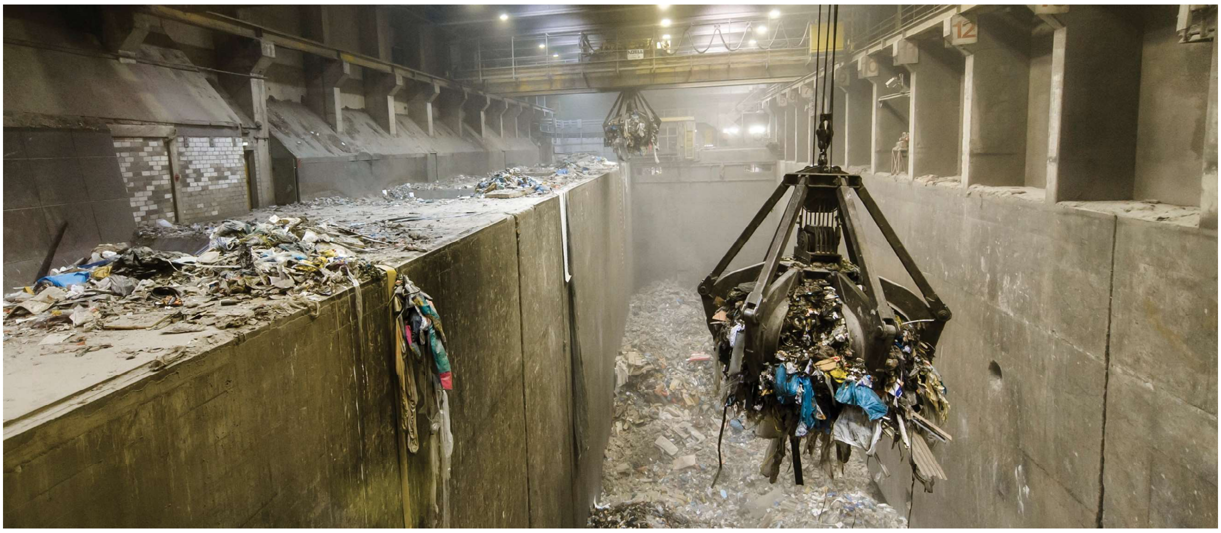
IMPACT: *If in-stream hydro grows to supply 1.7 percent of the world's electricity by 2050, it can reduce 4 gigatons of carbon dioxide emissions and save $1.8 trillion in energy costs. Communities in remote mountainous areas are among the last regions in need of electrification; in-stream hydro offers them a reliable and economical method of generating electricity.*

ENERGY

WASTE-TO-ENERGY

RANKING AND RESULTS BY 2050 #68

1.1 GIGATONS	$36 BILLION	$19.8 BILLION
REDUCED CO2	NET COST	NET SAVINGS



Some call this a solution, while others call it pollution. It is certainly the latter. Waste-to-energy is detailed here as a transitional strategy for a world that wastes too much. In *Drawdown*, there are several solutions that we call *regrets solutions*, and this is one of them. A regrets solution has a positive impact on overall carbon emissions; however, the social and environmental costs are harmful and high.

The waste incineration industry in the United States arose from the collapse of the nuclear industry in the 1970s and 1980s. Companies that benefited from building nuclear plants got into a business called "resource recovery," also nicknamed “trash to cash.” This solution does not eliminate waste: It releases the energy contained in plastic, paper, foodstuffs, and junk, and leaves a residual ash. In other words, it changes the form of the waste. Some of the heavy metals and toxic compounds latent within the trash are emitted into the air, some are scrubbed out, and some remain in the resulting ash. At that time, a hundred tons of municipal waste created thirty tons of fly ash, a granular substance laden with toxins. The ash goes to landfills lined with plastic to ensure that leachates from the ash do not seep into groundwater. How long the plastic liners last is not known. The amount of ash generated today is much lower due to newer techniques.

There are four methods used by industry to convert waste to energy: incineration, gasification, pyrolysis, and plasma. Waste-to-energy also refers to smaller conversion facilities sited at government agencies, companies, or hospitals that use one of these techniques to dispose of medical, manufacturing, or radioactive waste, as well as tires, sewage sludge, laboratory chemicals, or neighborhood garbage.

So why feature waste-to-energy *in Drawdown* at all? In a sustainable world, waste would be composted, recycled, or re-used; it would never be thrown away because it would be designed at the outset to have residual value, and systems would be in place to capture it. Yet cities and land-scarce countries such as Japan face a dilemma: What is to be done with their trash—a veritable Tower of Babel comprising tens of thousands of different materials and chemicals? Landfilling requires extensive tracts of land, which countries like Japan do not have or cannot afford. If landfill sites are available, burying waste creates methane gas from the decomposition of organic matter, a greenhouse gas that is up to thirty-four times more powerful than carbon dioxide over a one-hundred-year period. Waste-to-energy plants create energy that might otherwise be sourced from coal- or gas-fired power plants. Their impact on greenhouse gases is positive when compared to methane-creating landfills.

Today, the United States burns 29 million tons of garbage annually—12 percent of its total generated waste. The nation’s initial foray into incineration was a toxicological disaster. One study conducted in the 1980s of a New Jersey incinerator showed the following results: If 2,250 tons of trash were incinerated daily, the annual emissions would be 5 tons of lead, 17 tons of mercury, 580 pounds of cadmium, 2,248 tons of nitrous oxide, 853 tons of sulfur dioxide, 777 tons of hydrogen chloride, 87 tons of sulfuric acid, 18 tons of fluorides, and 98 tons of particulate matter small enough to lodge permanently in the lungs. The study also showed varying amounts of the persistent toxic pollutant dioxin, depending on the amount of paper and wood involved in incineration. Essentially, inert hazardous waste goes into an incinerator and bioavailable hazardous and toxic emissions come out.

Modern incinerators address these concerns in part. Employing considerably higher temperatures and equipped with scrubbers and filters, almost all traces of pollutants can be captured—but not all. For cities and urban communities, the allure of waste-to-energy plants is compelling. In Europe, more than 450 waste-to-energy plants exist, burning 25 percent of all waste. Sweden leads the field, importing 800,000 tons of garbage from other countries, at considerable cost in carbon emissions, to fuel its district heating plants—the most extensive network in the world. The Swedes assert that they are very careful about the trash they import: It has to be well sorted with all of the recyclables, including food, removed. Landfills are banned, so if it is not recycled, it is burned.

In a modern Swedish waste-to-energy plant the remaining ash is filtered, removing any metal bits, which are also recycled. Tile or ceramic pieces are gathered to use for gravel in road construction. The use of electric filters negatively charges and removes any particulate matter, and the remaining smoke is considered toxin-free and almost entirely consisting of water and carbon dioxide. Because of higher temperatures, there is a significant reduction in total fly ash. The small remainder goes to landfills. The Swedish municipal association believes that for every ton of garbage, imported or domestic, there is an equivalent savings of 1,100 pounds of carbon dioxide if compared to the garbage being landfilled.

As a strategy for managing our trash, waste-to-energy is better than the landfill alternative when state-of-the-art facilities are employed. In Europe, despite the market for trash (the Germans, Danes, Dutch, and Belgians also are in the business of importing garbage), the rate of recycling, including green waste, is going up, and a 50 percent recycling mandate is in place for the year 2050. In the EU, there is a strategy for addressing the whole waste stream as effectively as possible: Where more rubbish could be reduced, reused, recycled, or composted, it should be.

Waste-to-energy continues to evoke strong feelings. Its champions point to the land spared from dumps and to a cleaner-burning source of power. One ton of waste can generate as much electricity as one-third of a ton of coal. But opponents continue to decry pollution, however trace, as well as high capital costs and potential for perverse effects on recycling or composting. Because incineration is often cheaper than those alternatives, it can win out with municipalities when it comes to cost. Data shows high recycling rates tend to go hand in hand with high rates of waste-to-energy use, but some argue recycling could be higher in the absence of burning trash. These are among the reasons that construction of new plants in the United States has been at a near standstill for many years, despite evolution in incineration technology.

There is even greater cause for concern in low-income countries, where waste-to-energy can resemble the early toxic incinerators. Public health is particularly an issue in China and East Asia. That is where waste-to-energy is seeing its most rapid market growth, but also where pollution regulation and enforcement are weak. The Green Climate Fund, established by the United Nations, invests in waste-to-energy plants in low-income countries but requires waste sorting, recycling, and removal of toxics.

While some agencies and investors believe waste-to-energy is a renewable source of energy, it is not. Truly renewable resources, like solar and wind, cannot be depleted. There is nothing renewable about burning plastic athletic shoes, CDs, Styrofoam peanuts, and auto upholstery. Waste is certainly a repeatable resource at this point, but that is only because we generate so very much.

Drawdown includes waste-to-energy as a bridge solution: It can help move us away from fossil fuels in the near-term, but is not part of a clean energy future. Even when incineration facilities are state-of-the-art (and many are not), they are not truly clean and toxin-free. The Scotgen gasification incinerator in Dumfries, Scotland, was supposed to be advanced but proved to be one of the country’s worst polluters and dioxin emitters. The government shut it down in 2013. Although it may be technically possible to eliminate all dioxin releases, the reality is that measurable breaches of dioxin limits occur at waste-to-energy sites throughout the world. Thus, there are many reasons to oppose plants, especially existing facilities that do not meet the highest standard. But there is another reason we list this as a regrets solution. Waste-to-energy can impede emergence of something better: zero-waste practices that eliminate the need for landfills and incinerators altogether. If this sounds starry-eyed or impractical, know that ten large corporations have committed to zero waste to landfill, including Interface, Subaru, Toyota, and Google.

Zero waste is a growing movement that wants to go upstream, not down, in order to change the nature of waste and the ways in which society recaptures its value. It is saying, in essence, that material flows in society can imitate what we see in forests and grasslands where there truly is no waste that is not feedstock for some other form of life. It relies on green chemistry and material innovation that has the end in mind, not just the beginning. Like solar and wind energy, technologies that were once impractical and unaffordable, zero waste is an engineering and design revolution, which will make waste so valuable that the last thing you would want to do is burn or bury it. Rossano Ercolini of Lucca, Italy, is one of the leaders of the Zero Waste International Alliance. The teacher was galvanized to action when a proposed incinerator was to be built near his school. He successfully stopped that one, and didn't pause there. Through his efforts to promote recycling and waste reduction, 117 other Italian municipalities have shut down their waste-to-energy plants and committed to zero waste. That is a true solution, with nothing to regret. •

IMPACT: *The risks of waste-to-energy are significant, but it has some benefits: 1.1 gigatons of carbon dioxide emissions can be avoided by 2050, primarily due to reduced methane emissions from keeping waste out of landfills. Considering the disadvantages, this is a "bridge" solution—one that will decline as preferable waste-management solutions, including zero waste, composting, and recycling, become more widely adopted globally. Island nations, with limited available space, may continue to use waste-to-energy as an alternative to landfilling—employing more advanced technologies, such as plasma gasification, to limit the negative impacts. At a $36 billion cost to implement, savings over thirty years could be $20 billion.*

ENERGY
GRID FLEXIBILITY

RANKING AND RESULTS BY 2050

#77

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

During John Muir’s first summer exploring the Sierra Nevada, he wrote in his journal, “When we try to pick out anything by itself, we find it hitched to everything else in the Universe.” For more than a century, people have used this quote to describe the interconnectedness of ecosystems and the planetary ripple effects of everything from food to transport. It is also useful for describing the phenomenon of the grid: the dynamic web of electricity production, transmission, storage, and consumption that 85 percent of the world relies on. Increasingly, the phrase “global energy transition” gets bandied about, usually to describe a wholesale shift from fossil fuels to clean, renewable sources of energy. While this shift in sources is the crux of the matter when it comes to greenhouse gas emissions, broader change is afoot: a transformation of the entire grid system.

Some sources of renewable power have constancy akin to that of fossil fuel–generated electricity: geothermal steam, rushing water, or combusted biomass, to name three. Producing electricity from the wind and sun, however, is an intermittent endeavor. With everyday rhythms and variations in wind, they vary from minute to minute, day to day, and season to season. The month of November in Germany, for example, has notoriously low wind and sun, so extra production must come from elsewhere. In addition to variability, solar and wind generation is diverse, ranging from centralized and utility-scale to small and distributed, such as solar on rooftops. Integrating geothermal into the grid is a standard procedure, but the current grid was not designed for wind. Utilities and regulators around the world are grappling with the question: In a rapidly shifting landscape, how can the grid best align electricity supply and end-user demand, keeping lights on and costs in check?

The answer is *flexibility*. For electricity supply to become predominantly or entirely renewable, the grid needs to become more adaptable than it is today. The front-runners of renewable energy integration, such as California, Denmark, Germany, and South Australia, are showing that grid flexibility stems from a variety of measures—on both the supply and demand sides, as well as utility operations—and looks different in different places. A number of the solutions profiled in this book support a more pliable grid. Constant renewables, such as methane captured from landfills, are valuable complements to wind and solar photovoltaics. Combined-heat-and-power or cogeneration plants can be accessed quickly, especially if they store excess heat in large water tanks. A variety of utility-scale storage measures will be increasingly important, from the long-standing technology of pumped hydro to newer arrivals such as molten salt and compressed air. At a small scale, batteries are the key, including those within electric vehicles. Demand-response technologies, such as web-connected smart thermostats and appliances, can adjust consumers’ energy draw on the grid in real time to avoid times of peak demand.

Transmission and distribution networks—the connective tissue between generation and consumption—need to be strong to be flexible. Where grid connections span larger geographies, they encompass broader patterns of wind and sunshine: If the air is still in one place, it is likely moving in another. At any given moment, then, the total output of renewables is less variable. In Spain, the grid operator Red Eléctrica de España controls almost all of the country's wind power production. Working in the aggregate, it can control wind generation to specific levels within fifteen minutes. Interconnection with neighboring power systems, as exists in northwestern Europe, creates additional opportunities for production spillover and backup supply.

There are various operational practices that aid flexibility. When weather and electricity generation go hand in hand, as they do with wind and solar power, forecasting and prediction may be a utility's most important tool. In Denmark, predictions are still made a day in advance, but they also are updated in real time. Comparing forecasts to actual wind output throughout the day and night results in predictability being continually refined. Grid operators can adjust how far in advance generation is scheduled and the length of time for each segment of production. When necessary, suppliers can be required to curtail electricity generation, and negative prices may be used to discourage overproduction, however economically undesirable those measures may be.

By 2050, 80 percent renewable generation could be a global reality. In many grids around the world, renewable energy is already reaching 20 to 40 percent share, including variable renewables as well as constant. So far, the balancing act is working well—better, in fact, than many predicted. More and more jurisdictions soon will be pursuing advanced grid flexibility, integrating the mix of measures that works best for a particular context. Renewable sources in tandem with more flexible grids will make the global energy transition possible. While photovoltaic panels and towering turbines may garner most of the attention, flexibility is the means for renewables to become the dominant form of energy on the planet. •

IMPACT: *We do not model grid flexibility because it is a complicated, dynamic system, and it is nearly impossible to account for all local factors at a global scale. However, to grow beyond a 25 percent share of generation, variable renewable energy sources require grid flexibility. The emissions reductions from this solution are counted in the variable renewable solutions that could not reach their full potential without it.*

ENERGY
ENERGY STORAGE (UTILITIES)

RANKING AND RESULTS BY 2050

#77

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

About eleven thousand years ago, when we humans shifted from hunter-gatherer mode to permanent settlements and agriculture, we started learning about storage. We had no choice, really, because those first crops yielded temporary surpluses that had to be protected from mice and humidity. Earthen, wooden, then ceramic granaries were the early answers. Nowadays we excel at storage. If we make it, we contain it . . . with one notable exception. The most fundamental commodity in the industrialized world—electricity —is one for which storage in volume has not been considered. What is the hedge against brownouts, blackouts, and inefficiency? In the absence of large-scale energy storage, utilities rely on highly polluting "peaker" plants that they rev up to meet high demand. As we seek to reduce emissions from electricity production and enable the shift to variable renewable sources of power, storage is doubly vital.

Since utilities first delivered electricity to paying customers in San Francisco in 1879, the business plan has been to generate sufficient power to meet demand in real time. When the grid could not produce, the lights and motors went out. In some countries, that still happens regularly. As economies shift to variable renewables, management of the power grid with energy storage systems is critical. This includes daily, multiday, and longer-term or seasonal storage. When solar and wind power supplied a small fraction of the total electricity in the grid, their variability was not a major problem; traditional fossil fuel–powered plants could adjust for any shortfalls without undue stress. As renewables begin to account for 30 to 40 percent of total power, the variability becomes more complicated for the grid to cope with reliably and economically. In May 2016, Germany set a global record as the country ran on 88 percent renewable power for several hours, much of it from solar PV. The U.S. renewables record may have been set one February evening in Texas in 2015, when forty-odd wind farms accounted for 45 percent of the grid's total power generation. Unless renewable energy can be used or exported, peaks in production create surpluses that have to be thrown away because conventional power plants cannot be turned off. One way to overcome surplus is through high voltage direct current (HVDC) power lines that can extend energy for thousands of miles with small line losses. Additionally, there are a suite of energy-storage technologies that address precisely these issues.

How does a utility store large amounts of electricity? One option is pumping water from lower reservoirs into higher ones, ideally fifteen hundred feet higher. The water is released back down into the lower reservoir as needed and runs through power-generating turbines. Utilities pump the water at night, when electrical power is in surplus, and bring it down again when demand and prices peak. In an example, General Electric has teamed up with a German company to create energy when there is no wind. The project requires a sloping topography with four wind turbines working in concert to generate energy to pump water from a reservoir at a lower elevation to a reservoir at a higher elevation. When wind is lacking or demand is high, the water flowing downhill powers a conventional hydroelectric plant. All told, there are more than two hundred pumped storage systems in the world at present, accounting for 97 percent of global storage capacity. It is an opportunity that works when the topography obliges.

Plus and minus signs indicate the poles on the new energy storage facility at the Fraunhofer Institute in Magdeburg, Germany. During a full-scale test, the entire Fraunhofer research center was supplied with energy from the battery. The lithium-based storage system has an available capacity of 0.5 megawatts per hour and an output of one megawatt. The storage battery is housed in a 26-ton transportable container. This type of equipment is designed to stabilize intermittent and variable energy.

Nevada is experimenting with energy storage by rail. Here, where there is no water, gravity can still be enlisted. The system takes its cues from the myth of Sisyphus, forever pushing his boulder up a hill. When power is abundant, mining railcars freighted with 230 tons of rock and cement are sent up to a rail yard three thousand feet higher. The railcars are equipped with 2-megawatt generators that act as an engine on the way up. On the way down, a regenerative braking system converts rolling resistance to electrical power.

The technology at the core of both solutions is more than a century old. When the railcars are parked at elevation, they can sit there for a year and not lose any power, while reservoirs evaporate. Both systems share a key advantage: how quickly they can respond to demand. The ramp-up time to full power is seconds, whereas fossil fuel plants take minutes or hours. The grid needs storage at speed.

Concentrated solar power plants are also at the forefront of energy storage, where molten salt is used to hold heat until it is needed to generate electricity. A mix of sodium and potassium nitrate, these salts melt at temperatures above 435 degrees Fahrenheit and can absorb heat reflected by concentrated solar mirrors. Molten salt remains hot for five to ten hours, and returns as much as 93 percent of the energy absorbed. Now a common element of concentrated solar plants, molten salt storage allows generators to keep going hours after sunset.

Then, there are batteries at scale. Some utilities are installing banks of lithium-ion batteries to help meet peak demand. By 2021, Los Angeles plans to take its natural gas peaker plant off-line, replacing it with eighteen thousand batteries that will be charged by wind power at night and solar in the morning, while energy needs are low. And dozens of start-ups and established companies are racing to create low-cost, low-toxicity, and safe (no spontaneous ignition) batteries that will revolutionize energy storage from flashlights to utilities—batteries of the future.

IMPACT: *Taken on its own, the production of energy storage does not reduce emissions; instead, energy storage enables adoption of wind and solar energy.*

No carbon impact numbers are included above in order to prevent double counting with the variable renewable energy solutions themselves. As with other forms of grid flexibility, the costs and total growth are not modeled directly.

ENERGY

ENERGY STORAGE (DISTRIBUTED)

RANKING AND RESULTS BY 2050

#77

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

There is an energy transition under way, one as radical as the adoption of coal, oil, and gas at the beginning of the Industrial Revolution. Most would describe the transformation as the shift away from carbon-based fuels to renewable energy, and they would be right—in part. Another part of the breakthrough will be distributed energy storage—the ability to retain small or large amounts of energy produced where you live or work. If global warming is "the transformation that transforms everything," as sociology and human geography professor Karen O'Brien has observed, distributed energy storage may be the transformation that transforms the energy industry.

Where does your electricity come from? When energy is centrally generated and distributed from large power-generating plants—gas, coal, nuclear, hydro—it feeds into high-voltage transmission lines that crisscross the country into step-down transformers that flow into regional power grids and, finally, your home or place of work. Distributed energy systems turn this sequence on its head. No longer passive consumers, customers can become producers and buy or sell power to the grid when they choose. They can avoid peak demand charges and enable a more resilient grid, preventing demand spikes that can cause brownouts or grid failure.

The wind and sun have their own timetables, making renewable energy variable. That poses a critical challenge for utilities that need to closely monitor supply and demand. The capacity to turn on backup power-generating plants at a moment's notice—lest the grid go down—is critical. Creating a distributed energy storage system, or grid independence, requires affordable storage, and until now, prices for batteries have been prohibitively expensive. That is changing. There are two basic sources of storage: stand-alone batteries and electric vehicles. Storage costs are measured in kilowatt-hours. From $1,200 per kilowatt-hour in 2009, the cost has dropped to roughly $200 in 2016. Companies are now predicting $50 per kilowatt-hour in a few years. For $1,200 per kilowatt-hour, you can purchase a 24-kilowatt-hour energy storage system and get a car thrown in for free—the all-electric Nissan LEAF.

A Tesla Powerwall being installed and celebrated at the Rongomai School in Auckland, New Zealand. The primary school specializes in curriculum designed around Maori cultural values. The battery allows the school to be powered after hours and into the evening from its solar array.

Whether in a car, garage, or the basement of an office building, distributed energy storage is coming faster than expected. Just as every prediction of cost and growth in solar was underestimated for the past two decades, the predictions around battery prices keep missing the mark. In 2012, the global consultancy McKinsey & Company predicted $200-per-kilowatt-hour batteries by 2020, but both General Motors and Tesla achieved that in 2016.

At current cost, a $500 billion investment in distributed energy systems would save U.S. businesses and households $4 trillion in peak-demand utility billing over the next thirty years. Battery cost could halve in the next four years, further amplifying those gains. If storage is used to enable more reliance on renewables there will be substantial climate benefits. If storage is just used to shift peak demand to nights in systems that rely heavily on coal, there will be little benefit.

Not so long ago, solar photovoltaics had high carbon costs. So much coal-fired energy was required for the glass, aluminum, gases, installation, and 3,600-degree Fahrenheit sintering ovens, it would have been fair to call solar panels coal extenders. Today, the energy costs of making solar have dropped significantly. Batteries seem to be following suit; plummeting costs will likely be accompanied by less energy-intensive manufacturing methods. As that occurs, an entirely new energy grid will come online—one that promises to be more resilient and democratic—powered by sensors, apps, and software yet to be invented.

IMPACT: *Distributed energy storage is an essential supporting technology for many solutions. Microgrids, net zero buildings, grid flexibility, and rooftop solar all depend on or are amplified by the use of dispersed storage systems, which facilitate uptake of renewable energy and avert the expansion of coal, oil, and gas electricity generation. Adoption of distributed storage varies depending on whether it is used in an urban or rural setting; those dynamics are not explicitly modeled.*

ENERGY

SOLAR WATER

RANKING AND RESULTS BY 2050

#41

6.08 GIGATONS	$3 BILLION	$773.7 BILLION
REDUCED CO2	NET COST	NET SAVINGS

A solar water array in Esbjerg, Denmark, used for house and district heating, employs buffer tanks for thermal storage. Esbjerg, a port city on the Jutland Peninsula, runs almost entirely on renewable energy and is at the center of Denmark's offshore wind and wave energy industries.

For as long as people have bathed, they have sought ways to heat bathwater. During the nineteenth century, the most rudimentary solar-heating technology exposed dark-colored metal tanks to the sun. It worked but wasn't robust. In 1891, American inventor and manufacturer Clarence Kemp patented a design that improved performance dramatically by using the greenhouse effect. The Climax—the world's first commercial solar water heater—placed iron water tanks inside an insulated, glass-covered box, thereby increasing the tanks' ability to collect and retain solar heat. "Using one of nature's generous forces," Kemp's advertisements proclaimed, the Climax could provide "hot water at all hours of the day and night. No delay. Always charged. Always ready." A residential model cost $25.

At the turn of the twentieth century, solar water heating (SWH) spread across Southern California, as other entrepreneurs worked to improve on Kemp's invention. William Bailey's Day and Night model added a separate storage tank to the rooftop solar heat collector, and revolutionized the industry. As Miami boomed in the 1920s, so did solar collectors—some still operating atop art deco buildings today. During the 1930s, they became standard on public housing in the American South. Cheap energy in the post–World War II years stymied the industry in the United States, but the concept took off in Israel, Japan, and parts of South Africa and Australia. Throughout its history, SWH has risen and fallen based on the price of energy, as well as government intervention to support it.

Today, China is home to more than 70 percent of the world's SWH capacity, but the technology is in use in many countries and almost every climate, without freezing in winter or overheating in summer. In Cyprus and Israel, where the use of SWH has been mandated since the 1980s, 90 percent of homes have systems. Residential continues to be the primary application for sun-warmed water, though large-scale installations are on the rise. Some systems use tubes, while others employ flat plates; some rely on pumps, while others are passive. As Bailey found, good storage tanks are fundamental. All told, SWH is considered to be "one of the most effective technologies to convert solar energy into thermal energy," with payback periods as short as two to four years, depending on specifics of system, location, and alternatives.

What is also true today is that water heating is a major energy use. Hot water for showers, laundry, and washing dishes consumes a quarter of residential energy use worldwide; in commercial buildings, that number is roughly 12 percent. SWH can reduce that fuel consumption by 50 to 70 percent. But it has yet to be widely tapped as a resource because of up-front costs and complexity of installation, which are higher than gas and electric boilers. Increasingly, SWH gets considered alongside solar photovoltaics, when it comes to roof space, investment, and potential synergies or trade-offs between the two. To achieve uptake at the level Cyprus and Israel have accomplished, governments can require or incent use in new construction—and more and more they are. If the United States maximized its potential for SWH, the country could reduce natural gas consumption by 2.5 percent and electricity use by 1 percent, and avoid producing 57 million tons of carbon each year—as much as 13 coal-fired power plants or 9.9 million cars. With national ambitions for growth in Malawi, Morocco, Mozambique, Jordan, Italy, Thailand, and beyond, clearly SWH has not come close to reaching its zenith, even 125 years after the original Climax was first devised.

IMPACT: *If solar water heating grows from 5.5 percent of the addressable market to 25 percent, the technology can deliver emissions reductions of 6.1 gigatons of carbon dioxide and save households $774 billion in energy costs by 2050. In our calculations of up-front costs, we assume solar water heaters supplement and do not replace electric and gas boilers.*