We Have the Power

Realizing clean, renewable energy's potential to power America

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Written by:

Gideon Weissman, Frontier Group

Emma Searson, Environment America Research & Policy Center

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Table of contents

Executive summary

It is time for America to move beyond fossil fuels. Coal, oil and gas are responsible for a rapidly warming planet, for hundreds of thousands of deaths in the U.S. each year from air pollution, and for untold environmental damage. A shift to emission-free energy from the wind, sun and other renewable sources can solve many of America's most pressing environmental and public health challenges.

America has the power to build an energy system in which our energy comes from clean, renewable sources like the wind and sun. There are many potential paths America can take to build on our abundant clean energy potential and help America rapidly achieve a renewable energy system.

Policymakers at the local, state and federal level should make concrete commitments to move toward 100% clean and renewable energy by 2050 at the latest. By doing so, they will be building on the example set by seven states and more than 170 cities around the United States that have committed to clean electricity or clean energy.[1]

Renewable energy has tremendous promise as a tool to fight climate change, clean our air, and safeguard our environment.

- Pollution from burning fossil fuels is estimated to be responsible for more than one in 10 deaths in the United States each year – more than 350,000 total deaths in 2018.[2]
- Oil, coal and gas are responsible for 80%of all U.S. greenhouse gas emissions. Fossil fuels harm the climate when we burn them for energy and as a result of methane leaks that occur during mining, distribution and other parts of the fossil fuel life cycle.[3]
- Research shows that, even considering the life-cycle impacts of manufacturing and installing solar panels and wind turbines, a rapid transition to emission-free renewable energy would create a vastly cleaner, healthier, and more sustainable nation.[4]

America has abundant renewable energy resources capable of powering the nation. Data from the National Renewable Energy Laboratory (NREL) shows that America has access to enough sun and wind to power the nation many times over.

- America's solar energy resources – counting just utility-scale and rooftop PV – have the technical potential to produce 284 million GWh of electricity each year, equivalent to 78 times U.S. electricity use in 2020.[5] And America's wind power resources, both onshore and offshore, have the technical potential to produce 40 million GWh of electricity each year, equivalent to 11 times U.S. electricity use in 2020.[6]
- Every single state has either the wind or solar technical potential to power that state's current electricity use at least once over.[7] Eighteen states have the solar resources to power current electricity needs 100 times over, and five states have the wind resources to do so.
- Every single state other than Connecticut has either enough wind or solar technical potential to provide

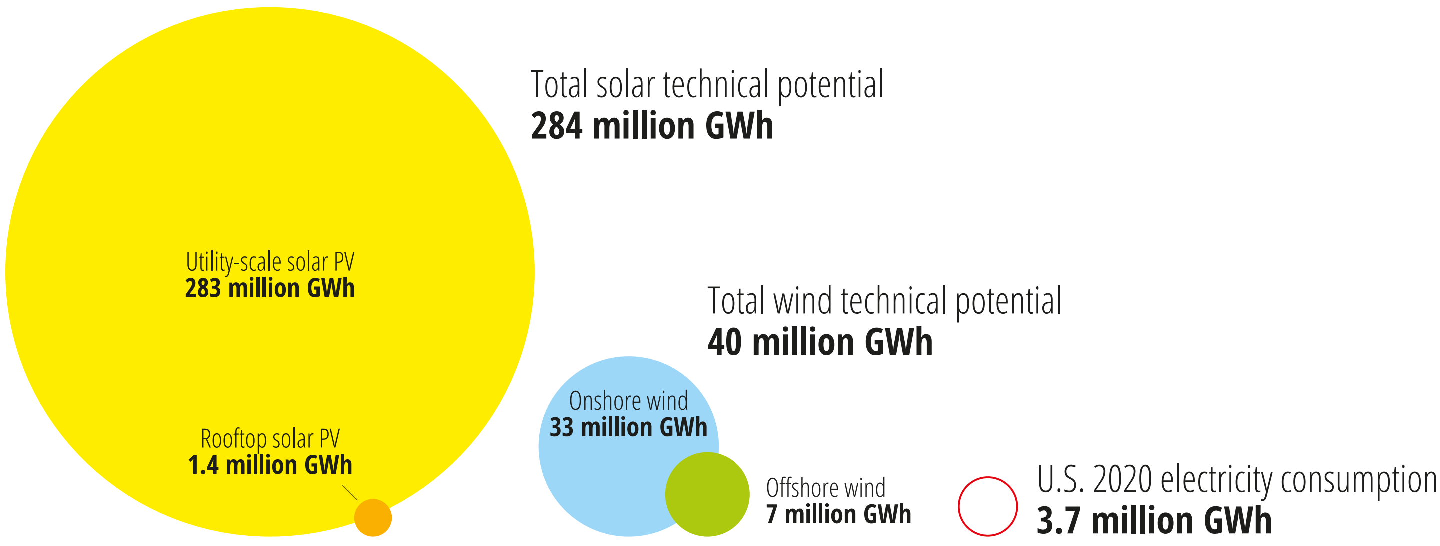

Figure ES-1. America's enormous wind and solar energy resources

all of its electricity needs under a 2050 scenario in which transportation, buildings and other applications have largely been made to run on electricity.[8]

Renewable energy can power our society 24/7/365. Research from academic and government sources has described many viable pathways by which America can meet our energy needs 24 hours a day, 365 days a year while relying mostly or entirely on renewable energy.[9] While researchers have disagreements on the best or most economical way to build a renewable energy system, there is broad agreement that an energy system largely powered by renewable sources is feasible.

- A 2019 article from the journal *Energy* reviewed 181 studies from around the world assessing the concept of 100% renewable electricity or total energy systems.[10] The article concluded that "[t]he majority of the reviewed studies find that 100% [renewable energy] is possible from a technical perspective, while only few publications argue against this."[11]
- Researchers have largely concluded that the technology we need for a renewable future is already available. As one study from *Nature Communications* put it, "currently available generation and storage technologies are sufficient for nearly 100% power system operation."[12] And from another study from *Renewable and Sustainable Energy Reviews*: "The technologies required for renewable scenarios are not just tried-and-tested, but also proven at a large scale."[13]
- NREL has used sophisticated modeling to simulate electric grids running on high levels of renewable energy. In its most recent study, focused on Los Angeles, NREL concluded that "[r]eliable, 100% renewable electricity is achievable — and, if coupled with electrification of other sectors, provides significant greenhouse gas, air quality, and public health benefits."[14]
- Researchers have identified key strategies that can help the U.S. achieve a largely renewable energy system in the shortest time and at the lowest cost. Such strategies include investing in transmission infrastructure to send solar or wind energy across the country to where it is needed, and building sufficient wind and solar power capacity to reduce the amount of storage needed for periods of lower power output.

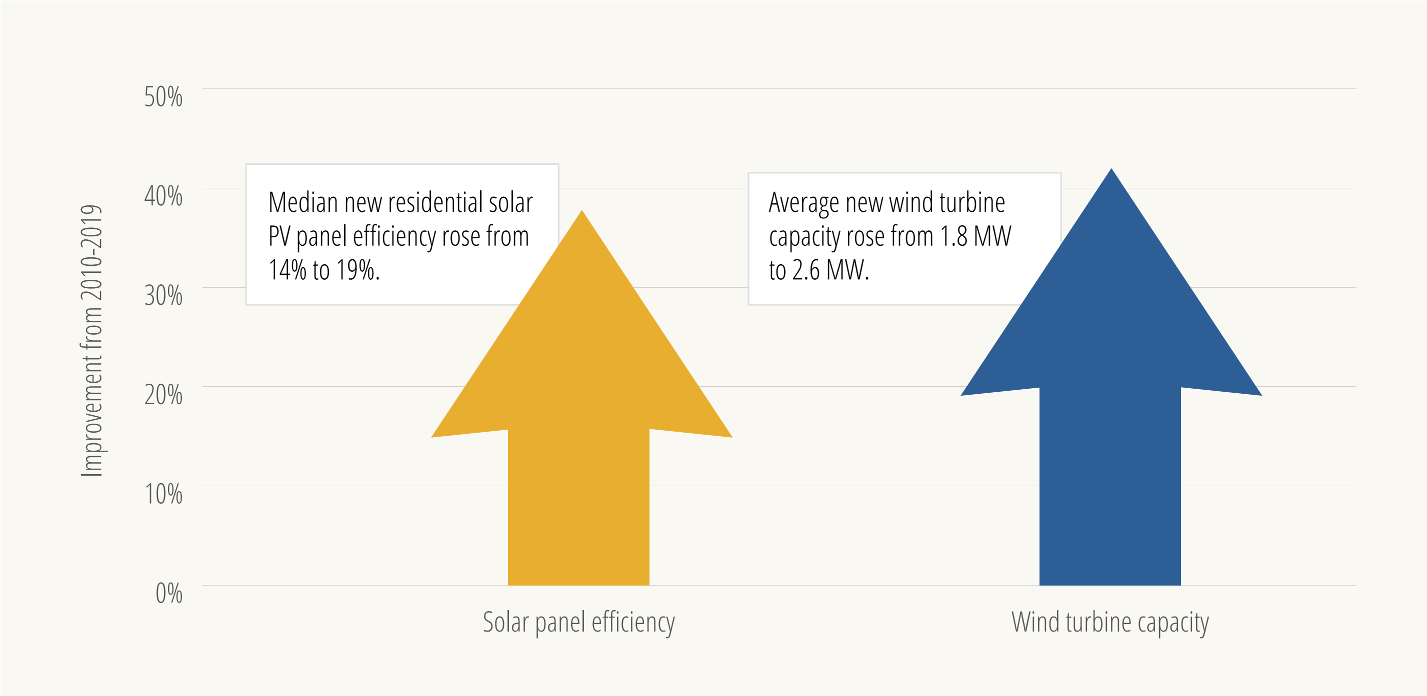

Figure ES-2. Solar panels and wind turbines are getting more efficient and powerful[39]

The keys to a 100% renewable future are within reach. The nation has ample potential to move forward rapidly in four key areas essential to a renewable energy future: building out renewable energy; modernizing the grid; reducing and managing energy use; and repowering our economy to take full advantage of clean energy.

1. Rapidly deploy clean energy. Over the last 20 years, the amount of electricity produced by wind and solar power in the U.S. grew more than 60-fold, accounting for 12% of all the electricity produced in America in 2020.[15] Technology and price trends point the way toward far faster progress in the years to come.

- Today's wind turbines and solar panels produce **more energy, in less space, for less cost, and with more flexibility** than ever before. The cost of wind power fell by 71% and utility-scale solar by 90% from 2009 to 2020.[16] In 2019, the median new residential solar panel was 37% more efficient than one installed in 2010.[17] And in 2019, the average installed wind turbine had 42% greater power capacity than one installed in 2010.[18]
- New renewable energy technologies that could one day help provide more stable and diverse options for providing renewable energy are on the way. **Floating offshore wind** turbines, which are dropping in price and have been successfully deployed in pilot projects, can be located in deep waters and provide access to wind resources off the West Coast of the U.S.[19] And advances in **enhanced geothermal** technology may soon allow more regions of the U.S. to tap into the nation's enormous potential for generating electricity using underground heat.[20]

2. Modernize the grid. The U.S. has laid the groundwork for providing reliable renewable power when we need it with a modern grid capable of storing energy, delivering energy across long distances, and reacting to changes in weather conditions.

- **Battery storage capacity** has skyrocketed as the cost per watt-hour of utility-scale battery storage has fallen dramatically, down 70% from 2015 to 2018.[21] Batteries are now often deployed alongside new wind and solar farms both for their ability to store energy for when energy output is low and to assist grid function by helping regulate grid frequency and respond to grid disturbances.[22] Long-term or seasonal energy storage solutions, like renewably-produced hydrogen, are being developed that could one day help the grid achieve renewable energy penetrations approaching 100%.[23]

- Expanding **transmission connections** allows for more efficient and flexible use of renewable resources, such as in Texas where new transmission lines helped unlock enormous wind resources in rural parts of the state.[24] Improving technology and falling costs for high-voltage direct current lines could soon allow the creation of important new transmission connections, including between the eastern and western U.S. grid systems.[25]

- New technologies and tools are ready to help build a smarter, more modern grid. **Smart inverters**, along with strategies like extracting stored kinetic energy from wind turbines, are already allowing clean energy technologies to respond to changes in grid conditions.[26] And sophisticated computing tools are making possible **advanced forecasting** that can provide grid operators with precise and granular information about renewable generation.[27]

3. Reduce and manage energy demand. The U.S. has enormous potential to cut energy use and make energy demand more flexible, which would reduce the amount of new infrastructure needed for a shift to renewable energy.

- Energy efficiency can cut U.S. energy use in half by 2050, according to research from the American Council for an Energy-Efficient Economy.[28] The U.S. can achieve **large energy reductions** through advanced new strategies like geotargeted efficiency programs and energy management and information systems, as well as expanding access to older tried-and-true methods.[29] For example, more than nine in 10 homes in the United States had not had an energy audit as of 2015.[30]

- **Demand response programs** can reduce peak energy demand and enable the grid to respond to changes in renewable energy supply. Research from 2019 found that by 2030 demand response could provide 200 GW of "economically feasible load potential," equivalent to 20% of peak load levels.[31]

- In 2018, utilities reported a total enrolled demand response capacity of 20.8 GW, equivalent to the power capacity of about 10,000 wind turbines.[32] Now, new technologies like **smart thermostats** and advanced metering infrastructure are enabling advanced demand response programs that can help create a more flexible and responsive electric grid.[33]

4. Repower everything with renewables. Technology is available to repower most direct uses of petroleum or gas with electricity, and to tap the nation's enormous potential for renewable heat and light.

- Electric vehicles (EVs) and buildings are far more efficient than fossil fuel technologies. A fully electrified and renewable energy system could **cut primary energy consumption by at least half**.[34]

- Proven technologies are readily available for **electrifying light-duty vehicles, residential buildings and commercial buildings**, which account for 45% of fossil fuel end-use combustion in the U.S.[35] EV technology in particular has dramatically improved in the last decade: The cost per watt-hour for EV batteries fell by 89% from 2010 to 2020, while the median driving range of EVs quadrupled.[36]

- New technologies could soon allow us to power more activities with clean energy. Advanced battery technology is becoming available for powering **medium- and heavy-duty freight**, and a recent Deloitte study found that, among surveyed **manufacturers**, companies aimed to electrify nearly 45% of their processes by 2035.[37]

- The U.S. can also tap into large amounts of renewable energy in the form of **heat.** The U.S. Department of Energy estimates that the U.S. has the economic potential for more than 17,500 geothermal district heating installations nationwide, with much of the potential located near major population centers including in the Northeast.[38]

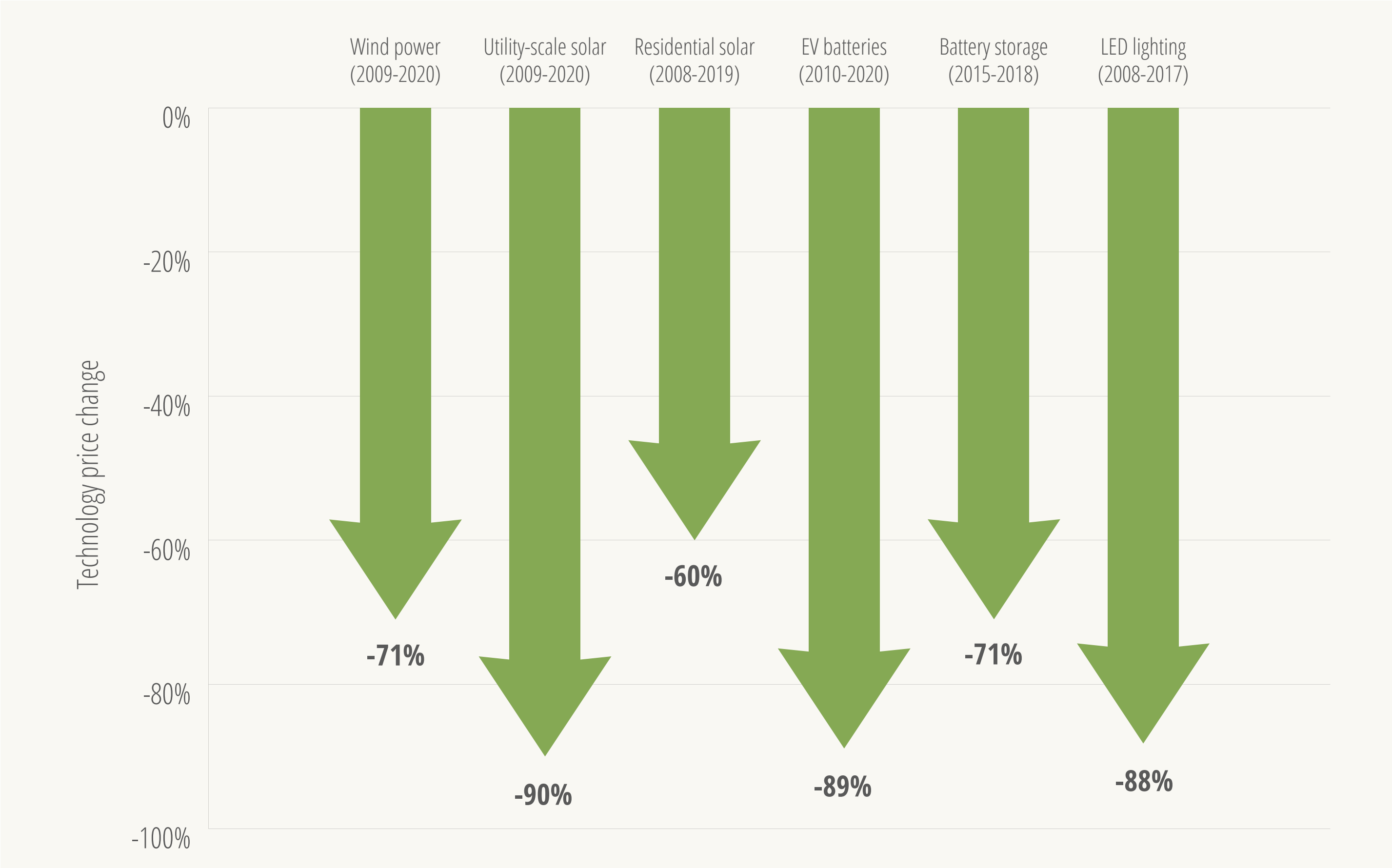

Figure ES-3. The rapid fall of clean energy prices[40]

The stage is set for a rapid transition to renewable energy. But time is of the essence. Policymakers must do all they can to accelerate a shift away from fossil fuels to an energy system in which the vast majority of our energy comes from renewable sources like the wind and sun. Policymakers at every level of government should set ambitious goals to transition both electricity and other energy uses to clean, renewable sources. And they should ensure those goals are achieved through policies that provide clean energy with the financial and regulatory support that it needs.

Quotes from recent research into high renewable energy systems

"This research highlights the technical feasibility and economic viability of 100% renewable energy systems including the power, heat, transport and desalination sectors."

– Dmitrii Bogdanov et al.[i]

"The majority of the reviewed studies find that 100% [renewable energy] is possible from a technical perspective, while only few publications argue against this."

– Kenneth Hansen et al.[ii]

"The technologies required for renewable scenarios are not just tried-and-tested, but also proven at a large scale."

– T.W. Brown et al.[iii]

"Reliable, 100% renewable electricity is achievable — and, if coupled with electrification of other sectors, provides significant greenhouse gas, air quality, and public health benefits."

– National Renewable Energy Laboratory (Los Angeles-focused study)[iv]

"The results clearly show that a 100% RE-based system is feasible and a real policy option at a modest cost."

– Arman Aghahosseini et al.[v]

"Achieving high reliability with solar and wind generation contributing >80% of total annual electricity demand will require a strategic combination of energy storage, long-distance transmission, overbuilding of capacity, flexible generation, and demand management."

– Matthew Shaner et al.[vi]

"We find that the cost of energy in a 100% WWS [wind, water and solar energy system] will be similar to the cost today. We conclude that barriers to a 100% conversion to WWS power worldwide are primarily social and political, not technological or even economic."

– Mark Delucchi and Mark Jacobson[vii]

"A rapid shift towards a new era of smart, renewable and sector-coupled energy supply, combined with clever demand-side measures and adaptations to the impacts of climate change, will allow us and our children to address the legacy of our past reliance on fossil fuels."

– Sven Teske et al.[viii]

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i Dmitrii Bogdanov et al., "Low-cost renewable electricity as the key driver of the global energy transition towards sustainability," Energy, Volume 227, doi: 10.1016/j.energy.2021.120467, 15 July 2021.

ii Kenneth Hansen et al., "Status and perspectives on 100% renewable energy systems," Energy, 175:471-480, doi: 10.1016/j.energy.2019.03.092, 15 May 2019.

iii T.W. Brown et al., "Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'," Renewable and Sustainable Energy Reviews, 92:834-847, doi: 10.1016/j.rser.2018.04.113, September 2018.

iv National Renewable Energy Laboratory, LA100: The Los Angeles 100% Renewable Energy Study – Executive Summary, March 2021, available at https://maps.nrel.gov/la100/report.

v Arman Aghahosseini, "A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions," Energies, 10(8):1171, doi: 10.3390/en10081171, 2017.

vi Matthew Shaner et al., "Geophysical constraints on the reliability of solar and wind power in the United States," Energy and Environmental Science, 11:914, doi: 10.1039/c8ee90019a, April 2018.

vii Mark Delucchi and Mark Jacobson, "Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies," Energy Policy, 39(3):1170-1190, doi: 10.1016/j.enpol.2010.11.045, March 2011.

viii Sven Teske et al., Achieving the Paris Climate Agreement Goals – Executive Summary, (Springer, Cham), 2 February 2019, p xxxv.

Introduction

On December 18, 2020, the three nearly 800-foot smokestacks of the Navajo Generating Station – one of the nation's largest coal-fired power plants – were demolished, about a year after the plant stopped producing power.[41]

The plant was located in the Navajo Nation in Arizona, just about 10 miles from the Utah state line, and during its 40-plus years of operation it was a constant source of dirty, dangerous pollution. Until it slowed operations in the 2010s, each year the plant released upwards of 15 million tons of carbon dioxide, along with 30,000 tons of sulfur dioxide and nitrogen oxides that cause smog and harm human health.[42] Members of Navajo Nation long pointed to the plant's operation as the culprit of a variety of health problems suffered by the community.[43] The plant's pollution even obscured views of the Grand Canyon.[44]

But the power plant was also a major power source for the bright lights of Las Vegas, and also provided electricity to places like Phoenix, Tucson, and Los Angeles.[45] In large part, these cities are now keeping the lights on by turning to clean, renewable power from the sun.

In Arizona, Nevada and California, solar power produced 17% of electricity in 2020, with a third of that power generated at small-scale installations on rooftops, businesses and other locations.[46]

The emergence of renewable energy as a viable replacement for fossil fuels is not limited to the Southwest. Since 2010, while more than 500 coal power units shut down around the country, generation from wind and solar grew five-fold.[47]

Today, renewable energy is now often not just the cleanest but also the cheapest source of energy available. It is now increasingly possible to envision a world not only without coal-fired power plants, but without oil and gas as well. As this report shows, technologies and strategies for harnessing, using and storing renewable energy are proven and ready for widespread adoption. Meanwhile, sophisticated research is showing that such tools are more than capable of powering society 24 hours a day, 365 days a year.

Arizona is demonstrating the early stages of what such a transition might look like. For example, the state has expanded efforts to store solar energy so that it can be used even when the sun is not shining, including by approving its first home energy storage incentive program in October 2020.[48] The state's energy efficiency standard has provided power savings equivalent to the energy use of 500,000 homes, reducing the amount of renewable energy infrastructure that it will take to power the state.[49] And many of the biggest Arizona, Nevada and California utilities are now part of a regional power market that is enabling renewable energy to be sent across more of the western U.S., providing geographic flexibility that will help support a highly renewable grid of the future.[50]

The replacement of dirty and dangerous sources of power like the Navajo Generating Station with clean, efficient energy technologies provides a glimpse of what a future of renewable energy could have in store.

Cleaner skies. Healthier communities. Less global warming. It's a future that is within reach, and one worth building.

The promise of renewable energy

In 2019, the United States burned 587 million tons of coal, 31 trillion cubic feet of gas, and 7.5 billion barrels of petroleum products.[51] These fuels lit our homes, powered our cars and trains, provided us with heat and refrigeration, and in general made much of modern life possible.

The world would be unrecognizable without the energy that we get from fossil fuels. At the same time, these fuels are driving many of the most severe crises facing the United States and the world, including global warming.

Renewable energy can be the key to a better future, one in which we have access to the energy we need to power our lives, while protecting our health and preserving a livable climate for future generations.

Protecting our health, safety and environment

Coal, oil and natural gas are driving many of the most serious threats to our health, safety and environment.

Burning fossil fuels is a major source of air pollution including fine particulate matter, ground-level ozone and sulfur dioxide.[52] Pollution from burning fossil fuels is estimated to be responsible for more than one in 10 deaths in the United States each year and more than 350,000 total deaths in 2018.[53] In many midwestern states pollution from burning fossil fuels is responsible for nearly one in five deaths each year.[54]

The damage wrought by fossil fuels goes far beyond the impacts of combustion and includes grave harm to public health and the environment caused by fossil fuel extraction, processing, and distribution. For example:

- Fracking can poison groundwater and creates air pollution from gas leaks.[55] Living in close proximity to gas fracking operations is associated with health problems during pregnancy, negative birth outcomes, and a variety of other public health issues.
- Mining coal – whether through mountaintop removal, strip mining, or open-pit mining – does irreversible damage to the environment and puts workers' health and safety at risk.[56]
- Transporting fossil fuels frequently results in spills, leaks and explosions. Since 2000, there have been hundreds of pipeline crude oil spills, many of which have done long-term damage to vulnerable waterways and ecosystems and the communities that depend on them.[57] Gas pipeline explosions and other incidents have caused dozens of deaths and hundreds of injuries since 2010.[58]
- Fossil fuel power plants consume enormous quantities of water for cooling. Coal plants also create millions of tons of coal ash waste that can damage waterways via both slow leaks over time, and sudden catastrophic spills.[59]
- Gas used in homes for cooking creates dangerous levels of indoor air pollution including carbon monoxide and nitrogen dioxide.[60]

The environmental and health impacts of renewable energy pale in comparison to those of fossil fuels, and America's increasing adoption of clean energy is already saving lives. Pollution reductions resulting from wind and solar power led to between 3,000 and 12,700 fewer premature deaths in the U.S. from 2007 to 2015.[61]

A wholesale shift to a cleaner energy system would bring "significant co-benefits" for human health and the environment, according to the Intergovernmental Panel on Climate Change (IPCC).[62] A 2019 study found that the combined climate and health benefits of a large-scale deployment of renewable energy in the United States, including the health benefits from reductions in pollutants like sulfur dioxide and fine particulate matter, could have a societal value worth trillions of dollars.[63] A large-scale shift to renewable energy would also lead to dramatic reductions in water use.[64] And while a renewable energy system would not be free of environmental impacts – such as those caused by mining raw materials, or using land for wind and solar farms – they can be mediated through recycling, efficiency and other measures.[65]

A critical tool against global warming

Global warming has already begun to wreak havoc on the United States and the planet. 2020 tied with 2016 as the warmest year on record, and over the course of the year the United States saw climate impacts including extreme drought, hurricanes, wildfires and flooding.[66]

Fossil fuels are the primary driver of global warming and are responsible for more than 80% of U.S. greenhouse gas emissions.[67] Fossil fuel-related greenhouse gas emissions are mostly from fuel combustion – such as in power plants, vehicles and industry – but also result from the gas leaks that occur during fossil fuel extraction and transportation.[68] These include methane leaks from coal mines and gas wells, and leaks from gas pipelines.[69]

The IPCC has found that if humanity can cut fossil fuel use by nearly half by 2030, and eliminate the use of fossil fuels except with carbon sequestration by 2050, we can avoid many of the worst impacts of global warming.[70] Reaching net zero emissions by 2050 would likely allow the world to remain within a carbon budget of 580 gigatons of CO_2, which is associated with an "even chance" of limiting global warming to 1.5° Celsius above pre-industrial levels.[71] Keeping temperature change under 1.5° Celsius would likely result in less sea level rise, less ecosystem loss, and less impact to our "health, livelihoods, food security, water supply, human security, and economic growth" according to the IPCC.[72]

Renewable energy sources like wind and solar power, which produce no emissions, can help replace fossil fuels and achieve the emission reductions necessary to prevent the worst impacts of global warming. Wind and solar generation offset around 330 million metric tons of greenhouse gas emissions in the U.S. just in 2020.[73]

Even considering the life-cycle impacts of renewable generation – such as emissions from manufacturing and transporting wind turbines and solar panels – renewable energy is still far cleaner than fossil fuel power plants. A 2014 National Renewable Energy Laboratory study assessed the implications of an 80% renewable electricity grid and found that it would result in greenhouse gas emission reductions of approximately 80% "on both a direct combustion basis and on a full life cycle basis."[74]

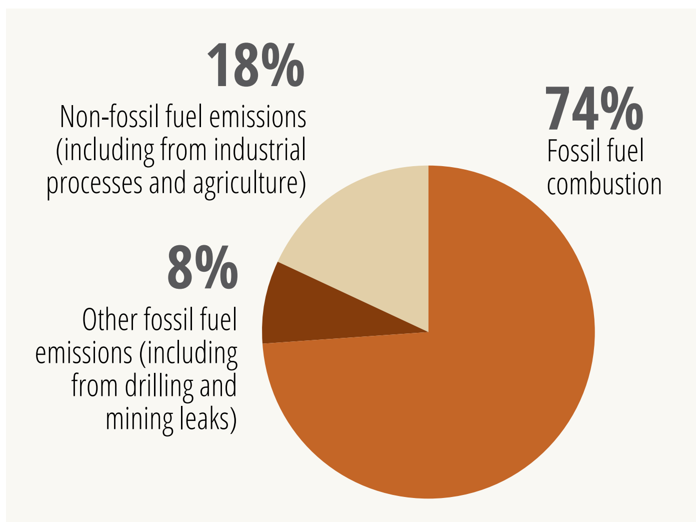


Figure 1. Fossil fuels were responsible for more than 80% of U.S. GHG emissions in 2019[75]

What is clean, renewable energy?

Every form of energy has an impact on our environment. But the impact of some forms of energy is much greater than others.

Truly clean, renewable energy is:

- **Virtually pollution-free** – It produces little to no global warming pollution or health-threatening pollution.
- **Inexhaustible** – It comes from natural sources that are regenerative or practically unlimited. No matter how much we use, there will always be more.
- **Safe** – It has minimal impacts on the environment, community safety and public health, and those impacts that do occur are temporary, not permanent.
- **Efficient** – It is a wise use of resources.

Some forms of renewable energy meet this definition of truly clean, provided that they are sited in appropriate locations with minimal impacts on ecosystems and wildlife. Solar and wind energy fit into this category, as do many types of ocean, tidal, river current and geothermal energy. By reducing the need for energy production, energy efficiency technologies can almost always be counted as truly clean energy, for their ability to deliver continuous environmental benefit at limited to no environmental cost.

Other forms of renewable energy carry more significant environmental trade-offs. Hydroelectric and biomass energy are two forms of renewable energy that often fail to meet the standard of truly clean energy. Conventional hydropower produces significant greenhouse gas emissions in the first few years after a dam is closed and the reservoir is created.[76] Biomass energy is often touted as a low-carbon alternative – despite the carbon dioxide emissions produced when it is burned – because the organic material once absorbed carbon dioxide from the atmosphere at the time it was grown. Biomass energy production can, however, cause air pollution and ecosystem damage, and its life-cycle carbon impacts are complex and not fully understood.[77] Both hydroelectric and biomass power can play a role in the transition to a 100% renewable energy system, but their impacts must be considered.

In addition to renewable energy sources, some non-renewable sources – such as nuclear energy – are sometimes considered "clean" on the basis of their low emissions of greenhouse gases when they generate electricity. However, nuclear power plants produce hazardous radioactive waste for which no safe, long-term storage solution has been found, and the process of mining uranium has severe environmental impacts. The risk of accidents at nuclear power plants – such as the Fukushima disaster in Japan in 2011 – must also be considered.

A rapid transition to clean, renewable energy is possible

Our reliance on fossil fuels is damaging the climate, polluting our air, destroying the natural world, and harming our health. For generations, escaping these impacts looked impossible. But there is already a better option: clean energy from renewable sources like the sun and the wind.

In recent years, researchers have documented the vast renewable energy resources available to the United States and have modeled how a transition to renewable energy might take place. And with recent advances in technology and growing experience with integrating clean energy into our lives, a future of renewable energy looks more possible than ever.

America's renewable energy resources are virtually unlimited

America has nearly limitless access to energy from the wind, the sun, the land and the oceans. Just a tiny fraction of these resources could power our entire society.

The National Renewable Energy Laboratory (NREL) has used advanced modeling to provide estimates of America's wind and solar energy resources. One way to understand the nation's total potential for producing energy using renewable resources is as "technical potential," which is the potential for generating electricity based on available technology, land-use and topographic constraints, and the size of the renewable energy resource.

It would not be wise or necessary to use anything close to America's full renewable technical potential. But the enormous amount of available and capturable energy is illustrative of the vastness of our renewable resources and their ability to power the nation.

America's wind and solar resources have the technical potential to power not just our current electricity use, but also the transportation, building and industrial energy consumption currently supplied by direct burning of fossil fuels.

- America's solar energy resources – utility-scale PV and rooftop PV – have the technical potential to produce 284 million GWh of electricity each year, equivalent to 78 times U.S. electricity use in 2020.[78] That is also equivalent to 36 times the estimated electricity needed to power the U.S. in 2050 in a scenario in which transportation, buildings and other activities are largely powered by electricity.[79] America's solar resources are even greater when including potential for floating photovoltaics and concentrated solar power.
- Wind power resources, both onshore and offshore, have the technical potential to produce 40 million GWh of electricity each year, equivalent to 11 times U.S. electricity use in 2020.[80] That is also equivalent to five times the estimated electricity needed to power the U.S. in 2050 in a scenario where transportation, buildings and other activities are largely powered by electricity.[81]

America's wind and solar resources are spread broadly throughout the country. Every single state has either

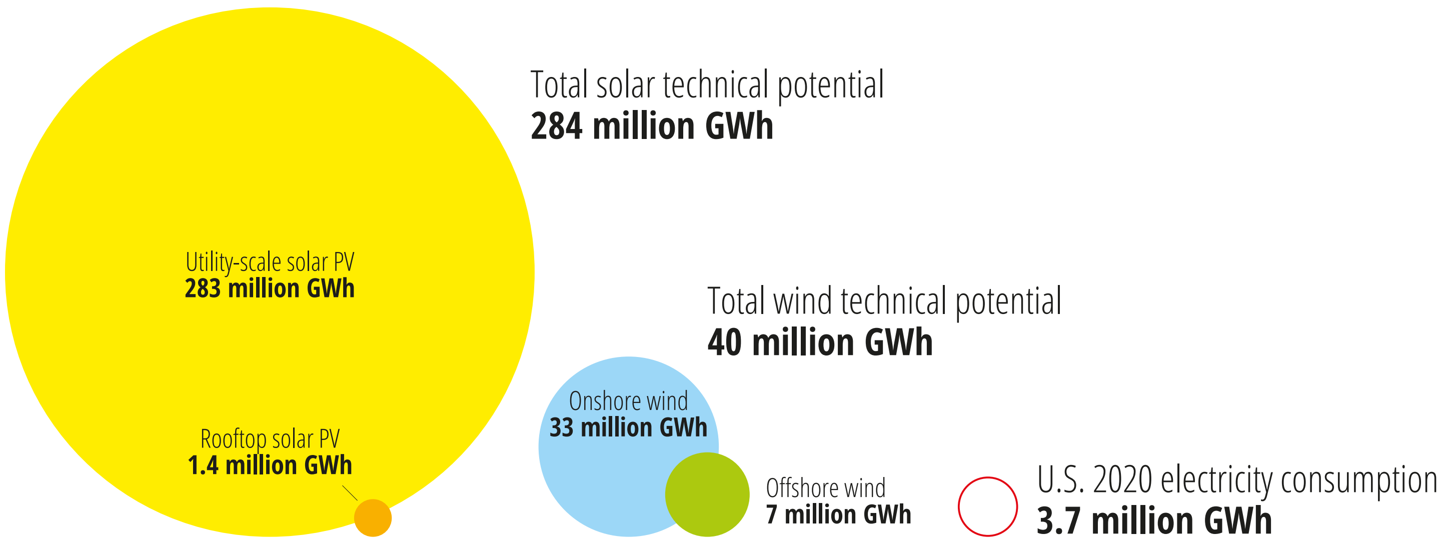


Figure 2. America's enormous wind and solar energy resources

the wind or solar technical potential to power that state's current electricity use at least once over.[82] Eighteen states have the solar resources to power current electricity needs 100 times over, and five states have the wind resources to do so. Every single state except Connecticut also has either the wind or solar resources to fully meet its electricity needs in 2050, even assuming large increases in electricity use under a scenario of rapid electrification.[83]

U.S. renewable resources go beyond solar panels and wind turbines. NREL has calculated that U.S. geothermal resources for producing electricity (both traditional hydrothermal and enhanced geothermal) have the technical potential to provide nine times as much electricity as the nation currently consumes.[84] Geothermal energy can also provide heating and cooling directly through heat pumps that take advantage of the stable temperature of the earth. The U.S. Department of Energy (DOE) estimates that U.S. geothermal heat pump technical potential is 580,000 GW_{th} (gigawatts-thermal).[85] By comparison, current geothermal heat pump installed capacity is approximately 17 GW_{th}, which the DOE estimates is equivalent to installations for about 2 million households.

Research also indicates enormous potential for generating electricity using marine and hydrokinetic energy, which is energy produced from rivers and ocean currents without the need for dams. Energy from these sources has the technical potential to provide about a third of total U.S. electricity use.[86]

The U.S. is not the only country with abundant sources of renewable energy. Researchers have determined that sufficient renewable energy resources are available around the world for every country on earth to meet its energy demand with renewable energy. As described by the 2019 book *Achieving the Paris Climate Agreement Goals*, "[v]arious research projects have analyzed renewable energy potentials and all have in common that the renewable energy potential exceeded the current and projected energy demands over the next decades by an order of magnitude."[87]

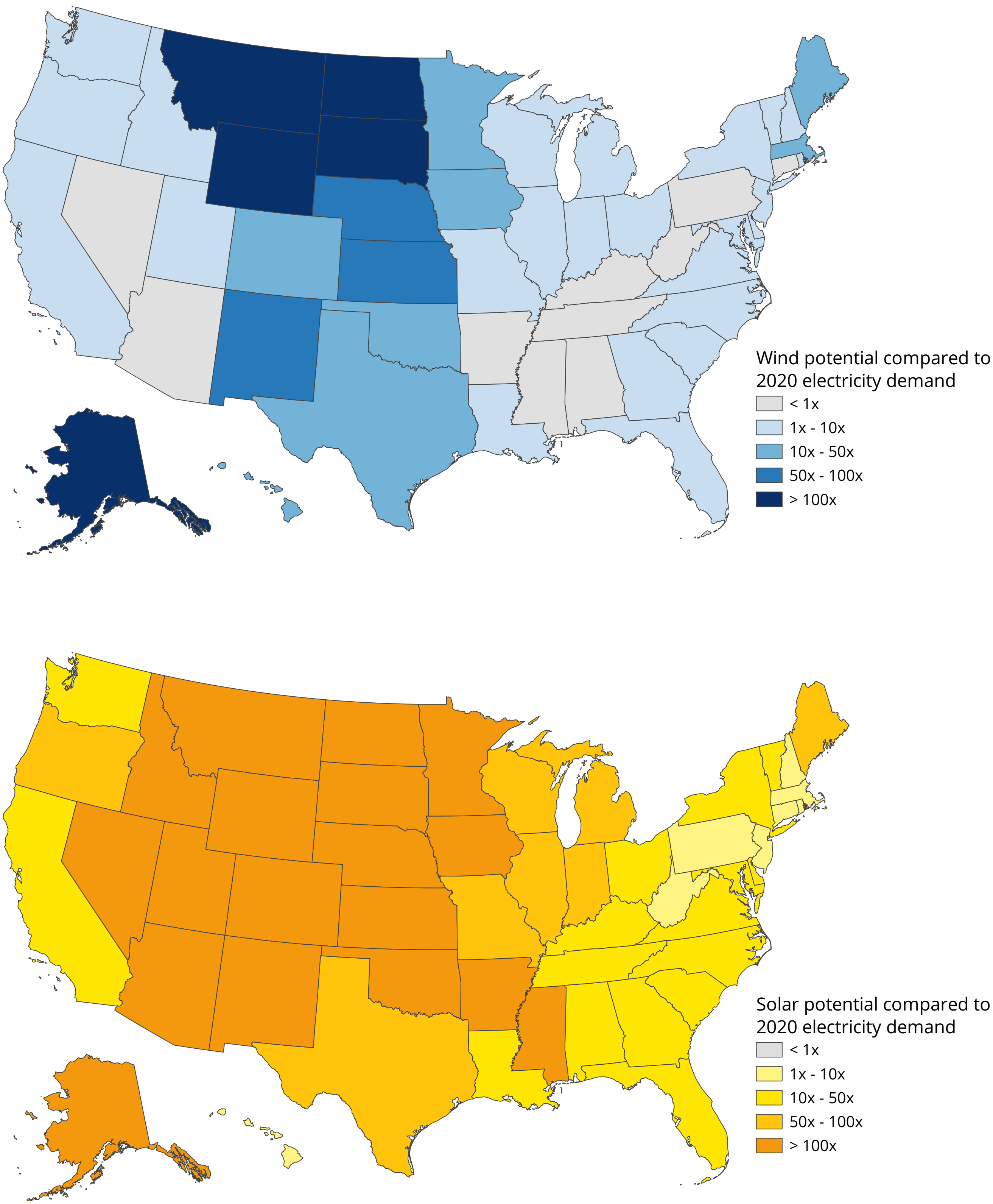


Figure 3. State wind and solar resources compared to current electricity demand[88]

Renewables can power our society 24/7/365

The U.S. has access to enough sun and wind energy to power the country many times over. But can the nation take advantage of these resources to actually power modern society?

Getting all or most of our energy from renewable sources such as wind and solar presents challenges. The wind and sun produce power that is dependent on the seasons, weather and time of day. Much of the energy we use today is obtained by burning fossil fuels directly in our vehicles, buildings and industrial plants – energy uses that are not always easily replaceable by clean energy sources. And renewable energy technologies have environmental impacts of their own, which could grow as deployment ramps up.

In recent years, researchers from a variety of academic, government and non-governmental institutions have worked to determine the feasibility of a renewable energy system, and assessed whether such systems can provide energy reliably and affordably within land use and material resource limitations.[89] Those studies have resulted in broad agreement that **an energy system in which most or all of our energy comes from renewable sources like the wind and sun can supply the electricity needed to power modern society 24 hours a day, 7 days a week, 365 days a year.**[90]

This broad agreement is illustrated by a 2019 article from the journal *Energy*, which reviewed 181 studies from around the world assessing the concept of 100% renewable energy, both for electricity-only and total energy systems.[91] The *Energy* article concluded that "[t]he majority of the reviewed studies find that 100% [renewable energy] is possible from a technical perspective, while only few publications argue against this."[92] Similarly, a 2019 study published in *Renewable and Sustainable Energy Reviews* reviewed 15 studies of high-renewable penetrations within the Americas, each of which reached similar conclusions about the feasibility of renewable energy systems.[93]

Much of the recent research into renewable energy systems has focused on how, exactly, systems supplied largely by intermittent renewable resources can supply energy 365 days a year, 24 hours a day.

Some of the most sophisticated research into this question as it relates to the United States has come from the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). NREL has performed detailed modeling of grids with high penetrations of renewable energy, to look at interactions of energy supply, demand and transmission down to time scales of just a few minutes. NREL has looked at systems of a wide variety of scope and size, including a 75% renewable grid for North America's Eastern Interconnection, and most recently a detailed assessment of 100% renewable energy for the city of Los Angeles. NREL has concluded that "[r]enewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the country."[94] NREL's most recent analysis of Los Angeles' energy system concluded that "[r]eliable, 100% renewable electricity is achievable — and, if coupled with electrification of other sectors, provides significant greenhouse gas, air quality, and public health benefits."[95]

Other research has provided insight into what it would take for the United States to repower with renewable energy as quickly, affordably and efficiently as possible.

One finding is that expanding the geographic breadth of the grid by increasing transmission capacity and connecting regional grids can allow more efficient and affordable use of renewable energy. A 2017 study from the journal *Energies* determined that connecting the grid at the country or even continent scale could make a transition to 100% renewable energy easier and cheaper, and that "a 100% RE-based system is feasible and a real policy option at a modest cost."[96] Similarly, NREL's Interconnections Seam Study found that connecting the U.S. Eastern and Western Interconnections would have particularly high economic value for a scenario with increased levels of renewable generation.[97]

Studies of cost efficiency have also found that various strategies for minimizing the need for energy storage capacity – which, at least today, is relatively expensive compared to other clean energy technologies – will reduce the cost of building toward a largely renewable energy system. A 2018 study from *Energy & Environmental Science* found that deploying abundant wind and solar capacity – enough to meet the needs of the system during periods of lower power output – could reduce the costs of a largely renewable grid by reducing the amount of energy storage needed.[98]

One potential obstacle for an energy transition is the scarcity of certain materials, such as cobalt, lithium and silver, which are used for components of clean energy technologies. Recent studies have assessed solutions to this challenge finding that some combination of recycling, improved efficiency of material use, and the continued development of technologies less reliant on rare metals can help ensure the availability of materials needed for a full shift to renewable energy.[99]

Pathways to a renewable future

How might the United States and the world actually go about building such an energy system over the next 30 years? Recent studies have provided detailed potential pathways of technology, politics and economics that could help bring about a transition to renewable energy.

One such study, published in *Energy* in 2021, describes a global shift to "100% renewable energy systems including the power, heat, transport and desalination sectors."[100] The study narrates a pathway in which "global electricity generation undergoes a rapidly evolving transition from predominantly fossil fuels in 2015 to 98% renewables in 2040, and entirely zero GHG emissions by 2050." It predicts that such a transition will require changes in energy policy, such as a shift of subsidies away from fossil fuels, and will present some challenges particularly "in the short term for developing countries with recent and new investments into fossil fuel assets." Ultimately, the study concludes that a 100% renewable energy system is technically feasible, "economically attractive," and will enable emission reductions in line with what science says is necessary to prevent the worst impacts of global warming.

And 2019 research published in *One Earth* described energy roadmaps for all countries "to move all energy to 100% clean, renewable wind-water-solar (WWS) energy, efficiency, and storage no later than 2050 with at least 80% by 2030."[101] The study assessed the land use implications of such a system, finding that globally utility-scale solar and onshore wind would require far less than 1% of available land: 0.166% and 0.480% of world land, respectively.

Building a renewable energy future

America has the renewable resources to power our lives, and researchers have determined that repowering with renewable energy is technically possible. The greatest question today is whether America can build such a system fast enough to prevent the worst impacts of global warming.

America's ability to build a renewable energy system will require action in four key areas:

1. Rapidly deploy renewable energy
2. Modernize the grid
3. Reduce and manage energy demand
4. Repower everything with renewables

The good news is that rapid progress over the last decade – including dramatic improvements in technology, falling prices, and successful deployments of clean energy technologies – has brought the ambitious vision of a society powered by 100% renewable energy within reach.

Rapidly deploy renewable energy

Renewable energy is on the rise. Over the last 20 years, America's wind and solar energy generation grew more than 60-fold.[108] By 2020, wind and solar accounted for 12% of all electricity generation – equivalent to the electricity needed to power 44 million homes.[109] And by the end of 2020, America was home to 60,000 wind turbines and more than 2 million rooftop solar installations.[110]

Renewable energy growth shows no signs of slowing down. Rather, recent cost and technological trends could lead the way toward far faster progress in the years to come, which will be necessary to achieve a renewable energy system by mid-century.

Clean energy prices have fallen sharply

Clean energy is more affordable than ever. Recent years have seen dramatic cost reductions for key technologies across the areas needed for a renewable future, including technologies for generating renewable electricity, using clean energy, reducing energy use, and building a more modern grid.

- The levelized cost of energy (LCOE) for wind power fell by 71% and for utility-scale solar by 90% from 2009 to 2020.[102] LCOE refers to the lifetime cost of a generation technology divided by total energy production.
- The cost per watt of residential solar fell by 60% from 2008 to 2019.[103]
- The cost per watt-hour for EV batteries fell by 89% from 2010 to 2020.[104]
- The cost per watt-hour for utility-scale battery storage fell 70% from 2015 to 2018.[105]
- The cost of LED lighting fell 88% from 2008 to 2017.[106]

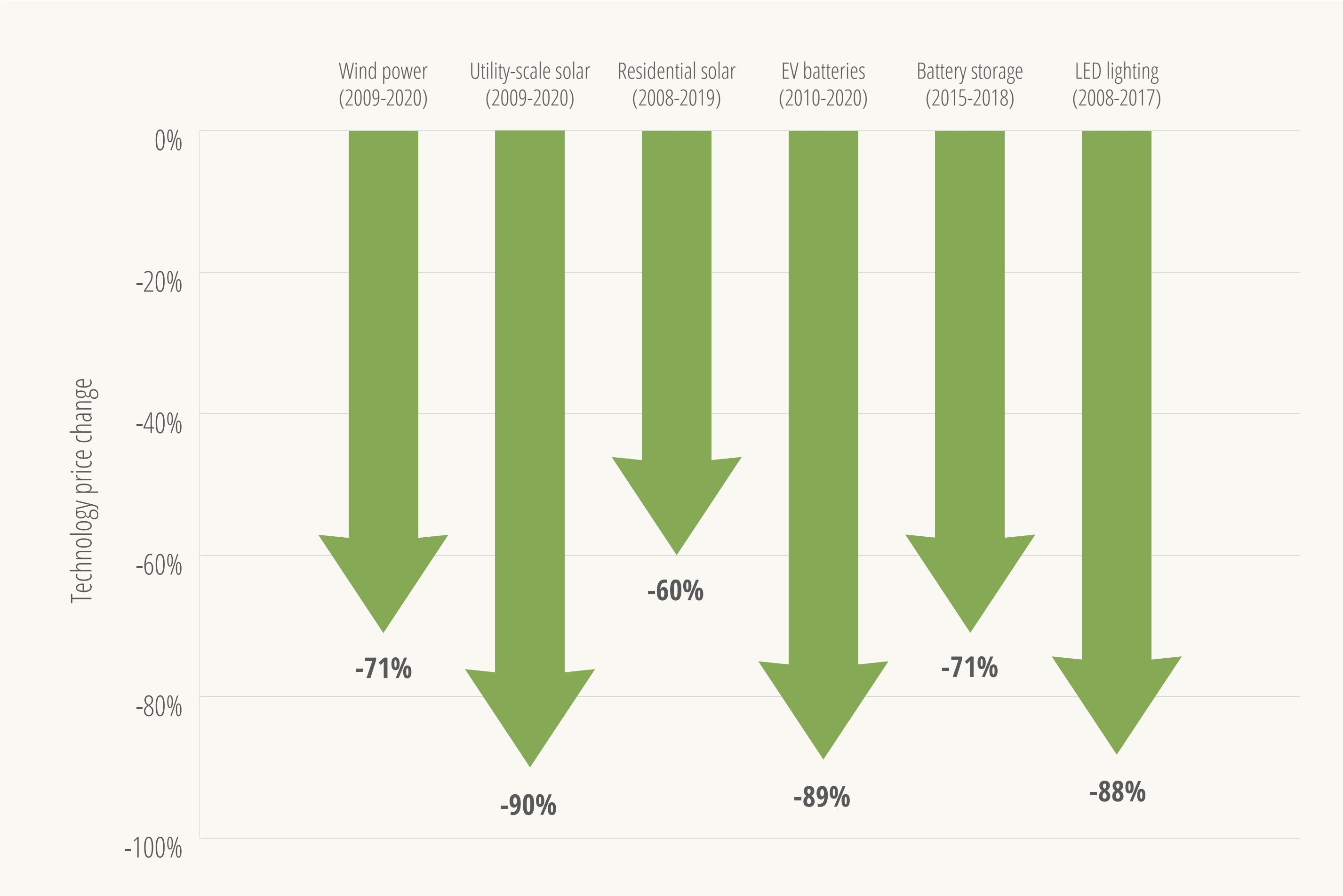


Figure 4. The rapid fall of clean energy prices[107]

Technology is improving and costs are falling

Today's wind turbines and solar panels are able to generate more energy, in less space, for less cost, and with more flexibility than ever before. In 2019, the median new residential solar panel was 37% more efficient than one installed in 2010.[111] Utility-scale solar energy systems have benefited from improvements in tracking technology that allow panels to change angles to follow the sun, or to maximize generation from diffuse light on cloudy days.[112] Wind turbine technology has also seen enormous improvements. In 2019, the average installed wind turbine had 42% greater power capacity than one installed in 2010, and the area swept by the average turbine's rotors doubled in that time period.[113]

As technology has improved, prices have plummeted. According to the consulting firm Lazard, which has been tracking energy costs for years, wind power was 71% cheaper in 2020 than in 2009 and the cost of solar energy dropped by 90% during that same period.[114] In many cases, getting energy from new wind turbines and solar panels is now cheaper than getting energy from *existing* coal and gas plants, let alone new ones.[115]

Declining costs have also made renewable energy cost-effective in parts of the country where it may not previously have been economically feasible. According to Lawrence Berkeley National Laboratory (LBNL) researchers, solar energy cost reductions mean that projects can now "pencil out financially even in less sunny parts of the country."[116]

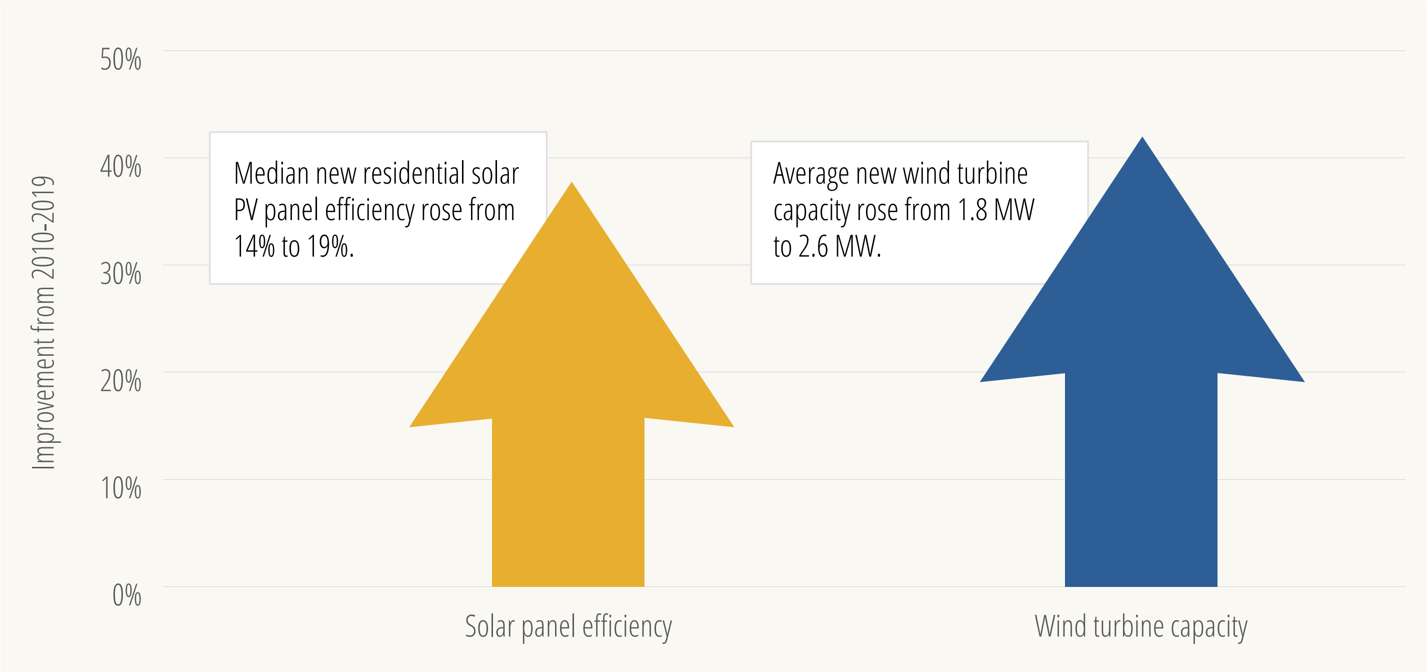


Figure 5. Wind turbines and solar panels are getting more efficient and powerful[117]

New renewable technologies are on the way

Researchers have largely concluded that the technology we need for a renewable future is already available. As one study from *Nature Communications* put it, "currently available generation and storage technologies are sufficient for nearly 100% power system operation."[118] And, from another study in *Renewable and Sustainable Energy Reviews*: "The technologies required for renewable scenarios are not just tried-and-tested, but also proven at a large scale."[119]

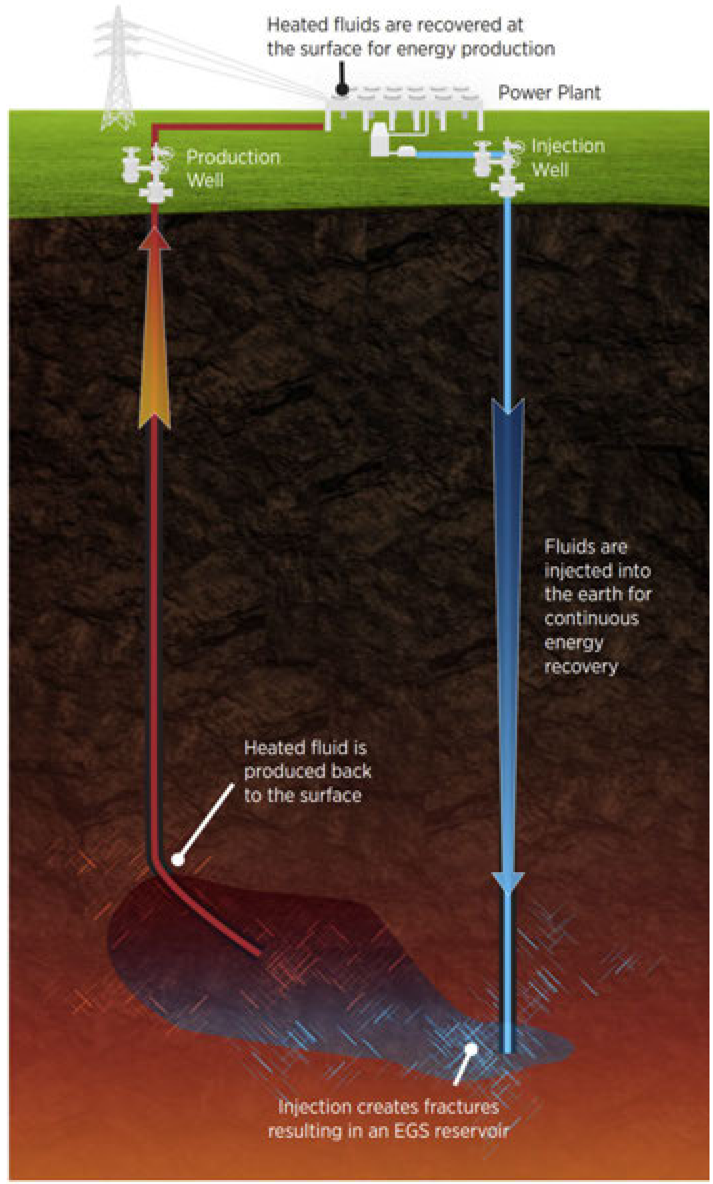
New renewable energy technologies are also on the way that could one day help provide more stable and diverse options for providing renewable energy, easing the transition to a renewable future.

Floating offshore wind turbines. To date, almost all of the world's offshore wind farms have used fixed-bottom turbines with structures drilled or driven into the ocean floor. Recent years, however, have seen the first pilot projects of floating wind turbines that can be placed in far deeper waters, such as those off of the U.S. West Coast. The company Equinor, which built the first commercial-scale floating wind farm, has reported dramatic cost reductions for floating wind technology for an upcoming project off the Norwegian coast.[120]

Geothermal energy. Geothermal power plants have provided stable and predictable electricity in the American West for years. They use wells drilled deep underground – usually a mile or two – to harvest heat energy in the form of water or steam, which then drives a turbine to produce electricity.[121] The U.S. Department of Energy (DOE) has recently highlighted the potential for the U.S. to get far more of its energy from geothermal sources, using new technologies that can expand the available geography for geothermal systems and increase the amount of power produced, including through the use of flexible "enhanced geothermal systems" (EGS).[122] The DOE estimates that continued technological improvements, particularly for EGS, "could increase geothermal power generation nearly 26-fold from today, representing 60 gigawatts-electric (GW_e) of always-on, flexible electricity-generation capacity" able to supply 8.5% of U.S. electricity by 2050.[123]

Floating solar panels. Sometimes called "floatovoltaics," floating PV panels are another "emerging, and increasingly viable" technology, according to researchers from the National Renewable Energy Laboratory (NREL).[124] Floating PV would add new flexibility for siting of solar energy projects, and could bring benefits such as reduced algae growth and reduced evaporation in reservoirs.[125] In October 2020, *PV Magazine* reported that floating solar was "nearing price parity" with land-based solar power, and that more than 20 floating solar projects would be operational in the U.S. by the end of that year.[126]

Wave and tidal power. Energy from ocean waves and tides could be a valuable asset to a renewable grid, as the energy contained in tides is consistent and can be accurately predicted not just days but years or centuries into the future.[127] While wave energy technology has not reached the point where it can provide large-scale power to the grid, it has seen continued improvement and has found uses in niche settings such as powering underwater vehicles.[128]



U.S. Department of Energy conceptualization of an enhanced geothermal system.[129]

Modernize the grid

A renewable energy system that can provide reliable power when we need it requires more than just wind turbines and solar panels – it will also need a modern grid capable of storing energy, delivering energy where it is needed, and reacting to changes in weather conditions.

America's electric grid has already adapted to higher levels of renewable energy without any negative effect on reliability, and in 2020 wind and solar accounted for at least a quarter of electricity generation in 11 states.[130] A Congressional Research Service (CRS) analysis of America's rapid integration of renewables found that "electric reliability was generally stable or improving over the 2013-2017 period."[131] Changes to the grid that have made this possible are now setting the stage for a grid of the future capable of supporting truly high penetrations of renewable energy.

The energy storage revolution has begun

Energy storage is likely a necessary part of any energy system largely reliant on variable, renewable energy sources. And while energy storage has existed for many years in the form of pumped hydroelectric installations, today's electric grid is undergoing a storage revolution built around new technology: advanced, high-capacity batteries that can play key support roles for a renewable grid thanks to their ability to charge and discharge quickly, not only storing energy but also helping maintain grid stability and responding to grid disturbances.[132]

Over the last decade, battery technology has rapidly improved and prices have fallen. Energy storage costs declined by 70% between 2015 and 2018.[133] At the same time, the pace of battery installations has increased, primarily at the utility scale but also in homes and businesses.[134] In March 2021, Wood Mackenzie reported that energy storage deployment had set a new record in Q4 2020 with more than 2,000 MWh of storage brought online, nearly triple the previous quarterly record.[135] Much of the new battery capacity came online with the primary purpose of supporting renewable energy.[136] This includes the world's largest battery storage system, the 1,200 MWh Moss Landing Energy Storage Facility in California, which came online in December 2020 and will typically charge using excess solar energy during daytime, and then provide power to the grid at night.[137]

Achieving penetrations of renewable energy approaching 100% could also require long-term energy storage to account for seasonal fluctuations in wind and solar generation and energy demand.[138] Although in their early stages, a variety of different solutions are being developed that could eventually fill this need. These include new forms of pumped hydro, as well as systems that store energy in the form of compressed air, liquid air, raised concrete blocks, or hydrogen.[139] NREL researchers have highlighted hydrogen as a promising seasonal energy storage solution that could be "cost-effective in future power systems."[140] Its value would be in part due to its ability to act as a "flexible energy carrier" that can be used not just for powering the grid, but also for transportation, industry and other activities.

The time is right for creating a more interconnected grid

The ability to send energy long distances, from sunny and windy areas to the places where it is needed, can greatly improve the efficiency and affordability of a renewable energy system.

In Texas, 3,600 miles of electric transmission lines built to carry wind power from the windy western part of the state to major centers of energy demand like Dallas, Houston and Austin have helped Texas become the nation's largest producer of wind power.[141] And in the western U.S., the Western Energy Imbalance Market (EIM) has expanded the geography of the grid in another way by evolving how electricity is bought and sold.[142]

The time is now right for building out new transmission connections, including between the eastern and western U.S., which could allow for far more flexibility in taking advantage, for example, of America's abundant wind resources in the middle of the country.[143] New transmission projects can take advantage of improved technology and lower costs for high voltage direct current (HVDC) transmission lines, which can send large amounts of electricity long distances far more efficiently than traditional alternating current lines.[144]

New technology is creating a smarter, more flexible grid

Other technologies and tools are ready to help build a smarter, modern grid that can put renewables to use reliably and efficiently. For example, smart inverter technology for distributed resources like rooftop solar panels and battery storage, and the use of stored kinetic energy for wind turbines, can respond to sudden changes in grid conditions to help maintain grid function.[145]

In addition, sophisticated computing tools like artificial intelligence have made possible advanced forecasting that can provide grid operators with precise and granular information about renewable generation.[146] Improvements in forecasting have been put to use in programs such as the Midcontinent Independent System Operator's (MISO) Dispatchable Intermittent Resource tariff, which gives wind farms more flexibility in providing power based on their own forecasts, and has helped reduce curtailments and make wind power more economical.[147]

Reduce and manage energy demand

No matter how cheap or advanced wind turbines and solar panels get, reducing the number that need to be built will reduce the cost and environmental impact of tomorrow's grid. Reducing energy consumption and creating lower and more flexible demand peaks are both important strategies for getting the most out of energy infrastructure during a transition to renewable energy, and for ensuring stability when power output changes. Both strategies also provide immediate benefits including reducing emissions and lowering energy costs for consumers.

America has enormous potential to reduce energy use

America has enormous potential to reduce energy use through efficiency. Energy efficiency can cut U.S. energy use in half by 2050, according to research from the American Council for an Energy-Efficient Economy (ACEEE).[148] And an Electric Power Research Institute (EPRI) analysis found that if all homes and businesses were to replace appliances and equipment reaching the end of their useful lives with the most efficient technologies, the U.S. could reduce electricity consumption by 13.9% through 2040.[149]

Energy efficiency has been a critical part of the U.S. economy for decades. Since the 1970s, efficiency improvements have met more than three-quarters of the increased U.S. demand for energy, even as our economy tripled in size.[150] As a result, the nation was able to skip unnecessary infrastructure projects and avoid their cost. Today, thanks to energy efficiency standards and programs, our appliances deliver better performance while using less energy, our buildings waste less energy through leaky windows and poorly insulated walls, and our cars and trucks go further on a gallon of gas.

Despite this progress, there is still vast potential to improve energy efficiency using tried-and-true methods that have been in use for decades. For example, more than nine in 10 homes had not had an energy audit as of 2015.[151] And there are many opportunities to reduce energy use through conservation, such as automatic controls to turn off lights in unoccupied rooms, or by encouraging shifts from more to less energy-intensive activities and modes of travel, such as from driving to transit, walking or biking.

There are also innovative new strategies for saving energy. ACEEE has documented recent efforts including pilot programs for smart thermostats, new geotargeted efficiency programs, and online marketplaces for energy-efficient products.[152] Lawrence Berkeley National Laboratory reports that using energy management and information systems (EMIS) to reveal hidden energy waste could, if adopted throughout the commercial sector, result in energy savings worth $4 billion per year.[153]

New building construction practices have the potential to achieve even more dramatic reductions in energy consumption. Examples include the ZERO Code building standard for supporting the construction of buildings that use no on-site fossil fuels, and the "passive house" building design standard, which began with the Passivhaus movement in Germany.[154] Passive house buildings are built to require only minimal heating and cooling to maintain comfortable temperatures, which is accomplished using design principles such as a high level of thermal insulation and ventilation systems that recover heat.[155] Such buildings are more likely to be able to meet their energy needs using solar panels and other onsite resources, rather than drawing power from the grid. For example, in October 2021 the nation's first hotel meeting passive house standards will open in New Haven, Connecticut, and will produce all its own energy for electricity and heating onsite.[156]

Demand response can create a more flexible, efficient grid

Giving the grid the flexibility to match energy demand with available resources can make the energy system more efficient and better able to integrate large amounts of variable, renewable energy. So-called demand response programs operate by managing non-essential energy use by industrial, commercial and residential customers who opt-in. By 2030, demand response could provide 200 GW of "cost-effective load flexibility potential," equivalent to 20% of peak load levels, according to research from the Brattle Group.[157]

Demand response programs have existed for decades, with the earliest programs primarily intended for reducing electricity demand in the case of power disruptions.[158] Now, new technologies and new policies are enabling programs that adjust energy use in real time, allowing a more flexible energy system better suited to rely on wind and solar power. Technologies include smart thermostats and new grid sensors.[159] New policies include a 2011 Federal Energy Regulatory Commission order, upheld by the Supreme Court in 2016, which requires that each demand response resource "must be compensated for the service it provides to the energy market at the market price for energy."[160]

A new generation of demand response programs is already being rolled out, providing energy and cost savings and helping the utilities match demand to available renewable supply. In 2018, utilities reported a total enrolled demand response capacity of 20.8 GW – equivalent to the power capacity of about 10,000 wind turbines.[161]

In Michigan, the utility Consumers Energy – which plans to run on 40% renewable energy by 2040 – has started giving away free smart thermostats to consumers who volunteer to have the temperature of their homes controlled on a limited number of days each year. In return, consumers, can expect electricity savings of around 20% during the summer.[162] To keep program participants comfortable, before a planned "energy savings event" the linked thermostat will automatically pre-heat a home (on a cold day) or pre-cool a home (on a hot day).[163]

Repower everything with renewables

Switching to 100% renewable energy throughout our economy will require more than just replacing current sources of electricity with wind and solar power. Most U.S. fossil fuel emissions are from burning fuels at the point of use, like gasoline for driving, natural gas for heating and cooking, and various fossil fuels for industrial activities.[164] Because most of our renewable energy resources are best captured in the form of electricity, achieving an energy system primarily powered by renewable energy will require switching most direct uses of petroleum or gas to electricity.

Electrifying transportation, heating and other activities will increase the amount of electricity needed to power society. But it will also significantly lower the total amount of energy society consumes. That is because most electric technologies are far more efficient than their fossil fuel counterparts. A fully electrified and renewable energy system could cut primary energy consumption by about half, even before accounting for efficiency improvements and a reduction in energy use for fossil fuel processing.[165] In transportation, energy savings are particularly dramatic. One study found that switching to electric vehicles can reduce energy consumption by 70% for the same travel.[166]

Electrification can also create new opportunities for easing the transition to renewable energy. Multiple studies and pilot programs have found that the batteries used in electric cars and other vehicles, or in EV charging stations, could help the grid by storing excess energy and charging during periods of low demand.[167] In addition, a 2021 study published in *Smart Energy* found that, particularly in cold regions, "building heat loads are found to correlate strongly with wind energy supply," suggesting that building electrification could improve efficient use of wind energy.[168]

While electricity can serve most of our energy needs, there may be some uses of energy – such as for airplanes or certain forms of manufacturing – for which it is less practical. In these cases, other forms of low- or zero-carbon clean energy, such as renewably generated hydrogen fuel or biofuels, may help facilitate the transition to 100% renewable energy.

Critical tools for repowering with renewables are already here

Two of the most important areas for electrification are transportation and buildings. In total, light-duty vehicles, residential buildings and commercial buildings account for 45% of fossil fuel end-use combustion in the U.S.[169] Light-duty cars and trucks account for more than half of all transportation emissions in the U.S. and more than a sixth of total national emissions.[170]

Transportation and buildings are ripe for rapid electrification. Technologies for both have seen dramatic improvements and price drops in recent years, and today these technologies, according to the National Renewable Energy Laboratory, represent the "low-hanging fruit" of electrification.[171]

Today, there are more than 1 million electric vehicles (EVs) on the road in the U.S., up from almost none just two decades ago, and annual sales reached nearly 300,000 in 2020.[172] In 2020, EVs in the U.S. displaced the use of 36,000 barrels of gasoline per day.[173] New EVs have driving ranges quadruple those of a decade ago, and falling prices – along with very low fuel and maintenance costs – mean that new EVs can save their owners thousands of dollars over vehicle lifetimes.[174]

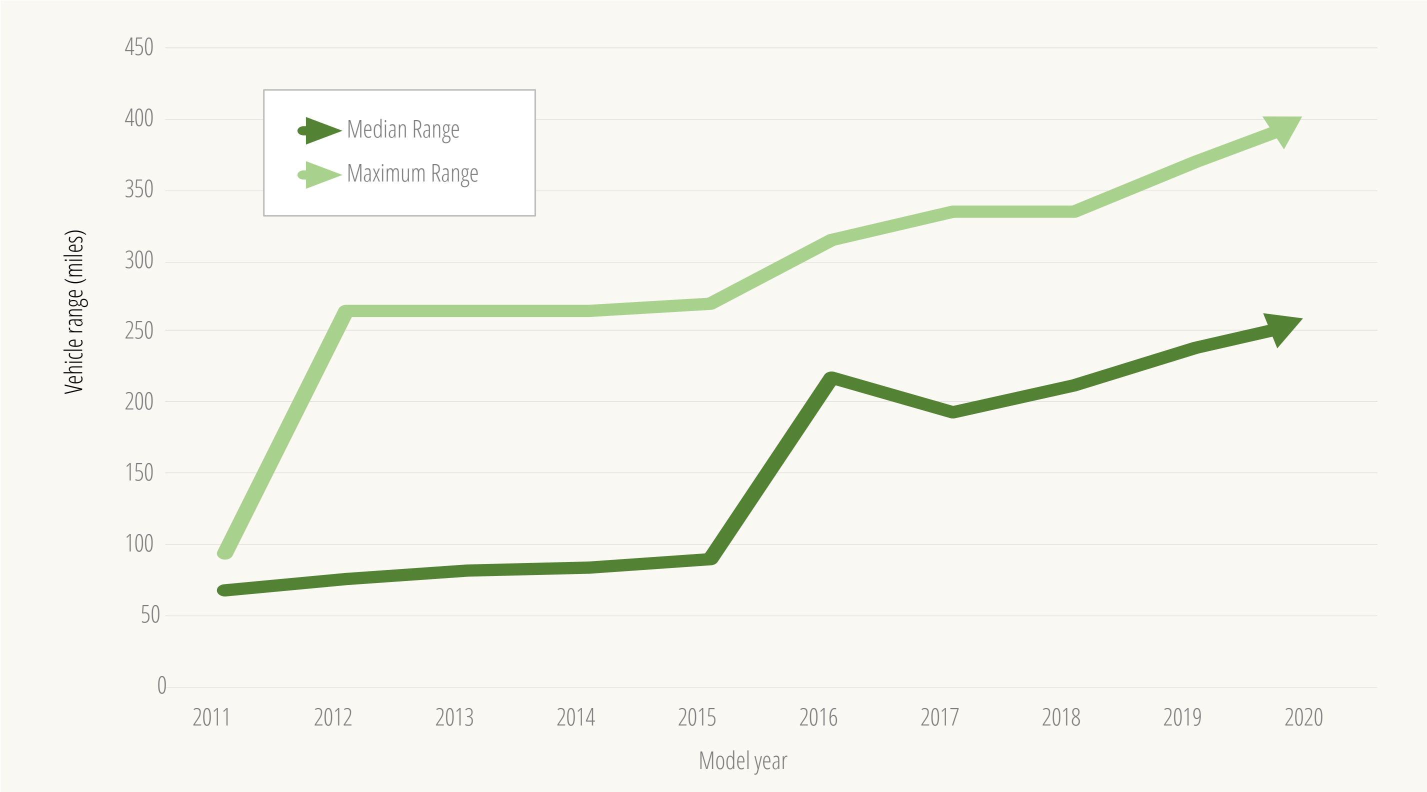
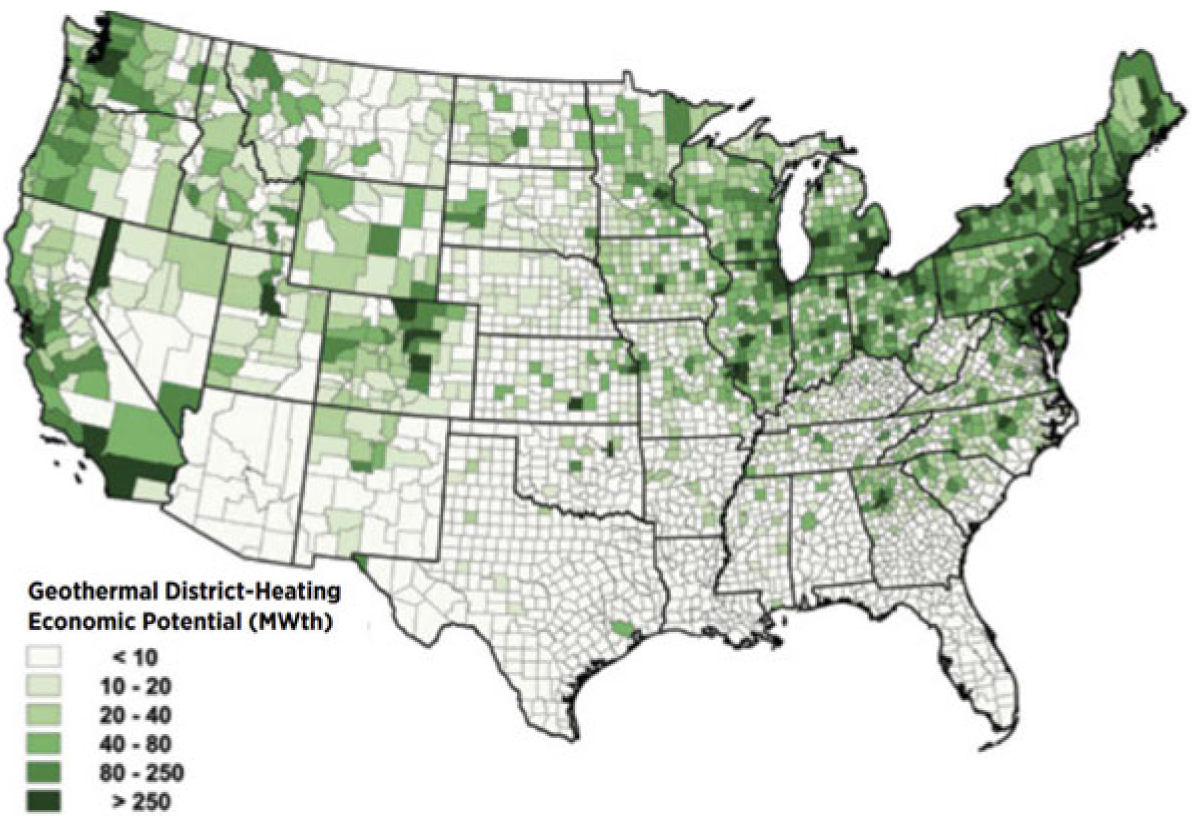


Figure 6. Median and maximum ranges of electric vehicles have quadrupled over the past decade[182]



The U.S. Department of Energy estimates that the U.S. has the economic potential for more than 17,500 geothermal district heating installations nationwide, with much of the potential located near major population centers including in the Northeast.[183] *Credit: U.S. Department of Energy*

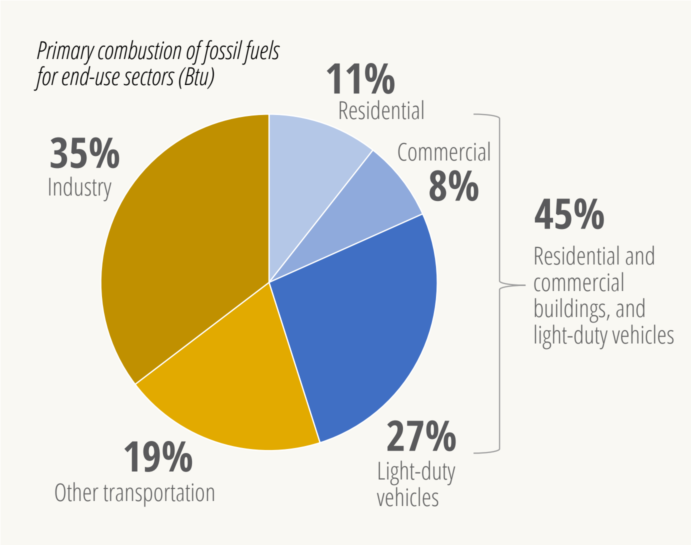


Figure 7. Electrifying light-duty vehicles and buildings would account for 45% of fossil fuel end-use combustion in the U.S.[184]

Technologies that can provide electric heat, hot water and cooking for buildings, such as heat pumps and induction stoves, have similarly seen growth and technological improvements. A Rocky Mountain Institute analysis found that, for new buildings, all-electric buildings using high-efficiency heat pumps now have a lower net present cost than mixed-fuel homes.[175] This is even true in northern cities like Boston, showing that modern heat pump technology can now work efficiently in cold climates.[176]

As electric building technology has improved, adoption has steadily increased. The U.S. saw 3.1 million sales of air-source heat pumps in 2019, which provide efficient electric heating and cooling.[177] The U.S. has also seen around 200,000 total sales of ground-source heat pumps, which tap into stable underground temperatures for heating and cooling.[178] Ground-source heat pump adoption in the U.S. was driven in part by 30% federal tax credits that were available from 2008 to 2016 and from 2018 to 2021.[179]

Renewable energy can also be used directly in the form of heat, rather than electricity. The U.S. Department of Energy estimates that the U.S. has the economic potential (i.e., cost-competitive development potential given resources and current technology) for more than 17,500 geothermal "district heating" installations serving groups of buildings nationwide, with much of the potential located near major population centers including in the Northeast.[180] In addition, a variety of systems are available today that can capture solar thermal energy in liquid, air collectors, or perforated metal designed to absorb heat.[181] These sources are in addition to traditional building techniques to harness energy from the sun and the wind to light, heat and cool buildings directly, without the need for mechanical systems.

Promising technologies are on the way for industry and transportation

There are no technological barriers standing in the way of the U.S. adopting clean, renewable energy to power most of our lives. For a complete transition from fossil fuels, however, the development of new technology will be necessary – and recent years have seen rapid advances in areas that could one day make it possible for renewable energy to power all of our lives.

Today, promising technology is under development for tackling some of the harder challenges in transitioning to renewable energy; in particular, industry, air travel and heavy freight via rail, truck and ship. End-use fossil fuel combustion from these activities account for, combined, about a quarter of U.S. GHG emissions.[185] Technologies for electrifying these activities, while in various stages of development, are being pursued by major industrial companies, often with federal policy support.

Industry

Repowering industrial activities that use direct fossil fuel combustion is an important, yet potentially challenging, step in reducing America's climate impact. Industrial end-use combustion of fossil fuels was responsible for 798 million metric tons of CO_2 emissions in 2019, more than all passenger cars.[186]

Electrification of industry is challenging because of the sheer variety of equipment types and processes, some of which require extremely high temperatures, as well as the high capital costs entailed in replacing equipment.[187] Nevertheless, many industrial companies are seeking to electrify, in part because doing so could improve industrial processes and bottom lines. The Department of

Energy has found that electric technologies could bring "improved process speed, improved product quality, manufacturing flexibility, and cleaner processing (less polluting emissions)."[188] As a result, many industrial companies are exploring ways to increase reliance on electricity. A recent Deloitte study found that, among surveyed manufacturers, companies aimed to electrify nearly 45% of their processes by 2035.[189]

Hydrogen produced with renewable energy presents a key opportunity for shifting industry away from fossil fuels, especially for those processes that are not easily electrified.[190] Certain industrial operations today, including production of ammonia, methanol and steel, already rely on hydrogen as a feedstock.[191] Hydrogen may also be able to replace natural gas in industrial heating equipment.[192] Hydrogen for all uses can be produced using renewable energy, for which the International Energy Agency estimates that production costs could "fall 30% by 2030 as a result of declining costs of renewables and the scaling up of hydrogen production."[193]

Transportation

Medium- and heavy-duty vehicles account for nearly a quarter of U.S. transportation energy use.[194] The development of electric trucks has been slower than for electric passenger vehicles, largely due to greater demands for battery capacity.[195] That is changing. Electric medium-duty trucks are available today, and the Rocky Mountain Institute reports that 19 models of zero-emission heavy-duty trucks, powered either by batteries or hydrogen fuel cells, are expected to be in production by 2023.[196] And many cities, transit and school agencies have already begun to adopt electric transit and school buses.[197]

Similar improvements in battery technology could soon be used for rail freight as well. Rail giant BNSF is currently developing battery-powered locomotives with support from the California Air Resources Board Zero- and Near Zero-Emission Freight Facilities program.[198] Railroads, particularly in denser areas, can also adopt traditional technologies – such as power from overhead wires or third rails – to provide electric train service.

Ending fossil fuel use for air travel, which accounts for more than 10% of U.S. transportation emissions, is a trickier challenge. Today's batteries are simply not ready to power commercial air travel, as even the most advanced batteries are able to store just a small fraction of the energy per weight that is contained in jet fuel.[199] Hydrogen-powered flight faces similar challenges.[200] The Department of Energy states that "[e]lectrification is not an option for commercial flight for decades, if not longer."[201] Nevertheless, electric and hydrogen planes are in development by companies like Airbus, as well as NASA.[202] Electric planes powered by renewable energy would produce no emissions, and would also be cheaper to maintain and far quieter.[203]

More likely in the nearer term could be the use of either sustainable aviation fuel (SAF), which is biofuel produced from sources such as food and forestry wastes, or renewably produced synthetic fuels.[204] SAF could allow air travel to end its dependence on fossil fuels until truly clean technologies are available. Shifting travel demand from air to rail could also ease the challenge of repowering the aviation sector with clean energy.

Conclusion: Policymakers must accelerate the transition to renewable energy

Renewable energy can solve many of America's most pressing challenges. A rapid shift is possible. And over recent decades, America has built a strong foundation for a future energy system in which the vast majority of our energy comes from renewable sources. Now, the nation must take bold steps to accelerate progress toward a renewable future.

The scale of the challenge ahead is enormous. Despite the progress of recent years, when looking beyond electricity, fossil fuels still account for nearly 80% of energy consumed in the United States.[205]

But by turning to proven policies and embracing new ideas, America can lead the world toward a future built around clean, renewable energy – not only helping to avert a climate catastrophe, but improving lives, communities, and the natural world in the process.

Policymakers at every level of government should:

Commit to a future of 100% clean, renewable energy by 2050 at the latest.

Across the country, seven states and more than 170 cities have already committed to achieving 100% renewable or zero-carbon electricity.[206] Other states, cities and government agencies, along with private companies and institutions, have also made commitments to phase out the use of fossil fuels in buildings or achieve 100% electric vehicle fleets.[207] And the state of California has committed to achieving carbon neutrality by 2045, which would entail using renewable energy to power most of society: electricity, transportation, buildings and industry.[208]

These ambitious clean energy goals are helping chart a course toward a renewable future. Ultimately, a federal goal will be critical for ensuring a coordinated national effort. At the same time, more state and city goals – not just for clean electricity, but for 100% clean energy – are necessary to ensure rapid, durable and effective action to promote clean energy, build continued support among the American public, and engage important stakeholders, including utilities and businesses.

Provide the necessary financial and regulatory support to achieve clean energy goals.

Policymakers should ensure that each building block of a renewable future has the policy support necessary to make clean energy adoption economical and easy. Specifically, policymakers should:

- *Accelerate clean energy deployment* through policies that:
  - Lower the cost of clean energy (net metering, tax incentives, grants and rebates);
  - Enable renewable energy development (create offshore wind zones and review projects in a

timely manner, remove red tape restricting rooftop solar);

  - Support renewable energy research (floating offshore wind; geothermal systems; floating PV; tidal and hydrokinetic energy); and
  - Address the environmental impacts of renewable energy development (support solar panel and battery recycling and reuse, ensure environmental precautions for new wind and solar farms).

- *Modernize the grid* through policies that:
  - Increase deployment of energy storage (energy storage goals, consumer programs to encourage consumer adoption of behind-the-meter energy storage, exploring the use of vehicle batteries for grid support);
  - Strengthen grid connections (build strategic new transmission lines); and
  - Encourage a stable and efficient grid (support smart inverter adoption, encourage renewable facilities to provide grid support services, encourage use of advanced renewable forecasting).

- *Maximize energy efficiency and demand response* through policies that:
  - Set strong standards for energy efficiency and accelerate the deployment of efficiency technologies (statewide efficiency standards, efficient equipment standards, weatherization and energy audit programs, utility efficiency programs for all sectors, support for development of efficient and low-carbon technology for industry); and
  - Implement demand response (statewide demand response goals, require utilities to adopt demand response programs).

- *Support electrification and other efforts to repower with renewables* through policies that:
  - Phase out fossil fuel equipment (vehicle electrification goals, limit gas connections in new buildings);
  - Encourage the use of renewable thermal energy (provide financial and regulatory support for renewable district heating, provide grants and rebates for solar thermal and geothermal energy for homes and businesses);
  - Support development of new technology for utilizing renewable energy (sustainable aviation fuel; renewable hydrogen production; fuel cells for long-distance transportation; long-term energy storage).

Appendices

TABLE A-1. WIND AND SOLAR TECHNICAL POTENTIAL AS SHARE OF STATE 2020 ELECTRICITY CONSUMPTION[209]

(Green highlight indicates renewable resource could supply state electricity demand)

State	Utility-scale PV	Rooftop PV	Onshore wind	Offshore wind	Total wind	Total solar
Alabama	44.85	0.31	0.00	0.63	0.64	45.16
Alaska*	1397.76		231.76		231.76	1397.76
Arizona	147.07	0.32	0.32		0.32	147.39
Arkansas	109.54	0.34	0.50		0.50	109.88
California	36.74	0.78	0.36	1.58	1.94	37.52
Colorado	182.38	0.42	19.44		19.44	182.79
Connecticut	1.01	0.55	0.00	0.25	0.25	1.56
Delaware	26.36	0.32	0.00	1.89	1.89	26.68
District of Columbia	0.00	0.18	0.00		0.00	0.18
Florida	21.93	0.43	0.00	3.28	3.28	22.36
Georgia	41.54	0.33	0.00	1.17	1.18	41.87
Hawaii*	4.79		0.89	11.46	12.36	4.79
Idaho	163.32	0.26	1.83		1.83	163.58
Illinois	62.18	0.40	4.93	0.13	5.06	62.58
Indiana	53.30	0.33	4.05	0.04	4.08	53.63
Iowa	140.97	0.33	34.61		34.61	141.31
Kansas	378.19	0.43	80.72		80.72	378.62
Kentucky	26.32	0.30	0.00		0.00	26.62
Louisiana	47.78	0.29	0.01	7.35	7.36	48.07
Maine	98.43	0.63	2.56	36.67	39.24	99.06
Maryland	10.68	0.42	0.06	1.67	1.74	11.10
Massachusetts	2.02	0.53	0.06	21.30	21.35	2.54
Michigan	54.77	0.49	1.50	2.07	3.57	55.26
Minnesota	173.36	0.42	22.88	0.01	22.88	173.79
Mississippi	105.74	0.32	0.00	0.21	0.21	106.06
Missouri	72.09	0.48	9.26		9.26	72.56
Montana	570.82	0.27	191.20		191.20	571.09
Nebraska	306.83	0.35	99.57		99.57	307.18
Nevada	226.88	0.37	0.47		0.47	227.24
New Hampshire	5.73	0.55	0.53	0.47	1.00	6.28

State	Utility-scale PV	Rooftop PV	Onshore wind	Offshore wind	Total wind	Total solar
New Jersey	6.78	0.42	0.00	3.93	3.93	7.21
New Mexico	650.94	0.40	55.57		55.57	651.33
New York	11.10	0.40	0.46	2.12	2.58	11.50
North Carolina	33.01	0.35	0.02	4.87	4.88	33.36
North Dakota	455.60	0.18	118.72		118.72	455.78
Ohio	26.52	0.38	0.92	0.45	1.37	26.90
Oklahoma	152.00	0.43	24.63		24.63	152.43
Oregon	79.08	0.34	1.44	4.83	6.28	79.42
Pennsylvania	4.38	0.36	0.06	0.09	0.15	4.74
Rhode Island	2.11	0.60	0.02	8.25	8.27	2.71
South Carolina	36.33	0.26	0.01	7.98	7.99	36.59
South Dakota	801.20	0.38	232.19		232.19	801.58
Tennessee	24.06	0.33	0.01		0.01	24.39
Texas	95.97	0.32	13.56	1.74	15.30	96.29
Utah	167.79	0.33	1.02		1.02	168.12
Vermont	10.64	0.64	1.47		1.47	11.29
Virginia	16.52	0.31	0.04	1.40	1.44	16.83
Washington	20.79	0.29	0.55	1.72	2.27	21.08
West Virginia	1.74	0.22	0.15		0.15	1.96
Wisconsin	75.46	0.41	3.78	0.72	4.50	75.87
Wyoming	374.07	0.16	107.88		107.88	374.22
Total	77.20	0.39	8.95	1.97	10.91	77.59

** Offshore wind potential not available for Alaska, and rooftop solar potential not available for Alaska or Hawaii.*

TABLE A-2. WIND AND SOLAR TECHNICAL POTENTIAL AS SHARE OF STATE 2050 ELECTRICITY CONSUMPTION UNDER NREL HIGH ELECTRIFICATION SCENARIO[210]

(Green highlight indicates renewable resource could supply state electricity demand)

State	Utility-scale PV	Rooftop PV	Onshore wind	Offshore wind	Total wind	Total solar
Alabama	24.85	0.17	0.00	0.35	0.35	25.03
Alaska*	486.30		80.63		80.63	486.30
Arizona	88.27	0.19	0.19		0.19	88.46
Arkansas	55.31	0.17	0.25		0.25	55.48
California	11.96	0.25	0.12	0.51	0.63	12.21
Colorado	89.80	0.21	9.57		9.57	90.00
Connecticut	0.39	0.21	0.00	0.10	0.10	0.60
Delaware	12.83	0.16	0.00	0.92	0.92	12.99
District of Columbia	0.00	0.06	0.00		0.00	0.06
Florida	11.07	0.22	0.00	1.66	1.66	11.29
Georgia	20.52	0.16	0.00	0.58	0.58	20.69
Hawaii*	1.84		0.34	4.41	4.75	1.84
Idaho	100.73	0.16	1.13		1.13	100.89
Illinois	22.80	0.15	1.81	0.05	1.85	22.95
Indiana	24.36	0.15	1.85	0.02	1.87	24.51
Iowa	75.74	0.18	18.59		18.59	75.92
Kansas	169.24	0.19	36.12		36.12	169.43
Kentucky	13.81	0.16	0.00		0.00	13.97
Louisiana	31.06	0.19	0.01	4.78	4.79	31.25
Maine	35.92	0.23	0.94	13.38	14.32	36.15
Maryland	3.96	0.15	0.02	0.62	0.64	4.11
Massachusetts	0.77	0.20	0.02	8.14	8.16	0.97
Michigan	19.07	0.17	0.52	0.72	1.24	19.25
Minnesota	68.46	0.17	9.03	0.00	9.04	68.63
Mississippi	58.03	0.18	0.00	0.11	0.11	58.20
Missouri	29.37	0.19	3.77		3.77	29.56
Montana	281.44	0.13	94.27		94.27	281.57
Nebraska	172.58	0.20	56.00		56.00	172.78
Nevada	153.80	0.25	0.32		0.32	154.04
New Hampshire	2.15	0.21	0.20	0.18	0.38	2.36

State	Utility-scale PV	Rooftop PV	Onshore wind	Offshore wind	Total wind	Total solar
New Jersey	2.89	0.18	0.00	1.67	1.68	3.07
New Mexico	312.24	0.19	26.66		26.66	312.43
New York	4.28	0.15	0.18	0.82	0.99	4.43
North Carolina	15.66	0.16	0.01	2.31	2.32	15.82
North Dakota	378.67	0.15	98.67		98.67	378.82
Ohio	11.20	0.16	0.39	0.19	0.58	11.36
Oklahoma	73.67	0.21	11.94		11.94	73.88
Oregon	41.89	0.18	0.76	2.56	3.33	42.07
Pennsylvania	2.36	0.20	0.03	0.05	0.08	2.56
Rhode Island	0.83	0.24	0.01	3.25	3.25	1.07
South Carolina	21.46	0.15	0.00	4.71	4.72	21.62
South Dakota	400.70	0.19	116.12		116.12	400.89
Tennessee	12.12	0.16	0.00		0.00	12.29
Texas	49.95	0.17	7.06	0.91	7.96	50.12
Utah	69.88	0.14	0.42		0.42	70.02
Vermont	3.73	0.23	0.52		0.52	3.96
Virginia	8.60	0.16	0.02	0.73	0.75	8.76
Washington	12.66	0.18	0.34	1.05	1.39	12.84
West Virginia	1.10	0.14	0.10		0.10	1.24
Wisconsin	28.03	0.15	1.40	0.27	1.67	28.18
Wyoming	273.42	0.11	78.86		78.86	273.54
Total	35.67	0.18	4.13	0.91	5.04	35.85

** Offshore wind potential not available for Alaska, and rooftop solar potential not available for Alaska or Hawaii.*

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