Accelerating the US Clean Energy Transformation

Challenges and Solutions by Sector

Charles F. Kutscher, Jeffrey S. Logan, Timothy C. Coburn
Renewable and Sustainable Energy Institute, University of Colorado Boulder

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University of Colorado Boulder
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Cover images clockwise from upper left:

A photovoltaic array with wind turbines (Pixabay)

The Bullitt Center in Seattle is the nation's first urban mid-rise commercial project to attempt the goals of the Living Building Challenge benchmark of sustainability in the built environment. (https://bullittcenter.org/building/photo-gallery/)

Steel pours from an electric arc furnace in Brackenridge, Pa. (Wikimedia Commons)

Electric car plugged into charging station

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ACRONYM LIST

ARRA	American Recovery and Reinvestment Act
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BECCS	bioenergy with carbon capture and storage
BEV	battery electric vehicle
Btu	British thermal unit
CDR	carbon dioxide removal
CCUS	carbon capture utilization and storage
CES	clean energy standard
CPP	Clean Power Plan
DACCS	direct air capture with carbon storage
DCFC	direct current fast charge(r)
DOE	US Department of Energy
EIA	Energy Information Administration (US DOE)
EPA	Environmental Protection Agency
EV	electric vehicle
GW	gigawatt (one million kW)
GWP	global warming potential
HDV	heavy-duty vehicle
HVAC	heating, ventilating, and air-conditioning
HVDC	high-voltage direct current
ICE	internal combustion engine
IoT	internet of things
IPCC	Intergovernmental Panel on Climate Change
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
LDV	light-duty vehicle
MW	megawatt (one thousand kW)
MWh	megawatt-hour
NET	negative emissions technologies
NREL	National Renewable Energy Laboratory
PEM	proton exchange membrane
PHEV	plug-in hybrid electric vehicle
PV	photovoltaics
R&D	research and development
RD&D	research, development, and deployment
SAF	sustainable aviation fuel
SCC	social cost of carbon
SMR	small modular reactor or steam methane reformation
SHEMS	Smart Home Energy Management System
TWh	terawatt-hour (a billion kWh)
VRE	variable renewable energy

Executive Summary

Cattle graze in the distance behind the turbines at a wind farm near Fluvanna, Texas.
(Leaflet via Wikimedia Commons)

Thirty-two years after scientist James Hansen warned Congress of the seriousness of climate change, it is finally being recognized as an existential crisis with enormous negative impacts on our planet. This report describes how we can eliminate the energy-related carbon dioxide emissions associated with the burning of fossil fuels, which represents three quarters of US greenhouse gas emissions.

The consequences of the slow US response to the COVID-19 pandemic should be considered a wake-up call regarding our failure to address climate change. In both cases, we have ignored scientists and ample warnings. But whereas our failure to adequately address the coronavirus pandemic will teach us how to prepare for future pandemics, there will be no second chance with climate change. Once the ice sheets have melted, they will not return, at least on a human time scale. And the human and economic toll caused by climate change will be vastly greater than that inflicted by the pandemic. It is thus imperative that we drive carbon emissions to zero as rapidly as possible.

Modeling has shown that if the world stops burning fossil fuels, we can avoid the worst impacts of climate change. But transitioning the US energy system from fossil fuels to non-carbon energy sources will provide a host of benefits beyond addressing climate change. Visible air pollution and associated healthcare costs will be reduced. Social equity will improve because low-income communities are disproportionately affected by the negative impacts of widespread fossil fuel use. And because this transition will produce a net increase in good-paying jobs, it will boost a post-COVID recovery.

This report covers the technologies that can allow us to transition away from fossil fuels in four major sectors: electricity generation, buildings, transportation, and industry. If electricity is viewed as a separate sector, as it is in this report, US energy-related carbon dioxide emissions were roughly 32% from electricity generation, 12% from commercial and residential buildings, 37% transportation, and 20% from industry in 2019, according to the US Department of Energy's Energy Information Administration. Approximately 74% of the generated electricity is consumed by buildings and the rest by industry. With the emissions associated with electricity generation distributed, the 2019 energy-related carbon dioxide emissions for the three end-use sectors were as follows: 35.2% buildings, 37.1% transportation, and 27.7% industry. All three end-use sectors make large contributions to carbon emissions, and decarbonizing them, along with the electricity sector, should be our highest priority.

Modeling has shown that if the world stops burning fossil fuels, we can avoid the worst impacts of climate change. Transitioning our energy system from fossil fuels to non-carbon energy sources provides a host of benefits beyond addressing climate change.

For each sector, we discuss solutions that can be applied immediately, along with remaining challenges in implementing them. Renewable technologies are now the lowest-cost sources of new electricity generation. Electrifying our energy needs as much as possible and generating that electricity with renewable sources is a key strategy in achieving the needed transition across all sectors. Because climate change damage has such high economic costs, providing government incentives to speed the transition is well justified. Therefore, in each of the four sectors we also include a list of policy options to promote decarbonization.

Electricity Sector

Electricity generation has experienced large reductions in carbon dioxide emissions in the United States since the 2008 recession, but the outlook is not all positive. Since roughly 2005, advances in hydrofracking and directional drilling have greatly increased the supply of low-cost natural gas. As a result, natural gas electricity generation has displaced much of the nation's coal-generated electricity. But even the highest-efficiency natural gas plants emit approximately half as much carbon dioxide as coal plants. As a result, overall power sector carbon dioxide emissions actually increased in 2018 due to the growth in gas generation. In addition, fugitive methane emissions from fracking sites and the rest of the gas distribution system have further exacer-

Wildflowers bloom near solar panels on Niwot Ridge in Boulder County, Colorado. (Jeff Lukas/CIRES)

bated global warming. At the same time, the costs of solar and wind electricity have decreased dramatically in the last decade, and a transition from fossil fuels to these two renewable technologies—and their enablers—is the linchpin of a climate change action strategy.

Because wind and solar are variable sources of electricity, steps must be taken to ensure that grid electricity remains reliable. These steps involve the following: deploying wind and solar together to take advantage of their complementary nature; maximizing spatial diversity of deployment to ensure smooth output; expanding transmission; and employing battery storage, which has dropped dramatically in cost. There are also a variety of demand flexibility options that can match electric demand to the variable renewable supply. These include smart meters, microgrids, home batteries, home energy management systems, and improved electricity pricing structures. Finally, dispatchable renewable energy generation provided by hydropower, geothermal power, and concentrating solar power with thermal storage can help firm up the variable renewable electricity supply.

To transition away from fossil fuels quickly enough, we believe a clean energy standard is needed for the electricity sector. Achieving 100% renewable electricity by 2035 is a challenging but achievable goal, and there should be intermediate targets set for the years 2025 and 2030 to ensure that progress is being made. To achieve the 2035 goal, federal policy must emphasize grid modernization and clearly guide a transition from natural gas to renewable generation. If Congress is unable to pass such a legislative package, a committee of legal and administrative experts should be convened to maximize decarbonization using existing legal statutes, new executive orders, and other policy levers. Non-federal actions, including state, local, and corporate action, are essential

The roof of a commercial complex in Boulder, Colorado, uses an angled mounting design to further optimize the efficiency of photovoltaic cells. (bouldercommons.com)

to achieving climate goals. Additional RD&D is also needed to accelerate development of technologies and methodologies that can enable clean generation, including long-duration storage, dispatchable zero-generation options, expanded transmission, and demand flexibility options.

Buildings Sector

The buildings sector is the largest primary energy user of all sectors. Also, 74% of generated electricity is consumed in buildings. Deploying energy efficiency measures in this sector will not only reduce the total energy needed but will also limit the amount of new renewable electricity generation that must be built. As the carbon emissions associated with building operation decrease, it will become more important to use construction materials that have low embodied carbon emissions.

The four steps needed to decarbonize the buildings sector are:

1. **Maximize energy efficiency.** In addition to reducing the amount of new electricity needed, this will limit the impact on utility bills and preserve resources.
2. **Electrify all buildings to make use of the emerging renewable electricity grid.** Modern heat pump systems can efficiently replace natural gas. Deployment should be coupled with energy efficiency improvements and rooftop and community photovoltaic systems.
3. **Take advantage of building response capability to match electricity demand to variable renewable energy supply.** This can be accomplished with controllable equipment, home energy management systems, home batteries, and home electric vehicle charging used in conjunction with a smart grid.
4. **Minimize embodied carbon emissions in building materials.** Both new construction materials and those used for energy efficiency improvements should be chosen to minimize embodied carbon emissions.

Researcher Andrew Meintz works with vehicle chargers at the National Renewable Energy Laboratory's Electric Vehicle Grid Integration area. (Dennis Schroeder/NREL 62139)

Economic recovery funds should be targeted to take advantage of the job creation and social equity improvement opportunities associated with building energy electrification and efficiency improvements. To promote energy efficiency, all residential and commercial properties should receive an energy audit and energy performance score prior to sale or rental. Beginning in the next two years, or as soon as possible, all new buildings should be all-electric, and conversion of existing buildings to all-electric should begin with a goal of having the buildings sector fully electrified by 2035, in time for a zero-carbon national electric grid. Federal, state and local government buildings should lead the way in the building sector energy transition. The government should provide low-interest loans and other financial incentives so that electrification does not cause an undue increase in homeowner utility bills. New building equipment and key appliances should be designed to support a clean grid by providing controllable demand response capability. Federal, state, and local "buy green" programs should promote the use of low embodied carbon materials in new buildings and retrofits.

Transportation Sector

Electrification is the key element for decarbonizing the transportation sector. Approximately 59% of US transportation emissions are due to light-duty vehicles, and battery EVs are a proven and growing means for transitioning these vehicles away from fossil fuels. Ongoing reductions in battery costs will allow EVs to soon achieve first-cost parity, and the rapid expansion of fast-charging stations across the country will make EVs practical for long-distance travel. Medium- and heavy-duty vehicles represent another 23% of greenhouse gas emissions in the transportation sector. Battery electric vehicles are making inroads here as well. For the heaviest and longest-range needs, fuel cell vehicles powered by hydrogen produced from renewable electricity via electrolysis are currently viewed as a viable option, but they will require financial incentives in the near term.

Some combination of electrification and hydrogen can decarbonize high-speed rail, marine shipping,

This electric-arc furnace melts steel and aluminum for rocket parts and aerospace applications at Michoud Assembly Facility, New Orleans, Louisiana. (Wikimedia Commons)

and short-haul aviation, but low-carbon sustainable aviation fuels will likely need to be developed for long-range air travel.

One positive outcome of the COVID-19 pandemic is that it has affected the American mindset about transportation. Telecommuting has become more widely accepted. The closing of many city streets to traffic to allow for more walking and outdoor dining has made the advantages of walkable communities more apparent. Local governments will play an important role in extending the shift from cars to pedestrians in a post-pandemic environment.

To decarbonize transportation, federal and state tax credits for EVs should be extended and expanded, and subsidies for gasoline should be rapidly phased out. Special attention should be focused on lower-income EV purchases so that everyone is encouraged to buy EVs. EV ownership should be incentivized by providing such things as EV parking spaces, allowing EV use in high-occupancy vehicle lanes, and completing a dense network of high-speed EV charging stations across the United States. The federal government—in coordination with state policies—should establish a goal that all new light-duty vehicles will be 100% electric by 2030 and enact a buy-back program for conventional vehicles.

Industrial Sector

The industrial sector produces a wide range of different products, each with different energy requirements. Industrial plants are spread throughout the United States, although Texas, Louisiana, and California are the largest industrial energy users and have the most industrial facilities. Petroleum refining is responsible for 18% of energy-related carbon dioxide emissions, but that will decline as the nation transitions away from fossil fuels. Process energy, and in particular process heating, are the biggest sources of emissions. For many of the heating needs, electricity can substitute for fossil fuels. For temperature needs below about 150°C, heat pumps can be used. Above that, electricity can be directly used but at a higher cost. For applications that are hard to electrify, hydrogen can be employed. Blue hydrogen produced from natural gas, but utilizing carbon capture and storage, can provide short-term needs, but green hydrogen produced from electrolysis of water using renewable electricity represents a capital investment that offers a long-term solution and should be emphasized. Much of the process heating needs are at temperatures below about 300°C and are therefore potential opportunities for solar industrial process heat.

Because industry is the most difficult sector to economically electrify, government financial incentives, emissions standards, and other actions will be needed. Converting existing process heat equipment to use electricity and hydrogen will require some redesign and rewiring, and a collaboration between the federal government and industry can play an important role in demonstrating and testing these modifications prior to widespread deployment. Federal RD&D should focus on reducing the costs of producing and using green hydrogen, with special emphasis on lowering the cost of electrolyzers and developing other green hydrogen production alternatives. The government should launch a program to explore the application of solar thermal energy to locations such as portions of California and Texas that have both a good solar radiation resource and large process heat needs.

Carbon Dioxide Removal Methods

Beyond efforts to prevent emissions at the source, carbon dioxide removal (CDR) options will also be needed. Biological techniques include reforestation and afforestation, as well as actions to end deforestation, enhanced soil carbon retention in agriculture, bioenergy with carbon capture and storage (BECCS), and biochar as a soil amendment. Non-biological techniques include enhanced rock weathering and direct air capture with carbon sequestration. Biological methods must be evaluated in terms of their impact on land use (including social and food production implications), and their carbon impact must be determined as a function of location and be evaluated relative to the undisturbed land. Both BECCS and direct air capture utilize deep geological storage and, assuming leakage is prevented, provide a level of permanence that other methods do not. Direct air capture has the advantage that it can be located at geologic sequestration sites. However, it is expensive and requires a large amount of energy. Efforts should focus on cost reduction and ways to utilize waste heat and carbon-free energy that does not compete with the displacement of fossil fuel combustion, which is a more effective and higher priority. (This report does not evaluate geo-engineering techniques to limit global warming such as solar radiation control methods.)

To more rapidly achieve net-zero carbon emissions, it makes sense to develop, test, and begin deploying many of these methods, but such action must not divert attention from transitioning away from fossil fuels as quickly as possible. Studies are needed to evaluate realistic potentials for all the methods. Biochar, soil carbon retention methods, and the application of enhanced weathering need to be evaluated in the field in terms of their impact on soil productivity and the level of carbon sequestration permanence. The federal government should support pilot plants to help lower the capital and operating costs of direct air capture plants and establish a modified tax credit for CDR that incentivizes long-term technology innovation while avoiding carbon dioxide leakage into other sectors of the economy (as occurs with the Enhanced Oil Recovery tax credit).

We must absolutely minimize the additional carbon dioxide we add to the atmosphere, and that means we must replace fossil fuels with carbon-free energy sources. Climate change is a serious but solvable crisis, and the sooner we work together to address it, the sooner we can reap the full range of benefits.

1.0 Background and Rationale

The Cal-Wood wildfire, the largest wildfire ever in Boulder County, Colorado, burns out of control in the distance behind wind turbines at the National Renewable Energy Laboratory. (Werner Slocum / NREL 62675)

It has been 32 years since Dr. James Hansen, then director of NASA's Goddard Institute for Space Studies, testified to the US Senate Committee on Energy and Natural Resources that, "Global warming has reached a level such that we can ascribe with a high degree of confidence a cause and effect relationship between the greenhouse effect and observed warming. … It is already happening now." (Hansen 1988).

In that same year, 1988, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC), which has conducted five major multi-year studies of increasing certainty and generated numerous other scientific reports on the subject. Various efforts over these years have attempted to create international agreements to reduce greenhouse gas emissions and limit temperature rise. The most recent and most promising was in Paris in December 2015: The United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21). There, representatives of 195 nations agreed to address climate change by taking the necessary measures to limit average global temperature rise to 2°C compared to pre-industrial times, with an aspirational goal of limiting warming to 1.5°C. Although the Paris agreement was a good first step, analyses have shown that even if the actual individual national pledges were all met, the temperature rise would reach approximately 3°C. And, in fact, most nations have not been meeting their pledges. Moreover, the Trump administration officially withdrew from the Paris agreement on Nov. 4, 2020. More than five years have passed since COP21, and studies since have confirmed that average global temperatures have risen a little over 1°C (1.8°F) from pre-industrial levels (IPCC 2018). We have already witnessed extreme precipitation and flooding, extensive droughts, and record wildfires.

The United States has less than 5% of the world's population but is responsible for about 25% of historic carbon dioxide emissions (Ritchie 2019a) and so has an obligation to address climate change. According to the EPA (EPA 2020c) 75.4% of US greenhouse gas emissions were the result of the burning of fossil fuels for energy. Thus, the most important thing we must do to mitigate global warming is transition from fossil fuels to sustainable, carbon-free energy sources.

The consequences of the slow US response to COVID-19 should be considered a wake-up call regarding our failure to address climate change. In both cases, we have ignored scientists and ample warnings, and public opinion has been swayed by disinformation. But whereas our failure to adequately address the coronavirus pandemic will teach us how to prepare for future pandemics, there is no second chance with climate change. Once the ice sheets have melted, they will not return, at least on a human time scale. And the human and economic toll caused by climate change will be enormously greater than what we have suffered from the pandemic. It is thus imperative that we drive carbon emissions to zero as rapidly as possible.

1.1 The high cost of climate change damage

For decades, extreme weather events cost the US economy an average of roughly $50 billion per year. However, in recent years, annual costs have reached as high as $200 to $300 billion as a result of disasters in which climate change played a notable role (NOAA National Centers for Environmental Information 2020). As we write this, record wildfires have been decimating California, Oregon, Washington, and Colorado, sending unhealthy, smoke-filled air throughout Western states.

Economists have attempted to calculate the economic cost of carbon dioxide emissions based on environmental and societal damage. This is expressed as a social cost of carbon, or SCC, in units of US$ per metric tonne (1,000 kg) of carbon dioxide (tCO_2). In 2016, the EPA updated earlier SCC estimates generated by an Interagency Working Group projecting 2020 SCC values as a function of different discount rates, concluding that they were: 12, 42, and 62 $/$tCO_2$ at discount rates of 5, 3, and 2.5%, respectively (IWG 2016; EPA 2016). In his seminal 2006 Stern Review (Stern 2006) Nicholas Stern used a discount rate of 1.4%, arguing that using a higher value places an unfair burden on future generations. In 2016 the National Bureau of Economic Research surveyed economists and climate scientists to obtain their estimates of the SCC and obtained median values, respectively, of $174 and $316 per tCO_2 (Pindyck 2016).

In September 2018 Katharine Ricke and colleagues (Ricke et al. 2018) published a study in which they followed recommendations of the US National Academy of Sciences and estimated the damages, and the costs of addressing these damages, country by country. They used a damage function (Burke, Hsiang, and Miguel 2015) that accounts for the fact that damage increases non-linearly with an increase in average global temperature. They determined a cost for each country per tCO_2 of global carbon dioxide emissions, using a discount rate for each country as a function of its growth rate, and then added these to determine a total global cost.

Adding all the country costs together yielded a median global SCC value of $417 per tCO_2, based on an average discount rate of about 3%. Regardless of which country emits a tonne of carbon dioxide to the atmosphere, that tonne can be considered to produce $417 of damage, although that damage is distributed unevenly around the globe. As a point of reference, if this social cost of carbon were used to account for the carbon dioxide emitted by burning a gallon of gasoline, using this estimate would add $3.71 to the cost. Many countries in Europe and elsewhere already have gasoline taxes that are (coincidentally) close to being commensurate with this level of climate change damage. For example, per-gallon gasoline taxes are $3.11 in Italy, $3.17 in Israel, and $3.36 in The Netherlands, compared to $0.56 in the United States (Watson 2019).

If we multiply the world's annual carbon dioxide emissions of 37 billion tCO_2 by an SCC of $417 per tCO_2, the social cost of those emissions is $15 trillion per year, or about 17% of the world's annual gross domestic product. Note that in 2006, the Stern Review estimated that the cost of climate change damage would be between 5% and 20% of the world GDP, and that mitigating it would incur an annual cost of only about 1% of the global GDP. Since that 2006 study, carbon emissions have continued to grow, increasing both the cost of climate change damage (which has been at the high end of estimates) and the difficulty of addressing it. On the other hand, the costs of wind and solar energy have decreased dramatically.

Because a global SCC of $417 per tCO_2 is much higher than the cost of most abatement measures, one can conclude, as Stern did, that the net cost of addressing climate change is much lower than the cost of paying for the damage if we don't act. Of course, it is prudent to minimize the amount of additional carbon dioxide we add to the atmosphere and also to draw down what is already there at the lowest possible cost. But this high social cost of carbon underscores the fact that climate change must now be treated as a true emergency and that the net cost of an energy transition (i.e., the cost of carbon-free energy minus the cost saved by not burning fossil fuels) is much less than the cost of the avoided climate change damage.

The social cost of carbon, or SCC, is an estimate of how much damage greenhouse gas emissions wreak on the environment and society. The high social cost of carbon underscores the fact that climate change must now be treated as a true emergency and that the cost of an energy transition is much less than the cost of the avoided climate change damage.

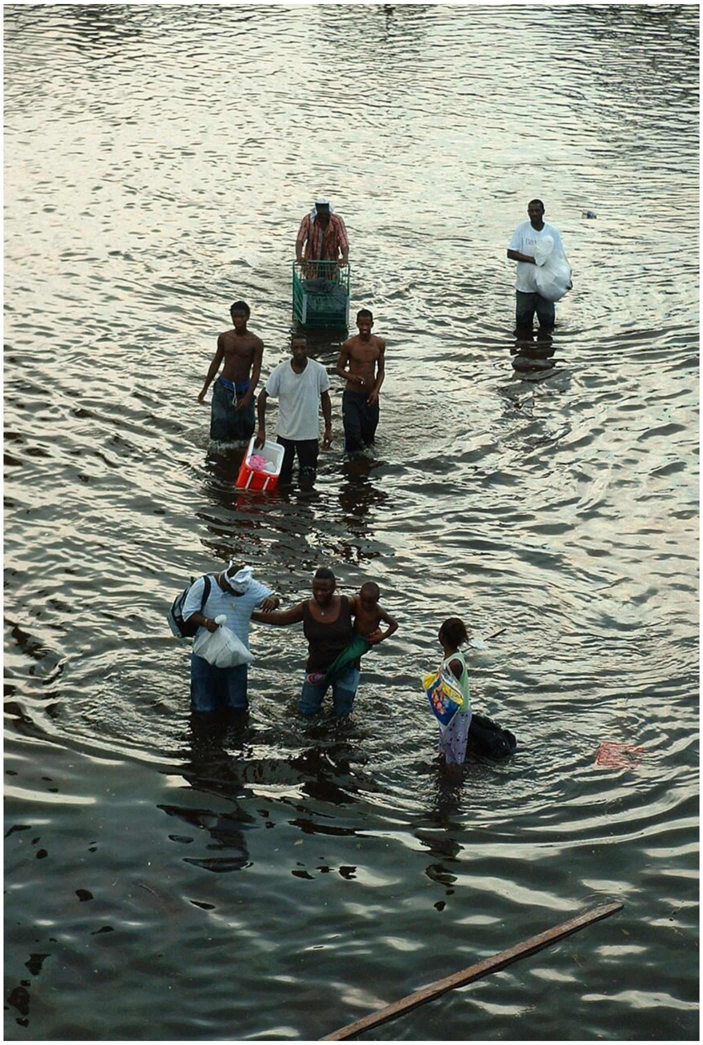
1.2 Recovering from the COVID-19 pandemic

The United States has experienced far more COVID-19 cases and deaths than any other country. With a little more than 4 percent of the world's population, the United States has had more than 20% of the cases (Chiwaya and Siemaszko 2020). As of December 15, 2020, US deaths totaled over 300,000, and more than 1.6 million have died worldwide (Johns Hopkins Center for Systems Science and Engineering 2020). The pandemic caused US unemployment to reach a peak of 25%, and total unemployment claims in 2020 have surpassed 50 million (Tampone 2020). The United States will thus face an enormous recovery, requiring many kinds of changes. The necessity of massive change also creates opportunities, however. For example, air pollution decreased during the pandemic, and some city dwellers accustomed to seeing smog obscure distant mountains could suddenly breathe clean air and see those mountains clearly. Recovering from the pandemic offers the opportunity for our nation to address long-standing problems and return to leadership on the world stage.

Climate change is now widely recognized as an existential crisis, and as we recover the US economy, it is critically important that the United States return to leadership in addressing climate change. Fortunately, there is precedent for a green economic recovery. Following the 2008 economic collapse, the Obama administration launched the American Recovery and Reinvestment Act (ARRA) of 2009, through which Congress eventually spent an estimated $821 billion (CBO 2012). Of this amount, more than $90 billion funded clean energy-related programs, which supported 900,000 job-years in clean energy fields between 2009 and 2015 (WH 2016). The majority of economists have concluded that the ARRA program played an important role in reducing unemployment (IGM Forum 2012). The COVID-19 pandemic is even more serious than the 2008 financial crisis, and Congress has already spent approximately $3 trillion to bolster the economy—over three times the ARRA expenditure.

It is not yet known how many permanent jobs will be lost as a result of the pandemic, but addressing unemployment and associated job creation will be major goals of any recovery effort. Prior to the pandemic, wind turbine technician and solar installer were two of the three fastest-growing jobs in the United States according to the US Bureau of Labor Statistics (BLS 2020). The Environmental and Energy Study Institute has reported that in 2019, wind power employed about 111,000 people, solar energy employed about 240,000 workers, and the energy efficiency sector employed 3.1 million (EESI 2019), or more than three times the number of jobs in the fossil fuel industry. Addressing the climate change crisis offers an outstanding opportunity to create net jobs (far above and beyond those eventually lost in the fossil fuel industry) and restore the economy.

Addressing climate change as a vehicle for helping the economy recover from the COVID-19 pandemic is a logical theme, supported by many studies both in the United States and internationally. In June 2020 the International Energy Agency published a detailed report (IEA 2020a) in which it recommended spending $1 trillion per year (about 0.7% of world GDP) for the next three years to improve sustainability in six key sectors: electricity, transport, industry, buildings, fuels, and emerging low-carbon technologies. That report emphasizes the significant job creation provided by wind and solar deployment; building energy efficiency; and electrification of the building, transportation, and industry sectors.



People walk through the New Orleans floodwaters to get to higher ground. New Orleans was under a mandatory evacuation order as a result of flooding caused by Hurricane Katrina in 2005. (Marty Bahamonde/ FEMA)

1.3 Addressing social justice

Transitioning away from fossil fuels will also play an important role in achieving environmental justice. The jobs created will cover a wide range of skill levels, and most are jobs that cannot be outsourced to other countries. Fossil fuel power plants are typically located in low-income neighborhoods, where the rates of childhood asthma and other health issues, as well as senior mortality, are much higher than average (Saylor 2011). Replacing these polluting power plants with a combination of central and distributed renewable generation, along with energy efficiency measures, will both clean the air and create jobs in these communities. Similarly, low-income communities tend to cluster around crowded urban highways (Halsey 2016). Replacing gasoline vehicles with electric vehicles will eliminate local tailpipe pollution and noise levels. It will also greatly reduce fuel and maintenance costs. Finally, low-income neighborhoods are often built in low-lying areas that suffer the most from flooding (NASEM 2019), so reducing atmospheric carbon dioxide levels should eventually reduce the severity of flooding caused by climate change-driven extreme precipitation events and storm surge.

1.4 The health benefits of transitioning away from fossil fuels

It is important to recognize that, in addition to climate change damage from greenhouse gas emissions, the burning of fossil fuels is responsible for air pollution and large associated healthcare costs. The negative impact of air pollution on public health has long been understood, and it has recently been shown that air pollution levels have contributed to the likelihood of COVID-19 deaths (Ogen 2020). A study by the Centre for Research and Energy on Clean Air (CREA) (Farrow, Miller, and Myllyvirta 2020) estimated the total annual economic costs from fossil fuel pollution for various countries around the world. The estimate for the United States was between $470 billion and $870 billion per year, with a central value of $610 billion per year. For comparison, in testimony to Congress on Aug. 5, 2020, Professor Drew Shindell of Duke University gave an estimate of $700 billion per year (Shindell 2020). The CREA report also estimated that 170,000 to 310,000 people in the United States die prematurely because of air pollution generated by burning fossil fuels. Thus, if the United States drastically reduces fossil fuel emissions as part of a climate change mitigation effort, US residents will benefit economically and health-wise from cleaner air even if other countries do not reduce their carbon emissions. The healthcare savings alone justify a transition away from fossil fuels.

1.5 Emerging recognition that climate change is an existential crisis

The good news is that in the last couple of years there has been a growing recognition around the world that climate change is a true emergency and that economic solutions exist to address the problem.

The healthcare savings alone justify a transition away from fossil fuels.

Fifteen-year-old Swedish student Greta Thunberg reasoned that there was little logic to going to school if, upon graduation, she would face a world devastated by climate change. Her simple protest of striking from school ignited a worldwide youth movement. In the United States the Sunrise Movement has energized young people and is impacting American politics, and it was given a seat at the table on the Biden-Sanders Unity Task Force, which was set up to allow the supporters of both presidential candidates to develop joint recommendations.

Climate change was a key topic at the Democratic primary debates. The Unity Task Force, a House Committee (HSCCC 2020a), and the Biden presidential campaign all released a series of ambitious recommendations for addressing climate change. The HSCCC has called for economy-wide net zero emissions by 2050 (HSCCC 2020b). The Unity Task Force has called for rapid deployment of wind and solar energy to achieve a carbon-free electric grid by 2035, as well as net zero emissions from all new buildings by 2030 (Kerry et al. 2020). And President-elect Joe Biden announced a plan to spend $2 trillion on clean energy over four years (Biden Campaign 2020).

There have also been many recent studies describing aggressive decarbonization pathways. The Goldman School of Public Policy of the University of California, Berkeley (Phadke et al. 2020) made use of grid modeling tools from the National Renewable Energy Laboratory (NREL) and others to lay out a pathway for achieving a 90% carbon-free electric grid by 2035. Although a bit short of the 100% goal of the Unity Task Force, the authors recognized the additional challenge of achieving the last 10%. The Rocky Mountain Institute published an economic stimulus strategy (RMI 2020) that lays out recommendations for electrifying buildings and transportation, with a National Climate Bank providing financing. At the time of publication of this report, The Sustainable Development Solutions Network had just published a “Zero Carbon Action Plan” for the United States (SDSN 2020).

1.6 The intent of this report

Because climate change is, indeed, an environmental and economic emergency, we agree with other studies that very aggressive goals are needed and that working toward those goals is exactly what we can and should do to support a post-pandemic economic recovery. Although there are other contributors to US greenhouse gas emissions, our report focuses on reducing the energy-related carbon dioxide emissions resulting from the burning of fossil fuels, because these emissions are by far the dominant cause of climate change. We must absolutely minimize the additional carbon dioxide we add to the atmosphere, and that means we must replace fossil fuels with carbon-free energy sources.

We review the various options for transitioning away from fossil fuels in four sectors with the largest emissions—electric power and the three end-use sectors of buildings, transportation, and industry—and discuss the various challenges and means for making these reductions. If electricity is viewed as a separate sector, US energy-related carbon dioxide emissions are allocated as follows: 31.6% electricity, 11.6% buildings, 37.1% transportation, and 19.7% industry (EIA 2019b). About 74% of the generated electricity is used in buildings and the rest by industry, so total energy-related carbon dioxide emissions can be allocated to each of the end-use sectors as follows: 35.2% from buildings, 37.1% from transportation, and 27.7% from industry.

This report focuses on potential solutions that we can begin to apply immediately, consistent with a long-term goal of achieving net negative carbon emissions economy-wide before 2050. For the various solutions, we review the technological state of the art and describe technical steps that are needed to drive US energy-related carbon dioxide emissions to zero. The main thrusts are to: 1) rapidly transition our electricity system to renewable energy, along with a portfolio of measures to ensure grid reliability, 2) maximize energy efficiency, 3) electrify everything we can, and 4) utilize renewable fuels, especially renewable hydrogen, for energy uses that are difficult to electrify. We will show that hydrogen has applications in all four sectors, but we have chosen to provide the most detail on hydrogen in the industrial section (Section 5).

Eliminating energy-related fossil fuel emissions will not be enough to restore atmospheric carbon dioxide levels, however. We must also address the carbon dioxide that is already in the atmosphere, which is mainly the result of historic fossil fuel emissions. Therefore, we conclude with an overview of the various options being explored to reduce atmospheric carbon dioxide, no single one of which is likely to produce all the needed reductions by itself. However, these are methods that will be needed *in addition to* the rapid deployment of clean energy technologies. Atmospheric carbon dioxide reduction efforts must not slow the transition away from the burning of fossil fuels.

For each area we also suggest some key policy options that can promote the needed changes. While R&D investments will help lower costs and achieve a full transition to carbon-free energy, it is important to recognize that our number-one focus must be to rapidly deploy the proven, low-cost solutions we already have. Ideally, Congress should enact aggressive national legislation, but if the political climate makes that difficult, most measures can be enacted at the state and local levels.

The value of the president declaring a national mission to address the climate crisis cannot be overstated. We believe that a dedicated White House climate change office can, even in the absence of Congressional action, provide critical leadership by focusing federal efforts on carbon reduction. For example, DOE programs should specifically target greenhouse gas emissions reductions as the most important objective. A White House climate change office can also support positive legislative actions being taken by state and local governments across the nation. And it can spearhead a public education campaign to counter disinformation on climate change—an effort in which scientists, educators, political and religious leaders, and journalists can all play important roles. Climate change is a serious but solvable crisis, and the sooner we work together to address it, the sooner we will gain all of the benefits.

2.0 Electricity Sector

A photovoltaic array with wind turbines
(Pixabay)

Sweeping changes have impacted the US electricity sector since the Great Recession of 2007-2008. Some of the dynamics include:

- The shale gas revolution, which increased domestic supply of natural gas and lowered its price. This resulted in a near doubling of natural gas generation, largely at the expense of coal. Correspondingly, natural gas emissions (both carbon dioxide from combustion and methane from leakage and venting) have risen considerably.
- A dramatic decline in the costs of solar PV and wind generation, making them the least expensive forms of new generation in most of the country.
- Ongoing reductions in the cost of energy storage—especially lithium-ion batteries—leading to greater deployment on their own and integrated with variable renewable energy (VRE) in systems that can act like short-term dispatchable resources.
- Increasing use of software tools and advanced digital technologies that allow better control of energy use, demand response, and integration of VRE.
- The decoupling of electricity demand and economic growth. Power demand has been flat over the past dozen years for the first time, largely due to new technologies and energy efficiency policies.
- The realization that the power sector can serve as the hub for decarbonization of much of the economy through "beneficial electrification."
- Growing impacts of climate change on the power sector, including wildfires, lower efficiencies of thermal generators due to higher temperatures, and other vulnerabilities that threaten infrastructure.
- New business models and technologies that encourage greater use of decarbonized and resilient power (community solar, microgrids, and transactive energy).
- The COVID-19 epidemic, which has challenged utilities and grid operators to deliver reliable and resilient electricity (which they have done), but also accelerated power system transformation.

Additional changes are underway, as many states and companies continue to push for bolder action to restore an economy damaged by the pandemic. This section focuses on key drivers, opportunities and challenges in the US electric power sector over the near- to mid-term (five to 30 years).

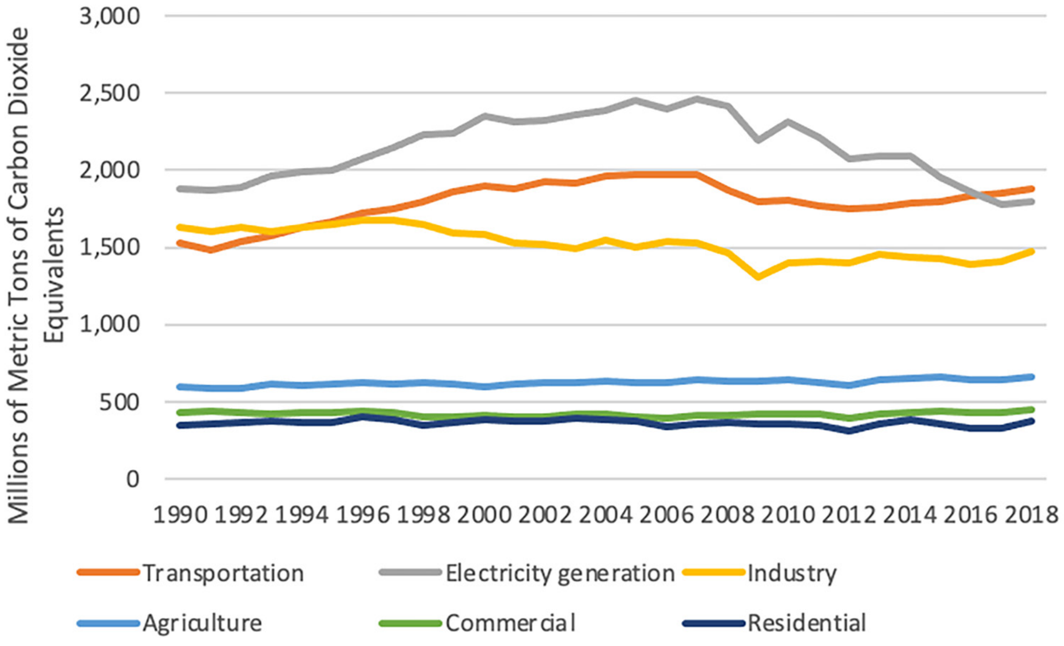


Figure 2.1. US greenhouse gas emissions by sector, 1990-2018. Electricity greenhouse gas emissions (gray) have declined sharply since 2007-2009, first because of the recession, then due to fuel switching. (EPA 2020b)

2.1 Power sector trends: Falling emissions, growing natural gas risks

Greenhouse gas (GHG) emissions in the US power sector have declined sharply since the Great Recession of 2007-2009 (Figure 2.1). The initial decline was due to a drop in overall power demand associated with reduced economic activity, but additional reductions through mid-2020 are mainly associated with fuel switching from coal to natural gas, increased use of renewables, more efficient use of electricity, and, most recently, the impacts of COVID-19 on the economy (Lindstrom 2018; Mohlin et al. 2018; Lee and DeVillibis 2020). Some of the reduction in power sector emissions may have been offset by increases in other sectors associated with the leakage and venting of methane during the natural gas production and transport lifecycle (Newell and Raimi 2014).

Among the six major sectors of the economy (Figure 2.1), only the power sector has experienced a significant decline in GHG emissions over the past decade. Reported US power sector GHG emissions declined by 27% between 2007 and 2018, while total GHG emissions fell by 10% (EPA 2020b). Both have continued to decline since then.

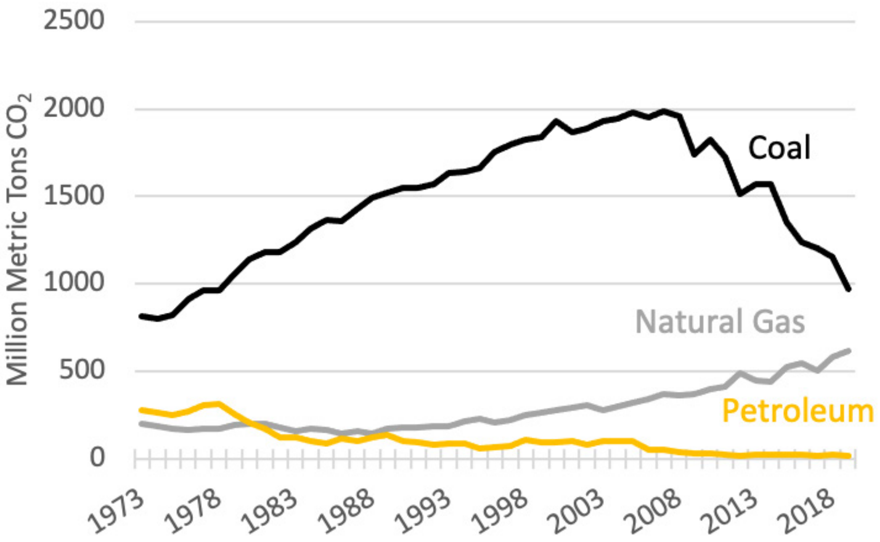


Figure 2.2. US power sector carbon dioxide emissions by fuel. In recent years, as emissions from coal plants have dropped, those from natural gas plants have risen. (EIA 2020c)

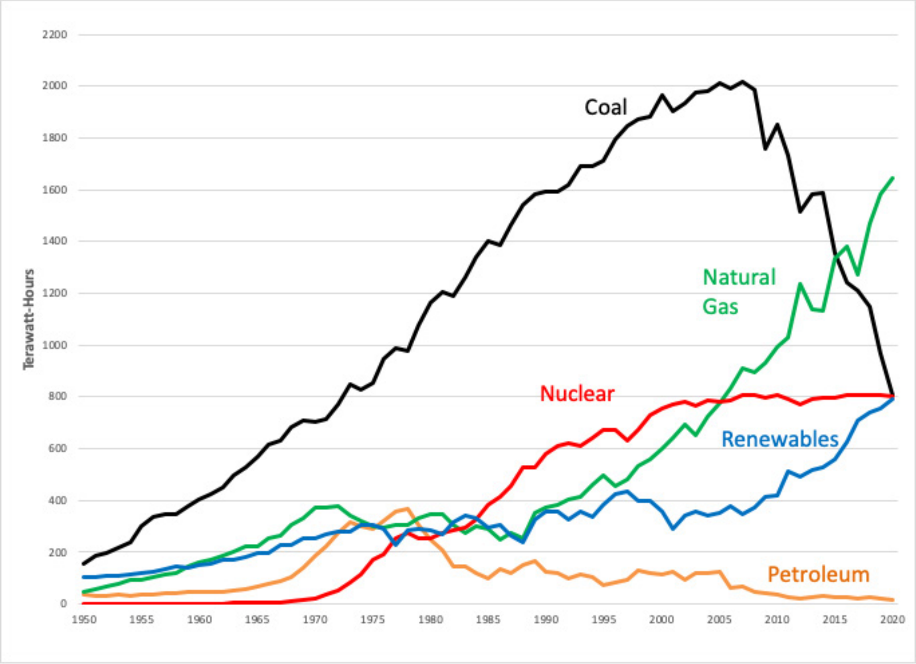


Figure 2.3. Annual US electric energy production by fuel type. As electricity generation by natural gas (green) has surged, coal generation (black) has plummeted. Renewable generation (blue) will likely exceed coal generation for the first time in 2020. (EIA 2020b)

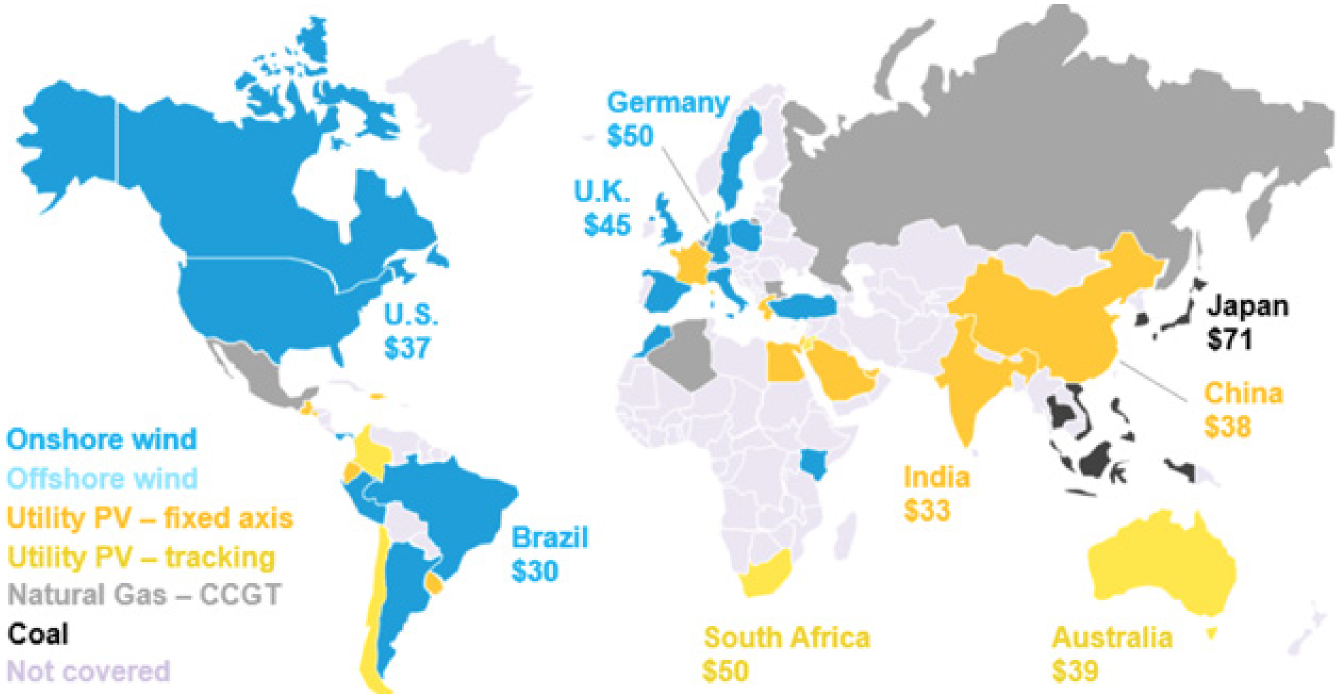
Decarbonization of the power sector so far has been one of the strongest areas of success in climate mitigation for the United States, and that success is despite the lack of a coordinated federal policy to decarbonize. While some countries (e.g., the United Kingdom and Denmark) have cut power sector emissions by a higher percentage than the United States has, none have reduced absolute emissions by as much since 2007 (Crippa et al. 2019). This fact could be used diplomatically by US negotiators if the country rejoins the international community in support of the Paris climate agreement; it may help restore credibility lost since the United States dropped out of the agreement (Chemnick 2020).

Not everything is positive in the power sector though. Natural gas has seen a surge in carbon dioxide emissions (Figure 2.2), although natural gas is at least marginally helpful if used to displace coal and petroleum generation. The actual benefit that gas delivers depends on the full lifecycle GHG emissions of methane production, delivery and use; and the appropriate methodology to calculate lifecycle emissions remains controversial among researchers (Raimi 2020; Heath et al. 2014; Lattanzio 2014; Alvarez et al. 2018). Furthermore, the entire economy must reduce emissions to zero as soon as possible to meet the Intergovernmental Panel on Climate Change's targets (IPCC 2019), and a doubling of natural gas emissions since 2005 does not help. A relatively modest number of new natural gas plants continue to come on-line each year, averaging about 6 gigawatts of new production annually from 2010 to 2018, and these could potentially become stranded assets if the United States addresses the climate challenge in the manner most scientists recommend.

Coal generation has fallen by about 1200 terawatt-hours since 2007, which is nearly as much as gas generation has risen since 1990 (Figure 2.3). Renewables are expected to exceed coal generation for the first time starting in 2020 (Balaraman 2020). Nuclear generation has remained relatively stable and supplies about 20% of US electricity needs, although recent nuclear plant closures have resulted in local increases in carbon dioxide emissions, and more closures are planned (Conca 2019). Petroleum used for the generation of electricity is now nearly inconsequential nationally, although petroleum generation remains important in some regions, including New England, for reliable generation during cold winter periods when natural gas supplies can be insufficient.

2.2 Wind and solar: Now the least costly options

Wind and solar power generation are now the cheapest sources of new generation in vast swaths of the United States and around the world. Bloomberg New Energy Finance estimates that in at least two-thirds of all locations—including the United States—wind and solar are the least expensive sources of unsubsidized, bulk power generation (Figure 2.4). This analysis is based on the levelized cost of energy (LCOE), which is one way to compare electricity costs among different generation options. LCOE analysis does not



Source: BloombergNEF. Note: LCOE calculations exclude subsidies or tax-credits. Graph shows benchmark LCOE for each country in $ per megawatt-hour. CCGT: Combined-cycle gas turbine.

Figure 2.4. International electricity costs by fuel type. Wind and solar power are now the cheapest source of energy in many parts of the world, highlighted in blues and yellows, respectively. (BNEF 2020b)

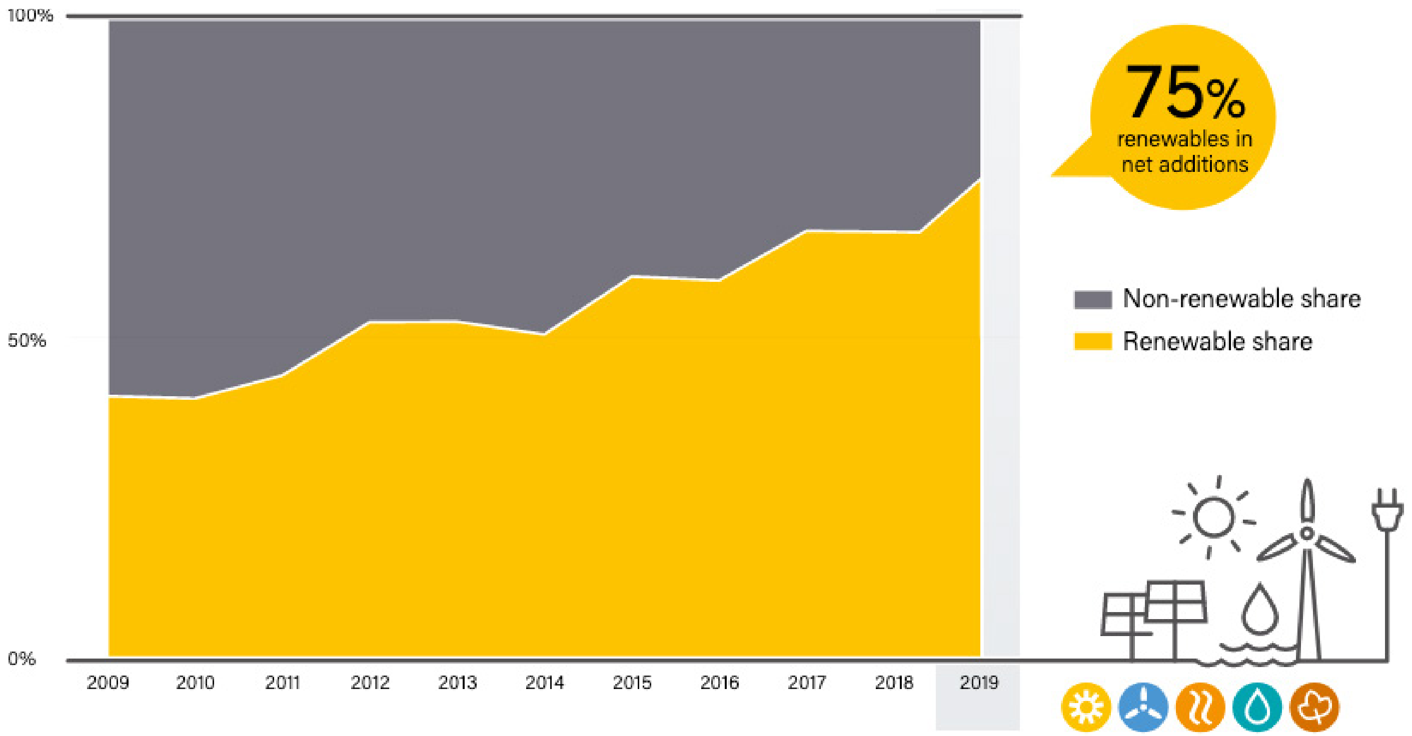


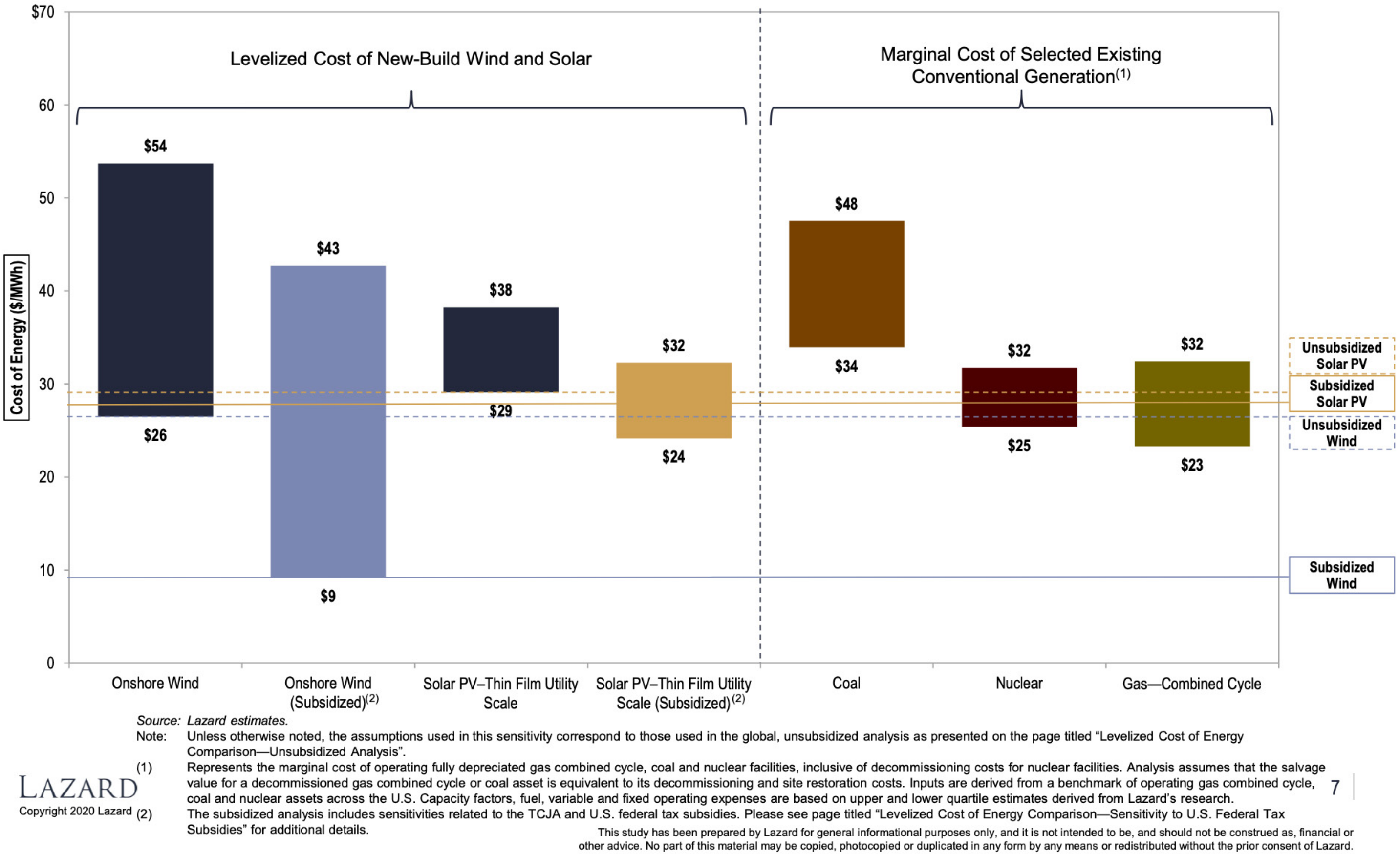
Figure 2.5 Global growth in renewable energy share. Around the world, new generating capacity is increasingly coming from renewables. (REN21 2020)

tell the whole story; it ignores many of the intangibles that different generators can provide (i.e., flexibility benefits, environmental characteristics, resiliency attributes). Even so, it is increasingly clear that variable renewable energy (VRE) is in high demand throughout the globe. In 2019, three-quarters of all new global generating capacity came from renewables, with wind and solar making up the vast majority of that portion (Figure 2.5); figures for the United States are similar (REN21 2020).

Figure 2.6 shows the levelized cost of new renewable electricity in the United States compared to the marginal cost of existing conventional generators (Lazard 2020). According to Lazard's most recent analysis, the cost of land-based wind systems has declined by 70% between 2009 and 2020, and utility-scale photovoltaics (PV) by 90% (using the LCOE metric). The costs have now thus declined to the point where the unsubsidized levelized costs for new wind and solar plants are competitive with or less expensive than the marginal operating and maintenance costs of existing coal, nuclear, and natural gas plants. NREL expects continued cost declines for both technologies (NREL 2020).

Costs for land-based wind and solar PV continue to decline, although at a somewhat slower rate, but other new technologies are also beginning to enter the market. Offshore wind has seen significant cost reductions recently. The first offshore wind installation in the United States, the 30-MW Block Island Wind Farm, began operating in 2016, and states such as New Jersey are planning large, strategic investments to serve as infrastructure hubs for new developments likely to occur in the US Northeast (Johnson 2020). Advantages of offshore wind include: high capacity factors due to more consistent wind speeds, limited need for long-distance transmission since they can be sited close to demand centers, and vast areas available for deployment.

If technological advances can be found for floating offshore wind, these systems will be able to provide important services to power markets on the US West Coast and beyond. Additionally, concentrating solar power systems, which can incorporate thermal storage for up to 14 hours, may see additional cost declines if technology improvements occur and supply chains develop as they did for PV. Finally, new types of solar PV, including perovskite technologies, could inspire additional cost reductions and efficiency improvements if durability concerns and other technical challenges are overcome (Leijtens et al. 2018). Continued federal research, development, and demon-



Source: *Lazard estimates.*

Note: Unless otherwise noted, the assumptions used in this sensitivity correspond to those used in the global, unsubsidized analysis as presented on the page titled "Levelized Cost of Energy Comparison—Unsubsidized Analysis".

(1) Represents the marginal cost of operating fully depreciated gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas combined cycle or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas combined cycle, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper and lower quartile estimates derived from Lazard's research.

(2) The subsidized analysis includes sensitivities related to the TCJA and U.S. federal tax subsidies. Please see page titled "Levelized Cost of Energy Comparison—Sensitivity to U.S. Federal Tax Subsidies" for additional details.

Figure 2.6. US levelized and marginal costs of wind and solar electricity vs. conventional sources. The levelized costs of new wind and solar plants are already on par with even the marginal operating and maintenance costs of existing coal, nuclear, and natural gas generation. (Lazard 2020)

stration of these technologies could make each commercial by 2030 or soon thereafter.

Other novel opportunities are likely to grow rapidly in the next several years. Floating PV, which can be installed on open bodies of water such as lakes and reservoirs, avoids land costs and reduces evaporation of valuable water supply. "Floatovoltaics" also increase PV efficiency by lowering operating temperatures. A recent study estimated floating PV could be suitable for about 12% of the area of human-made bodies of water and could generate almost 10% of current national generation (Spencer et al. 2019). Given that building rooftops have the technical potential to support distributed PV amounting to 39% of current national generation (Gagnon et al. 2016), and utility-scale PV applications many times higher (Lopez et al. 2012), floating PV could serve an important role in regions with suitable bodies of water.

Figure 2.7. Agrivoltaics example. NREL researchers observe a photovoltaic dual-use project in Massachusetts, simultaneously growing crops under PV arrays while producing electricity from the panels. (Dennis Schroeder / NREL 53113)

STATE	TARGET	YEAR	REQUIREMENT
California	100% clean	2045	required
Colorado	100% clean	2050	target
Hawaii	100% RE	2045	required
Maine	100% RE	2050	required
Nevada	100% clean	2050	target
New Jersey	100% clean	2050	target
New Mexico	100% clean	2045	required
New York	100% clean	2040	required
Puerto Rico	100% RE	2050	required
Virginia	100% RE	2045	required
Washington	100% clean	2045	required
Washington, DC	100% RE	2032	required
Wisconsin	100% clean	2050	target

UTILITY	TARGET	REGION
Avista	2045	WA, ID, OR
Duke Energy	2050	OH, KY, TN, NC, SC
Green Mountain Power	2025	VT
Idaho Power	2045	ID, OR
PSC New Mexico	2040	NM
Xcel Energy	2050	MN, MI, WI, ND, SD, CO, TX, NM

Figure 2.8. States and utilities with 100% clean energy goals. An increasing number of states (left) and utilities (above) now have 100% carbon-free power sector goals. (Adopted from UCLA 2019 and DSIRE 2020.)

Integrating PV with agriculture, sometimes called “agrivoltaics,” (Figure 2.7) can improve the social-license-to-operate in areas like New York where communities object to what is seen as the industrialization of farmland when new PV systems are installed. Agrivoltaics can support pollinator health, raise farming revenue by providing shading for specific cash crops (NREL 2019), and can provide shade for grazing livestock. Non-profit community solar projects or “solar gardens” are growing exponentially in states like California where governments have given them the authority to expand (Foehringer Merchant 2020).

End-of-life solutions for wind, solar, and batteries are needed to both extract longer-term value from these technologies and prevent them from going to landfills en masse. Researchers are currently studying circular-economy principles and how best to apply them to clean energy technologies and associated material supply chains (Heath et al. 2020).

2.3 Beyond federal gridlock

States, cities, utilities, and other companies are setting their own aggressive clean energy and carbon targets in the absence of federal action (Figure 2.8). As of September 2020, 11 states, one territory and one federal district had goals or mandates to zero out power sector emissions by mid-century, and a dozen others were actively considering similar measures (DSIRE 2020, Deyette 2019; UCLA 2019). Many others have strong, but not as attention-getting, targets. A growing number of utilities have enacted policies for 100% carbon-free or 100% renewable energy targets in their power sectors, some as early as 2040. Even utilities such as Tri-State—once a holdout for coal generation—in the Rocky Mountain region have charted new courses to grow wind and solar generation starting immediately (Pearl 2020). Nearly 25% of Fortune 500 companies have set targets to go net zero by 2030, a four-fold increase since 2015 (Natural Capital Partners 2019).

Some jurisdictions still oppose opening up to cleaner power. More should be done at the federal level to ensure the US power sector decarbonizes as quickly as possible. In addition to continuing to support VRE deployment, a federal clean power target can ensure that all states and jurisdictions move forward with clean electricity at the speed necessary to prevent the worst impacts of climate change. As with COVID-19, no one will be immune to the impacts of climate change, so everyone must take responsibility.

2.3.1 Targeting clean power

Despite the carbon mitigation achievements noted above, the United States lacks a federal policy for power sector emissions to encourage mitigation from all jurisdictions. Carbon taxes have long been discussed as an economy-wide tool to efficiently cut emissions. Several jurisdictions, including California and a bloc of US East Coast states, have already instituted carbon pricing (Larson 2018). As noted in several recent pieces, however, carbon taxes and another main carbon mitigation tool—cap-and-trade—have been falling out of favor (Roberts 2020b; Mildenberger and Stokes 2020). This is for a variety of reasons: They have been largely ineffective; fail to account for tax regressivity that further damages lower-income consumers (unless a controversial dividend component is included); and they set up a challenging political barrier (Mildenberger and Stokes 2020). A carbon tax-and-dividend approach can still be an economy-wide tool to steer investment and consumer behavior, but should not be the keystone of a carbon policy that needs to eliminate net emissions by 2050.

For the power sector, a clean energy standard (CES) has thus been gaining acceptance and support as a mitigation tool, especially since electrification can serve as the hub of economy-wide decarbonization. This approach sets targets for net-zero carbon generation options, similar to the way state renewable portfolio standards (RPSs) operate, but broader. It can avoid picking technology winners and set a level playing field for all low-carbon forms of energy, including energy efficiency. Unlike a carbon tax, a CES can support an environmental justice platform since it is not as regressive (Stronberg 2019).

A properly designed CES is likely to give states the most flexibility in establishing markets for zero-carbon generation within the larger confines of a federal legal framework and their own existing clean energy frameworks (C2ES 2019). A CES can include today's most economic resources like wind and solar, as well as hydropower, geothermal, and biopower (assuming appropriate lifecycle accounting), and it may encompass future evolutionary developments in natural gas (with carbon capture, utilization and storage), advanced nuclear power, marine and hydrokinetic power, and other advanced-generation options.

National CES legislation was introduced in Congress in 2019, but did not advance. The bill would have required every seller of retail electricity to boost sales of clean generation each year by a certain percentage until an ultimate target was reached. Clean energy credits associated with electricity generation could be traded much like renewable energy credits are traded in a renewable portfolio standards system. Careful design of a CES involves many options, as summarized in a recent Center for Climate and Energy Solutions briefing (C2ES 2019).

For the power sector, a clean energy standard has been gaining acceptance and support as a mitigation tool for decarbonization. This approach sets targets, avoids picking winners, and sets a level playing field for all low-carbon forms of energy, including efficiency. It also supports environmental justice platforms.

Unlike the Clean Power Plan (CPP) proposed by the Obama administration, a national CES would require congressional legislation rather than relying on existing authority under the Clean Air Act. In the event Congress is unable to pass a CES, the administration could return to a newer, stronger version of the CPP, although it will likely be legally challenged in the same way as the CPP has been (Magill 2016). If a congressional CES is unobtainable, the administration should convene Clean Air Act legal experts to improve the CPP and take other steps to decarbonize power generation as quickly as possible.

The House Select Committee on the Climate Crisis recently proposed as a CES target net-zero emissions in the electricity sector by 2040, and a simultaneous focus on environmental justice (HSCCC 2020b). This target aligns with a recent study from Energy Innovation and the University of California (Phadke et al. 2020).

2.3.2 VRE enablers

The issue with deploying variable renewable energy today is not so much one of initial costs, but of overcoming integration challenges, especially at very high penetrations, depending on the specific grid situation. Energy storage as well as a number of new VRE enablers can help overcome these challenges.

Some observers argue that VRE options are not cost-effective after renewables reach very high levels of the generation mix, and then conclude that VRE is therefore not a viable solution to the climate problem (Freed, Bennett, and Goldberg 2015; Cloete 2013). In mid-2020, VRE accounted for only about 10% of the generation mix (although states like California, Texas, and Iowa are much higher), so there is a huge

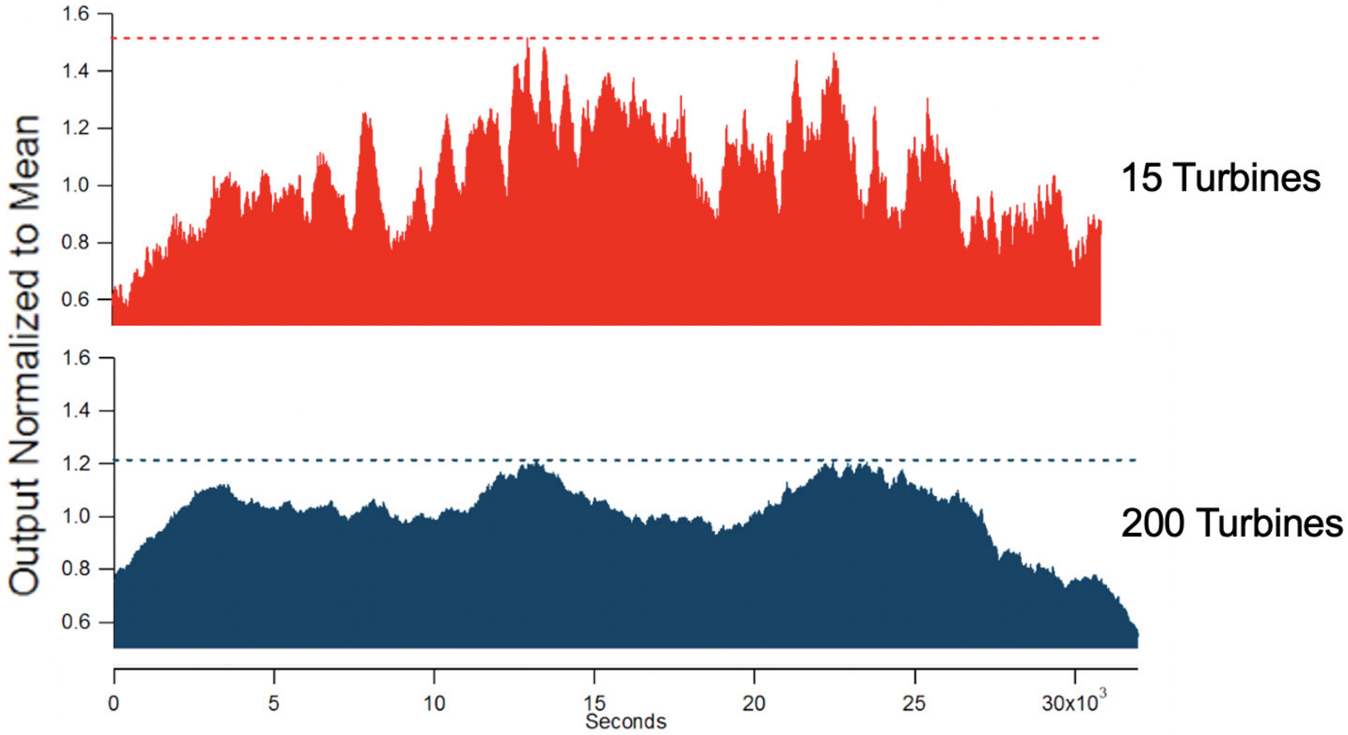


Figure 2.9 The impact of wind farm size on power output profile. Larger wind farms provide a much smoother output power than smaller wind farms illustrating the benefits of spatial extent for variable renewable energy sources. (Milligan and Kirby 2010)

potential for growth before we need to perfect other potential generation and enabling options.

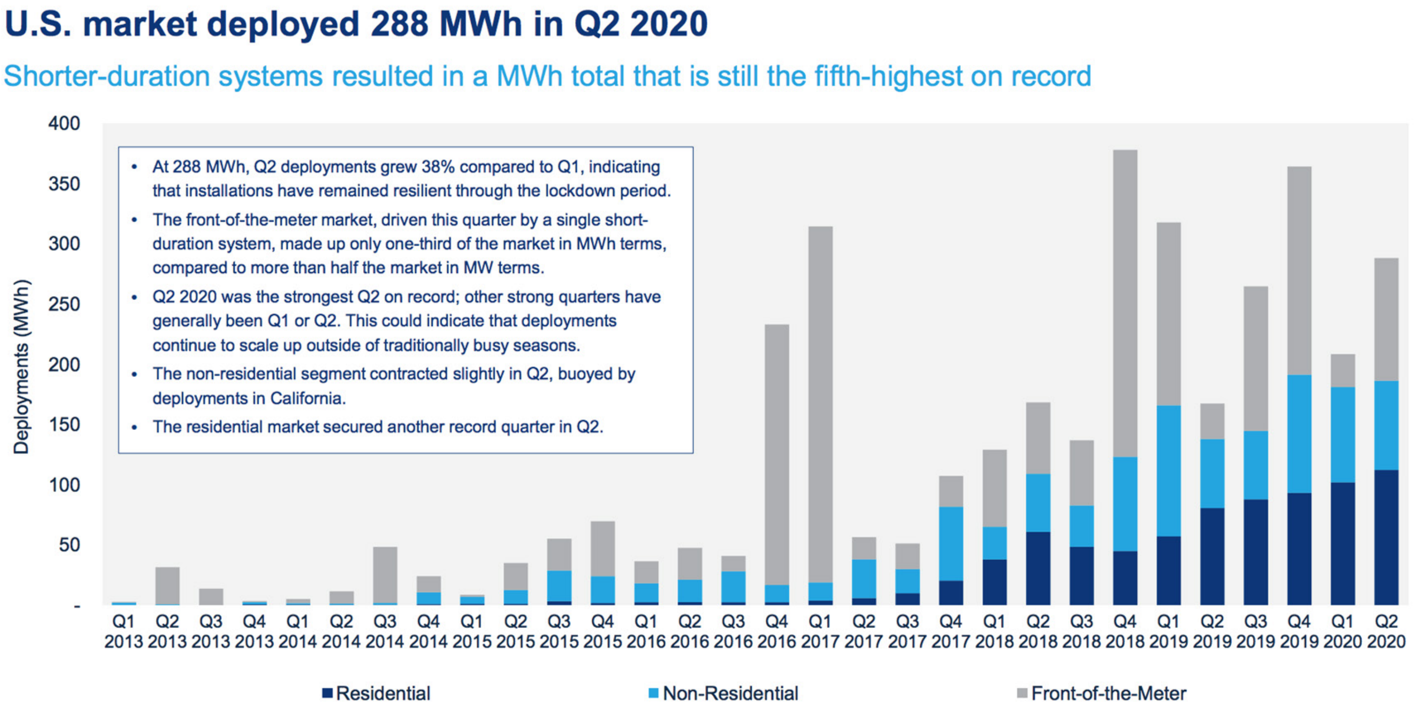
Some observers tried to blame a growing reliance on renewable energy for power generation shortages in California during a heat wave in August 2020 (Bermel, Wolff, and Forgey 2020). But most experts noted a combination of factors that led to the first rolling blackouts in nearly 20 years: elevated demand due to a historic climate change-driven heat wave; loss of in-state natural gas generation; limited transmission capacity; reduction in wind generation; and limited supply in neighboring states to export power to California (Kahn and Bermel 2020; CAISO, CPUC, and CEC 2020).

Power system planners and operators are using an increasing number of enabling tools to help integrate VRE into the grids. One of the most fundamental enablers is complementarity: Wind and solar PV, the fastest-growing and lowest-cost renewable technologies, tend to be complementary on both a diurnal and seasonal basis, so deploying them together helps provide firmer supply.

Other tools—advanced wind and solar forecasting techniques, sophisticated planning and operational modeling technologies, energy storage, demand response (especially in the buildings sector), new transmission, and larger balancing footprints for electric service territories—can help enable VRE integration (Cochran et al. 2014). Advanced software underpins many of these capabilities.

Figure 2.9 shows how spatial diversity of renewable energy generators can mitigate the variable nature of these resources. A large wind farm consisting of 200 turbines has a much steadier output than a smaller farm with only 15 turbines (Milligan and Kirby 2010).

Reliable, bulk electricity demand can be met by a varying combination of VRE, storage, and demand response (including smart vehicle charging, often referred to as V1G), instead of the traditional concept that output from plants, for example coal or nuclear, must be kept constant. Other new techniques stand on the doorstep to further VRE integration: vehicle-to-grid (V2G) services, which can incentivize an electric vehicle (EV) owner to charge during periods of high VRE output and send electricity back to the grid during peak load periods; microgrids that improve resiliency and reliability; aggregated demand response (the pooling together of customers who agree to modify their energy demand at key times of



U.S. market deployed 288 MWh in Q2 2020

Shorter-duration systems resulted in a MWh total that is still the fifth-highest on record

- At 288 MWh, Q2 deployments grew 38% compared to Q1, indicating that installations have remained resilient through the lockdown period.
- The front-of-the-meter market, driven this quarter by a single short-duration system, made up only one-third of the market in MWh terms, compared to more than half the market in MW terms.
- Q2 2020 was the strongest Q2 on record; other strong quarters have generally been Q1 or Q2. This could indicate that deployments continue to scale up outside of traditionally busy seasons.
- The non-residential segment contracted slightly in Q2, buoyed by deployments in California.
- The residential market secured another record quarter in Q2.

Figure 2.10. The growth in energy storage (2013-2020). Cost reductions in the energy storage market are leading to record deployment growth. (Wood MacKenzie 2020)

the day in exchange for compensation); and renewed market design concepts.

Energy Storage

Short- and long-term storage (or significant interconnection with other grids) will be needed for systems that rely on very high percentages of VRE generation. A variety of energy storage options now exist to cost-effectively improve reliability and integration of VRE on the grid. Lithium-ion batteries were once considered far down the supply curve in helping integrate VRE, but today's cost reductions are leading to record deployment growth each year, both behind-the-meter and front-of-meter (Figure 2.10). In September 2020, the world's largest lithium-ion battery storage project was completed in San Diego at 250 MW, although it is unlikely to hold this title for long given other large projects under development (Proctor 2020).

New battery chemistries and technologies are also under development that could overcome some of the performance, supply chain, and circular-economy limitations of lithium-ion batteries. Flow batteries are one example of an energy conversion device that can bring greater economies of scale to the storage market if more ideal chemistries can be demonstrated (Service 2018). For example, Dr. Michael Marshak and his team at the University of Colorado Boulder have recently demonstrated some of the highest-voltage aqueous flow battery operations reported yet, using a new negative electrolyte composed of earth-abundant chromium and an inexpensive chelating agent. This new electrolyte replaces expensive vanadium-based chemistries currently employed in commercial MW-level flow batteries (Knoss 2019). Other mechanical and thermal energy storage technologies are also likely to enter the market at competitive prices soon.

Longer-duration batteries are also emerging. Form Energy—a start-up with backing from Bill Gates—has signed an agreement with Great River Energy to pilot a 150-hour storage battery that will be deployed in North Dakota when a coal plant there closes (Spector 2020a). A recent techno-economic study of long-duration storage found that a combination of short-term (lithium-ion batteries) and long-term (hydrogen) storage could support a resilient grid operating on 100% wind and solar, although further cost reductions are needed to make it feasible (Dowling et al. 2020).

Green hydrogen, produced from electrolysis of water using wind and solar generation that might otherwise be curtailed, represents a key opportunity to provide both long-term energy storage and to address hard-to-decarbonize sectors of the economy such as steel, cement, and chemical production, as discussed in Section 5. Another long-term storage option that can assist integration of VRE is ammonia production, which uses similar electrolysis technology—ammonia is a key ingredient in agricultural fertilizer today. Additional federal R&D targeted at long-term storage requirements is needed for select sectors of the economy.

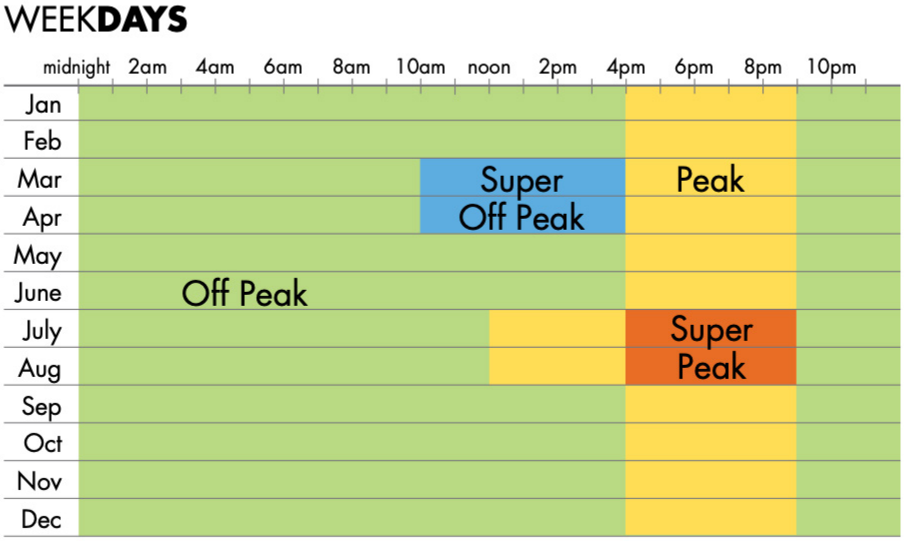


Figure 2.11. California time-of-use rates. California is rolling out optional time-of-use rate packages to all consumers, setting higher rates during peak times. (CAISO 2015)

Analytical tools

Analytical tools to help plan and simulate the expansion of VRE options into the grid rely on increasingly granular (in space and time) approaches. NREL is one public institution at the forefront of introducing new analytical tools and models that can help grid planners and operators build out their systems with confidence. NREL's PVWatts[1] and System Advisor Model (SAM)[2], for example, allow detailed planning of location-specific projects. Linking capacity expansion models with unit commitment models such as PLEXOS[3] can give planners greater insights on how to integrate increasing shares of VRE at least-cost, and focus on the challenges of reliability and resilience concerns (Brown et al. 2019; Phadke et al. 2020). Other tools are under development at NREL that allow stakeholders to better understand ways to overcome challenges related to electric vehicle charging and the grid, or hydrogen fueling infrastructure.[4] Finally, next-generation modeling techniques are under development that will enable market design changes to adapt to increasing shares of VRE that have zero marginal costs.

Flexible demand

Demand response and other forms of demand flexibility are increasingly recognized as valuable sources of grid flexibility services. By reducing generation needs during times of peak load or other forms of grid stress, demand flexibility can defer generation, transmission, and/or storage investments that would otherwise be needed to maintain reliability. If advanced communications and controls can enable high levels of demand shifting, demand response can also reduce grid energy costs and potentially help integrate more renewable generation, primarily by making use of energy that would otherwise have been curtailed. Smart vehicle charging is a special area of flexible demand.

Smart vehicle charging

Many jurisdictions are experimenting with smart EV charging, both adjusting the charging of vehicles when it helps the grid most (V1G) and allowing EVs to send power back to the grid when needed (V2G). The former can aid in the integration of VRE by incentivizing consumers to charge when wind and solar are plentiful and might otherwise be curtailed. The latter is still in the pilot phase and may become increasingly important as more EVs are purchased, creating greater and greater capacity to support high-demand periods of time. The federal government can help promote sharing of best

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[1] https://pvwatts.nrel.gov/

[2] https://sam.nrel.gov/

[3] PLEXOS is a commercial model developed by Energy Exemplar used by many utilities and grid operators to determine the least-cost way to dispatch power plants over a period of time given potential constraints. https://energyexemplar.com/solutions/plexos/

[4] https://www.nrel.gov/transportation/data-tools.html

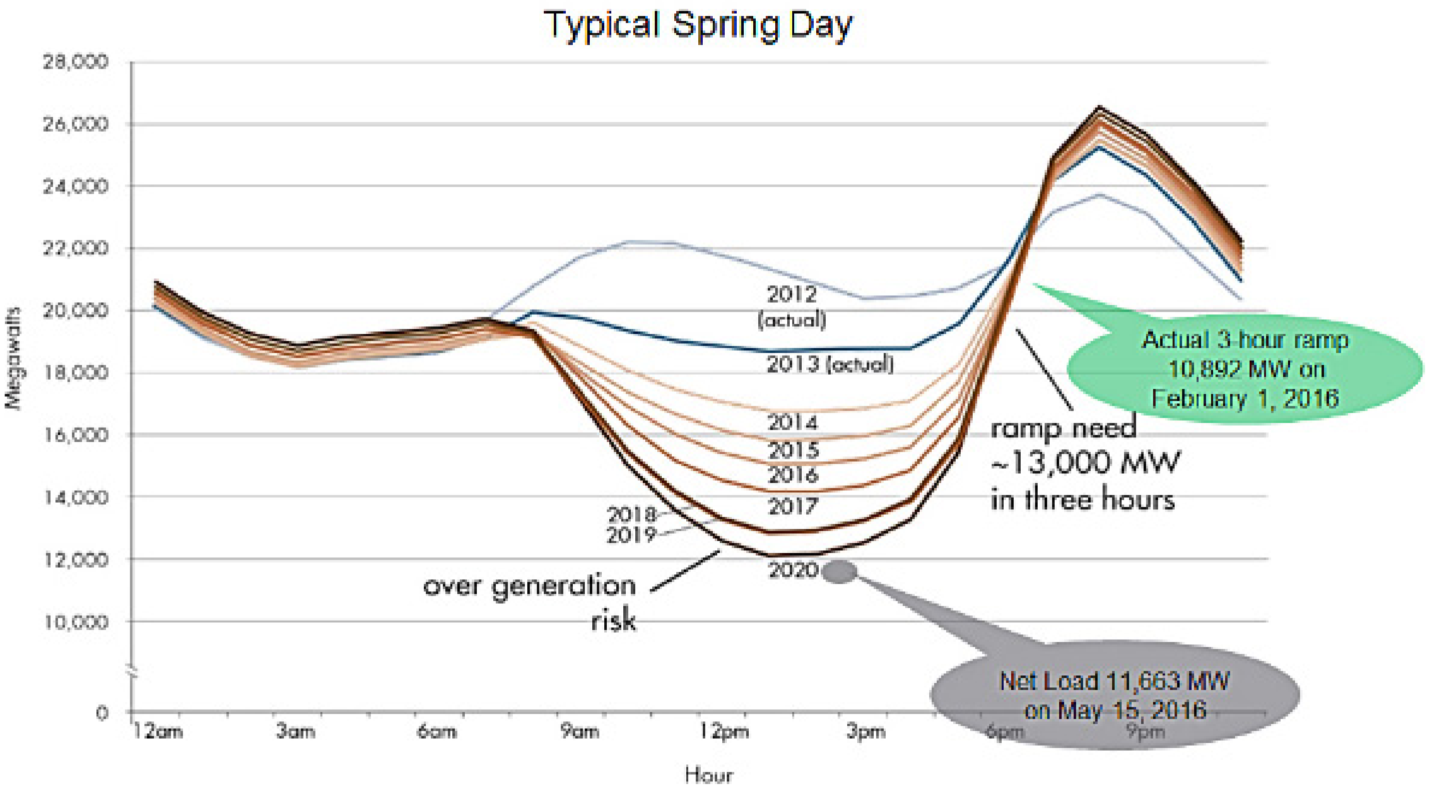

Figure 2.12. California's "duck curve." In late afternoon, solar output drops off, causing a rapid increase in demand for electricity from non-solar sources and creating a characteristic shape of the load curve. (CAISO 2016)

practices in advanced vehicle charging options with stakeholders across the country and should continue to fund RD&D to help overcome potential EV-grid integration challenges.

Time-of-use tariffs

Setting electricity rates low when VRE is abundant encourages its use then. Similarly, raising rates during times of high demand and low VRE output can encourage consumers to use less. California is rolling out optional time-of-use (TOU) rate packages to all consumers, setting the highest prices for electricity use between 4 pm and 9 pm (Figure 2.11). This is when demand is high, solar generation is rapidly declining, and other generators must come online rapidly to replace lost solar output. California utilities anticipate that TOU tariffs will not result in an overall change in electricity costs, at least if consumers pay attention to scheduled use of power. Real-time pricing is another option to make pricing signals even more granular than TOU tariffs, and could result in more efficient integration of VRE.

TOU tariffs help California deal with its "duck curve" challenge (Figure 2.12). The duck curve refers to periods in late afternoon and early evening when demand rises while solar output declines. This means that "net load" increases very rapidly and other generators need to rapidly come online and ramp up their output to balance supply and demand. California currently gets just over 20% of its total annual generation from solar (SEIA 2020); as more solar generation has come online in recent years, the ramp intensity has increased.

Challenges of getting to very high levels of VRE

There is robust debate today about barriers to 100% renewable electricity (Jacobson et al. 2015; Trabish 2017; Clack et al. 2017). But there is no reason we should not rapidly move forward from today's level of just over 10% VRE. The general consensus is that achieving VRE levels of 80-90% can be accomplished without too much technical, economic, institutional, or social difficulty (MacDonald et al. 2016; Phadke et al. 2020; Sepulveda et al. 2018). Above this level, many analysts acknowledge serious difficulties, especially if long-duration energy storage or interconnections with neighboring grids are not available at a moderate price (Jenkins, Luke, and Thernstrom 2018; Budischak et al. 2013). The lack of mechanical inertia

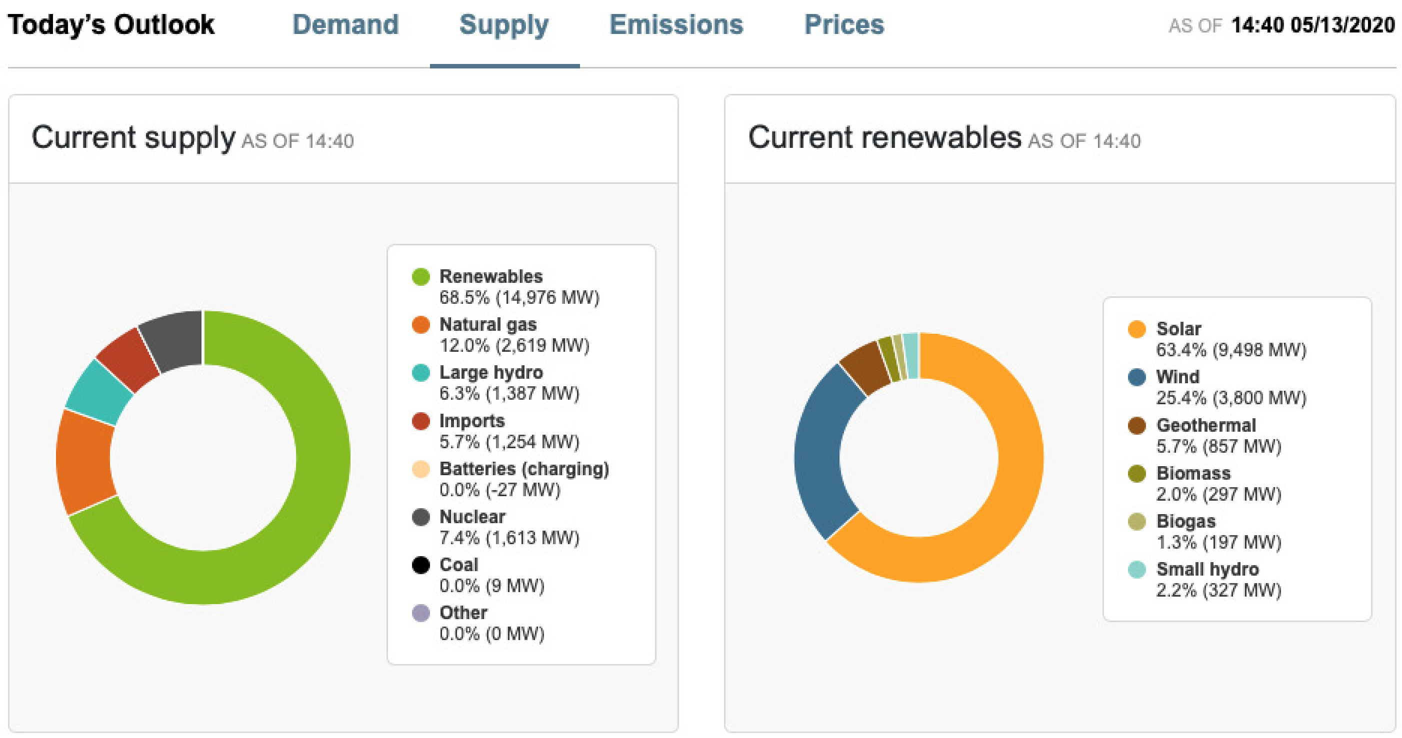

Figure 2.13. Contributions of the various renewable electricity sources in California. The California independent system operator generation mix on May 13, 2020, shows an increasing share of renewables and the dominance of solar. (www.caiso.com)

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in inverter-based generation systems introduces new challenges that require creative solutions. However, studies have shown that inverter-based systems can provide system stability and a full range of ancillary services if designed to do so (Kroposki et al. 2017). During the peak of coronavirus shutdowns in March and April, California routinely operated its grid with over 65% variable renewable electricity (Figure 2.13). Going beyond 80-90% VRE should be a priority RD&D area for the new administration and beyond.

2.4 The role of nuclear power

In the United States, the economics of commercial nuclear power production continues to be plagued by difficult operational, construction, and financial performance. Five states have chosen to support existing nuclear plants with incentives as they struggle to sell power into competitive wholesale markets in an era of low and declining prices (Morey 2019). While some stakeholders oppose nuclear power for a variety of reasons, replacing this zero-carbon generation source in the near-term would make the transition to renewables and efficiency even more taxing. Indeed, carbon emissions increase in states where nuclear plants are shut down (Clemmer et al. 2018). Thus, keeping these plants operating until they can be replaced by renewable or other zero-carbon sources will minimize the additional carbon added to the atmosphere. States should use transparent, inclusive, and legal means to subsidize existing nuclear power plants. Ohio lawmakers, some of whom are currently under investigation by the FBI, did not choose a transparent approach (Stokes 2020).

Building new, centralized nuclear power is currently not economical in the United States, as Figure 2.6 demonstrates. However, most plants that were constructed approximately four decades ago can still operate safely at relatively low marginal cost, although inspection measures need to be carefully followed when operating licenses are extended.

Some climate scientists have promoted new nuclear power plants as a source of reliable base load power. New approaches being pursued—such as small modular reactors and liquid fluoride thorium reactors, each designed to be inherently safer than today's large conventional light water reactors—offer potential advantages. It makes sense to pursue these concepts provided that a path to cost-effectiveness can be demonstrated and that nuclear investments do not crowd out a comprehensive zero-carbon RD&D energy portfolio.

Nevertheless, as the old concept of meeting base load with constant-output nuclear or coal power plants is replaced by a 21st-century grid operating with distributed energy resources, batteries, flexible demand response management, and more flexible transmission, it will likely prove a challenge for any nuclear reactor technology to compete against the very low and decreasing capital costs of solar, wind, and storage, as well as their inherently rapid deployment speeds.

2.5 Natural gas roadmap

While the advantageous economics of natural gas electricity generation has played a significant role in reducing carbon dioxide emissions by coal plants, it is unlikely to continue contributing as such moving forward. This is because a) coal generation now makes up less than 20% of the generation mix (down from 50% in 2008) and continues to decline rapidly, and b) wind and solar are now more compelling economically than gas-fired generation in many regions of the country. Furthermore, if we are to reduce GHG emissions to zero as soon as possible, increasing use of natural gas to generate power is inconsistent with accomplishing zero-carbon emission goals.

Using assumptions that are most favorable to natural gas, natural gas combustion for electricity generation produces about half the climate change-causing carbon dioxide emissions as burning coal (Heath et al. 2014; Lattanzio 2014; Alvarez et al. 2018). Nevertheless, despite the continued decline in coal generation, US power sector carbon dioxide emissions rose in 2018 for the first time in years due to growing use of natural gas. This indicates that the GHG reductions achievable by replacing coal with natural gas have reached the point of diminishing returns (Lindstrom 2019).

Consequently, any new natural gas power plants built today are most likely to become stranded assets as the power sector is rapidly decarbonized, and utility ratepayers will wind up footing the bill for these unnecessary costs. Eliminating natural gas generation over time will also reduce methane leakage at drilling locations and during processing, transmission, and distribution. Cutting methane leakage is essential not only for power generation, but also in industry and buildings, each of which consumes about one-third of total natural gas supply.

Investors, regulators, and grid operators must jointly reach agreements on how to phase out the use of natural gas in the power sector—and beyond. Establishing a clean energy standard as noted above would help, but a more integrated roadmap would help minimize overall costs, including stranded assets. States such as Texas, Colorado, and Wisconsin have used securitization to help shut down existing coal plants before the end of their normal economic lives, and the same technique can be used with natural gas plants (Trabish 2019).

2.6 Green grid infrastructure

Without reliable electricity service, the misery that Americans have endured during the COVID-19 era would have been greatly magnified. Imagine the impact that a major cybersecurity attack or other disruption would have on people working from home or serving on the front lines of essential services. The economic consequences would have been considerably heightened, social stability threatened, and overall geopolitical relations tested if power supply remained offline for a period of time. While oil and natural gas demand plummeted—leading to oversupply in those markets—residential power demand increased as decision makers issued stay-at-home orders in nearly all jurisdictions, demonstrating the essential nature of electricity.

Utilities have always taken electricity reliability very seriously, and utility regulators typically allow them to recover costs associated with reliability investments, but more could be done to prevent physical and cyber disruptions, ensure resiliency if such a disruption occurs, and upgrade aging equipment where performance is below peak. Furthermore, new grid infrastructure can enable integration of renewable power supplies. This is already evident. We continue moving from centralized one-way grids to two-way networks that can accommodate greater amounts of distributed energy resources, including rooftop solar, V1G and V2G EV charging, demand response, and energy efficiency.

Better linking together the three electricity interconnections (Eastern, Western, and ERCOT) in the United States could pay large dividends in terms

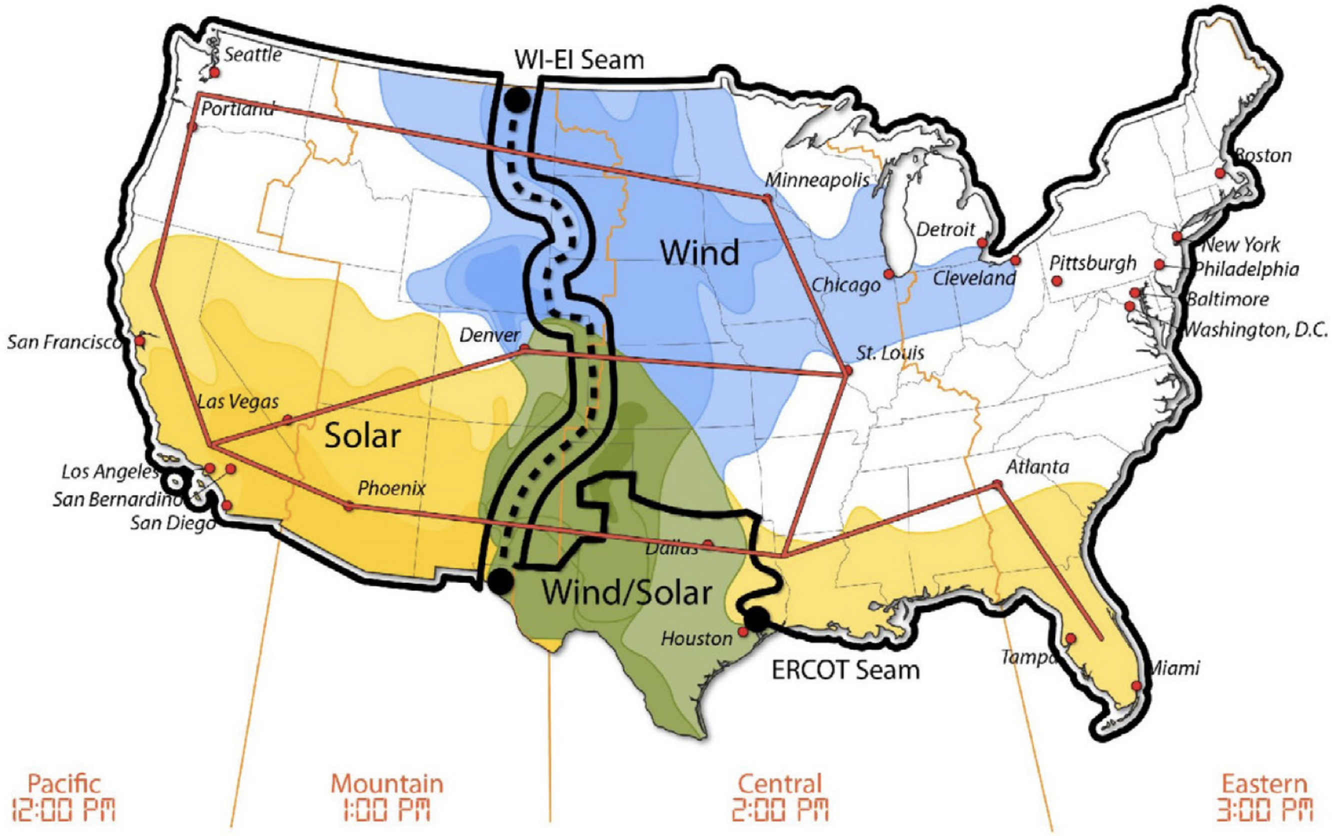

Figure 2.14. Linking the Western and Eastern interconnections with HVDC transmission. Better linking the electricity interconnections with HVDC lines, as shown in this map from NREL's "Seams" study, could reduce cost and improve the reliability of wind and solar. (Behr 2019)

of cost savings, reliability, flexibility, and carbon mitigation. Figure 2.14 shows a map from NREL's "Interconnection Seam Study" study showing how high-voltage, direct current (HVDC) transmission can move power across the "seams" separating the interconnects (Bloom et al. 2020). We need more studies on how to best integrate more interconnects and HVDC transmission infrastructure into existing systems, and there is an opportunity to tie post-COVID federal stimulus investments into this kind of effort—simultaneously stimulating the economy and building green infrastructure.

There is no doubt that upgrading and interlinking the entire US electrical grid will be capital intensive, but more robust interconnections and use of an HVDC macrogrid would give the United States a much-needed 21st-century electrical grid with lower overall costs, higher reliability, greater ability to integrate VRE, and immediate opportunities for plentiful creation of high-paying jobs. The NREL-led study indicated benefit-to-cost ratios of up to 2.9 depending on scenario, meaning that it is nearly three times cheaper to build out and operate the grid in an aggressive transmission scenario compared to the baseline scenario, over a 35-year period (Bloom et al. 2020).

Building new transmission is complicated because of social opposition to overhead lines, but the Minneapolis-based Direct Connect Development Company is advancing an innovative model to install an underground HVDC line to link the Midwestern MISO and PJM electricity markets (Midwestern Independent System Operator and formerly Pennsylvania, New Jersey, Maryland Independent System Operator)[5]. The underground line would run along existing rail right-of-way corridors and connect the renewables-rich MISO region with the population hubs in PJM.

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[5] More information on this HVDC line project is available at: https://soogreenhvdclink-os.com.

In addition to the benefits of more-integrated grids, there is also potential to provide greater federal focus on microgrid development (Mortier 2019). Campuses and neighborhoods using microgrids can be semi-independent islands connected to the larger grid, with their own solar generating sources and batteries. Microgrids are especially valuable for maintaining electric services when major hurricanes, wildfires, or other events take down transmission lines.

2.7 RD&D priorities in electricity

2.7.1 Electrification

A key challenge in the electricity sector is how to incentivize conversion of fossil fuel end-use applications such as petroleum-fueled internal combustion engines to electric, and building- or water-heating from natural gas to electric heat pumps. Companies and utilities may oppose the loss of natural gas revenue but welcome new electricity sales. Homeowners may be reluctant to retrofit the status quo for something new, as up-front costs can be high. However, there are ways to mitigate this, as discussed in Section 3. Cities are already taking action to restrict fossil fuel use in the residential buildings space. The federal government should lay out potential roadmaps for how cities can integrate greater electrification going forward.

2.7.2 Carbon capture, utilization, and storage

Currently, CCUS is only economical in niche applications, especially given the limited benefits of the 45Q tax credits[6] (Gonzales, Krupnick, and Dunlap 2020; J. Christensen 2019). The federal government should continue exploring opportunities in this space, however, given the significant potential for breakthroughs and the potential need to cut emissions even more rapidly. We should pursue all options to respond rapidly to the climate emergency, including CCUS, to avoid being caught unprepared, as we were with the coronavirus pandemic. We should invest in more RD&D on advanced capture methods and alternative fuel/thermodynamic cycles. It is important, however, that any efforts in this area do not distract us from the need to drive fossil fuel emissions to zero as rapidly as possible.

To lower cost and increase reliability of renewable power, we need HVDC links between electricity interconnections, but people generally do not like the most obvious solution: overhead powerlines. So a Minneapolis-based company came up with a proposed solution: install underground HVDC connections along existing rail lines.

2.7.3 Hydrogen and ammonia

Among the significant barriers to achieving the IPCC targets of less than 2°C warming are: 1) a commercial answer for hard-to-decarbonize sectors of the economy (such as steel and cement production, as described in Section 5), and 2) mid- to long-term storage in the electricity sector. The energy carriers of hydrogen and ammonia can help with addressing each of these problems. Unfortunately, today's hydrogen production relies on natural gas; expanded federal RD&D should focus on lowering the costs of green hydrogen production and other renewable fuel alternatives.

2.7.4 Circular economy for energy materials

Even if wind, solar, and energy storage make massive inroads into our economy, we need to develop solutions to their reliance on critical materials and ultimate destinations of those critical materials in the environment. The concept of a "circular economy"—where input materials are minimized, all materials are reused to the extent possible, and any remaining materials are recycled—is gaining increased traction in the sustainable development community. PV, wind, batteries, and other clean electricity technologies will not succeed in the long run without a solution to end-of-life issues. Eventually, products including reinforced fiberglass wind turbine blades, rare earth-based batteries, lead-based perovskite PV cells, and more will need to be redesigned to mini-

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[6] Section 45Q of the Internal Revenue Service tax code provides a tax credit on a per-ton basis for carbon dioxide capture projects. More information is available at: https://www.betterenergy.org/blog/primer-section-45q-tax-credit-for-carbon-capture-projects

mize all waste and reliance on critical-material supply chains, which have been the subject of renewed attention since COVID-19 swept the globe. Redesign will require breakthroughs in materials, chemistry, and next-generation computing.

2.7.5 Materials, chemistry, and next-generation computing

The building blocks of a clean energy economy rest on affordable and sustainable materials and components. The United States must continue leading in fundamental RD&D of materials and chemistry in order to unlock the potential of recyclable PV, wind turbines, storage, plastics, and vehicles. Next-generation computing, which includes artificial intelligence, machine learning, neomorphic and quantum computing, among others, holds the potential to not only unlock far greater energy efficiency in the economy, but also contribute to other strategic leadership areas of the global economy for US businesses.

2.8 Job creation

Just over 10 years ago, in the aftermath of the Great Recession, the United States passed the American Recovery and Reinvestment Act (ARRA) with approximately $90 billion dedicated to clean energy stimulus, much of that in sectors that rely heavily on electric power. That funding put many Americans back to work and built the foundation for today's much cleaner power sector. In today's unfolding coronavirus world, we can push that transition to the next level with carefully targeted support for energy efficiency, renewables, storage, and other cost-effective building blocks. These sectors support much more job creation than the fossil fuel or nuclear sectors do (Garrett-Peltier 2017).

Energy efficiency must not be ignored in the overall approach to minimize power sector emissions in a post-COVID-19 world for at least four reasons: 1) it will be essential in limiting the additional electric capacity that will be needed as we electrify the buildings, transportation, and industry sectors; 2) end-use efficiency is unsurpassed in its ability to create jobs; 3) energy efficiency delivers immediate and enduring savings to customers' energy bills; and 4) it is essential to meeting our climate goals affordably, reliably and securely. Energy efficiency is widely viewed as one of the greatest sources of jobs in the electricity sector: Recent estimates suggest that for every $1 million spent on a green transition, renewable energy delivers 7.5 direct and indirect jobs, energy efficiency, 7.7 jobs, and fossil fuels, 2.7 jobs (Garrett-Peltier 2017). Replicating efforts from the ARRA in 2009 to improve building envelope performance, HVAC, and appliance efficiency stand to deliver humanitarian and long-term climate dividends. Especially focusing on low- and moderate-income home and multifamily weatherization under a green recovery program is a better long-term investment than subsidizing their monthly energy bills (Aznar et al. 2019).

POLICY OPTIONS FOR THE ELECTRICITY SECTOR

A variety of legislative, executive order, and administrative actions can help promote carbon mitigation in the US power sector. Some of these levers are at the command of the new administration, and some would require approval of the Congress.

Set federal targets for clean electricity	• The new administration should move to restore confidence in US climate leadership by setting an ambitious target for power sector emissions reductions. To demonstrate its commitment, the United States should set an aggressive nationwide clean energy standard (CES) as soon as possible, with both interim and 2050 targets. In the event Congress is unable to pass such legislation, the administration should convene a panel of legal experts to develop a portfolio of actions that can be pursued under existing statutory provisions. Planners should keep in mind the goal of bringing net economy-wide emissions to zero by 2050, meaning that the power sector must be considerably ahead of this overall schedule. The United States should therefore target 2035 for 100% zero-carbon generation in

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Set federal targets for clean electricity (continued)

the electric power sector, with aggressive but achievable interim targets in 2025 and 2030.

- Policymakers should consider a carbon tax to accompany and complement the CES, but it should not be used as a substitute for a clean energy mandate. Carbon taxes should be set sufficiently high to motivate action and should contain a dividend component that returns to lower-income consumers at least as much carbon tax as they paid on a monthly or annual basis. If this cannot be accomplished through legislation, administrative actions with similar impacts should be explored.
- The United States is already making progress in transitioning its power sector by reducing emissions. After establishing new targets and actions, the country should rally other nations to raise their ambition by providing technical assistance and sharing lessons learned in deploying clean energy.
- The United States should continue retiring existing coal plants as rapidly as possible and cease construction of new natural gas-fired generation capacity to avoid future stranded assets.

Enact green stimulus in the power sector

- Green stimulus investments represent one of the most effective steps the United States can take to offset the evolving climate change crisis. Such actions come with added benefits for addressing domestic and global poverty, humanitarian and social justice issues, and even pandemic aid (for example, refrigeration and transportation are needed for global production and distribution of coronavirus vaccines).
- The transition to a fully decarbonized electricity sector can be accelerated by much higher levels of transmission capacity between the US electrical interconnections and by expanding HVDC networks. Such projects can take advantage of existing rights-of-way, placed underground to the extent possible. This effort would create high-paying jobs, reduce the delivered cost of electricity, and expand opportunities for areas rich in solar and wind resources to enter the market.
- Federal spending should be expanded to support increased RD&D and administrative action on topics related to achieving very high penetrations of renewable power generation, including: high-resolution grid integration studies, long-duration storage such as hydrogen and alternative battery chemistries, expanded cooperation between balancing areas, and related topics.
- As noted in Sections 3-5, energy efficiency is a key tool for green stimulus focus in the buildings, transportation, and industrial sectors, respectively. In some cases, directing support to fossil generators can achieve modest efficiency gains, although such investments should pass strict cost-benefit tests. Any remaining fossil plants should be slated for closure as soon as feasible, and efficiency improvements in older, carbon-intensive power plants should not serve to extend their lifetimes.
- Grid modernization efforts should focus in particular on three topics: cybersecu-

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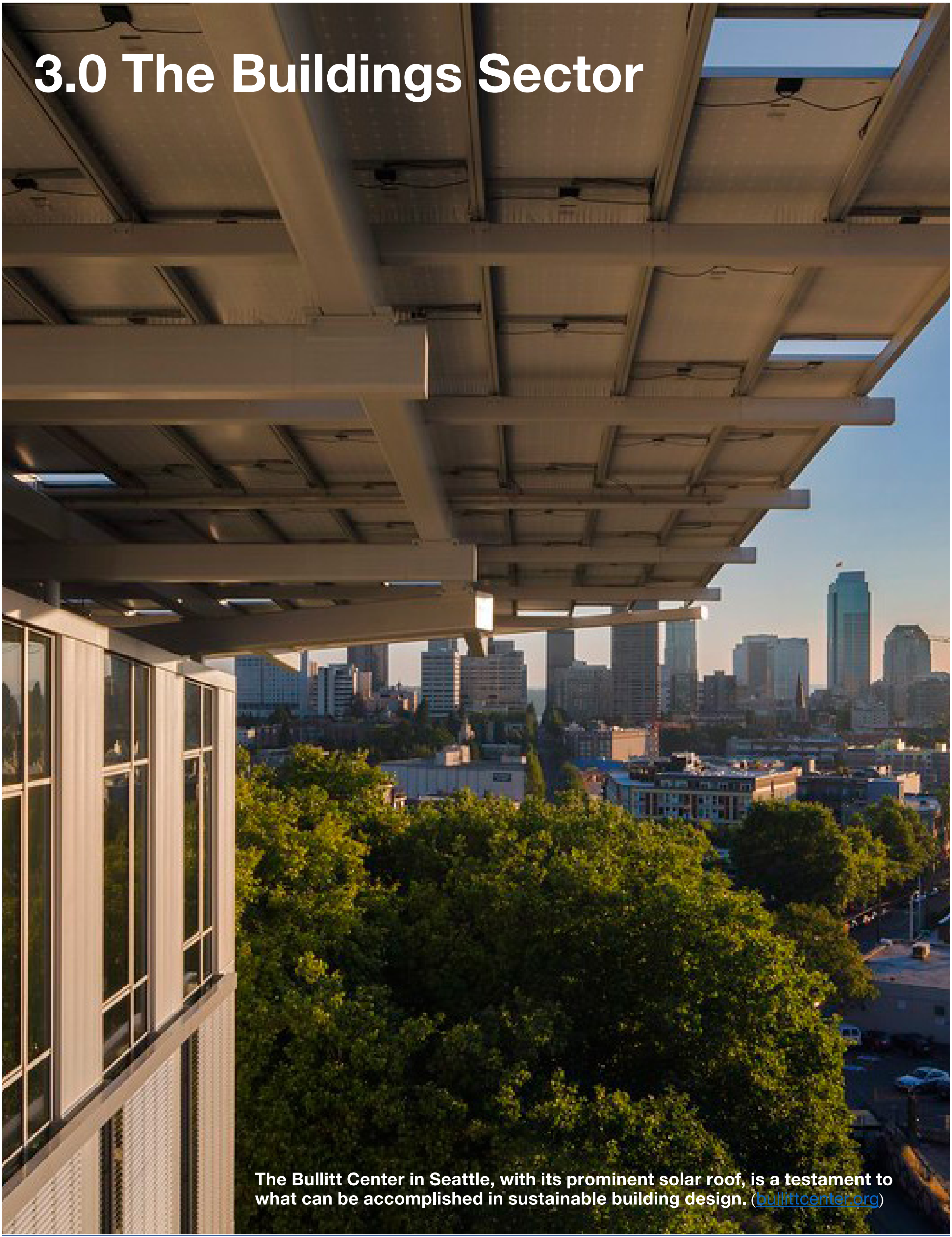
Enact green stimulus in the power sector (continued)

rity, grid integration of VRE and electric vehicles, and highly resilient grid infrastructure. These efforts address national security, environmental, and employment concerns at a key moment in history.

Other power sector priorities

- A variety of options exist to encourage the use of plentiful, carbon-free electricity at key times during the day. Time-of-use, real-time, and critical-peak pricing are tools that can help absorb electricity in times of oversupply, and are especially helpful for renewables when combined with energy storage.
- Electricity tariffs should be designed to encourage affordable electric vehicle charging. In some cases, demand charges—which aim to reduce peak loads—can do the opposite. Regulators should balance these goals in designing tariffs to accomplish both objectives.
- Aggregated demand response can be designed to bid into electricity markets to the maximum extent possible, consistent with reliability practices.
- Appoint commissioners at the Federal Energy Regulatory Commission who support innovative, market-based approaches to clean energy and who also understand how to use existing statutory authority to advance electricity transformation.
- Development of carbon-free technologies that can firm the electricity supply, including advanced geothermal power, concentrating solar power with thermal storage, marine hydrokinetic, advanced nuclear power, and CCUS are important for systems with high levels of variable renewable generation. However, it is essential that these technologies demonstrate a path to cost competitiveness by 2030 if they are to play a role in rapid decarbonization of the power sector.
- Research and deployment of advanced grid capabilities including microgrids, transactive energy, autonomous grids, and related technologies are needed to enable power system transformation.
- Fundamental research and development of the material science, computational, and biological science sectors can provide strategic leadership opportunities for the United States in clean energy technologies.

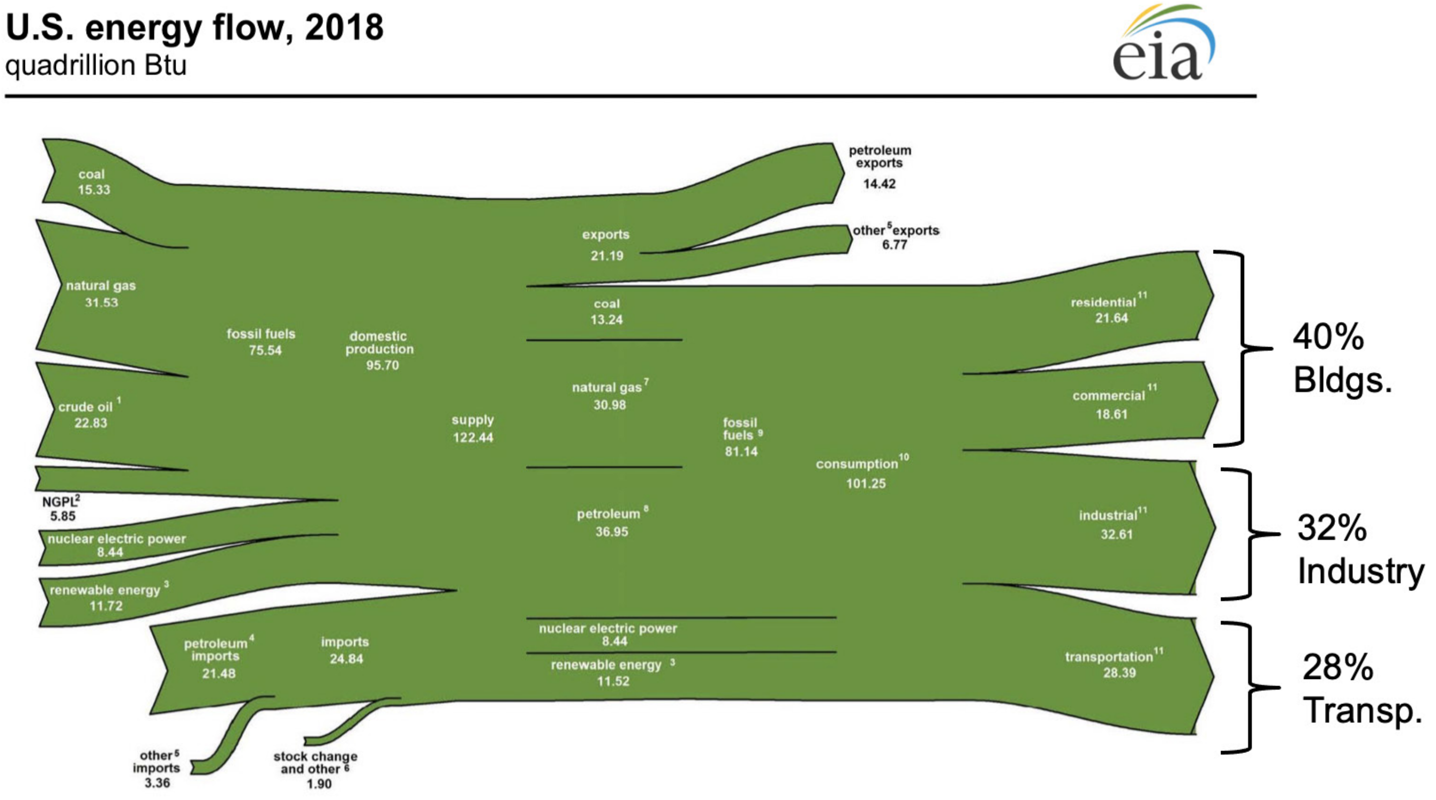
3.0 The Buildings Sector



The Bullitt Center in Seattle, with its prominent solar roof, is a testament to what can be accomplished in sustainable building design. (bullittcenter.org)

Although the US buildings sector is now a close second to transportation in terms of energy-related carbon dioxide emissions (when its share of electricity sector emissions is taken into account), it is the largest energy consumer and so provides a considerable opportunity for energy efficiency. Commercial and residential buildings account for 40% of US primary energy usage (Figure 3.1) and together represent the largest end-use sector of our nation's primary energy consumption. The energy split between residential and commercial buildings is fairly even, with residential buildings consuming 53.8% and commercial buildings consuming 46.2% of the 40.25 quadrillion BTUs consumed by buildings in 2018. Consequently, efficiency improvements in residential and commercial building energy usage represent the largest and most easily accessible opportunities for energy savings and associated GHG emissions reductions (McFarland 2019). Current energy sources for US buildings are dominated by natural gas and electricity (Figure 3.2), and so considerable savings in direct fossil fuel-related emissions can be obtained by converting building heating from natural gas to low- or no-carbon generated electricity while simultaneously decarbonizing electricity generation. (Note: We show this figure to illustrate the current fuel mix for the buildings sector, not EIA's projections, which do not reflect the aggressive decarbonization effort that is needed and is discussed in this report.) With the emissions associated with electricity generation distributed among the end-use sectors, the buildings sector was responsible for 35.2% of 2019 energy-related carbon dioxide emissions, compared to 37.1% for transportation and 27.7% for industry.

Buildings also offer a large potential to provide solar energy electricity generation and grid stabilization. A recent NREL study (Figure 3.3) concluded that US building rooftops could provide 38.6% of the national electric need (Gagnon et al. 2016). Because buildings use 74% of US electricity, demand response mea-



[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, biomass, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Natural gas only; excludes supplemental gaseous fuels.
[8] Petroleum products supplied.
[9] Includes -0.03 quadrillion Btu of coal coke net imports.
[10] Includes 0.15 quadrillion Btu of electricity net imports.
[11] Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note 1, "Electrical System Energy Losses," at the end of U.S. Energy Information Administration (EIA), *Monthly Energy Review* (April 2019), Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: EIA, *Monthly Energy Review* (April 2019), Tables 1.1, 1.2, 1.3, 1.4a, 1.4b, and 2.1.

Figure 3.1. US primary energy flow, 2018. The buildings sector consumes the largest share. (EIA 2019a)

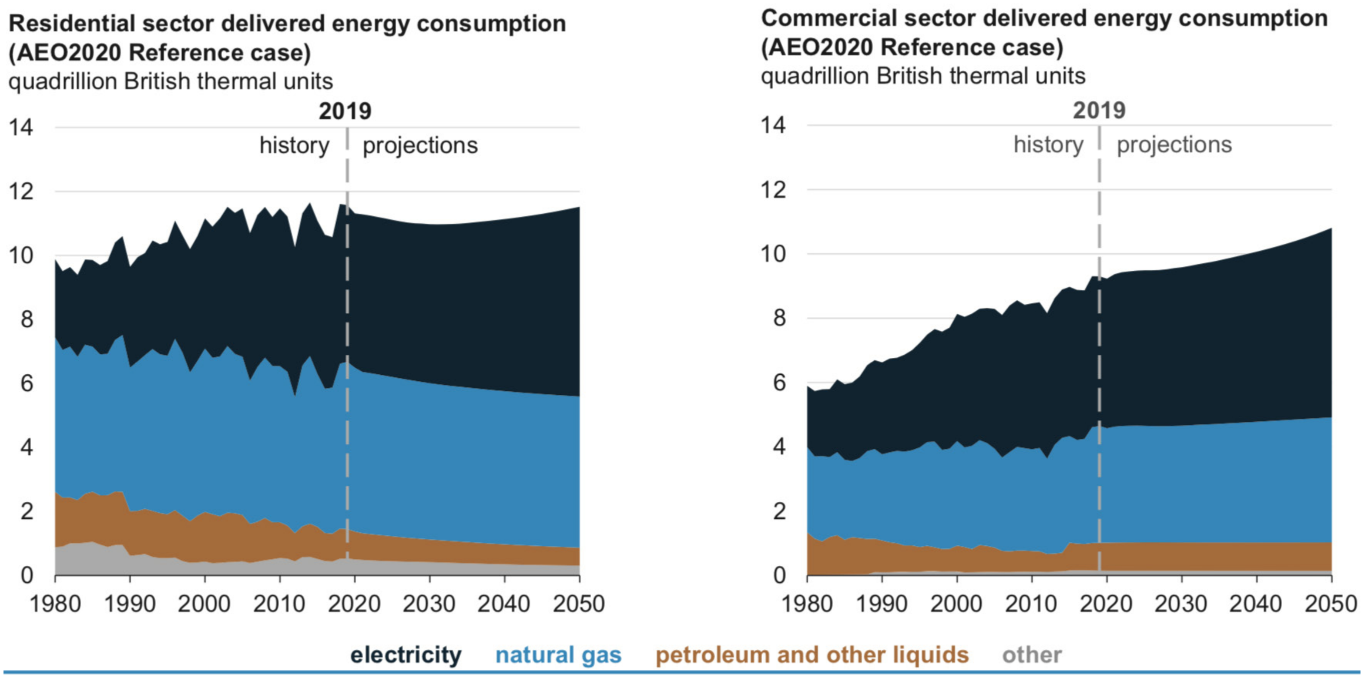


Figure 3.2. Energy consumption by fuel in US buildings. Electricity and natural gas are, by far, the two largest energy sources for US residential and commercial buildings. (EIA 2020a)

sures in buildings can play an important role in accommodating the variable nature of wind and solar electricity. Finally, addressing the embodied carbon emissions associated with the construction materials of new buildings can make an immediate contribution to reducing carbon emissions. Decarbonizing the buildings sector consists of four major simultaneous actions:

- Maximizing energy-efficiency use to minimize the amount of electricity needed as we fully electrify this sector.
- Converting buildings to all-electric so that they can utilize low-cost, low-carbon solar and wind electricity and supply on-site solar electricity to provide resilience and reduce the amount of central renewable electricity needed.
- Maximizing building demand response measures, including both real and virtual storage, to better enable the use of variable renewable electricity.
- Utilizing new and retrofit building materials, as well as those used for energy efficiency measures, that have low embodied carbon.

We will consider each of these separately and will then address a few related issues, including the

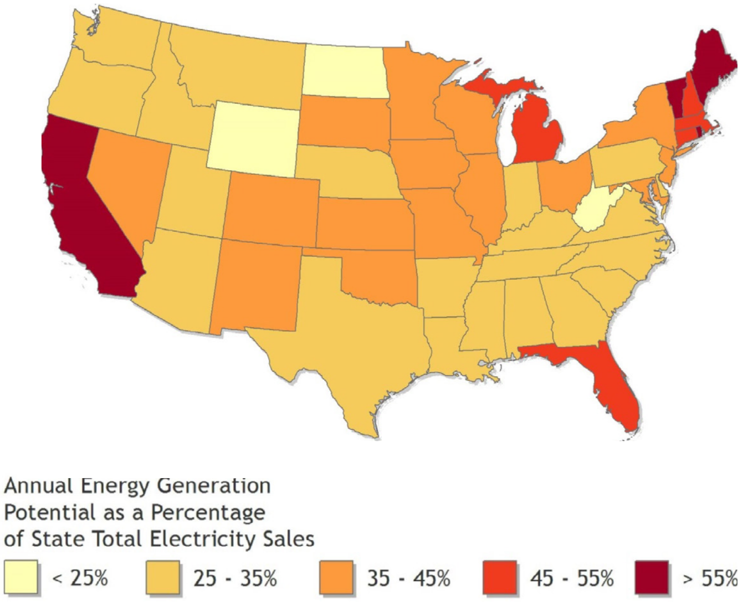


Figure 3.3. Electricity production potential for rooftop PV by state. This map shows the large potential rooftop PV generation from all buildings as a percentage of each state's total electricity sales in 2013. (Gagnon et al. 2016b)

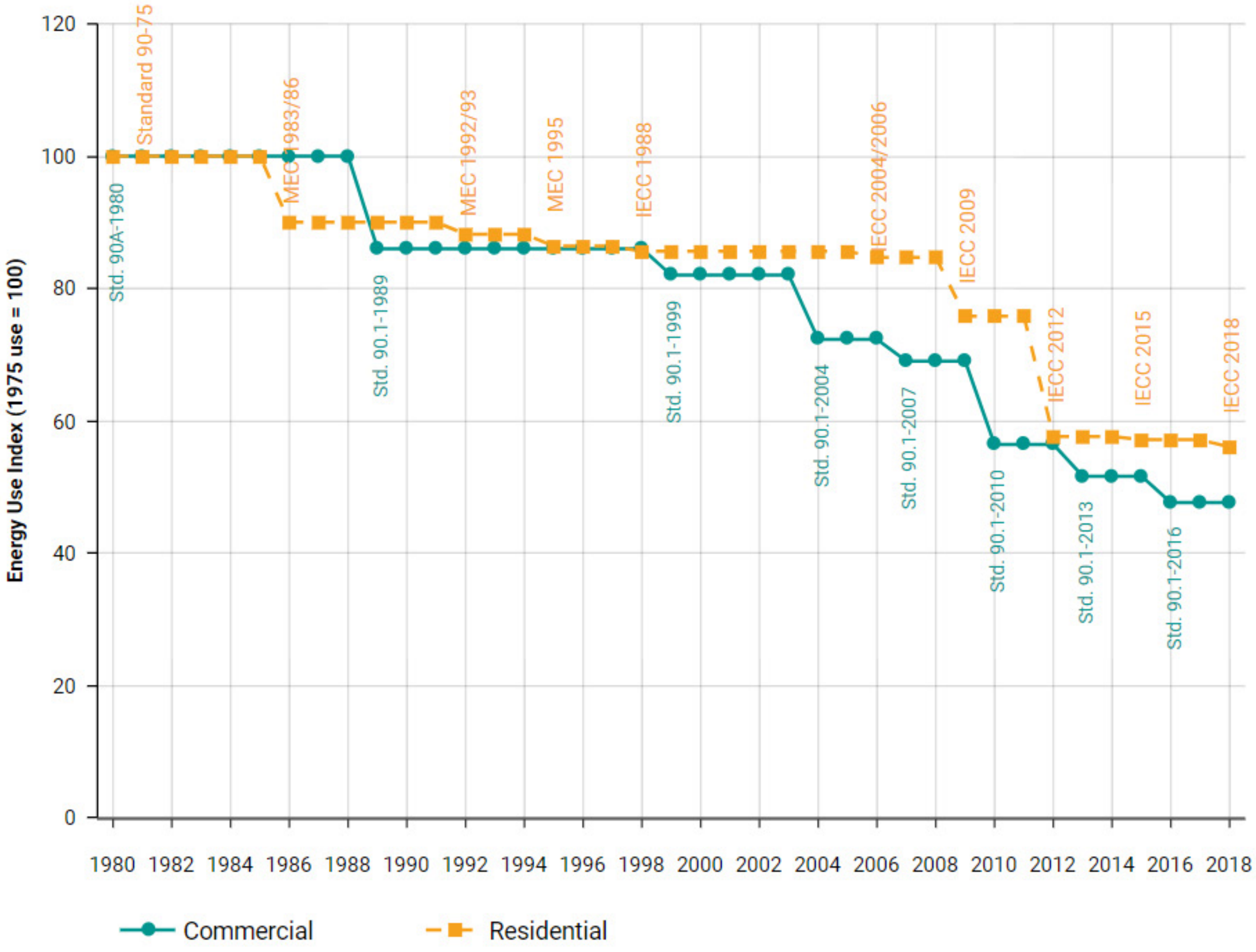


Figure 3.4. The reductions in energy use associated with model building energy codes, 1980-2018. Buildings designed to meet today's model building energy codes use about half the energy of buildings designed to meet 1980 codes. (ACEEE 2019)

potential decarbonization role of zero-energy communities.

3.1 Maximizing energy efficiency

In 2007 the American Solar Energy Society published a bottom-up study that estimated the extent to which energy efficiency and six renewable energy technologies could reduce US carbon emissions by 2030 (ASES 2007). Fully 57% of the carbon reductions were the result of energy-efficiency measures. Although the low cost of utility-scale wind- and PV-generated electricity now make these technologies competitive with many energy efficiency measures, it is still cost-effective to apply the lowest-cost efficiency measures in conjunction with rooftop PV. Applying energy efficiency measures will also allow us to limit electricity growth as we electrify everything we can, minimize the need for new generation and transmission, and utilize fewer raw materials. Because transitioning the electric grid to wind and solar affects the hourly electricity supply profile, attention must also be paid to how efficiency measures can help improve the demand profile and not just reduce the total energy use.

A key to determining opportunities for energy reductions in commercial buildings is the growing practice of benchmarking energy use required by many cities and states. Measuring energy use allows building owners to compare their performance to that of other buildings and identify where improvements can be made. The US Department of Energy (DOE) provides access to a number of benchmarking tools. To assist with benchmarking, the EPA created the Energy Star Portfolio Manager.®[1]. An important step in maximiz-

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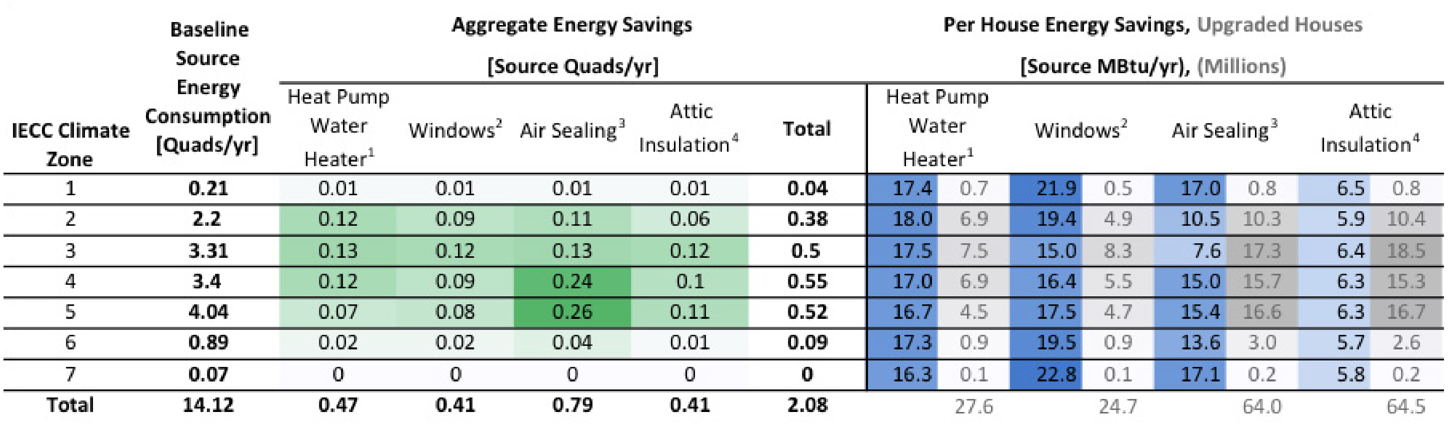
[1] https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager

Table 3.1. ResStock model results for different residential energy efficiency measures. The results for different climate zones show the primary (or source) energy savings potential of four energy efficiency measures used in detached single-family homes. (Excludes Alaska and homes with propane or atypical fuel types). Darker cells indicate higher performance. (See (PNNL 2012) for climate zones.)



IECC Climate Zone	Baseline Source Energy Consumption [Quads/yr]	Aggregate Energy Savings [Source Quads/yr]					Per House Energy Savings, Upgraded Houses [Source MBtu/yr], (Millions)							
		Heat Pump Water Heater[1]	Windows[2]	Air Sealing[3]	Attic Insulation[4]	Total	Heat Pump Water Heater[1]		Windows[2]		Air Sealing[3]		Attic Insulation[4]	
1	**0.21**	0.01	0.01	0.01	0.01	**0.04**	17.4	0.7	21.9	0.5	17.0	0.8	6.5	0.8
2	**2.2**	0.12	0.09	0.11	0.06	**0.38**	18.0	6.9	19.4	4.9	10.5	10.3	5.9	10.4
3	**3.31**	0.13	0.12	0.13	0.12	**0.5**	17.5	7.5	15.0	8.3	7.6	17.3	6.4	18.5
4	**3.4**	0.12	0.09	0.24	0.1	**0.55**	17.0	6.9	16.4	5.5	15.0	15.7	6.3	15.3
5	**4.04**	0.07	0.08	0.26	0.11	**0.52**	16.7	4.5	17.5	4.7	15.4	16.6	6.3	16.7
6	**0.89**	0.02	0.02	0.04	0.01	**0.09**	17.3	0.9	19.5	0.9	13.6	3.0	5.7	2.6
7	**0.07**	0	0	0	0	**0**	16.3	0.1	22.8	0.1	17.1	0.2	5.8	0.2
Total	**14.12**	**0.47**	**0.41**	**0.79**	**0.41**	**2.08**		27.6		24.7		64.0		64.5

ing energy efficiency in commercial buildings is to make building energy benchmarking standard across the country and part of the decision process in real estate transactions.

For new building construction, adopting improved energy codes across the country should be a key goal. Figure 3.4 shows how model building energy codes for both residential and commercial construction have improved, but these codes are adopted in a patchwork fashion across the country. An aggressive, national code for residential and commercial buildings would greatly reduce building energy use. Such a code should use the latest model national standards for commercial and residential buildings, e.g., ANSI/ASHRAE/IES Standard 90.1-2019 for commercial buildings and the International Energy Conservation Code (IECC) 2021 for residential buildings.

To accelerate emissions reductions in the buildings sector, advanced manufacturing techniques are being developed in conjunction with factory-built and modular construction. In this way, energy-efficiency measures and distributed energy resources such as batteries, rooftop PV, and home energy management systems can be integrated into buildings in a consistent and low-cost way. NREL is currently involved in a three-year project to explore this as part of DOE's Advanced Manufacturing Program.[2]

NREL has developed two large-scale analysis tools for identifying the most promising energy-efficiency measures in residential and commercial buildings: ResStock[3] and ComStock[4], respectively. These tools utilize a large quantity of existing data sets for developing statistically representative models to evaluate the impact of climate, building type and vintage, and local fuels and fuel prices to prioritize different efficiency measures.

In the case of ResStock, NREL has generated average national results. For example, Table 3.1 shows the energy savings potentials for four different energy-efficiency measures for detached single-family homes. NREL has also developed fact sheets for 48 states[5] and provides the modeling capability to others to allow results to be generated at a local level. For example, Radiant Labs has used the capability to generate results for Boulder, Colorado.

ComStock is a newer tool. Because of the wide variety of commercial building types, NREL is using the model to assist with specific needs. For example, NREL experts are collaborating with those leading the LA100 Project, which has a goal of achieving 100% renewable electricity for Los Angeles by 2045, along with aggressive targets for electrifying buildings and transportation.[6]

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[2] https://www.nrel.gov/buildings/industry-innovation.html

[3] https://www.nrel.gov/buildings/resstock.html

[4] https://www1.eere.energy.gov/buildings/publications/pdfs/rsf/performance_based_how_to_guide.pdf

[5] https://resstock.nrel.gov/factsheets/

[6] https://www.energy.gov/eere/buildings/downloads/openstudio-0

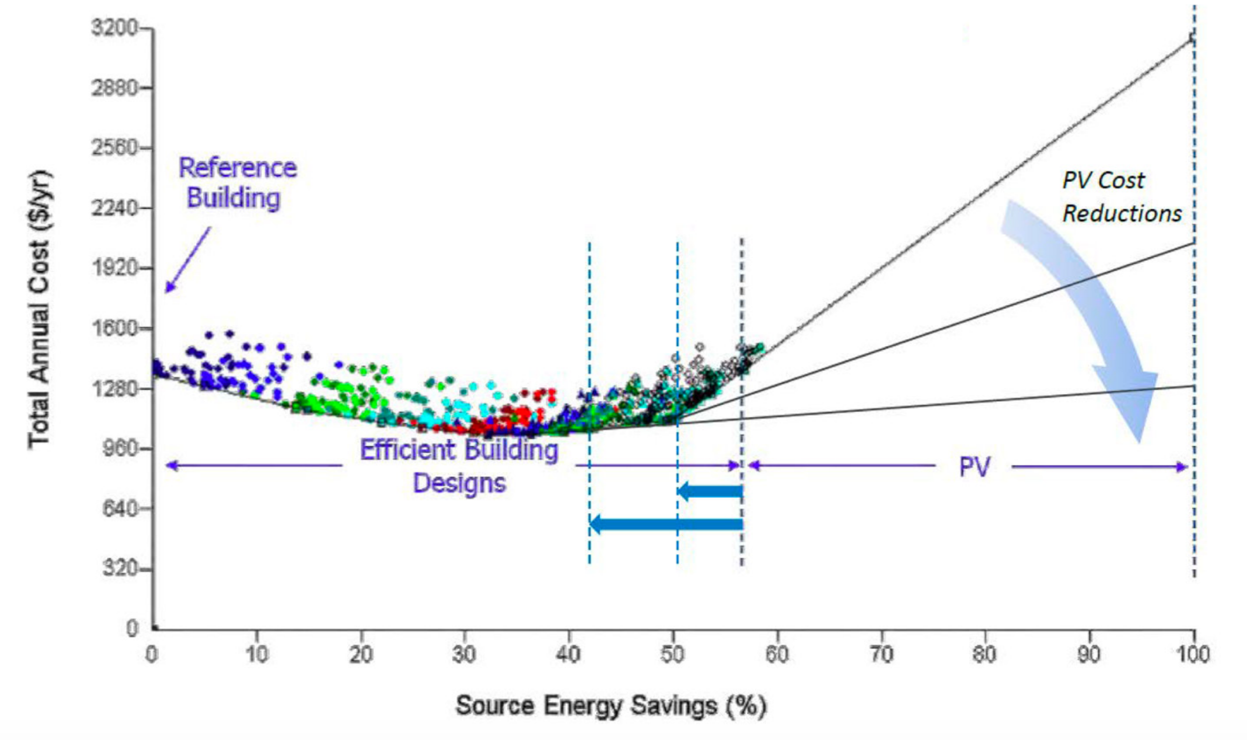

Figure 3.5. Example output from BEopt analysis showing total cost vs. energy savings. This shows the impact of various combinations of home energy-efficiency measures and the shift to earlier addition of rooftop PV as PV prices have declined. (Christensen et al. 2014, modified by David Roberts, NREL, to show impact of PV cost reductions.)

For maximizing efficiency in new construction, tools and guides are available for commercial buildings.

New building procurement should use a performance-based acquisition approach whereby design-build teams must submit bids that meet a specified Energy Use Intensity (EUI). NREL used this approach in the development of its Research Support Facility, the nation's largest net-zero energy office building, and they have developed a how-to guide.[7] DOE has developed the OpenStudio platform[8] for modeling building energy performance. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers has produced Advanced Energy Design Guides[9] originally covering 30% and 50% energy reductions in commercial buildings. ASHRAE now has guides for zero-energy buildings that produce enough on-site renewable energy to equal the total building energy use on an annual basis. As of this writing, these free guides are available for K-12 schools and small-to-medium office buildings, and more guides are under development.[10]

For both new homes and retrofitting energy efficiency measures, the BEopt model[11] allows for a range of energy efficiency measures to be evaluated on both a cost and performance basis. Figure 3.5 shows an example BEopt plot of total annual cost (annual utility bill plus annualized cost of energy-efficiency measures) for a wide variety of different combinations of efficiency measures versus the percent of source energy savings. The most cost-effective measures reduce the utility bill considerably more than the cost of the measures, themselves; but more expensive efficiency measures result in diminishing returns. Eventually a point is reached where the total annual cost is the same as the initial annual utility cost. In the example, this occurs at about 57% source energy savings. Further reductions in purchased source energy can then be met by adding photovoltaics. As

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[7] https://www1.eere.energy.gov/buildings/publications/pdfs/rsf/performance_based_how_to_guide.pdf

[8] https://www.energy.gov/eere/buildings/downloads/openstudio-0

[9] https://www.ashrae.org/technical-resources/aedgs

[10] https://www.ashrae.org/technical-resources/aedgs/zero-energy-aedg-free-download

[11] https://beopt.nrel.gov

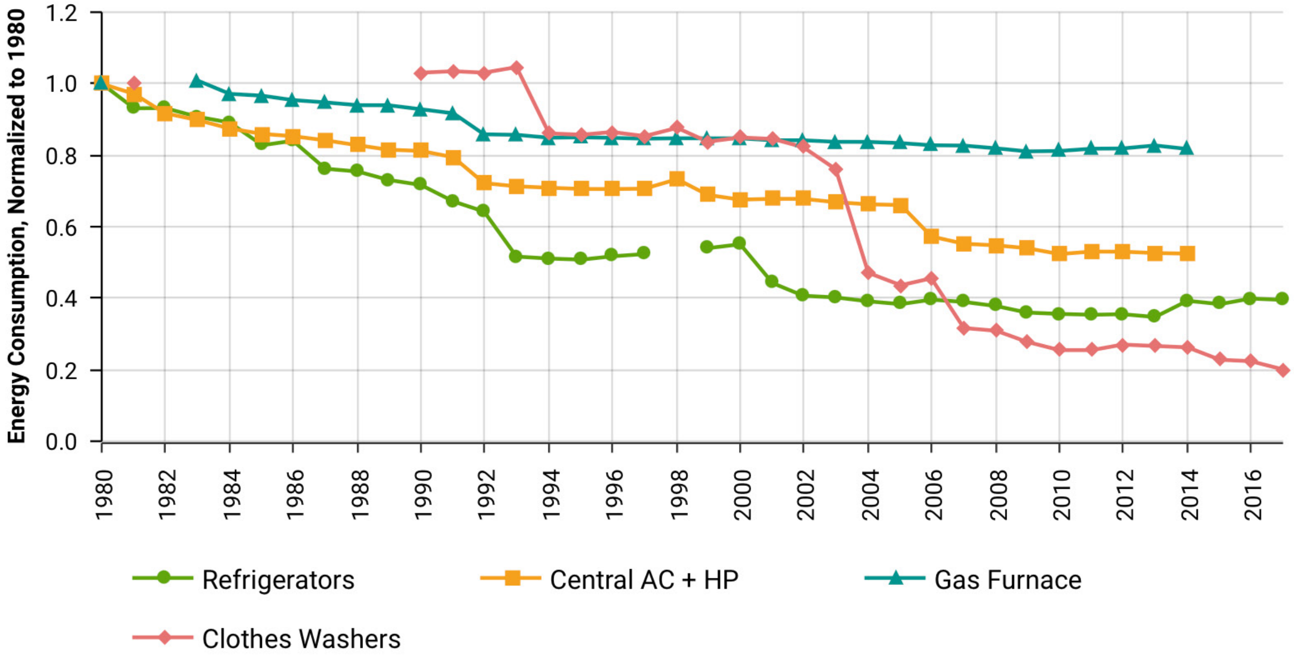

Figure 3.6. Relative energy consumption of US appliances and equipment, 1980-2017. The Energy Star program has resulted in a dramatic reduction in the average energy consumption of new appliances sold in the United States. (ACEEE, Alliance to Save Energy, and The Business Council for Sustainable Energy, https://energyefficiencyimpact.org)

PV costs have dropped, the slope of the PV curve has decreased, and the transition from energy-efficiency measures to PV occurs sooner. New homes should be designed to meet the 2021 International Energy Conservation Code (IECC) (Urbanek 2020) and should be designed to be net zero or near-net-zero if there is available unshaded roof for a sufficient-size solar photovoltaic array.

Cities have largely been leading the way in addressing climate change. Although zero-energy buildings are becoming more prevalent and are even appearing in some state and local building codes, we can achieve a net-zero energy built environment more rapidly and more cost-effectively if we address carbon emissions on a district or community scale. Multi-use districts or communities allow for economies of scale, better load profile control, shared equipment, and efficient transfer of energy between buildings. By co-locating housing, places of work, restaurants, recreational facilities, transportation costs and energy use are minimized. This approach is described in more detail in Section 3.5.

Perhaps the greatest achievement in energy efficiency has been the federal government's Energy Star program,[12] which has dramatically improved the efficiency of building equipment and appliances (Figure 3.6). As one example, a refrigerator today uses only about one-fourth of the energy of refrigerators in the 1970s, yet costs less and is larger. This program should continue and be expanded.

Before leaving the subject of energy efficiency, we should recognize that economists often refer to the "rebound" effect, whereby consumers who apply energy-efficiency measures partially negate some of the advantages by using more energy. Examples are a Prius driver who now drives more miles or a homeowner who installs LED light bulbs but leaves them on. Although this is a real effect that should be accounted for, it is a smaller effect than many economists assume. (Nadel 2012) estimates that direct and indirect rebound effects combined total about 20%. Rebound effects do not negate the fact that many energy efficiency measures are the most cost-effective means of reducing carbon emissions (Nadel, Elliott, and Langer 2015).

3.2 Converting buildings to all-electric

As explained in Section 2, with solar and wind electricity now less expensive than natural gas in most

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[12] https://www.energystar.gov/

locations and with the cost of batteries dropping dramatically, it is time to transition from natural gas to renewable energy in the electricity sector. Similarly, to meet challenging carbon emissions goals, we must also transition away from the use of natural gas in buildings.

Modern heat pumps are extremely efficient at providing building heating and cooling, even in cold climates, and will serve as the centerpiece of building electrification. New buildings, both commercial and residential, will be the easiest to electrify, as no rework or natural gas infrastructure will be needed (Billimoria et al. 2018). Ground-source, or geothermal, heat pumps offer very high performance due to the fact that the ground temperature is generally closer to the indoor temperature than outside air, and they are especially well suited for new construction.

Although electrifying existing commercial buildings is more challenging than for new buildings, they can utilize various forms of heat recovery and storage to improve performance (Nadel and Perry 2020).

A typical home natural gas water heater lasts eight to 12 years, and a gas furnace lasts 15 to 30 years, so installing these devices can result in carbon emissions for as many as three decades. As a result, many cities are now banning the use of natural gas in new homes. Berkeley was the first city to pass a ban, and many other cities in California and Massachusetts have followed suit.

Existing homes will be the most challenging to electrify. In cases where an existing home is heated with a forced air furnace and ductwork, the installation of conventional air source heat pumps may be the lowest-cost approach. For homes that use baseboard heating and do not have ductwork, ductless mini-split units can be installed. Current commercial ductless mini-split units are extremely efficient because they directly distribute the refrigerant fluid to each unit. They can provide a coefficient of performance of 2.0 or greater at outdoor temperatures of -5°F, meaning that they provide at least twice as much heat as electric resistance heating for the same amount of electrical energy input. Although efficient, the actual heating capacity of heat pumps is much lower at very low outdoor temperatures and so performance varies with climate zone (Dichter and Aboud 2020). Installing heat pumps in conjunction with high building insulation levels appropriate to the local climate will minimize the need for augmentation with electric resistance heating.

A refrigerator today uses about one-fourth of the energy of refrigerators in the 1970s, yet costs less and is larger. This is a direct outcome of the federal government's Energy Star program, which has dramatically improved the efficiency of building equipment and appliances—and which should be expanded.

Electric heat pump water heaters and clothes dryers can operate much more efficiently than electric resistance units. Although many homeowners have traditionally preferred the control and speed they get when cooking on a natural gas cooktop as opposed to electric resistance elements, modern induction electric cooktops are now very popular with top chefs because of their rapid heating and fine adjustment capabilities. In addition, it has been shown that gas stoves can cause significant indoor air pollution (such as nitrogen dioxide emissions) that results in health impacts, especially in children, and cooking with electricity is therefore healthier (Roberts 2020a). Installing an exhaust range hood or kitchen exhaust fan can reduce emissions associated with both gas and cooking pollution, but simply switching from a gas to an inductive stove can eliminate the source of dangerous nitrogen oxide emissions (Imbler 2020).

Various things can improve the economics of electrifying existing homes:

- Eliminating natural gas can avoid a monthly hook-up charge.
- Switching from natural gas to electricity can be cost-effective when a gas furnace or gas water heater has failed or when a homeowner wants to install central air conditioning, because a new heat pump (which provides both heating and cooling) eliminates the need to purchase this other equipment. However, when a water heat-

er or furnace fails, the homeowner or landlord should address the problem immediately. This means that electric service should be installed beforehand and that contractors must be trained to perform rapid replacements with heat pumps.

- A program that combines financed energy-efficiency measures and rooftop PV along with electrification can avoid the increase in utility bill that might otherwise result in switching from cheap natural gas to more expensive electricity. Energy-efficiency measures can reduce the total electricity needed and might avoid the need for an electric service upgrade. Rooftop PV can also lower the electric bill. The PV system can be purchased outright via a cash payment, but paying with a low-interest loan or through third-party financing, or by purchasing electricity from a community solar garden, can spread out the capital costs over time such that the homeowner sees a net decrease in their monthly payment (energy bill plus any loan costs). By combining energy-efficiency measures with rooftop PV, building electrification should also prove to be an outstanding post-COVID job creator.
- Time-of-use electric rates can allow a homeowner or home energy management system to operate some equipment and appliances during times of low electricity rates. Especially when coupled with home batteries, time-of-use rates can lower electric bills.

A challenge in electrifying buildings is that in many parts of the country contractors have insufficient experience with heat pumps and heat pump water heaters, and supply chains are inadequate. To get around the dual problems of cost and experience, one approach is to target initial market penetration in locations where higher-cost propane is used for heating. This will provide better economics and allow for a market to develop.

The ideal goal is for buildings to be not only all-electric but net-zero, meaning they produce enough renewable energy to equal their annual energy use. Building rooftops provide considerable area for PV arrays, although many roofs are shaded. In such cases, community solar or solar gardens provide an option that is generally lower in cost than a rooftop installation. PV can also be provided elsewhere on a site associated with a building or a group of buildings, such as a campus (open fields, atop parking garages, etc.).

DOE has developed PVWatts,[13] a simple tool for sizing a PV array. PVWatts can also be run as one of the tools within DOE's System Advisor Model[14] and can even be used within the BEopt model described in the previous section.

When electrifying buildings, it is important to consider the actual and potential greenhouse gas emissions associated with the working fluids used by heat pumps, typically referred to as refrigerants. With climate change increasing the frequency of severe heat waves and with those in developing nations seeking a more comfortable lifestyle, global use of air conditioners is growing significantly. Fully electrifying building space conditioning with heat pumps will further exacerbate the situation because the refrigerant working fluids used in the heat pumps (and air conditioners in climates where buildings require cooling only) are also strong greenhouse gases themselves. These gases contribute to warming if they get into the atmosphere, as often occurs at the end of equipment life. When chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) refrigerants were phased out by the Montreal Protocol because of their destructive effects on Earth's ozone layer, an important co-benefit was reduced potential greenhouse warming. Unfortunately, their replacements, hydrofluorocarbons (HFCs), have high global warming potentials, making them thousands of times as powerful as carbon dioxide.

While it is important to reuse or destroy refrigerants when a heat pump, air conditioner, or refrigeration equipment is replaced, some leakage will inevitably occur, so it is important to transition to refrigerants with lower global warming potentials (GWPs). The EPA began regulating leakage rates and GWPs of refrigerants in 2015 as part of its Significant New Alternatives Policy (SNAP), and industry made progress developing lower-GWP alternatives. California is in the process of establishing guidelines that will limit the GWP of refrigerants to less than 750, and a number of states have adopted SNAP rules that limit the use of HFCs (Butsch 2020).

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[13] https://pvwatts.nrel.gov

[14] https://sam.nrel.gov

Electrification of the buildings sector will likely increase the amount of electricity that must be generated. However, NREL's Electrification Futures Study (Mai et al. 2018) shows the increase to be relatively modest because today's heat pumps are highly efficient and because higher-efficiency electric appliances will replace simple electric resistance heating (e.g., induction cooktops replacing electric resistance ones). In addition, if energy-efficiency measures and rooftop solar PV systems are combined with electrification, the burden on central electricity generation will be even lower. However, the additional electricity needed for winter heating in cold-weather climates, and the lower efficiency of electric vehicles in the winter, together mean that there will be an increase in winter electricity needs. The consequence is that some utilities that currently experience their peak demand in the summer could see their peak shift to the winter.

3.3 Building demand response measures

Utility operators are accustomed to addressing varying demands on the grid. As the national electric grid adds more solar and wind energy, operators must also address the variable nature of their electricity supplies. Buildings use 74% of grid electricity and can be designed to use that electricity at times that are beneficial to the grid. For example, dishwasher use can be shifted to optimum times. The hot water tank associated with a home heat pump water heater typically has a volume of between 50 and 80 gallons. That storage tank can be heated to a high temperature at a time that shifts the utility load curve and minimizes the homeowner's electricity bill. Homes also have a certain amount of thermal mass. By precooling or preheating a home prior to a period of high electric demand, the inherent thermal storage of a home can be used to shift the load, allowing electricity supply and demand to be better matched. In commercial buildings, hot- or cold-water storage tanks or ice storage can be used to shape the demand profile and reduce demand charges. In addition, a home battery can be charged and discharged to accommodate grid needs.

Also, as transportation becomes electrified, electric vehicles can charge both at work and at home. As the percentage of renewable energy on the grid increases, there will be times when there is surplus renewable electricity. By providing attractive rates to EV owners, their vehicle batteries can be charged during times of surplus, which better uses available renewable electricity and helps keep electric rates down. In the future, it may also be advantageous to allow

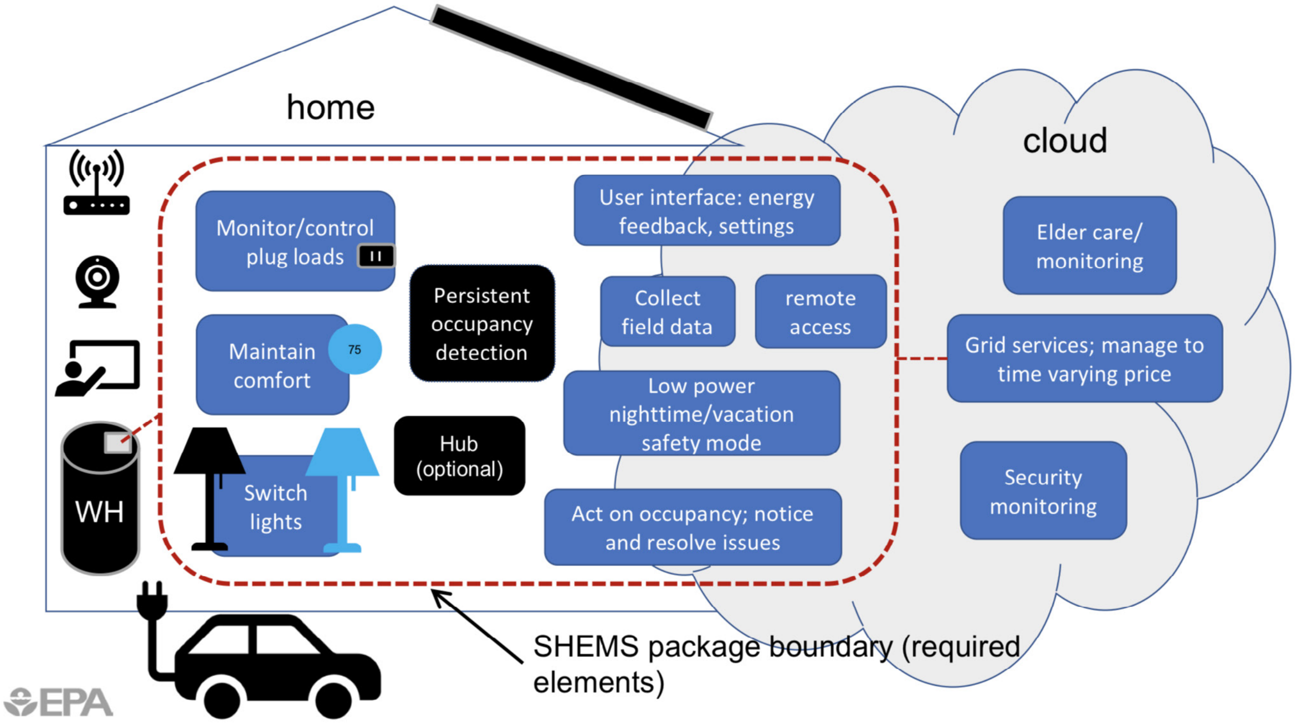

Figure 3.7. EPA Energy Star Smart Home Energy Management System (SHEMS) package. This system takes advantage of the large potential for demand response in buildings to improve grid reliability. (Daken 2019)

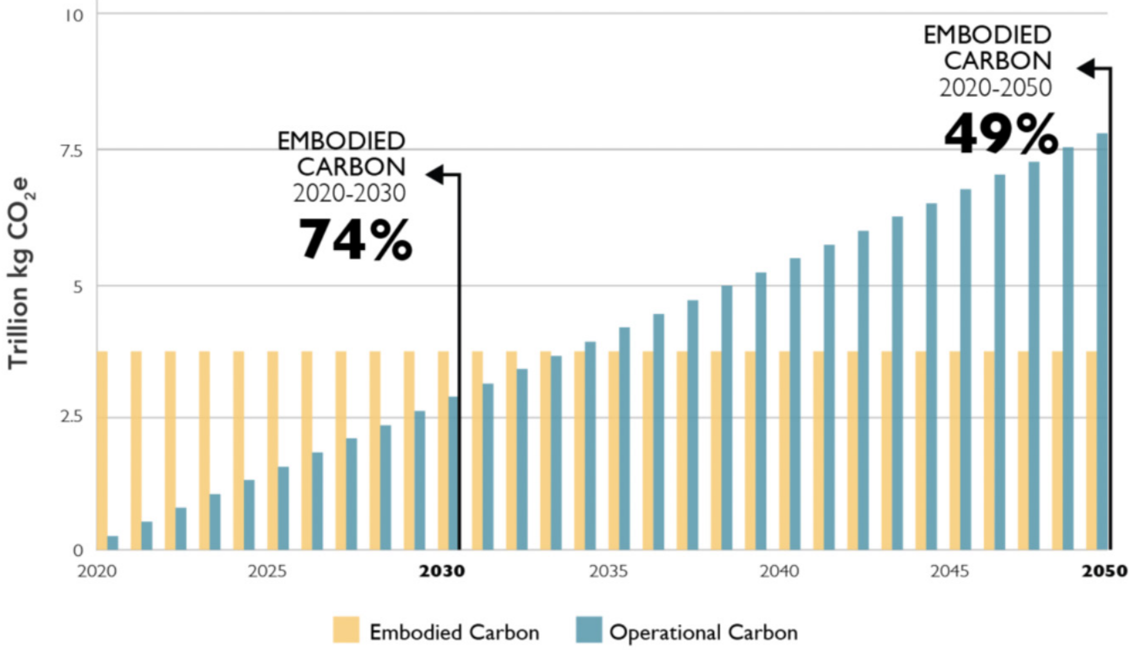

Figure 3.8. The percent of a building's total carbon emissions due to the embodied carbon as a function of building age. Under a business-as-usual scenario, the embodied carbon for a building built in 2020 represents 74% of its total carbon emissions 10 years later and still represents nearly half the total emission 30 years after construction. (Architecture 2030, https://architecture2030.org/new-buildings-embodied/)

EV battery electricity to be sold back to the grid (so-called vehicle-to-grid, or V2G, technology, described further in Section 4.2) although EV manufacturers do not currently allow that use in the vehicle warranty.

To take advantage of demand response, or flexible load, capability, we will need more Wi-Fi-enabled appliances (engineered with adequate cyber security) that can both respond to price signals and account for consumer preferences (e.g., through learning algorithms). Home energy management systems will control the time-of-use of various equipment and appliances. Smart electric meters and two-way communications between utilities and buildings will allow controls to operate in conjunction with utility needs. The EPA is developing an Energy Star Smart Home Energy Management System (SHEMS) specification (Figure 3.7) to allow for broad compatibility (Daken 2019).

3.4 Low-carbon building materials

In the past, the embodied carbon emissions associated with buildings were considered small relative to the emissions associated with a building's energy use over its lifetime. Several factors are now changing that view. First, as buildings become much more efficient, their energy use and therefore carbon emissions decrease greatly. Second, as buildings electrify and that electricity is provided by wind and solar, the carbon emissions associated with the building operation approach zero. Finally, because climate change is a true crisis that must be addressed in the near term, the emissions associated with a building at the current time become more important than the emissions over the building life. So, for all these reasons, decarbonizing the buildings sector must include consideration of decarbonizing the building construction itself.

Architecture 2030 is a non-profit organization established in 2002 with the mission of transforming the built environment to address the climate change crisis. Among other things, it has compared the embodied carbon in all the global projected building construction between 2020 and 2030 to the carbon released in the operation of those buildings.[15] The embodied carbon emissions associated with construction do not accumulate, as do the emissions associated with operating the building. For a build-

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[15] https://architecture2030.org/new-buildings-embodied/

ing built in 2020, by 2030 the embodied carbon represents about three-quarters of the total accumulated emissions (Figure 3.8). By 2050, it still represents about half the total accumulated emissions. And as buildings electrify and that electricity is increasingly supplied by solar and wind, the operational emissions will decrease, making the embodied emissions even more significant than displayed in the figure.

A whole-building life-cycle assessment should be conducted in the design of all new buildings. A description of available tools can be found at the Building Green website (Melton 2019). Many tools are free, such as the Embodied Carbon in Construction (EC3) tool[16] and Athena's Impact Estimator for Buildings.[17]

Steel and concrete construction materials represent a significant fraction of carbon emissions embodied in new building construction. Architecture 2030 has set a target of zero embodied carbon emissions by 2050 and has developed a Carbon Smart Materials Palette to allow designers to choose versions of materials that minimize embodied carbon.[18]

Concrete, and in particular the Portland cement contained in concrete, is a major source of carbon emissions and so low-carbon concrete mixes should be specified. The amount of cement needed should be minimized and supplementary cementitious materials (SCMs) from non-fossil fuel-based sources should be substituted. In the case of steel, recycled steel should be used when possible and both new and recycled steel should be produced from electric arc furnaces, ideally running off renewable electricity. Structural wood, in particular cross-laminated timber (CLT) has become popular, although there is debate about its overall impact on carbon sequestration compared to leaving forest timber undisturbed. Architecture 2030 has recommended that builders use reclaimed, salvaged, or recycled wood products when possible and otherwise specify wood from new growth, sustainably managed forests.[19] Minimizing carbon emissions in the manufacture of steel and concrete is discussed further in Section 5.

Concrete, and in particular the Portland cement contained in concrete, is a major source of carbon emissions. Many other building materials also have significant "embodied" carbon emissions. All new building design should include a life-cycle assessment of climate impact; there are many tools available today to help.

The impact of embodied carbon emissions should also be considered when choosing energy-efficiency products for new and existing buildings. For example, high levels of insulation are important in minimizing a building's energy use, and insulation materials differ in terms of their embodied carbon emissions. Blown-in materials such as fiberglass and cellulose, have a lower carbon footprint than rigid and spray foam insulations, and this should be taken into account in a life-cycle assessment of emissions.

Architecture 2030 has summarized key steps to reduce embodied emissions:[20]

- Use or repurpose existing buildings.
- Use salvaged and/or recycled materials.
- Optimize systems for material efficiency.
- Specify materials that naturally sequester carbon.
- Specify materials manufactured with renewable energy.
- Design for durability.
- Choose the right materials for your climate (e.g., durability to heat or moisture).
- Get to know the supply chain for your specific project.
- Understanding your region and source locally.
- Use low-emissions transportation.
- Establish carbon targets.

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[16] https://www.buildingtransparency.org/en/

[17] http://www.athenasmi.org/our-software-data/impact-estimator

[18] https://materialspalette.org/palette/

[19] https://materialspalette.org/wood/

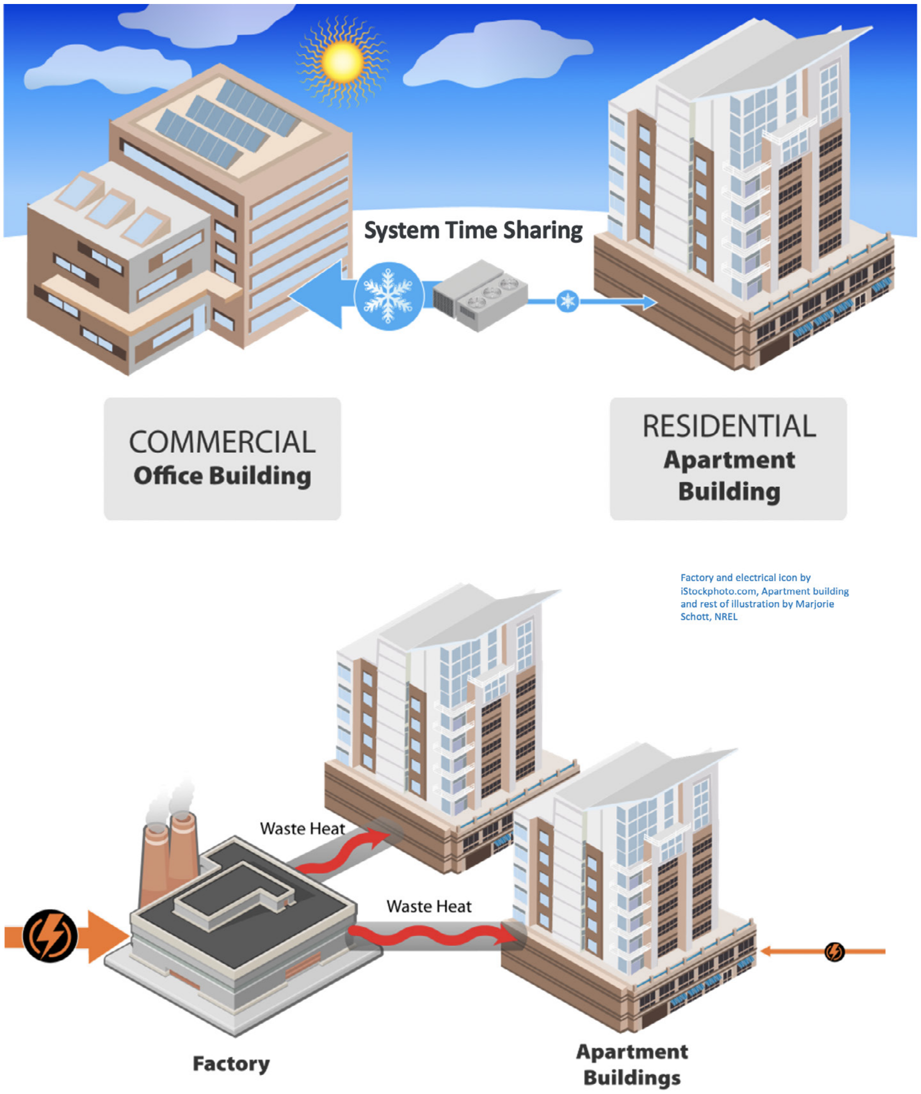
[20] https://architecture2030.org/new-buildings-embodied/

Federal, state, and local governments can address this issue by specifying low embodied carbon materials in “buy green” purchase provisions.

3.5 Zero-energy districts and communities

While we have focused on the decarbonization of individual buildings, there are numerous advantages to addressing districts or communities of buildings. Multi-use communities that combine housing, places of work, restaurants, recreational centers, and other uses minimize transportation emissions. Large equipment such as heat pumps can serve multiple buildings and may be shared by different buildings at different times (Figure 3.9). Heat can be transferred from buildings needing cooling to those needing heating. Waste heat from factories can heat apartment buildings at night. Wastewater streams can be efficiently tapped as both heat sources and sinks. District heating and cooling systems can benefit from economies of scale. An entire district can be net-zero energy without each individual building having to meet that standard.

Multi-use communities that combine housing, places of work, restaurants, recreational centers, and other uses minimize emissions from transportation—and can use shared equipment, such as heat pumps, to serve different buildings at different times. An entire district can be net-zero energy without each individual building having to meet that standard.



Factory and electrical icon by iStockphoto.com, Apartment building and rest of illustration by Marjorie Schott, NREL

Figure 3.9. Equipment sharing in a district energy project. District energy designs can take advantage of system sharing day (top) and night (bottom). (Courtesy Marjorie Schott, NREL)

Heating and cooling are the biggest building energy loads in existing buildings, and district design strategies allow for these loads to be greatly reduced. District heating has long been used in Europe, as well as in some US colleges and other campuses, but these systems typically use a central heating (or cogeneration) plant that burns natural gas to heat water or steam that is circulated to the various buildings. To achieve zero-carbon emissions, the latest strategy uses a design

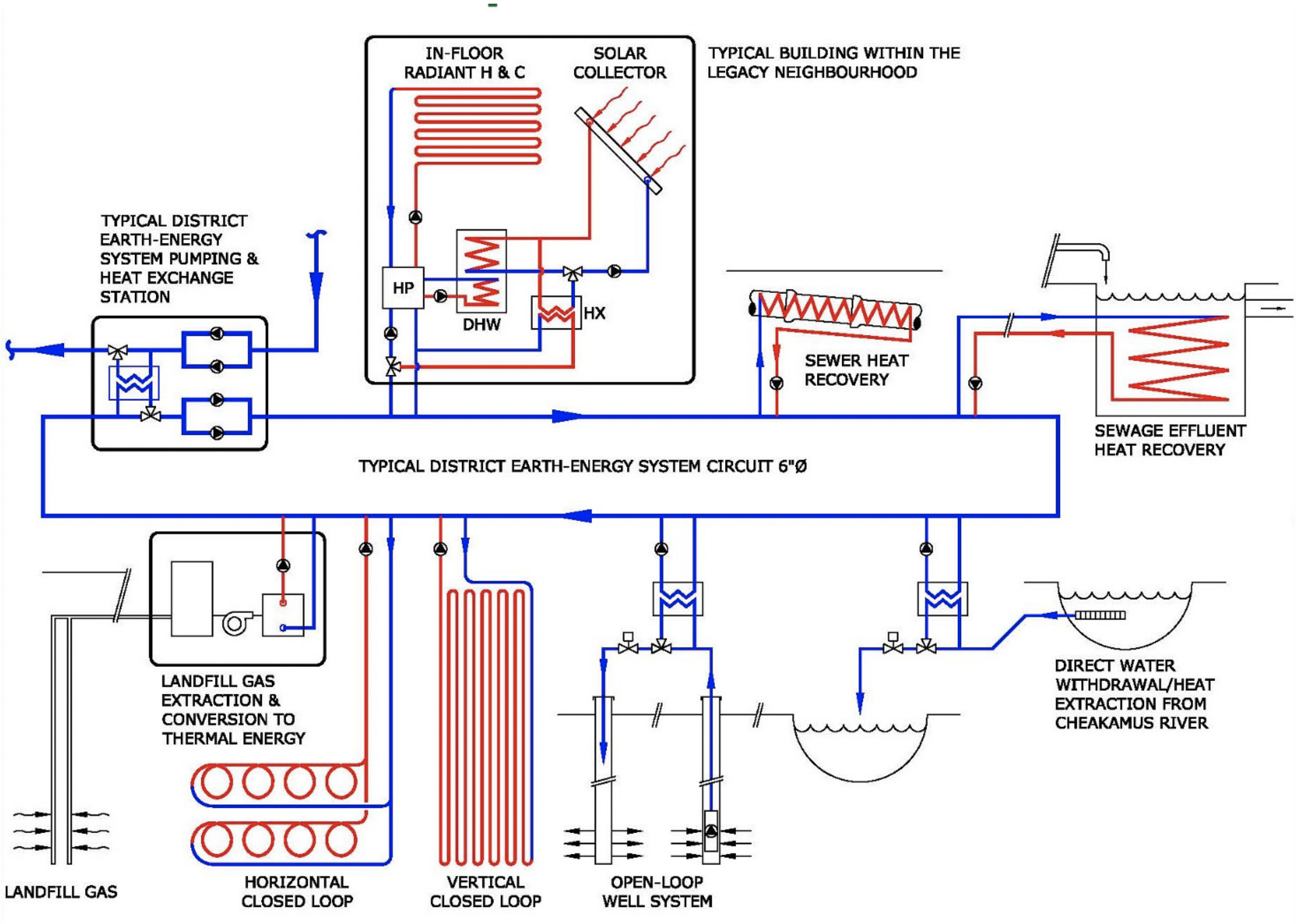


Figure 3.10. The ambient loop district heating and cooling concept. This modern concept, originally developed for the Whistler Olympic Village as shown here, can utilize a multitude of heat sources and sinks. (Integral Group, with thanks to Vladimir Mikler, originator of the schematic and the ambient loop district energy concept.)

known as an "ambient temperature loop," or ambient loop for short, which can simultaneously and efficiently provide both heating and cooling to different buildings (Mikler n.d.) The ambient loop concept was first developed by Integral Group Vancouver for the Whistler Olympic Village (Figure 3.10).

In a typical system, a pump circulates water through an uninsulated pipe network buried below the frost line. The temperature of the soil is near the annual ambient air temperature, and the water communicates with it thermally. Heat can be added to the water by buildings rejecting heat or removed by buildings needing heat. Heat pumps or heat recovery chillers located at individual buildings or at other points along the ambient loop add and extract heat from the loop and can also move heat between geothermal wells and the circulating water. To further ensure that the water is maintained in the optimum temperature range for maximum heat pump performance, a central plant is used. This plant can use cooling towers or wastewater to reject heat or it can add heat via renewable sources like wastewater, solar thermal collectors, renewable fuel, or ground- or air-source heat pumps powered by renewable electricity.

An example of a zero or near-zero energy district is the Whisper Valley Community being developed in Austin, Texas (Kutscher 2020). It consists of all-electric homes that use the latest energy-efficient appliances, commercial buildings, two schools, and a 600-acre park. The district uses ground-source heat pumps located at each home. The heat pump ground loops are connected to an ambient loop that runs throughout the housing complex. Each home also contains an optional 5-kW rooftop solar photovoltaic

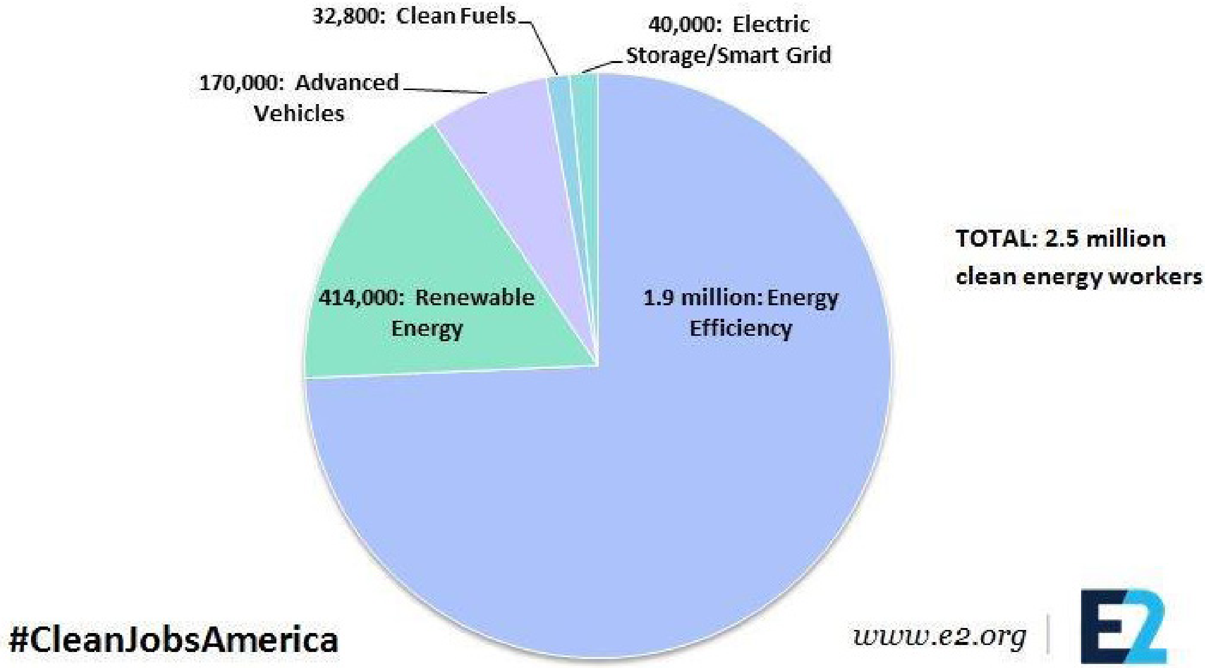


Figure 3.11. Clean energy workers by sector. Energy efficiency jobs represent about three-quarters of the 2.5 million clean energy jobs in the United States. (E4TheFuture 2019)

array. The developer has stated that the economy of scale provided by working at a district scale allows for the homes to be sold at a median cost of $50,000 below Austin's median home cost.

NREL has developed a software development kit called URBANopt that models rooftop PV arrays, ambient loops, electric demand response measures, etc., and the kit can be integrated into other computer models to aid in the design of zero-energy districts.[21] NREL engineers are providing general technical support for the National Western Center project in Denver and several other district projects, and NREL has just released a new guide to planning high-performance districts and communities (Pless, et al. 2020). The New Buildings Institute's database of zero-energy buildings and districts shows that in 2019, there were 81 existing and 499 under development in the United States and Canada (New Buildings Institute 2019).

3.6 Job creation

Energy efficiency is the biggest creator of clean jobs in the United States (Figure 3.11) and this is dominated by the buildings sector. These jobs break down as follows: 23% in Energy Star appliances and efficient lighting; 15% in building materials and insulation; 12% in services such as building auditing and certification; and 49% in HVAC, or heating, ventilating, and air conditioning (E4TheFuture 2019).

As pointed out above, electrifying existing buildings in an economically acceptable way may involve combining electrification equipment installation with improved energy efficiency as well as rooftop photovoltaics. At present, only one in four US homes (Woodward 2019) and only 7% of commercial buildings (Deason et al. 2018a) are all-electric. This means that a massive amount of building stock will need to be addressed. HVAC contractors experienced at installing natural gas furnaces and water heaters will have to become trained in installing heat pump units. Handling this transition will require both training of existing workers and hiring new workers.

The COVID-19 pandemic has taught us that virus spread is of special concern in indoor spaces. The virus is spread both through large droplets that travel a short distance and via aerosols that can remain airborne for a considerable period of time. To allow the economy to recover and protect against future

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[21] https://www.nrel.gov/buildings/urbanopt.html

pandemics, efforts to weatherize and electrify buildings should be accompanied by measures that can also reduce viral spread. This will entail such things as increasing outdoor air ventilation rates, installing heat or enthalpy recovery ventilators to minimize the negative impacts of these additional ventilation loads, installing HEPA air filters and purification systems, and improving indoor air distribution patterns. This is an evolving issue, and the American Society of Heating, Refrigerating and Air-Conditioning Engineers is an important source of up-to-date information (ASHRAE 2020). With the increasing incidence of wildfires, attention will also need to be paid to filtering smoke from outside air.

According to one recent California report (Jones et al. 2019) "building electrification in California could support an average of 64,200-104,100 jobs annually, after accounting for losses in the gas industry." As California has 12% of the US population, this suggests that the total jobs in the US needed to carry out full building electrification by 2045 would be somewhere between 500,000 and 1 million permanent jobs. Achieving building electrification by 2035, a much more aggressive target to minimize additional climate change damage, the number of new jobs increases to roughly 1.5 million. These job numbers do not account for the workers needed to upgrade energy efficiency, install rooftop solar photovoltaic systems on existing buildings, install energy management systems (all of which would help reduce a building owner's electricity bills as they convert from natural gas to electricity), or upgrade ventilation systems in a post-COVID environment.

POLICY OPTIONS FOR THE BUILDINGS SECTOR

Many diverse actions could promote decarbonization of the diverse buildings sector in the United States. Below, we've grouped them according to type of measure.

Maximizing energy efficiency

- The energy performance and carbon emissions of all commercial buildings with a floor area greater than 25,000 square feet should be benchmarked and published.
- Beginning as soon as possible, all residential and commercial properties should receive an energy audit prior to sale or rental and receive an energy score that is communicated to buyers. Home Energy Rating Score[22] should be used for new homes and Home Energy Score for existing homes (NAHB 2019). The Building Energy Asset Score should be used for commercial and multi-family buildings. Mortgage industry requirements should be updated to include an estimate of monthly energy cost in determination of affordability and loan qualification.
- All new home equipment and appliance replacements should meet the latest Energy Star requirements.
- DOE should complete the series of ASHRAE Net-Zero Energy Design Guides to cover the full range of building types and provide training in their use.
- Performance-based procurement should be used for new commercial buildings, and the buildings should be designed and built to use half the energy of commercial buildings specified in the 2019 standards of ANSI/ASHRAE/IESNA, Standard 90.1-2019, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.[23]
- The United States should adopt a national building energy/carbon code designed

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[22] https://www.energy.gov/eere/buildings/building-energy-asset-score

[23] https://www.ashrae.org/technical-resources/bookstore/standard-90-1

Maximizing energy efficiency

to make all new buildings have net-zero carbon emissions (utilizing either on-site or off-site renewable energy) by 2030 and achieve a LEED Net Zero rating.[24]

- Building on its previous success, the Energy Star program should be expanded to achieve greater efficiency improvement compared to 2020 for all electric building appliances and HVAC equipment.
- The Weatherization Assistance Program provides important benefits, including job creation, emissions reductions, and support for low-income consumers. It should be expanded and provided with more funding.

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[24] https://www.usgbc.org/programs/leed-zero

Transition to all-electric buildings

- All new residential and commercial buildings should be all-electric beginning as soon as possible, preferably within two years.
- Tax incentives for electric heat pumps, home batteries, and home energy management systems are needed to accelerate the transition to all-electric buildings.
- All existing residential and commercial buildings should be all-electric by 2035. To minimize the economic impact on homeowners, energy-efficiency measures, rooftop PV, batteries, and home energy management systems (in conjunction with time-of-use electricity rates) should be deployed as a package along with all-electric equipment and appliances. Tax incentives should be provided for heat pumps and other electric appliances. Financing mechanisms such as low-interest loans, PACE (property-assessed clean energy) programs, and others can amortize the up-front capital costs over time. Where rooftop PV can be installed, power purchase agreements or loans can be designed such that there is no net increase in the utility cost to the homeowner when amortized over a 20-year period. Where rooftop solar is not practical, participation in community solar gardens should be promoted. All of these measures should be integrated into the Weatherization Assistance Program to the extent possible.
- Although rooftop PV installation is generally more expensive than large, centralized systems, it is synergistic with electrification, it provides excellent spatial diversity for the electricity supply, and rooftop area represents a large resource potential. As a result, it should continue to receive a federal tax credit (along with all solar energy systems). In addition, it is important to continue the practice of net metering. Home battery installations should also be incentivized with a significant tax credit.
- All new government buildings should be fully electrified and net-zero energy. Existing government buildings should be made highly energy-efficient and lead the way in electrification.
- Beginning as soon as possible, all new homes should be equipped with at least one 240-V, 100-amp outlet to allow for future installation of a Level 2 electric vehicle charging station.

POLICY OPTIONS CONTINUED ON NEXT PAGE

Zero-Energy Districts and Communities	• New developments should follow a zero-carbon, walkable community approach that takes advantage of economies of scale and employs a modern district heating and cooling system.
Building demand response measures	• Beginning as soon as possible, all home heat pump water heaters, electric HVAC equipment, and key appliances that can make a significant contribution to demand response should be Wi-Fi-enabled and EPA Smart Home Energy Management System-compliant. • Similarly, all new homes should be equipped with a smart meter and an EPA-compliant SHEMS or equivalent.
Low-carbon building materials	• All new buildings should meet the AIA Architecture 2030 Challenge of reducing embodied carbon emissions. Accordingly, a whole building life-cycle assessment should be conducted to show the following reductions in global warming potential relative to the 2020 industry-wide average for a building of a similar type as follows: —45% or better by 2025. —65% or better by 2030. • Insulation and other materials used for energy-efficiency retrofits should meet the same embodied carbon reduction criteria and time schedule as for new buildings.
Multi-family buildings	• Electric vehicle charging infrastructure should be included in the parking requirements for all multifamily buildings. • Landlords should prominently display expected average utility costs for their units in the lease contract prior to having a tenant sign a new lease.

The energy-efficient campus of the National Renewable Energy Laboratory in Golden, Colorado, employs state-of-the-art sustainability features, including the nation's largest net-zero energy office building. (Josh Bauer/NREL 59215)

4.0 The Transportation Sector

A Chevy Volt charges up with photovoltaic-generated electricity at the National Renewable Energy Laboratories in Golden, Colorado. (Matthew Staver / NREL 39252)

Transportation is a critical and complex component of the US economy. Transportation modalities, information and control systems, infrastructure, and fuels pose significant opportunities and challenges on the road to transformation. In the United States, transportation now contributes the largest fractions of total GHG emissions—roughly 28% as of 2018—and its share is growing (EPA 2020a; Green and Parkhurst 2018; NAS 2018). Among the various sources of transportation sector GHG emissions, light-duty vehicles comprise the largest percentage by far (Figure 4.1).

The United States is addressing transportation sustainability in a number of ways, but is moving from an earlier focus on fuel efficiency toward a greater emphasis on electrification and advanced vehicle technologies, plus associated strategies intended to reduce overall vehicle miles traveled (VMT). Advanced technologies include zero-emissions vehicles (ZEVs) such as battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs or PEVs), and fuel cell vehicles (FCVs). Such technologies, which encompass the light-duty vehicle (LDV), heavy-duty vehicle (HDV), and off-road categories, can reliably and efficiently operate on clean, sustainable energy; but they require transformation of associated infrastructure, including electricity grids, fueling/charging stations, fuel generation/distribution/storage facilities, mobility networks, and more.

While PEVs, BEVs, and FCVs are production-ready technologies that are already in use within the United States, we need more dramatic efforts in the transportation, fuels, and policy/planning sectors if GHG reduction goals are to be met (Joselow 2018). It is unlikely that anything short of full electrification will allow us to achieve needed climate and sustainability goals. Hence, we must deploy more low-carbon vehicles, refine existing systems and networks to accommodate greater numbers of vehicles, adopt market-promoting and system-supporting policies, and devise innovative financing mechanisms to ensure the durability of this transformation.

Fuel efficiency alone cannot improve quickly enough to overcome the impact of a larger population traveling more miles in bigger and more numerous petroleum-fueled vehicles. Nor can it address related challenges, such as increased longevity of legacy on-road vehicles, a rapidly expanding freight logistics sector that is heavily reliant on diesel fuel, deep-rooted consumer behaviors and preferences, and transportation policies and systems that perpetuate reliance on single occupant auto-mobility (Schaffer, Sims, and Corfee-Morlot 2014; Monschauer et al. 2019). Even the initiative to improve fuel efficiency through Corporate Average Fuel Economy (CAFE) standards has been under pressure from the Trump administration.

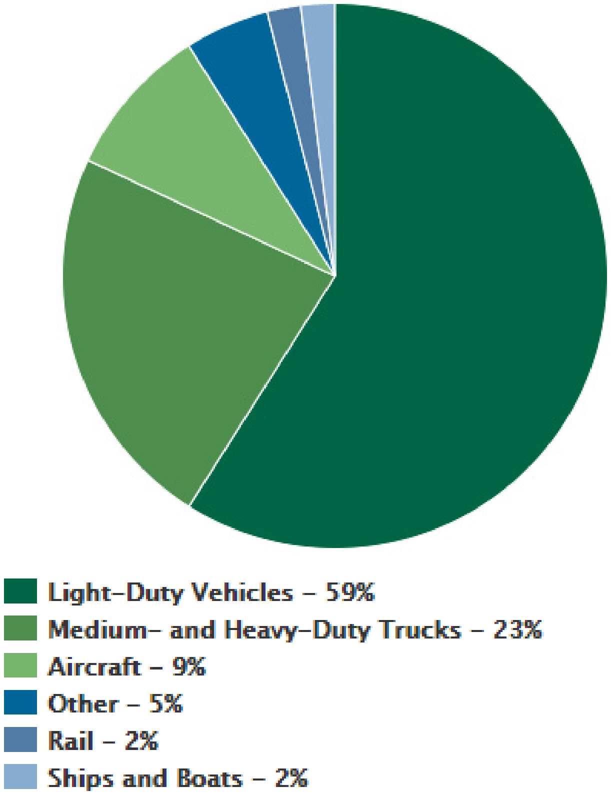
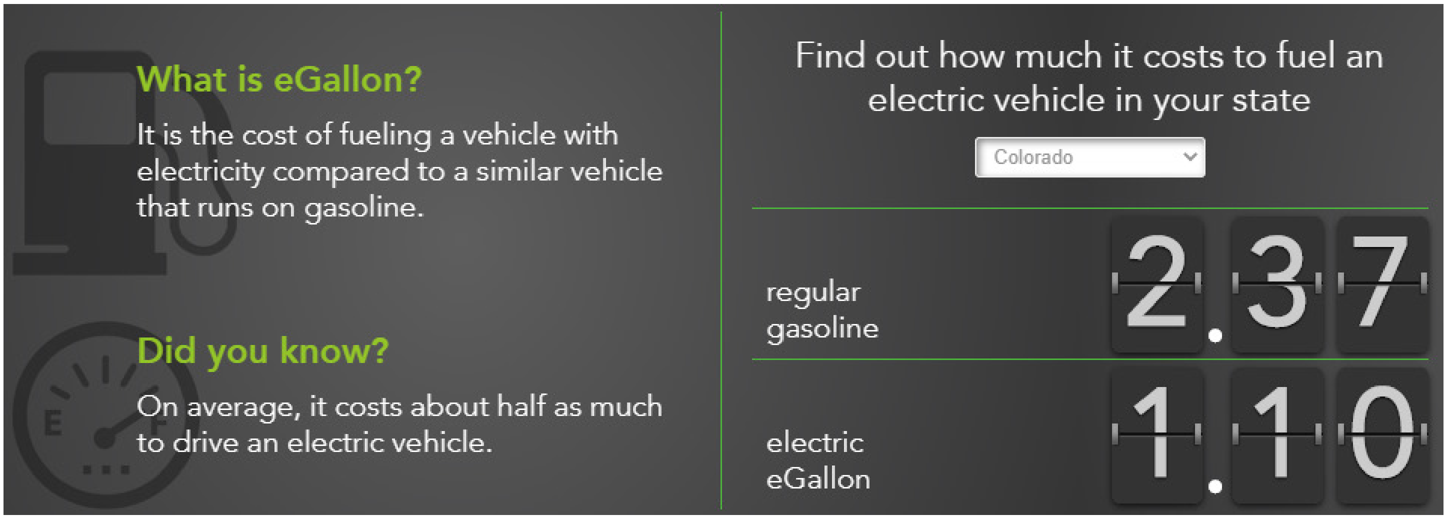


Figure 4.1. 2018 US transportation sector GHG emissions by transport type. Transportation emissions are dominated by light-duty vehicles. Transportation emissions do not include emissions from non-transportation mobile sources such as agriculture and construction equipment. “Other” sources include buses, motorcycles, pipelines, and lubricants. (EPA 2020a)

4.1 Dueling crises: climate change and COVID-19

The COVID-19 pandemic has upended commerce (ITF 2020a), mobility, and social norms in ways that are unprecedented. The travel and transportation industries have been particularly impacted as daily transactional and social interactions among people have been severely restricted. Even in the wake of a successful vaccination program, the ways in which society approaches transportation and mobility may be altered for years to come. Some behavioral initiatives and policies previously established to mitigate



What is eGallon?

It is the cost of fueling a vehicle with electricity compared to a similar vehicle that runs on gasoline.

Did you know?

On average, it costs about half as much to drive an electric vehicle.

Find out how much it costs to fuel an electric vehicle in your state

Colorado

regular gasoline 2.37

electric eGallon 1.10

Figure 4.2. Comparative cost of driving with gasoline and electricity. The cost of purchasing energy for an electric car is generally about half that for a gasoline car. EVs also have considerably lower maintenance costs. Information shown for Colorado only; last updated August 31, 2020. (https://www.energy.gov/maps/egallon.)

the emissions impact of transportation, particularly in population-dense urban areas, may need to be reimagined to minimize the potential for disease transmission (ITF 2020b). Otherwise, individuals who would ordinarily choose mass transit options, including air travel, may feel compelled to return to individualized transportation modes that are perceived to be safer, translating to more single-occupancy cars on the road, more vehicle miles traveled, more near-term petroleum-based fuel consumption, and an attendant loss of already-realized GHG emissions improvements.

Times of challenge always present profound opportunities, and the advent of COVID-19 is no exception, particularly with regard to transportation (Papandreou 2020) and other energy end uses. As the world recovers from the pandemic, we have an opportunity to align economic redevelopment and climate change action to create a cleaner and better planet in a shorter time frame than was previously imagined. For the transportation sector, reducing mobility (e.g., via more telecommuting, distance learning, and virtual meetings, all of which have become commonplace during the pandemic) is a powerful decarbonization force. The next best ways to decarbonize transportation are to increase mass transit and transition to zero-carbon vehicles. Given the current uptake of BEVs, rapid transition to full electrification of the light-duty vehicle sector is a realizable goal.

There are a number of improvements that can help accelerate this transition, including greater access to and from electrical grids, more rapid and advanced charging systems, longer-lived and faster charging batteries, a denser network of charging stations, enhanced connectivity, and related technology, all described in more detail below.

4.2 Vehicle electrification: the key to decarbonization

The path to decarbonization of the transportation sector goes through vehicle electrification (WEF 2019). Electric vehicles (EVs) are energy-efficient, environmentally friendly, and exhibit excellent performance over their lifetimes. The US Environmental Protection Agency estimates that EVs convert more than 77% of the energy they take in the form of electricity from the grid to wheel power[1], whereas comparable conventional vehicles convert on the order of 12%-30% of energy stored in gasoline to wheel power1. EVs have no tailpipe emissions of their own, but there are lifecycle emissions, for example, emissions from the source of electricity used for charging and emissions associated with the manufacture of the vehicle. Also, the cost to operate an EV is much lower than the cost to operate a gasoline- or diesel-powered vehicle (Figure 4.2). Further, EVs are quieter and operate more smoothly, have stronger and more

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[1] https://www.fueleconomy.gov/feg/evtech.shtml

rapid acceleration, and require much less lifetime maintenance than comparable internal combustion engines (ICEs) vehicles.

The key issues for consumers are: 1) initial vehicle cost, 2) vehicle operating range, or the distance a vehicle can travel on a single battery charge, 3) battery life, which has to do with performance degradation over time, 4) access to charging facilities, and 5) charging time (NRC 2015). These and other buyer concerns—such as perceptions about the driving and ownership experience, reluctance to downsize, and the ability to see electricity as a transportation fuel—represent both challenges and opportunities for the EV marketplace. Hence, to ensure maximum EV adoption in the shortest amount of time, the following steps and initiatives should be undertaken.

4.2.1 Reduce initial vehicle cost

On the whole, EVs currently have a higher initial purchase price than comparable ICE vehicles, largely due to battery costs. Without considering any federal, state, or local assistance, the initial price premium for new/unused LDVs can be 20%-30%. Smaller differentials are anticipated as battery costs decline, and the total life-cycle costs of owning and maintaining EVs are lower than for ICE vehicles. Still, despite rising EV sales, achieving significant market penetration in the United States will require a shift in the current thinking and manufacturing paradigms that ensure EVs are the vehicles of choice for the middle class. Expanding access to a broader swath of the population is what Gurley (2019) and others refer to as “accelerating equity.” Such a shift will require public investments to redirect the automotive industry, its manufacturing processes, and its business models, so that it can more effectively focus on mainstreaming EV technology.

4.2.2 Enhance battery technology with regard to cost and range

The battery is the single costliest component of an EV, and it is also among the most expensive items to replace. A full, new replacement battery pack can cost $5,000-$10,000. Automakers help buyers offset this potential cost by providing a warranty on the battery, in most cases for eight years or 100,000 miles. Additionally, battery costs are declining (Figure 4.3) and will continue to do so as more vehicles are sold, technology improves, and supply chains and manufacturing processes become more efficient.

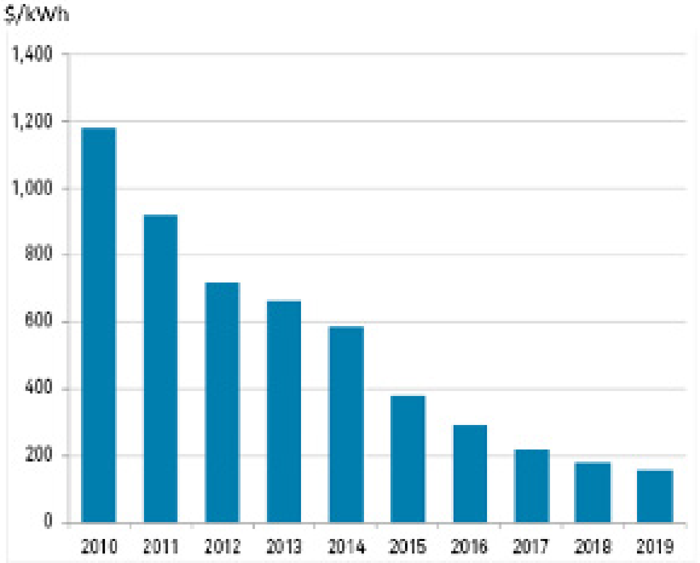

Figure 4.3. Battery pack prices, 2010-2019. Prices are projected to continue their steep decline. (Keen 2020)

Per kWh cost has fallen rapidly from about $1,100 in 2010 to $156 in 2019 (BNEF 2019; Goldie-Scot 2019). Manufacturers are continually developing batteries that are also longer-lived, more energy dense, and lighter weight.

Still, further reductions in battery cost are needed. The US Department of Energy’s Vehicle Technologies Office estimates that battery cost will need to decline to below $125/kWh before owning and operating a light-duty EV will be as cheap or cheaper than a comparable ICE vehicle. The agency’s own goal is $100/kWh. Bloomberg New Energy Finance forecasts that this price will be achieved by 2023 (Curry 2017; Day 2019). Unfortunately, there is not a comparable and favorable cost horizon for batteries that power HDVs, particularly for over-the-road long-haul vehicles.[2]

In terms of range, there are many light-duty EVs on the road today that can travel 200 or more miles without recharging (Gorzelany 2019). The US Department of Energy’s Vehicle Technologies Office estimates a range of 300 miles is needed to make light-duty EVs broadly attractive to the US market. Tesla’s North American Model S Long Range Plus vehicles have an EPA-rated range of 402 miles (Tesla Team 2020), so battery technology is clearly advancing on this front. Other manufacturers are developing EVs with a range of about 300 miles. Batteries

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[2] https://www.energy.gov/eere/vehicles/batteries.

with even longer range mean greater vehicle weight, more materials consumption, and greater emissions associated with the manufacturing process. An expanded network of very fast charging stations can reduce the needed battery size and vehicle range.

Although other types of batteries are in service, particularly for hybrid electric vehicles (HEVs) and vehicles engaged in commercial applications, current research for the light-duty EV market largely focuses on improving lithium-ion batteries, which are likely to continue to be the predominant EV power source for the foreseeable future. A number of other chemistries (Iclodean et al. 2017), including varieties of lithium-ion chemistries, are also under investigation. These, along with advanced component materials and structural configurations, are expected to lead to even more rapid improvements. Solid-state batteries are also on the horizon (Pasta et al. 2020; Baldwin 2020). Advancing battery technology for both light- and heavy-duty applications is central to expanding the country's EV fleet.

4.2.3 Boost battery manufacturing and expand the supply chain

A robust manufacturing complex and a stable supply chain are essential for boosting EV adoption. The three parts of battery manufacturing—cell production, module production, and pack assembly—can take place at the same location; but in the current environment, they typically do not, creating a dynamic and complex supply chain. Cells destined for EVs sold in the United States are produced in Japan, South Korea, and the United States, with pack assembly primarily occurring in the United States. Because of the three separate production phases, it is often difficult to determine how many "battery manufacturing plants" exist at any one time. Estimates reported in the literature range from three in 2015 to five in 2017 to more than 100 at the present time, a number which likely includes multiple start-up companies that are working on advanced battery technologies.

Today, battery manufacturing plants are mostly taken to mean the megafactories or gigafactories, similar to Tesla's Nevada production facility, that are springing up around the world. Of those entering service in 2019, about two-thirds were in China (Eddy, Pfeiffer, and van de Staaij 2019). China, Japan, and South Korea have dominated cell production, although there has been a recent surge in new plant construction in Europe (Willing 2020). Until recently, Tesla's Nevada site was the only major production facility in the United States, though General Motors and South Korea's LG Chem have now formed a joint venture to build a cell manufacturing plant in Ohio (Abuelsamid 2020), and South Korea's SK Innovation plans to expand its two-year-old plant in Georgia (Berman 2020). Until these facilities are operational, most battery components will continue to be imported from outside the country.

The bottom line is that more US manufacturing is needed to stimulate robust expansion of domestic EV sales, but it will take validation of a vigorous EV market to justify adding additional manufacturing capacity—an unfortunate chicken-and-egg situation. Because the United States lacks the critical metal resources necessary to mass-produce all battery components domestically, our reliance on foreign producers will continue until effective alternatives to existing lithium-ion chemistries are developed. Pursuit of such technologies, coupled with healthy incentives to support domestic manufacturing capacity expansion, is vital to decarbonization of the country's transportation sector (Mai 2019). In addition, we need effective trade policy to keep components that cannot be produced domestically flowing into the country so that the expanding EV market is not limited by supply issues (Spector 2020b). Further, due to ongoing concerns about the long-term availability of lithium, nickel, cobalt, and other elemental metals used in lithium-ion batteries, we must be prepared with appropriate policies and strategies to deal with tight supplies in the international arena (Cohen 2020).

Growth in the EV market, both domestically and abroad, will undoubtedly increase scrutiny of the supply chain on all of these fronts (Robinson 2020). To diminish potential bottlenecks, we believe the United States must:

- Devise specific incentives to encourage the manufacture of more batteries on US soil.
- Aggressively support technology development centered on longer-lasting batteries.
- Objectively pursue evidence about the long-term impacts of large quantities of lithium-ion batteries on the environment.

4.2.4 Resolve battery operational, environmental, and end-of-life concerns

For all their positive attributes, lithium-ion batteries are not without problems. They are temperature-sensitive and do not perform well in extreme climates (Rugh, Pesaran, and Smith 2011). There are safety concerns, including heat dissipation, thermal runaway events, low-temperature charging conditions, crash/shock consequences, and cell stress and aging associated with normal vehicle operations (Stephens et al. 2017). Performance is degraded under some user recharge protocols. There are serious concerns about environmental and social impacts of extracting the elemental resources used in battery production, including the use of child labor for cobalt mining in the Democratic Republic of the Congo (Elkind, Heller, and Lamm 2020).

The disposal of EV batteries will become an urgent issue as the United States achieves large EV market penetration. Various ideas have been proposed, including recycling, refurbishing, remanufacturing, or repurposing the batteries, along with crushing and smelting to extract/recover the elemental compounds. Lacking an economically viable technology for recycling multiple chemistries, it is often cheaper to mine elements as raw materials than to recycle them.

Refurbishing and/or repurposing EV batteries may be the best alternative, particularly in the context of promoting a circular economy. When a battery becomes too exhausted for vehicle use, it may retain significant capacity to collect and discharge electricity—enough, perhaps, to serve as a home storage unit, to power street lighting, or to serve as stationary grid-tied storage devices for utilities (Bosselman 2019; Neubauer et al. 2015; Engel, Hertzke, and Siccardo 2019; Elkind 2014).

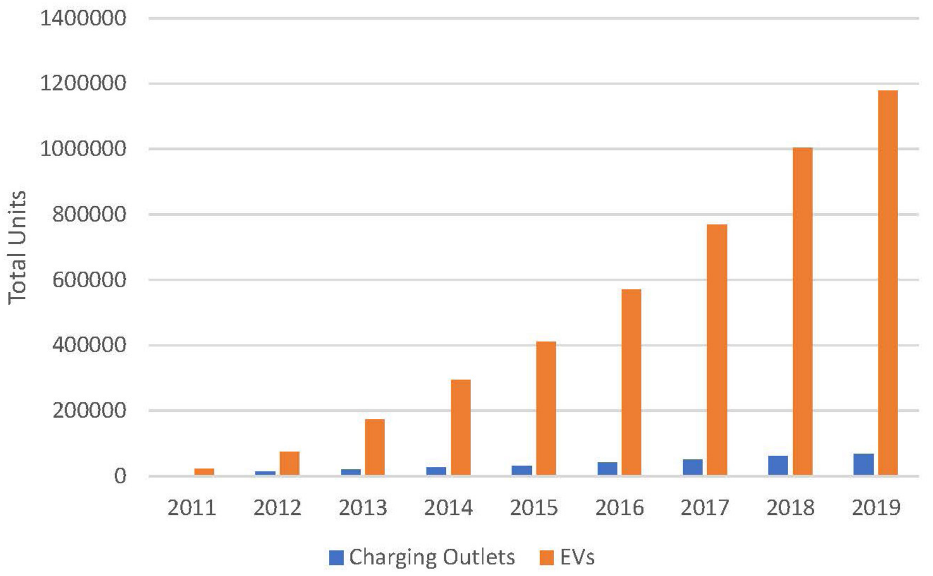

Figure 4.4. Cumulative EVs versus cumulative charging outlets in the United States, 2011-2019. Charger growth has not kept up but has improved recently. Charging connector counts for 2018 and 2019 represent partial years. The EV total for 2019 is rounded. (Data from multiple sources)

The challenges associated with renewing or disposing of depleted EV batteries will no doubt spur new industries, business opportunities, and job creation (Stringer and Ma 2018). They will also likely result in increased regulation, specifically around accumulation, transportation, and recycling, that mimics lead-acid battery programs already in place at state and federal levels.

Clearly, battery construction and size are key to widespread EV adoption by the public. The United States must fund and support innovation focused on the development of batteries that are compact, have longer lives, can power EVs for sufficient distances, and can be recharged quickly (Gorner and Teter 2020).

4.2.5 Expand and improve charging infrastructure

Widespread access to battery recharging facilities is critical to an electrified transportation system. Similar to the ability to refuel ICE vehicles essentially on demand, individual consumers and fleet managers must be convinced that their EVs can be “refueled” essentially on demand, to eliminate range anxiety (Narassimhan and Johnson 2018).

While rapid strides have been made in the deployment of charging infrastructure throughout the United States in recent years, the pace of deployment still lags EV sales (Figure 4.4). By mid-2019, there were more than 20,000 public and non-residential private (e.g., businesses) EV charging stations with more than 68,800 connectors (outlets or charging units), an increase in connectors of more than 60% from 2016. Mid-2019 to mid-2020 likely saw another 14% increase (Wagner 2020). The vast majority of these facilities are located in California. By contrast, there are 100,000 or more gasoline/diesel filling stations around the coun-

Pickering Associates' carport structure and 4 EV charging stations; 40kW solar, Parkersburg, West Virginia.
(Kelly Bragg / West Virginia Clean Cities / NREL 61267)

try, although this is somewhat of an apples-to-oranges comparison since most EV charging occurs at home.

Counting the numbers of stations and connectors can be somewhat confusing because there are different power levels. In mid 2019, roughly 84% of the 68,800 connectors were Level 2 units and the remainder were direct current fast charger (DCFC) units. For comparison:

- Level 1 charging (similar to a residential 120 V outlet plug) has a power level of 1.9 kW and adds two to five miles of range per hour of charging, or up to 40 miles of range in eight hours of charging for a mid-sized vehicle.
- Level 2 charging (similar to a residential 240 V plug) provides up to 22 kW of power and adds 10-25 miles of range per hour of charging, up to 160 miles in eight hours of charging.
- Most commercial DCFCs provide power levels of 50 kW and can add 60-80 miles of range for every 20 minutes of charging.[3]
- The original Tesla Supercharger network had power levels of up to 150 kW while the latest units are 250 kW or higher. These chargers can typically provide 80% battery charge within 20-30 minutes.
- The Electrify America network is installing some fast chargers with as much as 350 kW of power.

In the United States, charging networks are dominated by a few major players who provide access to charging largely on a subscription or pay-as-you-go fee basis: ChargePoint, Tesla, EVgo, EV Connect, Electrify America, and Blink. Non-residential EV charging has the potential to become a significant industry, with the major automakers, oil companies, and power providers getting onboard (Valdes-Dapena 2019). Significant expansion of existing networks is being planned, in some cases involving joint ventures or collaborative efforts with travel-related entities such as major truck stop companies and convenience store chains. ChargePoint and Electrify America have announced plans to allow joint roaming access to their mutual networks in much the

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[3] https://afdc.energy.gov/fuels/electricity_stations.html

same way that wireless communications companies share cell towers (Korosec 2019). Facilitating interoperability among network providers is one of the keys to optimizing the EV charging experience.

The United States also needs inter-urban, optimally situated charging networks. Because most EV charging is done at home or at work, it is not necessary to retrofit every existing gasoline/diesel station in the United States with EV charging stations, as is being done in Germany (Steitz and Taylor 2020), but it is within reason to expect that many in or near urban areas will be. Public charging stations serve long-distance travel and transportation of goods, and they are also essential for those who want to purchase an EV, but cannot charge at home (e.g., street parking only, apartment buildings without a sufficient number of charging stations, university dormitories).

The ability to recharge an EV at home is the ideal situation for local driving (Morris 2019), for which Level 2 and even Level 1 charging may be adequate. Most daily drivers do not need to fully charge their vehicle's battery every day if they don't drive that much, in the same way that most ICE vehicle owners do not need to refuel every day. But challenging questions arise in multi-occupancy situations (DeYoung et al. 2019). Who pays for the infrastructure (procurement, installation, operation, and maintenance)? How is vehicle electricity usage billed? Community charging, in which the costs of infrastructure and electricity are shared through covenant requirements, may be feasible for some, but not all, situations.

To achieve full electrification, businesses must also be incentivized to provide charging facilities at work, recreation, entertainment, and shopping locations. Urban and city center parking garages will need to be reconfigured to incorporate sufficient charging capabilities. A number of companies (e.g., Walmart, REI, Whole Foods) are already moving in this direction, but more capacity will be needed as EVs become more ubiquitous. Again, the issue of who pays for infrastructure deployment often remains unresolved and may have to be addressed statutorily (EV Connect 2020). Utility ownership may raise questions concerning the appropriate use of ratepayer funds on public charging facilities and whether investment in such facilities by regulated monopolies gives them an unfair competitive advantage (Khan and Vaidyanathan 2018). Furthermore, different kinds of electric vehicles have different charging paradigms. For example, transit buses have special requirements because they operate around the clock and generally do not travel very far in terms of mileage.

Reducing charge time is partly a facility or infrastructure issue, but also has to do with the ability of the battery itself to accept the charge and the type of charging port available on the vehicle. Infrastructure-to-vehicle interoperability is key to optimizing the charging experience. As indicated previously, lithium-ion batteries do not perform optimally or fully charge easily in extreme temperatures—when drivers also do not want to be standing around waiting for their battery to recharge. Further, continuous and repeated fast charging can stress the battery and lead to more rapid degradation (Coren 2019b). Research into alternative charging strategies—including Wi-Fi enablement (Andrews 2020), wireless inductive charging, dynamic charging (Zhao et al. 2018), and alternative battery structures and chemistries that are practical in size and more amenable to fast charging—is proceeding at a fast clip, but more funding support is needed.

Developing and deploying an expansive charging network to support electrification of the transportation sector will require a capital investment in the United States through 2030 on the order of $11 billion (Engel et al. 2020), assuming current projections hold true, with more than $2.5 billion needed in major US metropolitan areas through 2025 (Nicholas 2019). The United States currently lags much of the world in terms of charging capacity infrastructure and will need to make a major investment relatively soon to satisfy demand and meet transportation-related GHG emissions reduction goals.

4.2.6 Improve vehicle design, functionality, and appeal

Until recently, one of the major roadblocks for potential EV purchasers was the limited number of available vehicle models, the fact that they were downsized in the minds of many consumers, and their unconventional appearance. Prospective buyers want the benefits an EV brings, but they also still want a good-looking and functional automobile that has high performance (speed, acceleration, range, payload, durability, etc.) (Kumar and Alok 2020). But consumers are now finding that it is possible to get what they want, albeit at a higher purchase price. Further, since light-duty trucks and sport utility vehicles (SUVs) are among the best-selling vehicle segments in the United States, Tesla and others are moving quickly to produce comparable EVs (Baldwin 2019). These are the kinds of vehicles that will provide the impetus to get EV adoption to the next level (Bellan 2018). Because the lead time necessary to bring a new vehicle model to market is long and costly, expanding model availability and functionality will likely require significant federal and state financial incentives.

4.2.7 Integrate vehicles, buildings, and the grid

The transportation and buildings energy sectors intersect at the point where EVs tie into the grid that powers residences and commercial facilities. Layered on top of this intersection are the policies and regulations that govern access to, and connectivity with, the grid, and electricity rate structures. Across much of the country, EVs are still viewed primarily as electricity consumers rather than as potential electricity suppliers or storage devices, even though it is now clear that smart charging can be advantageous to utilities. Even so, regulations governing distributed storage (much liked distributed generation) have not yet been uniformly adopted. Evidence from other countries suggests that increased EV penetration will not lead to significant increases in peak load. Rather, it will help to positively reshape the load curve, particularly with time-of-use (TOU) and other favorable rate structures (Engel et al. 2020). While most US electricity providers are already moving toward some form of TOU pricing, more aggressive and consumer-friendly policies are needed, along with incentives that take advantage of the storage potential that EVs bring to the grid.

Connecting more EVs to the grid increases electricity sales, creates a more diverse pool of electricity customers, and can optimize grid capacity (Khan and Vaidyanathan 2018). When grid-connected, EVs provide many of the same storage features as other stationary storage devices, providing, for example, storage options when an oversupply of renewable energy generation might otherwise be curtailed. With advanced grid capabilities (e.g., smart charging and communications) they can be actively managed to reduce charging impacts.[4]

One-way vehicle-to-grid communication (V1G) permits utilities to control or manage charging (i.e., control charging time and speed) to optimize load. Vehicle-to-building (V2B) or vehicle-to-house (V2H) charging allows vehicle owners to use their vehicle's charged batteries to power their dwellings and office/work spaces. It has been reported that new Tesla models contain the inherent capability to do bidirectional charging. V2B does not provide stored energy to the grid, but it does flatten the load, and can provide back-up resources to power buildings when outages occur. It can be more cost-effective than home batteries and allow rooftop PV owners to continue to use solar power during grid outages as well as take power from the EV battery.

Two-way vehicle-to-grid (V2G) communication facilitates two-way flow of electricity through the meter, allowing the utility to use EVs as a distributed resource for grid stabilization (Noori et al. 2016). This has the potential to yield an additional source of revenue for the vehicle owner, utility, and grid operator, and may reduce the total cost of vehicle ownership. There are many issues surrounding V2G that are yet to be resolved, including preventing cybersecurity intrusions (Khan and Vaidyanathan 2018).

To accommodate vehicle-building integration, buildings must be EV-ready. Hence, by code, all new construction should require EV readiness, meaning that garages and parking areas are wired appropriately and provide space for charging facilities. In addition, funding and/or financial incentives can be provided to encourage building owners to retrofit existing construction, including service panel upgrades. In general, zoning codes should be changed to encourage the proliferation of EV-ready construction (Khan and Vaidyanathan 2018).

These kinds of operating scenarios and business models will be most effective if they are accompanied by electricity pricing scenarios that incentivize EV owners to participate. TOU pricing should expand beyond the home to cover charging everywhere. Even for charging at home, rate structures can be made more friendly, including hour-to-hour dynamic pricing, the elimination of demand fees, or compensation of EV owners for the use of their vehicles as storage devices.

Smart charging and its advantages can only be accommodated through grid modernization. Connecting large numbers of EVs to the grid without some way to manage charging can be a difficult challenge for utilities and grid operators if charging occurs

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[4] https://energystorage.org/why-energy-storage/applications/transportation-storage/

at high-demand periods (Teter, Tattini, and Petropoulos 2020). Hence, as discussed in Section 2, a fully smart grid is clearly the most direct and efficient path to electrification of the transportation system.

4.3 EV market penetration and future projections

In 2018, the United States had more than one million EVs on the road (ANL 2020). Based on monthly data provided by Argonne National Laboratory, sales of EVs (PHEVs and BEVs combined) have risen rapidly since 2016, increasing from 159,616 that year to 361,315 in 2018. Due to a decline in sales of PHEVs, total sales dipped in 2019 to 325,839, but sales of BEVs continued to climb, almost entirely attributable to Tesla's Model 3 (ANL 2020). Despite the impressive year-over-year gains, there is still a long way to go to full penetration of the light-duty market. The 2018 and 2019 totals represent no more than 2% of all US LDV sales (Ritchie 2019). Most projections put the market share of light-duty EVs at 7-10% by ~2025 (Figure 4.5).

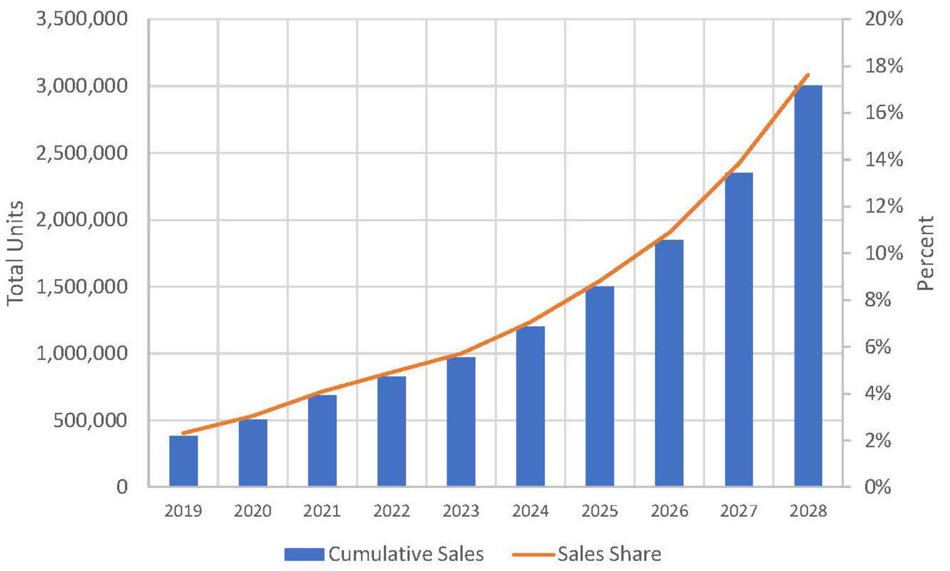

Figure 4.5. Cumulative EV sales projected to 2028. Rapid growth is predicted, but it falls short of emissions reduction needs. (McDonald 2019)

The picture for electric-drive HDVs is somewhat different. While specialty vehicles, such as forklifts and golf carts, have been largely electrified for many years, there are no electric long-haul freight transport vehicles currently in routine service. This sector, which is rapidly expanding in the United States, is difficult to electrify (see Section 4.5.1). Still, several manufacturers, including Tesla, have significant development efforts underway (Downing 2020). Short-haul delivery trucks and vans, garbage haulers, snow plows, school buses, and even some short-haul tractor-trailer rigs, as well as public transit buses, are more promising applications. Amazon and UPS are moving forward with plans to electrify their delivery truck and van fleets, as are companies like Anheuser-Busch, which transports larger payloads shorter distances (Gilroy 2019), and Penske, which serves the leasing/rental market (Clevenger 2019).

The total number of electric buses in the United States today remains small (about 650 out of a total of about 70,000), but demand is high, and in 2019, all but five states had initiated some kind of electric bus program (Tigue 2019; Silver, Jackson, and Lee 2019). About one-third of all transit buses in the United States are currently projected to be electric by 2045 (Horrox and Casale 2019), largely driven by California's push for a 100% EV bus fleet by 2040 (CARB 2018). By contrast, China now has more than 500,000 electric buses of all types (Sustainable Bus 2020).

4.4 Getting legacy vehicles off the road

To effectively transition to electrified transportation the United States must address the millions of legacy ICE vehicles already on the road and the fact that new ones are being added every day. This is partly a social equity issue: Many people cannot afford to replace their current mode of transportation with an EV. Following the lead of other countries around the world (Slezak 2017; BBC 2017; Coren 2018), the federal government should immediately enact a moratorium on ICE vehicle manufacturing and sales to be phased in over 10 years, to mitigate potential economic shock. Policies to specifically remove existing ICE vehicles from service, analogous to the "cash for clunkers" buy-back programs, are also needed. Due to the time required for effects to fully take hold, there is an urgent need to start now.

At least 10 states already have some form of EV sales mandate (Shama 2019), and California has recently announced it will phase out sales of all new ICE cars and passenger trucks by 2035 (Hull, Coppola, and Baker 2020); so the idea of limiting sales of ICE vehicles is not new. However, as currently configured, mandates only ensure a certain percentage of new-car sales to be EVs; these will not reduce the ICE vehicle population fast enough. Expanded contracting or leasing programs with more favorable terms for EV acquisitions that leverage cost and risk could help expand the population more rapidly, particularly for HDVs.

In 2017 (Arbib and Seba 2017) published a widely read study that gave very optimistic projections for the growth of EV sales based on the belief that private vehicle ownership would be rapidly replaced by a form of transport as a service (TaaS), often called ride-hailing. Their point was that customers would find this service more affordable than owning a vehicle, and fleet owners would want to minimize their operating expenses by using driverless, autonomous electric vehicles that would incur minimal fuel and maintenance costs. Autonomous vehicles that can communicate with each other also have the potential to reduce traffic congestion (UC 2019). The assumption was that the growth of this industry would spur a rapid transition from gasoline vehicles to autonomous EVs. How quickly such a transition might ultimately occur depends on consumer preferences and how quickly autonomous vehicles meet the needed performance and safety requirements.

Even without autonomous vehicles, however, there is already movement among some types of fleet-oriented corporations toward 100% electrification, the most recent and notable being Lyft's announcement that it intends for its fleet to be 100% electric by 2030 (Pyper 2020). Companies such as Schneider Electric and Unilever that are headquartered elsewhere but have operations in the United States have made similar commitments. A number of other companies are transforming large percentages of their fleets through participation in initiatives such as the Corporate Electric Vehicle Alliance and EV100 (Automotive Fleet 2020).

As a show of leadership and commitment to the driving public, all federal, state, and local fleets should immediately transition to 100% EVs. Comparatively speaking, the total number of vehicles is small, but the message to consumers around the country is very important. Several state and local jurisdictions have already made this commitment.

An electric bus charging station at the Kimball Junction Transit Center in Park City, Utah. (Margaret Smith / Akimeka / NREL 61251)

Federal, state, and local authorities should also endorse and support technological developments that can reconfigure at least some percentage of existing ICE vehicles. As an example, Volkswagen has developed an EV retrofit kit for its VW Beetle, an initiative that all manufacturers should be encouraged to pursue (O'Kane 2019).

As various jurisdictions move more aggressively to transform the on-road vehicle population to 100% EVs, care must be taken to prevent unintended consequences, such as people purchasing more ICE vehicles before they go away (BBC 2020). Moreover, government actions and incentives are required to assist automakers in their efforts to reconfigure existing manufacturing facilities and retool the workforce. New skills will be required and new jobs will be created as EV-related technologies expand.

4.5 Difficult-to-decarbonize sectors: aviation, marine, rail, and long-distance road transport

Long-distance road transport, aviation, shipping and rail are among the most difficult parts of the transportation system to decarbonize. Combined, they account for only about six percent of GHG emissions on a global basis (Davis et al. 2018); however, all three sectors are rapidly expanding, both within the United States and abroad, and must be addressed in any comprehensive strategy to achieve sustainability goals.

4.5.1 Long-distance road transport

As already discussed, HDVs (used in long-distance, cross-country shipping, and transportation of goods) are more difficult to electrify than LDVs. Long-hauling is very sensitive to fuel price, payload capacity, time-to-delivery constraints, destination and delivery route optimization, and the total distance to be traveled. For example, 500 miles is roughly the sweet spot in terms of fueling range for tractor-trailer rigs, and this would require a very large and heavy battery. The cross-country charging network is not yet extensive enough nor is recharging fast enough to meet these needs.

Until appropriate electrification capabilities become available, the US trucking industry should continue to pursue carbon-neutral or low-carbon fuels. Among the most promising technologies for powering long-haul trucks are hydrogen fuel cells and hybrid hydrogen-battery combinations, along with direct hydrogen fueling, which alleviate the range restriction of battery-only options and can be produced from carbon-free sources. The US Department of Energy's advanced truck technologies program targets hydrogen-fueled long-haul tractor-trailer combinations (Marcinkoski et al. 2019), and industry competitors such as Nikola, Tesla, Volvo, and Cummins are developing fuel cell and battery platforms. Such efforts will put cost-comparable trucks on the road by 2030 (Mihelic et al. 2019), but without additional incentives, it may take much longer to get enough of them in service to significantly impact GHG reductions. Biofuels also hold promise for the HDV sector, but remain constrained by production process limitations (Davis et al. 2018).

Regardless of fuel choice, the United States should further incentivize manufacturers to speed up innovation of advanced engine and drivetrain technologies; substantially ramp up hydrogen production and processing; address fuel availability and filling technology; and commit significant resources to infrastructure expansion and build-out (Mahone et al. 2020; FCHEA 2020). These and other issues must be championed at the federal and state levels to ensure progress toward a more sustainable long-haul trucking fleet.

4.5.2 Aviation

Aviation is perhaps the most difficult transportation sector to decarbonize, and yet emissions associated with the combustion of jet fuel (kerosene) continued to rise (pre-pandemic) at a steady rate of about 2% per year during 2000-2019 (Teter et al. 2020). Absent a generational breakthrough in battery technology, it is highly unlikely that complete electrification of the commercial aviation sector will be feasible simply due to weight constraints. Some aspects of commercial transportation, such as air taxis and short flights by smaller aircraft, might be electrified in part, but this could create competition with more efficient high-speed rail (Section 4.5.4).

Apart from gains in efficiency, the best decarbonization scenario for commercial flight involves the use of alternative fuels such as cellulosic biofuels or synthetic jet fuels as part of an overall net-zero emissions strategy for the country. Such fuels, collectively referred to as sustainable aviation fuels (SAFs), are not new concepts, and they are technically feasible, but their uptake has been sluggish, hampered by unreliable feedstocks, processing inefficiencies, the high costs of refinery construction and other infrastructure, and more (Searle 2018). Nonetheless, replacing conventional jet fuel with plant-based fuels, or blending the two, would be a step in the right direction. Ramping up biofuel production to serve the aviation sector will require substantial financial incentives and collaboration among various industries, including agriculture, aircraft manufacturing, airports, the aviation travel industry, and the financial sector, as well as government agencies such as the Federal Aviation Administration (Searle 2018; ICAO 2016; Dichter et al. 2020).

Synthetic jet fuel (also sometimes called electrofuel or efuel) is a promising idea that is already on the horizon. The technology involves combining green hydrogen (produced from the electrolysis of water using renewable electricity) and carbon dioxide obtained from waste streams, carbon capture, or atmospheric carbon dioxide removal methods. Although not currently cost competitive, synthetic jet fuel may offer a viable long-term solution, particularly if green hydrogen becomes more affordable and supported by a sufficient supply chain and distribution infrastructure.

The use of either biofuels or synthetic fuels will require various policy interventions and financial incentives to spur sustained demand (Scheelhaase, Maertens, and Grimme 2019). One option is to require a percentage of conventional jet fuel to contain biofuels, much the same way that most automotive fuels are required to contain a proportion of ethanol without requiring automotive engine modifications.

Another option would be to treat SAFs more favorably in EPA's renewable energy compliance system, renewable identification numbers (RINS), than biodiesel used in other transportation sectors (DOE 2016).

In fact, successful expansion of SAF usage may depend on expanded electrification of on-road transportation. Broad adoption of unblended SAFs, however, will require redesign of aircraft propulsion systems, supported by public and private financial investment. Further, because the aviation fuel market is very price-sensitive, the United States may need federal initiatives to establish a durable market for SAFs at a competitive price.

Regardless of fuel selection, the United States should consider establishing GHG standards for all aircraft operating in the country. The Environmental Protection Agency and Federal Aviation Agency are already working on this, in concert with the International Civil Aviation Organization of the United Nations (EPA 2020e), because of the transnational nature of commercial air transportation (IRENA 2017).

Commercial aviation, in particular, has been severely impacted by the COVID-19 pandemic, creating the opportunity to reimagine what commercial air travel will look like post-pandemic. Now is the time to promote a cleaner, more sustainable air transportation sector, moving the country more rapidly to the use of SAFs than might have previously been thought possible.

4.5.3 Marine transportation

Like air transportation, marine transportation, particularly the shipping of goods, is a difficult-to-decarbonize sector but one that is extremely important in the push to meet climate change and sustainability goals. Currently responsible for about 2% of US GHG emissions (EPA 2020a), and about 2.5% worldwide (Czermanski et al. 2020), the sector has been growing rapidly (pre-pandemic) as international trade and commerce swell to meet the needs of a rapidly expanding global population (Olmer et al. 2017). While most international marine shipping involves container ships, bulk carriers, and oil tankers, the total fleet includes fishing vessels (private and commercial), cruise ships, tug boats, personal recreation boats, ferries, offshore supply vessels, fuel bunkering tankers, and vessels operated by the US Navy and Coast Guard.

Various efforts are underway to reduce maritime operations' GHG emissions. For example, the International Maritime Organization has targeted a 70% reduction in carbon dioxide emissions (relative to 2008) for all of its members by 2050, with further reductions beyond that (Czermanski et al. 2020; Shell 2020). Such reductions can likely only be achieved by employing a combination of approaches, including more-efficient operations, advanced propulsion and engine technologies, energy efficiency, and use of alternative fuels. While all of these approaches can pay dividends, the primary focus is on fuels.

Marine transportation relies chiefly on the combustion of fossil fuels, including heavy fuel oil (HFO), marine gas oil (MGO), liquefied natural gas (LNG), and various forms of diesel; in terms of emissions, HFO is one of the dirtiest fuels available. Potential alternatives include biofuels and synthetic fuels, as in aviation, and various forms of hydrogen and ammonia (Kastner et al. 2020; Hansson et al. 2020). Biofuels are viable for shipping and other marine applications today, but inadequate supply and insufficient delivery infrastructure are serious constraints, given competition from other transportation sectors.

Marine transportation was partly electrified in the early 1900s (passenger liners and some military vessels), but by mid-century it had almost exclusively transitioned to the use of relatively cheap and accessible liquid fuels. In the push to reduce marine GHG emissions, the industry is exploring electrification options. There are many efforts to pursue electrification of ferries, tug boats, personal watercraft, private fishing boats and other vessels involved in short-haul applications.

Among them: A ferry operating in the Danish portion of the Baltic Sea employs a 4,300-kWh battery, and a Swedish ferry will soon have a total battery capacity of 50,000 kWh (Macola 2020). However, full battery operation of long-distance cargo ships and oil tankers is difficult given their size and weight, cargo weight when fully loaded, and long distances to be traveled.

Nuclear power has provided electricity to efficiently operate military vessels for decades and will continue to play a significant role in these and related applications (Ragheb 2011). The low fuel cost and other benefits, though, are offset by high costs for supporting infrastructure, which limits non-military applications. This situation may change with the continued development of small modular reactor (SMR) systems and associated technology, which could power smaller military naval vessels.

While there are many options for reducing GHGs in the marine transportation sector, no apparent dominant solution has emerged (Shell 2020). The industry anticipates that most new propulsion systems will involve some form of electrified powertrain (electric hybrids, full battery power, fuel cells, or hydrogen or ammonia-fueled generators). Vessels of the future may even harvest wave energy for power (Blenkey 2020). Overall, the ability to repower existing vessels is extremely important to reducing GHGs, because of the cost and long lives of ships and other marine assets.

The COVID-19 pandemic has dramatically impacted marine shipping in negative ways (AAPA 2020), and the United States has the opportunity to spur economic recovery in this sector while focusing on the transition to cleaner marine transportation. In particular, a more significant push must be made to increase the supply and delivery capabilities of alternative fuels as part of an overall net-zero emissions strategy. Other important measures include:

- Establishment of emissions-free zones in and around ports, where berthed vessels have outsized impacts on local air quality.
- Incentivizing investment in port refurbishment and onshore infrastructure, e.g., management, storage, and distribution of low- and zero-carbon fuels; shore-based recharging capabilities, plus increased power generation and grid access; improved fuel bunkering infrastructure; and proliferation of “smart” ship-to-shore communications and operating capabilities.
- Strengthening US energy efficiency standards for marine operations—and enforcement.
- Promoting and incentivizing more rapid development of engines, propulsion systems, and associated technologies, particularly as they relate to electrification of power trains and onboard systems.
- Pursuing greater regulatory alignment of maritime operations in international waters and promoting more uniform emissions control strategies in commonly shared shipment lanes and transshipment facilities (e.g., Panama Canal, Louisiana Offshore Oil Port, and Port of Long Beach).

4.5.4 Rail transportation

Of the hard-to-decarbonize transportation sectors, the most progress to date has been in rail transportation. Already one of the most energy-efficient transportation modes, rail accounts for about 9% of global passenger movement and about 7% of global freight, but only about 3% of global transportation energy use (Tattini and Teter 2020). Rail is responsible for about 2% of all transportation GHG emissions in the United States

In the largest US cities, electrified trolleys, light rail, and subway systems are common in mass transit where routes are relatively short and trains are grid-connected, not battery-powered. Rail transport of goods, cargo, and people cross-country is a different matter entirely. Direct grid connections are essentially non-existent along track rights-of-way, tracks are not electrified, and the vintage and extent of the entire US rail system constrain development of a grid-enabled, all-electric network. Furthermore, as in the case of long-distance transportation by air and sea, weight and distance issues present challenges to full battery electrification.

Diesel is the primary fuel source for locomotives today, so diesel alternatives such as synthetic fuel, fuel cell technology (possibly hydrogen-based), hybrid diesel-electric propulsion systems, and onboard energy storage systems are the most probable options for further decarbonizing rail. The use of other lower-carbon fossil fuels such as LNG may also make near-term sense in a net-zero emissions strategy. Retrofitting and repowering the existing rolling stock for alternative fuels may delay the adoption of these technological enhancements, because of asset cost and longevity (DOE 2015a).

Rail operators and owners must be incentivized to replace diesel locomotives before the end of their normal service lives or to pursue repowering initiatives (Streichfuss, Schwilling, and Berger 2019). Other financial incentives are needed to encourage development of new engine and propulsion systems, and vehicle weight reduction innovations. Further improvements in overall energy efficiency for the rail sector can be made by focusing on traction, braking, rail lubrication to reduce friction, and other operational parameters. For existing electrified networks, the transition to a 100% zero-carbon electric grid will drive those net emissions to zero. Most importantly, until full electrification can be achieved, there is an urgent need to scale up production of

Electric light rail carries evening commuters home past the the downtown Denver, Colorado skyline, reducing traffic. (Dennis Schroeder / NREL 27460)

alternative fuels such as biofuels and to expand the associated infrastructure.

4.6 Mode shifting in transportation

In the context of transporting people, goods, and freight long distances cross-country, mode shifting can play an important role in the push to reduce overall GHG emissions (Kaack et al. 2018; Nelldal and Andersson 2012). Mode shifting is the idea of streamlining and optimizing logistics and supply chain networks to use the cleanest forms of transport available at the time. In many cases, this would mean shifting transportation from trucks or air to rail or water (Delasalle and Erdenesanaa 2019; McKinnon 2016).

Mode shifting must involve improved strategies for managing demand. Shifting freight and passenger transportation toward greater utilization of rail, for example, will require the United States to ramp up its efforts to deploy high-speed passenger train technology, optimize rail freight networks, upgrade infrastructure, and improve fuels and propulsion systems.

In the transportation sector, there will likely be significant cultural barriers to mode shifting, because people, customers, and organizations are used to doing things certain ways.

Given its potential to reduce overall GHG emissions, the United States should adopt a more proactive stance that promotes mode shifting, perhaps with regulation and certainly with education. Campaigns and economic incentives that focus on the potential climate and economic advantages of a modal shift could substantially change the way the country thinks about on-demand access to goods and services. Given that the US mindset is already shifting on so many fronts as a result of the COVID-19 pandemic, now is the time to push for real change in these sectors that could result in substantial emissions reductions.

4.7 Transforming mobility systems and norms

Ultimately, decarbonization of transportation cannot succeed without changing the way consumers and companies conceive of mobility. No suite of government actions will work if the public cannot be truly convinced of their importance and value to the country's well-being. So federal, state, and local authorities must exhibit leadership, promoting the country's health and welfare by giving up personal vehicle use, purchasing an EV, or taking the train instead of a faster airline flight.

Many approaches have been taken in recent decades to alter personal mobility behavior and reduce travel demand, including investments in public/mass transit, enactment of ride sharing and teleworking programs, and implementation of alternating travel day and variable parking management strategies. Still, uptake is limited and congestion continues to expand. Congestion pricing, mileage-based taxation, "feebates," pay-as-you-drive variable insurance programs, and other policies can discourage the use of private vehicles and promote the acquisition of cleaner ones.

However, the United States is likely to be more successful if it adopts a total systems perspective, bringing in urban and transport planning, geography, data science, civil and environmental engineering, and other disciplines. The systems approach also promotes a reimagination of what mobility truly is and how mobility needs can be better met (e.g., see various reports from the Smart Mobility Consortium, DOE 2020).

Improving transportation networks can cut GHG emissions by making transportation more efficient. Traffic modeling and route optimization tools eliminate bottlenecks, reduce idling time, and enhance flow. Other measures, such as replacing static intersections with roundabouts, can be enabled further by advances in information and communications technology, big data, and analytics (Osorio and Nanduri 2015b; 2015a; Adacher and Tirolo 2016).

Rethinking urban land use is making a difference, as well. Holistic "smart cities" concepts (BAI Comms 2019) often include vehicle-free pedestrian zones and "clean streets" programs that promote foot traffic and non-motorized mobility. Both concepts end up reducing total vehicle use by returning city streets to the inhabitants. Some cities have implemented these measures in response to the COVID-19 pandemic, closing certain streets to vehicles to allow socially distanced walking and outdoor dining space for restaurants.

Systems thinking extends beyond on-road vehicles and traffic congestion. For example, widespread commercial use of unmanned, electrified aircraft (drones) for package delivery and other service applications is on the near horizon. These will eliminate the need for a significant portion of on-road delivery vans and trucks, but they raise questions about use of the nation's air space.

The US air traffic control system has been overutilized and underfunded for years, and a next-generation air traffic control system—one that fully integrates unmanned aircraft—has the potential to improve safety, reduce fuel use and flight delays, minimize noise, curtail tarmac idling, and provide clearer and faster plane-to-tower and tower-to-tower communications (Gerdes 2016).

There are many other opportunities to substantially reduce GHG emissions in a reimagined and streamlined transportation system. Mode shifting, as previously described, can help, and can even be implemented in the personal transportation space, with autonomous vehicles and other types of mobility services as options (Kauppila 2019). Green freight programs that track and promote efficient truck operations and technologies (Teter, Petropoulos, and Tattini 2020) are important, too. In the context of urban mobility, the idea is to create a fully integrated city characterized by seamless intermodal travel (Goodall et al. 2017).

The importance of all the foregoing measures cannot be overestimated in the push for a greener transportation sector. It is worth noting that under full electrification of even the LDV sector, the rationale for these measures as emissions reduction mechanisms essentially evaporates—though their contribution to reducing congestion remains. Electrification will not reduce urban traffic congestion in its own right (Kauppila 2019); and so, a combination of electrification and system innovation is key to moving transportation forward.

4.8 A smart and clean transportation system

The road to a cleaner transportation system clearly passes through the internet. Rapidly evolving connectivity, combined with data, analytics, artificial intelligence, and machine learning, are disrupting the ways in which citizens, businesses, and governments view mobility and transportation, both personally and commercially. From ride-hailing and ride-sharing apps to optimization of fleet portfolios, transit schedules, capacity planning, and traffic management to Wi-Fi-enabled battery charging and vehicle-to-system communications, the internet of things (IoT) is revolutionizing the ways in which people and products move around the globe (Cuddy et al. 2014). This transition to a smart, more fully integrated transportation system is directly tracking the move to a cleaner one. Achieving these mutual objectives requires a systems approach and close collaboration among all stakeholders (Hautala et al. 2014). It also requires sufficient federal and state support to guarantee deployment of the IoT infrastructure necessary for a next-generation transportation system that fulfills the growing expectations of consumers.

4.9 Transportation-related jobs and economic growth

The move to decarbonize the transportation sector and transform it into a greener, more energy-efficient economic engine will result in many new jobs, as existing companies alter their business models, and as new entities emerge to serve the transformation (Skinner et al. 2014). Transportation intersects multiple sectors of the economy, so as a new age of mobility progresses, there will be operating adjustments.

Job creation estimates for transforming the transportation sector are wide ranging, because so many parts of the economy will be touched, but all project substantial increases, from hundreds of thousands to two or more million (Winebrake, Green, and Carr 2017; Melaina et al. 2016; Becker, Sidhu, and Tenderich 2009). New jobs will include engineers and scientists working on advanced batteries and alternative fuels, infrastructure designers, constructors, installers, newly skilled fleet public transportation managers, IoT and digital communications specialists, skilled workers servicing and repairing vehicles, safety technicians, and more.

Because electric vehicles require much less maintenance and repair than gasoline vehicles, some businesses or parts of businesses (e.g., repair shops, automobile dealerships) may face revenue declines or job losses. Federal and state officials must begin now to provide the workforce training programs necessary to support a transformed industry (Harsdorff et al. 2020). Authorities must also work with industry stakeholders to ensure that newly created jobs remain in the United States (UAW 2018).

Transformation of the US transportation sector will lead to gains in overall economic growth, typically measured by gross domestic product (GDP). In an electrified LDV market alone, consumers will save money on fuel and maintenance and likely spend savings in other areas. Estimates of the size of this economic shift range from hundreds of millions to billions of dollars (Winebrake, Green, and Carr 2017). Widespread adoption of EVs could contribute to overall economic growth in the $20 billion range by 2040 (Melaina et al. 2016), although this early estimate may also underestimate the potential.

Particularly in light of the seismic social and economic shifts related to the COVID-19 pandemic, now is the time to take full advantage of the benefits a transformed transportation industry can yield.

4.10 Social equity and human health impacts

The impacts of transportation-related emissions on human health have been a major scientific focus since at least the early- to mid-1980s (Vostal 1980; McClellan et al. 2016; Watson, Bates, and Kennedy 1988). This research has even found its way into the well-known and ongoing Framingham Heart Study, inaugurated in 1948 (Rice et al. 2015). While early work centered on emissions of fine particulates, considerable effort has now been devoted to cataloging adverse effects of nitrogen oxides, carbon monoxide, volatile organic compounds, polycyclic aromatic hydrocarbons, and more (Manisalidis et al. 2020). Human diseases linked to these air pollutants include cardiovascular events and diseases including chronic obstructive pulmonary disease (COPD), asthma, bronchitis, and lung cancer. The literature connecting vehicle emissions to degraded public health is vast and compelling enough that largely in response, the US Environmental Protection Agency-established National Ambient Air Quality Standards for "pollutants considered harmful to public health and the environment" (HEI 2010; Dorans et al. 2016; EPA OAR 2016; Anenberg et al. 2019).

In the early- to mid-2000s individual states also began to formulate various policy initiatives to address growing public health concerns (Wargo et al. 2006). Significant improvements have been realized, yet further reductions are needed and will be difficult to achieve without a dramatic change in the transportation paradigm (Sawyer 2010). A transition away from fossil-fueled vehicles to zero- or near-zero-emissions vehicles is the only feasible way to effectively mitigate transportation-related health impacts (Requia et al. 2018; Choma et al. 2020).

A variety of other issues associated with increasing transport demand also affect human well-being. Water pollution and extreme weather events associated with climate change, for example, are attributable in part to transportation sector emissions (Meyer and Elrahman 2019; Nieuwenhuijsen and Khreis 2020). And on the flip side, smart urban planning programs, such as those promoting walkability or access to food and health care, can boost health and lower emissions.

Approaching transportation from the standpoint of human well-being also addresses deeper concerns about social equity and inclusion (DOT 2013). In the planning and development of new vehicles, transportation routes, and mass transit capabilities, decision makers must take care to not inadvertently discriminate against individuals for whom cost or access are limited. For example, as noted by (Litman and Brenman 2012), the mobility needs of teenagers and younger adults are often overlooked in transportation planning and delivery. Similarly, physically, economically, and socially disadvantaged individuals are meaningfully impacted by an automobile-centric transportation system (Litman and Brenman 2012). Hence, policy makers must promote actions and plans that consider the entire spectrum of human transport and mobility concerns (Bell and Cohen 2009; Malekafzali 2009; Manaugh, Badami, and El-Geneidy 2015; Litman 2020).

4.11 Tools for modeling the transportation system

The US Department of Energy, in collaboration with the national laboratories, has developed a number of software tools for modeling and analyzing transportation systems. Developed by Argonne National Laboratory (ANL), the Alternative Fuel Life-Cycle Environmental and Economic Transportation system is a tool for estimating petroleum use, GHG emissions, air pollutant emissions, and cost of ownership of light-duty and heavy-duty vehicles[5]. It contains a separate Heavy Duty Vehicles Emissions Calculator to determine the various emissions of heavy-duty vehicles powered by diesel, electric, propane, and natural gas. The Autonomie Vehicle System Simulator, developed in conjunction with General Motors, is a MATLAB©-based environment and framework for automotive control system design, simulation, and analysis that covers energy consumption and performance analysis throughout the entire vehicle development cycle[6]. A third tool, POLARIS, is a high-performance, open-source, agent-based modeling framework designed for simulating large-scale transportation systems[7].

NREL has similarly developed various simulation, modeling, and financial analysis tools to address transportation systems and technology[8]. The Automotive Deployment Options Projection Tool (ADOPT) allows a user to estimate vehicle technology improvement impacts on future US LDV sales, energy use, and emissions. One can explore, for example, how lower battery prices or different fuel prices would affect EV sales. The Future Automotive Systems Technology Simulator (FASTSim) provides a way to compare powertrains and estimate the impact of technology improvements on light-, medium-, and heavy-duty vehicle efficiency, performance, cost, and battery lifebattery life. And the Battery Lifetime Analysis and Simulation Tool (BLAST) assesses battery lifespan for behind-the-meter, vehicle, and stationary applications. Other NREL tools include EVI-Pro Lite, an EV infrastructure projection framework; HIVE, a highly integrated vehicle ecosystem simulator; and MEP, a mobility energy productivity metric[9].

Numerous other capabilities have been developed by various state and federal agencies, research consortia, academic institutions, and commercial entities. A number of traffic simulation models and approaches, for example, are described in a 2015 Transportation Research Board circular (TRB 2015), and the Federal Highway Administration maintains the Strategic Highway Research Program C20 freight demand modeling system. The National Energy Modeling System developed by the US Energy Information Administration contains a transportation demand module (EIA

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[5] https://afleet-web.es.anl.gov/home

[6] https://www.nrel.gov/transportation/sustainable-mobility-initiative.html

[7] https://www.anl.gov/es/polaris-transportation-system-simulation-tool

[8] https://www.nrel.gov/transportation/data-tools.html and https://www.nrel.gov/hydrogen/data-tools.html.

[9] https://www.nrel.gov/transportation/sustainable-mobility-initiative.html

2019b). At the international level, the International Energy Agency maintains the Mobility Model, which is used to consider a number of different scenarios that feed into its World Energy Model (IEA 2020b). Most US state transportation departments pursue modeling, simulation, and analysis activities at some level (e.g., the California Department of Transportation’s Demand Modeling and Simulation Branch and the Virginia Transportation Modeling and Accessibility Program). Feng Xia’s and his colleagues’ work on approaches for modeling and analysis of large-scale urban mobility for green transportation is but one example of academic work being done in this area (Xia et al. 2018).

POLICY OPTIONS FOR THE TRANSPORTATION SECTOR

While the US transportation sector is broad and far-reaching, there are numerous actions local, state, and federal agencies, collaborating with public and private corporations, can and should take to immediately accelerate the transition to an emissions-free system.

Personal and fleet EVs

- To accelerate the transition to EVs, legislate a national moratorium on sales and production of light- and medium-duty internal combustion vehicles by 2030.
- To get the most fuel-inefficient vehicles off the road, adopt a progressive cash buy-back policy, especially focusing on the needs of low-income consumers.
- To set an example for all stakeholders, all federal, state, and local light-duty vehicle fleets should transition to EVs by 2025.
- Incentivize automakers to fast-track production and manufacturing of light- and heavy-duty EVs through innovative financing, market-making, and other economic support mechanisms.
- Require federal, state, and local authorities to establish preferential advantages for EV ownership such as tax credits (especially for low-income consumers), access to high-occupancy vehicle lanes, and low-cost parking.
- Repurpose and upgrade roadways, parking facilities, and related mobility corridors to eliminate obstacles to EV operations, and reform building codes to facilitate EV connectivity.
- Coordinate with electric utilities to promote efficient and cost-effective home charging, as well as streamlined access to vehicle batteries for use in grid/load stabilization.

Heavy-duty vehicles

- Provide federal funds to support the development of low- or near-zero-emission fuel alternatives, including hydrogen, ammonia, and selected biofuels, until such time as full electrification can be achieved.
- Require all heavy-duty vehicles in the United States to meet net-zero emissions by 2040, through legislation or regulation.
- Provide federal and state economic incentives to drive heavy-duty EV manufacturing.
- Increase federal and state R&D funding to support a rapid transition to a net-zero HDV fleet.

POLICY OPTIONS CONTINUED ON NEXT PAGE

Regulatory and funding mechanisms	• Expand high-speed passenger rail transportation and redesign, retrofit, and upgrade the rail freight transportation system. Promote infrastructure modernization, operational efficiency, network optimization, and adoption of low- and near-zero emissions fuels, prioritizing electrification of routes currently using diesel. • Provide low-cost government loans and favorable tax structures to promote conversion of rental car, ride-hailing, and package delivery fleets to EVs. • Redesign and redevelop the nation's air traffic control system, including measures supporting low-altitude/low-speed unmanned autonomous vehicle delivery systems to promote efficient, low-emissions operations. • Modernize the nation's marine shipping and transportation sectors by deploying state-of-the-art vessels powered by zero- or near-zero carbon emissions fuels retrofitting or retiring legacy vessels, optimizing schedules and logistics, and improving overall operational efficiency. • Increase funding for R&D efforts aimed at reducing battery cost, improving battery technology, developing new battery types, expanding and improving charging capabilities and infrastructure, and developing vehicle-to-grid technology. • To maximize efficiency and safety, utilize the full potential of big data, analytics, and information and communication technologies to reconceptualize and reengineer the US transportation system. • Promote transportation mode shifting for both people and freight prioritizing mass transit, telecommuting, walkable communities, and urban pedestrian zones.

5.0 The Industrial Sector

Steel pours from a 35-ton electric furnace in Brackenridge, Pa. Quality steels and alloys are produced in these furnaces, which allow greater control of temperature than other conversion furnaces.

The industrial sector will be difficult to decarbonize because of its diversity, high capital equipment investment, and international market competition, which creates pressure to keep production costs low. As with the buildings and transportation sectors, the keys are to minimize energy use and electrify the sector to the greatest extent possible. The challenge is that this sector is the most difficult to electrify, so low-carbon renewable fuels and, in the near term, some amount of carbon capture and sequestration will also be needed. In this section we will address ways to replace fossil fuels used for industrial energy. According to EIA, about 7% of fossil fuels are not combusted but are used in the production of a wide variety of products, such as asphalt, lubricants, and feedstocks for industrial chemical production (Francis 2018). Efforts are underway to substitute lignocellulosic biomass for these feedstocks (Roddy 2013), but that is outside the scope of this report.

5.1 Minimizing energy use and waste

The US Energy Information Administration estimates energy-related carbon dioxide emissions for various slices of the US industrial sector (Figure 5.1). Transitioning from petroleum to renewable

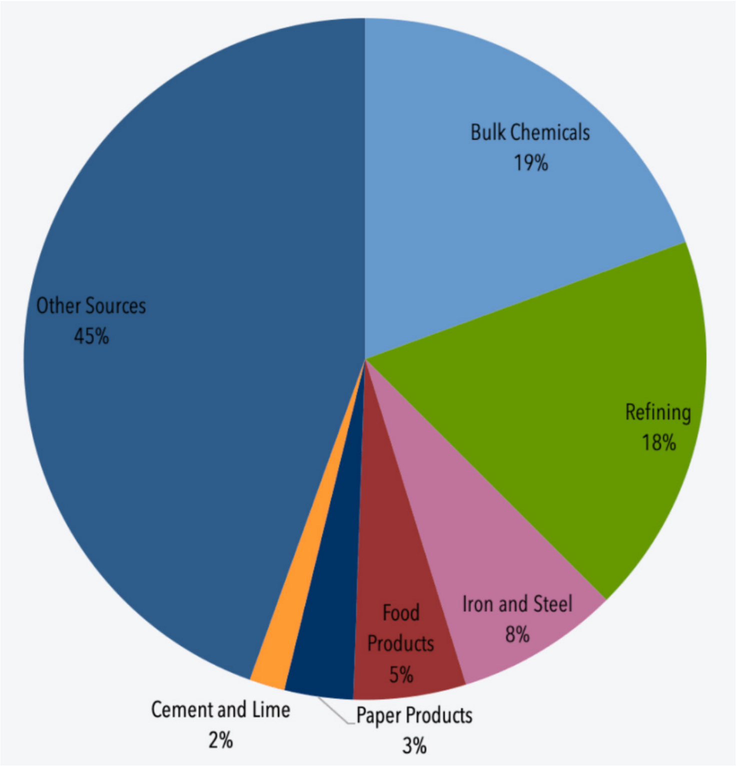

Figure 5.1. 2019 US industry energy-related carbon dioxide emissions. Emissions are distributed among many different types of industries. (EIA 2020b)

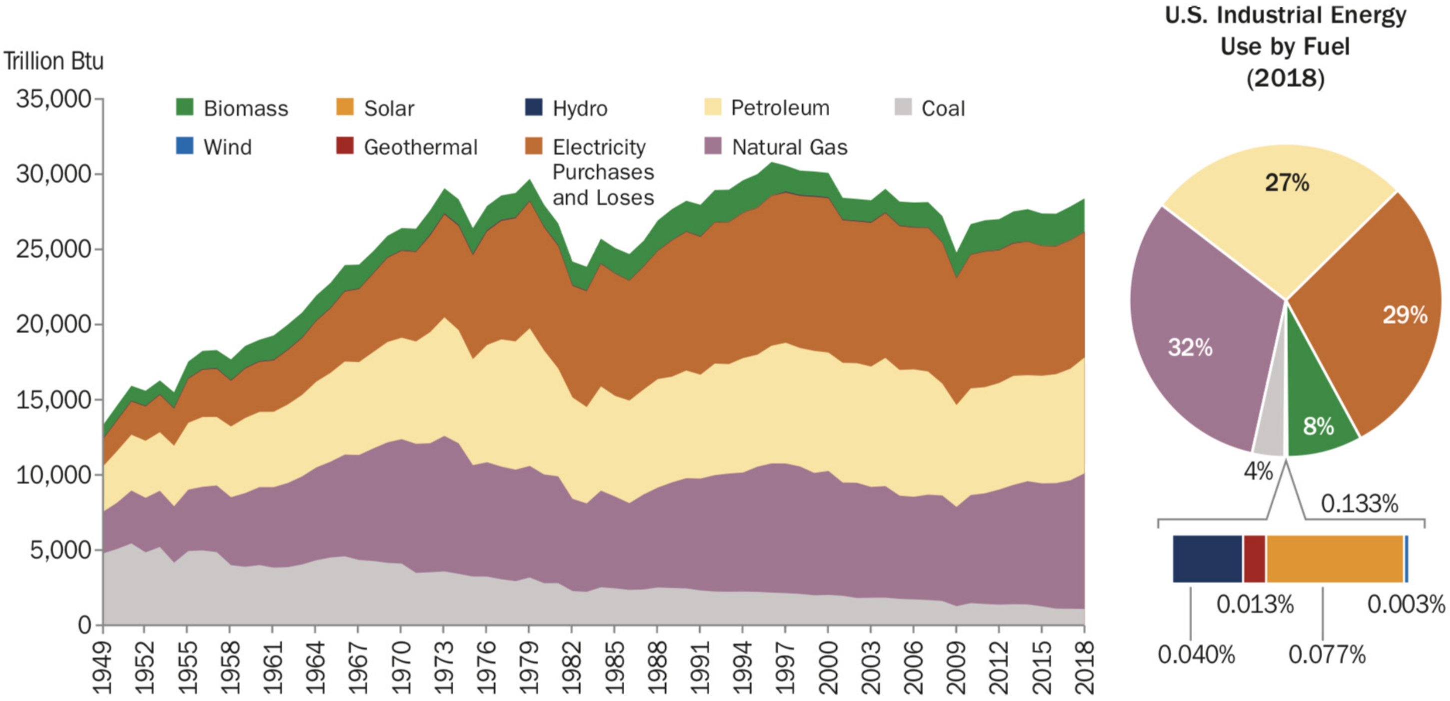

Figure 5.2. US industrial energy use by fuel (1949-2018). Industrial emissions are spread fairly evenly between electricity, natural gas, and petroleum, with biomass currently representing the only significant renewable energy contributor (not accounting for the renewable portion of electricity). (Liu and McMillan 2020)

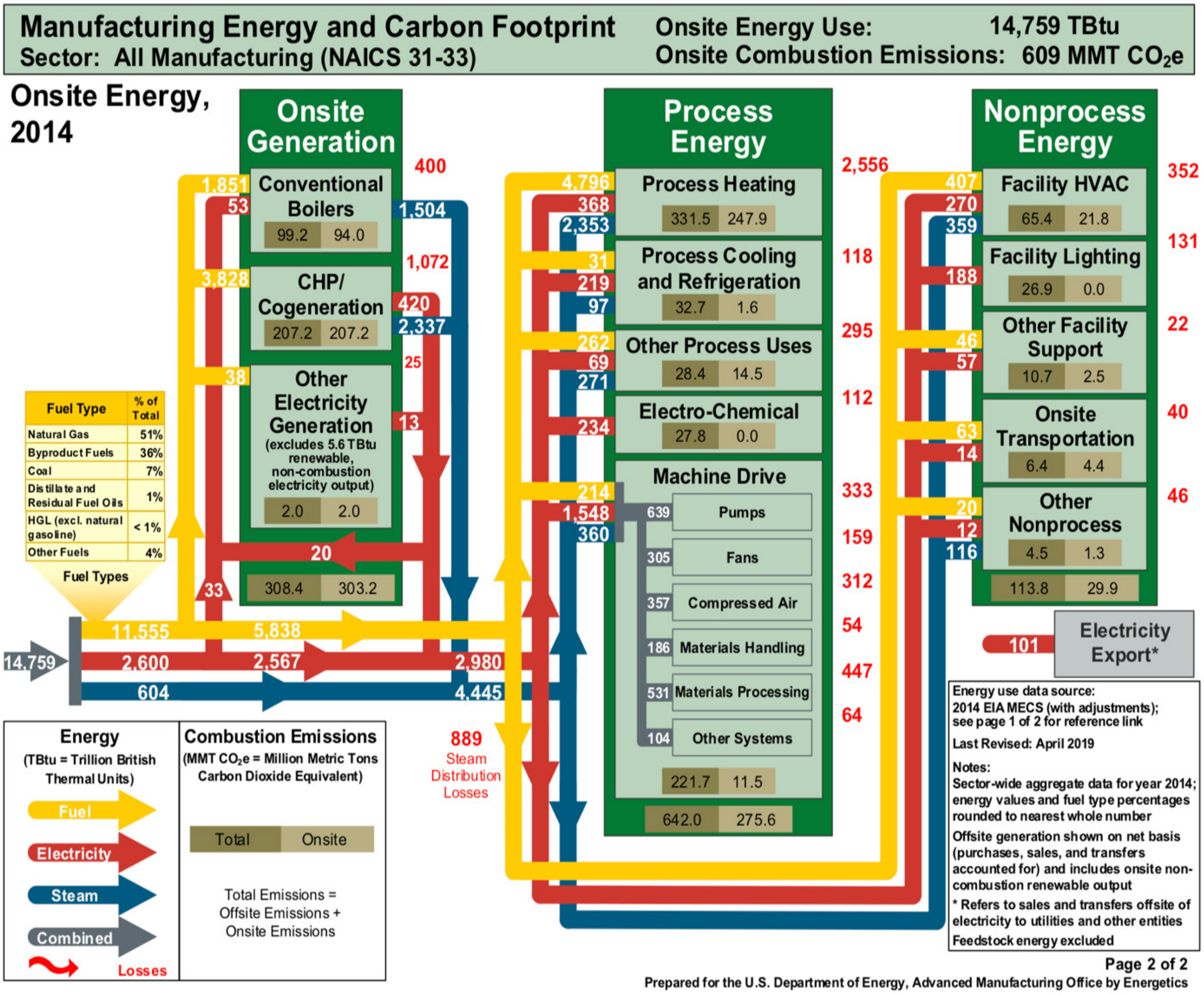

Figure 5.3. US energy consumption and greenhouse gas emissions for the various manufacturing processes. Process heating and onsite combined heat and power (CHP) are the biggest contributors to manufacturing sector energy consumption and emissions. (DOE 2019)

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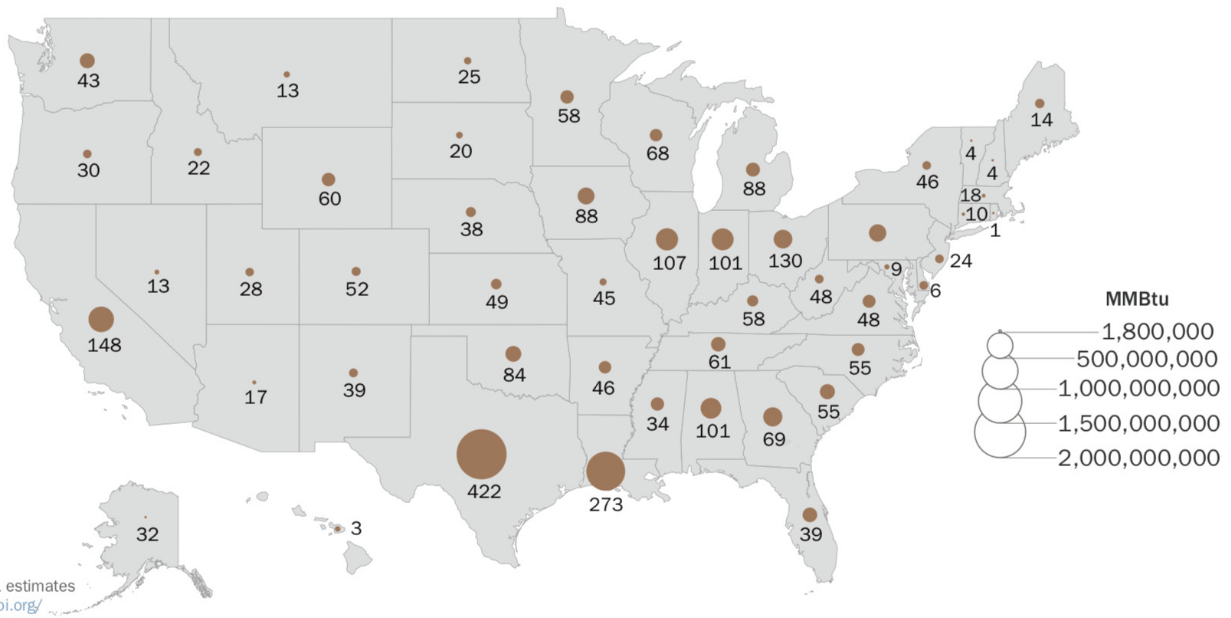
energy sources will directly reduce the size of the second-largest sector, refining. Fuel use is already shifting in this sector. In recent years, for example, US industry has come to rely less on coal and more on natural gas (Figure 5.2), reflecting a similar change in the electric power sector. Although the renewable share of industrial energy has increased, it is mainly biomass.

In the US manufacturing sector, process energy is the biggest source of greenhouse gas emissions, and process heating is its biggest emitter (Figure 5.3). Significant emissions also result from machine drives, cogeneration, and non-process energy (mostly HVAC and lighting). Overall, some solutions are obvious: The HVAC can be electrified as in buildings, LED lighting can reduce lighting loads, and both of these can be provided by a grid increasingly powered by wind and solar. The cogeneration can be provided by a combination of electrification, renewable fuel, and renewable electricity from on- or off-site. Much of the machine-drive energy can be reduced by transitioning to more efficient equipment and powering by a cleaner grid.

However, the industry sector is complex, as is obvious in Figure 5.3, with many different processes and facilities, and that complexity creates a challenge for



Source: NREL estimates (https://dx.doi.org/10.7799/1575074, https://github.com/NREL/Industry-energy-data-book)

Note: Data does not include feedstock energy use.

Map based on Longitude (generated) and Latitude (generated) and Latitude (generated). Details are shown for State Name. For pane Latitude (generated) (2): Size shows sum of MMBtu TOTAL. Numeric values represent the count of large energy users by state.

© 2019 Mapbox
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Estimates of Large Energy Users and County Energy Use

Figure 5.4. US industrial energy use (by size of circles) and number of facilities by state, 2016. Texas, Louisiana, and California are the largest industrial energy users in both respects. (Liu and McMillan 2020)

decarbonization. So it makes sense to look at where industrial energy use is concentrated (Figure 5.4). Texas, Louisiana, and California are the three largest users of industrial energy; however, in Texas and Louisiana, a great deal of the energy is for petroleum refining. This will decline as more end uses in transportation and buildings shift from oil and gas, respectively, to electricity. Texas has excellent wind resources, which can also benefit neighboring Louisiana; and both California and Texas have good solar resources, so they have good potential for utilizing renewable electricity and renewable fuels.

The IPCC Fifth Assessment Report's Working Group III (Fischedick et al. 2014) summarized ways to reduce industrial emissions as follows:

- Reducing carbon emissions per unit of energy by substituting carbon-free sources for fossil fuel.
- Reducing energy consumed per unit of material (generally considered energy efficiency).
- Using less material. This can involve minimizing waste or recycling.
- Using less product to provide the needed service, such as using more durable or higher-strength materials.
- Reducing the use of the product. For example, telecommuting reduces the need to produce transportation vehicles.

Substituting carbon-free sources, the first bullet above, means replacing fossil fuels with renewable electricity and renewable fuel, which we cover in Section 5.2. Opportunities to improve energy efficiency, the second bullet, have generally focused on motors, compressed air systems, and refrigeration systems (Kutscher, Milford, and Kreith 2018). Heat recovery and use of waste heat for power production are also important energy-saving measures (Lovins 2018), and there are many examples of overall system improvements, such as designing piping systems for low pumping power and improved control systems to significantly reduce energy consumption (Rissman et al. 2020). One area that has not been fully exploited is the use of variable speed drives on motors. When motors are used to power pumps and fans, the pumping or fan power increases with the cube of the motor speed. As a result, in cases where multiple units operate in parallel (e.g., air-cooled condenser fans), slowing down all units when needs are reduced consumes much less energy than switching some units off. Variable speed flow can also improve the efficiency of heat pumps and refrigeration units.

Industrial plant owners should be encouraged to enact energy management programs. The International Standards Organization ISO 50001 standard provides a framework for improving energy efficiency through an energy management system. The US Department of Energy provides a navigator to guide plant owners through the process.[1] Plant owners can also receive federal Energy Star certification. An Energy Star benchmarking guide[2] provides plant owners with guidance on how to benchmark performance using energy performance indicators (EPIs) for their industry.[3]

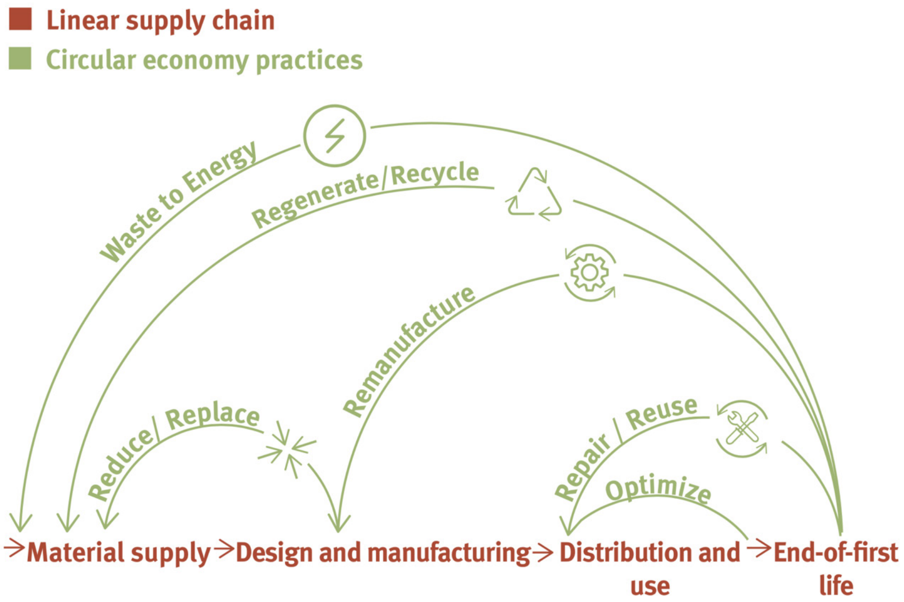

Figure 5.5. Comparison of a linear and a circular economy. A circular economy is much more sustainable than a traditional approach. (https://www.unido.org/our-focus-cross-cutting-services/circular-economy)

Regarding waste minimization, McKinsey (McKinsey & Company 2010) identified eight different kinds of waste that can be reduced in the industrial sector. These are:

- Overproduction (e.g., venting steam).
- Waiting (e.g., a process at partial power waiting for material).
- Transport (e.g., piping leaks).
- Overspecification (e.g., kiln operating at too high a temperature).
- Inventory (e.g., allowing material to cool down requires reheat).
- Rework/scrap (e.g., poor product quality requires production to be redone).
- Inefficient processes (e.g., failure to recover waste heat).
- Failure to achieve employee potential (e.g., inadequate efficiency training).

Ideally, industries should develop sustainable processes that result in zero waste. This is the concept of a circular economy (Figure 5.5); the United Nations Industrial Development Organization provides a number of reports that provide guidance on pursuing a circular economy.[4]

In the Fifth Assessment Report, the IPCC went so far as to identify specific ways to reduce greenhouse gas emissions in various industries (Table 5.1).

Although these decarbonization tactics are all promising, the EIA does not project much improvement in energy efficiency in the industrial sector, with the exception of cement and lime (Figure 5.6). Efforts to reduce waste and improve efficiency should continue, but the rapid decarbonization that is needed will necessarily come from electrification and switching to low-carbon fuels, covered in the next section.

5.2 Electrification and low-carbon fuels

An axiom of the decarbonization movement has been "electrify everything," so that the energy can be provided by low-cost, carbon-free wind and solar. Industrial processes that currently use grid electricity will be decarbonized via the clean energy transition of the power sector. Some industrial processes will be difficult to electrify, and fuel alternatives will be needed. Figure 5.7 shows the temperature ranges of different industrial processes and the carbon-free fuel options, including biomass, nuclear, and hydro-

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[1] https://navigator.lbl.gov/

[2] https://www.energystar.gov/sites/default/files/tools/EPIBenchmarkingGuide_form.pdf

[3] https://www.energystar.gov/industrial_plants/measure-track-and-benchmark/energy-star-energy

[4] https://www.unido.org/our-focus-cross-cutting-services/circular-economy

Table 5.1. Example improvements to reduce greenhouse gas emissions in various industries.

Industry	Example Improvements
Iron and Steel	• Improved heat recovery from process streams • Recycling of structural steel • Adoption of more realistic structural safety margins for buildings
Cement	• Adoption of EPA Energy Performance Indicator score to identify potential improvements • Harvesting of carbon dioxide • Production of higher-strength, longer lasting concrete
Chemicals	• Generating pure waste streams to enable more recycling • Greater adoption of combined heat and power • Material-conserving plastic packaging
Pulp and Paper	• Improved heat recovery in drying process • Greater paper recycling • Reduced paper weight and duplex printing
Non-ferrous metals (e.g., aluminum)	• Adoption of improved electrolysis methods • Minimization and reuse of scrap
Food processing	• Less energy-intensive drying techniques, e.g., mechanical dewatering • Local sourcing of food • Transition from meat to vegetarian foods
Textiles and Leather	• More efficient motors and boilers
Mining	• Apply latest resource characterization methods to obtain higher quality ore and reduce amount crushing and grinding • Use of more efficient crushing technologies • Great metal recycling

(Fischedick et al. 2014)

gen (Sandalow et al. 2019a). Biomass incurs processing and transportation costs and there can be many demands on its limited supply. Even if biomass is used properly, it takes time for new biomass growth to remove an amount of carbon dioxide from the atmosphere equivalent to that emitted by biomass energy production. (Bruggers 2020; Sterman, Siegel, and Rooney-Varga 2018). Nevertheless, there are some industrial processes where replacing fossil fuel with biomass can be an appropriate way to reduce carbon emissions.

Advanced nuclear generally refers to small modular reactors (abbreviated SMR but not to be confused with steam methane reforming). While the nuclear industry hopes that standardized, factory production of these units will lower costs, the current cost of

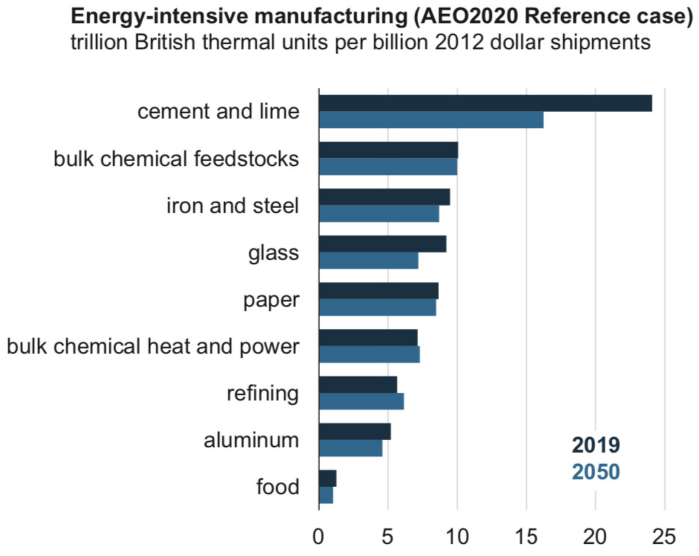

Figure 5.6. Energy intensity of different manufacturing industries. Cement and lime stand out as having the highest energy intensity. (EIA 2020b)

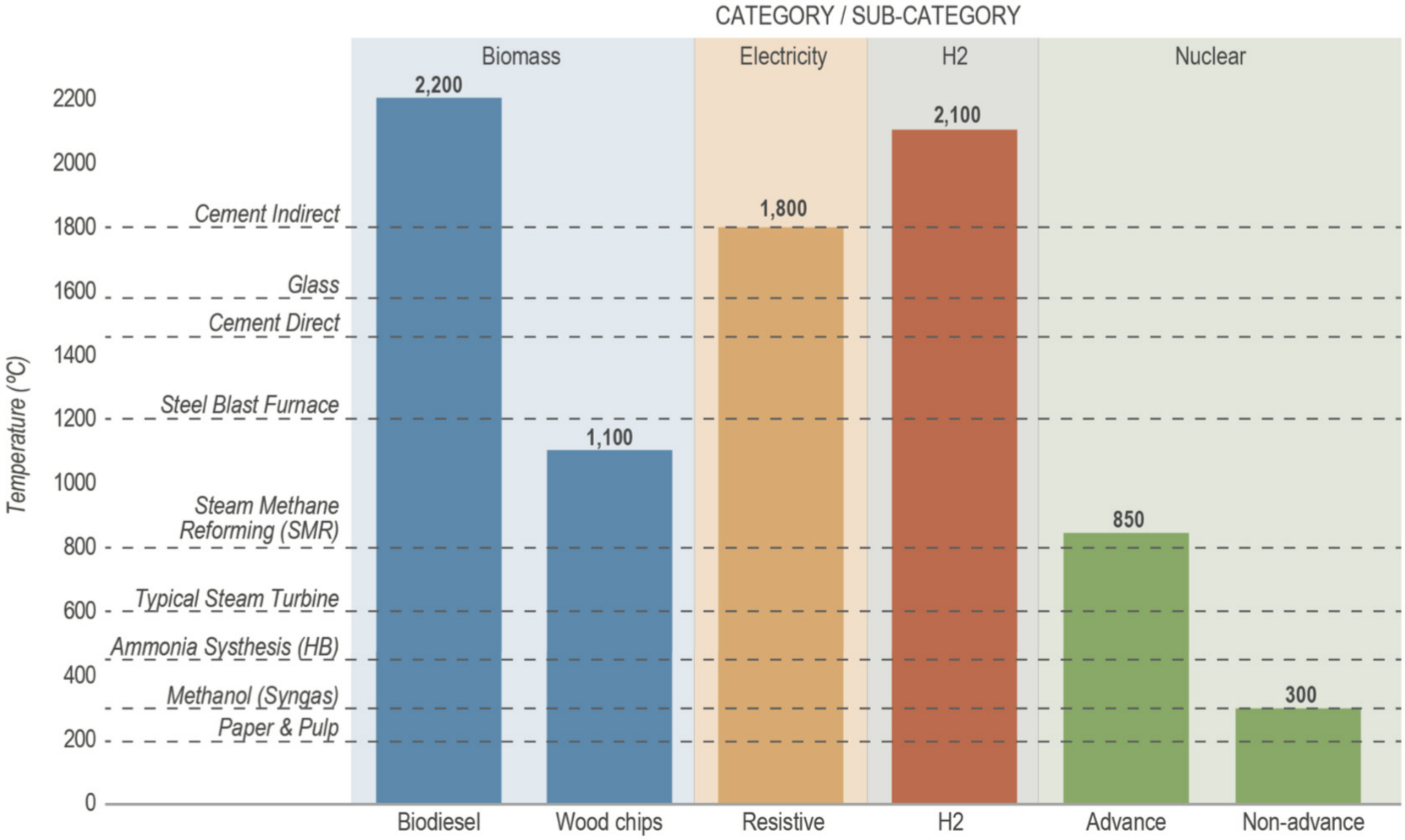

Figure 5.7. Temperature requirements of key industrial processes vs. temperature limits of low-carbon options. Clean energy sources can provide the process temperatures that are needed. (Sandalow et al. 2019)

new nuclear power in the United States is four times the cost of solar and wind, based on the levelized cost of electricity (Section 2). It will be a challenge for new reactor technology to overcome such a large cost gap, especially considering that solar, wind, and battery prices are still dropping. By the time reactors are ready for commercial deployment, renewable electricity and electrolyzer costs will be lower yet.

We believe that renewable electricity and hydrogen (the latter for processes difficult to electrify) are the most promising long-term options for producing heat. However, especially in the near term, decarbonization will likely also involve some use of biomass, as well as carbon capture utilization and storage (CCUS), which employs a combination of geologically sequestering the carbon dioxide and using it for finished products such as plastics or other materials. (Of note here: Geological sequestration might be considered practically limitless, but the potential to use carbon dioxide for products would eventually be exhausted.) Although hydrogen from renewable sources is currently expensive, the successes of wind and PV have shown that deployment itself lowers costs through learning curves, and this will likely be the case for hydrogen. Two other heating options not included in Figure 5.7 are worth considering. Renewable natural gas from dairy farms and other sources can reduce high global warming potential (GWP) methane emissions and replace some natural gas, but the available quantities are limited. Some usage alone or mixed with hydrogen can be beneficial. Secondly, solar thermal energy is an option, and is discussed in Section 5.4.

5.2.1 Electrification

According to EIA, certain industries offer notable opportunities for fuel switching from high-carbon to low- or zero-carbon fuels:

- A considerable amount of natural gas is used in the food and glass industries, mostly for process heating.
- Coal is the primary fuel in the iron and steel industry.
- Natural gas and hydrocarbon gas liquids are used in the bulk chemicals industry as feedstocks, and for heat and power production.

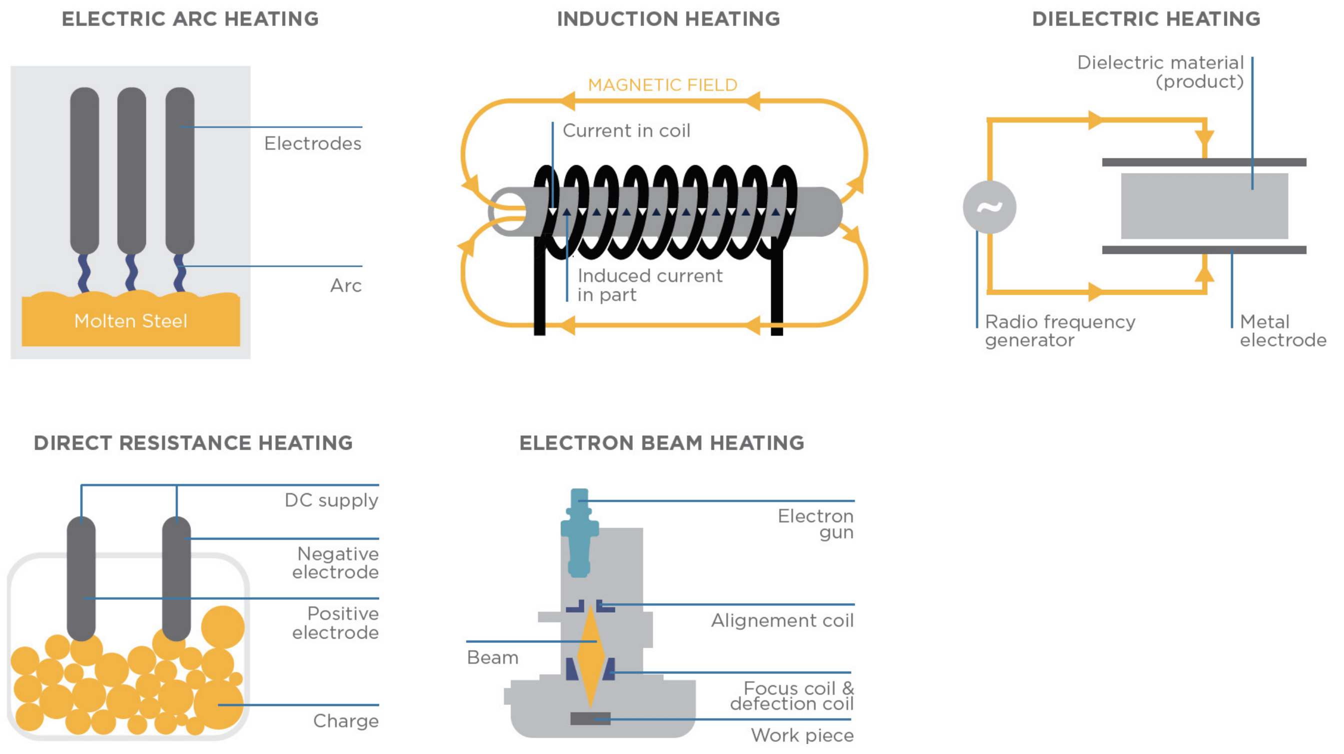

Figure 5.8. Electric heating methods. There are a variety of means by which electricity can provide process heat. (Friedmann, Fan, and Tang 2019)

- Petroleum is used in agriculture, including to power field equipment.

In building applications, heat pumps offer an important efficiency advantage over electric resistance heating, and they can be an excellent option for industrial processes operating at temperatures up to about 150°C (or higher if a high heat source temperature is available). However, heat pumps are not effective for the higher temperatures needed for many industrial processes, which leads us to the need to: 1) electrify processes using renewable-produced electricity and 2) use renewable fuels.

A wide range of process heating options are available today (DOE 2015b). Electric heating can make use of an increasingly clean electric grid. It is easy to modulate, provides good temperature control (as opposed to fuels, which have a particular combustion temperature), and has high reliability (although high-temperature electrodes must be periodically replaced). The most common way to heat with electricity—used in baseboard heating and traditional electric cooktops—is indirect resistive heating, in which electricity is passed through a resistive heating element and the heat is transferred to the process. The upper temperature limit of a resistance heater is 2,500°C using tungsten alloys, which covers most industrial needs[5]. Heating a material directly is even more efficient, and various direct heating technologies (Figure 5.8) can heat indirectly as well. Table 5.2 shows common means by which electricity can provide heat.

Lawrence Berkeley National Laboratory evaluated the direct electrification potential by 2050 of different industries based on three different studies (Deason et al. 2018b). Its results (Table 5.3) suggest that most industrial sectors can achieve full direct electrification by 2050—except for petrochemicals and iron, metals, and steel manufacturing.

(Steinberg et al. 2017) identified the following barriers to industrial electrification:

- Low natural gas prices.
- Aversion to process disruption.
- Capital investment decision making.

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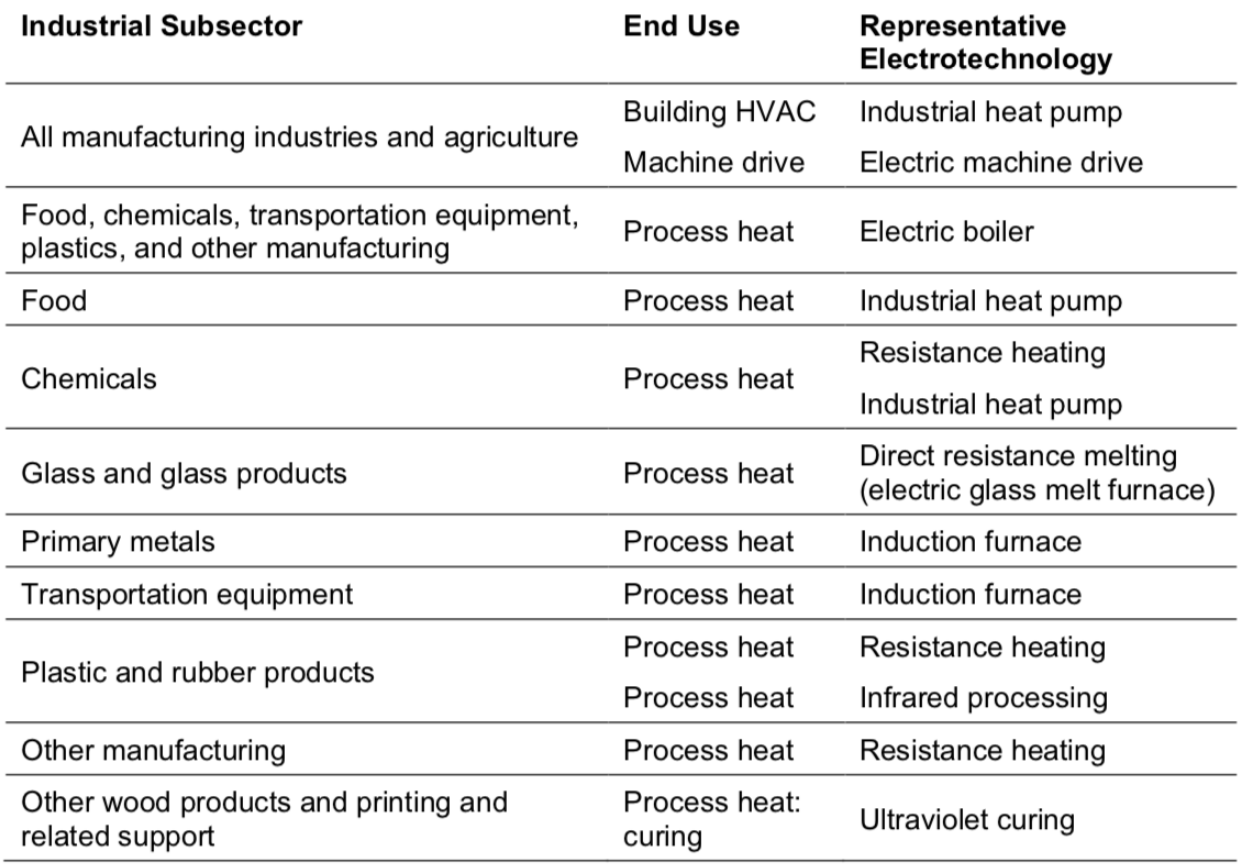
[5] https://www.globalspec.com/learnmore/manufacturing_process_equipment/heating_cooling_equipment/industrial_heaters_heating_elements/resistive_heating_elements

Table 5.2. Electric technologies matched to different industrial subsectors. A variety of different electric technologies are available to provide the various industrial needs. (Jadun et al. 2017)



Industrial Subsector	End Use	Representative Electrotechnology
All manufacturing industries and agriculture	Building HVAC	Industrial heat pump
	Machine drive	Electric machine drive
Food, chemicals, transportation equipment, plastics, and other manufacturing	Process heat	Electric boiler
Food	Process heat	Industrial heat pump
Chemicals	Process heat	Resistance heating Industrial heat pump
Glass and glass products	Process heat	Direct resistance melting (electric glass melt furnace)
Primary metals	Process heat	Induction furnace
Transportation equipment	Process heat	Induction furnace
Plastic and rubber products	Process heat	Resistance heating
	Process heat	Infrared processing
Other manufacturing	Process heat	Resistance heating
Other wood products and printing and related support	Process heat: curing	Ultraviolet curing

These could be addressed by a combination of a sufficiently high carbon price, federal tax incentives, and federal mandates for carbon dioxide emissions reductions. However, industrial plants have large capital investments, and plant owners likely will be resistant to changing over to electrical equipment in the near term, even where electrification is feasible. As in the case with electrifying buildings, there is an economic advantage to electrifying when fossil fuel-fired equipment reaches its end of life. However, this gradual transition may not be consistent with the needed speed of decarbonization. Planned replacement can avoid downtime and provide efficiency advantages, in addition to speeding decarbonization. In addition, electrification of industry means installing high-voltage in-plant wiring and controls and addressing increased demand on the electric distribution grid.

Thus while electrification will play an important role for new industrial plants and for existing plants, we also need to focus on replacing fossil fuels with renewable fuels.

5.2.2 Low-carbon fuels: the case for green hydrogen

Some industrial processes release carbon dioxide in high concentrations. In these cases, CCUS may be a cost-effective decarbonization approach in the near term. In addition, there are processes where burning a carbon-based fuel is advantageous to the process and substituting with biomass or biofuel is appropriate. But for deep decarbonization of industry, there is a great deal of attention being paid to the use of hydrogen fuel, which may prove especially important for processes that are difficult to electrify. And whereas electricity is generally used only for heating, hydrogen can be used both as a heating fuel and for certain processes that use hydrogen as a chemical input (such as ammonia production).

There is an immediate carbon savings in switching from fossil fuel to hydrogen produced by electrolysis using solar- and wind-generated electricity—and renewably produced hydrogen does not require harvesting and transporting, as biomass does. This approach is being aggressively pursued in Europe.

Table 5.3. Electrification potential summary of three industry electrification studies. (Deason et al. 2018b)

Sector	Direct Electrification of Process Heating -- Potential by 2050	Reference	Technologies
All sectors – conventional boilers	100%	Steinberg et al. (d)	All conventional boilers electrified
Cement	100% (a)	Lechtenböhmer et al. 2016; Purr et al. 2014	Electrification of end uses (e.g., plasma-based heating), electrolysis production of hydrogen, and renewable natural gas production for fuel
Chemicals	100%	Steinberg et al. 2017(d)	Industrial process heat pumps
Chemicals (chlorine and ammonia)	100% (b)	Lechtenböhmer et al. 2016	Electrification of end uses, electrolysis production of hydrogen
Chemicals (petrochemicals)	0% (c)	Lechtenböhmer et al. 2016	No direct electrification; fossil fuels replaced by electrolysis production of hydrogen and renewable natural gas production for both process fuel and petro chemical feedstocks
Food	100%	Steinberg et al. 2017(d)	Industrial process heat pumps
Food	100%	Purr et al. 2014	Various electro technologies
Glass	100%	Steinberg et al. 2017(d); Lechtenböhmer et al. 2016; Purr et al. 2014	Electrification of end uses, resistance heating and melting
Iron and steel	21%	Steinberg et al. 2017(d)	Electric arc furnaces
Iron and steel	100%	Lechtenböhmer et al. 2016; Purr et al. 2014	Electric arc furnaces, electrowinning; plasma or induction ovens for smelting
Lime	100%	Lechtenböhmer et al. 2016	Electrification of direct end uses
Metal fabrication	100%	Steinberg et al. 2017(d)	Induction heating
Metal fabrication (foundries)	> 50%	Purr et al. 2014	Electric furnaces
Nonferrous metals, excluding aluminum	100%	Steinberg et al. 2017(d)	Electrolytic reduction
Pulp and paper	100%	Steinberg et al. 2017(d)	Industrial process heat pumps

(a) Purr et al. 2014 describes the transition away from fossil fuel-based heating in the production of cement to a combination of electrification of direct end uses, electrolysis production of hydrogen, and renewable natural gas production for fuel. Electrification potential is quoted as 100% here, because this report also states that high temperature furnace processes for cement can be fully electrified.

(b) Electrolysis-produced H2 is used as a feedstock for ammonia.

(c) Zero direct electrification of end uses is assumed, but electricity is used extensively for hydrogen and syngas/Fischer-Tropsch naphta production.

(d) Steinberg et al. 2017 recently modeled the impact of high electrification of end uses by 2050 on the US electricity grid. The Steinberg et al. study is largely based on market potential analysis conducted by the Electric Power Research Institute (EPRI 2010). The “high electrification scenario” in Steinberg et al. assumes the following: (i) all conventional boilers converted to electric boilers by 2050; and (ii) all process heating is 100% electrified by 2050 in the following sectors: electrolytic reduction of nonferrous metals (excluding aluminum), induction heating for metal fabrication, resistance heating and melting for glass, and industrial heat pumps in the food, pulp and paper, and chemicals sectors. Iron and steel is assumed to be 21% electrified by 2050. This cap is due to “the nascence of the arc furnace production route and the limits to available scrap that would be required for expanded arc furnace production.” Key electro-technologies include induction melting, resistance heating and melting, and heat pumps.

The challenge is that it is currently an expensive approach, including the need for changes in capital equipment.

The current costs of renewable hydrogen are higher than the cost of fossil fuels with carbon capture and storage, so some people have promoted CCS as the most cost-effective means to reduce industrial carbon emissions today. Most hydrogen today is produced from natural gas via steam methane reforming (SMR) and is referred to as grey hydrogen. Capturing and sequestering the carbon dioxide generated by this process is the cheapest way to currently produce low-carbon hydrogen ("blue hydrogen") and is likely to be used in the short term if hydrogen can be produced where geologic storage of the captured carbon dioxide is available.

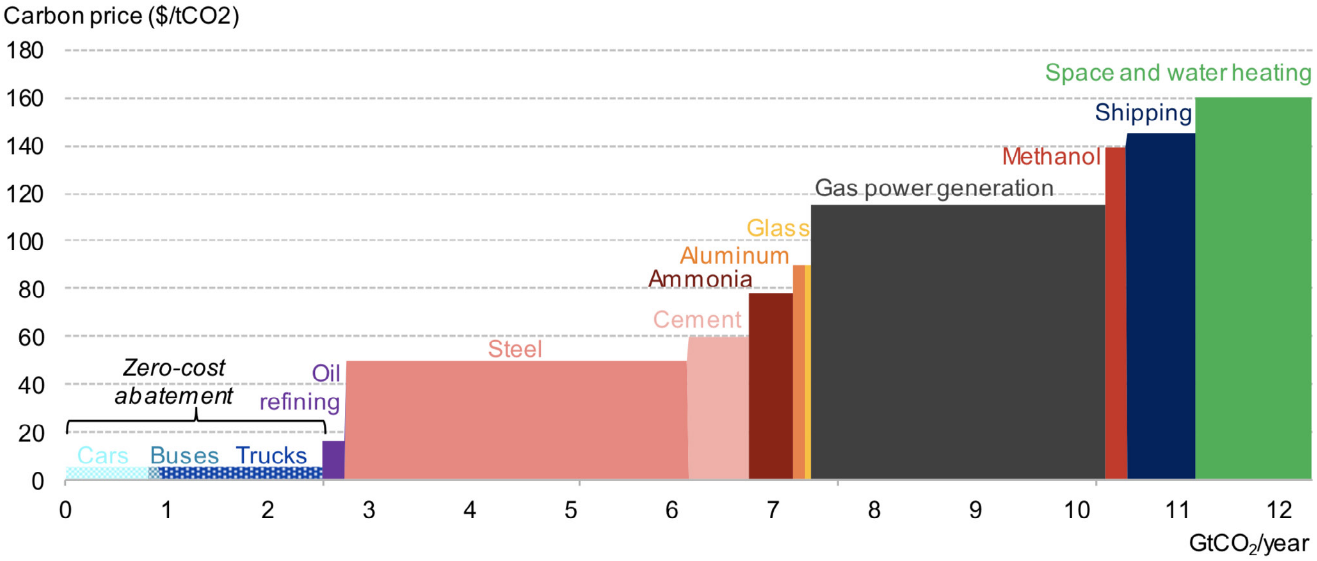
Hydrogen produced from 100% renewable energy, which generally means electrolysis using renewable electricity, is called green hydrogen. The United States levelized cost of blue hydrogen with 89% CCS is in the range of $1.71-2.15/kg. Grid electrolysis (90% utilization) is considerably higher: $4.50 to $6.04/kg (Friedmann, Fan, and Tang 2019). Of course, the US grid is currently only about 40% carbon-free electricity (EIA 2020d), but the fraction of renewable electricity will increase rapidly under any serious decarbonization effort, so this cost is a reasonable representation of the future price of green hydrogen if we assume no reductions in the electrolyzer or grid electricity costs. Note also that industry-rich Texas, with its wind power, and California have cleaner electricity than the national average. Green hydrogen may be cost-competitive with CCS in about five to 10 years, based on projected reductions in the costs of both electrolyzers and renewable electricity.

Electrolyzers use electricity to split water into hydrogen and hydroxide ions, and they produce hydrogen and oxygen at the negative (cathode) and the positive (anode) electrodes, respectively. On average, electrolysis to produce 1 kg of hydrogen consumes 50-55 kWh of electricity and about 2.5 gallons of pure water. Electrolyzers are generally divided into three types. Alkaline electrolyzers (AEL), which have the largest market share, use an alkaline solution electrolyte with the electrodes separated by a diaphragm. They do not require an expensive catalyst. Polymer electrolyte membrane electrolyzers, also called proton exchange membrane (PEM) electrolyzers, use a polymer membrane between the two electrodes through which protons pass. PEM electrolyzers can operate at high current densities and respond rapidly to intermittent power sources (like renewables) but require an expensive catalyst. Solid oxide electrolosis cell electrolyzers have high efficiencies but must operate at high temperatures (500-850°C). A new variant of the PEM electrolyzer is the anion exchange membrane (AEM) in which hydroxide ions pass through the membrane. The advantage of the AEM approach is that it does not require an expensive catalyst.

Although pure hydrogen is incompatible with natural gas piping, the existing trenches and rights-of-way for natural gas pipes could be effectively used for hydrogen piping. However, as the electrical grid rapidly transitions to solar and wind electricity, it will be possible for many companies to tap this electricity to produce green hydrogen on site using large electrolyzers that serve an entire industrial development site or just an individual company. A potential advantage of on-site electrolysis is that the oxygen by-product could be used for clean combustion of the hydrogen, or it could be used in a hybrid approach whereby natural gas is burned with pure oxygen, allowing carbon dioxide to be easily extracted from the flue stream and sequestered.

The produced hydrogen cost is the sum of the life-cycle cost of the electrolyzer and the cost of the electricity consumed. Although hydrogen would typically be used by industry 24 hours per day, electrolysis could be performed using only low-cost, nighttime electricity or operated so as to provide demand response for the electric grid. Hydrogen production is often cited as a means for using excess solar- and wind-generated electricity to avoid curtailment, although there will likely be competitive uses for this electricity, such as charging EVs. Size optimization of on-site electrolyzers would account for the daily amount of hydrogen needed, the electricity rate structure, the cost of hydrogen storage, and the impact of partial utilization on the levelized cost of hydrogen. There are a variety of ways to store hydrogen on site: as a compressed gas, as a cryogenic fluid, or as a solid in a hydride. Storage cost depends on the storage type and size. The cost of high-pressure hydrogen storage is currently about $14/kWh of electrolyzer electricity (Ordaz, Houchins, and Hua 2015).

Companies will choose large, central electrolyzers or smaller ones based on costs and needs. Large elec-



Source: BloombergNEF. Note: sectoral emissions based on 2018 figures, abatement costs for renewable hydrogen delivered at $1/kg to large users, $4/kg to road vehicles. *Aluminum emissions for alumina production and aluminum recycling only. Cement emissions for process heat only. Refinery emissions from hydrogen production only. Road transport and heating demand emissions are for the segment that is unlikely to be met by electrification only, assumed to be 50% of space and water heating, 25% of light-duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.*

Figure 5.9. The impact of a carbon price on the affordability of utilizing green hydrogen for different uses. The marginal abatement cost of decarbonizing industry with hydrogen fuel varies considerably with industry type. This plot assumes a $1/kg hydrogen cost in 2050. (BNEF 2020a)

trolyzers generate hydrogen with greater economy of scale than small ones, but if smaller electrolyzers are mass produced, they could be highly affordable. PEM electrolyzers may be suitable for distributed applications because they are low maintenance, although AEM electrolyzers could prove even more cost-effective. Areva H2Gen is testing a large, 1-MW PEM electrolyzer, which they claim can produce hydrogen at a cost of $3.90/kg, if operated close to 100% utilization with an electricity cost of $0.055/kWh (Lichner 2020).

When used to produce heat, blue hydrogen costs about $14/GJ, which is close to that of electric heating at about $17/GJ (Friedmann, Fan, and Tang 2019). As noted earlier, hydrogen from grid electrolysis is currently two to three times the cost of blue hydrogen.

The cost of both solar- and wind-generated electricity has continued to decrease (see Section 2) and the cost of electrolyzers is also dropping (Glenk and Reichelstein 2019). Glenk and Reichelstein estimate that if market trends for electrolyzers and renewable energy continue, renewable hydrogen could be competitive for industrial applications in 10 years. Every effort should be made to hasten this transition.

Bloomberg New Energy Finance has examined the costs of utilizing hydrogen in different sectors of the economy (BNEF 2020a). In particular, they look at the impact of carbon prices on hydrogen adoption by sector, assuming that the cost of hydrogen falls to $1/kg by 2050. At that price for hydrogen, a carbon price of $50 per tCO_2 would be enough to switch steelmaking to renewable hydrogen. Slightly higher carbon costs of $60/$tCO_2$ would shift cement producers to use renewable hydrogen for heat, $78/$tCO_2$ would see a switch in energy use for ammonia synthesis, and $90/$tCO_2$ for aluminum and glass manufacturing (Figure 5.9). Note the very low abatement costs for transportation in Figure 5.9; the use of hydrogen for heavy-duty transportation is covered in Section 4. Note, too, that these carbon prices are much lower than the $417/$tCO_2$ discussed in Section 1 and also much lower than the European tax on gasoline.

Because green hydrogen is expected to be cost-effective within the next decade and because it will

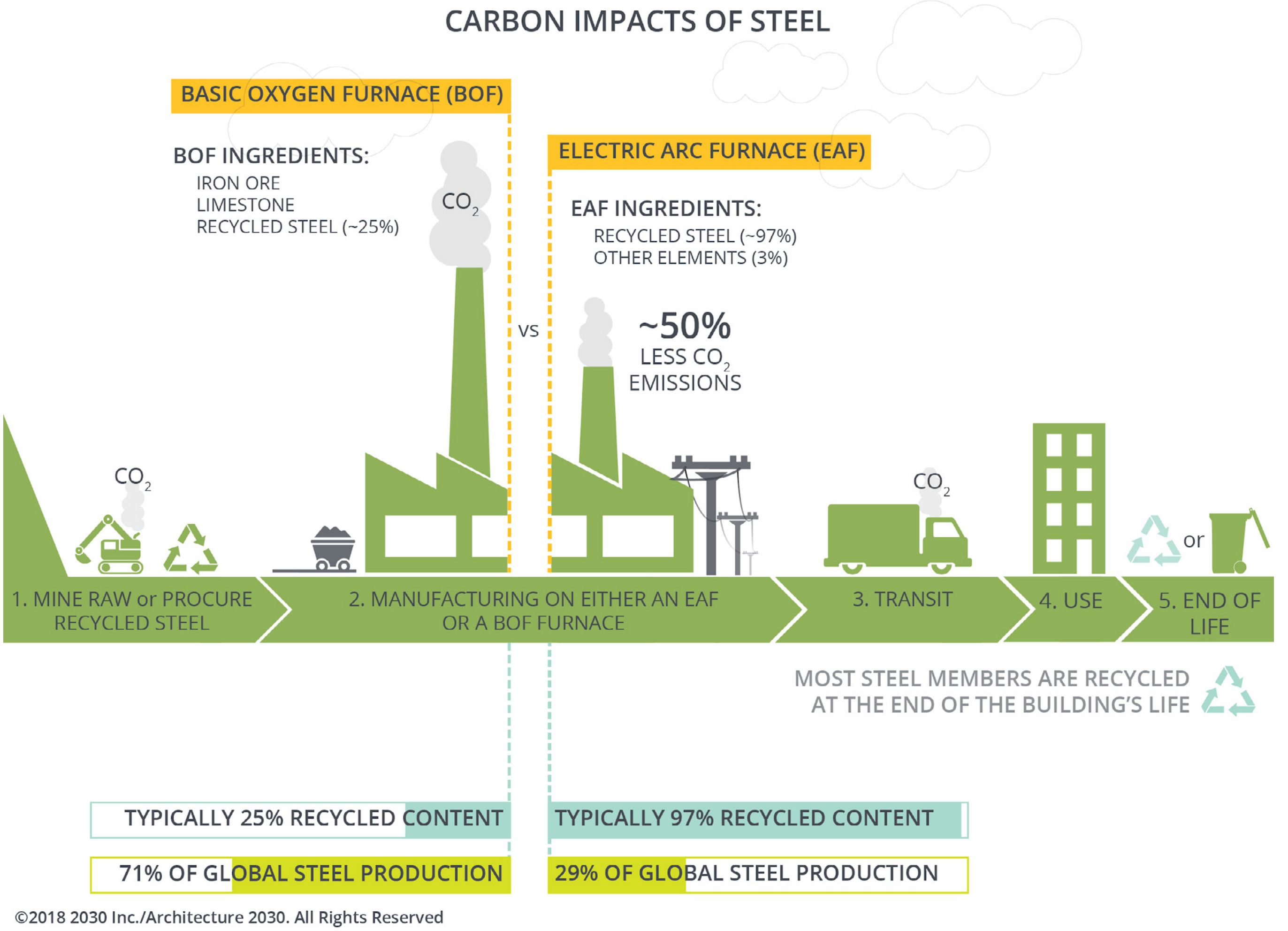


Figure 5.10. A schematic showing the carbon dioxide emissions associated with various stages of steel production for two different proccesses. Producing steel with an electric arc furnace results in significantly less emissions than the use of a basic oxygen furnace. (Architecture 2030 2018)

take some time to convert industrial equipment, it makes sense to begin now to work on the transition to the use of green hydrogen. As pointed out by (Vogt-Schilb and Hallegatte 2014), using the cheapest near-term abatement option (e.g., blue hydrogen) can make long-term climate goals more difficult to achieve.

5.3 A closer look at three industries: steel, concrete, and chemicals

As was shown in Figure 5.1, industrial energy is used for a wide range of applications and products. The refining industry is currently a large segment, but it will shrink rapidly as we transition away from fossil fuels. Of the remaining categories, most involve relatively low-temperature process heat, which should not be particularly difficult to decarbonize. However, three products contain special challenges: steel, concrete, and chemicals. The United States is no longer a major producer of steel and cement, but they are important US imports associated with significant carbon emissions, and domestic production may increase under efforts to restore US manufacturing. In each of these categories, there are clear opportunities for carbon emissions reductions, via electrification and the use of green hydrogen.

5.3.1 Steel production

Figure 5.10 shows the carbon emissions associated with two types of steel production. Large integrated steel mills use a blast furnace-basic oxygen furnace that burns coal to melt down raw iron ore mixed with a small percentage of recycled steel. A major function of the blast furnace is to provide carbon to reduce the raw iron (i.e., reduce its oxygen content) and remove impurities in the ore such as silicon, sulfur, and phosphorus (Center for Metals Produc-

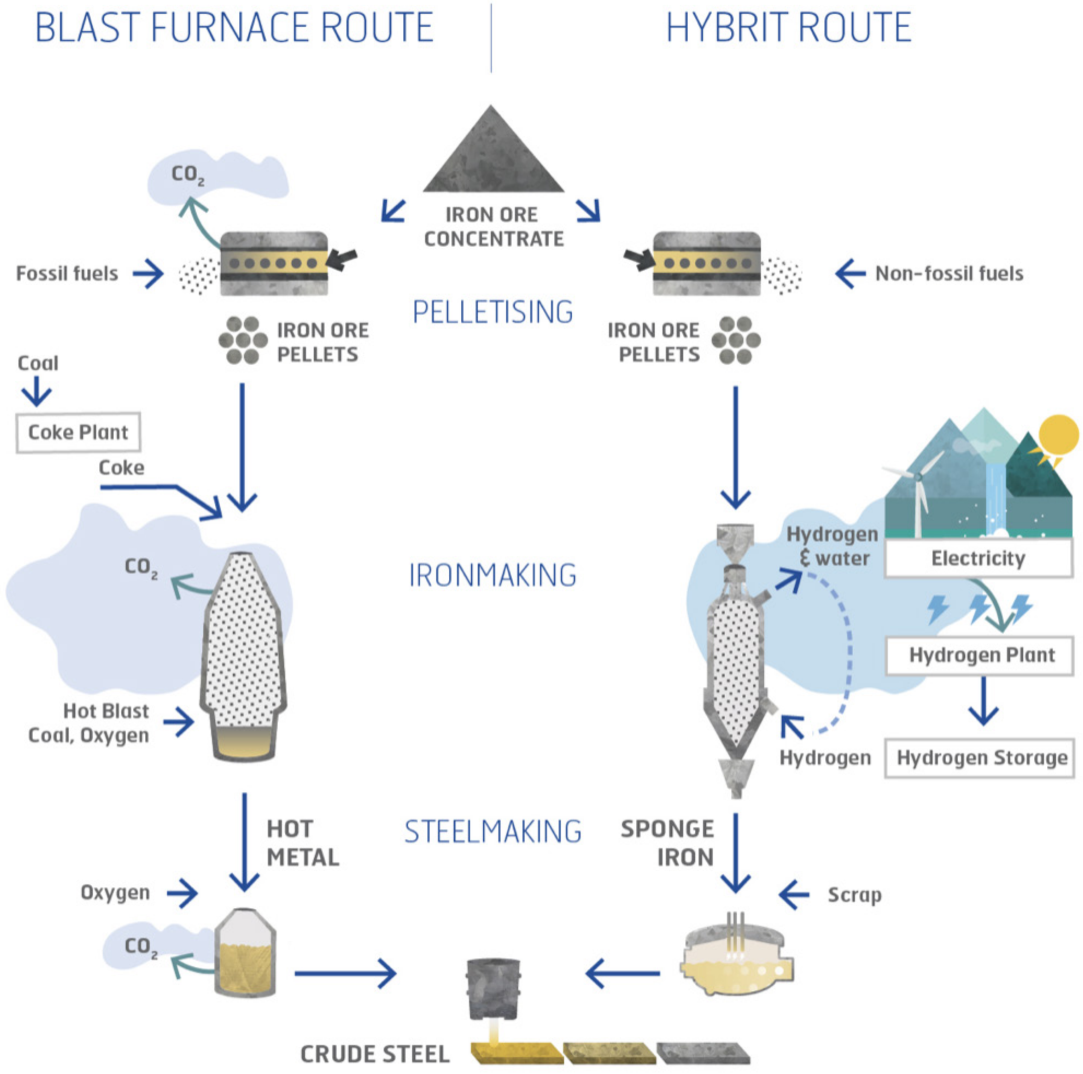


Figure 5.11 A schematic showing the processing of raw iron ore using the HYBRIT direct reduced iron (DRI) process compared to conventional processing. oThe HYBRIT process reduces carbon dioxide emissions by substituting hydrogen for coke in the reduction of iron oxides. (Courtesy of Vattenfall, LKAB and SSAB, partners in the HYBRIT project)

tion 1985). In smaller mills, electric arc furnaces melt scrap iron and steel to produce new steel. They have lower emissions both because they use more recycled material and because they use electricity instead of fossil fuel. As more of the grid becomes powered with wind and solar, the emissions associated with electric arc furnaces will decrease further. The US steel industry is already fairly electrified: About 75% of US steel is produced largely from recycled steel using electric arc furnaces, compared to a worldwide number of 35% (Thompson 2018). Because the amount of scrap steel in the world is growing, there should be a gradual shift to more electric arc furnaces, which can process this type of steel.

Electric arc furnaces do not have a source of carbon and so cannot be used to reduce raw iron. However, a process known as direct reduced iron (DRI) can be used to produce iron of sufficient quality for an electric arc furnace. DRI converts iron oxides to fairly pure iron that can then be converted to steel in an electric arc furnace. So instead of coke combining with the iron ore oxygen in a coal-fired blast furnace to form carbon dioxide, the hydrogen combines with oxygen to form water. In Europe, pilot plants are producing DRI from green hydrogen using the HYBRIT DRI process.[6] This combination of using green hydrogen to process raw iron ore, which then goes into an electric arc furnace powered by renew-

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[6] https://www.hybritdevelopment.com/articles/three-hybrit-pilot-projects

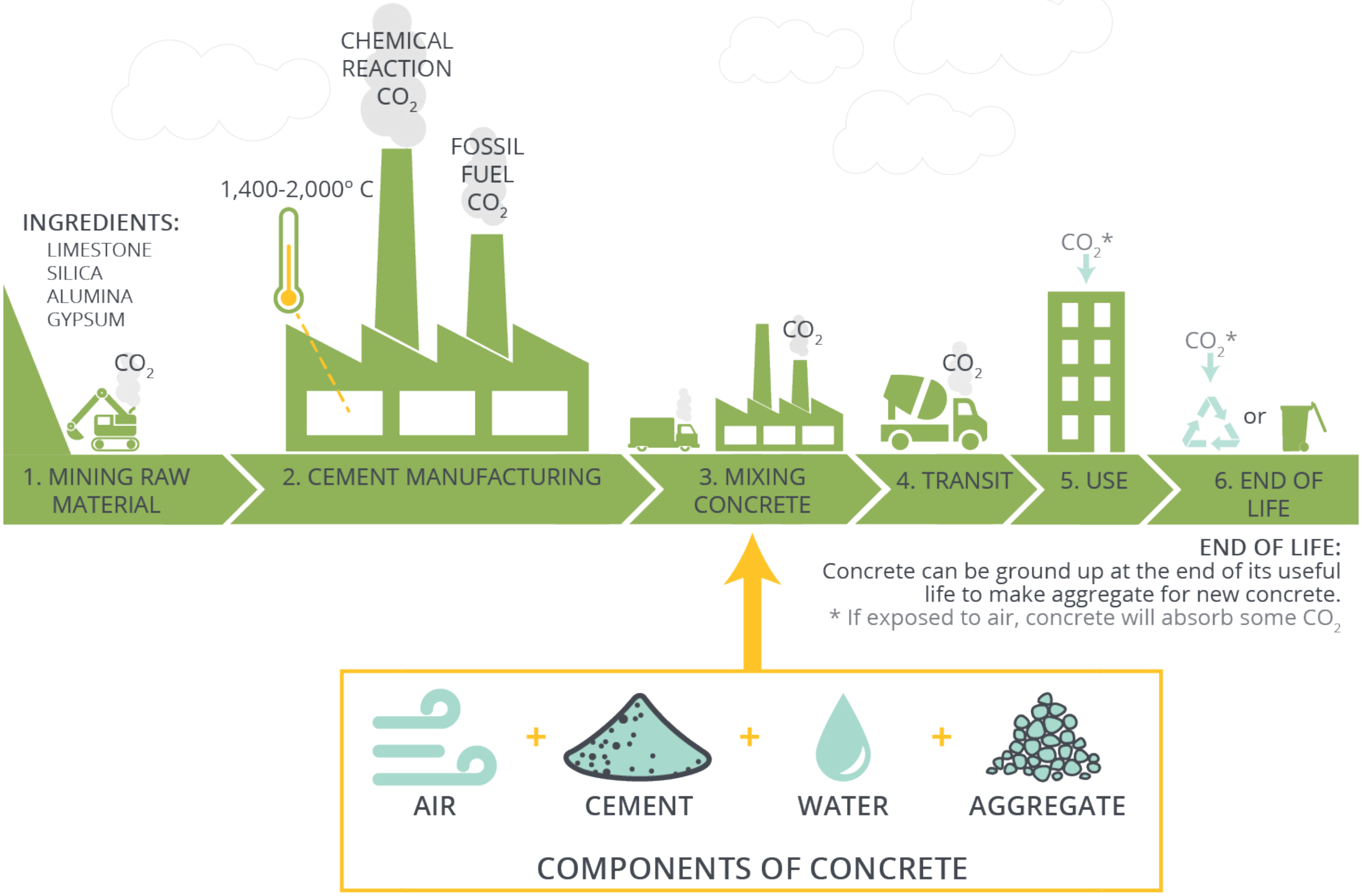

Figure 5.12 A schematic showing the carbon dioxide emissions associated with various stages of concrete production. The emissions are dominated by the production of cement. (Architecture 2030 2019)

able electricity, is a way to produce carbon-free steel. The HYBRIT process is shown in Figure 5.11.

Existing basic oxygen furnaces entail a large capital equipment investment and will continue to operate as long as sufficient quantities of recycled steel are not available. Decarbonizing them will likely involve some combination of CCS, biomass, and hydrogen fuel injection (Sandalow et al. 2019b). Lawrence Hooey et al. (2013) showed that use of an amine-type solvent for post-combustion capture of carbon dioxide in BOF flue gas could reduce carbon dioxide emissions by 47% at a cost of $56 per ton.

5.3.2 Concrete production

Concrete production is responsible for about 2% of US energy-related carbon dioxide emissions and represents as much as 8% of global carbon dioxide emissions. This fact, together with increasing urbanization and construction around the world, has drawn a lot of attention to the need to reduce concrete manufacturing emissions. Cement is a key ingredient in the manufacture of concrete (Figure 5.12), and cement production is emissions-heavy, releasing carbon dioxide through fossil fuel burning and when limestone is broken down to form clinker cement, the binder in concrete. Various means are being explored to reduce the emissions associated with cement. These include:

- Use of supplementary cementitious materials, such as ground-up, recycled, post-consumer glass, fly ash from coal plants, blast furnace slag, and rice husk ash, reduces the percentage of clinker cement that must be produced.
- Carbon dioxide capture and injection back into the concrete mix.
- Use of higher-efficiency kilns.

It has been shown that cement manufacture can be electrified. Vattenfall and Cementa in Sweden have completed a feasibility study indicating that cement can be produced by electric plasma heating (Vattenfall 2019). This doubled the cost of cement production, although they state that it only increased the cost of the final concrete product by a few percent. A side benefit is that an electric kiln would increase the concentration of the process carbon dioxide emissions, making capture of that carbon easier.

As in the case of steel, blue or green hydrogen could be used in place of fossil fuels where thermal energy is needed. However, the radiation heat transfer in a kiln heated by hydrogen combustion would differ from that of a coal-fired kiln, so R&D on hydrogen-fueled kilns is needed. And use of hydrogen would only reduce emissions from the heating process. Because carbon emissions occur both in the breaking down of limestone and in the heating process, cement manufacture is a strong candidate for CCS. Many European Union scenarios studied use biomass for heating, especially in the early years of industrial transition, in some cases deployed with CCS (Janssen 2020). However, as pointed out earlier, the total carbon and environmental impacts of using biomass for combustion must be taken into account.

5.3.3 Chemicals production

The chemical sector is the largest industrial contributor to greenhouse gas emissions, but it is very diverse, featuring many different products. According to EPA[7], the three largest greenhouse gas emitters in the chemical production sector are: petrochemicals (31.3%), hydrogen (23.8%), and ammonia (18.9%). As we decarbonize, petrochemical production will decline, and hydrogen production will shift to electrolysis using renewable electricity. In the case of many other chemicals, natural gas is used to fire an industrial boiler to produce steam at temperatures below 600°C—instead, this can be provided by electric resistance heating. Industrial decarbonization studies tend to focus on two energy consumers: ammonia and methanol, which use natural gas both for process heat and as a feedstock.

Ammonia has many uses, such as a zero-GWP refrigerant and as an energy carrier (Sections 2 and 4), but currently, 80% of it is used for fertilizers. Most ammonia is produced by the Haber-Bosch process, which breaks the nitrogen molecular bond and adds hydrogen, requiring considerable pressure and heat. Waste heat is captured in multiple steps. The hydrogen is typically produced from SMR. One near-term way to reduce carbon emissions would be to oversize the SMR process and produce additional blue hydrogen that can be used to provide the process heating. In the long run, however, green hydrogen should be used for ammonia production.

Methanol is used in many products such as solvents, adhesives, windshield washer fluid, and antifreeze. It is made from syngas, a combination hydrogen, carbon monoxide, and some carbon dioxide. Methanol production has grown in the United States as a result of methanol exports to China (Teller 2015). Methanol production and distillation occur at temperatures below 300°C, and it should be relatively easy to provide the heat input with electric resistance heating or hydrogen. The George Olah renewable methane plant in Iceland combines captured carbon dioxide with green hydrogen (produced via electrolysis using electricity from a geothermal power plan) in a proprietary process (Chemicals Technology n.d.). Methanol can also be produced from renewable natural gas and biomass.

For industry as a whole, CCS can contribute to carbon reductions associated with process emissions and, in the near term, for blue hydrogen production. But full decarbonization means that fuels will mainly be replaced by a combination of renewably produced electricity and green hydrogen, and early commitment to that path seems prudent. This is consistent with a net-zero emissions scenario in the Energy Policy Simulator[8] developed by Energy Innovation, which, based on a number of baseline policy assumptions, shows a nearly equal split between hydrogen and electricity as fuels in a decarbonized US industry sector by 2050 (Figure 5.13).

The manufacturing industry is very diverse, and we have only touched the surface regarding specific opportunities to reduce greenhouse gas emissions. Rissman and colleagues (2020b) cover industry from a global perspective, and (Friedmann, Fan, and Tang 2019) provide cost estimates for process heating using blue vs. green hydrogen, biomass, advanced nuclear, and electric resistance heating using grid electricity.

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[7] https://www.epa.gov/ghgreporting/ghgrp-chemicals

[8] https://us.energypolicy.solutions

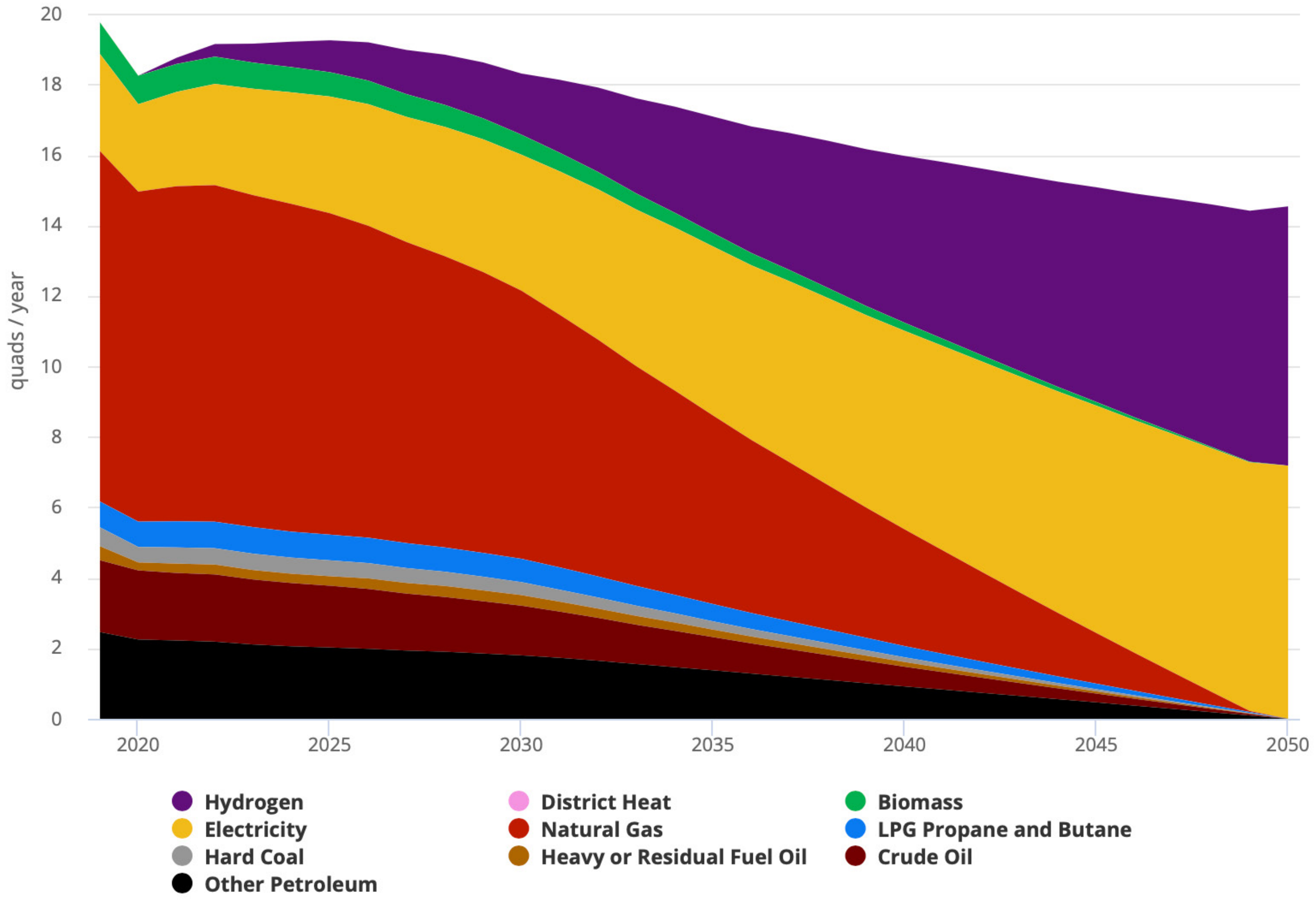


Figure 5.13. Projected 2018-2050 US industry fuel use for a net zero emissions scenario in Energy Innovation's Energy Policy Simulator. This result shows roughly a 50-50 split between electricity and hydrogen by mid-century. (Note that this only shows fuel used for energy and not chemical feedstocks.) (Rissman et al. 2020b)

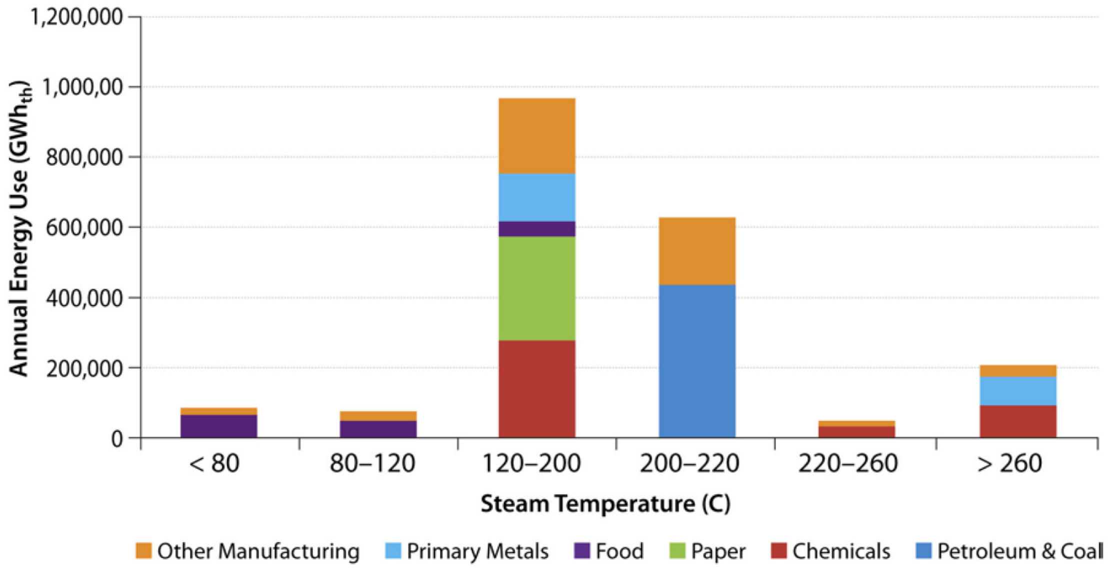


Figure 5.14. Annual energy use and temperature needs for different industrial uses of process steam. The majority of natural gas used in the United States to produce industrial process steam is at temperatures below 260°C. (Adapted from data published in (Fox, Sutter, and Tester 2011).

5.4 Lower-temperature process heat: an opportunity for solar thermal

The great majority of industrial process steam production occurs between 120° and 300°C (Figure 5.14). Heat pumps can provide process heat up to a temperature of about 150°C. Above that temperature, a heat pump can be augmented by electric resistance heating or hydrogen fuel can be used to replace natural gas. But solar thermal collectors are also an option in locations with good solar energy resources. The temperature range of 120-300°C is ideal for tracking, line-focus solar concentrators such as parabolic trough and linear Fresnel collectors. Over the last 40 years, the cost, performance, and reliability of line-focus collectors, especially parabolic troughs, have improved greatly as a result of efforts by the international concentrating solar power (CSP) industry and the US Department of Energy. While low-cost solar photovoltaics have become the dominant solar technology, they cannot compete with the efficiency of solar thermal collectors for heat production. Parabolic trough collectors can convert on the order of 60-70% of incoming solar energy to heat, compared to only 17-22% conversion to electricity for commercially available PV.

Concentrating solar collectors do require locations with clear skies and high direct normal irradiance (DNI). California's Central Valley has high DNI resources and also has significant industrial steam generation from natural gas, so it is an ideal place to start. Recall that California is one of the top three states for industrial energy use, and the state has aggressive decarbonization goals. While the ultimate contribution of solar thermal energy will likely be small compared to renewable electricity and green hydrogen, it could play an important niche role, especially in California.

5.5 Job creation

While we are not aware of any studies on the job potential for decarbonizing US industry, it is clear that the challenges presented should provide many openings for good-paying jobs. Electrification of industrial process heat will mean that existing kilns will need to be redesigned to replace fossil fuels with electricity. This will entail modeling and testing to provide the proper heat flux distribution and upgrading of electrical wiring and controls. Analysis of process energy flows may allow the use of heat pumps at higher temperatures if low-temperature waste heat can be utilized. The needs will likely vary greatly from one industry or product to another, creating many job opportunities. Replacing fossil fuel with hydrogen will similarly require modeling, testing, and implementation. There will probably also be some needs for CCUS. The wide variety of processes and the unique challenges each conversion presents mean that high-paying engineering specialists and skilled technicians will be needed.

POLICY OPTIONS FOR THE INDUSTRIAL SECTOR

Industrial equipment involves large capital investments with long lifetimes. Electrifying many processes will be challenging, and renewable hydrogen is currently expensive. Thus this sector can benefit the most from federal financial incentives. To decarbonize the US industrial sector, we recommend several policy options.

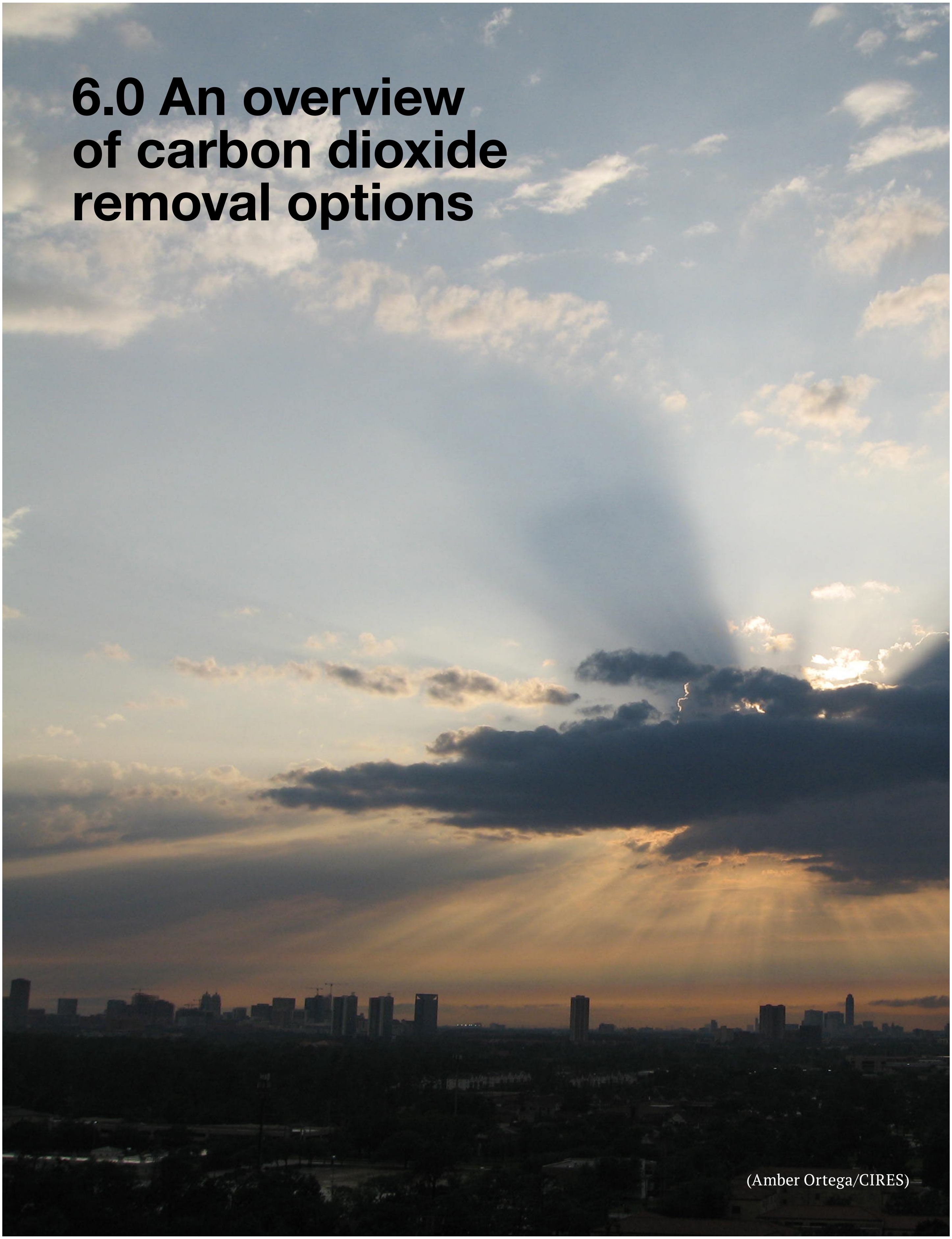
Technological and R&D actions

- Given the large role for process heat in industry, electrify as much of the heating requirement as possible, including the use of heat pumps for lower-temperature needs.
- Federal government efficiency standards for key components such as motors and compressors should be strengthened to aid in industrial decarbonization.
- A federal RD&D effort aimed at reducing the cost of renewable hydrogen production and hydrogen storage should be strengthened.
- A federal RD&D effort in collaboration with industry should identify oppor-

CONTINUED ON NEXT PAGE

Technological and R&D actions (continued)	tunities for the adoption of electrification and hydrogen fuel use in industrial processes and develop and test the equipment to convert from fuels to electricity and hydrogen, including the development of electric and hydrogen-fueled kilns and furnaces. • The US Department of Energy should partner with the European Union and other climate leaders to combine hydrogen roadmap efforts and share RD&D progress. • Evaluate the opportunity to replace natural gas used for industrial process steam with solar thermal collector fields, with perhaps first demonstrations carried out within California's Central Valley and/or within the state of Texas.
Government economic actions	• Industries should be motivated to consider the long-term costs of carbon emissions in their decision-making processes. Mandates and carbon pricing should incentivize the industrial transition to electricity and low-carbon fuel, as well as waste minimization, recycling, and energy-efficiency measures to reduce the energy need. • Maintain the capability of domestic industry to compete in the world market by working with international partners to agree on fair tax structures that support reduction of embedded carbon in internationally traded industrial products.

6.0 An overview of carbon dioxide removal options



(Amber Ortega/CIRES)

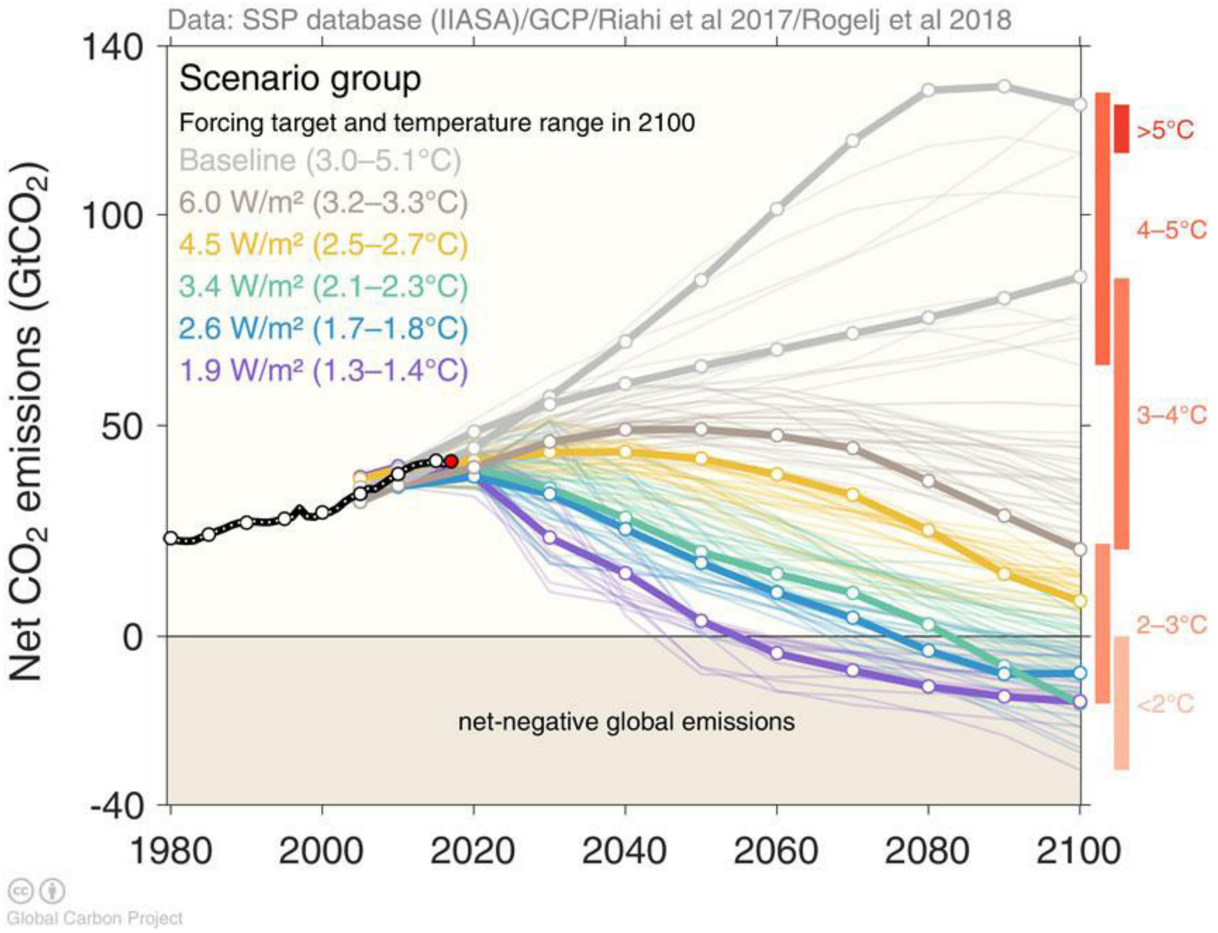


Figure 6.1. Annual net carbon dioxide emissions (in $GtCO_2$/yr) pathways from 1980 to 2100 for different scenarios. Of the various pathways, those that result in a temperature rise of less than 2°C indicate that net negative emissions must be achieved by some time after mid-century. (Carbon Brief 2018 with data from SSP database (IIASA)/GCP/Riahi et al. 2017/ Rogelj et a. 2018. Courtesy Glen Peters.)

In this report we have presented the technology approaches to drive fossil fuel emissions to zero in the key economic sectors. Fossil fuel emissions are the major cause of carbon dioxide emissions today as well as the past, responsible for the roughly 45% increase in atmospheric carbon dioxide that has already occurred. In this section we provide an overview of technologies being explored to address these historic emissions.

To limit global average temperature rise to 1.5°C to 2°C compared to pre-industrial levels will likely require both 1) driving emissions to zero, and 2) drawing down atmospheric carbon dioxide using carbon dioxide removal (CDR) methods, also called negative emissions technologies. Figure 6.1 shows the pathways of annual net carbon dioxide emissions (emissions minus amount removed from the atmosphere) required to achieve various temperature targets; note that net emissions must go negative to achieve the 2°C target by the end of this century. How much carbon must be removed from the atmosphere will depend on how rapidly we drive emissions to zero. Because solar and wind electricity are now so low in cost, deploying them to eliminate additional emissions is the most cost-effective way to minimize atmospheric carbon dioxide. So while we can begin to deploy means to remove atmospheric carbon dioxide, this should not be done in any way that compromises emissions reduction. That is, the first priority is to use renewable electricity to eliminate emissions, not to power those atmospheric carbon dioxide removal methods that are energy-intensive.

The most widely studied approaches for removing atmospheric carbon dioxide (Figure 6.2) can be characterized broadly as biological and non-biological:

Biological:

- Reforestation and afforestation.

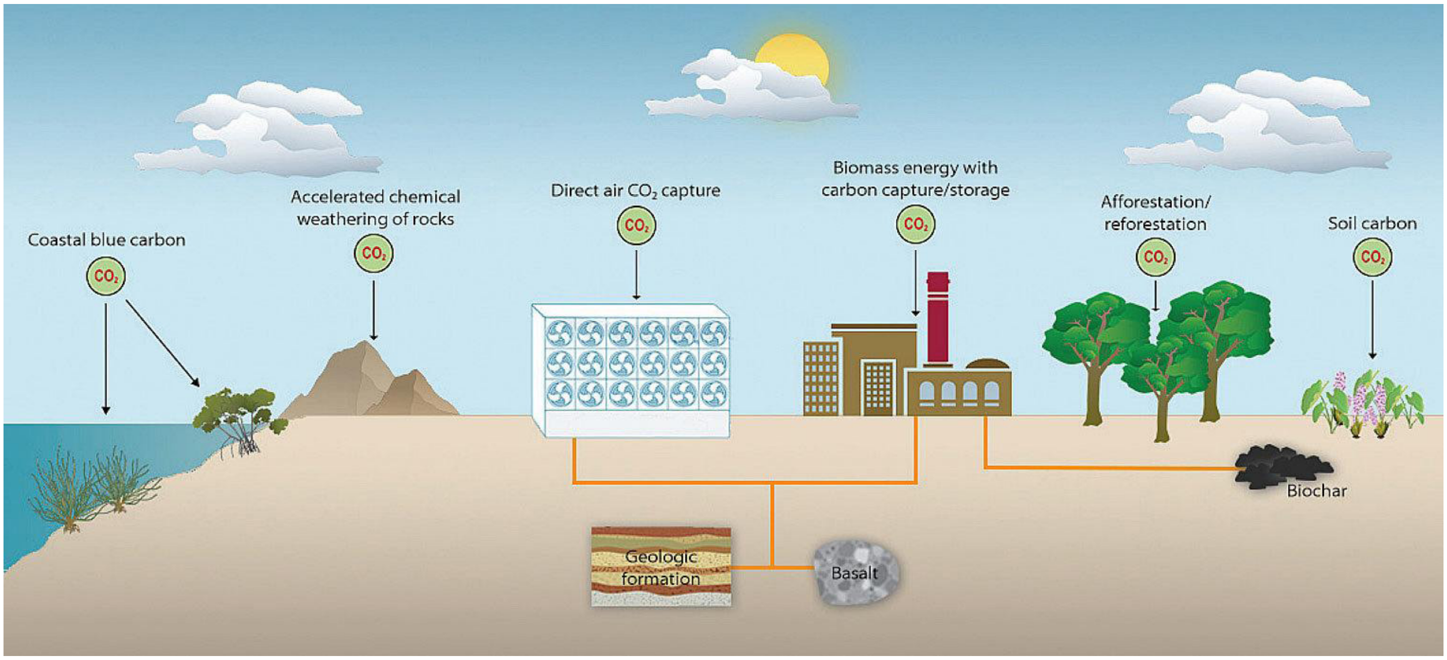


Figure 6.2. Negative emissions technologies. Multiple approaches for atmospheric carbon dioxide removal are being studied. (National Academies of Sciences, Engineering, and Medicine. 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. https://doi.org/10.17226/25259. Reproduced with permission from the National Academy of Sciences, Courtesy of the National Academies Press, Washington, D.C.)

- Enhancing soil carbon retention via regenerative agriculture.
- Bioenergy with carbon capture and storage (BECCS).
- Biochar.

Non-biological:

- Enhanced rock weathering.
- Direct air capture.

For both BECCS and direct air capture, the intention is to store the captured carbon dioxide in deep geologic sites. However, some of the captured carbon dioxide could also be used in the production of other products as described by (Hepburn et al. 2019), although it is important that even that amount of carbon dioxide is sequestered from the atmosphere.

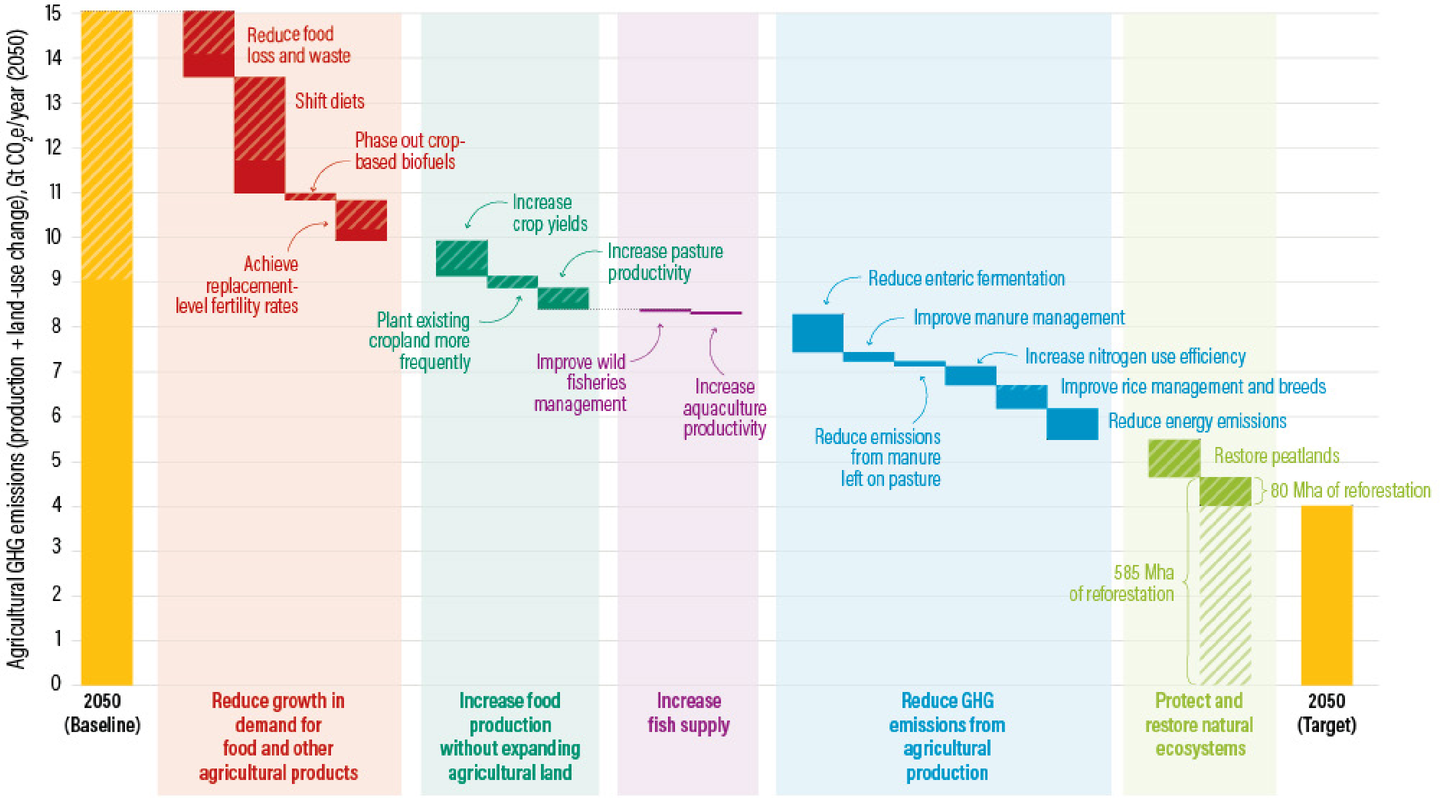
6.1 Biological methods

6.1.1 Reforestation and afforestation

Reforestation refers to replanting areas that have been deforested; afforestation is planting new forests. It is estimated that between 1990 and 2017, the Earth's land surface sequestered about 30% of anthropogenic carbon dioxide emissions; tropical forests account for about half of the carbon stored in vegetation (Hubau et al. 2020). But forests are in decline, especially in the Amazon Basin. Continuing efforts are needed to halt deforestation and to increase forested land.

In 2019, Jean-Francois Bastin and colleagues created quite a stir with a paper that argued aggressive planting of a trillion trees could sequester 200 billion tons of carbon, or 200 GtC (equivalent to 733 Gt carbon dioxide), from the atmosphere and address two-thirds of human emissions (Bastin et al. 2019). Numerous scientists took issue with this claim. First, as climate scientist Stephan Rahmstorf pointed out (Rahmstorf 2019), the 200 GtC is only about one-third of the total amount mankind has added to the atmosphere, not two-thirds.

Also, because of interchange with ocean and forests, 200 Gt of negative carbon emissions would actually remove only about 120 Gt from the atmosphere, which would occur over a 50-100 year period as trees are planted and grow. Joseph Veldman and colleagues wrote a rebuttal to Bastin, et al. arguing that the 200-billion-ton figure was too high by a factor of five, due in part to not accounting for soil organic carbon in treeless areas (Veldman et al. et al. 2019). While this would still be a significant amount, large-scale tree planting competes with other land uses and does



Note: Solid areas represent agricultural production emissions. Hatched areas represent emissions from land-use change.
Source: GlobAgri-WRR model.

Figure 6.3. Potential steps to reduce agricultural greenhouse gas emissions and promote carbon sequestration. This shows the results of one study that identified five wide-ranging agricultural solutions. (Ranganathan et al. 2020)

not guarantee permanence due to potential fires and governments that promote deforestation.

Eliminating deforestation and encouraging more forest growth remain important in the drawdown of atmospheric carbon dioxide, but it is important to understand that forestation is not enough. Given that scientific controversy remains, more study is needed regarding the true potential and the best way to accomplish it.

6.1.2 Improved agricultural practices

Improving our use of soil generally refers to carbon-smart farming practices. In particular, regenerative agriculture consists of a number of practices that can potentially sequester more carbon in the soil. These are:

- No- or low-tillage methods, which help keep carbon in the ground.
- Biodiversity of crops, which helps maintain healthy microbe communities.
- Crop rotation and cover crops, to avoid erosion associated with bare soil.
- Minimal use of chemicals to avoid disturbing microorganisms.

In addition to these, research is underway to transition from annual crops to perennial crops, which avoid soil disturbance and grow deep root systems. In particular, intermediate wheatgrass is being bred as a wheat replacement. Unlike wheat, it is a perennial plant and does not have to be reseeded every year. It is being test marketed by General Mills under the registered trademark Kernza® (bakeryandsnacks.com 2019). Although it grows roots that are 10 feet deep—twice as deep as conventional wheat—it produces smaller seeds and is still in development.

As with forestation, measurements of the carbon sequestration role of regenerative agriculture vary considerably and are subject to scientific debate. Although it is generally agreed that regenerative agriculture is good for the soil, the longevity of carbon

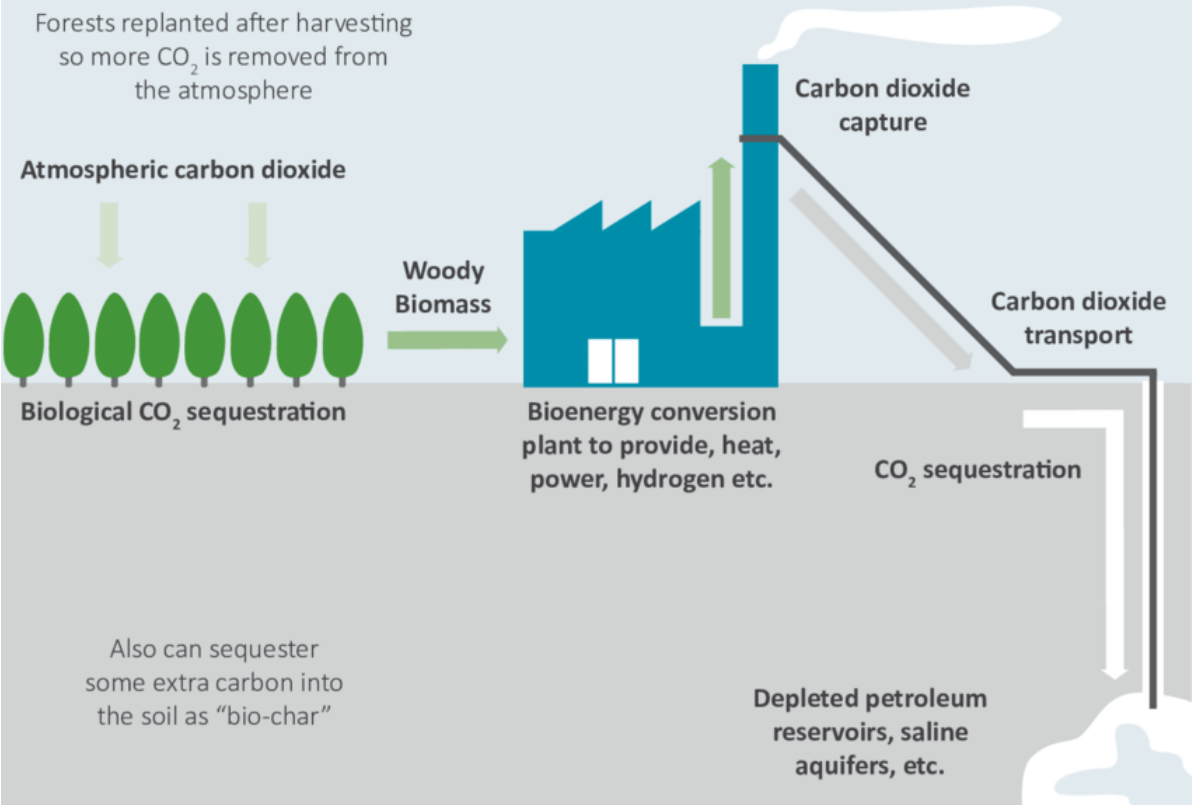


Figure 6.4. The BECCS (Bio-Energy with Carbon Capture and Storage) process. This process is net-negative because it geologically sequesters carbon dioxide that the biomass removed from the atmosphere during its growth. (McGill 2019)

storage is uncertain. The authors of a World Resources Institute article (Ranganathan et al. 2020) point out that even most farmers who use no-till practices plow up their soil every few years, thus releasing sequestered carbon. They also argue that applying manure in one place means it is taken from somewhere else, raising the issue of additionality and overall accounting that must be addressed carefully for biologically based climate change measures. The authors recommend five steps (Figure 6.3) to reduce agriculture emissions and sequester more carbon in the soil.

6.1.3 Bioenergy with carbon capture and storage

To address carbon emissions, the federal government spent considerable research funds developing carbon capture and storage (CCS) technology for use with coal-fired power plants. The concept of bioenergy with CCS (BECCS) is an effort to achieve carbon negativity. The process (Figure 6.4) transports carbon dioxide from the atmosphere to geologic storage locations: Growing plants capture carbon dioxide from the atmosphere, and are then used in bioenergy production. Carbon dioxide is captured during the bioenergy production or consumption process, and geologically sequestered. The Illinois Industrial CCS facility, a corn ethanol operation owned by Archer Daniels Midland, is currently the only large-scale BECCS facility that stores captured carbon dioxide in a deep geologic site (Consoli 2019).

The IPCC sees BECCS as an important potential contributor to limiting future temperature rise, reporting, "The distribution of the mitigation effort across sectors is strongly influenced by the availability and performance of BECCS and large-scale afforestation" (Stocker et al. 2013). In a special report on keeping temperature rise below 1.5°C, IPCC looked at four energy-use scenarios. In scenario 4, the most energy-intensive one, the authors considered one carbon dioxide removal method, BECCS, and it was seen as crucial: "Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS." (IPCC 2018).

Daniel Sanchez and colleagues determined BECCS is a promising means to provide carbon-negative power across western North America, concluding "… BECCS, combined with aggressive renewable deployment and fossil fuel emission reductions, can enable a carbon negative power system in western North

America by 2050 with up to 145% emissions reduction from 1990 levels" (Sanchez et al. 2015).

Like other biological means for carbon emissions reductions, BECCS seems to have as many detractors as proponents, and studies produce varied results. Among the concerns about BECCS are questions about how long it takes to make up for the carbon that biomass was sequestering before it was harvested. Also, BECCS requires a lot of land and water, may impact food prices, and can reduce biodiversity by emphasizing energy crops. (Harper et al. 2018) state, "The effectiveness of BECCS strongly depends on several assumptions related to the choice of biomass, the fate of initial above ground biomass, and the fossil fuel emissions offset in the energy system. Depending on these factors, carbon removed from the atmosphere through BECCS could easily be offset by losses due to land use change. If BECCS involves replacing high-carbon content ecosystems with crops, then forest-based mitigation could be more efficient for atmospheric carbon dioxide removal than BECCS."

The success of BECCS also depends on achieving reliable long-term underground storage of captured carbon dioxide without leakage.

6.1.4 Biochar

Biochar is the charcoal-like material that results from subjecting biomass (preferably waste materials) to temperatures of 350-600°C in oxygen-deprived conditions. In the hours-long process of "slow pyrolysis," the biomass feedstock is converted to a combination of ~25-35% biochar and the rest biofuel. The exact composition of biochar depends on the feedstock and how it is heated, but typically, about 70% of the biochar mass is carbon. While the biofuel can be used to displace carbon-emitting fossil fuels, the biochar can be added to soil, at least temporarily sequestering carbon that was removed from the atmosphere by plant growth (there is debate about how long the carbon is sequestered). When added to soil, biochar can also enhance soil properties making the soil more productive. It can improve soil water retention and reduce soil acidity (Chen et al. 2019). It works best in poor or environmentally contaminated soils; one recent study showed no benefit to plant growth in better quality soils (Meschewski et al. 2019).

There are potential drawbacks to biochar. For example, harvesting crop residues to produce biochar can result in a decrease in the soil quality where it was harvested. It can also reduce seed germination. As with any use of biomass, transportation costs of feedstocks are an issue. Perhaps the most challenging aspect of biochar is that its impacts vary greatly with soil quality. Because of its promise as a means of carbon sequestration, more large-scale field testing is needed in different soil types to better understand its overall effects. Work is also needed to identify and evaluate the market potential for biochar, including various non-agricultural markets.

6.2 Non-biological methods

6.2.1 Enhanced weathering

Rock weathering naturally reduces atmospheric carbon dioxide on very long time scales. Today, natural rock weathering absorbs about 0.3% of global fossil fuel emissions (Beerling and Long 2018). The concept of enhanced weathering involves spreading pulverized silicate rock on the land or ocean to greatly accelerate the natural weathering process. There is special interest in using the crushed rock as a fertilizer on agricultural land. The rock reacts with atmospheric carbon dioxide to form bicarbonate, which lowers the pH of the soil. Crop yields can be improved, but mining, crushing, and transporting the rock take significant amounts of energy, and acidic runoff from the rock can have negative environmental consequences.

Applying this approach in China, India, the United States, and Brazil could help achieve average global CDR goals of 0.5 to 2 gigatonnes of carbon dioxide per year at costs (extraction only) of approximately $80 to $180 per tonne of carbon dioxide (Beerling et al. 2020). And combining this inorganic method with organic soil sequestration techniques, like biochar, could have synergistic effects (Lehmann and Possinger 2020). Lehmann and Possinger point out, however, that such techniques involve dealing with vast areas of land and millions of farmers. So it is important to establish that these measures are equitable and economically advantageous to farmers.

6.2.2 Direct air capture with carbon storage

An alternative carbon dioxide removal method receiving increasing attention is the direct air capture with carbon storage (DACCS). The concept is to pass air through mass exchange devices that pull carbon dioxide out of the air, which can then be geologically sequestered. The challenge with this approach is that despite having a strong greenhouse impact, carbon dioxide is a trace gas in the atmosphere, comprising only about .04% of the air. That means that large quantities of air must be moved through capture equipment to extract significant amounts of carbon dioxide. Moving that much air requires significant fan power. In addition, approximately 80% of the total energy needed is thermal energy used to release or "regenerate" the captured carbon dioxide.

The regeneration temperature needed is a function of the type of material used to capture the carbon dioxide. It is as high as 900°C for liquid solvents. Solid sorbents can be regenerated at about 100°C, allowing for the use of a wide range of low-temperature heat sources. (McQueen et al. 2020) evaluated the use of waste heat from geothermal and nuclear power plants for use with solid sorbent technology. Waste heat from concentrating solar power plants could also be used, as well as low-temperature geothermal resources that are not suitable for power production. Dedicated use of solar thermal energy is yet another possibility. None of these heat sources would compete with renewable electricity used to displace fossil fuels, which must be the first priority for carbon-free electricity. Fan power could potentially be provided by renewable electricity that would otherwise be curtailed (either by storing it in batteries or only operating when it is available), although this increases life-cycle cost, and there will likely be many uses competing for surplus renewable electricity.

Besides the thermal and fan energy required for DACCS, capital equipment costs are also high. Mass transfer is proportional to the product of the concentration gradient and the surface area. A small concentration gradient means a lot of surface area is needed, which entails high materials and capital equipment costs. There are some relatively small additional costs associated with compressing and geologically sequestering the captured carbon dioxide, but DACCS has the advantage that it can be located at geologic sequestration sites, especially if these coincide with low-cost heat sources.

(Breyer, Fasihi, and Aghahosseini 2020) modeled the cost and hourly performance of a solid sorbent-based, direct air capture system (without storage) in the Maghreb region of North Africa, powered by renewable electricity, mostly photovoltaics. In that region of good solar radiation and projecting declining costs for renewable energy and batteries, they conclude that costs would drop by about half in the next 30 years, from 105€/tCO_2 (\$117/tCO_2) in 2030 to 55€/tCO_2 (\$61/tCO_2) in 2050. The cost of geologic sequestration must be added to that, perhaps on the order of an additional \$10 per tCO_2.

According to the International Energy Agency[1], there are currently 15 direct air capture plants operating throughout the world, and a plant that would capture 1 megaton of carbon dioxide per year is under development in the United States. As pointed out by June Sekera and Andreas Lichtenberger, "Direct air capture can likely reduce the stock of atmospheric carbon dioxide if powered by non-carbon fuel sources and if the captured carbon dioxide is simply sequestered rather than being reused" (Sekera and Andreas Lichtenberger 2020). Existing plants use the captured carbon dioxide in various ways, and there is currently no market incentive to geologically store captured carbon dioxide.

6.3 Summary of potentials and costs

(Fuss et al. 2018) reviewed the literature for negative emissions technologies and developed estimated ranges for global carbon sequestration potential and costs, and these are shown in Table 6.1. As indicated in Figure 6.1, net negative emissions must reach 5 to 15 $GtCO_2$ per year depending on the pathway.

Table 6.1 Potentials and costs for different negative emissions (carbon dioxide removal) technologies.

NET	Potentials ($GtCO_2$/yr.)	Cost (US\$/tCO_2)
Reforestation/ Afforestation	0.5 – 3.6	5-50
Soil Capture	2-5	0-100
BECCS	0.5-5	100-200
Biochar	0.5-2	30-120
Enhanced Weathering	2-4	50-200
DACCS	0.5-5	100-300

(Sabine Fuss et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environ. Res. Lett. . DOI: 10.1088/1748-9326/aabf9f)

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[1] https://www.iea.org/reports/direct-air-capture

Note, too, that these technologies could compete for the same land and so are not necessarily additive. In comparing the different options, it should be noted that both BECCS and DACCS involve deep geologic sequestration of carbon dioxide, offering a degree of permanence that the biological approaches do not.

POLICY OPTIONS FOR CARBON DIOXIDE REMOVAL

Although our immediate emphasis must be on transitioning from fossil fuels to carbon-free energy sources, we should also pursue opportunities to remove the carbon dioxide that has already been added to the atmosphere. It is likely that this will involve a combination of different approaches.

General policy options

- CDR methods should be deployed as soon as they are deemed environmentally safe and do not compromise the speed at which we replace fossil fuels. If sectors that are harder to decarbonize such as industry and large transportation lag, early implementation of CDR can potentially allow us to achieve net negative emissions sooner.
- Establish a modified tax credit for CDR that incentivizes long-term technology innovation and avoids carbon dioxide leakage in other sectors of the economy (such as occurs with the Enhanced Oil Recovery tax credit).

Biological methods

- Afforestation and reforestation are among the lowest-cost approaches to achieve negative emissions, but the first thing that must be done is to reduce deforestation. Using substitutes for palm oil in food and other products will remove a financial incentive for deforestation and oil palm planting in Indonesia and other parts of the world. In some places, such as Brazil, the international community may need to pay governments to keep existing forests intact.
- Study and quantify the potential impact of tree planting. Given the optimistic claims made, studies are needed to determine what the realistic potentials are, the best locations, and the societal impacts.
- Further investigate the best techniques for regenerative agriculture. Research and development efforts should also be aimed at improving the productivity of perennial crop alternatives.
- Fund research to better understand all biological techniques’ land impacts, net carbon removal potential, and the permanence of the removal.
- Evaluate BECCS from a total system standpoint that accounts for the carbon sequestration and productivity that would have occurred for the disturbed land as well as impacts on land owners, ecosystems, and food production. Efforts should be aimed at providing a map of locations with the greatest net improvement from applying BECCS.
- Conduct biological and economic research on the impacts of biochar, which depend on the feedstock and the particular soil to which it is supplied. Field test different combinations of feedstocks and soils to evaluate the varying impacts, the length of time that carbon will be sequestered in the soil, and consequences for the land from which feedstock residues are taken. Determine the most promising markets for biochar.
- For soil capture, BECCS, and biochar, which have potential for increasing crop yields, evaluate if these would provide sufficient economic benefit to farmers or if government financial incentives are needed.

POLICY OPTIONS CONTINUED ON NEXT PAGE

Non-biological methods	• Evaluate the impact of enhanced weathering on the rate of carbon sequestration and soil productivity. Environmental assessment studies are needed to determine the long-term consequences on the land to which it is applied and any collateral impacts, e.g., from runoff. • Focus DACCS research on lowering material and capital costs, reducing energy requirements, and utilizing carbon-free sources of heat. DACCS should not be deployed in ways that compete with the use of carbon-free energy to displace fossil fuels. Pilot plants should be built to gain experience and improve market readiness. Carbon pricing and other market incentives should be considered to support this.

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