Reflections from the Boardroom

America's energy sector is a key driver of job creation, growth, and competitiveness throughout the economy. Delivering secure, diverse, affordable, and reliable energy to U.S. businesses and consumers is essential to maintaining economic growth while improving standards of living. At the same time, it is imperative that we accomplish these objectives while reducing our impact on the environment and addressing the climate challenge. There are thus many competing forces and factors in tension with each other within the U.S. and global energy systems.

The U.S. today is in an enviable position with respect to our energy future. However, we acknowledge the risks associated with climate change and how these risks and the policies adopted to address them could threaten this future. Meeting the dual challenges of maintaining economic growth by providing diverse, affordable and reliable supplies of energy while addressing climate change will require the development and deployment of new technologies and a supportive policy environment to eliminate barriers to their use. We are optimistic that technology and sensible, supportive government policies offer us a path to manage successfully the challenges we face.

The energy sector is undergoing dramatic shifts in terms of how energy is produced and used. Unprecedented U.S. oil and gas production has structurally altered both our domestic energy landscape and the globe's. Increasing attention to how and where energy is sourced has pushed corporate purchasing of renewable power to an all-time high, and advances in storage technology have many optimistic about the technology's potential to fundamentally change the way energy is used.

As the nation's business leaders, the members of the Business Roundtable understand the opportunities and challenges presented by the changing energy landscape. It is important that public policy enable companies and individuals to harness these new opportunities with strong infrastructure and a stable regulatory regime. To address our challenges, we need public policy that brings together the public and private sectors to collaborate in innovation through research and development, to utilize digital tools while protecting personal privacy, and to enhance our environmental performance toward a truly competitive and environmentally sustainable economy.

EXECUTIVE SUMMARY

America's energy sector is a key driver of job creation, growth, and competitiveness throughout the economy. Delivering secure, diverse, affordable, and reliable energy to U.S. businesses and consumers is essential to maintaining economic growth while improving standards of living. At the same time, it is imperative that we accomplish these objectives while reducing our impact on the environment and addressing the climate challenge.

This report reviews America's 21st century energy needs and opportunities, highlights major trends in the energy sector, discusses the implications of those trends, and assesses the promise of and challenges to particular technological breakthroughs. It examines the United States' current energy landscape and how much has changed from the recent past. It explores some of the major trends that have taken the U.S. energy system from one reliant on seemingly sparse domestic resources and volatile markets to a global energy supplier, with significant diversification, and a downward trend in emissions. This report also recognizes the dual challenge of meeting growth in global energy demand while simultaneously reducing global emissions and environmental impact.

<u>Oil and Gas Production</u>

Early in the 21st century, there were concerns about America's ever increasing-reliance on imported oil and natural gas, but that has now fundamentally changed. While the United States is still very much part of global energy markets, the "shale revolution" has fundamentally altered and enhanced the country's energy security situation and changed the U.S. into a fossil fuel production powerhouse. In fact, in 2018, the United States likely passed Russia and Saudi Arabia to become the largest crude oil producer in the world,[1] and it has been the world's top producer of natural gas since 2009.[2]

The abundance of natural gas offers an opportunity for the United States not only to strengthen its energy independence and security, but also to provide the economy with an affordable energy source and feedstock. Natural gas is expected to continue growing as a share of U.S. power generation, due to its low cost and its ability to reduce greenhouse gas emissions as power generators switch from coal to gas. Moreover, the shale revolution has had important geopolitical and economic ramifications. Growing shale oil production, for instance, has made the United States more resilient to changes in global oil supplies and prices. Likewise, this growing abundance has led to increases in LNG and oil exports from the United States to markets around the world. In 2017, for the first time since 1957, the United States exported more natural gas than it imported.[3]

<u>Renewable Energy</u>

While shale production has been one of the leading stories of 21st century American energy, another has been the boom in renewables deployment. Costs for solar and wind power have plummeted, while the technologies themselves have improved. Renewables (primarily wind and solar) have accounted for the majority of U.S. electric generating capacity added each year since 2013 (though in 2018, renewables may get edged out by natural gas additions).[4] Over the past decade, installed U.S. wind capacity has tripled and solar capacity has increased six-fold.[5]

Government policies and improved economics have been vital drivers for both renewables and energy storage. Given climate concerns and the significant reductions in cost, renewables are projected to continue to grow in penetration, accounting for 20% of net U.S. electricity generation by 2020.[6] Very high penetrations of renewables, however, also bring challenges and costs related to the variability of generation, the need for storage, and other issues. For instance, due to the variability of wind and solar energy, power systems with high shares of these resources have much greater overall installed capacity than more diversified power systems and must maintain significant dispatchable capacity to ensure demand can be met at all times. Greater required installed capacity and the lower energy-density of wind and solar resources also significantly increases the land use consequences of power systems dominated by variable renewable resources. Meanwhile, many electric utilities are facing significant pressure, both from changing technologies and from rapidly evolving consumer (and investor) preferences. As evidenced by the boom in corporate renewables procurement, customers are pushing for more choice, more control, and cleaner sources for their electricity, increasingly demanding their own bespoke mix of electricity via local energy resources.

Energy Efficiency

Energy efficiency has continued to improve, leading to generally flat or declining energy demand across most sectors in the United States.[7] With continued improvements in the energy efficiency of lighting, appliances, vehicles, industrial processes, and more, limited energy demand growth is expected going forward. Total electricity use in the United States is expected to rise only marginally over the next few decades.[8] Yet, according to DOE's Building Technologies Office, there is significantly more that can be done in the U.S. specifically with residential and commercial buildings efficiency, which represents a large portion of U.S. energy consumption.[9] Globally, however, energy demand has been booming, and that growth is expected to continue, though global energy efficiency improvements mean the energy demand growth will not be as large as it might otherwise have been.[10]

Transportation

Energy efficiency has been improving in the U.S. transport sector as well. Domestic oil consumption is projected to generally decrease through the mid-2030s due to improved vehicle fuel efficiency. Motor gasoline consumption is projected to decrease by more than 30% between 2017 and 2050, and because of improved fuel economy, heavy-duty diesel vehicles are projected to use about the same total amount of fuel in 2050 as in 2017, despite increased freight truck travel.[11]

Recently, a significant amount of attention has been focused on electrification of transport, specifically for passenger cars. Sales of battery-electric vehicles (and plug-in hybrids) have been growing, but even so, they only represent about 1% of vehicle sales – and a far smaller percentage of the overall fleet. Looking ahead, some project U.S. sales of battery EVs to increase from less than 1% in 2017 to 12% in 2050 (with plug-in hybrids growing from 1% to 2%), driven by declining battery costs and state policies.[12] Municipal bus fleets are also starting to transition to alternative fuels, such as natural gas and electricity, though less than 0.5% of the U.S. public bus fleet is electric.[13] While the most ambitious forecasts suggest that all bus purchases will be electric by 2030, other forecasts put the figure somewhere between 27% and 60%. Either way, the trends suggest rapid growth in this area.[14] Furthermore, hydrogen fuel cells are another option for electrifying transport and are being pursued by some auto manufacturers, though they thus far have not received the same level of attention, or deployment as battery-electric vehicles. While gasoline vehicles are still expected to remain dominant through at least mid-century,[15] electric vehicles, whether powered by a battery or a hydrogen fuel cell, could have significant implications for U.S. oil consumption and emissions from the transport sector. In heavy-duty vehicles and freight rail, a greater role for natural gas is expected.[16]

<u>Energy Storage</u>

Cost-effective storage technologies are key to allowing greater intermittent renewable generating resources to be added to the grid. Similar to renewables, precipitous declines in price and improvements in technology have likewise led to a rise in deployment of energy storage. The price for lithium-ion batteries dropped 73% between 2010 and 2017, from $1000/kWh to about $270, and could drop to about $73/kWh by 2030.[17] As of mid-2018, energy storage deployment had grown by 60% over mid-2017 in terms of megawatts and by 200% in terms of megawatt-hours (MWh), with much of that growth occurring behind the meter. U.S. energy storage annual deployments are expected to accelerate markedly over the next few years, growing from almost 400 MW in 2018 to over 2 GW by 2020 and nearly 4 GW by 2023.[18] Globally, some project that the energy storage market will grow to a cumulative 942 GW by 2040, driven by sharply falling battery prices, government policies, and growing adoption of electric vehicles and solar power.[19]

Improvements in battery (and other storage) technologies could have huge implications for the future energy mix. Continued improvements in battery technologies and costs could make variable renewable generation into a dispatchable resource, provide a range of services to the grid, and accelerate the electrification of transport (bringing a new source of both electricity load and potential distributed storage options onto the grid). New battery chemistries are also being explored, including ones that do not rely on critical minerals such as lithium and cobalt, though the challenge is always producing these new configurations on a commercial scale.

<u>Distributed Energy Resources (DERs) and Decentralization</u>

Storage and renewables are also part of the vanguard of DER technologies that are decentralizing energy supply. As of 2017, distributed solar, distributed energy storage, small-scale combined heat & power (CHP), residential smart thermostats, and electric vehicles provided more than 46 GW of flexible capacity for the U.S. grid – a figure expected to double to 104 GW by 2023.[20]

The U.S. electricity grid is shifting from one based on centralized generation to one that incorporates both centralized and decentralized DER technologies. Continued proliferation on the grid of assets such as distributed solar, storage, small wind, natural gas-fired fuel cells, and demand management is forcing some in the utility sector to grapple with and explore fundamental changes in how the grid works, as more and more activity is occurring behind the meter.[21] For instance, efforts at demand response and load-shifting can move energy use to periods of maximum energy production. This is a paradigm shift from the current model; rather than supply chasing load, this model involves load moving to match supply.[22] The challenges and flexible capacity that DERs provide to the grid are expected to continue growing rapidly over the next few years.[23]

Digitalization

Many of the advances in American energy in the 21st century have come about not only because of improvements in energy technologies but also because of improvements in information and communications technologies. Together, these technological breakthroughs are enabling a new era of energy digitalization, dominated by crosscutting digital tools and platforms — including artificial intelligence, blockchain, the internet of things (IoT), and big data analytics — that can be applied to the energy system in myriad ways.[24] Advances in computing and machine learning have enabled automation and advanced functionality to be embedded within energy delivery systems and distribution networks, and increasingly affordable and sophisticated sensing, communications, and controls technologies have made demand response more powerful, increased the deployment of "smart" devices (e.g., thermostats) and smart meters in homes and buildings, and helped accelerate the evolution of a multi-directional, more distributed, more dynamic smart grid.[25] In the oil, gas, and mining sectors, technologies such as sensors, artificial intelligence, machine learning, and drones are helping companies better understand subsurface conditions and improve operations and maintenance.

Digitalization and advanced data analytics are also playing (and are expected to continue to play) a meaningful role in grid operations and consumer energy choice. The vast volume of data generated by smart meters, smart IoT devices, grid sensors, and other technologies will only grow as the grid modernizes. This has increased the role and potential value of big data analytic software and services to help the grid run smoothly and to help customers optimize their energy use.

Infrastructure

American energy infrastructure is struggling to keep up. Booming oil and natural gas production, for instance, has been constrained by inadequate take-away capacity (e.g., pipelines).[26] The U.S. manufacturing renaissance spurred by abundant and affordable natural gas will need better infrastructure to move more natural gas to facilities. Improved access to world energy markets through new export infrastructure remains essential. At the same time, increased deployments of distributed energy resources (DERs) and weather-dependent renewables are creating stress on an aging grid that was largely constructed in the 1950s and 1960s and was designed for one-way power flows from large, centralized generation stations.[27]

Increased renewables, DERs, and digitalization capabilities are shifting the grid from a centralized, one-way system to a more distributed, multi-directional system, with significant implications for utility business models and for how the grid should be maintained and upgraded. Many utilities are deploying a range of advanced sensors as an underlying component of smarter grids, as they can provide real-time insights into grid conditions, improve reliability, enhance responsiveness to disruptions and outages, and support further integration of distributed energy.[28] A responsive, decentralized energy system that processes and analyzes huge amounts of data also requires robust broadband infrastructure, particularly in underserved rural areas of the country. Moreover, increased demand for renewables could also spur the need for new transmission lines and significant transmission updates to bring power from where it is most efficiently generated to where it is needed to meet demand.

Climate Change

The need to significantly reduce greenhouse gas emissions over the coming decades will continue to be a major driver of change beyond market and technology driven efficiency. Increasingly affordable renewables will continue to rise in deployment to achieve emission reductions, though there may well be cost and feasibility constraints that eventually limit the scope of deployment. Increasingly affordable and abundant natural gas has likewise helped spur emission reductions (due to fuel-switching from coal) and can continue to do so for some time, particularly if methane emissions from the production and distribution system can be addressed. In the long term, carbon capture, utilization, and storage (CCUS) technologies will be essential to ensuring a continued role for fossil fuels in a carbon-constrained world.

Meeting the dual challenges of maintaining economic growth by providing diverse, affordable, and reliable supplies of energy while addressing climate change will require the development and deployment of new technologies and a supportive policy environment to eliminate barriers to their use. Increased research and development is needed on CCUS and other emission-reducing innovations, including technological breakthroughs to reduce emissions outside the power sector (e.g., in the transportation, industrial, and buildings sectors). New technologies and business practices will also be needed to address the range of ways energy use and production are changing and to reduce emissions at the lowest cost to society.

Breakthrough Technologies

Some technologies that could fundamentally change the U.S. (and global) energy landscape are currently at a nascent stage and their promise lies over the horizon. Forecasting how various technologies will develop and deploy and what impacts those technologies will have involves some measure of speculation, and all such projections should be made with humility. Some of these technologies may not fulfill the promise they appear to hold, while others may exceed it. New technologies could – and almost certainly will – enter the picture. This report takes a deeper look at the promise and potential realities of technologies particularly worthy of continued attention including advance nuclear, CCUS, hydrogen, advanced digitalization, and substitute materials.

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AMERICAN ENERGY IN THE 21ST-CENTURY

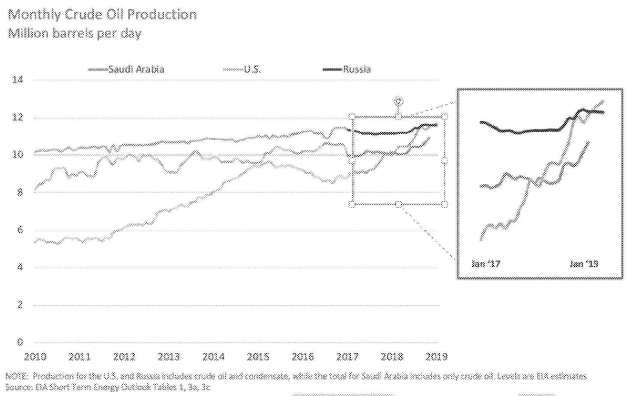
INTRODUCTION AND KEY TRENDS

The energy sector is undergoing a number of significant transformations. For example, an unprecedented surge in U.S. oil and gas production has structurally altered both the domestic and global energy landscape. Increased interest in how and where energy is sourced has driven corporate purchases of renewable power to all-time highs, and advances in storage technology have the potential to fundamentally change the way energy is used in the future. As illustrated in the table below, these trends cut across all sectors of the energy sector and affect every corner of the U.S. economy.

Key Trends	
Oil & Gas Production	In 2018, the United States likely passed Russia and Saudi Arabia to become the largest crude oil producer in the world, and it has been the world's top producer of natural gas since 2009.
New Generating Capacity	Renewables and Natural Gas have accounted for the majority of new U.S. electric generating capacity.
Energy Demand	Energy efficiency has continued to improve, leading to generally flat or declining energy demand across most sectors in the United States. Globally, energy demand has steadily grown – driven by demand in non-OECD countries
Energy Storage	Driven by sharply falling battery prices, government policies, and growing adoption of electric vehicles (EVs) and solar power, U.S. energy storage deployments are expected to accelerate markedly over the next few years.
DERs & Decentralization	The U.S. electricity grid is shifting from one based on centralized generation to one that incorporates both centralized and decentralized DER technologies. The challenges and flexible capacity that DERs provide are expected to grow rapidly.
Digitalization	Advances in computing and machine learning have enabled automation and advanced functionality to energy delivery systems and distribution networks. "Smart" devices are a multi-directional, distributed, smart grid.
Infrastructure	American energy infrastructure is struggling to keep up with the sectors rapid changes. Oil and natural gas production have been constrained by inadequate pipeline capacity.

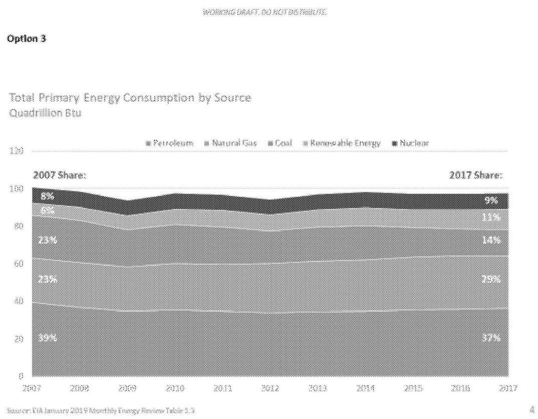
<u>The United States Is Now the Largest Global Crude Oil Producer</u>

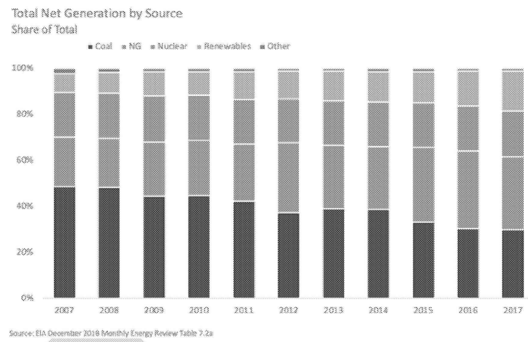
Early in the 21st century, there were concerns about America's ever increasing-reliance on imported oil and natural gas. That concern has now faded. While the United States is still very much part of global energy markets, the shale revolution has fundamentally altered and enhanced the country's energy security situation and changed the U.S. into a fossil fuel production powerhouse. In fact, in 2018, the United States likely passed Russia and Saudi Arabia to become the largest crude oil producer in the world,[29] and it has been the world's top producer of natural gas since 2009.[30]



<u>Shifting U.S. Energy Mix</u>

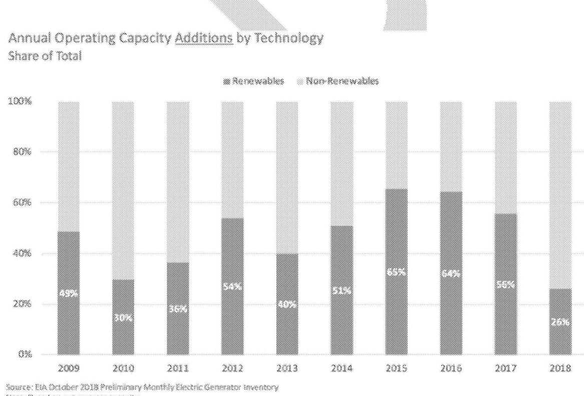
The U.S. energy mix has experienced a shift in recent years due to the rise in natural gas production and growing penetration of renewable energy resources. The U.S. energy mix in 2017 was 37% petroleum, 29% natural gas, 14% coal, 11% renewables (e.g., hydro, biomass, wind, solar), and 9% nuclear.[31] Compared to 2007, coal's share of the mix has decreased by 39%, while renewables' share has nearly doubled and natural gas' has increased by 26%. The rise in fossil fuel production from shale plays has been one of the main drivers in the shifting U.S. energy mix, as advances in drilling and resource extraction technologies (e.g., horizontal drilling, hydraulic fracturing) have lowered the costs of production and have allowed previously uneconomic or technically inaccessible resources to be developed. In 2015, hydraulically fractured wells provided about two-thirds of U.S. natural gas production and about half of U.S. crude oil production.[32] Within just the U.S. electricity sector, the shift has followed a similar trend but even more pronounced, with coal's share declining while natural gas and renewables have each seen their shares grow.[33]



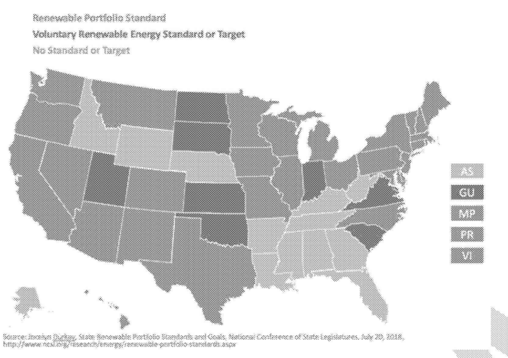


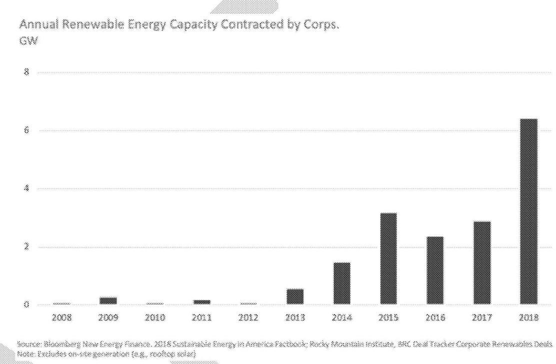
Renewables Account for Majority of New Generating Capacity

As with shale production, the boom in renewables deployment has been one of the leading stories of 21st century American energy. Once viewed as uncompetitive with conventional fuels and niche, renewable energy has grown increasingly cost competitive and has become mainstream. Costs for solar and wind have plummeted over the past decade, while deployments have boomed, driven by federal tax credits, state policies, corporate procurement, and consumer demand. Renewables (primarily wind and solar) have accounted for the majority of U.S. electric generating capacity added each year since 2013 (though in 2018, renewables may get edged out by natural gas additions).[34] As of mid-2018, more than 90 GW of wind capacity had been installed in the United States, generating about 6% of U.S. electricity, as well as more than 58 GW of solar, generating more than 1% of the nation's electricity.[35] These figures represent a tripling of installed U.S. wind capacity and a six-fold increase in installed solar capacity over the past decade.[36] In some parts of the United States, the costs of building new wind and solar generation have fallen below the costs of running existing coal-fired power plants.[37] It is important to note, however, that the 'cost' of various electric generation resources do not necessarily equal their value to the system. Penetration of these variable renewable energy sources is expected to continue.



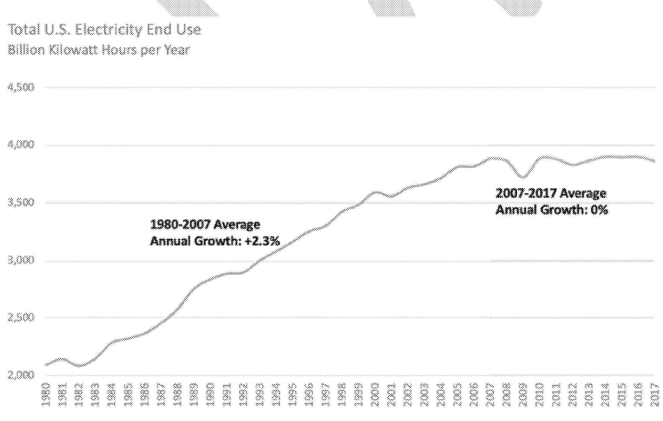
Government policies and improved economics have been vital drivers for both renewables as well as storage. For instance, in addition to federal tax credits, 29 states plus the District of Columbia have a renewable portfolio standard that requires a certain share of generation from renewable sources, with many states requiring 25 percent or more renewable generation by a target date.[38] Several states have also adopted energy storage targets.[39] The plummeting costs and the increased attention to corporate sustainability commitments have also spurred significant renewable energy purchasing (e.g., through long-term power purchase agreements) by large corporate electricity users. Since 2013, dozens of companies have made deals for more than 14 GW of renewables capacity.[40]





<u>Energy Efficiency Has Flattened U.S. Demand Growth While Global Demand Continues to Rise</u>

Energy efficiency has continued to improve, leading to generally flat or declining energy demand across most sectors in the United States.[41] With continued improvements in the energy efficiency of lighting, appliances, vehicles, industrial processes, and more, limited energy demand growth is expected going forward. For example, total electricity use in the United States is expected to rise only marginally over the next few decades.[42] Globally, however, energy demand has been booming, and that growth – driven by demand in non-OECD countries – is expected to continue, though global energy efficiency improvements mean energy demand growth will not be as large as it might otherwise have been.[43]



Energy Use in the U.S. Transportation Sector

Energy efficiency has been improving in the U.S. transport sector as well. U.S. oil consumption is projected to generally decrease through the mid-2030s due to improved vehicle fuel efficiency. Motor gasoline consumption is projected to decrease by more than 30% between 2017 and 2050, and because of improved fuel economy, heavy-duty diesel vehicles are projected to use about the same total amount of fuel in 2050 as in 2017, despite increased freight truck travel.[44]

Recently, a significant amount of attention has been focused on electrification of transport, specifically for passenger cars. Sales of battery-electric vehicles (and plug-in hybrids) have been growing, but even so, they only represent about 1% of vehicle sales – and a far smaller percentage of the overall fleet. Moreover, municipal bus fleets are also starting to transition to alternative fuels, such as natural gas and electricity, though less than 0.5% of the U.S. public bus fleet is electric (compared to more than 15% in China).[45] Additionally, hydrogen fuel cells are another option for electrifying transport and are being pursued by some auto manufacturers, though they thus far have not received the same level of attention, or deployment as battery-electric vehicles. As of 2017, there were only a few thousand commercial fuel cell electric vehicles sold or leased worldwide, with the United States having the largest fleet at about 4,500.[46] While gasoline vehicles are still expected to remain dominant through at least mid-century,[47] electric vehicles, whether powered by a battery or a hydrogen fuel cell, could have significant implications for U.S. oil consumption and emissions from the transport sector. In heavy-duty vehicles, ships, and freight rail, a greater role for natural gas is expected.[48]

Energy Use in the U.S. Manufacturing Sector

The U.S. manufacturing renaissance has been spurred to a large extent by abundant and affordable natural gas as created by the shale revolution. Manufacturing accounts for one-third of the energy consumed in the United States. By 2040, the shale gas boom could create 1.41 million new manufacturing jobs in the United States and generate annual cost savings for manufacturers of $34.1 billion due to lower energy and feedstock costs.[49] As energy technologies evolve, infrastructure must evolve with it. Policies must facilitate the deployment of new pipelines and electric transmission lines, energy transport by rail, energy export terminals, carbon capture and utilization infrastructure, distributed resources, microgrids, energy storage and demand-side management technologies. In addition, the manufacturing sector continues to employ onsite solar and carbon neutral biomass when feasible and also invest in energy efficiency. Most energy-intensive U.S. manufacturers face continuing cost pressure because they operate in highly competitive global markets, thus driving them to reduce energy costs whenever possible. As a result, the energy intensity of U.S. manufacturing has continued to decrease, according to the latest data from EIA's Manufacturing Energy Consumption Survey (MECS). From 2010 to 2014, manufacturing fuel consumption increased by 4.7%, while real gross output increased by 9.6%—or more than twice that rate—resulting in a 4.4% decrease in energy intensity.[50]

Storage Isn't Here….But Its Coming

One of the key evolving trends in the electricity space has been the declining costs and growing deployment of energy storage. Non-hydro energy storage technologies are currently dominated by lithium-ion batteries but also include other battery technologies, compressed air, thermal storage, flywheels, and pumped hydroelectric storage. Lithium-ion battery prices have declined significantly year after year, similar to (but behind) the trajectory followed by solar, and much of the growth in storage deployment has happened behind the meter. Driven by sharply falling battery prices, government policies, and growing adoption of electric vehicles (EVs) and DERs, U.S. energy storage deployments are expected to accelerate markedly over the next few years.[51]

DERs and Decentralization

Storage and renewables are also part of the vanguard of DER technologies that are decentralizing energy supply. For instance, since 2005, the residential solar market has grown by about 44% per year, and by the end of 2017, there were roughly 1.6 million residential solar PV systems in the country.[52] Residential solar system prices dropped about 61% and commercial solar systems about 65% between 2010 and 2017.[53] As of 2017, distributed solar, distributed energy storage, small-scale combined heat & power (CHP), residential smart thermostats, and electric vehicles provided more than 46 GW of flexible capacity for the U.S. grid – a figure expected to double to 104 GW by 2023.[54]

The U.S. electricity grid is shifting from one based on centralized generation to one that incorporates both centralized and decentralized DER technologies. Continued proliferation on the grid of assets such as distributed solar, storage, small wind, natural gas-fired fuel cells, and demand management is forcing some in the utility sector to grapple with and explore fundamental changes in how the grid works, as more and more activity is occurring behind the meter.[55] The challenges and flexible capacity that DERs provide to the grid are expected to continue growing rapidly over the next few years.[56]

New Era of Digitalization

Many of the advances in American energy in the 21st century have come about not only because of improvements in energy technologies but also because of improvements in information and communications technologies. Together, these technological breakthroughs are enabling a new era of energy digitalization, dominated by crosscutting digital tools and platforms — including artificial intelligence, blockchain, the Internet of Things, and big data analytics — that can be applied to the energy system in myriad ways.[57]

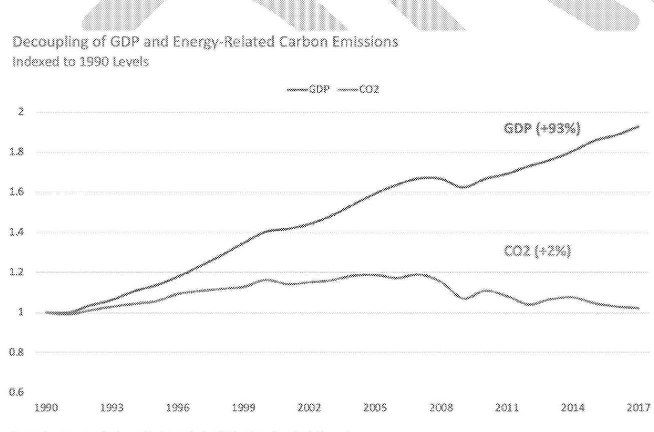
Advances in computing and machine learning have enabled automation and advanced functionality to be embedded within energy delivery systems and distribution networks, and increasingly affordable and sophisticated sensing, communications, and controls technologies have made demand response more powerful, increased the deployment of "smart" devices (e.g., thermostats) and smart meters in homes and buildings, and helped accelerate the evolution of a multi-directional, more distributed, more dynamic smart grid.[58] In the oil, gas, and mining sectors, technologies such as artificial intelligence and drones are helping companies better understand subsurface conditions and improve operations and maintenance.

Inadequate Infrastructure

American energy infrastructure is struggling to keep up with some of these energy trends. Booming oil and natural gas production, for instance, has been constrained by inadequate take-away capacity (e.g., pipelines).[59] The U.S. manufacturing renaissance created by abundant and affordable natural gas will need better infrastructure to move more natural gas to facilities. At the same time, increased deployments of DERs and weather-dependent renewables are creating stress on an aging grid that was largely constructed in the 1950s and 1960s and was designed for one-way power flows from large, centralized generation stations.[60]

U.S. Economy Has Grown Significantly While CO2 and Conventional Pollutants Have Declined

Fundamentally intertwined with developments in the energy sector in the 21st century is the increased societal concern about the environmental impacts of energy production and use, particularly with regard to global climate change. Conventional air pollutants have declined precipitously in the United States since 1980,[61]. Greenhouse gas emissions in the United States have been declining as well, particularly in the power sector. According to EIA, "U.S. electric power sector carbon dioxide emissions (CO2) have declined 28% since 2005…CO2 emissions from all other energy sectors fell by only 5%." The electric sector has outpaced all others largely because of improved energy efficiency, deployment of renewables, and the partial shift from coal-fired generation to natural gas.[62] Still, global energy-related greenhouse gas emissions continue to rise,[63] and pressure is growing to transition to a low-carbon economy, with a 20-fold increase in the number of climate laws and policies around the world since 1997.[64]



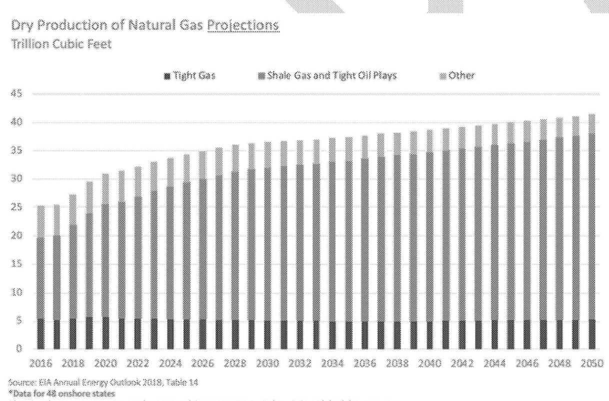
LOOKING FORWARD/IMPLICATIONS

The implications of these trends are multifaceted. Growing renewables and DERs are enabling consumers to seek customized energy and electricity solutions and creating new challenges to grid operations. Digital tools are developing that can assist load management and demand response, but also raise concerns over cybersecurity and data privacy. Global demand for energy is projected to continue to grow - driving future U.S. oil and gas production. Climate concerns are leading more and more local, state, and national governments to push alternative fuels and carbon constraining policies.

Below is a discussion of how these trends are impacting the energy sector.

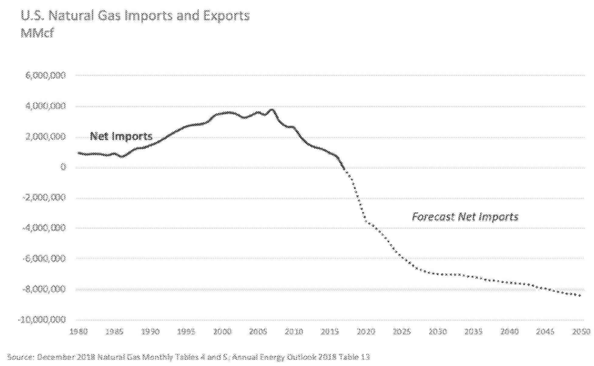
<u>Oil and Gas Sector</u>

As noted earlier, the United States likely passed Russia and Saudi Arabia in 2018 to become the largest crude oil producer in the world,[65] and it has been the world's top producer of natural gas since 2009.[66] Looking ahead, global demand for oil and gas is projected to grow. Continued oil and gas production will be necessary to fulfill and maintain the position of the United States as a global energy provider. The United States is projected to account for almost three-quarters of oil production growth and 40% of natural gas production growth globally through 2025.[67] Domestic production of natural gas is projected to grow from almost 28 trillion cubic feet in 2016 to almost 34 trillion in 2020, more than 39 trillion in 2030, more than 41 trillion in 2040, and more than 44 trillion in 2050, with shale gas responsible for much of the increase.[68]



The abundance of U.S. oil and gas as a result of the shale revolution has had important geopolitical and economic ramifications. Growing shale oil production, for instance, has made the United States more resilient to changes in global oil supplies and prices. Likewise, the growing abundance of American natural gas has led to increases in LNG exports from the United States to markets around the world. Imports of both oil and gas are projected to continue dropping over the next few decades.[69] In 2017, for the first time since 1957, the

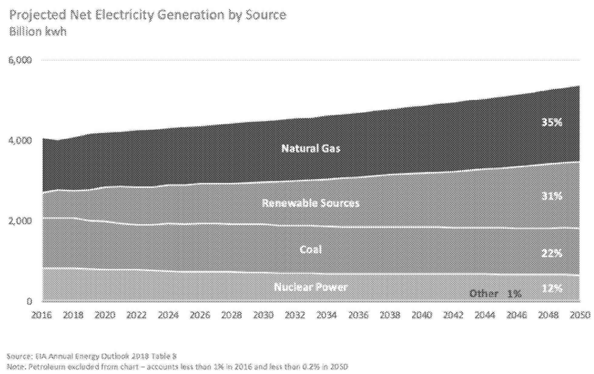
United States exported more natural gas than it imported.[70] Imports of both oil and gas are projected to continue dropping over the next few decades.[71]



This offers an opportunity for the United States to not only strengthen its energy independence and security, but also to provide the economy with an affordable energy source and feedstock. The shale revolution has fundamentally recast the role of natural gas in America's energy landscape, as well as other economic sectors reliant on natural gas feedstock – such as petrochemical and chemical sectors. In the electricity sector, natural gas is expected to continue growing as a share of U.S. power generation, due to its low cost and its ability to reduce greenhouse gas emissions as power generators switch from coal to gas. As both global demand for energy supply and emissions reductions continue to grow, in parallel pressure will also continue to grow to further lower the greenhouse gas footprint of fossil energy production. Methane emissions, again, play a role in that, as do efforts such as utilizing renewable energy to power exploration and production operations.

<u>Renewable Energy</u>

Government policies and improved economics have been vital drivers for renewables. The plummeting costs and the increased attention to corporate sustainability commitments have also spurred significant renewable energy purchasing by large corporate electricity users. Given climate concerns and the significant reductions in cost, renewables are expected to continue to grow in penetration. For example, in the manufacturing sector, there is a trend to shift more energy consumption usage, when feasible, to evening hours to take advantage of cheap wind energy. Other manufacturing sectors have seen an increase usage of renewables for their on-site energy generation, including solar and carbon free biomass energy at some facilities. These trends have heightened the impact of renewables in the industrial energy arena leading to improved facility self-sufficiency while reducing overall emissions and reliance on the grid. Renewables are projected to account for 20% of net U.S. electricity generation by 2020, 23% by 2030, 27% by 2040, and 30% by 2050.[72]



Many advocates are pushing for 100% renewable energy commitments from cities, states, and companies, and dozens of cities and companies, as well as a few counties and states, have committed to 100% renewable energy targets. However, very high penetrations of renewables bring significant challenges and costs related to the variability of generation, the need for storage, and other issues.

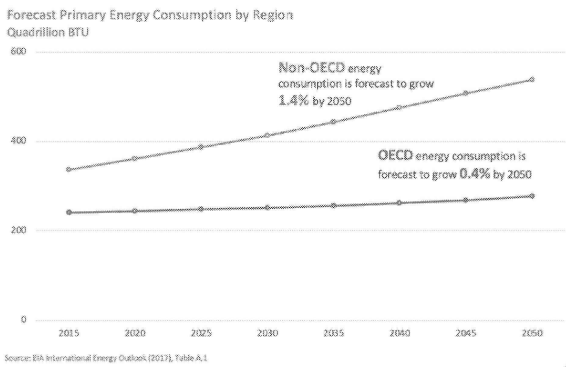
In particular, solar energy has a very predictable daily generation curve. As the sun comes up, it ramps up – peaking in generation around midday, followed by a slow decline until the sun sets. However, electricity demand follows a much different trajectory that ramps up as the sun rises but flattens during the midday before spiking in the evening (after sun down). Because renewables electricity is not dispatchable (it's there when it's there, and not when it's not), grid operators have to manage dispatchable load around renewables' generation.

Additionally, due to the variability of wind and solar energy, power systems with high shares of these resources have much greater overall installed capacity than more diversified power systems and must maintain significant dispatchable capacity to ensure demand can be met at all times. Greater required installed capacity and the lower energy-density of wind and solar resources also significantly increases the land use consequences of power systems dominated by variable renewable resources. A literature review of several studies on high renewable penetration concluded "that balanced portfolios made up of zero- and low-carbon baseload resources, as well as wind and solar, are the most cost-effective means of producing electricity and reducing carbon.[73]" Conversely, a renewables heavy grid would require significant over development of installed capacity. An 80% renewables electricity grid for the United States would require approximately 2050-2200 GW of installed capacity.[74] As of 2018, the U.S. had just under 1200 GW of installed capacity.[75]

<u>Energy Efficiency</u>

The cheapest energy is generally energy that is not used. In OECD countries, energy demand is mostly flat despite economic growth, reflecting improvements in energy efficiency[76] U.S. energy intensity (energy used per unit of economic growth) has improved steadily for years, and energy efficiency, fuel economy improvements, and structural changes in the economy suggest that energy intensity will continue to decline for decades to come. By 2050, U.S.

energy intensity is projected to be 42% lower than in 2017.[77] Conversely, globally energy demand has been booming, and that growth – driven mostly by demand in non-OECD countries – is expected to continue, with world energy consumption projected to grow by 28% between 2015 and 2040.[78]



Looking specifically at electricity, energy efficiency has continued to improve in the United States, across sectors.[79] Going forward, total electricity use in the United States is expected to rise only marginally over the next few decades.[80] Furthermore and as previously mentioned, energy efficiency has been improving in the U.S. transport sector, and oil consumption is projected to generally decrease through the mid-2030s due to improved vehicle fuel efficiency.

Yet, there is significantly more that can be done in the U.S. – specifically with buildings. According to DOE's Building Technologies Office, "we spend more than $400 billion each year to power our homes and commercial buildings, consuming approximately 74% of all electricity used in the United States, about 40% of our nation's total energy bill. And much of this energy and money is wasted—over 30% on average. If we cut the energy use of U.S. buildings by 20%, we could save approximately $80 billion annually on energy bills and help create jobs."[81]

Transportation

While petroleum has been, is, and projects to continue to be the primary energy source for the transportation sector, electric and fuel cell vehicles are expected to begin edging their way into the transportation fuel source mix. Energy efficiency has been improving in the U.S. transport sector as well. Domestic oil consumption is projected to generally decrease through the mid-2030s due to improved vehicle fuel efficiency. Motor gasoline consumption is projected to decrease by more than 30% between 2017 and 2050, and because of improved fuel economy, heavy-duty diesel vehicles are projected to use about the same total amount of fuel in 2050 as in 2017, despite increased freight truck travel.[82]

Recently, a significant amount of attention has been focused on electrification of transport, specifically for passenger cars. Sales of battery-electric vehicles (and plug-in hybrids) have been growing, but even so, they only represent about 1% of vehicle sales – and a far, far smaller percentage of the overall fleet. Looking ahead, some project U.S. sales of battery EVs to increase from less than 1% in 2017 to 12% in 2050 (with plug-in hybrids growing from 1% to 2%), driven by declining battery costs and state policies.[83] Projections of annual EV sales globally generally reach into the tens of millions by 2030.

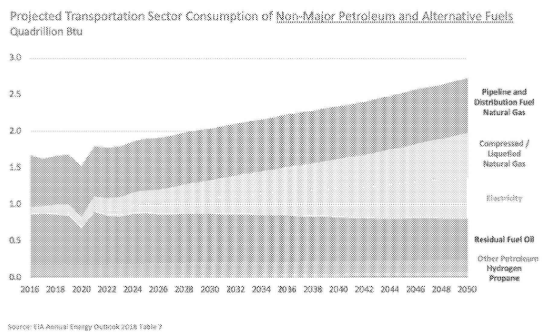
The growth in electrified transport means more distributed battery resources that can connect to the grid to provide energy storage, frequency regulation, or other grid services; vehicle-to-grid (V2G) technologies – which are still mostly in pilot project mode and are more conceptual than commercial – are likely to grow in penetration and sophistication as electrification of transport accelerates. The growth in EVs will also create new load opportunities for electricity providers during a period of otherwise flat or declining demand, and providers will likely utilize more time-based charging incentive programs to shift EV charging to periods of excess generation.

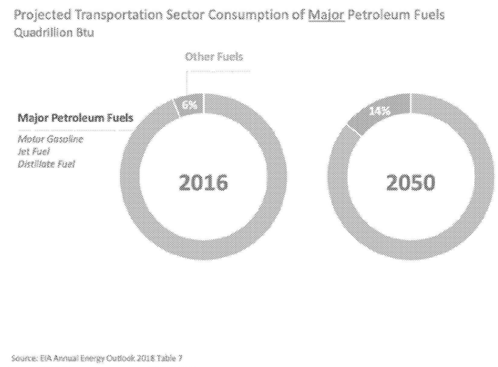
Municipal bus fleets are also starting to transition to alternative fuels, such as natural gas and electricity, though less than 0.5% of the U.S. public bus fleet is electric (compared to more than 15% in China).[84] While the most ambitious forecasts suggest that all bus purchases will be electric by 2030, other forecasts put the figure somewhere between 27% and 60%. Either way, the trends suggest rapid growth in this area.[85]

While currently, the biggest use of hydrogen fuel cells globally is for stationary power, they are also another option for electrifying transport and are being pursued by some auto manufacturers. As of 2017, there were only a few thousand commercial fuel cell electric vehicles sold or leased worldwide, with the United States having the largest fleet at about 4,500.[86] There are also several thousand fuel cell forklifts in operation globally, as well as the beginnings of potential applications in trucks, buses, rail, and other modes of transport[87] (The biggest use of fuel cells globally is for stationary power.) Some project there will be 1 million fuel-cell electric vehicles in the global fleet by 2030 and 10 million by 2040.[88]

Biofuels were the focus of many alternative energy policies at the beginning of the 21st century. Today, most of the gasoline in the United States contains at least 10% ethanol. However, the land use challenges and the conflict of “food vs. fuel” has pushed most biofuel efforts to derive fuel from plant and other organic wastes rather than grains. Additionally, the scale of production needed to impact the fuels market is greatly handicapped by the diffuse nature of the feedstock (plants grown across thousands of acres of land). Current research in advanced biofuels has thus focused on algae (which can be grown in vats at the production facility) and specific niches of fuels (such as diesel and aviation). Advanced biofuels have not advanced at the rate many hoped when U.S. government support and mandates were expanded in 2007, but there are still potential market opportunities. Growing pressure for aviation emission reductions and continued breakthroughs in algae and other waste-derived fuels could converge to provide a liquid fuels solution to the sector.

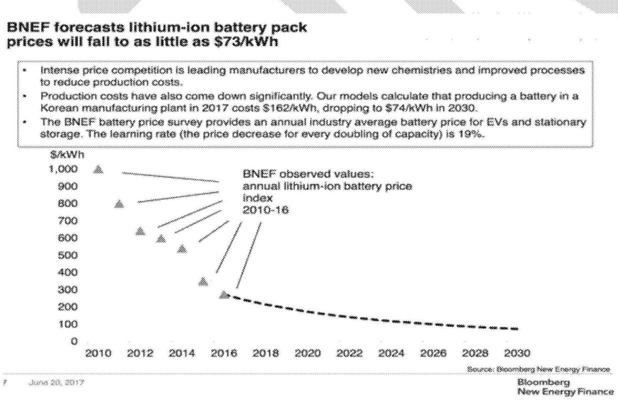
While gasoline vehicles are still expected to remain dominant through at least mid-century,[89] electric vehicles, whether powered by a battery or a hydrogen fuel cell, could have significant implications for U.S. oil consumption and emissions from the transport sector. In heavy-duty vehicles and freight rail, a greater role for natural gas is expected.[90]





Energy Storage

Cost-effective storage technologies are key to allowing greater intermittent renewable generating resources to be added to the grid. Similar to renewables, precipitous declines in price and improvements in technology have likewise led to a rise in deployment of energy storage. The price for lithium-ion batteries dropped 73% between 2010 and 2017, from $1000/kWh to about $270, and could drop to about $73/kWh by 2030.[91] As of mid-2018, energy storage deployment had grown by 60% over mid-2017 in terms of megawatts and by 200% in terms of megawatt-hours (MWh), with much of that growth occurring behind the meter. U.S. energy storage annual deployments are expected to accelerate markedly over the next few years, growing from almost 400 MW in 2018 to over 2 GW by 2020 and nearly 4 GW by 2023.[92] Globally, some project that the energy storage market will grow to a cumulative 942 GW by 2040, driven by sharply falling battery prices, government policies, and growing adoption of electric vehicles and solar power.[93]



Greater penetrations of variable renewable generation will require greater use of flexible, fast-ramping resources.[94] Natural gas could play an important role in balancing variable renewable generation, although storage will also play a key role. Improvements in battery (and other storage) technologies could have huge implications for the future energy mix. Continued improvements in battery technologies and costs could make variable renewable generation into a dispatchable resource, provide a range of services to the grid, and accelerate the electrification of transport (bringing a new source of both electricity load and potential distributed storage options onto the grid). New battery chemistries are also being explored, including ones that do not rely on critical minerals such as lithium and cobalt, though the challenge is always producing these new configurations on a commercial scale. In addition, there is a need for greater research and development on long-duration energy storage options.

DERs and Decentralization

As of 2017, distributed solar, distributed energy storage, small-scale combined heat & power (CHP), residential smart thermostats, and electric vehicles provided more than 46 GW of flexible capacity for the U.S. grid – a figure expected to double to 104 GW by 2023.[95] Looking further ahead, distributed solar capacity in the United States is expected to grow 9% per year in the residential sector and 6% per year in the commercial sector from 2017 to 2050, to a combined total of around 250 GW, while other distributed generation resources (e.g., small wind, CHP) are projected to grow more slowly and reach about 16 GW by 2050.[96] The growth in DERs has also led to growth in advanced microgrids, which are localized grids that can disconnect – or island – from the bulk power grid and autonomously provide power by relying on resources such as distributed solar, battery storage, natural gas generators and fuel cells, CHP systems, and smart controls.

The growth in variable renewables, storage, DERs, and digitalization described earlier have also spurred changes in how energy is used. For instance, efforts at demand response and load-shifting can move energy use to periods of maximum energy production. This is a paradigm shift from the current model; rather than supply chasing load, this model involves load moving to match supply.[97]

The rise in decentralization means that many electric utilities are facing significant pressure, both from changing technologies and from rapidly evolving consumer (and investor) preferences. As evidenced by the boom in corporate renewables procurement, customers are pushing for more choice, more control, and cleaner sources for their electricity, increasingly demanding their own bespoke mix of electricity via local energy resources. Growing on-site and distributed generation opportunities for residential, commercial, and industrial consumers are also enabling customers to use more of their own power and less power from the grid. This is forcing utilities to grapple with new rate structures and valuation of transmission to avoid the "utility death spiral" – reductions in consumer reliance on the grid lead to fewer kilowatt-hours across which utilities can spread their fixed costs, which leads to higher rates, which in turn incentivizes further reductions in grid reliance, and so forth.

Digitalization

Digitalization and advanced data analytics are playing (and are expected to continue to play) a meaningful role in grid operations and consumer energy choice. Already, more than half of all U.S. households have had a smart meter installed, allowing for two-way communications between electric companies and customers; installations were expected to reach 76 million by the end of 2017 and are projected to reach 90 million by 2020.[98]

Many of these personal and home devices are connected to communications networks – creating the "Internet of Things" (IoT) – to provide a wide variety of services and applications. The number of connected IoT devices is forecast to grow from 8.4 billion in 2017 to over 20 billion by 2020.[99] The vast volume of data generated by smart meters, smart IoT devices, grid sensors, and other technologies will only grow as the grid modernizes. This has increased the role and potential value of big data analytic software and services to help the grid run smoothly and to help customers optimize their energy use.

Greater deployments of EVs, renewables, DERs, and communications and data analytics technologies suggest more broadly that demand response and load shifting will have an increasingly important role to play in America's energy future. Smart appliances and devices in buildings could be key enablers of enhanced demand response, and the increased digitalization of the grid will play an important role in managing energy, improving efficiency, and balancing power supply and demand.

Infrastructure

Beyond the need for increased storage capabilities, changes in the mix of energy sources will necessitate modernizing our energy infrastructure. Increased renewables, DERs, and IT and communications capabilities are shifting the grid from a centralized, one-way system to a more distributed, multi-directional system, with significant implications for utility business models and for how the grid should be maintained and upgraded. Several states are pursuing initiatives to modernize their grids and utility regulations in light of new technologies and consumer demands. Many utilities are likewise deploying a range of advanced sensors as an underlying component of smarter grids, as they can provide real-time insights into grid conditions, improve reliability, enhance responsiveness to disruptions and outages, and support further integration of distributed energy.[100] A responsive, decentralized energy system that processes and analyzes huge amounts of data also requires robust broadband infrastructure. [101]

Increased demand for renewables could also spur the need for new transmission lines to bring power from where it is most efficiently generated to where it is needed to meet demand. Studies have suggested, for instance, that the Eastern U.S. grid could handle 30% renewables penetration – 10 times the gigawatts of renewables currently on the system – within 10 years, but only with significant transmission upgrades.[102] Building transmission lines can be a difficult, time consuming process, given the difficulty of securing rights of way and necessary permits, but there could be opportunities for building new high-voltage direct current transmission lines in existing rights of way, such as along railroad corridors.

Likewise, growth in domestic production of shale oil and natural gas requires modernizing infrastructure to increase take-away capacity. Domestic production has faced bottlenecks in the form of inadequate pipeline capacity, and stakeholders are therefore advocating for increased pipeline construction. In many locations, though, pipeline construction faces continual opposition from landowners along the routes and from environmental advocates. A sustainable U.S. manufacturing renaissance will need new and expanded natural gas infrastructure.

Climate Change

The need to significantly reduce greenhouse gas emissions over the next couple of decades will be a major driver of change beyond market and technology driven efficiency. Increasingly affordable renewables will continue to rise in deployment to achieve emission reductions, though there may well be cost and feasibility constraints that eventually limit the scope of deployment. Increasingly affordable and abundant natural gas has likewise helped spur emission reductions (due to fuel-switching from coal) and can continue to do so for some time, particularly if methane emissions from the production and distribution system can be addressed – and in the long term, carbon capture, utilization, and storage (CCUS) will become increasingly essential to ensure a continued role for fossil fuels in a carbon-constrained world.

Meeting the dual challenges of maintaining economic growth by providing diverse, affordable, and reliable supplies of energy while addressing climate change will require the development and deployment of new technologies and a supportive policy environment to eliminate barriers to their use. Increased research and development is needed on CCUS and other emission-reducing innovations, including technological breakthroughs to reduce emissions outside the power sector (e.g., in the transportation, industrial, and buildings sectors). New technologies and business practices will also be needed to address the range of ways energy use and supply are changing and to reduce emissions at the lowest cost to society.

BREAKTHROUGH TECHNOLOGIES

Some technologies that could fundamentally change the U.S. (and global) energy landscape are currently at a nascent stage and their promise lies over the horizon. Forecasting how various technologies will develop and deploy and what impacts those technologies will have involves some measure of speculation, and all such projections should be made with humility. Some of these technologies may not fulfill the promise they appear to hold, while others may exceed it. New technologies could – and almost certainly will – enter the picture. The technologies below, however, seem particularly worthy of continued attention.

Advanced Nuclear

The Promise

Nuclear power currently provides roughly two-thirds of America's carbon-free power. However, the current generation of nuclear power plants is struggling to stay economically competitive and attempts to build new plants have either failed or gone way over schedule and over budget. Advanced nuclear energy will likely be required if America hope to realize an economical, dispatchable, low-carbon power system.

Advanced nuclear energy – a term that encompasses both small modular reactors (SMRs) and non-light water reactors – involves new methods of operation, new types of coolants, and new form factors. Advanced nuclear has flexibility, dispatchability, extraordinarily high energy density, increased safety, and the ability to be used in both electric and non-electric applications – all while producing no carbon emissions. Advanced nuclear reactors have the potential to be far cheaper than traditional light-water reactors and to load-follow or utilize energy storage technologies to better integrate with high levels of variable renewable energy.[103] Their much smaller size opens up new markets in smaller grids, reduces the total capital cost, and allows the potential use of factory-based and advanced manufacturing techniques.[104] The smallest of these reactors, known as microreactors, effectively act as nuclear-powered batteries and can provide highly reliable, clean power to remote communities.[105] Some reactors under design will be able to produce high-temperature process heat for industrial and chemical processes.[106] Other reactor concepts (e.g., liquid metal or molten salt cooled) allow for smaller reactors and more passive safety features, while "fast reactors" (which operate with much higher energy neutrons) can significantly reduce the lifetime of nuclear waste products.[107]

<u>How Likely the Promise is to be Realized</u>

Dozens of companies across the United States are pursuing advanced nuclear concepts, including at least five that are already working with the Nuclear Regulatory Commission. As of early 2018, there were more than 70 advanced nuclear projects being pursued by companies, universities, and national labs across North America.[108] There has been progress (with bipartisan support) at the Nuclear Regulatory Commission, at the Department of Energy, and in Congress to support advanced reactor designs and development.

Advanced nuclear development in the United States, however, is hindered by a lack of high-assay low-enriched uranium (and U.S. enrichment capacity to produce it), lack of a centralized fast reactor testing facility, the need for more advances in materials engineering, and regulations designed for the last generation of reactors that do not necessarily correspond with the attributes of advanced reactors. The projected timelines for actual deployment are also distant. While the first advanced reactors – SMRs – could be online by the mid-2020s,[109] the Department of Energy (as of early 2017) had a goal that at least two non-light water advanced reactor concepts will have reached sufficient maturity and licensing review progress to allow construction to begin by the early 2030s.[110] In addition, advanced nuclear will have to be competitive with renewables and natural gas, whose costs have been coming down; this is why some advanced reactor developers are focusing not just on technological improvements but also on designing for cost-competitiveness.[111]

Carbon Capture, Utilization, & Storage

<u>The Promise</u>

It has become increasingly clear that tackling climate change will not only require reducing emissions, but also addressing emissions that have already been emitted or that are still being emitted. Carbon capture, utilization, and storage (also referred to as “carbon capture”, “CCS”, or “CCUS”) refers to a suite of technologies that selectively capture carbon dioxide from flue gas or the atmosphere and then either repurpose the captured carbon dioxide in the production of commodities (e.g., carbon fiber, fuels) or store it (e.g., underground).

Robust, affordable CCUS will be essential for providing a continued role for fossil fuels – including natural gas – in a future of low-carbon power. CCUS can also significantly mitigate industrial process emissions; indeed, in some industries such as cement production, CCUS is the only option for fully abating process-related carbon dioxide emissions.[112] In addition, CCUS is a vital component of “negative emissions technologies” that remove and sequester carbon dioxide from the atmosphere, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC).[113]

Numerous assessments of how to limit warming to 2°C, including from the Intergovernmental Panel on Climate Change and the International Energy Agency, have found that the likelihood of success is far higher and the costs far lower when CCUS is included as a mitigation option.[114] Negative emissions technologies are even more essential if the goal is to meet more stringent 1.5°C climate targets.[115]

<u>How Likely the Promise is to be Realized</u>

There is already a solid base of experience and infrastructure regarding CCUS. Carbon capture projects were first deployed in the United States nearly half a century ago for enhanced oil recovery.[116] Today, over 20 million metric tons of carbon dioxide is captured from U.S. manmade sources each year and transported through over 5,000 miles of carbon dioxide pipelines.[117] In addition, the past couple of years have seen the commercialization of the first carbon capture system at a U.S. coal-fired power plant and initial testing of a new design for a natural gas plant that can capture all carbon dioxide emissions.[118] Congress also passed in 2018 an extension and expansion of the 45Q tax credit for CCUS, which is expected to spur more activity in the area.

While encouraging, many CCUS technologies in the development pipeline have yet to scale up. The reality is that there are fewer than two dozen large-scale CCS facilities operating globally,[119] and CCS developments in the power and industrial sectors are far off track for reaching the scale (and affordability) needed.[120] Projects face a number of hurdles including unique environmental permitting requirements (including for carbon dioxide pipelines), uncertain long-term liability, financing challenges associated with high capital cost and often first-of-a-kind commercial projects, and the slow development of climate policies around the world.[121]

Hydrogen

<u>The Promise</u>

Like electricity, hydrogen is a flexible energy carrier that can be produced from a range of primary energy sources and can be used across sectors. Because of its flexibility and wide array of potential applications, hydrogen has the potential to be a key part of a future energy system that has significantly lower levels of emissions of greenhouse gases and other air pollution.

Hydrogen could serve as a means to store and transport renewable energy, enabling large-scale renewable energy integration and long-duration energy storage. It could power hundreds of millions of vehicles around the world (particularly in heavy-duty and long-range applications). It could be routed through existing natural gas infrastructure to provide about 10% of global demand for heating in buildings, could be utilized for medium- and high-heat industrial processes, and could be used as a renewable feedstock in some industrial production (e.g., for steel). All of these uses, accounting for 18% of total final energy consumed by 2050, could result in significant reductions of greenhouse gas emissions and conventional air pollutants, 20 million fewer barrels of oil per day consumed in the transportation sector, and 30 million jobs created globally.[122]

In the United States, 10 million metric tons of hydrogen are produced annually, the vast majority of which via steam-methane reformation of natural gas.[123] Low-carbon hydrogen could be produced from fossil fuels via this and other methods if CCUS is added to the process.[124] There is also growing global interest and investment in producing zero-carbon renewable hydrogen by powering electrolysis with wind or solar to produce methane or ammonia (i.e., hydrogen-rich compounds that are easier to transport).[125]

<u>How Likely the Promise is to be Realized</u>

It sometimes seems as if the promise of the hydrogen economy has been on the horizon for decades. Many of the technologies needed already exist but are nowhere near their potential scale, as in the case of the hydrogen fuel cell vehicle deployment levels noted earlier. Realizing the promise of hydrogen would require massive increases in investment, deployment of hydrogen infrastructure, and scaling up of manufacturing capacities, as well as support from long-term policy.[126] In addition, hydrogen will have to compete against other technologies, such as, in the transport space, batteries that are experiencing growing market share and plummeting costs. Still, the current drive for a low-carbon energy system, long-term energy storage, and reduced greenhouse gas emissions in sectors where such reductions are harder to achieve (e.g., industrial manufacturing) give reason for cautious optimism about the future of hydrogen.

Advanced Digitalization

<u>The Promise</u>

Many of the most exciting and potentially impactful technologies in the energy sector are not energy technologies but rather fall in the realm of digitalization and IT. Over the next few decades, digital technologies and advances in data analytics and connectivity will likely make energy systems around the world more connected, efficient, reliable, and sustainable. Annual benefits to the energy sector from digitalization are projected to rise from $17 billion in 2017 to $38 billion in 2025, with the fastest growth in technologies and services that provide flexibility to the grid and leverage residential energy loads.[127]

Digitalization could bring widespread deployment of autonomous vehicles, intelligent homes, and on-demand additive manufacturing (3-D printing). Big data analytics could optimize transport routes, reduce vehicle fuel use, optimize building energy performance, improve power plant and grid operation, boost the benefits of demand response, and decrease oil and gas production costs.[128] Blockchain could enable secure, low-cost, decentralized electricity transactions and ultimately enable peer-to-peer electricity transactions, in addition to a range of other applications.[129] Artificial intelligence and machine learning could change how and when electricity is used in a building, how to site shale wells so as to best take account of stakeholder concerns, and how the grid responds automatically and in real time to disruptions and price signals.[130] Growing deployments and sophistication of smart devices, appliances, and machines could create a truly massive Internet of Things, with huge numbers of connected devices interacting with each other and with the grid.[131]

<u>How Likely the Promise is to be Realized</u>

Often the biggest difficulty with evaluating digital technologies is separating hype from potential. Surely, some of these innovations will turn out to be more hype than substance, but the impacts digitalization is already having on the energy sector (and life more broadly) suggest that the disruption will only accelerate.

While adoption of some of these digital innovations remains nascent, many do not require more R&D, they just need to be utilized. However, often policies adopted prior to the emergence of these digital innovations (e.g., Federal Power Act, state renewable portfolio standards) are creating barriers to their adoption. Analog reporting requirements, legal documents, and transactions continue to be the only means “acceptable” regulators and legal institutions for the mere fact that the underlying rules were written in an analog era. Action by Congress, agencies, RTOs/ITOs, state utility regulators, and others will be needed to scale to a digital energy future.[132]

Substitute Materials

<u>The Promise</u>

Advances in material science could have enormous repercussions on the U.S. energy sector in the 21st century in a wide range of ways. Although many substitute material advances have already occurred, though much more is possible in the years ahead.

Many clean energy technologies, from batteries to solar panels to wind turbines, rely on critical or near-critical minerals such as lithium and neodymium. Limited supplies of these minerals could present an obstacle to further commercialization and deployment of these technologies. Efforts are underway not only to diversify supplies of these minerals but also to develop substitutes for them. Progress has already been made in reducing reliance on such minerals for permanent magnets and for lighting,[133] and a range of advanced battery technologies that do not rely on critical minerals are under development.[134]

In the vehicle space, one of the key methods for improving vehicle efficiency is lightweighting – replacing heavier materials such as steel with lighter ones such as cellulosic fiber and various polymers and alloys – as it takes less energy to move and accelerate a lighter vehicle. Using lightweight materials and high-efficiency engines enabled by advanced materials in a quarter of the U.S. fleet could save more than 5 billion gallons of fuel a year by 2030, without sacrificing safety. Some materials that could drastically reduce the weight of vehicles, such as carbon fiber, are currently too expensive for widespread utilization.[135] Further developing advanced, lightweight materials requires significant testing, computational tools, and manufacturing, such as through DOE's Lightweight Materials Consortium.

With regard to construction, new combinations of materials reduce emissions associated with cement and concrete production. A range of materials have been developed or tested to replace clinker in Portland cement, and alternative products have been developed with various additives and binders, which could lead to significant reductions in greenhouse gas emissions from cement production and manufacturing.[136] There has also been some movement to replace concrete and steel in construction with wood, which (in the form of cross-laminated timber) is starting to be used as a low-carbon material in tall building construction.[137]

How Likely the Promise is to be Realized

The above examples are just a few of the many possibilities of how substitute materials could affect energy and emissions. Some of these alternative materials require additional testing to ensure adequate performance. Others need government standards or changes to existing regulations to allow greater use of them in the market. Materials science, however, will clearly continue to advance and contribute to the evolution of the energy sector in both predictable and unexpected ways.

CONCLUSION AND RECOMMENDATIONS

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Secure, diverse, affordable, and reliable supplies of energy have been the foundation of a strong U.S. economy, but other attributes are increasingly being seen as important as well. Ensuring robust, affordable energy for the world while reducing emissions and facilitating consumer choice is a considerable challenge – one that requires technological innovation, sound policies, and political and corporate commitment. Barriers to innovation have to be reduced, and research, development, and deployment of new, affordable, and scalable technologies have to be robustly supported. Growth in the energy industry must be facilitated at the same time that the drive for deep emission reductions is accelerated.

In light of the developments and trends highlighted in this report, the Business Roundtable offers the following recommendations to facilitate economic growth, environmental stewardship, and enhanced energy security:

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A draft narrative that attempts to synthesize/update the recommendations and tie them to the trends and implications outlined in the report:

- *Foster innovation by sustaining public investments in a diverse portfolio of pre-commercial research and development activities* – The development and deployment of new, efficient, low-carbon technologies are vital to effectively responding to concerns about global climate change while meeting rising energy demands to support economic growth. Reducing emissions from the U.S. energy system will be much more easily achieved with significant technological innovation, so investments in research, development, and demonstration of new low-carbon technologies must be increased in the public and private sectors to levels commensurate with the magnitude of the climate challenge. RD&D programs should be better coordinated across economic sectors and focused on technologies with the greatest promise in reducing greenhouse gas emissions on a lifecycle basis. Support is essential not only in basic research but also at various other points to help technologies such as advanced nuclear, CCUS, energy storage, and others achieve readiness for commercialization.

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