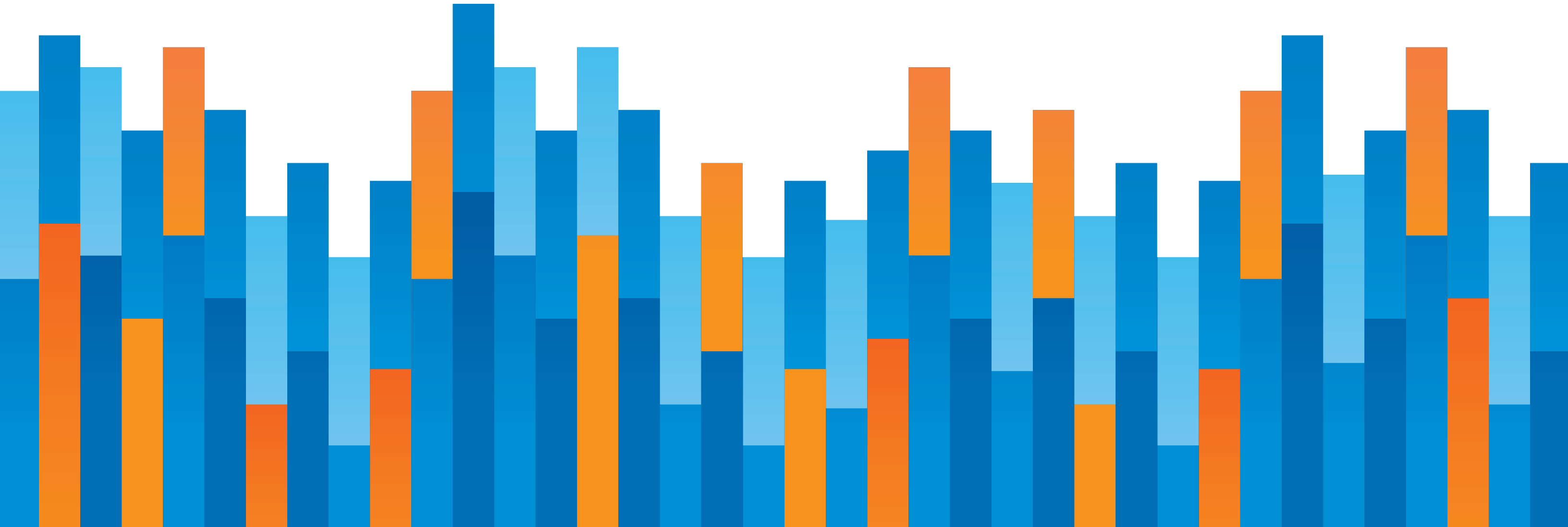
reason
FOUNDATION

EVIDENCE-BASED POLICIES TO SLOW CLIMATE CHANGE

by Julian Morris

October 2021



EXECUTIVE SUMMARY

Human emissions of greenhouse gases (GHGs) are contributing to a rise in global average temperatures, with potentially significant effects on the climate. In response, governments around the world have introduced policies intended to reduce emissions of GHGs. Most of these policies are “top-down” and include: mandatory restrictions on emissions, mandatory use of certain “low carbon” technologies, and subsidies to specific technologies.

This study finds that such top-down policies’ approach to controlling GHG emissions may not be as effective as bottom-up approaches that harness the natural tendency of entrepreneurs and innovators to identify more efficient and cost-effective ways to produce goods and services.

The study identifies several key trends that suggest bottom-up approaches are already delivering results:

- Energy use per dollar of GDP has been declining at a fairly constant rate in the U.S. for about a century.
- Emissions of carbon dioxide (CO_2) per dollar of GDP have been falling faster than the rate of decline in energy use for the past half century, both in the U.S. and globally.
- Over the past 30 years, emissions of other GHG per dollar of GDP have been falling faster than emissions of CO_2 globally.

These trends are largely driven by improvements in efficiency and changes in the sources of energy, including a centuries-long shift toward more energy-dense, lower-carbon fuels. These improvements were mainly driven by market forces, not government intervention.

While continued improvements in energy efficiency may slow or even stop the growth in energy use, they are unlikely to lead to a reduction in energy use, let alone a reduction in CO_2 emissions. As such, if reductions in carbon dioxide emissions are to occur, they will need to come primarily from a continued shift toward lower-carbon fuels.

Currently, about 90% of the world's energy and 80% of U.S. energy are supplied by carbon-based fuels. Numerous lower-carbon energy sources are currently available and are able cost-effectively to supply some portion of current energy demand. Unfortunately, however, attempts to shift largely or exclusively to zero-carbon fuels in the short term are likely to be prohibitively costly.

- Hydropower can only be cost-effectively produced in locations that are geologically suitable.
- Geothermal energy can be cost-effective in certain locations and applications.
- Solar and wind power can be cost-effective in a relatively wide range of locations and applications but cannot be relied upon by themselves to supply power because the sun only shines for an average of 12 hours per day and the wind does not blow continuously. For these intermittent power sources to form a significant proportion of energy supply, storage (such as batteries) or back-up generation will be needed.
- Battery storage is currently not cost-competitive with natural gas as a source of back-up power for renewable energy systems.
- Nuclear power remains an important source of energy in the U.S., but the cost of a new nuclear power plant is more than twice the cost of a new natural gas-fired power plant per kW of energy generated.

For low- and especially zero-carbon energy to become the dominant source of power in the U.S. and globally, continued innovation is key. The question is, which policies are most appropriate to drive such innovation?

In some cases, innovation may be technology-specific. For example, improvements in the cost-efficiency of very-low-risk modular nuclear reactors may result from learning-by-doing, which would occur if many such nuclear reactors were to be built. Likewise, similar improvements in cost-effectiveness might occur in the production of grid stabilization technologies necessary for managing intermittent power sources. But that does not justify policies specifically targeting such technologies. It is impossible to know either which technologies will exist in the future, or how much they will cost, so policies should not explicitly favor one technology over another. Mandates and subsidies that encourage only one or a narrow set of technologies are thus unlikely to be a cost-effective way to drive innovations that will reduce carbon emissions.

In other cases, innovations may derive laterally from innovations in other technologies. For example, large-scale battery storage technology has already benefited from dramatic improvements in lithium-ion batteries initially developed for laptops and other small consumer electronics. Likewise, geothermal energy generation is already benefiting from innovations developed to enable extraction of oil and natural gas from shale formations.

Because many factors are geographically specific, the optimal combination of lower carbon technologies will vary significantly from place to place. It will also change over time as innovation drives down costs. So, policymakers should avoid one-size-fits-all, top-down approaches and instead look at ways to encourage innovation and implementation from the bottom up—both in general and specifically in energy markets.

Some of the most important factors affecting innovation in general are:

- Competition, both in general and specifically in capital markets;
- Flexible labor markets;
- Low personal and corporate taxes; and
- Streamlined, cost-effective regulation.

Meanwhile, governments could improve the prospects for low-carbon energy generation specifically by taking actions to:

- De-monopolize electricity markets;
- Remove trade barriers in the energy sector (both exports and imports);

- Reduce subsidies and tax expenditures for energy and energy-related technologies;
- Streamline permitting for all forms of energy generation, including nuclear; and
- Eliminate arbitrary, technology-specific energy mandates.

Innovation has the potential dramatically to reduce carbon emissions over the course of the next half century. Indeed, if the U.S. were to adopt the pro-innovation approach outlined here, U.S. GHG emissions could fall to zero, or close to zero, by about 2060. Globally, it could take a little longer, but with a concerted effort to remove barriers to innovation, GHG emissions could approach zero in the last two decades of the century without any need for explicit restrictions on CO_2 or other GHGs.

TABLE OF CONTENTS

PART 1 **INTRODUCTION** **1**
PART 2 **GLOBAL WARMING AND GHG EMISSIONS** **3**
PART 3 **GDP, ENERGY INTENSITY, AND GHG EMISSIONS** **7**
PART 4 **ENERGY DENSITY** **11**
PART 5 **DEMATERIALIZATION** **20**
5.1 COMPUTERS 22
5.2 DATA TRANSMISSION 24
5.3 LIGHTING 26
5.4 FOOD PRESERVATION 27
5.5 BEVERAGE CANS 27
5.6 SYNERGIES AND THE SINGULARITY 28
PART 6 **THE CAUSES OF INCREASES IN ENERGY DENSITY AND DEMATERIALIZATION** **30**
6.1 OPPORTUNITY, COMPETITION, AND INNOVATION 30
6.2 MORE, FROM LESS 32
6.3 ECONOMIC GROWTH, INSTITUTIONS, AND PEAK GHG EMISSIONS 33
6.4 IS THERE A ROLE FOR GOVERNMENT REGULATION AND/OR SUBSIDIES? 38
PART 7 **PROSPECTS FOR INCREASED ENERGY EFFICIENCY** **43**
7.1 ARE CONSUMERS LEAVING MONEY ON THE SIDEWALK BY NOT ADOPTING ENERGY EFFICIENCY IMPROVEMENTS? 43
7.2 MORE EFFECTIVE BOTTOM-UP SOLUTIONS TO THE PROVISION OF INFORMATION 49
7.3 DO ENERGY EFFICIENCY IMPROVEMENTS LEAD TO LOWER EMISSIONS? 51
7.4 BEWARE OF POLICIES THAT ARE NOT COST-EFFECTIVE OR ARE EVEN COUNTERPRODUCTIVE 52
7.5 CONCLUSIONS OF PART 7 56
PART 8 **PROSPECTS FOR LOW-CARBON ENERGY GENERATION** **58**
8.1 NATURAL GAS 59
8.2 NUCLEAR POWER 61
8.3 HYDROELECTRIC 64
8.4 GEOTHERMAL 65
8.5 WIND 68
8.6 SOLAR 68
8.7 INTERMITTENCY, CAPACITY FACTORS, SPINNING RESERVE, AND STORAGE 68
8.8 COMPARING THE EFFECTS OF MEETING ENERGY DEMAND WITH DIFFERENT SYSTEMS 74
8.9 TRADE-OFFS AND THE OPTIMAL ENERGY MIX 82
8.10 BARRIERS TO INNOVATION AND IMPLEMENTATION OF LOW-CARBON TECHNOLOGIES 83
8.11 CONCLUSIONS 93

PART 9 CONCLUSIONS: COMMON SENSE POLICIES TO ACCELERATE DECARBONIZATION 94
9.1 RECOMMENDATIONS 95
9.2 RETURNING TO THE HYPOTHETICAL 107
ABOUT THE AUTHOR 108

FIGURES AND TABLES

Figure 1: Global Mean Temperature Change 4
Figure 2: Global Mean Temperature Anomaly and CO_2 Concentration 5
Figure 3: Global GDP and Emissions of GHGs 6
Figure 4: U.S. Primary Energy Consumption per Dollar of GDP and Energy-Related Emissions of CO_2 per Dollar of GDP 8
Figure 5: U.S. Energy Consumption and Energy-Related Emissions of Carbon Dioxide 9
Figure 6: Human Emissions of Carbon Dioxide and All GHGs, Global 9
Figure 7: Total Global GHG Emissions and GHG Emissions per Unit of GDP 10
Figure 8: Areas of Virgin Forest in 1620, 1850, and 1926 12
Figure 9: Forest Cover in the U.S., 2000 14
Figure 10: Change in Forest Cover in the U.S., 1630–2012, Millions of Acres 14
Figure 11: Changes in Primary Energy in the U.S. Over the Past 240 Years 16
Figure 12: U.S. Energy Use per Dollar of GDP, 1850-2006 17
Figure 13: Emissions for Different Hydrocarbon Fuels 18
Figure 14: U.S. Primary Energy Consumption by Fuel Source, Quadrillion BTU 19
Figure 15: Total World Energy Consumption by Fuel Source, Terawatt Hours (TWh) 19
Figure 16: The Development of More Energy-Efficient Cooking Technologies 21
Figure 17: Moore's Law: Transistors per Microprocessor 23
Figure 18: Energy Consumption per Transistor 24
Figure 19: Energy Intensity of Internet Data Transmission 25
Figure 20: Energy Efficiency of Light Sources 26
Figure 21: Kurtzweil's Extension of Moore's Law 29
Figure 22: The Environmental Kuznets Curve 34
Table 1: EKC Turning Points for Water Pollution 34
Table 2: Range of EKC Turning Points for Air Pollution 35
Figure 23: Spontaneous Shifts in Prices of Fuels 39
Figure 24: U.S. Natural Gas Output and Prices 59
Figure 25: Natural Gas Proved Reserves 60
Figure 26: Types of Steam Geothermal Power 66
Figure 27: Wind Power Density Over Time 69

Figure 28: Maximum, Minimum, and Average Monthly Capacity Factors for Utility Scale Electricity Generation in the U.S. in 2019 70
Figure 29: Lithium-Ion Battery Prices per kWh (US$) 77
Figure 30: Total Installed Cost for Utility-Scale Lithium-Ion Battery Systems of Varying Sizes 78
Table 3: Competitive Versus Traditionally Regulated Electricity Markets 84
Table 4: Core Damage Frequency for Different Types of Nuclear Reactor 91

PART 1

INTRODUCTION

Human emissions of greenhouse gases (GHGs) are contributing to a rise in global average temperatures. Concerns about the effects of increased temperature stemming from further increases in atmospheric GHG concentration have led governments around the world to implement policies that aim to reduce GHG emissions.

“Unfortunately, many of the policies so far implemented have done little to reduce GHG emissions or reduce the risk of future temperature increases, at enormous cost.”

Unfortunately, many of the policies so far implemented have done little to reduce GHG emissions or reduce the risk of future temperature increases, at enormous cost. The Renewable Fuels Standard, discussed in Part 7, is an extreme example, but there are many others. Going forward, it is important to identify cost-effective policies to reduce GHG emissions and thereby slow the rate of climate change.

This study examines and explains the mechanisms underpinning reductions in GHG emissions and describes a set of policy changes that would achieve such reductions cost effectively. It begins in Part 2 with a simple description of the relationship between economic activity, GHG emissions, and global warming. Part 3 delves more deeply into the changing relationship between economic activity and emissions and offers a hypothetical projection of future emissions based on this changing relationship.

Parts 4 and 5 consider the role of energy density and dematerialization as explanations for the changing relationship between output and emissions. Then, Part 6 assesses various factors that underpin both increasing energy density and dematerialization.

Part 7 evaluates the prospects for increasing energy efficiency both in general and through targeted policies. Part 8 identifies technologies and policies that might lead to lower-carbon energy generation. Finally, Part 9 draws together the several strands of policies discussed throughout the paper and offers conclusions.

PART 2

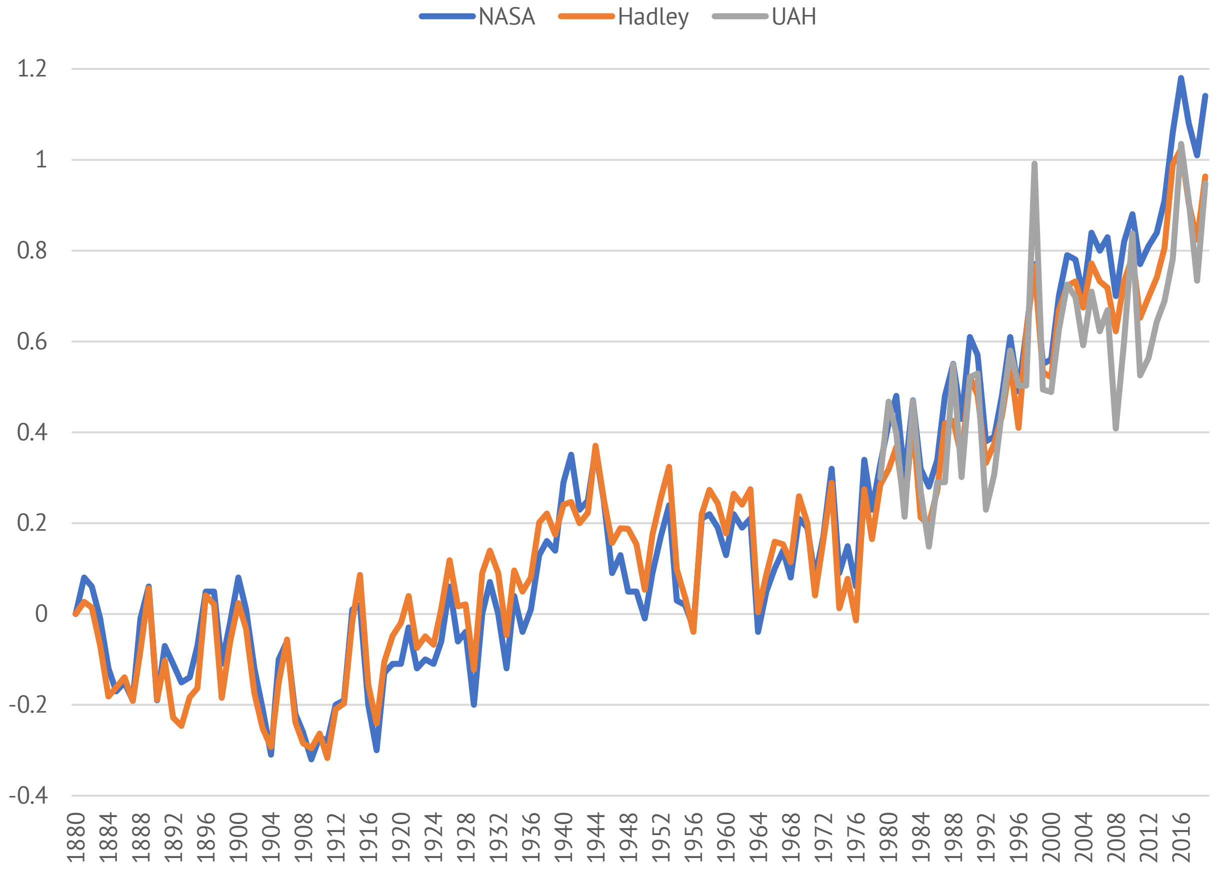
GLOBAL WARMING AND GHG EMISSIONS

Since 1880, the lower atmosphere has warmed on average by about one degree Celsius (1.4 degrees Fahrenheit). This can be seen in Figure 1, which shows changes in global average temperature since 1880 in °C, as estimated from ground and sea thermometers by NASA (blue line) and by the UK Met Office's Hadley Center (orange line), as well as those estimated from infrared spectrometers on satellites by the University of Alabama at Huntsville (UAH, gray line).[1]

---

[1] NASA: GISTEMP Team, 2021: "GISS Surface Temperature Analysis (GISTEMP), version 4," NASA, Goddard Institute for Space Studies, accessed September 2021, https://data.giss.nasa.gov/gistemp/ ; "HadCRUT4 Data: download," Met Office, UK, Hadley Centre, accessed September 2021, https://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html; "Microwave Sounding Unit Temperature Anomalies," National Centers for Environmental Information, National Oceanic and Atmospheric Administration, accessed September 2021, https://www.ncdc.noaa.gov/temp-and-precip/msu/

FIGURE 1: GLOBAL MEAN TEMPERATURE CHANGE (LOWER TROPOSPHERE, °C, REBASED, 1880)



Source: Author's calculations based on data from NASA, the Hadley Centre, and UAH.

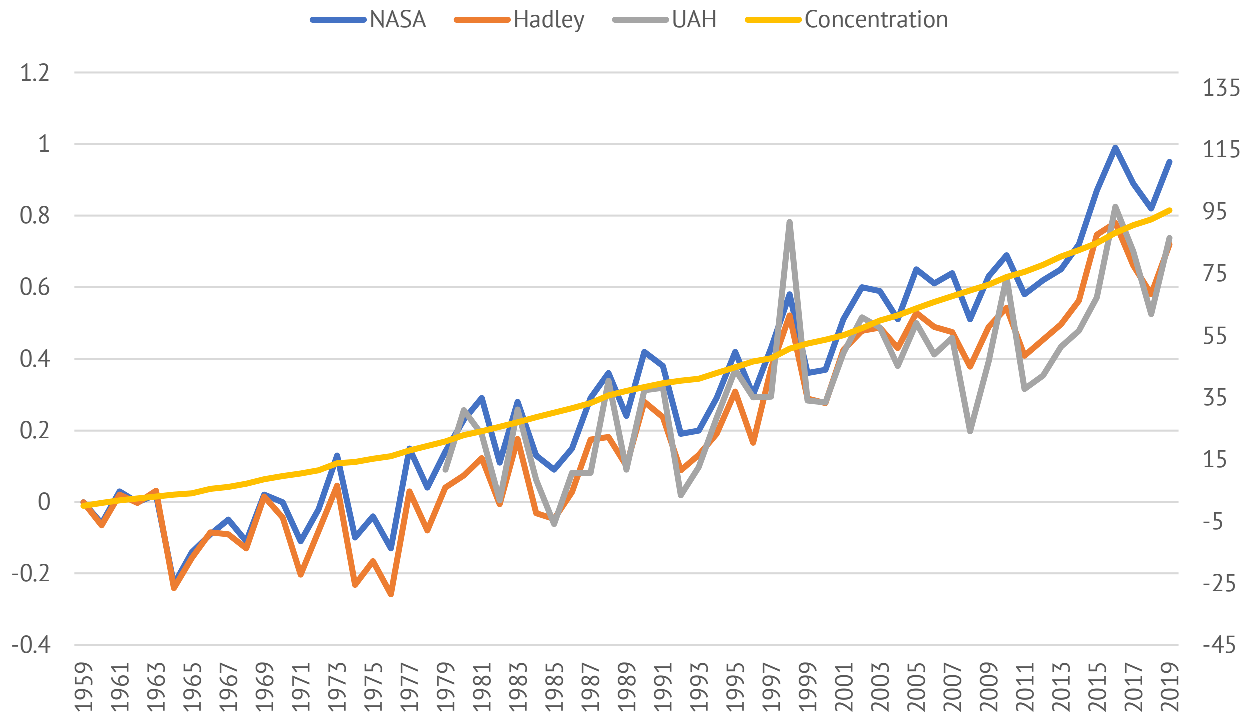
While many factors affect the global climate, it is now established that part of the warming, especially since the 1960s, has been a result of increased atmospheric concentrations of various greenhouse gases (GHG), especially carbon dioxide (CO_2), as can be seen in Figure 2. (The scales have been adjusted to make the relationship between temperature and carbon dioxide concentrations clear.) The correlations between the Mauna Loa carbon dioxide concentration data and the NASA temperature data (from 1959), Hadley Centre temperature data (from 1959), and UAH temperature data (from 1979) are 0.96, 0.93, and 0.76.[2] While

---

[2] Temperature data as above. Mauna Loa carbon dioxide concentration data from "GML Data Finder," NOAA Global Monitoring Library, accessed September 2021, https://www.esrl.noaa.gov/gmd/dv/data/index.php?site=MLO&parameter_name=Carbon%2BDioxide

not in itself definitive proof, when combined with a solid theoretical relationship between carbon dioxide concentrations and greenhouse warming, that is strongly suggestive of a causal relationship.[3]

FIGURE 2: GLOBAL MEAN TEMPERATURE ANOMALY (°C, LEFT) AND CO_2 CONCENTRATION (PPM, RIGHT)



Source: Author's calculations based on data from NASA, the Hadley Center, UAH (as for Figure 1), and the Mauna Loa observatory.

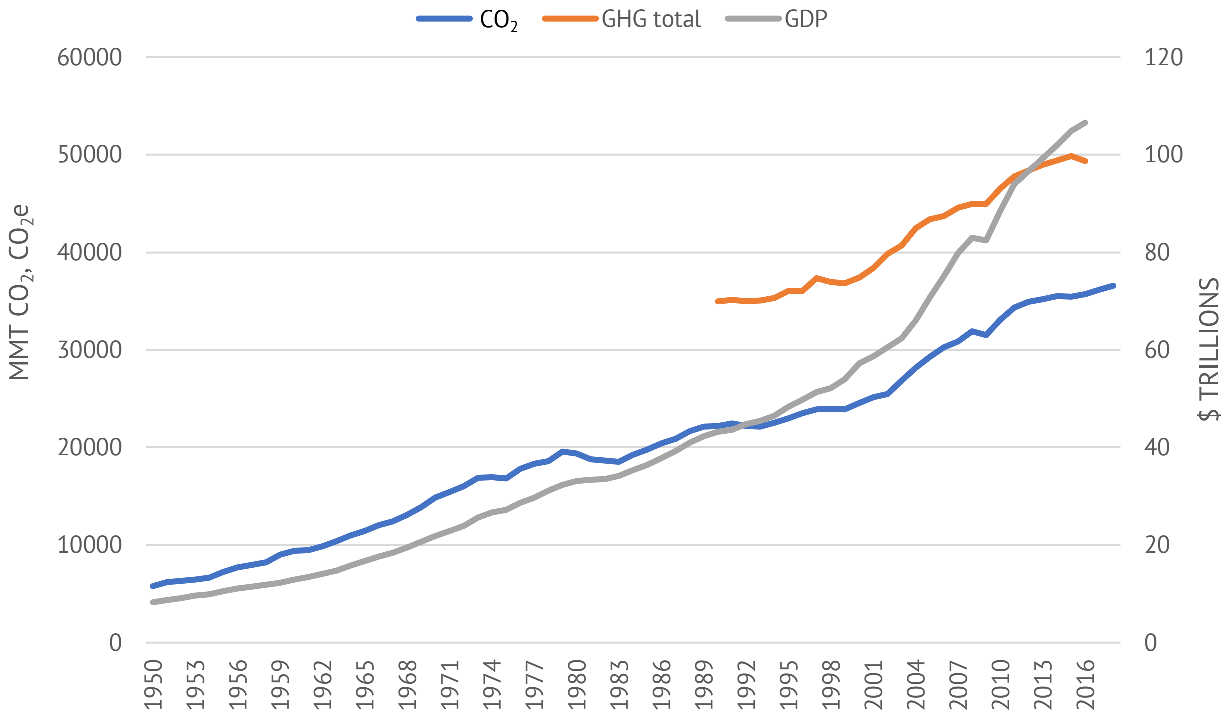
This increase in concentration of GHGs is largely a result of increased emissions by humans, which in turn has coincided with a dramatic increase in economic activity. This can be seen in Figure 3, which shows growth in global GDP (gray line, right axis, in US$ trillions), carbon dioxide (blue line, left axis, in million metric tons (MMT)), and all GHGs (orange line, left axis, MMT of CO_2 equivalent (CO_2e)). Because each GHG has different characteristics, the composite measure of GHG emissions ($CO_{2e}e$) is obtained by converting each type of

---

[3] Adolf Stips et al., "On the causal structure between CO2 and global temperature," *Scientific Reports*. Vol. 6, 2016, 21691. https://www.nature.com/articles/srep21691#Tab1

GHG emission into its "carbon dioxide equivalent," based on its relative potential to cause global warming, then multiplying each by the amount emitted, before summing.[4]

FIGURE 3: GLOBAL GDP (RIGHT AXIS, $TRILLIONS) AND EMISSIONS OF GHGS (LEFT AXIS, MMT CO_2, CO_2E)



Source: Author's calculations based on data from BP "Statistical Review of World Energy," https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html and World Bank Open Data, https://data.worldbank.org /

The relationship between GHG emissions per unit of output seems to have decreased considerably over the past 30 years. This metric, called GHG "emissions intensity," is an important element in understanding GHG emission trends. The next part discusses this relationship in more detail.

---

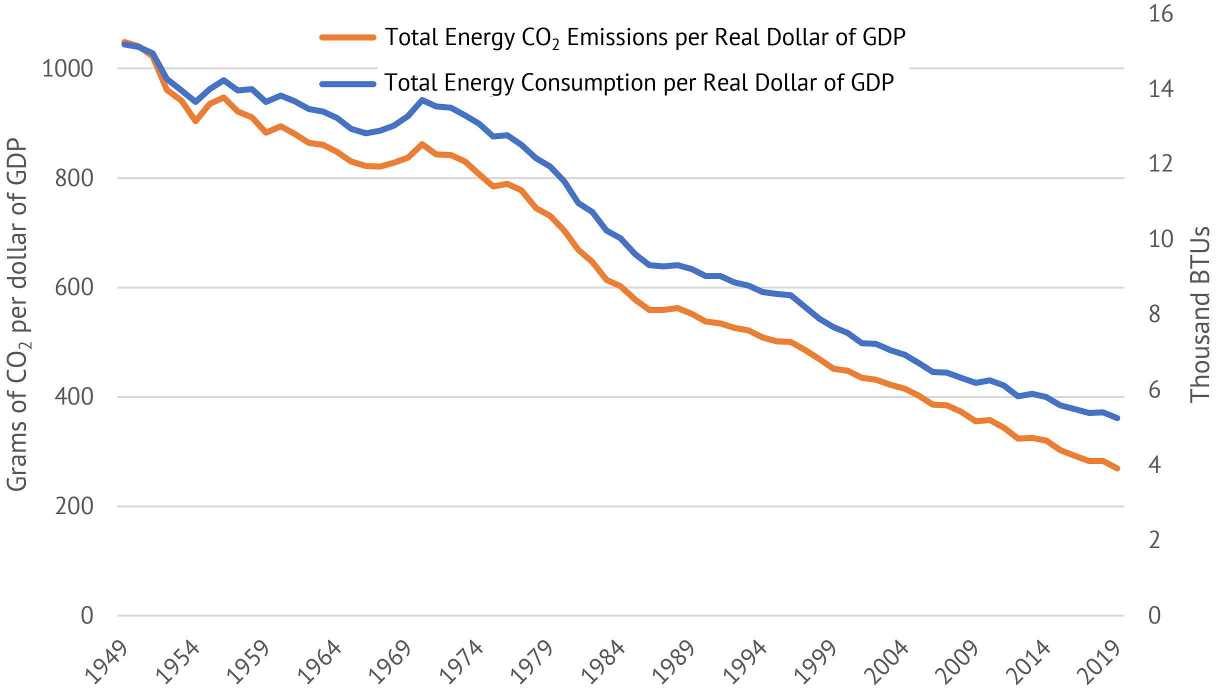
[4] Most other GHGs have higher global warming potential than CO_2. For example, a ton of methane has the global warming potential of about 25 tons of CO_2. So, when calculating CO_2e, the number of tons of methane emissions is multiplied by 25. (Note that the GHG total used here does not include any chemicals that have negative global warming potential, such as sulphate aerosols. For a discussion of this potentially confusing other use of "carbon dioxide equivalence," see: Zeke Hausfather, "Understanding Carbon Dioxide Equivalence: Common Climate Misconceptions," *Yale Climate Connections*, January 20, 2009, https://yaleclimateconnections.org/2009/01/common-climate-misconceptions-co-equivalence/)

PART 3

GDP, ENERGY INTENSITY, AND GHG EMISSIONS

Since 1949, the amount of energy used per real dollar of GDP in the United States has declined by 65%, from 16,000 BTU to 6,000 BTU (a metric called "energy intensity"), while emissions of carbon dioxide per real dollar of GDP (that is, CO_2 emissions intensity) have fallen by 74%, from 1.1 kg per dollar of GDP to about 0.27 kg per dollar—as can be seen in Figure 4.

FIGURE 4: U.S. PRIMARY ENERGY CONSUMPTION (BLUE LINE, THOUSAND BTUS, RIGHT AXIS) PER DOLLAR OF GDP AND ENERGY-RELATED EMISSIONS OF CO_2 (GRAMS OF CO_2) PER DOLLAR OF GDP (ORANGE LINE, LEFT AXIS)

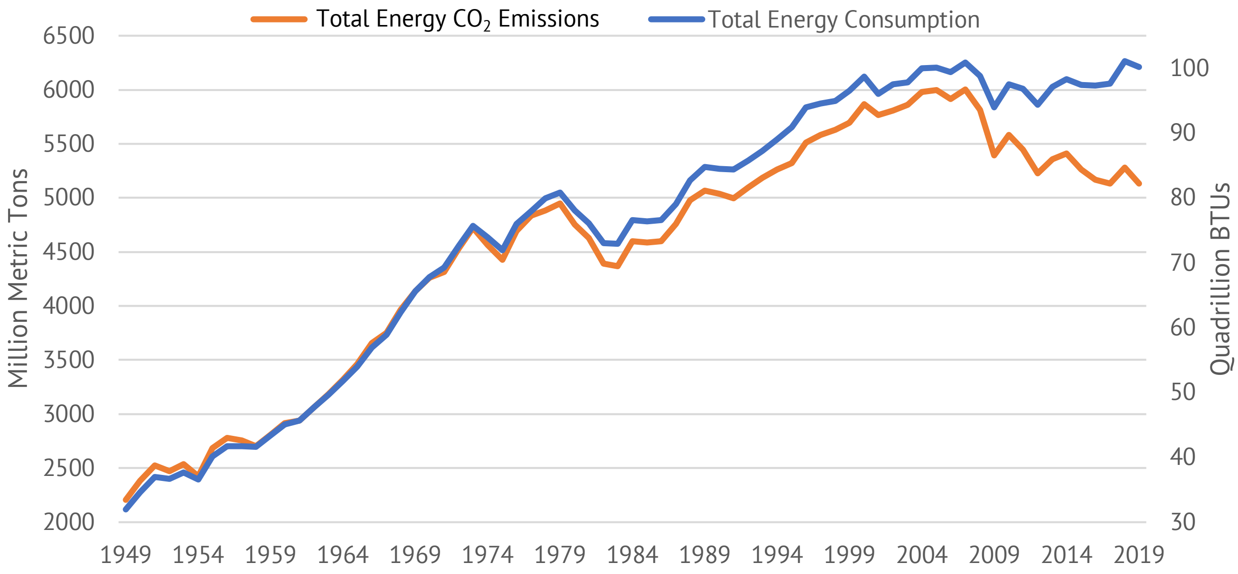


Source: Author's calculations, based on data from U.S. Energy Information Administration

As a result, even with rising population and economic activity, total energy consumption in the U.S. has leveled off over the past 10 years, while CO_2 emissions have fallen—as can be seen in Figure 5.

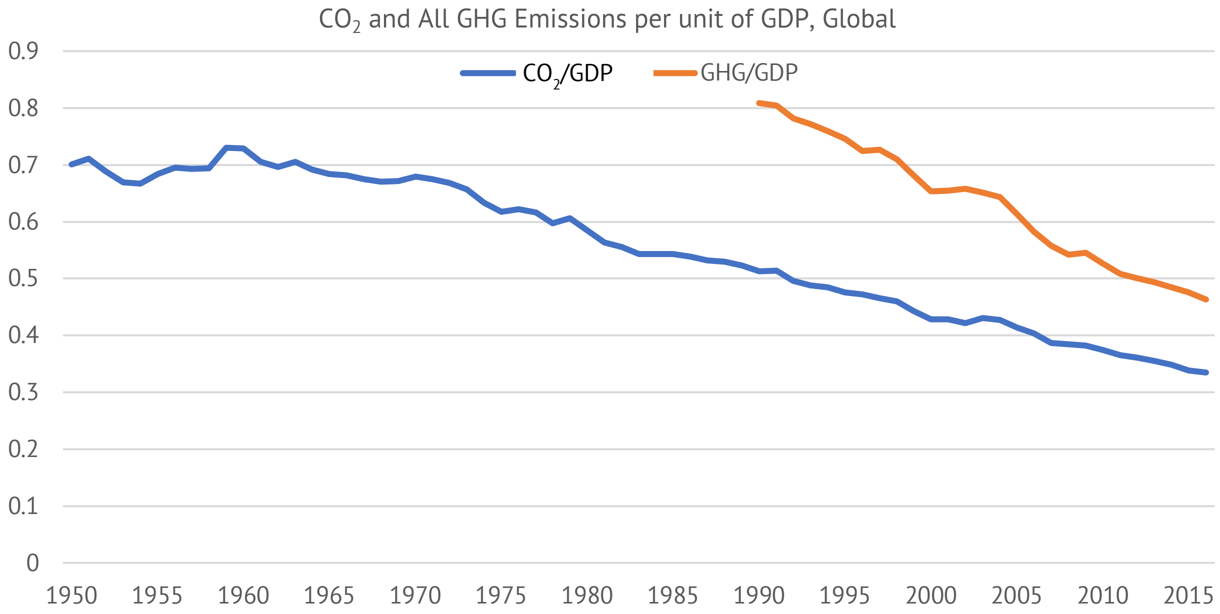
At a global level, annual emissions of carbon dioxide and other GHGs have continued to increase (as we saw in Figure 2), but the rate of emissions per unit of output has been declining in a similar fashion to U.S. emissions, as can be seen in Figure 6.

FIGURE 5: U.S. ENERGY CONSUMPTION (QUADRILLION BTUS, RIGHT AXIS) AND ENERGY-RELATED EMISSIONS OF CARBON DIOXIDE (MILLION METRIC TONS, LEFT AXIS)



Source: Author's calculations, based on data from the U.S. Energy Information Administration.

FIGURE 6: HUMAN EMISSIONS OF CARBON DIOXIDE (KILOGRAMS) AND ALL GHGS (KILOS OF CO_2E PER DOLLAR OF GDP), GLOBAL

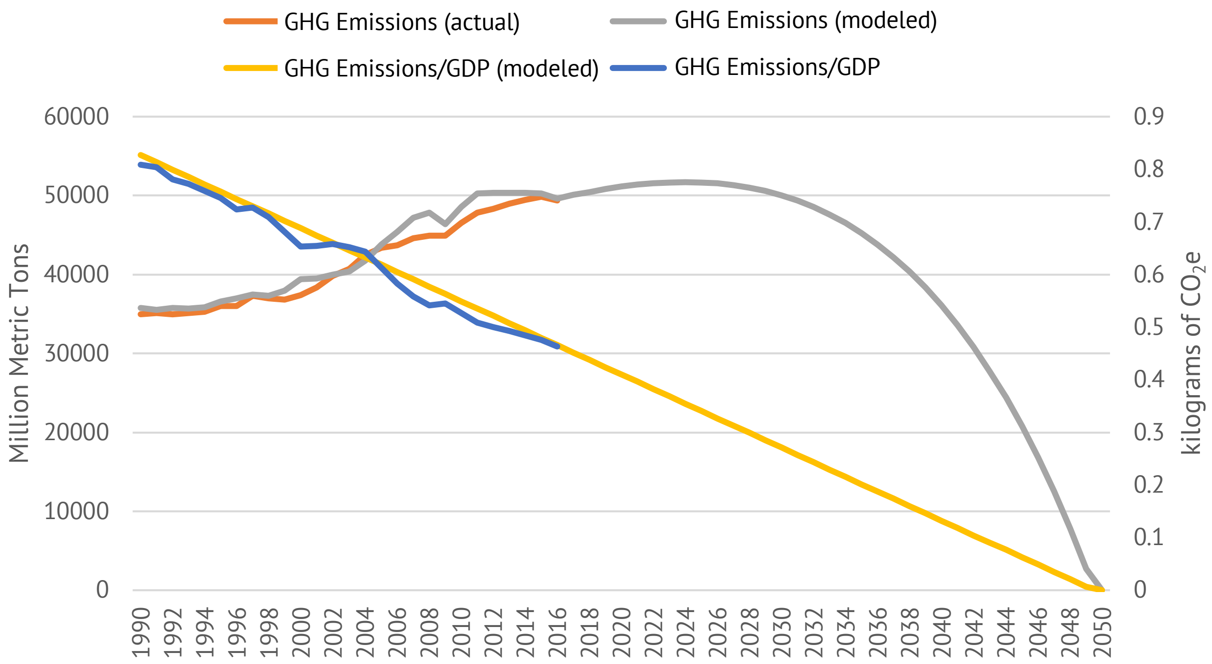


Source: Author's calculations, based on data from www.ourworldindata.org.

If these trends were to continue, the rate of increase of CO_2 and GHG emissions would decline in the next few years and would begin falling after about 2030, reaching zero by about 2050. Figure 7 shows these trends using a simple linear extrapolation of the GHG emission/GDP ratio and assuming that global GDP grows at an annual rate of 4% (the average rate since 1950).

Of course, there is no certainty that these trends will continue. Indeed, there are good reasons to think that eliminating GHG emissions altogether by 2050 is rather fanciful. But the extrapolation is nonetheless useful, since it shows what could happen if the 30-year almost-perfectly linear trend in reductions of GHG emissions per unit of GDP were to continue for another 30 years or so. More importantly, it raises the questions: what led to this trend in the first place—and what might lead to its continuation? The answer to this question has, broadly, two components: changes in energy density and dematerialization (that is, the general reduction in use of materials per unit of good or service provided). The next two parts look in more detail at these explanatory factors.

FIGURE 7: TOTAL GLOBAL GHG EMISSIONS (MILLION METRIC TONS, LEFT AXIS) AND GHG EMISSIONS PER UNIT OF GDP (KILOGRAMS OF CO_2E, RIGHT AXIS)



Source: Author's calculations, based on data from ourworldindata.org

PART 4

ENERGY DENSITY

As noted above, one of the factors contributing to the decline in energy intensity and carbon emissions per unit of GDP is increasing “energy density.” This section explores the meaning of energy density and the ways it has changed over the past several centuries.

Energy density is the amount of energy stored in a specific mass of a fuel source. It is usually measured in megajoules per kilogram (MJ/kg). Since 1 MJ = 239 kilocalories (kCal) and 1 kg = 2.2lbs, 1 MJ/kg = 526 kCal/lb. (Rather confusingly, one kCal is one “food calorie,” which is the energy needed to raise one gram of water one degree Celsius. So, when a nutrition label says that one “serving” of a food item contains 100 “calories,” it actually contains 100 kCal.)

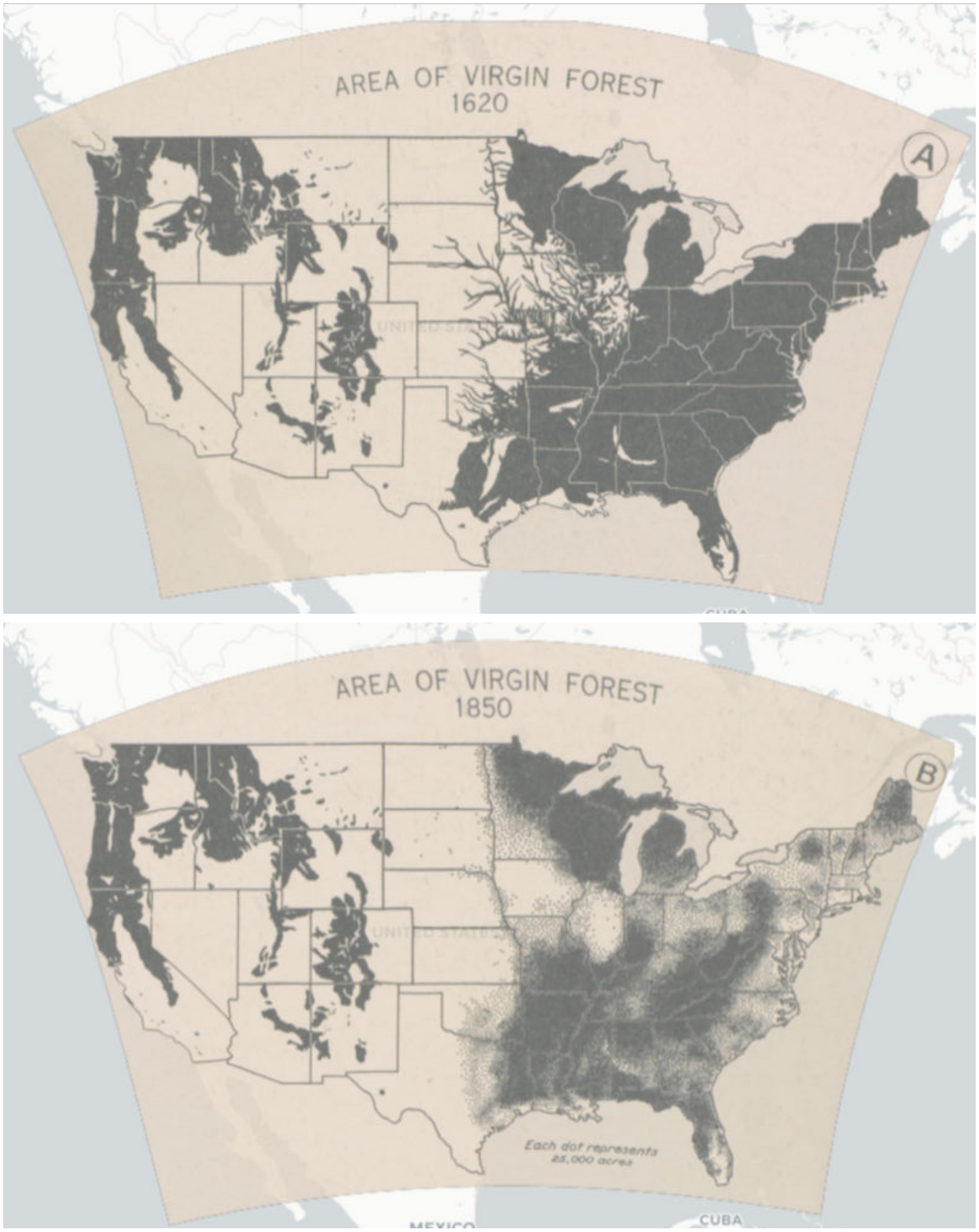
Until about 200 years ago, most energy came from burning biomass—primarily wood—which has an average energy density of around 14 MJ/kg (or 7,378 kCal/lb).[5] This low density meant that large amounts were required to supply significant amounts of power. As demand for power increased during the Industrial Revolution, the relatively low energy density of wood led to rapid deforestation. This progression can be seen in Figure 8 below,

---

[5] Food and Agriculture Organisation, *Wood Fuels Handbook*. Rome: United Nations, 2015. http://www.fao.org/3/a-i4441e.pdf.

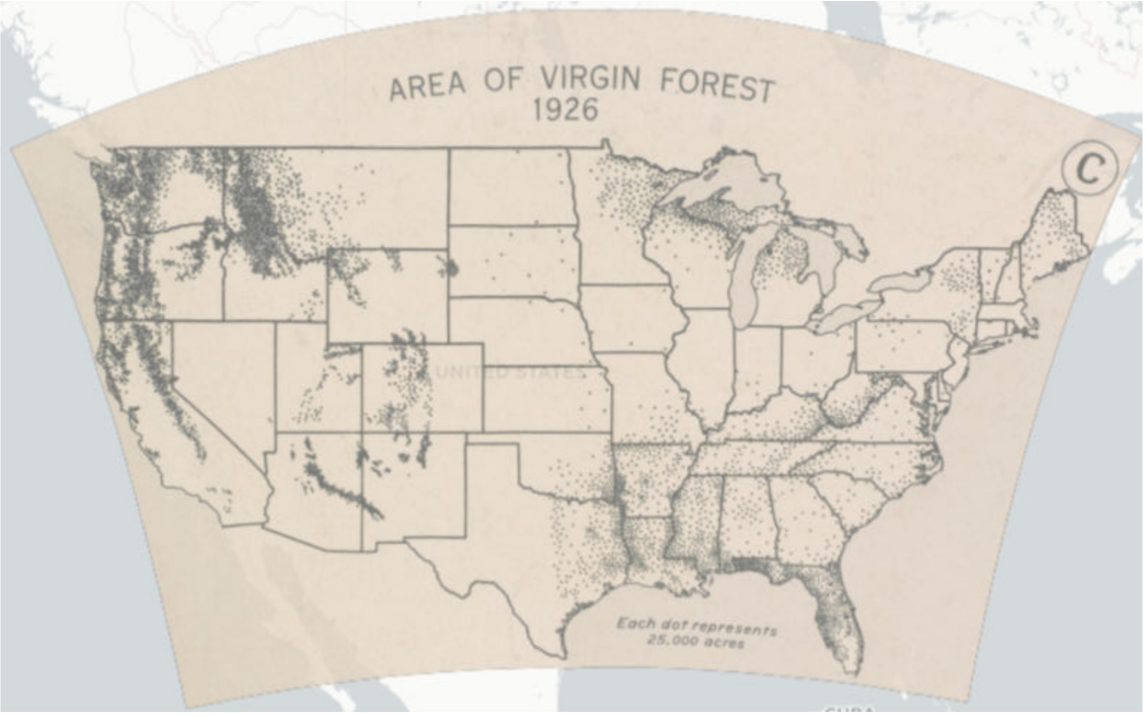
which shows how the forested area of the U.S. shrank from over 1,000 million acres in 1600 to around 700 million acres in 1926.[6]

FIGURE 8: AREAS OF VIRGIN FOREST IN 1620, 1850, AND 1926



---

[6] "U.S. Forest Facts and Historical Trends," Michigan Forests Forever Teachers Guide, https://mff.forest.mtu.edu/TreeBasics/Trends.htm (based on Forest Service and other data).



Source: Historical Atlas of the U.S.

In response to the increasing scarcity and cost of wood, alternative sources of energy were developed. During the course of the late 18th and 19th centuries, coal, which has an average energy density of around 27 MJ/kg and is present in great abundance below much of the earth's surface, gradually replaced wood as the primary source of energy.[7]

While wood had primarily been used as a source of heat for cooking and heating homes, the switch to more energy-dense, readily transportable, and highly abundant coal enabled the development of new technologies, most notably the steam engine, which in turn enabled much more efficient mechanization of manufacturing and transportation.

The switch away from burning wood also helped stop the decline in forest cover over the course of the past century, and there has even been some regrowth, as can be seen in Figures 9 and 10.

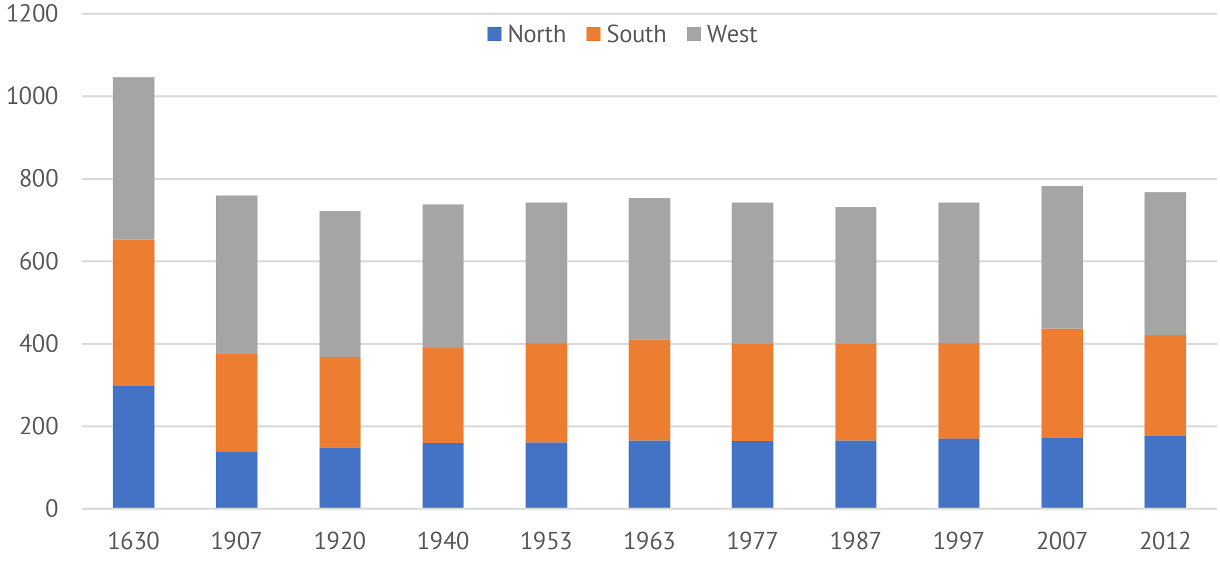
---

[7] Ibid. And see also this fact sheet: "Heat Values of Various Fuels," World Nuclear Association, http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

FIGURE 9: FOREST COVER IN THE U.S., 2000

Source: https://en.wikipedia.org/wiki/Forest_cover_by_state_and_territory_in_the_United_States#/media/File:Aboveground_Woody_Biomass_in_the_United_States_2011.jpg

FIGURE 10: CHANGE IN FOREST COVER IN THE U.S., 1630–2012, MILLIONS OF ACRES



Source: "U.S. Forest Facts and Historical Trends," Michigan Forests Forever Teachers Guide, https://mff.forest.mtu.edu/TreeBasics/Trends.htm (based on Forest Service and other data).

But while wood and coal provided thermal energy, or heat, neither were very efficient sources of light. Until the 19th century, the primary sources of light during the hours of darkness were tallow candles and oil lamps that burned lard. In the late 18th century, spermaceti, a waxy substance found in the head cavities of sperm whales, began to replace tallow as the most popular type of candle.[8] Spermaceti candles burned brighter and cleaner than tallow candles. And for a while sperm whales were very abundant, making spermaceti candles cheaper too.

The abundance of whales also led to the use of whale oil in lamps, where it was valued for the superior quality of light that it produced. Meanwhile, “The demonstrated demand for high-quality lighting spurred innovation and competition. Lard oil improved due to new refining techniques in the late 1830s, gas lighting companies operated in the five largest cities by 1840, and camphene [a mixture of alcohol and camphor] entered the lighting market in the 1830s.”[9]

Whale-oil lamps and others that burned camphene and lard became very popular and soon outstripped candles as the main source of light during darkness in the U.S. The popularity of these lamps led to increased demand for sperm whale oil.

By the end of the 19th century, whales were becoming scarce, reducing availability and driving up the price of spermaceti and whale oil.

By the end of the 19th century, whales were becoming scarce, reducing availability and driving up the price of spermaceti and whale oil.[10] Fortunately, an alternative had already

---

[8] Jane Brox, *Brilliant: The Evolution of Artificial Light,* (New York: Houghton Mifflin Harcourt, 2010). 42.

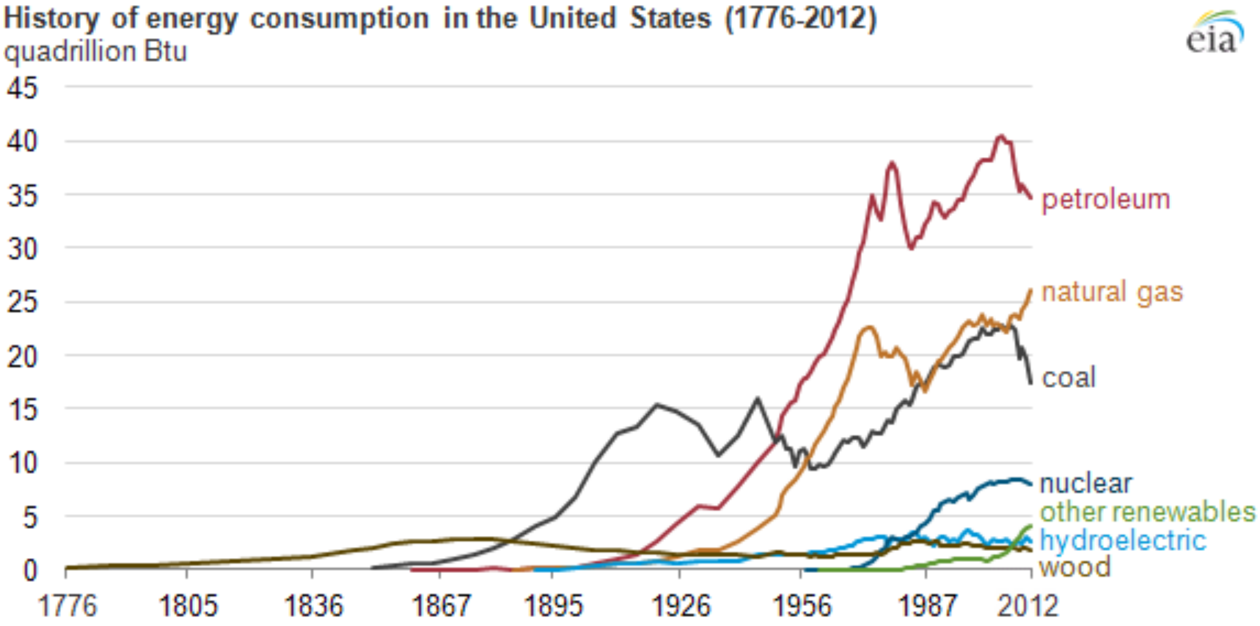
[9] Peter A. O'Connor and Cutler J. Cleveland, “U.S. Energy Transitions 1780–2010,” *Energies,* Vol. 7(12), 2014, 7955-7993, https://www.mdpi.com/1996-1073/7/12/7955/htm

[10] Lance E. Davis, Robert E. Gallman, and Karin Gleiter, *In Pursuit of Leviathan: Technology, Institutions, Productivity, and Profits in American Whaling, 1816-1906,* (Chicago: University of Chicago Press, 1997).

been discovered. In 1847, James Young developed a method for refining a light oil from petroleum that could be used in lamps.[11] Innovations in drilling and refining gradually increased availability and reduced the price of this substitute. As the price of whale oil rose, refined petroleum became the basis for both lamps and candles.

Wider availability of low-cost petroleum, meanwhile, stimulated the development of other uses for it. Petroleum-based fuels (including gasoline and diesel) are nearly twice as energy-dense as coal—providing around 45 MJ/kg—making them well suited for powering vehicles.[12] Following the development of the internal combustion engine, gasoline-powered vehicles soon displaced heavier, less-efficient coal-powered vehicles and horse-drawn vehicles.

FIGURE 11: CHANGES IN PRIMARY ENERGY IN THE U.S. OVER THE PAST 240 YEARS



Source: "Energy sources have changed throughout the history of the United States," Energy Information Administration, July 3, 2013. https://www.eia.gov/todayinenergy/detail.php?id=11951

In the past two decades, new extraction technologies have revolutionized the production of oil and natural gas, especially from shale deposits. As a result, the U.S. in particular has experienced a resurgence in oil and gas production—and a commensurate fall in the price

---

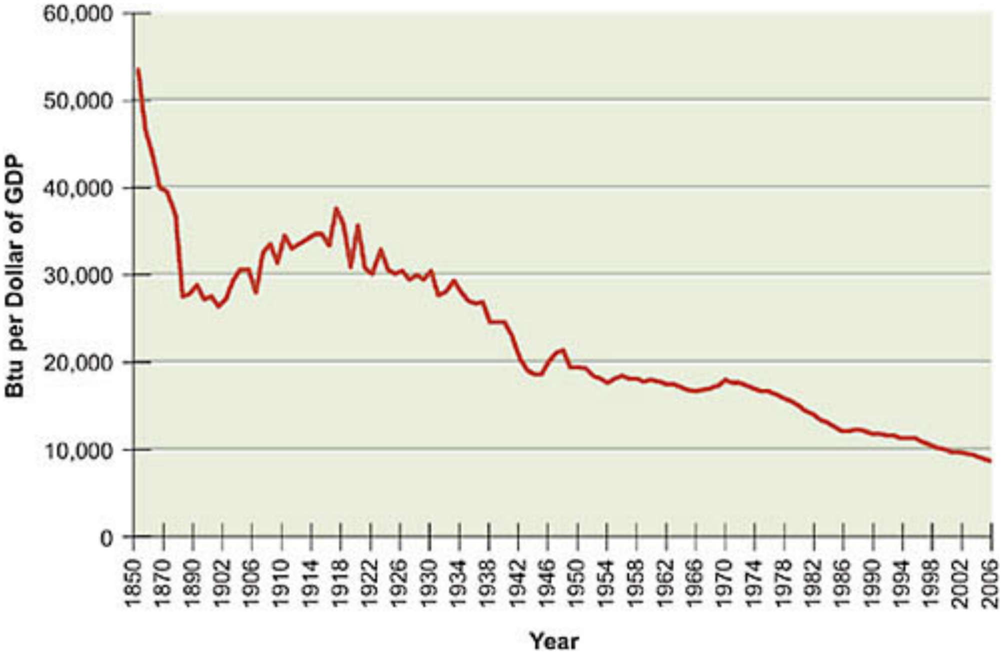
[11] Richard C. Selley, *Elements of Petroleum Geology*, 2nd Edition, (London: Academic Press, 1998).

[12] "Heat Values of Various Fuels," World Nuclear Association.

of these energy sources. With natural gas becoming plentiful and inexpensive, power generators and other heavy users of energy have shifted to the use of this fuel. Methane, the main constituent of natural gas, has an energy density of 55 MJ/kg (when liquefied)—about twice the density of bituminous coal.[13]

The shift toward denser fuels is a key reason for the long-term decline in energy use per dollar of GDP, as can be seen in Figure 12, which shows among other things the effect of the transition from wood to coal after 1850.

FIGURE 12: U.S. ENERGY USE PER DOLLAR OF GDP, 1850-2006



Source: ***Real Prospects for Energy Efficiency in the United States*****, (Washington, DC: National Academy of Sciences, 2010), Chapter 3. https://www.nap.edu/read/12621/chapter/3**

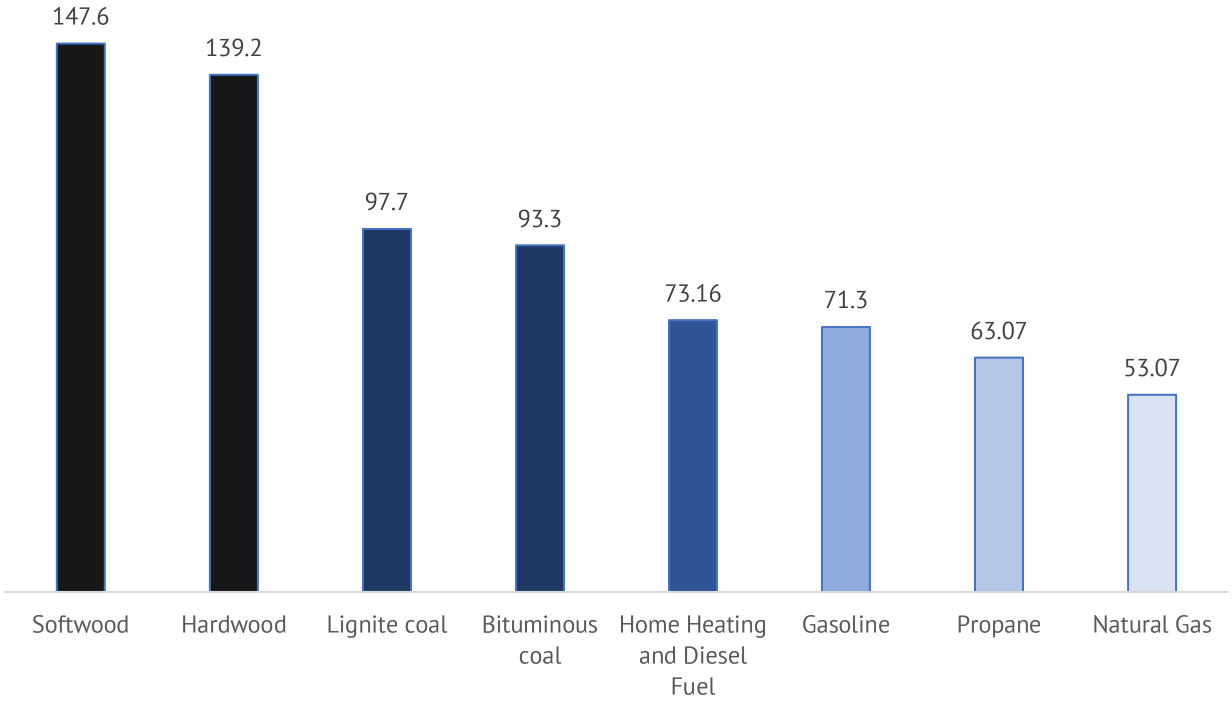
An important feature of these changes is the trend toward more energy-dense hydrocarbon fuels, such as methane, which have a higher hydrogen:carbon ratio (methane has between four and 12 times as many hydrogen atoms per carbon atom than coal, which means it releases about half the amount of carbon dioxide per unit of energy released than coal

---

[13] Ibid.

does).[14] So the shift toward denser fuels has also meant a reduction in emissions of carbon per unit of energy produced, as shown in Figure 13.[15]

FIGURE 13: CO_2 EMISSIONS (KG PER MILLION BTUS) FOR DIFFERENT HYDROCARBON FUELS



Source: Adapted by author from Energy Information Administration and Futuremetrics[16]

Hydrocarbon fuels still represent the vast majority of energy consumed in the U.S. (about 80% if one excludes biomass)–see Figure 14.

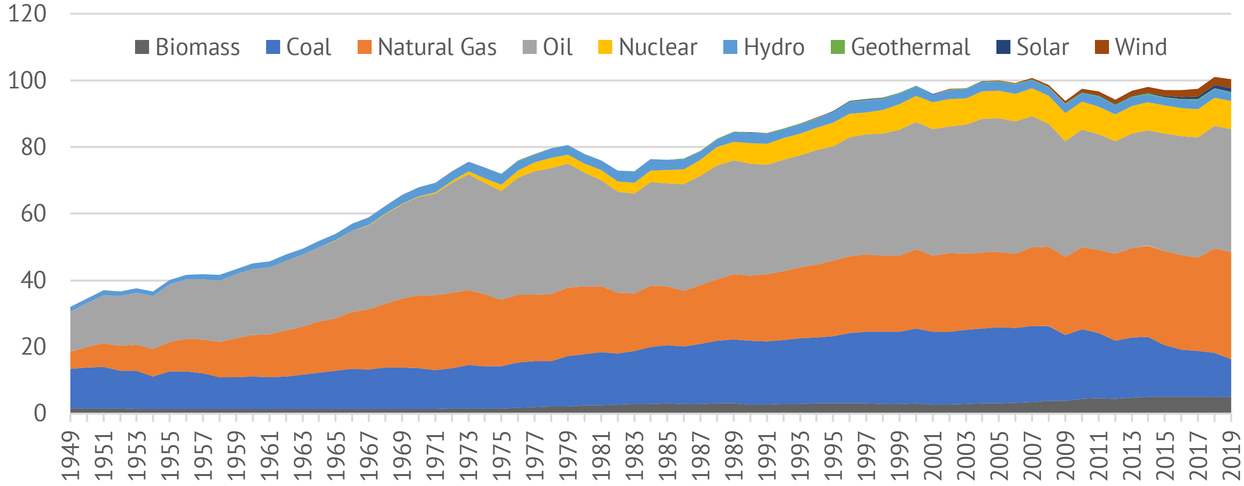
---

[14] In fuels with a higher hydrogen:carbon ratio, a greater proportion of energy is released through the oxidation of hydrogen. “Energy from Fossil Fuels,” West Oregon University, https://www.wou.edu/las/physci/GS361/Energy_From_Fossil_Fuels.htm

[15] The exception to the hydrogen:carbon ratio in the fuels shown is wood, which has about the same proportion of hydrogen as coal but relatively less carbon; however, its cellulosic structure and porosity make it less dense and more prone to contamination with water, which reduces its efficiency and leads to higher carbon dioxide emissions per unit of energy produced.

[16] Figures for all except wood from “Carbon Dioxide Emissions Coefficients,” U.S. Energy Information Administration, (https://www.eia.gov/environment/emissions/co2_vol_mass.cfm); wood based on William Strauss and Laurenz Schmidt, “A Look at the Details of CO_2 Emissions from burning Wood vs. Coal,” FutureMetrics, January, 2012, http://futuremetrics.info/wp-content/uploads/2013/07/CO2-from-Wood-and-Coal-Combustion.pdf (adjusted by assuming 20% moisture content).

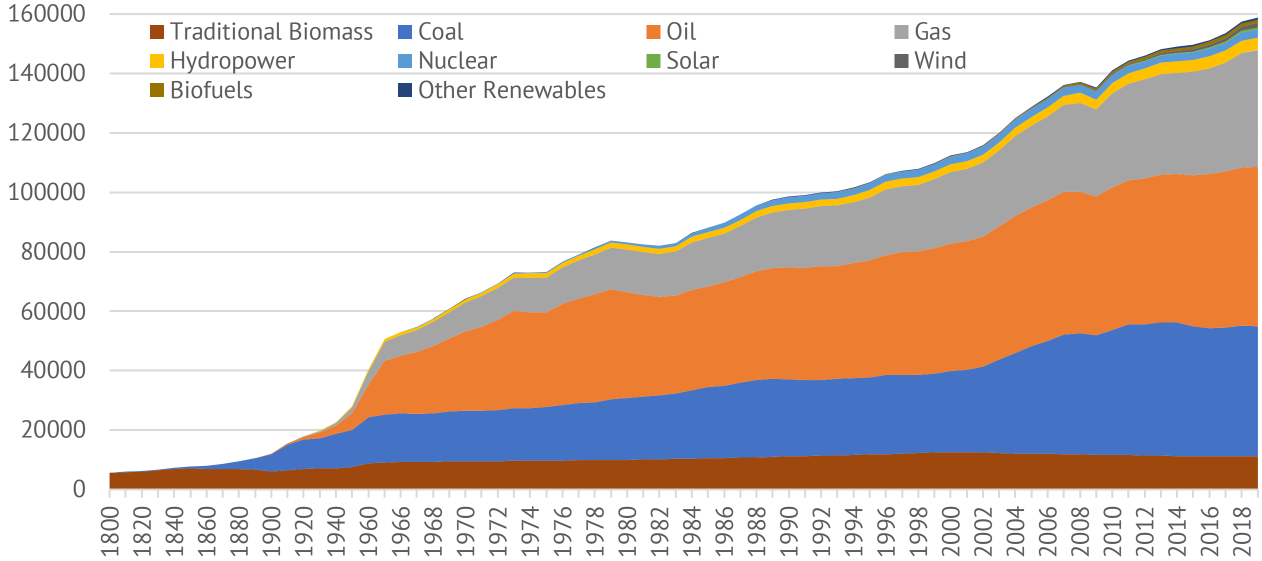
FIGURE 14: U.S. PRIMARY ENERGY CONSUMPTION BY FUEL SOURCE, QUADRILLION BTU



Source: U.S. Energy Information Administration, Monthly Digest, https://www.eia.gov/totalenergy/data/monthly/

Hydrocarbons represent an even greater proportion of energy consumed worldwide (over 90%)—see Figure 15. But the availability of natural gas has been increasing, which could lead to a reduction in coal use, as it has done in the U.S., with commensurate reductions in GHG emissions per dollar of output in the short term, and the cost of non-hydrocarbon sources of energy has been declining, which could lead to dramatic declines in emissions per dollar in the medium term; this is discussed in detail in Part 8.

FIGURE 15: TOTAL WORLD ENERGY CONSUMPTION BY FUEL SOURCE, TERAWATT HOURS (TWH)



Source: Hannah Ritchie and Max Roser, *Energy*, Our World in Data, https://ourworldindata.org/energy

PART 5

DEMATERIALIZATION

The transition from less-dense to more-dense forms of energy described in Part 4 has coincided with a huge number of other innovations that have improved the efficiency with which energy is used. Consider the case of cooking. Open hearth wood fires, which were first used by humans at least 1.5 million years ago, but are still used in many places today,[17] have a thermal efficiency of about 14%.[18] Around 20,000 years ago, hunter-gatherers living in what is now China developed ceramic pots that enabled heat to be retained more effectively.[19] Modern versions of such pots achieve an efficiency of around 24%.[20] The more-enclosed ovens that became common in Ancient Greece and Rome (and pizza ovens of today) achieve similar efficiencies. While numerous innovations and refinements evolved in subsequent millennia, the next significant invention in thermal efficiency was arguably the gas stove in 1828, which has an efficiency of about 36%.[21] Next came the electric

---

[17] John A.J. Gowlett and Richard W. Wrangham, "Earliest fire in Africa: towards the convergence of archaeological evidence and the cooking hypothesis," *Azania: Archaeological Research in Africa*, Vol 48 (1), 2013, 5-30, https://www.tandfonline.com/doi/full/10.1080/0067270X.2012.756754

[18] Grant Ballard-Tremeer and H.H. Jawurek, "Comparison of five rural, wood-burning cooking devices: Efficiencies and emissions," *Biomass and Bioenergy,* Volume 11, Issue 5, 1996, 419-430.

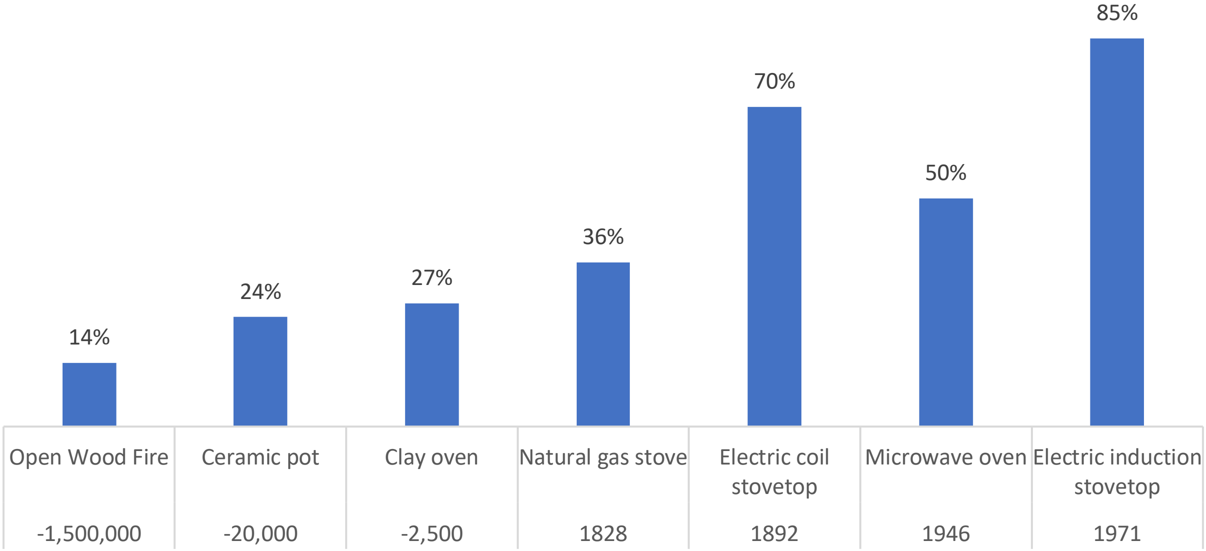
[19] X. *Wu et al., "Early Pottery at 20,000 Years Ago in Xianrendong Cave, China," Science, 336, 2012, 1696–1700.*

[20] Ballard-Tremeer and Jawurek, "Comparison of five rural, wood-burning cooking devices."

[21] Lisa Bramen, "Cooking Through the Ages: A Timeline of Oven Inventions," *Smithsonian Magazine,* November 18, 2011, https://www.smithsonianmag.com/arts-culture/cooking-through-the-ages-a-timeline-of-oven-inventions-380050/; S. Juglai, S. Tia and W. Trewetasksorn, "Thermal efficiency

stovetop, in 1892, which has an efficiency of about 70% (though of course this doesn't count the losses that occur during the generation and transmission of electricity). The microwave oven, first developed by Raytheon in 1946, offers numerous advantages for specific applications but is actually less efficient at boiling water than an electric coil stovetop.[22] The most efficient conventional cooking device currently on the market is the electric induction stovetop, which was invented in 1971, and has an efficiency of about 85%.[23] This evolution in cooking efficiency is summarized in Figure 16.

FIGURE 16: THE DEVELOPMENT OF MORE ENERGY-EFFICIENT COOKING TECHNOLOGIES



Sources: Ballard-Tremeer and Jawurek, "Comparison of five rural, wood-burning cooking devices;" Juglai, Tia, and Trewetasksorn, "Thermal efficiency improvement of an LPG gas cooker by a swirling central flame;" and Wirfs-Brock and Jacobson, "A Watched Pot."

While cooking technologies have been gradually evolving for millennia, most of the significant innovations occurred in the past two centuries and are associated with wider developments in the availability and use of increasingly energy-dense fuels, i.e. natural gas

---

improvement of an LPG gas cooker by a swirling central flame," *International Journal of Energy Research,* 25(8), 2001, 657-674 (noting that more recent swirling flame stove tops are about 50% efficient).

[22] Jordan Wirfs-Brock and Rebecca Jacobson, "A Watched Pot: What Is The Most Energy Efficient Way To Boil Water?" *Inside Energy,* February 23, 2016, http://insideenergy.org/2016/02/23/boiling-water-ieq/#:~:text=An%20electric%20stovetop%20is%20about,varies%20from%20kettle%20to%20kettle.

[23] Infrared stovetops have a similar efficiency—and have the advantage of working with a wider range of pans.

and coal (the latter being the main source of energy for the production of electricity until recently). This pattern of exponential innovation, which is directly tied to the development and use of more energy-dense fuels and electrification, is seen in many other technologies. For many modern products, the timeframes are even more compressed.

“

In general, today’s consumer products typically use far fewer resources per unit of output or service provided and result in fewer emissions, including of greenhouse gases, than equivalent products produced 10, 20, or 50 years ago.

”

In general, today’s consumer products typically use far fewer resources per unit of output or service provided *and* result in fewer emissions, including of greenhouse gases, than equivalent products produced 10, 20, or 50 years ago. The process by which this occurs is often called “dematerialization.”[24] Consider the examples described in the following subsections.

5.1 COMPUTERS

Computers offer probably the most astounding example of dematerialization. Early computers were vast, heavy, expensive, and slow. The ENIAC, for example, occupied about 1,800 square feet, weighed 30 tons, consumed 160 kilowatts of energy, cost $600,000 (in 1997 dollars), and was capable of processing only about 300 instructions per second.[25]

---

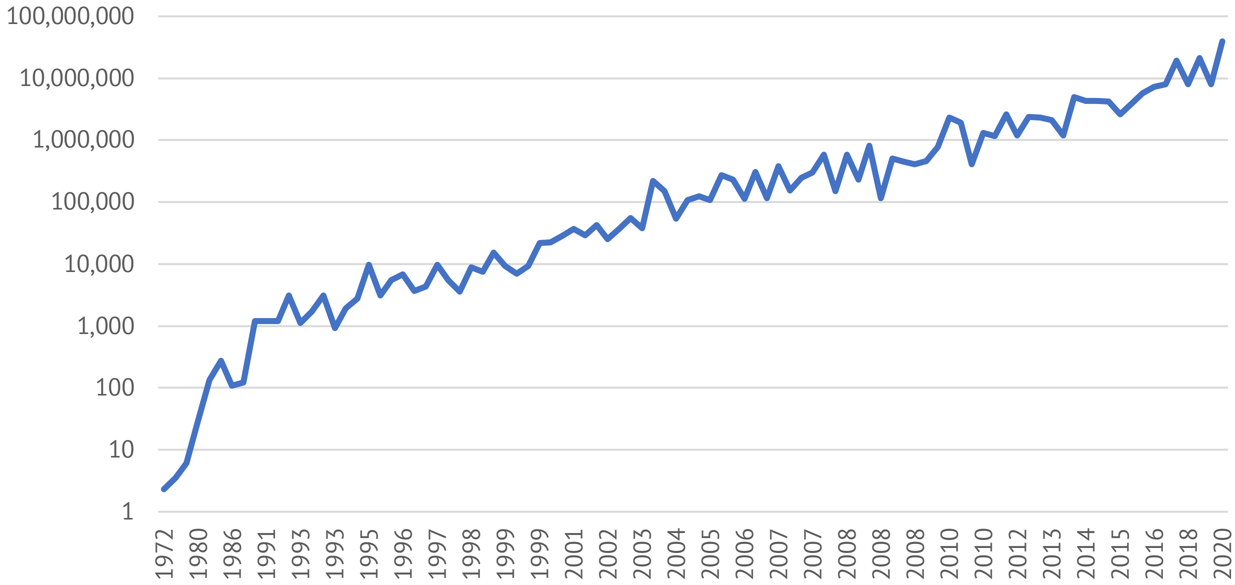
[24] The concepts underpinning dematerialization can be traced to Nathan Rosenberg’s work on innovation. See: Nathan Rosenberg, *Inside the Black Box: Technology and Economics,* (London: Cambridge University Press, 1982). The concept itself was first explored most explicitly in Robert Herman, Siamak A. Ardekani, and Jesse H. Ausubel, “Dematerialization,” *Technological Forecasting and Social Change,* Vol 38(4), 1990, 333-347.

[25] Mary Bellis, *The History of the ENIAC Computer,* ThoughtCo, Updated 7/31/2017, https://www.thoughtco.com/history-of-the-eniac-computer-1991601 and Hans Moravec, *Robot: Mere Machine to Transcend Mind,* (New York: Oxford University Press, 1998). https://www.frc.ri.cmu.edu/~hpm/book97/ch3/processor.list.txt

Today it is possible to purchase a fully functioning computer (the Raspberry Pi 400i) that processes over 2,000 million instructions per second, fits inside its own conventional-looking keyboard, offers numerous ports, consumes about 15W of power, and costs only $70.[26]

Much of the advance in computing power and reductions in size and cost has come from developments associated with the microprocessor. In 1965, Gordon Moore, co-founder of chip maker Intel, observed that the density of microprocessors had doubled every year since 1958 and predicted that such an exponential increase in density would continue.[27] This relationship became known as Moore's law—and it has held more or less consistently since Moore made it—see Figure 17.

FIGURE 17: MOORE'S LAW: TRANSISTORS PER MICROPROCESSOR (LOG SCALE)



Source: Karl Rupp, "48 Years of Microprocessor Trend Data," https://github.com/karlrupp/microprocessor-trend-data/tree/47382e2e3c653d71ebae66d8e8aecc088866543d/48yrs

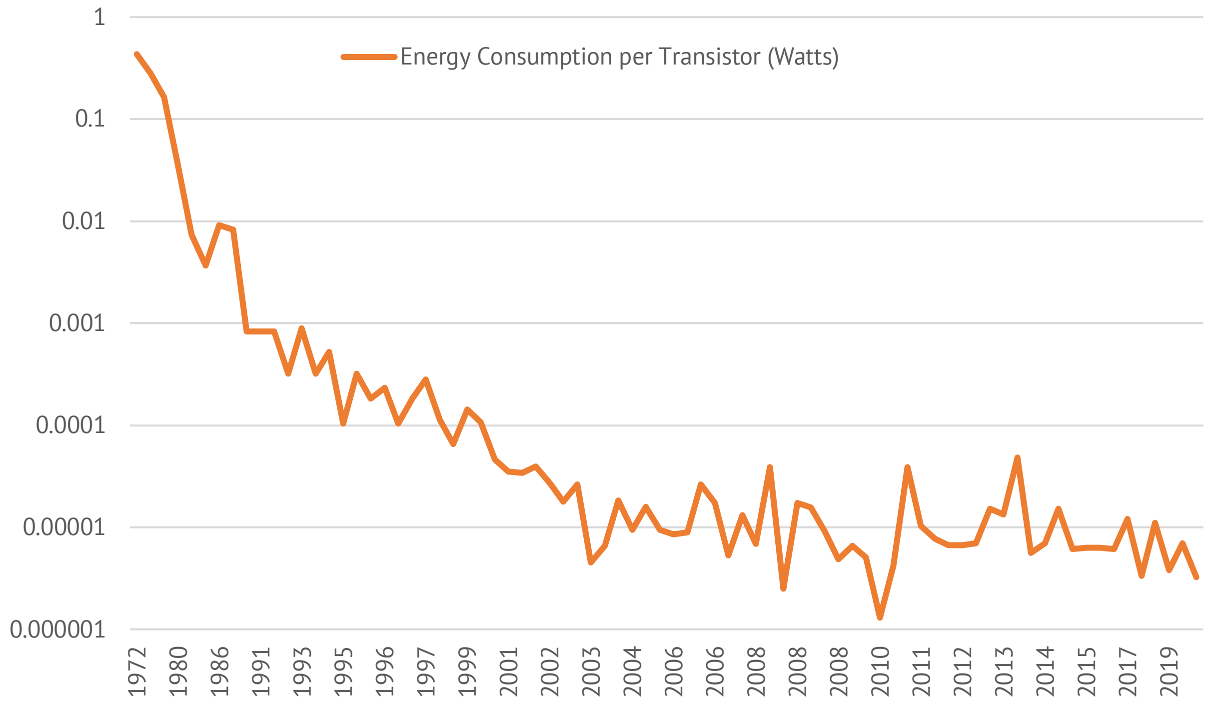
---

[26] In some respects, the earlier Raspberry Pi Zero W is even more impressive: It can process over 800 MIPS and consumes only one watt of power. Nick Heath, "Raspberry Pi Zero W: Hands-on with the $10 board." *Techrepublic.com.* February 28, 2017, http://www.techrepublic.com/article/raspberry-pi-zer o-wireless-hands-on/; and "How much power does Pi Zero W use?" RasPi.TV, http://raspi.tv/2017/how-much-power-does-pi-zero-w-use; (0.18 amps at 5.19 volts = 0.93 watts).

[27] Michael (Siyang) Li, "Keeping Up with Moore's Law," *Dartmouth Undergraduate Journal of Science,* May 29, 2013, http://dujs.dartmouth.edu/2013/05/keeping-up-with-moores-law/#.WSh8j2jyvb0

While energy consumption per microprocessor has increased over the same time, that has occurred at a more or less linear rate. As a result, the energy consumption *per transistor* has declined logarithmically, as can be seen in Figure 18.

FIGURE 18: ENERGY CONSUMPTION PER TRANSISTOR (WATTS, LOG SCALE)



Source: Author's calculations based on Karl Rupp, "48 Years of Microprocessor Trend Data." https://github.com/karlrupp/microprocessor-trend-data/tree/47382e2e3c653d71ebae66d8e8aecc088866543d/48yrs

5.2 DATA TRANSMISSION

Over the course of the past three decades, there has been a dramatic shift in the way that data are transmitted. Of particular significance is the switch from copper cables to fiber optic cable. That has entailed a significant reduction in energy and natural resource use relating to the materials themselves. A kilogram of fiber optic cable can carry about 100,000 times as much data as a kilogram of copper cable.[28] Meanwhile, according to Dow Corning, the production of two kg of copper, enough for 200 meters of cabling, releases about 1,000kg of CO_2e, whereas the production of an equivalent length of fiber-optic cable

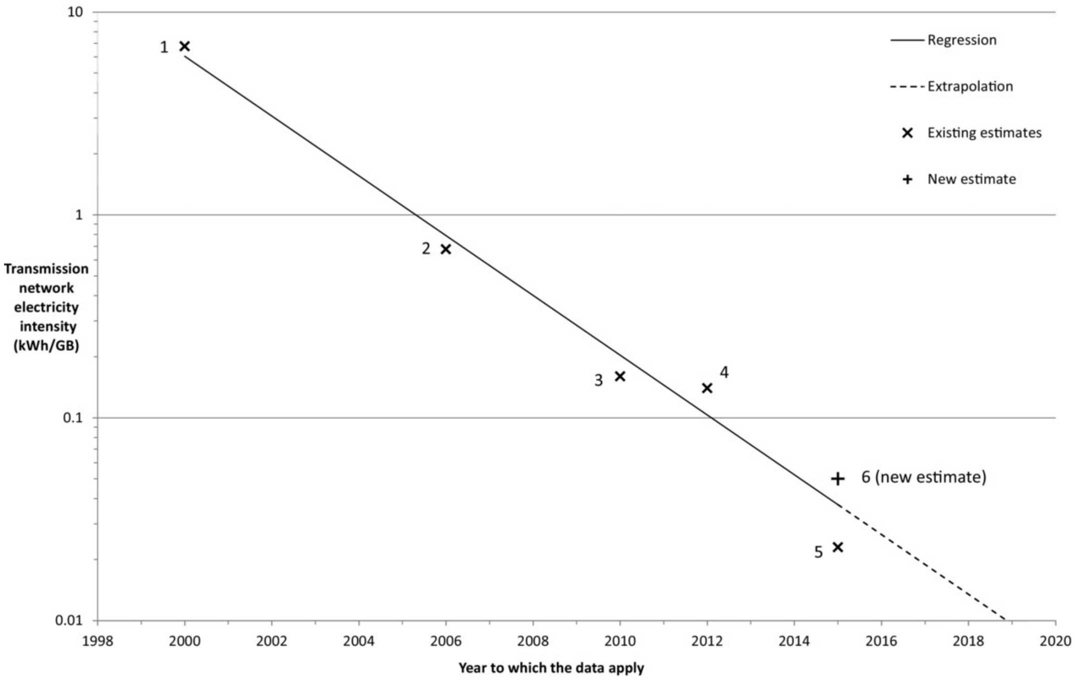
---

[28] Karthikeya Boyini, "Comparison of Fiber Optics and Copper Wire," Tutorials Point, August 2, 2018, https://www.tutorialspoint.com/Comparison-of-Fiber-Optics-and-Copper-Wire

releases only about 0.06kg of CO_2e.[29] In other words, per GB of installed data transfer capacity, fiber is 167 million times as efficient as copper in terms of emissions of CO_2e.

In addition, the switch from copper to fiber optic cable and efficiency improvements of the latter have resulted in an astounding reduction in emissions per GB of data transferred. Figure 19 shows the decline in energy use (kWh) per gigabyte (GB) of data transfer on the Internet from 2000 to 2015.[30] As can be seen, the reductions in energy use follows a similar pattern to Moore's law.

FIGURE 19: ENERGY INTENSITY OF INTERNET DATA TRANSMISSION (KW/GIGA BYTE, LOG SCALE)



Source: Joshua Aslan, Kieren Mayers, Jonathan G. Koomey, and Chris France, "Electricity Intensity of Internet Data Transmission: Untangling the Estimates," *Journal of Industrial Ecology*, Vol. 22(4), 2017, 785-798, Figure 3.

---

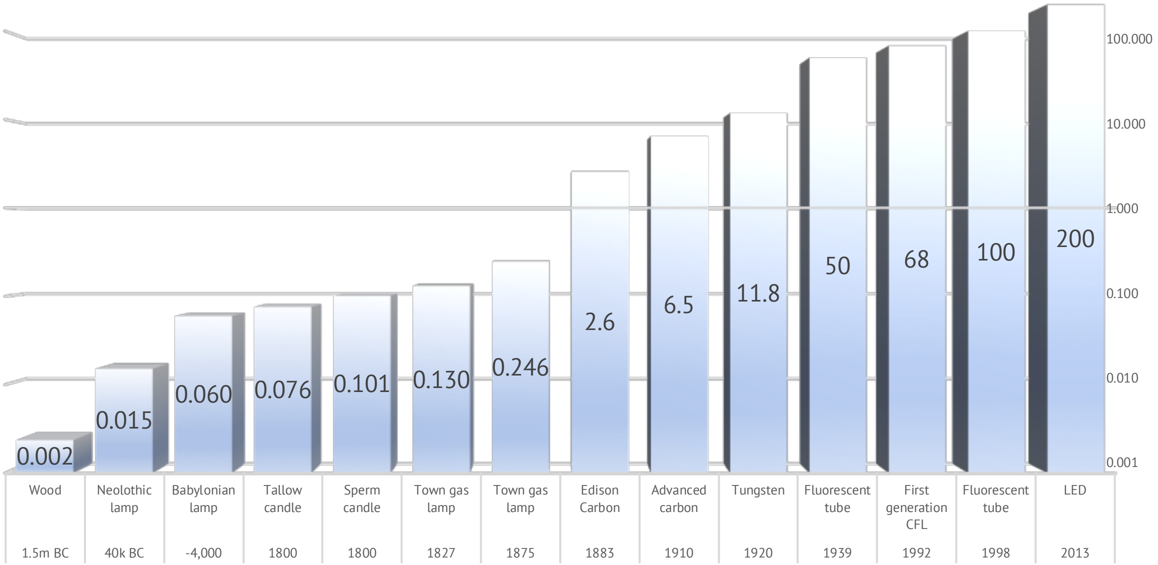
[29] Martin Sedgwick, *Our digital infrastructure needn't cost the earth,* Carbon Smart and City Fibre, 2019. https://www.cityfibre.com/wp-content/uploads/2018/04/Carbon-Smart-Our-digital-infrastructure-neednt-cost-the-earth-1.pdf, citing a study by Dow Corning.

[30] Joshua Aslan, Kieren Mayers, Jonathan G. Koomey, and Chris France, "Electricity Intensity of Internet Data Transmission: Untangling the Estimates," *Journal of Industrial Ecology,* Vol. 22(4), 2017, 785-798, https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12630

5.3 LIGHTING

Figure 20 shows the development of lighting technologies, from wood fires to LEDs, which shows an exponential rate of improvement. In the first 1.5 million years of human existence, lighting efficiency rose about 10-fold, from 0.002 lumens/watt of a typical open fire around 1.5 million years ago to 0.015 lumens/watt of a neolithic oil lamp.[31] From 40,000 years ago to 4,000 years ago, efficiency quadrupled to 0.06 lumens/watt. It then rose slowly until the development of town gas lamps in 1827, which had an efficiency of about 1.3 lumens/watt.[32] Following the invention of the electric filament lamp, efficiency suddenly grew dramatically, from 2.6 lumens/watt for Edison's original lamp in 1883, to 50 lumens/watt for early fluorescent tubes in 1950, to 200 lumens/watt for modern LEDs.[33] In just 200 years, the efficiency of light sources has increased over 1,000 fold.

FIGURE 20: ENERGY EFFICIENCY OF LIGHT SOURCES (LUMENS PER WATT, LOG SCALE)



Sources: Nordhaus, *Do Real-Output and Real-Wage Measures Capture Reality?*; Phillips, "Lighting world first"; and Hyperikon, "Luminous Efficiency."

---

[31] William Nordhaus, *Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not.* Yale University Cowles Foundation Paper No. 957, 1998.

[32] Ibid.

[33] Phillips, "Lighting world first: Philips breaks 200 lumens per watt barrier," 2013, https://www.philips.com/consumerfiles/newscenter/main/design/resources/pdf/Inside-Innovation-Backgrounder-Lumens-per-Watt.pdf ; Hyperikon, "Luminous Efficiency," https://www.hyperikon.com/hub/basics/luminous-efficacy/

5.4 FOOD PRESERVATION

Humans have been preserving foods for thousands of years, using techniques such as drying, fermenting, pickling, curing, and storing in solutions of sugar or honey.[34] These techniques enable food to be stored with minimal spoilage for far longer than otherwise would have been the case, providing sustenance during winter months when food is scarcer. But such techniques are resource-intensive and unsuitable for many types of food.

The development of modern food preserving systems, beginning with the steel can at the end of the 18th century, dramatically increased the efficiency of preservation, enabling a wider variety of food to be stored for longer and distributed further afield than had previously been possible. During the 20th, numerous innovations, including more-effective refrigeration, accelerated this process. Aseptic (bacteria-free) packaging, first developed by Tetra Pak in 1961,[35] has enabled the distribution of a wider range of liquid products with long shelf-lives that do not require refrigeration.

5.5 BEVERAGE CANS

Until the early 1970s, nearly all beverage cans were made from steel. When empty, a 12-ounce can from that era weighed about 1.7 ounces.[36] By contrast, a similar can from 2010 weighed about 0.7 ounces—a reduction of around 60%.[37] When aluminum beverage cans were first introduced in the 1960s, a 12-ounce can weighed about 0.66 ounces. By 1994, the vast majority of beverage cans in the U.S. were made from aluminum and typically weighed 0.48 ounces—about 30% less than their 1960s counterparts.[38] Similar “lightweighting” improvements have occurred in many areas of packaging.[39] The reduction

---

[34] Brian A. Nummer, *Historical Origins of Food Preservation,* National Center for Home Food Preservation, May 2002, https://nchfp.uga.edu/publications/nchfp/factsheets/food_pres_hist.html

[35] Tetra Pak, “History,” https://www.tetrapak.com/about/history

[36] *The Beverage Can: A White Paper*, Can Makers, 2010, https://canmakers.metalpackagingeurope.org/sites/default/files/downloads/The-Beverage-Can-A-White-Paper.pdf

[37] Ibid.

[38] William F. Hosford and John L. Duncan, “The Aluminum Beverage Can,” *Scientific American,* September 1994. 48–53, http://www.chymist.com/Aluminum%20can.pdf

[39] Flexible Packaging Association, “Lightweight Advances in Flexible Packaging: FPA Member Case Stories,” https://www.flexpack.org/assets/1/6/FPA_Lightweighting_Case_Stories.pdf

in packaging weight has reduced energy and resource use in the production of packaging, as well as lowered transportation costs and associated emissions per item shipped.

> *The reduction in packaging weight has reduced energy and resource use in the production of packaging, as well as lowered transportation costs and associated emissions per item shipped.*

5.6 SYNERGIES AND THE SINGULARITY

While this process of dematerialization has been going on for decades, if not centuries, recent developments may be speeding it up. The ability to transfer data over the Internet has reduced the use of physical resources that previously were used to deliver all manner of products, from books, magazines, and newspapers to music and movies. Estimates suggest that delivery of audio and video content via the Internet has significantly reduced energy consumption and associated emissions.[40]

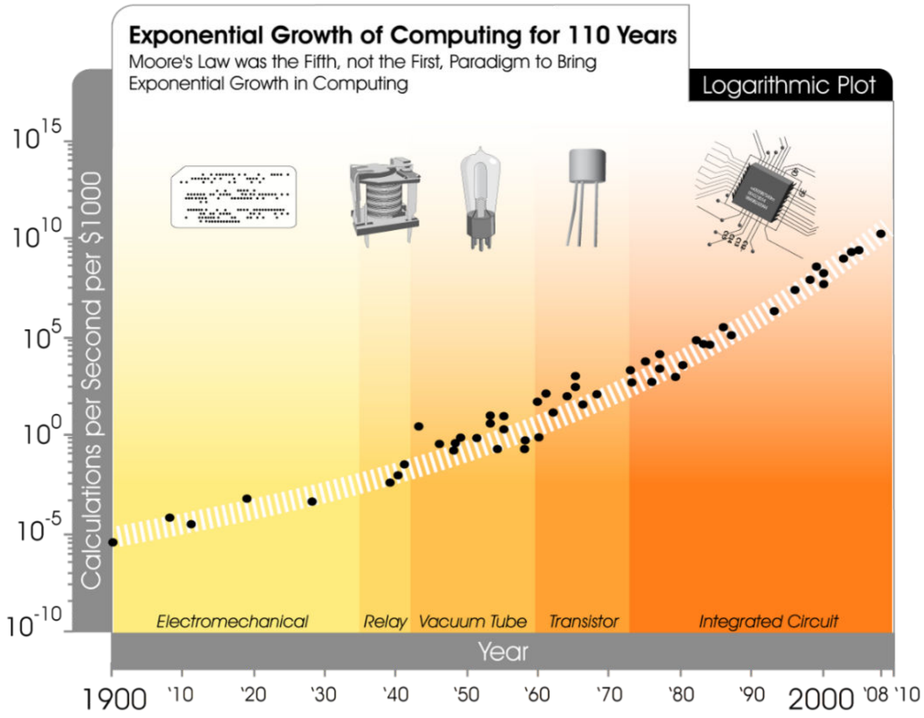
To be sure, many people continue to read books and newspapers made from paper—and some people still buy CDs, DVDs, Blu Ray discs and even LPs. But the trend toward dematerialization seems inexorable as the quality of virtual products available improves and cost declines. Ray Kurzweil has extended Moore's law back to 1900, to show that it applies to previous generations of information processing devices—see Figure 20. And Kurzweil, somewhat speculatively, has extended the concept to other areas of technological development, making the case that innovation is accelerating.[41]

---

[40] Christopher L. Weber, Jonathan G. Koomey, and H. Scott Matthews, "The Energy and Climate Change Implications of Different Music Delivery Methods," *Journal of Industrial Ecology,* V 14(5), 2010, 754-769; and Arman Shehabi, Ben Walker, and Eric Masanet, "The energy and greenhouse-gas implications of internet video streaming in the United States," *Environmental Research Letters,* Vol 9(5), 2014.

[41] Ray Kurzweil, "The Law of Accelerating Returns," March 7, 2001, http://www.kurzweilai.net/the-law-of-accelerating-returns

FIGURE 21: KURTZWEIL'S EXTENSION OF MOORE'S LAW (CALCULATIONS PER SECOND PER $100, LOG SCALE)



Source: Ray Kurzweil, "Exponential Growth of Computing," April 9, 2010. https://www.kurzweilai.net/exponential-growth-of-computing#!prettyPhoto

A word of caution comes from Rob Gordon, who notes that growth in productivity has declined in spite of an apparent increase in innovation.[42] Meanwhile, Tyler Cowen and Ben Southwood have argued that innovation itself has slowed, as a result (in part at least) of specialization and bureaucratization.[43] However, in light of the rapid changes that have occurred in the past year, it is possible that these trends are reversing, with new technology leading to increased productivity and rapid innovation now occurring in many areas, especially biomedical research, not to mention some of the innovations discussed later in this paper.[44]

---

[42] Robert J. Gordon, "Why Has Economic Growth Slowed When Innovation Appears to Be Accelerating?" NBER Working Paper 24554, April 2018, http://www.nber.org/papers/w24554

[43] Tyler Cowen and Ben Southwood, "Is the rate of scientific progress slowing down?" George Mason University Working Paper in Economics No. 21-13, August 5, 2019, https://ssrn.com/abstract=3822691

[44] Tyler Cowen, "What might an end to the Great Stagnation consist of?" *Marginal Revolution*, December 13, 2020, https://marginalrevolution.com/marginalrevolution/2020/12/why-did-the-great-stagnation-end.html

PART 6

THE CAUSES OF INCREASES IN ENERGY DENSITY AND DEMATERIALIZATION

In this study, we are ultimately interested in understanding which policies might most cost-effectively reduce global emissions of carbon dioxide and other GHGs. Given the importance of increases in energy density and reductions in use of energy per unit of output as drivers of changes in those emissions, it is helpful to understand what caused the innovations that have so far occurred.

6.1 OPPORTUNITY, COMPETITION, AND INNOVATION

At an abstract level, all innovations, ultimately, are driven by individuals acting in response to perceived opportunities. In the case of innovations that led to the increases in energy density discussed in Part 3 and the increases in energy efficiency in Part 4, a key perceived opportunity was the ability to reduce the cost of energy inputs to producers and consumers. By reducing the costs of inputs to products, a producer can keep prices down, making them more attractive to consumers. However, consumers are interested not only in the purchase price of a product but also its operating cost. So, producers may seek opportunities to lower the operating costs of a product such that for at least some consumers the total cost of ownership is reduced. (The total cost of ownership will vary depending on the usage of the product, which will typically not be the same for every consumer.) This has the effect of making such a product more attractive to some consumers even if the purchase price is higher than less-efficient products.

The need to identify and act on such opportunities is especially important when there are competing suppliers, since each supplier will seek to identify ways to reduce costs and thereby win customers. As such, competition is of fundamental importance to the process of innovation.

> *…competition is of fundamental importance to the process of innovation.*

The opportunity to reduce the cost of energy inputs largely explains changes in the sources of primary energy over the past 200 years, especially the shift from wood to coal to natural gas, as described in Part 3. Meanwhile, the opportunity to reduce total costs of operations explains the development and improvement of the steam engine, steam turbine (which generates electricity), internal combustion engine, and diesel engine. It also explains, in part at least, the development of lighter-weight containers because energy is required not only to produce but also to transport such containers. And it helps explain the development of aseptic containers, which do not require refrigeration, thereby reducing the energy needed to store foods and liquids.

But reducing the cost of energy inputs was not the only opportunity driving improvements in energy efficiency. In many cases, the opportunity was improved performance. This is true for the development of electricity as a source of power, which was initially expensive to install but offered enormous convenience and improved safety compared to light from gas and candles. It is also true for automobiles, which were faster than horses and did not require naps. And it is true for increases in the density of transistors on microprocessors.

6.2 MORE, FROM LESS

Once these performance-enhancing innovations had occurred, competition led to further innovations that drove down costs. Seeing an opportunity to profit from mass production, Henry Ford implemented production-line systems, thereby driving down the cost of producing cars.[45] Likewise, Nikola Tesla developed a high-voltage alternating current system, which enabled electricity to be distributed over distance at much lower cost than Thomas Edison's direct current system, and thus made more-efficient, large-scale centralized generation feasible.[46] Gordon Moore and Robert Noyce, founders of Intel, identified more-effective ways to miniaturize transistors and pack them more densely on chips at lower cost.[47]

> “*Once the opportunity to produce at scale was identified, competitors have continuously sought to develop better, less costly ways to supply consumers—with cars, electricity, computers, and all manner of other products.*”

But, of course, such innovations did not begin or end with Ford, Tesla, and Moore. Ford didn't even invent the production line—he copied it from Chicago meatpackers who had been using it since the 1870s.[48] Once the opportunity to produce at scale was identified, competitors have continuously sought to develop better, less costly ways to supply

---

[45] *Henry Ford: Assembly Line*, The Henry Ford Museum, 2013. https://www.thehenryford.org/collections-and-research/digital-collections/expert-sets/7139/

[46] Bernard Carlson, “Edison and Tesla's cutthroat ‘Current War' ushered in the electric age,” *History Magazine,* September 27, 2019, https://www.nationalgeographic.com/history/magazine/2016/07-08/edison-tesla-current-war-ushered-electric-age/

[47] Intel, *Intel's Founding,* Intel, https://www.intel.com/content/www/us/en/history/virtual-vault/articles/intels-founding.html

[48] “Swift & Company's Meat Packing House, Chicago, Illinois, “Splitting Backbones and Final Inspection of Hogs,” 1910-1915,” The Henry Ford Museum, 2013, https://www.thehenryford.org/collections-and-research/digital-collections/artifact/354536/

consumers—with cars, electricity, computers, and all manner of other products. And as costs have fallen, access has increased, leading to more widespread adoption, which in turn has created opportunities for further cost reductions as well as quality improvements.

Thus, contrary to those who argue that economic growth necessarily entails ever increasing use of resources,[49] under the right conditions, the development and adoption of new technologies can result simultaneously in economic growth and aggregate dematerialization. Moreover, this process can become self-reinforcing. Indeed, as Andrew McAfee shows, that is precisely what has happened over the past quarter-century in the United States.[50]

So, what are the conditions that enable countries to move past "peak-stuff" and produce "more from less"? McAfee argues that there are four drivers (he calls them "the four horsemen of the optimist"): technology, capitalism, public awareness, and responsive government.

6.3 ECONOMIC GROWTH, INSTITUTIONS, AND PEAK GHG EMISSIONS

Related to McAfee's "more from less" is a concept known as the environmental Kuznets curve ("EKC"), which has found an inverted U relationship between economic activity (i.e. GDP per capita) and various measures of resource use and pollution. That is to say: initially, as GDP/capita increases, measures of environmental degradation worsen; at a certain level of GDP/capita, the degradation peaks; and at higher levels of GDP/capita, it falls, often precipitously. Figure 22 is a graphical representation of the EKC, while Tables 1 and 2 provide example estimates of the turning point for some environmental variables (amounts are GDP per capita adjusted for inflation).

---

[49] Such claims have been made for decades. A recent example is Janez Sušnik, *Economic Growth & Resource Use – What's the Link?* United Nations University, 2016. http://collections.unu.edu/eserv/UNU:5622/DNC2015_PolicyBrief_No1.pdf

[50] Andrew McAffee, *More from Less, (*New York: Scribner, 2019).

FIGURE 22: THE ENVIRONMENTAL KUZNETS CURVE (Y AXIS IS ENVIRONMENTAL DEGRADATION)

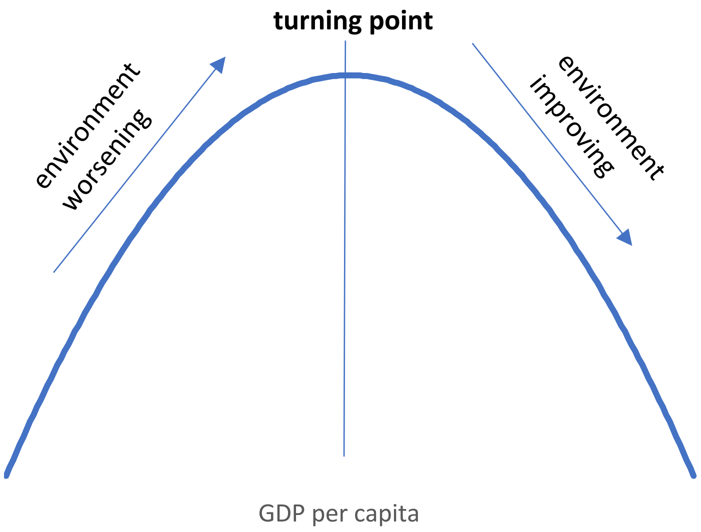


TABLE 1: EKC TURNING POINTS FOR WATER POLLUTION (GDP PER CAPITA, 2021 US$)

Pollutant	Turning Point
Lead	$25,935
Fecal coliform	$19,760
Chemical oxygen demand	$19,513
Biological oxygen demand	$18,772
Cadmium	$12,350
Arsenic	$12,103
Total coliform	$7,410
Dissolved oxygen	$6,669
Nitrates	$4,940

Source: Adapted from Grossman and Krueger, “Economic growth and the environment.”

TABLE 2: RANGE OF EKC TURNING POINTS FOR AIR POLLUTION (GDP PER CAPITA, 2021 US$)

Pollutant	**Turning Point (2021 US$)**	
	Low	High
Nitrogen Oxide	$36,309	$37,297
Carbon Monoxide	$24,453	$24,947
Suspended particulates	$18,031	$20,007
Sulfur dioxide	$14,079	$17,043

Source: Matthew Cole, A.J. Rayner and J.M. Bates, "The environmental Kuznets curve: an empirical analysis," ***Environment and Development Economics,*** **Vol. 2(4), 1997, 401-416.**

There is solid empirical evidence for the existence of the EKC for certain pollutants, both internationally and domestically in the U.S.[51] There is also evidence of an EKC for land conservation.[52] But like Moore's law, the EKC is just an empirical observation. Nonetheless, it also has some intuitive appeal. Higher GDP/capita can lead directly to improvements in the environment because wealthier people can afford less-polluting technologies (electric or gas fired heating, for example, is far less polluting than poorly flued wood fires)[53] and set aside more land for conservation. But places with higher GDP/capita also tend to have better, more-responsive institutions, including stronger legal protections against pollution (both from private law and from public law).[54] Indeed, in most cases places with higher

---

[51] Thomas M. Selden and Daqing Song, "Environmental quality and development: is there a Kuznets curve for air pollution emissions?" *Journal of Environmental Economics & Management,* 27, 1994, 147–162; George Grossman and Alan Krueger, "Economic growth and the environment," *Quarterly Journal of Economics,* 3, 1995, 53–77; Douglas Holtz-Eakin and Thomas Selden, "Stoking the fires? CO2 emissions and economic growth," *Journal of Public Economics,* 57, 1995, 85–101; and John A. List and Craig A. Gallet, "The environmental Kuznets curve: does one size fit all?" *Ecological Economics,* 31, 1999, 409–423.

[52] Enrico Maria Mosconi, et al., "Revisiting the Environmental Kuznets Curve: The Spatial Interaction between Economy and Territory," *Economies,* 8, 2020, 74 and Richard J. Culas, "Deforestation and the environmental Kuznets curve: An institutional perspective," *Ecological Economics,* 61(2), 2007, 429-437.

[53] Nigel Bruce et al., "Indoor air pollution in developing countries: a major environmental and public health challenge," *Bulletin of the World Health Organization,* 78 (9), 2000, 1078-1092, https://www.who.int/bulletin/archives/78(9)1078.pdf

[54] Bruce Yandle, "Environmental Turning Points and the Race to the Top," *Independent Review,* IX (2), 2004, 211-226, https://www.independent.org/pdf/tir/tir_09_2_3_yandle.pdf and Culas "Deforestation and the environmental Kuznets curve."

GDP/capita have become wealthy because those underlying institutions are more supportive of technological innovation, which is ultimately the source not only of the higher output but also more resource-efficient production and products.[55]

> *… places with higher GDP/capita also tend to have better, more-responsive institutions, including stronger legal protections against pollution (both from private law and from public law).*

Economists have understandably been intrigued by the possibility that there might be an EKC for GHGs and have undertaken dozens of studies. While some of these found an EKC effect, others did not, and most were inconclusive.[56] One reason for this is that the research has tended to focus narrowly on the relationship between GDP/capita and GHG emissions. Moreover, most studies were of either one country or a small subset of countries with similar institutional environments. Such studies thus effectively preclude any assessment of the role of institutions. They also miss the potential for dynamic change—i.e. changes over time in the level of GDP/capita at which emissions begin to decline as a result of innovations (such dynamic change is implicit in the simplistic projection of GHG emissions per unit of GDP described in Part 2 of this study).

However, a recent study did look at the relationship between GHG emissions/capita, GDP/capita, and the set of institutional quality measures used in the Fraser Institute's Economic Freedom of the World (EFW) index. [57] The study, undertaken by Christian

---

[55] Daron Acemoglu, Simon Johnson, and James A. Robinson, "Institutions as the Fundamental Cause of Long-Run Growth," NBER Working Paper W10481, May 2004, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=541706; and Dani Rodrik, A. Subramanian, and F. Trebbi, "Institutions Rule: The Primacy of Institutions over Geography and Integration in Economic Development," *Journal of Economic Growth,* 9(2), 2004, 131-165.

[56] Muhammad Shahbaz and Avik Sinha, *Environmental Kuznets Curve for CO2 Emission: A Literature Survey,* (Munich: MPRA, 2018). https://mpra.ub.uni-muenchen.de/86281/1/MPRA_paper_86281.pdf

[57] *Economic Freedom in the World,* (Vancouver: Fraser Institute, 2020). https://www.fraserinstitute.org/economic-freedom/approach

Bjørnskov, a professor of economics at the University of Aarhus in Denmark, used data from 155 countries at five-year increments starting in 1975, and its findings are noteworthy:[58]

- First, excluding autocracies and major oil producers, on average, per capita emissions of CO_2 rise until a country reaches a per capita income of about $85,000, after which they fall.
- Second, the level of GDP at which per capita CO_2 emissions begin to fall is lower in countries with more economic freedom; for countries with an economic freedom rating of eight or more, which is approximately the top 10% most free countries, the turning point is per capita income of about $63,000. Thus, for "rich, economically free democracies such as Australia, the U.S., Canada, and large parts of Northern Europe" per capita CO_2 emissions would appear to have peaked and are now declining.
- Third, peak CO_2 emissions may have also been reached in several middle-income countries that rank highly on measures of economic freedom, including Chile, Costa Rica, and Panama.
- Fourth, the turning point for per capita emissions of all GHGs would appear to be significantly lower than for CO_2. For countries that scored eight or higher on economic freedom, the turning point came at a GDP per capita of about $25,000.

Moreover, Prof. Bjørnskov found that when he analyzed the effects of different components of the EFW index on GHG emissions, the two components that were most highly correlated were (a) quality of the legal system (comprising measures of the protection of property rights, enforceability of contracts, and adherence to the rule of law (i.e. judicial independence, etc.)) and (b) policy quality (being a composite of sound money, freedom to trade, and the absence of overly restrictive regulation). As a result, Prof. Bjørnskov's concludes that for GHGs, "further economic development is likely to lead to reduced emissions in most Western societies, as long as their policies are consistently economically free."[59] And he observes, again for GHGs as a whole:

---

[58] Christian Bjørnskov, "Economic Freedom and the CO2 Kuznets Curve," Working Paper: Aarhus University and Research Institute of Industrial Economics, 8 January 2020. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3508271

[59] Ibid.

> *Overall, although the theoretical considerations are decidedly mixed, the empirical evidence is not. Environmental Kuznets Curves are typically situated to the left in economically free societies, indicating earlier adoption of clean technology and faster transition towards a low-emissions society. Conversely, although many of them proclaim a better environment as a central political aim, interventionist governments are likely to achieve the opposite.*

In other words, the most effective way to achieve a reduction in GHG emissions is to ensure that markets are free to operate, supported by solid legal institutions, and not overly burdened by regulatory restrictions.

6.4 IS THERE A ROLE FOR GOVERNMENT REGULATION AND/OR SUBSIDIES?

So far, little has been said about attempts by governments to stimulate improvements in energy density and/or dematerialization, or indeed to control pollution or otherwise protect the environment. This is not because the author believes the government has played no role. Indeed, governments have played important roles. But per the work by Prof. Bjørnskov cited above, the most important role played by government has been to provide a solid framework for entrepreneurs to develop innovative goods and services.

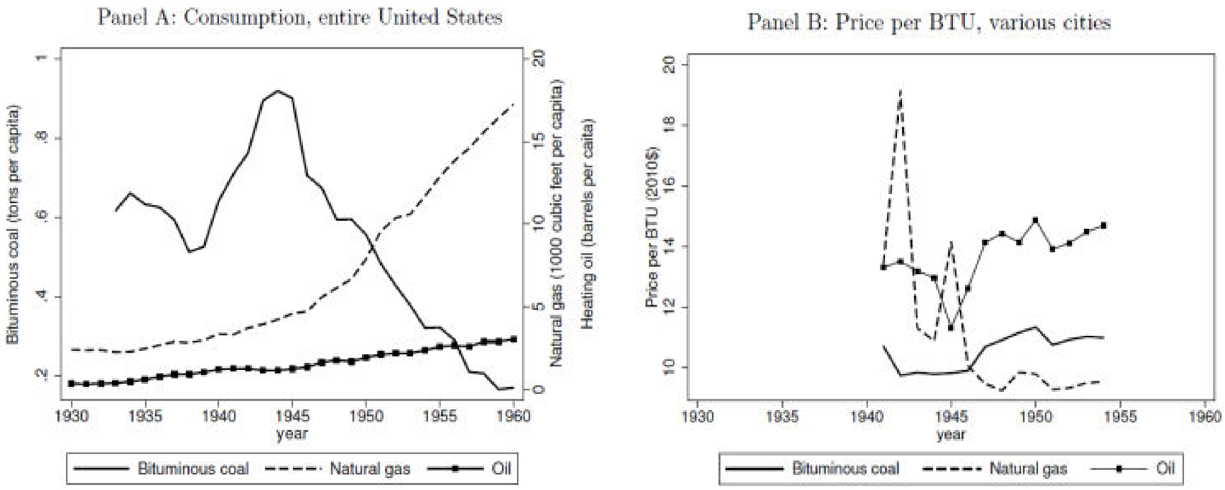
Some environmental improvements have come about serendipitously as a result of reductions in the relative price of less-polluting technologies. A good example of such a spontaneous shift occurred in the U.S. between 1945 and 1960, as documented in a 2014 study by Alan Barreca, Karen Clay, and Joel Tarr.[60] Following the war, oil pipelines that had been built as part of the war effort were repurposed to supply natural gas. Meanwhile, a series of strikes caused coal supplies to fall temporarily, leading to an increase in the price of coal. As a result, the price of natural gas relative to coal fell dramatically. In response, there was a dramatic shift from using coal as a primary source of heat to burning natural gas, with the proportion of U.S. households burning coal falling from 41% in 1945 to 9% in 1960. These shifts can be seen in Figure 23. Barreca et al. found that the shift from burning

---

[60] Alan Barreca, Karen Clay, and Joel Tarr, *Coal, Smoke, and Death: Bituminous Coal and American Home Heating*. NBER Working Paper, 19881, February 2014. http://www.nber.org/papers/w19881

coal to burning natural gas led to significant reductions in pollution and consequent significant reductions in mortality.[61]

FIGURE 23: SPONTANEOUS SHIFTS IN PRICES OF FUELS



Source: Barreca, Clay, and Tarr, *Coal, Smoke, and Death: Bituminous Coal and American Home Heating.*

But spontaneous shifts to less polluting technologies are not the whole story by a long stretch. Societies with better institutions also typically have strong laws limiting emissions of noxious air and water pollutants. Some of these are private laws that protect property owners from “nuisance.”[62] Others are government regulations that specifically limit particular emissions or activities.

Government regulations have been particularly important for reducing pollution caused by the widespread use of otherwise-beneficial technologies. Examples include: restrictions on the use of lead and volatile organic compounds (precursors of ground-level ozone) in

---

[61] Ibid.

[62] Julian Morris, “Climbing out of the Hole: Sunsets, Subjective Value, the Environment, and the English Common Law,” *Fordham Environmental Law Review,* Vol 14(2), 2002. https://ir.lawnet.fordham.edu/cgi/viewcontent.cgi?article=1577&context=elr; and Richard A. Epstein, “From Common Law to Environmental Protection: How the Modern Environmental Movement Has Lost Its Way,” *Supreme Court Economic Review,* Vol. 23, 2015, https://www.journals.uchicago.edu/doi/full/10.1086/686476

gasoline,[63] and restrictions on emissions of particulate matter from industrial smokestacks and other sources.[64]

These private laws and public regulations have incentivized investments in new technologies that reduce emissions. However, in some cases they have not incentivized the most cost-effective technologies. For example, the "New Source Performance Standards" introduced under the Clean Air Act in 1977 mandated the use of sulfur scrubbers in new plants; these benefited the owners of the existing power plants, which were grandfathered in, producers of high-sulfur coal, and the manufacturers of desulfurization equipment.[65] Meanwhile, the producers of low-sulfur varieties of coal were harmed and, because the rules only applied to new power plants, they did little to improve the environment.

> *These private laws and public regulations have incentivized investments in new technologies that reduce emissions. However, in some cases they have not incentivized the most cost-effective technologies.*

In general, economists have cautioned against the kinds of technology-specific regulations that have been used widely in the U.S., arguing instead for the adoption of ambient air quality standards combined with tradeable emissions permits.

---

[63] U.S. EPA, *History of Reducing Air Pollution from Transportation in the United States,* (Washington, DC: U.S. Environmental Protection Agency). https://www.epa.gov/transportation-air-pollution-and-climate-change/accomplishments-and-success-air-pollution-transportation; and S. Winkler et al., "Vehicle criteria pollutant (PM, NOx, CO, HCs) emissions: how low should we go?" *NPJ Climate and Atmospheric Science,* Vol. 1. Article 26, 2018. https://www.nature.com/articles/s41612-018-0037-5).

[64] Brian Vastag, "The Long Fight Against Air Pollution," *Smithsonian Magazine,* April 18. 2010.

[65] This sorry tale is expertly documented in Bruce Ackerman and William Hassler, *Clean Coal/Dirty Air,* (New Haven: Yale University Press, 1981.

In response, the EPA and some state regulators have in some cases adopted such emissions trading systems. Not only do such systems impose fewer costs (because plants with lower abatement costs cut back more and sell permits to plants with higher abatement costs), they also incentivize the development of innovative solutions that may not have been considered by those development technology-specific standards. Empirical evidence supports the contention that permit trading schemes improved the incentives to innovate relative to non-tradeable permits or technologically specific standards.[66]

6.4.2 THE EFFECT OF GOVERNMENT REGULATION ON ENERGY DENSITY AND DEMATERIALIZATION

“*In some cases, ambient air quality standards combined with tradeable permits have incentivized increased thermal efficiency—since cleaner burning furnaces produce fewer harmful pollutants.*”

In some cases, ambient air quality standards combined with tradeable permits have incentivized increased thermal efficiency—since cleaner burning furnaces produce fewer harmful pollutants. And they have also more directly incentivized industrial users and power plants to switch to lower emitting sources, such as natural gas. These can be seen as “price” or “cost” effects: by driving up the cost of burning coal, the regulations incentivize coal users to burn coal more efficiently or to switch to using a fuel source that has lower net costs, such as natural gas. So, regulation of conventional pollutants has contributed to

---

[66] Suzi Kerr and Richard G. Newell, "Policy-Induced Technology Adoption: Evidence from the U.S. Lead Phasedown," *Journal of Industrial Economics,* 51, 2003, 317-343; Tom Tietenberg, “The Tradable Permits Approach to Protecting the Commons: What Have We Learned?” *The Drama of the Commons,* Eds. Elinor Ostrom et al., (Washington DC: National Academy of Sciences, 2002). https://www.nap.edu/read/10287/chapter/9; and Tom Tietenberg, *Emissions Trading: Principles and Practice,* (Washington, DC: Resources for the Future, 2006).

dematerialization (using less coal per unit of energy generated) and a shift toward more energy dense fuels (natural gas).[67]

Many economists have argued that directly and intentionally increasing the cost of using fuels that emit carbon dioxide by imposing a tax on emissions of CO_2 or by introducing a CO_2 emissions trading program should also incentivize the development of technologies that reduce CO_2 emissions. However, a very recent comprehensive review of studies of such effects, concluded:

> *Some articles find short-term operational effects, especially fuel switching in existing assets, but no article finds mentionable effects on technological change. Critically, all articles examining the effects on zero-carbon investment found that existing carbon pricing scheme [sic] have had no effect at all. We conclude that the effectiveness of carbon pricing in stimulating innovation and zero-carbon investment remains a theoretical argument. So far, there is no empirical evidence of its effectiveness in promoting the technological change necessary for full decarbonization.* [68]

Given the lack of evidence for the effectiveness of carbon taxes and tradeable permits in driving innovations that would lead to significant reductions in CO_2 emissions, it is arguably even more important to understand what are the current drivers and constraints on such innovation. To that end, the next two parts consider some ways in which GHG emissions reductions might be achieved through a combination of wide adoption of innovative energy efficiency technologies (Part 7) and low-carbon energy sources (Part 8)—and what role institutions might play in the development and adoption of such technologies.

---

[67] Marc Paolella and Luca Taschini, "An Econometric Analysis of Emission Trading Allowances," *Journal of Banking and Finance,* Vol. 32 (10), 2008.

[68] Johan Lilliestam, Anthony Patt, and Germán Bersall, "The effect of carbon pricing on technological change for full energy decarbonization: A review of empirical ex-post evidence," *WIREs Climate Change*, 12, 2021. https://onlinelibrary.wiley.com/doi/epdf/10.1002/wcc.681

PART 7

PROSPECTS FOR INCREASED ENERGY EFFICIENCY

Increased energy efficiency can come from two sources: wider adoption of existing technologies and the development and adoption of new technologies. In this section, we discuss factors that might influence the prospects for each of these and their potential effect on carbon emissions.

7.1

ARE CONSUMERS LEAVING MONEY ON THE SIDEWALK BY NOT ADOPTING ENERGY EFFICIENCY IMPROVEMENTS?

Looking both in the U.S. and at the world as a whole, there are wide disparities in the extent to which energy-efficient technologies have been adopted. Understanding why such disparities exist may help improve adoption.

There is an old joke that as two economists are walking down the street, one says to the other: “Look, there’s a $20 bill.” The other economist replies, “Can’t be. Someone would already have picked it up.” The first economist nods sagely and the pair walk right on past the bill. The joke works (after a fashion) because it describes a caricature of economists, who are thought to assume that markets are perfectly efficient and always in equilibrium; every transaction that could possibly occur at any point in time is assumed to occur, instantaneously—even, absurdly, the collection of a $20 bill from a sidewalk that might have fallen just before the economists walked on by.

While it is unlikely that any economist would assert the impossibility of there being a $20 bill on the sidewalk, many economists make errors that are almost as ridiculous. Specifically, they frequently assume that if a possible transaction has not taken place, it must be because of a "market failure." A case in point is the assumption that there are innumerable energy efficiency improvements that could take place, thereby saving consumers money but, due to various alleged market failures, do not. Consumers of energy, it is asserted, are leaving millions or even billions of $20 bills on the sidewalk.[69] This phenomenon has been dubbed the "energy paradox"[70] or the "energy efficiency gap."[71]

> *The energy paradox is often alleged to result from consumers failing adequately to take into account the benefits, in terms of reduced future expenditures on energy, of more energy-efficient products.*

The energy paradox is often alleged to result from consumers failing adequately to take into account the benefits, in terms of reduced future expenditures on energy, of more energy-efficient products. In essence, the argument is that consumers are selectively myopic, discounting future expenditures on energy at a higher rate than other costs, such as payments on loans used to purchase the more efficient product. But are consumers

---

[69] Jerry Hausman, "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables," *Bell Journal of Economics,* Vol. 10 (1), 1979, 33–54; and Avraham Shama, "Energy conservation in US buildings, solving the high potential/low adoption paradox from a behavioral perspective," *Energy Policy,* Vol. 11 (2), 1983, 148–167.

[70] Adam Jaffe and Robert Stavins, "The Energy Paradox and the Diffusion of Conservation Technology," *Resource and Energy Economics,* Vol. 16, 1994, 91–122.

[71] Adam Jaffe and Robert Stavins, "The Energy-Efficiency Gap: What Does It Mean?" *Energy Policy,* Vol. 22 (1994), 804–810.

actually selectively myopic regarding energy efficiency? Until recently, there was little good empirical evidence either way. However, in the past decade several careful studies have sought to investigate the extent of such myopia. In general, these studies show that consumers do take into account expected differences in energy costs associated with their purchase. This is true both for automobile purchases[72] and for houses[73]—two of the items most commonly thought to be subject to irrational purchasing behavior. In other words, they are not selectively myopic.

7.1.1 STUDIES ON VEHICLE PURCHASES

In a 2013 paper published in the *American Economic Review*, Meghan Busse, Christian Knitttel, and Florian Zettelmeyer investigated the effect of a change in the price of gasoline on prices of and demand for new and used cars with different fuel economy ratings.[74] They found that a $1 per gallon change in gas prices increased the price differential between the highest and lowest fuel economy quartiles of used cars by $1,945. For new cars, the effect on price differentials was smaller, at $354, however they found that when gas rose by $1 in price, the market share of the most fuel-efficient quartile rose by 21.1%, while the market share of the least fuel-efficient quartile fell by 27.1%. Based on these findings, the authors then estimated the implicit discount rates applied by vehicle purchasers to the cost of gas usage and concluded that they "correspond reasonably closely to interest rates that customers pay when they finance their car purchases." In other words, they find little evidence that consumers are selectively myopic with regard to vehicle fuel economy.

---

[72] Meghan R. Busse, Christopher R. Knittel, and Florian Zettelmeyer, "Are Consumers Myopic? Evidence from New and Used Car Purchases," *American Economic Review,* Vol. 103(1), 2013, 220–256; Hunt Allcott and Nathan Wozny, "Gasoline prices, fuel economy, and the energy paradox," *Review of Economics and Statistics,* Vol. 96 (5), 2014, 779–795; James M. Sallee, Sarah E. West, and Wei Fan, "Do consumers recognize the value of fuel economy? Evidence from used car prices and gasoline price fluctuations," *Journal of Public Economics,* Vol. 135, 2016, 61–73; and Kevin A. Hassett and Gilbert E. Metcalf, "Energy Conservation Investment: Do Consumers Discount the Future Correctly?" *Energy Policy*, 21, 1993, 710–16.

[73] Erica Myers, "Are Home Buyers Inattentive? Evidence from Capitalization of Energy Costs," *American Economic Journal: Economic Policy,* Vol. 11(2), 2019, 165–18. https://www.aeaweb.org/articles?id=10.1257/pol.20170481; and Erdal Aydin, Dirk Brounen, and Nils Kok, "Information Asymmetry and Energy Efficiency: Evidence from the Housing Market," *Journal of Urban Economics,* Vol 117, 2020. https://www.sciencedirect.com/science/article/abs/pii/S0094119020300140?via%3Dihub

[74] Busse, Knittel, and Zettelmeyer, "Are Consumers Myopic?," 220-256.

In a 2014 paper published in the *Review of Economics and Statistics*, Hunt Alcott and Nathan Wozny used data from 86 million sales of used vehicles at auto dealerships and wholesale auctions to evaluate the relationship between expected changes in gas prices (using the price of oil futures contracts as a proxy) and changes in the price of vehicles of different fuel economy.[75] They found that "vehicle prices move as if consumers are indifferent between one dollar in discounted future gas costs and only 76 cents in vehicle purchase price." In other words, consumers seem to show mild myopia regarding the prospective savings from purchasing more fuel-efficient vehicles. However, the authors found that most of this myopia was a result of consumers who purchased much older vehicles. As they note:

> *In other words, consumers seem to show mild myopia regarding the prospective savings from purchasing more fuel-efficient vehicles. However, the authors found that most of this myopia was a result of consumers who purchased much older vehicles.*

"We show that the result that consumers undervalue gas costs is largely driven by older vehicles: prices for vehicles aged 11–15 years appear to be highly insensitive to gasoline prices, while prices for relatively-new used vehicles move much more closely to the theoretical prediction." (The "theoretical prediction" being that prices of vehicles would move one-to-one with the present discounted cost of future gas purchases.) This is not surprising, for two reasons: first, there are far fewer vehicles older than 10 years on the road, so consumers would be less able to make direct comparisons between such vehicles based on fuel economy. Second, purchasers of older vehicles are more likely to face financial constraints that effectively raise their discount rate above the 6% rate assumed by the authors: for lower-income consumers, low-cost car loans may not be available, so the

---

[75] Hunt Allcott and Nathan Wozny, "Gasoline prices, fuel economy, and the energy paradox," *Review of Economics and Statistics*, Vol. 96 (5), 2014, 779–795.

relevant discount rate would be the cost of financing using a credit card or other higher-cost form of financing, such as a payday loan.[76]

In a 2016 paper published in the *Journal of Public Economics*, James Sallee, Sarah West, and Wei Fan used data from wholesale used car auctions, comparing prices of vehicles of identical types and vintages but different mileage (and hence different life expectancies), at various points in time. This enabled the authors to evaluate the effects of changes in gas prices on the sale prices of vehicles with different fuel economy characteristics. The authors conclude, "Our data suggest that used automobile prices move one for one with changes in present discounted future fuel costs, which implies that consumers fully value fuel economy."[77]

Based on these carefully constructed studies, there is little reason to believe that the majority of consumers are myopic when it comes to evaluating the relative costs of future gasoline expenditures.

> *Based on these carefully constructed studies, there is little reason to believe that the majority of consumers are myopic when it comes to evaluating the relative costs of future gasoline expenditures.*

7.1.2 STUDIES ON HOME IMPROVEMENTS

The installation of thermal insulation in walls and ceilings, more thermally insulating windows and, in hotter climates, the use of more reflective materials on ceilings and windows, can substantially reduce energy use. While such technologies are often

---

[76] Kevin A. Hassett and Gilbert E. Metcalf, "Energy Conservation Investment: Do Consumers Discount the Future Correctly?" *Energy Policy*, 21, 1993, 710–16.

[77] James M. Sallee, Sarah E. West, and Wei Fan, "Do consumers recognize the value of fuel economy? Evidence from used car prices and gasoline price fluctuations," *Journal of Public Economics*, Vol. 135, 2016, 61–73.

incorporated in new buildings, they are often not retrofitted to old buildings, even when doing so might appear to result in a reduction in the total cost of ownership of the building. Many explanations are offered for this phenomenon, including lack of access to capital for upgrades and difficulties recouping investments from renters (for owners of rental properties).[78]

Most of these explanations really reduce to claims regarding informational asymmetries. Capital is not made available because banks are unable to observe the loan's effect on the borrower's ability to repay. Potential renters are unable to ascertain in advance the cost advantages of a building's thermal properties. And so on. In principle, these problems could be solved or at least reduced through more-effective mechanisms for sharing information regarding the thermal efficiency of buildings and the potential effects on cost of occupancy. In practice, however, it can be difficult and costly to establish such facts. So, while analysts might hypothesize that such problems could be reduced by introducing mandates to share information, or by providing federal subsidies to home improvement loans, such mandates and subsidies have a cost.

> *“…while analysts might hypothesize that [lack of data] problems could be reduced by introducing mandates to share information, or by providing federal subsidies to home improvement loans, such mandates and subsidies have a cost.”*

Erica Myers, an economist at the University of Illinois, has conducted a series of studies looking at the energy efficiency gap as it relates to domestic dwellings. In a paper published in the *American Economic Journal: Economic Policy*, Professor Myers sought to

---

[78] National Academies of Science, Engineering and Medicine, *America's Energy Future: Technology and Transformation*, (Washington, DC: National Academies Press, 2009), 135-137. https://www.nap.edu/read/12091/chapter/8

address directly the question of selective myopia.[79] Using data on purchases of homes in Massachusetts of varying ages and fuel types, combined with data on the relative cost of fuels, she found that home buyers appear to fully capitalize fuel expenditures at discount rates similar to mortgage rates. In other words, Prof. Myers' analysis suggests that there is little evidence of homebuyers being selectively myopic regarding energy efficiency.

> *…Prof. Myers' analysis suggests that there is little evidence of homebuyers being selectively myopic regarding energy efficiency.*

A somewhat similar analysis of home sales in the Netherlands, by economists Erdal Aydin and Kick Kok of Maastricht University and Dick Brounen of the University of Tilburg, published in the *Journal of Urban Economics* in 2020, found that energy efficiency was fully capitalized into the prices of homes.[80]

7.2

MORE EFFECTIVE BOTTOM-UP SOLUTIONS TO THE PROVISION OF INFORMATION

Separate from the apparently illusory myopia used to justify energy efficiency mandates, it is often claimed that consumers do not have access to relevant information on energy efficiency upon which to base decisions about total cost of ownership. Government "solutions" to these alleged information asymmetries tend to come in the form of one-size-fits-all top-down mandates. Examples include energy ratings on water heaters that state the average annual cost of operation for a household, and "MPG" rating stickers on vehicles.

---

[79] Erica Myers, "Are Home Buyers Inattentive? Evidence from Capitalization of Energy Costs," *American Economic Journal: Economic Policy*, Vol. 11(2), 2019, 165–18. https://www.aeaweb.org/articles?id=10.1257/pol.20170481

[80] Erdal Aydin, Dirk Brounen and Nils Kok, "Information Asymmetry and Energy Efficiency: Evidence from the Housing Market," *Journal of Urban Economics*, Vol 117, 2020, 103243. https://www.sciencedirect.com/science/article/abs/pii/S0094119020300140?via%3Dihub

In many cases, such rating information is better than no information. Nonetheless, such ratings can lead to inappropriate decisions, because they are based on average use under particular circumstances and very few consumers are “average” users—and comparisons based on “average” use can be misleading. Moreover, “MPG” ratings are non-linear, which can lead to biased decisions.[81] And in some cases, such government-mandated ratings are costly but useless; for example, a study on Dutch housing found that government-mandated “energy performance certificates” do not convey useful information to property buyers.[82]

For many years, companies such as Consumer Reports have been testing consumer products on many dimensions, often including energy efficiency, thereby enabling purchasers to weigh up product characteristic trade-offs in a more meaningful way.

For many years, companies such as Consumer Reports have been testing consumer products on many dimensions, often including energy efficiency, thereby enabling purchasers to weigh up product characteristic trade-offs in a more meaningful way.[83] Competition between these private providers is almost certainly a more effective stimulus to innovations that would result in the provision of more-relevant information to consumers than top-down mandates. Indeed, the mere fact that at least two independent private providers undertake their own fuel economy estimates is testament both to the latent demand for such information and to the inadequacy of the mandated labels.

---

[81] Bart de Langhe, Stefano Puntoni, and Richard Larrick, “Linear Thinking in a Nonlinear World: The obvious choice is often wrong,” *Harvard Business Review,* May–June 2017. https://hbr.org/2017/05/linear-thinking-in-a-nonlinear-world

[82] Aydin et al. “Information Asymmetry and Energy Efficiency.”

[83] *Consumer Reports*, “Best & Worst Fuel Economy for Cars, SUVs, and Trucks,” https://www.consumerreports.org/fuel-economy-efficiency/best-worst-fuel-economy/

Over the past decade, entrepreneurs have developed numerous Web-based systems that make it a little easier to calculate the likely operational cost of energy-intensive items. For example, a group of manufacturers and distributors of HVAC units developed http://www.hvacopcost.com/, which enables users to calculate the annual operation cost of their current and alternative HVAC systems. Meanwhile, numerous companies have developed devices that help reduce energy consumption. The simplest of these provide basic information about the sources of energy use, thereby enabling consumers to adjust their habits in ways that reduce energy use. More-sophisticated devices use algorithms to do the same in a more automated way.[84]

In conclusion, on the basis of the studies discussed herein, which are among the best available, there is little reason to believe that the market for energy efficiency in general is inefficient. Meanwhile, government interventions in the provision of energy efficiency information are often not cost-effective and, as in the case of MPG mandates, can lead to biases. As such, interventions intended to address such inefficiency tend to do more harm than good. Rather than seeking to identify and implement top-down solutions, governments should leave information provision to the private market.

7.3

DO ENERGY EFFICIENCY IMPROVEMENTS LEAD TO LOWER EMISSIONS?

A paradoxical effect of energy efficiency improvement is that, because it reduces the cost of using a product, consumers tend to use the product more—somewhat offsetting the benefit of the increase in efficiency. Think about lightbulbs. If it costs $1 an hour to keep a room lit using incandescent bulbs, then there is a relatively strong incentive to make sure the lights are turned off when the room is unoccupied. But if one switches to LEDs that provide the same amount light for only 10¢ per hour, the incentive to switch off the lights is rather lower. Indeed, the switch to LEDs contributed to a 10% increase in the brightness of the earth's surface between 2013 and 2017.[85] This is part of what is known as the

---

[84] For example, Electric Choice https://www.electricchoice.com/blog/green-apps-track-energy-usage/

[85] Tom Bawden, "Rise in energy-saving LED lighting has increased light pollution," *inews.co.uk,* November 23, 2017. https://inews.co.uk/news/environment/light-pollution-getting-worse-energy-saving-lamps-105718

"rebound effect"—in this case, it is the *direct* rebound effect, since it works directly on the consumption of the same good.

In addition, by reducing the total cost of ownership of products, energy efficiency improvements save consumers money, some of which will be spent on other items that use energy. The resultant increase in energy use is known as the *indirect* rebound effect.

In combination, these (direct + indirect) rebound effects could potentially offset all the energy savings resulting from an energy efficiency improvement. Worse, some people have hypothesized that the rebound effect could lead to a net increase in emissions—an effect dubbed *the backfire effect*. In practice, while the size of the rebound effect varies considerably depending on many factors, there is no evidence that it is anywhere close to 100%. Estimates suggest that the overall rebound effect is likely between 5% and 40%.[86]

However, over time, economic growth, which results from all manner of innovations (including those that increase energy efficiency), increases income, some of which is spent on energy. As a result, while energy efficiency improvements are likely to help slow down growth in demand for energy, they may not lead to absolute reductions in demand.

7.4

BEWARE OF POLICIES THAT ARE NOT COST-EFFECTIVE OR ARE EVEN COUNTERPRODUCTIVE

As discussed extensively in Parts 5 and 6, most innovations leading to more efficient use of energy occur as a natural response to market incentives. Meanwhile, as noted above, policies intended to improve energy efficiency often do not achieve their end, do so at a cost that exceeds the benefits, or could be achieved more effectively by the private sector. But in some cases polices intended to improve energy efficiency not only do not have the desired effect but have other unintended economic and/or environmental effects. The following offer a few examples.

---

[86] Kenneth Gillingham, David Rapson, and Gernot Wagner, "The Rebound Effect and Energy Efficiency Policy," *Review of Environmental Economics and Policy,* Vol. 10(1), 2016, 68-88.

7.4.1 FEDERAL HOME ENERGY EFFICIENCY SUBSIDIES

In a 2017 paper, Hunt Allcott and Michael Greenstone evaluated existing federal programs targeted at addressing home energy efficiency improvements and found that, on average, the energy efficiency savings achieved were only 58% of those predicted and that, as a consequence, those programs *reduced* welfare by $0.18 per $1 spent.[87] The authors do suggest some policy proposals, which they hypothesize would generate positive net returns if perfectly implemented but whether in practice such measures would generate net benefits—given the near certainty of imperfect implementation—is unclear.

7.4.2 THE RENEWABLE FUEL STANDARD

Ethanol has been used as a fuel in vehicles since 1826, and Nicolaus Otto, inventor of the internal combustion engine, developed an engine that ran on ethanol in 1876.[88] Henry Ford also experimented with using ethanol to power his Model T in 1908.[89] But gasoline was more cost-effective and ethanol use doesn't seem to have been widespread. However, following the OPEC oil embargo of 1973, which severely limited oil supplies in the U.S. and drove up prices, the idea of blending ethanol with gasoline in order to increase the Octane rating gained adherents and popularity, especially following the phase-out of tetraethyl lead.[90] After oil prices dropped in the 1980s, federal subsidies to ethanol production helped keep it in the blend. Subsequent restrictions on other additives, including methyl tert-butyl ether (MTBE) and benzene, toluene, ethyl-benzene and xylene (sometimes called BTEX) gave further impetus to the use of ethanol.[91]

The Alternative Motor Fuels Act of 1988 and the Energy Policy Act of 1992 established additional incentives to use ethanol, but these had limited effects on total ethanol use in

---

[88] Lyle Cummins, *Internal Fire* (Warrenton, Pa.: Society of Automotive Engineers, 1989).

[89] Daniel Strohl, "Fact Check: Henry Ford didn't design the Model T as a multi-fuel vehicle," *Hemmings,* April 23rd, 2017. https://www.hemmings.com/stories/2017/04/23/fact-check-henry-ford-didnt-design-the-model-t-as-a-multi-fuel-vehicle

[90] Jessie Stolark, *Fact Sheet - A Brief History of Octane in Gasoline: From Lead to Ethanol,* Environmental and Energy Studies Institute, March 30, 2016. https://www.eesi.org/papers/view/fact-sheet-a-brief-history-of-octane

[91] Ibid.

gasoline.[92] These federal mandates and subsidies notwithstanding, until the mid-2000s, the blending of ethanol with gasoline was thus largely a market response.[93] The big change came in 2006, with the introduction of the Renewable Fuel Standard (RFS). Mandated under the Energy Policy Act of 2005, the RFS requires gasoline blenders to use a minimum amount of ethanol in gasoline. Under the Energy Independence and Security Act of 2007, the minimum amount of "renewable fuel," which includes ethanol and biodiesel, is required to rise gradually to 36 billion gallons in 2022.[94]

"*While one key objective of the RFS is to reduce gasoline and diesel use and thereby reduce GHG emissions, in practice it may have the opposite effect. This is because the production of biofuel itself consumes energy—and often more energy is used on its production than is released by the biofuel that is produced.*"

While one key objective of the RFS is to reduce gasoline and diesel use and thereby reduce GHG emissions, in practice it may have the opposite effect. This is because the production of biofuel itself consumes energy—and often more energy is used on its production than is released by the biofuel that is produced. Take ethanol, which remains the dominant biofuel produced under the RFS. Under optimal conditions, it is possible to obtain more energy from producing ethanol than is consumed during production (including farming and distilling), though even then the energy returned on (energy) investment (EROI) ranges from 1.2 to 1.7—i.e. for every BTU of energy used in production, between 1.2 and 1.7 BTUs

---

[92] Ibid.

[93] There were also some state initiatives, such as public-private partnership in Minnesota, Kris Bevill, "Building the 'Minnesota Model'," *Ethanol Producer Magazine,* March 10, 2008. http://ethanolproducer.com/articles/3855/building-the-minnesota-model

[94] Environmental Protection Agency, *Overview for Renewable Fuel Standard,* https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard

are returned.[95] In practice, much ethanol is produced on marginal land, which requires more fertilizer, water, and other inputs. In such cases, the EROI ratio for ethanol production can be close to or even less than 1.[96] Since the energy used to produce such ethanol mainly comes from burning hydrocarbons, the total emissions of producing and using ethanol as a fuel may actually be greater than the total emissions of simply using gasoline.

“*To make matters worse, diverting fertile land to produce feedstock that is used to produce ethanol rather than food causes food prices to rise.*”

To make matters worse, diverting fertile land to produce feedstock that is used to produce ethanol rather than food causes food prices to rise. Meanwhile, using marginal land that would not otherwise be used to produce food causes other forms of environmental degradation, including fertilizer runoff, which leads to eutrophication of lakes, streams and rivers,[97] while the additional water used can contribute to the depletion of aquifers.[98]

7.4.3 CALIFORNIA'S BUILDING CODES

In a 2019 paper, Chris Bruegge, Tatyana Deryugina, and Erica Myers evaluated the effects of building codes in California on energy use.[99] They found that the codes reduced energy use only in the second-lowest quintile, due to a reduction in the size of dwellings among

---

[95] Roberto Leonardo Rana, et al., “Trends in Scientific Literature on Energy Return Ratio of Renewable Energy Sources for Supporting Policymakers,” *Administrative Sciences,* 10(2), 2020, 21. https://www.mdpi.com/2076-3387/10/2/21/htm

[96] Ibid.

[97] Michael Chislock, et al., “Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems,” *Nature Education Knowledge,* Vol. 4(4), 2013, 10.

[98] US Geological Survey, *Groundwater Decline and Depletion*, https://www.usgs.gov/special-topic/water-science-school/science/groundwater-decline-and-depletion?qt-science_center_objects=0#qt-science_center_objects

[99] Chris Bruegge, Tatyana Deryugina, and Erica Myers, “The Distributional Effects of Building Energy Codes,” *Journal of the Association of Environmental and Resource Economists,* 6, 2019, 95-106. https://www.journals.uchicago.edu/doi/abs/10.1086/701189?journalCode=jaere

lower-income households, but energy use actually *increased* in the lowest quintile. Meanwhile, the value of homes of lower income households fell, while those of upper income households increased. In other words, California's building codes have little effect on energy use but are regressive.

7.4.4 CAFE STANDARDS

More generally, energy efficiency subsidies and mandates have the effect of diverting resources toward specific technologies. While this may result in some energy efficiency improvements *in those technologies,* it comes at the cost of diverting resources away from a wide range of other technologies. This is particularly a problem for policies such Corporate Average Fuel Economy (CAFE) standards, which are widely acknowledged to be highly inefficient: estimates suggest that the same improvements in fuel economy could be achieved at about one quarter the cost through fuel taxes or as an addition to mileage-based user fees.[100] (This is not necessarily an argument in favor of higher fuel taxes or adding an emission charge component to mileage-based user fees. It is merely to observe that the CAFE standards are highly inefficient relative to those alternatives.)

> “*More generally, energy efficiency subsidies and mandates have the effect of diverting resources toward specific technologies.*”

7.5 CONCLUSIONS OF PART 7

So, what can be done to promote innovation and adoption of energy efficient technologies? Governments might begin by reviewing their existing programs that subsidize and/or mandate energy-efficient products with an eye to: (1) eliminating programs such as the RFS that clearly have adverse consequences that outweigh any benefits; (2) reforming

---

[100] Julian Morris and Arthur R. Wardle, *CAFE and ZEV Standards: Environmental Effects and Alternatives,* (Los Angeles: Reason Foundation, 2017). https://reason.org/wp-content/uploads/2017/08/cafe_zev_standards_environment_alternatives.pdf

inefficient programs so that they more cost-effectively achieve their objectives. Such reforms could potentially free up billions of dollars that could be spent on other innovations and generally contribute more to economic growth, thereby accelerating demand for more energy-efficient products and processes. Governments might also identify other impediments to innovation, the removal of which would lead to increased innovation and economic growth in general. Space precludes a detailed discussion of these but, needless to say, the identification and removal of such impediments should be a high priority.

PART 8

PROSPECTS FOR LOW-CARBON ENERGY GENERATION

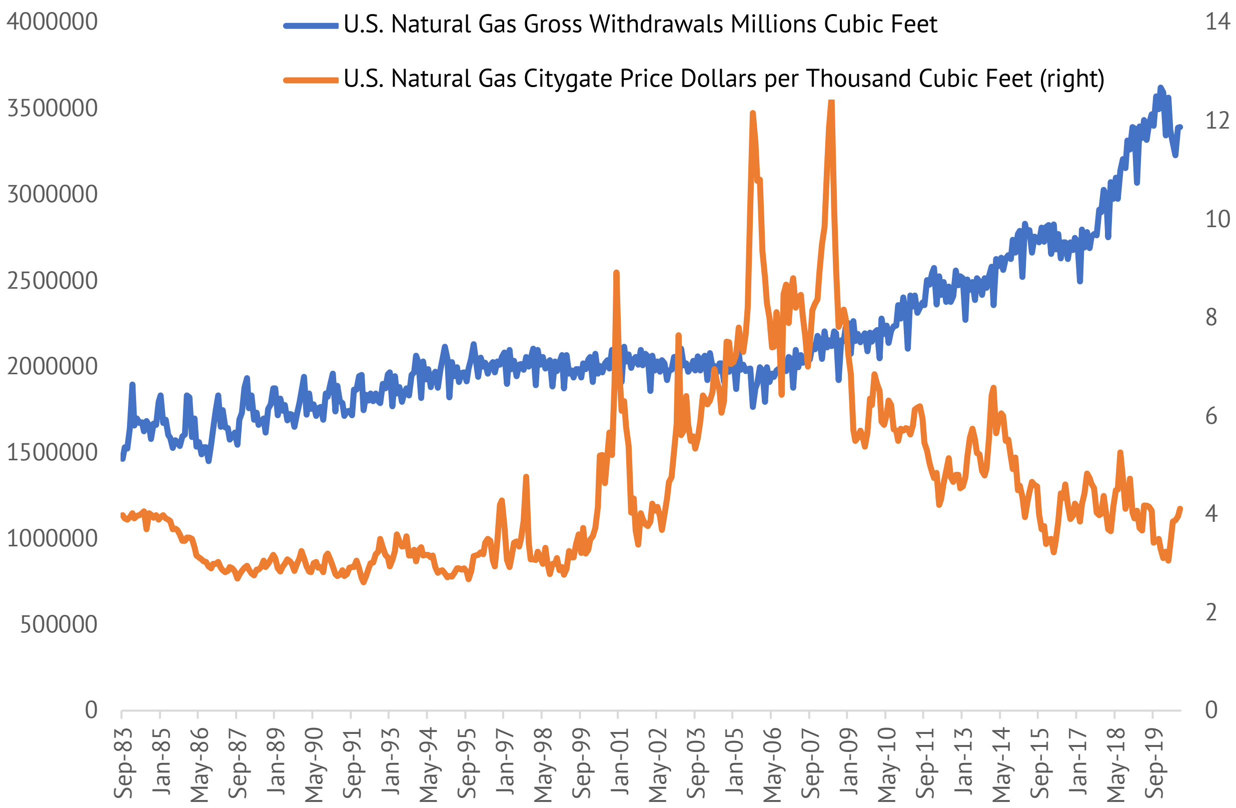
Part 6 showed that while improvements in energy efficiency may slow growth in energy use or even reduce it somewhat, they are unlikely to reduce it substantially—at least in the short-to-medium term. As such, if reductions in carbon dioxide emissions are to occur, they will need to come primarily from a shift toward lower-carbon fuels. This section considers some of the technologies that might contribute to that shift.

> *…if reductions in carbon dioxide emissions are to occur, they will need to come primarily from a shift toward lower-carbon fuels.*

8.1 NATURAL GAS

As noted in Part 3, burning natural gas produces about 40% less carbon per unit of energy generated than burning coal. So, switching from coal to gas as a source of energy generation results in a considerable reduction in carbon emissions. Indeed, much of the reduction in CO_2 emissions observed in the U.S. over the past decade has occurred as a result of such a switch. And that switch was, in turn, made possible by a dramatic increase in production and reduction cost of natural gas—as can be seen in Figure 24. (Stricter emissions standards for generators also played a role, by driving up the relative cost of burning coal.)

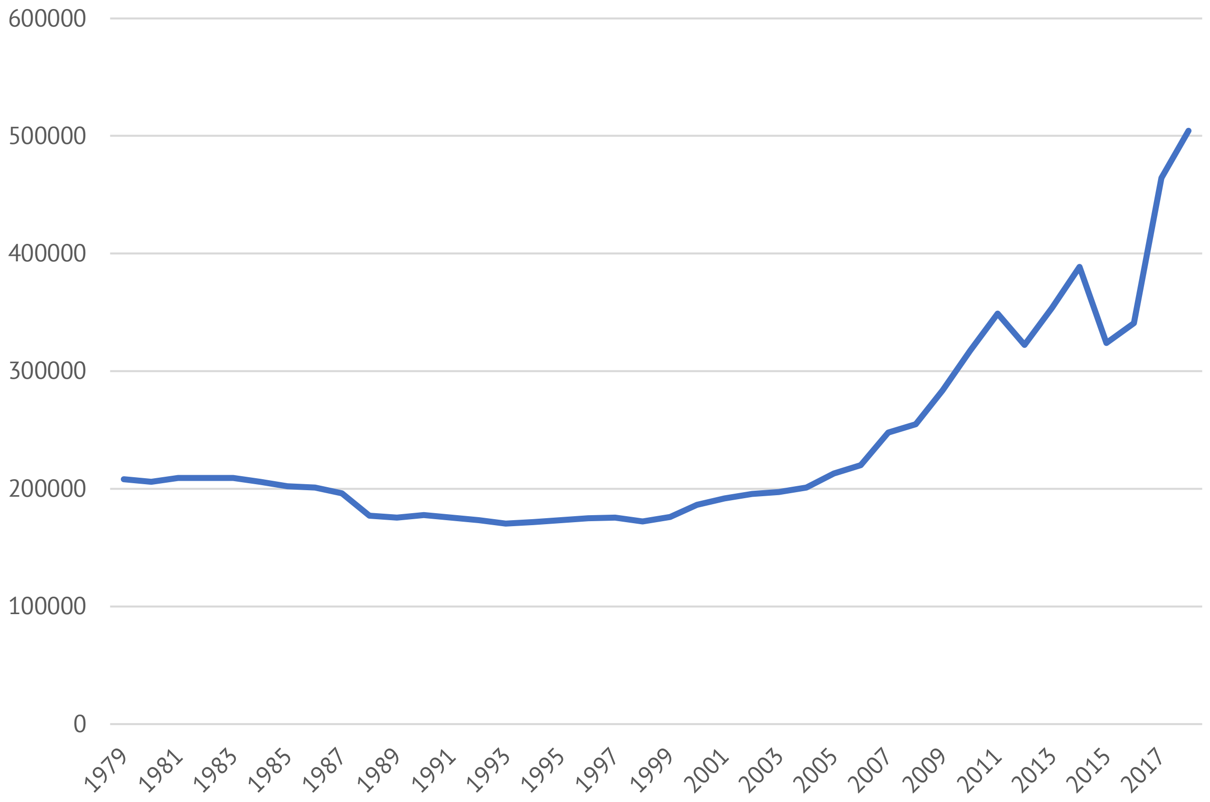
FIGURE 24: U.S. NATURAL GAS OUTPUT AND PRICES (MONTHLY)



Source: Energy Information Administration, "Natural Gas Monthly," https://www.eia.gov/naturalgas/monthly/

The dramatic increase in production occurred following innovations that have enabled the cost-effective extraction of oil and natural gas trapped in microscopic pores in shale,[101] through hydraulic fracturing, or “fracking.” These innovations, which included major advances in 3-D seismic imaging and horizontal drilling, in addition to numerous injection techniques, have also led to a dramatic increase in reserves. By the end of 2018, “proved” reserves were 504 trillion cubic feet (Tcf), which is more than double their level as recently as 2005. In addition, estimates by the Department of Energy put “unproved” reserves at about 2,390 Tcf. At current rates of use, total (“proved” plus “unproved”) reserves would be sufficient to meet U.S. needs for the next 70 years.

FIGURE 25: NATURAL GAS PROVED RESERVES (U.S., BILLION CUBIC FEET)



Source: “U.S. Crude Oil and Natural Gas Proved Reserves, Year-end 2019,” Energy Information Administration, January 11, 2021, https://www.eia.gov/naturalgas/crudeoilreserves/

---

[101] Debin Xia, Zhengming Yang, Tiening Gao, Haibo Li, and Wei Lin, “Characteristics of micro- and nano-pores in shale oil reservoirs,” *Journal of Petroleum Exploration and Production Technology,* 2020. https://link.springer.com/article/10.1007/s13202-020-01012-1

In principle, natural gas could supply considerably more of the U.S.' energy demand and in the process reduce GHG emissions further. For example, if it were to replace energy currently produced from coal, U.S. carbon dioxide emissions would fall by about 4.5%.[102]

8.2 NUCLEAR POWER

Nuclear power could be a highly cost-effective low-carbon power source. Fissile uranium has an effective energy density of approximately four million MJ/kg.[103] That makes it about 100,000 times as dense as any hydrocarbon source and 33,333 times as dense as hydrogen.[104] Moreover, practically no carbon is released during the operation of a nuclear reactor (unless you count emissions from the hydrocarbon-fueled vehicles of workers going to and from the plant)—though some is released during construction, mining, processing, and disposal/decommissioning).[105]

> *Nuclear power could be a highly cost-effective low-carbon power source.*

Nuclear power currently supplies about 8.5% of U.S. energy (representing about 20% of U.S. electricity generation). Most of that is generated by older nuclear reactors; the average

---

[102] Coal currently supplies about 11% of total U.S. primary energy. 40% of 11% is 4.5%.

[103] The theoretical energy density of fissile uranium is about 80 million MJ/kg. However, about 95% of this energy is dissipated in a fission nuclear reactor (to avoid an uncontrolled chain reaction that would result in a large explosion and the release of significant amounts of radioactive material into the atmosphere), so the actual energy density of a nuclear reactor is "only" about four million MJ/kg. "Energy density calculations of nuclear fuel," What is nuclear, https://whatisnuclear.com/energy-density.html

[104] Patrick Molloy, "Run on Less with Hydrogen Fuel Cells," *ACT News*, September 25, 2019. https://www.act-news.com/news/fcevs-run-on-less/

[105] Of course, if mining, processing, and transportation were powered with zero carbon sources, these emissions would also disappear.

reactor age is 38 years.[106] As of the end of December 2019, there were 96 nuclear electricity generating units operating at 58 nuclear plants in 29 states. The oldest of these, Nine Mile Point 1, began commercial operations in 1969. The newest, the Tennessee Valley Authority (TVA) Watts Bar Unit 2, came online in 2016 and was the first new nuclear power plant in the U.S. since 1996, when TVA's Watts Bar Unit 1 came online. There are currently two new nuclear reactors being built in the U.S.; Vogtle 3 and 4, being built in Georgia, are advanced pressurized water reactors with a combined output of about 2.5 GW.[107]

“*The paucity of new nuclear reactors in the U.S. is largely a consequence of the high cost of building such reactors.*”

The paucity of new nuclear reactors in the U.S. is largely a consequence of the high cost of building such reactors. Unlike most other forms of electricity generation, for which costs have fallen, the cost of building a nuclear reactor has *increased* over the course of the past three decades.[108] This cost escalation is largely a result of regulations put in place following the 1979 Three Mile Island incident and the 1986 Chernobyl disaster. These regulations have affected costs both directly and indirectly. The direct effect has come from increased expenditures necessitated to meet regulatory requirements. The indirect effects are a result of the small number of new reactors that have been built as a result. Whereas other forms of electricity generation have benefited from innovations resulting both from competition and from learning-by-doing, the small number of new reactors built in recent decades has meant both little competition and very little learning-by-doing.

---

[106] *Nuclear Explained,* U.S. Energy Information Administration, April 15, 2020. https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php#:~:text=Electricity%20generation %20from%20commercial%20nuclear,is%20about%2038%20years%20old.

[107] Georgia Power, “Plant Vogtle 3 and 4,” https://www.georgiapower.com/company/plant-vogtle.html

[108] Philip Eash-Gates, et al., “Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design,” *Joule,* 4(11), November 18, 2020, 2348-2373. https://www.cell.com/joule/fulltext/S2542-4351(20)30458-X?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS254243512030458X%3Fshowall%3Dtrue

While very few nuclear power plants have been built in the U.S. in recent decades, new reactor designs have been developed, some of which show considerable promise in terms both of cost and safety. The U.S. NRC recently approved the design of NuScale's small modular reactor, almost four years after the initial application was made.[109] But Nuscale faces numerous other regulatory hurdles before it can begin building a plant.

Other countries are continuing to build nuclear reactors. Around the world, 50 reactors are under construction.[110] Of those, 16 are being built in China. Moreover, China is at the forefront of building reactors with innovative designs, including newer, larger, and safer pressurized water reactors, and, more importantly, new ultra-safe small modular reactors.[111]

> *…China is at the forefront of building reactors with innovative designs, including newer, larger, and safer pressurized water reactors, and, more importantly, new ultra-safe small modular reactors.*

While it is impossible to know what the cost of building and operating a new nuclear reactor might be in 10 or 20 years, it seems plausible that those costs could fall considerably relative to current costs—if they are permitted! Given the potential for nuclear power to provide reliable baseload power in quantities sufficient to meet all of U.S. demand for the foreseeable future with close to zero carbon emissions, it would seem to be a "no-brainer" to permit private sector developers to begin building new reactors.

---

[109] U.S. Nuclear Regulatory Commission. "Design Certification Application – NuScale." https://www.nrc.gov/reactors/new-reactors/smr/nuscale.html

[110] *Plans For New Reactors Worldwide,* World Nuclear Association, January 2021. https://www.world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx#:~:text=About%2050%20power%20reactors%20are,and%20the%20United%20Arab%20Emirates.

[111] "China launches small reactor project in push for nuclear dominance," *Reuters*, July 18, 2019. https://www.reuters.com/article/us-china-nuclearpower-idUSKCN1UD0W9

There is insufficient space in this study to detail all the regulatory changes that might be necessary to facilitate the development of new nuclear facilities. But one way to move forward might be to pare back federal regulatory requirements (as discussed further in subsection 8.10.4). States could then make their own decisions regarding permitting. Currently, several states have introduced additional restrictions on the development of new nuclear power plants,[112] although their ability so to do is highly circumscribed due to federal preemption under the Atomic Energy Act.[113] Presumably states without such restrictions might be more open to permitting new plants, if federal preemption were relaxed.

8.3 HYDROELECTRIC

> *While hydro power can be cost-effective, depending on the hydrology of the location in which the dam and reservoir are located, opportunities to significantly increase capacity are limited.*

Hydroelectric power is produced by capturing the energy of falling water via generating turbines. Hydroelectric generators supplied approximately 80 gigawatts of power in 2019, representing about 2.5% of U.S. energy; about half of that power was produced in three states: Washington, Oregon, and California.[114] Installed capacity of hydro has increased over the past two decades but both the proportion of power generated from hydroelectricity and the absolute amount have fallen.[115] While hydro power can be cost-effective, depending on

---

[112] “States Restrictions on New Nuclear Power Facility Construction,” National Conference of State Legislatures, August 17, 2021. https://www.ncsl.org/research/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility.aspx

[113] Todd Garvey, *State Authority to Regulate Nuclear Power: Federal Preemption Under the Atomic Energy Act*, (Washington, D.C.: Congressional Research Service, 2011. https://www.hsdl.org/?view&did=718958

[114] “Hydropower explained,” U.S. Energy Information Administration, April 8, 2021. https://www.eia.gov/energyexplained/hydropower/where-hydropower-is-generated.php.

[115] “November 2020 Monthly Energy Review,” Energy Information Administration, November, 2020. https://www.eia.gov/totalenergy/data/monthly/archive/00352011.pdf

the hydrology of the location in which the dam and reservoir are located, opportunities to significantly increase capacity are limited. These opportunities are constrained further by difficulties obtaining permission to develop new hydropower. Beyond geological feasibility, ironically, one of the main constraints on building new hydropower in many cases is the uncertainty and high cost associated with meeting the requirements of state environmental regulations and the National Environmental Policy Act (NEPA)—discussed further below.[116]

8.4

GEOTHERMAL

There are several types of geothermal power. One type, the ground source heat pump, takes advantage of the relatively constant temperature of the earth a few feet below the surface to supply heat during the winter and to cool during the summer. Such systems can be cost-effective but only work at small scale.

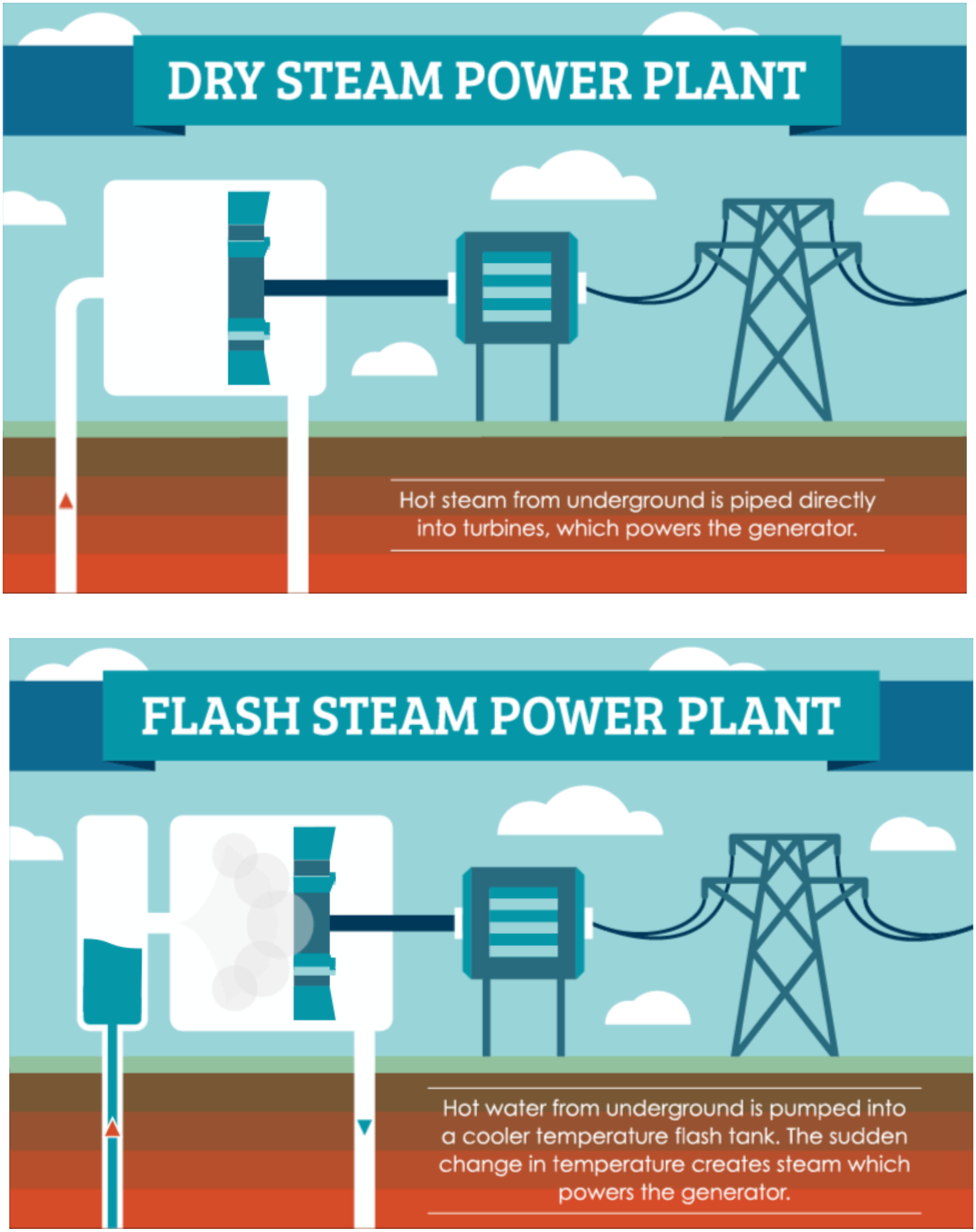
The second main type of geothermal power, known as steam-based geothermal, involves drilling boreholes deep enough to reach hot rocks and then obtaining steam, either from natural underground wells ("dry steam") or injected through one of the boreholes ("flash steam," which is used to drive turbines.[117] In principle, steam-based geothermal energy can be produced practically anywhere. In practice, it is only economically viable where hot rocks are sufficiently close to the surface. However, a newer type of steam-based geothermal plant, called binary cycle, uses a heat exchanger to generate power from rocks at a much lower temperature.

---

[116] For example, RAPID, "Hydropower Environmental Review Overview, Regulatory and Permitting Information Desktop Toolkit," 2019. https://openei.org/wiki/RAPID/Roadmap/9_(2); and Rebecca Kern, "Permit Delays Dam Up Hydro Projects, Relicensing Costs Millions," *Bloomberg Law*, October 30, 2018. https://news. bloomberglaw.com/environment-and-energy/permit-delays-dam-up-hydro-projects-relicensing-costs-millions

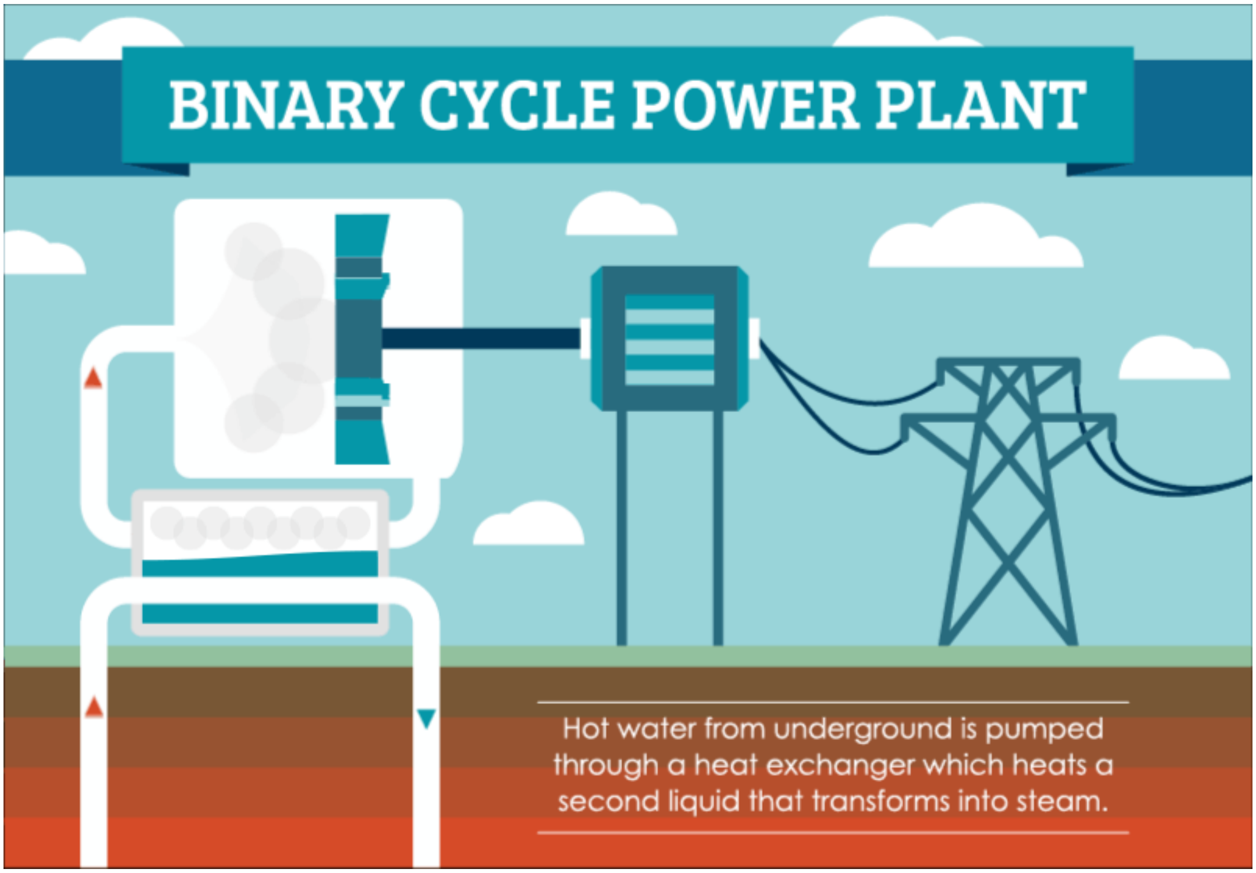
[117] U.S. Energy Information Administration, "Geothermal explained," November 19, 2020. https://www.eia.gov/ energyexplained/geothermal/geothermal-power-plants.php

FIGURE 26: TYPES OF STEAM GEOTHERMAL POWER



Hot steam from underground is piped directly into turbines, which powers the generator.

Hot water from underground is pumped into a cooler temperature flash tank. The sudden change in temperature creates steam which powers the generator.



Source: "How Geothermal Energy Works," Save On Energy, https://www.saveonenergy.com/how-geothermal-energy-works/

Steam geothermal power currently represents only about 0.4% of U.S. electricity, the vast majority of it in California and Nevada.[118] However, its cost has been falling, as drilling technologies and seismic imaging have improved, largely as a result of innovations associated with fracking.[119] And, as noted, the ability to use lower-temperature rocks widens its potential application further.[120] Indeed, the vast majority of new geothermal steam power stations in the U.S. use binary cycle.[121] As a result, it is possible that with further cost-reducing innovation geothermal energy could become a more cost-competitive source of power across the U.S.

---

[118] Ibid.

[119] "Hot Rocks," *The Economist*, August 16, 2014. https://www.economist.com/business/2014/08/16/hot-rocks

[120] Glacier Partners, *Geothermal Economics 101: Economics of a 35 MW Binary Cycle Geothermal Plant*, (New York: Glacier Partners, 2009). https://openei.org/w/images/d/d4/Geothermal_Economics_101_-_Glacier_Partners.pdf

[121] "US Geothermal Power Technology Shifts from Steam to Binary Cycle," *Journal of Petroleum Technology*, August 5, 2020. https://jpt.spe.org/us-geothermal-power-technology-shifts-steam-binary

8.5 WIND

Modern wind generators harness the power of the wind to drive turbines that generate electricity. Improvements in the efficiency of such generators have made wind a more cost-competitive source of electricity. But as discussed in subsection 8.7, things are a bit more complicated. At present, wind supplies about 2.5% of U.S. energy.[122]

8.6 SOLAR

There are broadly two types of solar power generator: solar thermal and solar photovoltaic. Solar thermal power stations use reflectors to concentrate solar power on a boiler, which then produces steam to drive turbines that generate electricity (i.e. using similar technology to that used in thermal coal power stations). Solar photovoltaic (PV) power is produced by exposing material made from a semiconductor, such as silicon, to light, causing electrons to be released.

While solar thermal generation was once thought to be promising, it has been eclipsed by solar PV, whose costs have fallen dramatically in the past decade. Indeed, there has been much talk of solar PV becoming cheaper than coal and natural gas. The reality is a bit more complicated, as discussed in subsection 8.7. Solar power currently supplies about 1.5% of U.S. energy.[123]

8.7 INTERMITTENCY, CAPACITY FACTORS, SPINNING RESERVE, AND STORAGE

While the cost of generating electricity from wind and solar power have been falling, their very nature means that they cannot produce energy continuously. Wind generators are only able to operate when wind is capable of producing about 200 watts per square meter.[124] Figure 27 shows two illustrative examples of wind power variability over time; in the left figure, power is generated for more than 50% of the time, while in the right figure it is

---

[122] Energy Information Administration. “November 2020 Monthly Energy Review.”

[123] Ibid.

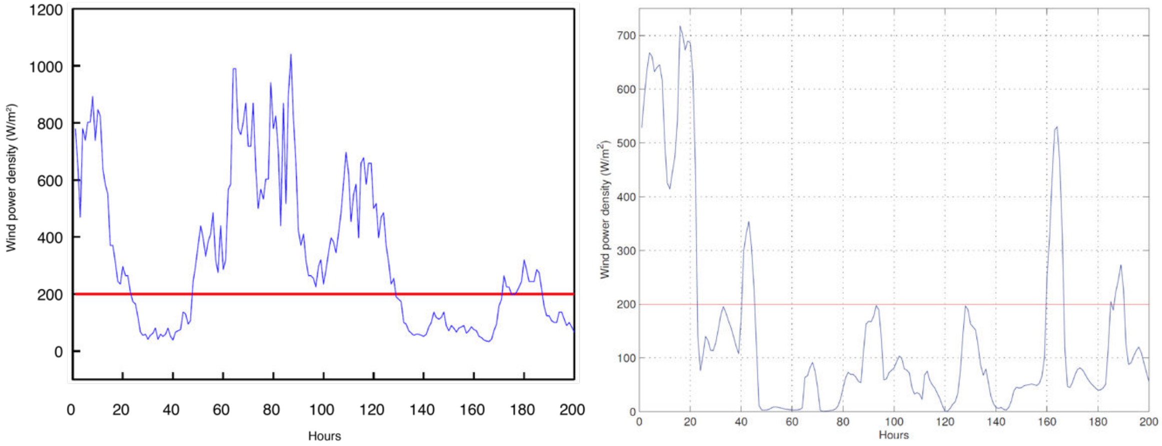
[124] Guorui Ren, Jinfu Liu, Jie Wan, Yufeng Guo, and Daren Yu, “Overview of wind power intermittency: Impacts, measurements, and mitigation solutions,” *Applied Energy,* 204, 2017, 47-65.

generated for less than 20% of the time; in both cases the amount of power generated is highly variable.

> *While the cost of generating electricity from wind and solar power have been falling, their very nature means that they cannot produce energy continuously.*

Similarly, solar power is only available for at most 12 hours per day, on average (more in summer, less in winter), and varies considerably depending on location (less in the North, due to the angle of incidence of the sun) and weather conditions (clouds substantially reduce the amount of energy).

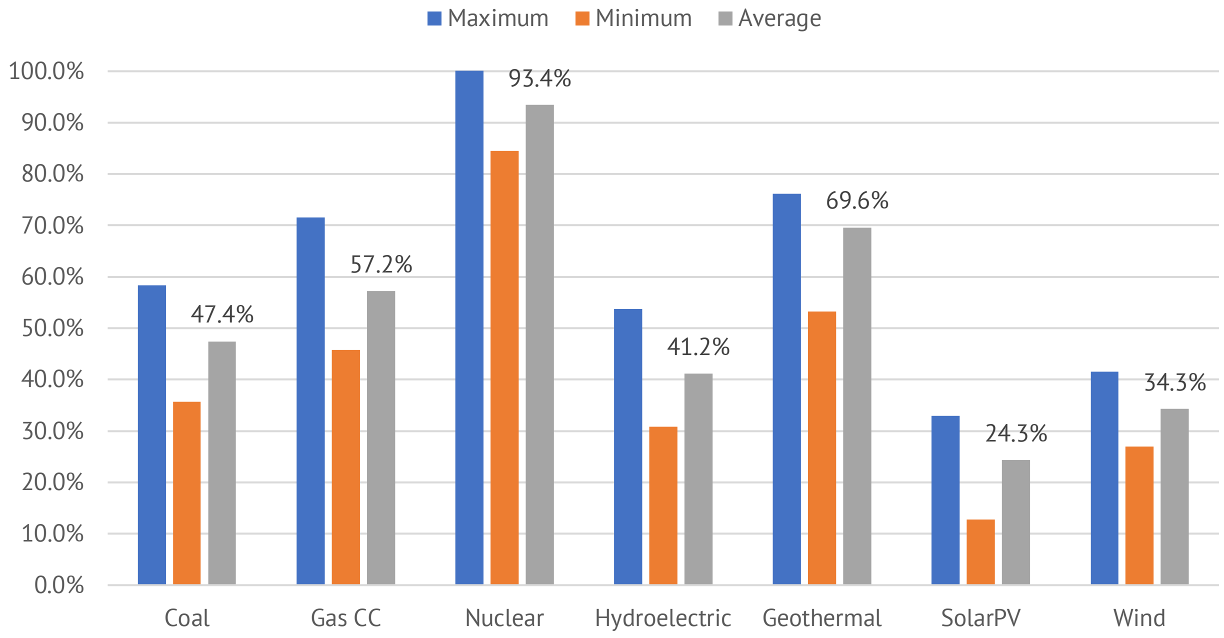
FIGURE 27: WIND POWER DENSITY OVER TIME



Sources: Guorui Ren, Jinfu Liu, Jie Wan, Yufeng Guo, Daren Yu, "Overview of wind power intermittency: Impacts, measurements, and mitigation solutions," ***Applied Energy*** **204, 2017, 47-65. (Left) U. Bhaskar Gunturu and C. Adam Schlosser, "Characterization of wind power resource in the United States."** ***Atmospheric Chemistry and Physics*****, 12, 2012, 9687–9702. (Right)**

Both wind and solar energy are thus considered “intermittent” (they do not produce electricity continuously). As a result, they have low “capacity factors”—i.e. the amount of energy actually delivered as a proportion of total installed capacity. In 2019, wind generators in the U.S. had an average capacity factor of 34.3.[125] That means they delivered 34.3% of what they could in principle deliver if working continuously at maximum output. Solar PV, meanwhile, typically had an average capacity factor of 24.3—but during the winter months its capacity factor fell as low as 12.8%.[126] By contrast, hydroelectric and natural gas combined cycle plants had average capacity factors of 41.2% and 57.5%, while nuclear reactors had a capacity factor of 93.4%. Figure 28 shows the maximum, minimum, and average monthly capacity factors for utility-scale power plants of various types in the U.S. in 2019.

FIGURE 28: MAXIMUM, MINIMUM, AND AVERAGE MONTHLY CAPACITY FACTORS FOR UTILITY SCALE ELECTRICITY GENERATION IN THE U.S. IN 2019



Source: “Electric Power Monthly, Tables 6.7.A and B (Capacity Factors),” U.S. Energy Information Administration. https://www.eia.gov/electricity/monthly/

---

[125] U.S. Energy Information Administration, “Electric Power Monthly, Table 6.7.B Capacity Factors,” accessed September 2021, https://www.eia.gov/electricity/monthly/

[126] Ibid.

The intermittency and consequent low-capacity factors for wind and solar mean that they are not suitable, on their own, for the generation of what is known as "baseload" power—that is the power needed, more or less continuously, to supply consumer needs for heat, air conditioning, light, and so forth—let alone for meeting industrial users' needs.

The intermittency and consequent low-capacity factors for wind and solar mean that they are not suitable, on their own, for the generation of what is known as "baseload" power—that is the power needed, more or less continuously, to supply consumer needs for heat, air conditioning, light, and so forth—let alone for meeting industrial users' needs. They are also not suitable for what is known as "dispatchable" power—that is, power that can be supplied on demand. To the extent that wind and solar produce energy in a complementary fashion (i.e. where the wind is stronger at night), the intermittency can be partially offset by using a combination of these two sources.[127] But even in a large grid, complementarity would be insufficient to address periods when it is dark and the wind is not blowing much. For example, a recent study looking at 40 years of data for Poland found that a grid system with wind-solar complementarity would suffer resource droughts—defined as a 24-hour period during which insufficient power is supplied—on 6.3% of days.[128] As a result, the grid must be supplemented either by "spinning reserve" (i.e. typically generators running on natural gas that can be spun up quickly in response to a fall in supply from intermittent producers) or storage.

---

[127] António Couto and Ana Estanqueiro, "Exploring Wind and Solar PV Generation Complementarity to Meet Electricity Demand," *Energies,* Vol 13, 2020, 4132. https://www.mdpi.com/1996-1073/13/16/4132/pdf; Joanna H. Slusarewicz and Daniel S. Cohan, "Assessing solar and wind complementarity in Texas Renewables," *Wind, Water, and Solar,* Vol 5(7), 2018. https://jrenewables.springeropen.com/articles/10.1186/s40807-018-0054-3; and A.A. Solomon, et al., "Exploiting wind-solar resource complementarity to reduce energy storage need," *AIMS Energy*. 8(5), 2020, 749–770. https://www.aimspress.com/fileOther/PDF/energy/energy-08-05-749.pdf

[128] Jacob Jurasz, et al., "Complementarity and 'Resource Droughts' of Solar and Wind Energy in Poland: An ERA5-Based Analysis," *Energies*, Vol. 14, 2021, 1118. https://doi.org/10.3390/en14041118

8.7.1 SPINNING RESERVE

A power source that is used as spinning reserve typically operates continuously and is spun up to produce more power as needed. Natural gas is well suited to such an operation. However, using a natural gas generator for spinning reserve inevitably reduces its capacity factor, meaning that expensive equipment is used at below capacity for between 15% and 35% of the time. In addition, burning natural gas emits GHGs, so using a combination of intermittent renewables (solar and wind) and natural gas still emits between 65% and 85% of the GHG emissions as using natural gas alone.

8.7.2 STORAGE

> “*An alternative to using spinning reserve is to store some of the energy generated when intermittent sources are operational and use it when those intermittent sources are idle.*”

An alternative to using spinning reserve is to store some of the energy generated when intermittent sources are operational and use it when those intermittent sources are idle. Storage can also be used to meet peak demand in conventional systems, thereby reducing the capacity of baseload power needed. A 2019 report from the Department of Energy reviewed several storage technologies: lithium-ion (Li-ion) batteries, lead-acid batteries, redox flow batteries, sodium-sulfur batteries, sodium metal halide batteries, zinc-hybrid cathode batteries, pumped storage hydropower (PSH), flywheels, compressed air energy storage (CAES), and ultracapacitors.[129] Numerous other storage systems are either already deployed or in development, including molten-salt, superconducting magnets, and hydrogen.[130]

---

[129] K. Mongird, et al., *Energy Storage Technology and Cost Characterization Report,* (Washington, D.C.: Department of Energy, July 2019). https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf

[130] *U.S. Grid Energy Storage Factsheet*, (Ann Arbor: University of Michigan Center for Sustainable Systems, September 2020). http://css.umich.edu/sites/default/files/US%20Grid%20Energy%20Storage_CSS15-17_e2020.pdf

Currently, the most widely available form of storage in the U.S. is pumped storage hydro (PSH), which uses the energy from excess baseload power (such as off-peak power generated by a nuclear power station) or from intermittent sources to pump water into an elevated reservoir and then release it when needed to generate hydroelectric power. The Department of Energy report found that the cost of PSH is $165 per kWh. Approximately 97% of current storage capacity in the U.S. is in the form of PSH. While there remain opportunities to expand this storage both by building new reservoirs and by building pumping stations on existing underutilized reservoirs, the availability of PSH, like hydro itself, is limited by geological factors.

Compressed air energy storage (CAES) works by storing compressed air in an underground cavern that is then heated and expanded in a turbine, driving a generator.[131] There are currently only two CAES plants in operation globally, one in Germany, the other in Alabama, both built in former salt mines. These CAES systems supplement natural gas turbines, but by increasing the efficiency of the turbine they reduce those emissions by 40%-60%. The Pacific Northwest National Laboratory has investigated the use of CAES to supply balancing loads in a geothermal energy system, which would not require the use of natural gas.[132] While the Department of Energy estimates the cost of CAES at $105 per kWh, making it the most cost-effective storage solution, it is unlikely to be feasible in many locations for geological reasons.

Flywheels store kinetic energy; a large metallic wheel inside a low-friction enclosure is spun at high speed using a dynamo powered using excess electricity. When additional electricity is required, the dynamo is used in reverse. There are currently three flywheel storage systems in the U.S.

The various battery storage solutions work by converting electrical energy to chemical energy for storage and then converting the energy back when needed. The Department of

---

[131] "Mechanical energy storage," Energy Storage Association, https://energystorage.org/why-energy-storage/technologies/mechanical-energy-storage/

[132] B. P. McGrail, et al., *Techno-economic Performance Evaluation of Compressed Air Energy Storage in the Pacific Northwest* (Richland, Washington: Pacific Northwest National Laboratory, February, 2013). https://caes.pnnl.gov/pdf/PNNL-22235.pdf

Energy report found that lithium-ion is the most cost-effective battery storage system, with a total project cost of $489 per kWh in 2018—which it expects to fall to $362 by 2025.[133]

8.8 COMPARING THE EFFECTS OF MEETING ENERGY DEMAND WITH DIFFERENT SYSTEMS

This subsection considers several alternative ways in which the U.S. might meet future energy demand. In each case, total energy demand is assumed to remain constant due to energy efficiency improvements. Meanwhile, it is presumed that thermal coal is phased out of the energy generation mix owing to its relatively high GHG (and other harmful air) emissions. It should be noted that these alternatives are intended to be illustrative, not prescriptive; for a discussion of the optimal energy mix, see section 8.9.

> “*Switching from coal to natural gas would, as noted above, reduce U.S. GHG emissions by about 5%. But how much would this cost?*”

8.8.1 SWITCHING ELECTRICITY GENERATION TO NATURAL GAS

Switching from coal to natural gas would, as noted above, reduce U.S. GHG emissions by about 5%. But how much would this cost? As of September 2020, the U.S. had installed capacity of 223 GW of coal generators operating at an average annual capacity factor of 47.5%. The Department of Energy estimates the average cost to convert a coal plant to

---

[133] Mongird et al., *Energy Storage Technology*, Table ES1. A rather bizarre feature of many reports relating to energy storage is the use of rated power to denote storage amounts, rather than the system’s storage capacity. So, while it is easy to find references to the total amount of energy that could be supplied at a particular moment, it is difficult to find accurate estimates of the total amount of energy that can be stored. The Environment and Energy Study Institute states (“Fact Sheet: Energy Storage (2019),” February 22, 2019, https://www.eesi.org/papers/view/energy-storage-2019) that in 2017, the U.S. had energy storage capacity of 431 MWh. There is 22GW of PSH, but even if PSH was the only storage available, that would imply only about one minute’s worth of electricity was available from PSH generators, which seems improbable.

burn natural gas as $226/kWh. The thermal efficiency of a plant converted from coal to gas is about the same, so replacing all coal-fired generation would entail a capital expenditure of around $50 billion. However, the cost of operating a natural gas power station is about 23% lower than the cost of operating a coal power station at current prices, so the annual cost of operating the converted power stations would be about $900m lower (at current prices). Of course, these averages mask considerable cost heterogeneity, and it is likely that it would be economically efficient to convert only some existing coal generation to gas. Meanwhile, numerous coal plants are coming to the end of their life; since the cost of both building and operating a new gas-fired generator is lower than the cost of building and operating a new coal-fire generator, it would make economic sense to replace those older coal stations with new gas generators. Indeed, over the course of the next 15 years, it is likely that the majority of coal-fired generation could be cost-effectively replaced with natural gas generators, assuming the cost differential between coal and gas remains.

8.8.2 GOING 100% ELECTRIC AND MEETING INCREMENTAL DEMAND THROUGH RENEWABLE GENERATION AND STORAGE

Some advocates and policymakers have proposed replacing all existing hydrocarbon-based energy with renewable power. What would be the cost of such a switch?

“

Electric power currently represents only about 37% of all power usage in the U.S. The remainder is consumed though direct consumption of fuel in vehicles, homes, and industry. If all this energy were to be replaced with electricity, the U.S. would have to more than double its electricity generation.

”

Electric power currently represents only about 37% of all power usage in the U.S. The remainder is consumed though direct consumption of fuel in vehicles, homes, and industry. If all this energy were to be replaced with electricity, the U.S. would have to more than double its electricity generation. Assuming some complementarity that enables a combined capacity factor of 33% for wind and solar (which is being quite generous), achieving that with intermittent sources would require installing approximately nine TW (terawatts) of new wind and solar.

In addition, if intermittent sources of energy were to replace all current hydrocarbon sources of electricity generation (i.e. all electrical power except nuclear, hydropower, and geothermal—which together supply about 10% of U.S. energy), the U.S. would require storage capacity capable of delivering 3,000 GW—i.e. enough to replace 80% of current electricity at peak demand when intermittent producers are supplying only about 10% of power. That's about a 100-fold increase over current levels. Moreover, the storage *capacity* would have to be sufficient to supply that energy for a period of at least 18 hours.[134] In other words, 55 terawatt hours (TWh) of storage.

While PSH and CAES may currently be the lowest cost forms of storage, geological limits mean that most new storage is likely to come from other sources. Currently, the focus is on battery storage. While it is possible that other systems might be more cost-effective in the future, it is worth looking at the implications of primarily building battery-based storage.

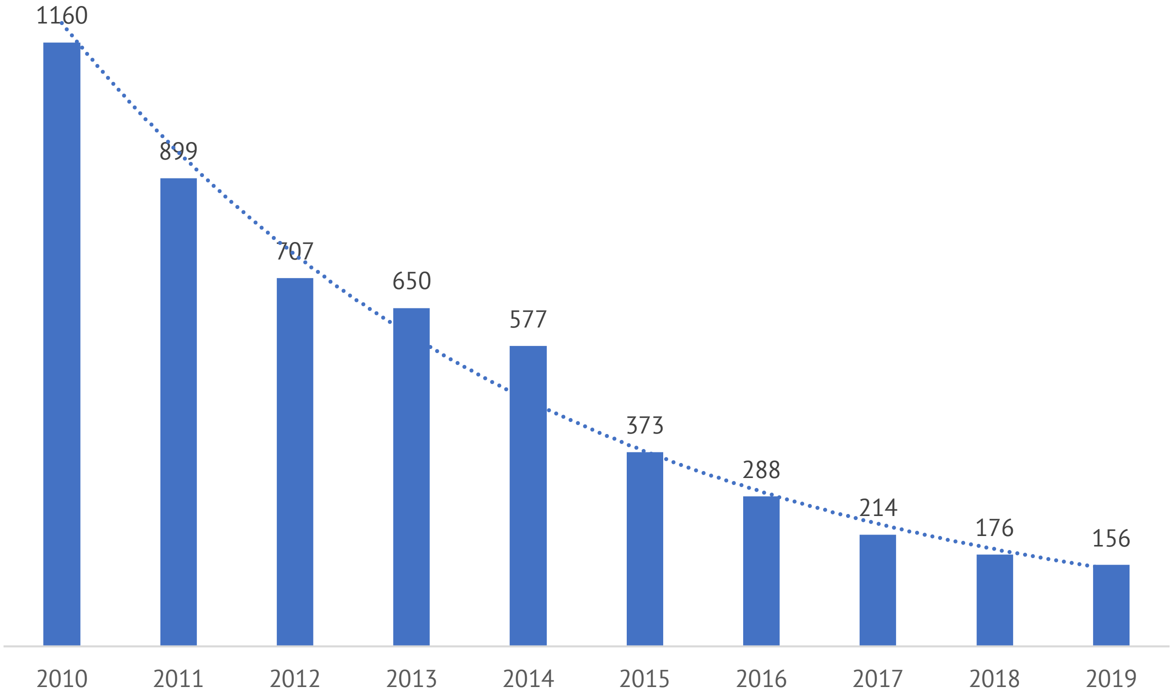
A recent Bloomberg New Energy Finance report notes that the cost of lithium-ion batteries has been falling dramatically for the past decade and by 2019 had come down to $156/kWh.[135] As Figure 29 shows, this decline almost perfectly follows an exponential curve.

---

[134] "Performance review: Nuclear, Fossil Fuels, and Renewables during the 2019 Polar Vortex," Wood MacKenzie, February 7, 2019. https://www.woodmac.com/reports/power-markets-performance-review-nuclear-fossil-fuels-and-renewables-during-the-2019-polar-vortex-99948

[135] Logan Goldie-Scot, "A Behind the Scenes Take on Lithium-ion Battery Prices," *BloombergNEF*, March 5, 2019. https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

FIGURE 29: LITHIUM-ION BATTERY PRICES PER KWH (US$)



Source: Logan Goldie-Scot, "A Behind the Scenes Take on Lithium-ion Battery Prices," Bloomberg New Energy Finance, March 5, 2019. https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

If prices continue to fall at the same exponential rate, they will drop below $100/kWh by 2021, below $50/kWh by 2024, and below $10/kWh by 2031. Whether that cost reduction is achievable is, of course, an open question; it would require solving some significant challenges regarding increasing the energy density of materials. It also depends on the cost of the materials that go into battery production. An analysis from 2019 that looked at various potential cathode materials and different configurations suggests that a cost of $50/kWh might be achievable.[136] However, a projection by IHS Markit suggests that it will take until 2024 for the price to fall below $100/kWh and that by 2030 the price is likely to be around $73/kWh.[137] Meanwhile, Figure 30 shows an analysis by Alex Keller at

---

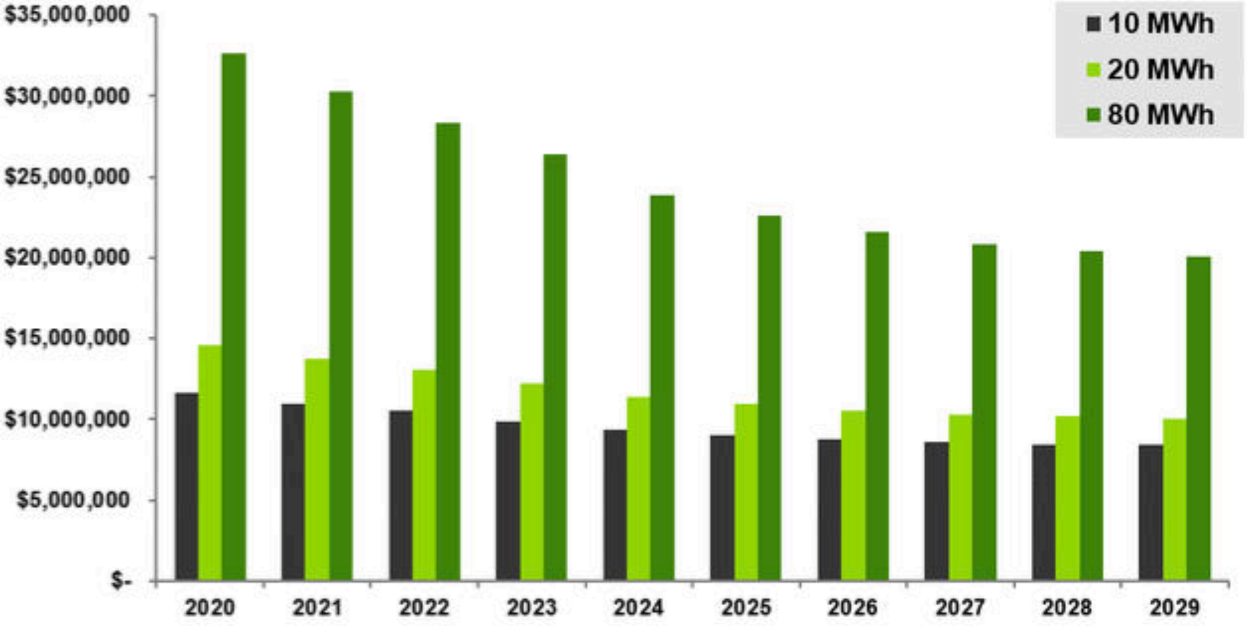
[136] Marc Wentker, Matthew Greenwood, and Jens Leker, "A Bottom-Up Approach to Lithium-Ion Battery Cost Modeling with a Focus on Cathode Active Materials," *Energies,* 12, 2019, 504.

[137] D. Sengupta, "Average Cost of Lithium-ion Battery Cell Likely to Plummet to $100/kWh in 2023: Report," *Mercom India*, September, 25, 2020. https://mercomindia.com/average-cost-lithium-ion-battery/

Guidehouse consultants projecting that the average cost would fall below $100/kWh by 2023, reaching $66.6/kWh by 2029.[138]

It should be noted that the cost of the batteries themselves is only part of the total cost. Installation costs are significant—but there are also economies of scale. Using his base projection of declining battery cost, Alex Eller estimates that the total installation cost for an 80 MWh battery system would fall by around 50% from $32.5 million today to around $20 million in 2029.

FIGURE 30: TOTAL INSTALLED COST FOR UTILITY-SCALE LITHIUM-ION BATTERY SYSTEMS OF VARYING SIZES



Source: Colthorpe, "Guidehouse: Lithium battery cell prices to almost halve by 2029."

Since any switch to renewables would occur over time, it is worth considering the annual investment required in electricity generation and storage. First a few assumptions:

- The cost of installing solar generation and lithium-ion storage falls by 5% each year.

---

[138] Andy Colthorpe, "Guidehouse: Lithium battery cell prices to almost halve by 2029," *Energy Storage News,* June 9, 2020. https://www.energy-storage.news/news/guidehouse-lithium-battery-cell-prices-to-almost-halve-by-2029

- The cost of installing wind generation falls by 3% each year.
- The amount of generation and storage installed increases at 20% per year, in order to take advantage of declining costs.
- Future costs are discounted at 3% per year.
- From 2021 to 2035, total installed capacity of renewable generation is 9 TW.
- From 2021 to 2035, total installed capacity of battery storage is 55 TWh.

Using these assumptions and the Department of Energy's costs for installation of solar and wind as the baseline, the total discounted installation cost of a switch away from fossil fuels to renewables between 2021 and 2035 would be approximately $20 trillion, which averages to an annual cost of $1.3 trillion. This does not include operational cost and it does not take into account the need to replace battery storage, the declining performance of batteries over time, the operation and maintenance cost, or the cost of additional grid connections (including the costs of purchasing rights of way and associated negative externalities associated with the use of eminent domain[139]). In other words, it is almost certainly a low-ball estimate.

The $1.3 trillion estimate equates to approximately 6.6% of GDP. Over the past 50 years, domestic U.S. investment has averaged about 17% of GDP. So, based on these numbers, switching to renewable generation would mean diverting nearly 40% of U.S. investment away from other investments and toward these low-carbon energy sources.

Of course, once installed, this combination of wind, solar, and batteries would be generating power, which would reduce the need to spend resources on hydrocarbon fuels. In 2019, total hydrocarbon fuel costs were about $500 billion. Based on the above-described schedule of investment in wind, solar, and battery storage, the net present value of the total savings on fuel between 2021 and 2035 is approximately $2 trillion.[140] In other words, over the next 15 years, the installation of wind plus solar plus batteries would have a net cost of $18 trillion.

---

[139] Andrew P. Morriss, Roy Brandys, and Michael M. Barron, "Involuntary Cotenants: Eminent Domain and Energy and Communications Infrastructure Growth," *LSU Journal of Energy Law and Resources,* Vol. 3, 2014, 29-. https://scholarship.law.tamu.edu/facscholar/157/

[140] Author's calculations based on data from Energy Information Administration – available upon request.

8.8.3 GOING 100% ELECTRIC USING NUCLEAR POWER

Unlike wind and solar, nuclear power stations generate electricity day and night and are not affected by the amount of wind or clouds. However, the Department of Energy estimates that a new advanced nuclear power plant costs close to $6,000 per kWh, so converting the U.S. entirely to electric power using only new advanced nuclear would cost around $18 trillion. Moreover, the annual operations and maintenance costs of nuclear are about twice those of coal generators, three times the cost of on-shore wind, four times the cost of solar, and five to ten times the cost of natural gas generators.

> *… over the next 15 years, the installation of wind plus solar plus batteries would have a net cost of $18 trillion.*

For nuclear power to become an attractive option, its capital costs would have to fall considerably. This is not infeasible, however. A 2016 study by the Breakthrough Institute looked at the costs of new nuclear power plants in seven countries and found that the U.S. had experienced the highest cost escalation, whereas Japan and South Korea, where new nuclear power stations continued to be built through the late 2000s, had experienced cost reductions over time, with the most recent builds having a capital cost of around $2000/kWh. At that cost, switching to nuclear would be vastly less expensive than a combination of wind, solar, and battery storage. But it is likely that with additional innovation, the cost of nuclear power would fall further. (It is worth noting that the Fukushima reactor that was damaged by a tsunami in 2011 was an older-style design, having been commissioned in 1967 and opened in 1971; the three plants operating at the time of the disaster were all constructed by 1974.[141] Moreover, in spite of the seriousness of the incident, a recent report from the UN Scientific Committee on the Effects of Atomic

---

[141] *Japan Nuclear Power Reactors,* International Atomic Energy Association, 2011. Archived at: https://web.archive.org/web/20110528122321/http://www.iaea.org/cgi-bin/db.page.pl/pris.powrea.htm?country=JP;

Radiation found little evidence of substantial harm resulting from radiation released from the reactor during or after the incident.[142]) This issue is discussed further in section 8.10.4.

8.8.4 OTHER OPTIONS

The U.S. might reduce its energy-related carbon emissions in a vast array of other ways,[143] including:

- Using excess electricity (e.g. from nuclear plants or intermittent sources) to produce “green” hydrogen to power vehicles (an option favored by Japan).
- Carbon capture and storage, i.e. capturing carbon dioxide emissions from combusted hydrocarbons and storing them either below ground or in the deep ocean.
- Carbon sequestration, i.e. extracting carbon dioxide from the atmosphere. Numerous technologies could achieve this, ranging from biological, to chemical, to physical systems.

Some of these technologies, such as planting fast-growing crops and trees, are already commercially viable at relatively low cost (e.g. less than $10 per ton).[144] Others, such as oil-producing algae[145] or fertilizing the oceans to produce plankton[146] may become so in the future. Whether “green” hydrogen or carbon capture and storage will ever become commercially viable remains unclear.

---

[142] United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources, Effects and Risks of Ionizing Radiation UNSCEAR 2020 Report, Scientific Annex B: Levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Station: implications of information published since the UNSCEAR 2013 Report*, United Nations, 2021. https://www.unscear.org/docs/publications/2020/UNSCEAR_2020_AnnexB_AdvanceCopy.pdf

[143] For a more comprehensive list and discussion of such technologies see National Academies of Science, Engineering and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,* (Washington, D.C.: National Academies Press. 2019). https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

[144] Bronson W. Griscom, et al., “Natural climate solutions,” *Proceedings of the National Academy of Sciences,* vol 114 (44), October 31, 2017, 11645-11650. https://www.pnas.org/content/114/44/11645

[145] Dhani S. Wibawa, et al., “Microalgae Oil Production: A Downstream Approach to Energy Requirements for the Minamisoma Pilot Plant,” *MDPI Energies,* February 28, 2018. https://www.mdpi.com/1996-1073/11/3/521/pdf

[146] R.S. Lampitt, et al., “Ocean fertilization: a potential means of geoengineering?” *Philosophical Transactions of the Royal Society A,* 2008, 3663919–3945. http://doi.org/10.1098/rsta.2008.0139

8.9 TRADE-OFFS AND THE OPTIMAL ENERGY MIX

All energy generation technologies involve trade-offs. Some of these are environmental: hydroelectric reservoirs flood valleys, destroying wildlife habitat; thermal solar plants and windmills kill birds; hydrocarbon generators emit various pollutants during operation (and coal plants typically emit considerably larger quantities per unit of electricity generated than natural gas plants); lithium-ion battery storage requires large amounts of lithium and often other elements, such as cobalt, that entail the release of significant emissions to air and water during the mining process; nuclear power generates radioactive waste material that requires careful disposal; and so on. Some trade-offs are financial; as noted above, attempting to replace baseload dispatchable power sources such as coal and natural gas with a combination of intermittent sources and batteries is likely to be enormously expensive in the short term.

The existence of these trade-offs is often ignored by vested interests and ideologues, who claim that their preferred technology is superior in every way. This is unfortunate because it distorts the conversation about rational energy policy and leads to policy decisions that are not in the best interests of the American people. The RFS is a case in point, but similar observations can be made about renewable portfolio standards and other technology-specific subsidies and mandates.

> “*Mandates and subsidies that encourage only one or a narrow set of technologies are unlikely to be a cost-effective way to reduce carbon emissions.*”

In some cases, innovation may be technology-specific. For example, improvements in the cost-efficiency of very-low-risk modular nuclear reactors may result from learning-by-doing, which would occur if many such nuclear reactors were to be built. Likewise, similar improvements in cost-effectiveness might occur in the production of grid stabilization technologies necessary for managing intermittent power sources.

Other innovations may derive laterally from innovations in other technologies. For example, large-scale battery storage technology has already benefited from dramatic improvements in lithium-ion batteries produced for laptops. Likewise, geothermal energy generation is likely to benefit from innovations in fracking for oil and natural gas from shale.

Mandates and subsidies that encourage only one or a narrow set of technologies are unlikely to be a cost-effective way to reduce carbon emissions. In reality, it is impossible to know either which technologies will exist in the future, or how much they will cost. As such, policies should not explicitly favor one technology over another. Instead, it is worth thinking about various combinations of lower carbon technologies being brought online as they become cost-effective. This is likely to vary significantly from place to place and will change over time as innovation drives down costs. So, policymakers should avoid one-size-fits-all top-down approaches and instead look at ways to encourage innovation and implementation from the bottom up.

8.10

BARRIERS TO INNOVATION AND IMPLEMENTATION OF LOW-CARBON TECHNOLOGIES

As noted in Part 5, the primary driver of innovation and access to new technologies is competition. A bottom-up approach to innovation and implementation of low-carbon technologies would thus harness competition between suppliers of energy. Instead of focusing on the promotion of particular technologies, policymakers might instead look at existing barriers to competition. Some of these are structural, some are project-specific, and some are specific to particular technologies, especially nuclear. This subsection addresses each in turn.

8.10.1 REMOVING STRUCTURAL BARRIERS TO COMPETITION

Unfortunately, most energy markets are currently not nearly as competitive as they could be. This is a consequence of swathes of regulation of various kinds, at both federal and state levels.

Table 3, which was produced by NERA, compares the functioning of electricity systems that are subject to competitive markets with those that are subject to traditional regulation. It neatly encapsulates the key benefits of competitive markets over regulated supply.

TABLE 3: COMPETITIVE VERSUS TRADITIONALLY REGULATED ELECTRICITY MARKETS

	Competition	**Traditional Regulation**
Funding	Company funds investments with the expectation that it will be able to charge customers prices that justify those costs.	Ratepayers fund prudently incurred investments in rate base with a virtual certainty of recovering the costs.
Price Determination	Prices set in a market by supply and demand with open-ended possibilities for pricing structures, which means choice for consumers.	Prices set based on cost with limited menu of regulated tariffs.
Market Concentration	Multiple firms compete with one another, with potential competitors providing competitive pressure as well.	Generally one firm, once with a franchise.
What Is Built	Companies, in response to customer demand, will be more likely to invest in less traditional and more energy-efficient forms of generation, including renewables.	Regulators approve what utilities build. This may or may not be the lowest cost investment, and may or may not be technologically innovative.
Capital Structure	Less use of leverage perhaps, reflecting greater investment risk, but more potential for innovative financing arrangements.	Traditional utility regulation accommodates the use of more debt, but limits innovation.
Who Bears Risk of Bad Investments?	Investors.	Consumers.
Market Activity	The competitive environment is dynamic and subject to entry and exit. This creates a powerful incentive for firms to increase operating efficiency.	Static. Subject to bureaucratic process.
Cost Allocation	Value branding. Independent power companies have a greater opportunity to market different services to different customers.	Cost averaging. Through the regulatory process, costs incurred are averaged out when determining rates, and the ratepayers that incur specific costs may not necessarily pay for them.

	Competition	**Traditional Regulation**
Keys To Success	Ability to compete on price, terms, and non-price attributes such as billing arrangements and product innovation (such as green power).	Prudence and accountability in decision making; competence working with regulatory and political policy. Ability to overcome market failures.
Vertical Integration	Greater vertical separation of regulated and competitive activities.	Typically vertically integrated, subject to an internal system of command.
Ownership and Investment	Risk and return expectations will be relatively higher. This will affect what types of entities hold ownership stakes.	Risk and return expectations will be relatively lower. This will affect what types of entities hold ownership stakes.
Marketing	Increased need for marketing, and development of innovative products. Focused on meeting individual customer needs through innovation.	Reduced need for marketing and business development. Largely focused on providing one-size-fits-all solutions for customers.
Price Stability	If price stability is desired by customers, competitive retailers will make such a product available.	The regulatory process eventually allows recovery of all prudent costs. Rates can be slow to respond to changing conditions due to regulatory lag.
Price Signals	Prices tend to reflect marginal costs, the most accurate representation of opportunity cost.	Retail prices can become distorted from marginal costs through the ratemaking process.

Source: NERA, Competitive Electricity Markets: The Benefits for Customers and the Environment, (Cambridge, MA: NERA Consulting, 2008). https://www.nera.com/content/dam/nera/publications/archive1/PUB_CompetitiveElectricityMarkets_Feb2008.pdf

There is insufficient space in this study to offer a detailed analysis of the various barriers to competition, many of which are state-specific. However, given that the main barrier to competition in most cases is the incumbent monopolist, one approach, advanced by energy economist Lynne Kiesling and supported by a range of other experts, is to "quarantine the monopolist" in much the same way that AT&T's monopoly was quarantined following its break-up in 1982 and similar to the way in which Texas quarantined its incumbent electrical utility.[147] Kiesling summarizes the approach thus:

---

[147] Lynne Kiesling, "Incumbent Vertical Market Power, Experimentation, and Institutional Design in the Deregulating Electricity Industry," *The Independent Review,* 19 (2), Fall 2014. 239–264; and Lynne Kiesling and Michael Giberson, *Electric Competition in Texas: A Successful Model to Guide the Future,* (Conservative

> *[E]liminate the incumbent default-service model and prohibit incumbent regulated utilities from offering products or services beyond their regulatory remit. In other words, follow the Texas model of retail competition, which quarantines the regulated wires monopoly and focuses on creating an institutional environment in which competitive rivalry grounded in entrepreneurial experimentation can thrive.*[148]

Kiesling notes that this is more likely to lead to the kind of disruptive innovation experienced in other sectors of the economy, resulting in increases in efficiency, reductions in cost, and reductions in emissions.

8.10.3 REFORMING FEDERAL ENVIRONMENTAL REGULATIONS THAT IMPEDE NEW PROJECTS

Paradoxically, one of the major barriers to the development of low-carbon technologies is federal regulation, which raises the cost of many kinds of new projects, including the development of new nuclear plants, fracking sites (especially on federal land), wind and solar electric generating units.

Paradoxically, one of the major barriers to the development of low-carbon technologies is federal regulation, which raises the cost of many kinds of new projects, including the development of new nuclear plants, fracking sites (especially on federal land), wind and solar electric generating units. By impeding these new projects, the regulation slows down and generally undermines competition—as both the number of competitors and the variety of projects will be lower than would otherwise be the case. And by impeding competition,

---

Texans for Energy Innovation, July 2020). https://www.conservativetexansforenergyinnovation.org/wp-content/uploads/2020/07/CTEI-Research-Paper-July-2020-3.pdf

[148] Ibid. at 244.

such regulation slows down the process of innovation, which, as discussed above, is largely driven by competition between entrepreneurs seeking to deliver higher quality goods and services at lower cost.

Among the most significant barriers is the National Environmental Policy Act (NEPA) of 1969. Introduced on the premise that the United States needed "a national policy to deal with environmental crisis, present or impending,"[149] NEPA has arguably been used less as a means of addressing environmental problems and more as a means of deterring certain kinds of economic activity, even when that activity is likely to yield net environmental benefits (such as fracking—see below). Many of the problems associated with NEPA emanate from its lack of a requirement to consider costs or even prioritization. This is true both for the original mandate and for the 1977 CEQ regulations that currently govern implementation of NEPA.[150]

> *"Many of the problems associated with NEPA emanate from its lack of a requirement to consider costs or even prioritization."*

As discussed previously, fracking has contributed to a dramatic increase in the availability of natural gas, reducing its price and enabling power generators to switch from coal to gas. It has thus done more than any other technology to reduce carbon dioxide emissions from electricity generation.[151] Yet, in spite of the abundance of shale gas deposits on federal land, there has been relatively little fracking on federal land compared to the amount of fracking on private and state land.[152] One reason is compliance with NEPA. Indeed, several

---

[149] U.S. Senate, "Report to accompany S. 1075." 9, https://ceq.doe.gov/docs/laws-regulations/Senate-Report-on-NEPA.pdf

[150] Council on Environmental Quality. "Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act." *Federal Record*. 42 FR 26967, May 25, 1977.

[151] Seth Whitehead, "EIA: U.S. Carbon Emissions Fall Again In 2017, 'Mainly' Because Of Natural Gas," *Energy In Depth,* February 12, 2018. https://eidclimate.org/eia-u-s-carbon-emissions-fall-2017-mainly-natural-gas/

[152] "Oil and Natural Gas Booms on Private and State Lands," Institute for Energy Research, April 14, 2015. https://www.instituteforenergyresearch.org/fossil-fuels/gas-and-oil/oil-and-natural-gas-production-

anti-development groups recently sued the Bureau of Land Management (BLM) over a plan to permit fracking on BLM land in California—arguing that it was in violation of NEPA.[153] It should be noted that while fracking can pose environmental risks, if carried out with suitable precautions, these can be minimized. One risk frequently highlighted by opponents of fracking is contamination of drinking water, yet a major EPA report on the subject in 2015 found very few instances of drinking water contamination from thousands of fracking sites.[154] By contrast, the suit brought against BLM sought a broad prohibition on fracking.

> “*It should be noted that while fracking can pose environmental risks, if carried out with suitable precautions, these can be minimized.*”

A recent Council on Environmental Quality rulemaking on NEPA is a step in the right direction.[155] It should help streamline the NEPA process and result in fewer preliminary injunctions being issued by courts, which historically have often been based on mistakes, or oversight that is “sometimes trivial and commonly hypothetical in preparing an EIS or EA.”[156] However, more can certainly be done to ensure that NEPA is implemented in a way

---

booms-on-private-and-state-lands-plummets-on-federal-lands/; and David Blackmon, “The Drilling Boom on Federal Lands Is Driven More by Price Than Policy,” *Forbes,* October 29, 2018. https://www.forbes.com/sites/davidblackmon/2018/10/29/the-drilling-boom-on-federal-lands-is-driven-more-by-price-than-policy/#338cb7786c15

[153] Rachel Frazin, “Green groups sue Trump administration over California fracking plans analysis,” *The Hill,* January 14, 2020. https://thehill.com/policy/energy-environment/478236-greens-accuse-blm-of-not-sufficiently-considering-fracking-impacts

[154] Environmental Protection Agency, *Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources,* (Washington, DC: Environmental Protection Agency, 2015). Executive Summary here: https://www.epa.gov/sites/production/files/2015-07/documents/hf_es_erd_jun2015.pdf

[155] Julian Morris, *Reason Foundation Comment: Update to the Regulations Implementing the Procedural Provisions of the National Environmental Policy Act. CEQ–2019–0003 (85 FR 1684)*, (Los Angeles: Reason Foundation, 2020). https://reason.org/commentary/comment-national-environmental-policy-act-ceq-2019-0003-85-fr-1684/

[156] Mark C. Rutzick, *A Long and Winding Road: How the National Environmental Policy Act Has Become the Most Expensive and Least Effective Environmental Law in the History of the United States, and How to Fix It*, (Washington, DC: Regulatory Transparency Project, October 16, 2018), 6. https://regproject.org/paper/national-environmental-policy-act/

that is consistent with its original purpose and not used as an arbitrary and capricious barrier to economic development and environmental improvement.

In addition, companies seeking to undertake certain drilling activities on federal or Indian lands, including for oil, gas, and geothermal energy, are required to obtain a permit to drill. A recent report notes that while the BLM has been approving an average of 254 drilling permits per month, it has a backlog of 5,000 applications, which at that rate would take 20 months to process.[157] As with NEPA, delays can be very expensive: when drilling rights have already been procured, such delays mean that capital is effectively idle. In March 2020, the Government Accountability Office issued a report that made three recommendations to the director of the BLM that would expedite the application for permit to drill (APD) process. Most importantly, it recommended the development of "a documented process to consistently implement the APD prioritization process."[158]

8.10.4 REFORMING FEDERAL REGULATION OF AND ELIMINATING SUBSIDIES TO NUCLEAR ENERGY

Nuclear power is largely a creature of the federal government. The world's first nuclear reactors were funded entirely by the federal government, partly to develop energy sources and partly to produce materials for atomic bombs.[159] While private companies subsequently developed and built new reactor designs, governments have continued to play a highly active role both in subsidizing and in regulating nuclear power.

Currently, nuclear power in the U.S. is regulated by the Nuclear Regulatory Commission, which was created by and operates under the Atomic Energy Act, and also implements a range of other legislation including:

- The Energy Reorganization Act of 1974

---

[157] Ed Crooks, "The US government speeds up drilling permit approvals," Wood MacKenzie, 21 June 2021. https://www.woodmac.com/news/opinion/the-us-government-speeds-up-drilling-permit-approvals/

[158] GAO, *Oil and Gas Permitting: Actions Needed to Improve BLM's Review Process and Data System,* (Washington, DC: U.S. Government Accountability Office, March 2020). https://www.gao.gov/assets/710/705590.pdf

[159] Herbert L. Anderson, "Early Days of the Chain Reaction," *Bulletin of the Atomic Scientists,* Vol. 29 (4), April 1973, 8-12. https://books.google.co.uk/books?id=IgwAAAAAMBAJ&pg=PA10&redir_esc=y#v=onepage&q&f=false

- Various Reorganization Plans
- The Nuclear Waste Policy Act of 1982
- The Low-Level Radioactive Waste Policy Amendments Act of 1985
- The National Environmental Policy Act

There is also separate legislation governing the mining and importation of uranium.

A 2017 analysis by the American Action Forum (AAF), a Washington D.C.-based non-profit headed by former chief economist of the President's Council of Economic Advisors, Douglas Holtz-Eakins, estimated the costs of regulatory compliance on existing and new nuclear plants.[160] The study found that between 2006 and 2015, existing nuclear plants incurred regulatory liabilities totaling $15.7 billion, which is an average of $219 million per plant. Moreover, these liabilities have been increasing year on year, with average annual cost per plant rising from $9.6 million in 2006 to $32.7 million in 2015. In addition, plants must pay large fees to the NRC for the privilege of being regulated. In 2015, these fees averaged $22 million per plant.[161] Unsurprisingly, many plants have become uneconomic, which explains the decision to close them.

For new plants, the AAF study cites the estimate produced by the Breakthrough Institute, which found that the cost of a new plant is about $11,000 per kW, which is an order of magnitude higher than the cost of a new gas-fired plant. AAF notes that much of this cost is due to a combination of delays associated with obtaining approval from the NRC, which can take many years, and compliance with NRC regulations. The AAF notes that these costs are not justified by the underlying risks of nuclear power. Indeed, since the risks associated with new plants are far lower than those associated with current plants, priority should be given to finding ways to reduce compliance costs and approval so that new plants can be built. The AAF provides a table comparing the NRCs maximum permissible core damage frequency (CDF)—i.e. the likelihood of core damage occurring—with the potential to cause a meltdown. The table is repeated below. As is clear, even current plants are twice as safe as

---

[160] Sam Batkins, Philip Rossetti, and Dan Goldbeck, *Putting Nuclear Regulatory Costs in Context,* (Washington, D.C.: American Action Forum. 2017). https://www.americanactionforum.org/research/putting-nuclear-regulatory-costs-context/#ixzz6gAGn2JOW

[161] Ibid.

the NRC requirement, while new plants range from 33 times as safe (for Advanced Pressurized Water Reactors, APWR) to 10,000 times as safe (for NuScale's small modular reactors).

> *For new plants, the AAF study cites the estimate produced by the Breakthrough Institute, which found that the cost of a new plant is about $11,000 per kW, which is an order of magnitude higher than the cost of a new gas-fired plant.*

TABLE 4: CORE DAMAGE FREQUENCY FOR DIFFERENT TYPES OF NUCLEAR REACTOR

Plant Type	CDF per Year	Safer than NRC Requirement by a Factor of...
NRC Requirement	1 in 10,000	N/A
Current Plants	1 in 20,000	2
US-APWR	1 in 300,000	33
APR1400	1 in 2,000,000	217
AP600	1 in 5,000,000	588
AP1000	1 in 60,000,000	6,061
NuScale	1 in 100,000,000	10,000

Source: Batkins, Rossetti, and Goldbeck, *Putting Nuclear Regulatory Costs in Context*.

Space does not permit a detailed analysis of all the regulatory requirements under which nuclear power operates. Moreover, as the AAF report notes: "The NRC needs reform, but identifying specific policy changes will require testimony from nuclear experts experienced with the regulatory process and capable of identifying regulations that may be high in cost without any reduced risk (for example, analog vs. digital instrumentation)."[162] Sadly, in spite of the evidence that regulatory compliance costs are the fundamental barrier inhibiting the

---

[162] Ibid.

development of new nuclear reactors in the U.S., a recent report from the Department of Energy entitled “Restoring America’s Competitive Nuclear Advantage” made no real mention of them.[163] Worse, to the extent that the report addressed nuclear power generation (as opposed to mining uranium), it focused mainly on government-funded initiatives.

> *…once the overwhelming burden of regulation has been reduced, the federal government should stop providing subsidies.*

It is perhaps not surprising that the Department of Energy should argue that new federal programs are necessary to restoring America’s competitive nuclear advantage. It is, after all, a federal agency that oversees the disbursement of billions of dollars in subsidies every year. And of course, as noted above, nuclear power is largely a creature of the federal government. But if nuclear power is to have a future as part of the energy mix, that has to change in two ways. First, as noted, federal regulation of nuclear power must be reformed so that it more cost-effectively addresses the risks. Second, once the overwhelming burden of regulation has been reduced, the federal government should stop providing subsidies. Of course, subsidy hogs will continue to argue that they are needed to make the technology competitive. But the reality is that until the federal government scraps its subsidies, the industry will not have sufficient incentives to develop and implement truly competitive reactor designs.

---

[163] Department of Energy, *Restoring America’s Competitive Nuclear Energy Advantage,* (Washington, D.C.: U.S. Department of Energy, 2020). https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring%20America%27s%20Competitive%20Nuclear%20Advantage-Blue%20version%5B1%5D.pdf

8.11 CONCLUSIONS

This section began with a review of various energy technologies. It found that in the short term, the least costly way to reduce carbon emissions is likely to be continued switching from coal-fired electricity generation to natural gas. To the extent that coal plants are nearing the end of their useful life, the switch would occur naturally.

Attempting more ambitious reductions in carbon emissions in the short term would likely impose very large costs. This is because of the high cost (at present) of building the necessary plants, whether those are nuclear or some combination of wind, solar, and battery storage.

Attempting to accelerate the development of lower-cost ways of reducing carbon emissions through subsidies or other protection to early-stage technologies is very unlikely to be cost-effective because it is impossible to know which technologies are worth subsidizing. The history of such subsidies and mandates, which range from renewable portfolio standards to the renewable fuel standard to the renewable energy production tax credit, does not bode well.

Rather than attempting to pick winners through mandates and subsidies, the best way to incentivize the development of more efficient and lower-carbon energy generation technologies is to let markets operate properly. That means eliminating as far as possible barriers to competition and reducing the burden of regulation. While there is no guarantee that the resultant technologies will provide zero-carbon energy for less than the cost of electricity produced from natural gas today, the likelihood of such an outcome would be greatly increased.

PART 9

CONCLUSIONS: COMMON SENSE POLICIES TO ACCELERATE DECARBONIZATION

As this paper has demonstrated, decarbonization of the U.S. economy is occurring as a result of a combination of increasing energy density of fuels, increasing energy efficiency of production and consumption, and, more recently, a switch to lower-carbon and zero-carbon energy sources.

Part 3 hypothesized that if the 30-year linear trend in GHG/GDP emissions were to continue into the future, then global GHG emissions might peak in the next decade and begin to fall—reaching zero emissions by around 2060.

Parts 4 and 5 explained how this trend arose, through a combination of the use of increasingly dense sources of energy and dematerialization. Part 6 outlined the processes that underpinned those changes.

Part 7 showed that while increased energy efficiency is likely to slow the growth of energy demand and might reduce it gradually, it will not—indeed cannot—reduce it dramatically in the short to medium term. It also cautioned against poorly designed attempts to speed up the development and adoption of energy efficiency improvements, many of which are not cost-effective and some of which impose costs far in excess of any benefits.

Part 8 showed that in the short term, the most cost-effective way to reduce carbon emissions is likely to come from continuing the switch away from burning coal and toward burning natural gas. Meanwhile, in the medium term, a switch to nuclear power might be more cost-effective than a combination of intermittent "renewable" fuels, such as wind and solar, and backup generation—if the costs of new nuclear plants can be brought down to the levels achieved in South Korea, or lower. That means reducing the regulatory burden and eliminating subsidies.

Innovations in fracking and heat exchanges may make geothermal energy cost-effective in a wider range of locations. If that is the case, this could also become an important source of low-carbon power in the medium term.

While innovations in wind and solar are likely to continue to reduce the costs of these sources, their intermittent nature means that for them to become truly competitive, there will have to be major advances in storage technologies. As such, widespread adoption could take 30-50 years. Pushing for early adoption of such technologies would be enormously costlier than alternatives.

9.1 RECOMMENDATIONS

Given the foregoing, the following draws together the disparate policy analyses and conclusions discussed in this study and offers some additional policy ideas.

9.1.1 ADOPT POLICIES THAT PROMOTE INNOVATION

The evidence from Part 5 suggests that there is a strong negative correlation between economic freedom and GHG emissions per unit of output.[164] This is probably because

---

[164] Ibid., section 5.2 especially.

societies that are more economically free tend to have higher rates of innovation, as has been demonstrated in several studies.[165] As the authors of one such study, which considered patenting activity among 5809 firms in 29 countries, note:

> *[We] find strong and robust evidence of a positive relationship between corporate innovation and the cross-country differences in economic freedom. This finding suggests that firms domiciled in a country with a sound regulatory system, limited government, regulation efficiency, and open markets facilitate corporations undertaking innovative activities.*[166]

Economists Jie (Jack) He of the University of Georgia and Xuan Tian of Tsinghua University reviewed recent literature on culture and institutional factors that influence rates of innovation (measured by investments in R&D and rates of patenting).[167] They found that the main factors that exert a positive influence on innovation are:

- The ability to form companies and thereby share risk
- The ability to raise capital through equity markets
- Access to credit through banks
- Competition in the supply of credit, especially by private banks
- The ability to hire talent through flexible labor markets
- Openness to immigration, which affects both the supply of talented employees and the number of highly motivated entrepreneurial innovators
- Managerial quality
- The extent of product market competition
- Openness to foreign ownership

---

[165] Hui Zhu and Steven X. Zhu, “Corporate innovation and economic freedom: Cross-country comparisons,” *The Quarterly Review of Economics and Finance,* Vol. 63, 2017, 50-65; D.L. Bennett and, B. Nikolaev, “The Historical Prevalence of Infectious Diseases and Global Innovation,” *Proceedings of the Academy of Management,* Vol. 2019, No. 1, 2019. https://journals.aom.org/doi/10.5465/AMBPP.2019.15643abstract; and Daniel L. Bennett and Boris Nikolaev, “Entrepreneurship and Free Enterprise. Economic Freedom, Public Policy, and Entrepreneurship,” *Economic Freedom of the World: 2019 Annual Report*, Eds. James Gwartney et al., (Vancouver, BC: Fraser Institute. 2019). https://www.fraserinstitute.org/sites/default/files/economic-freedom-of-the-world-2019.pdf

[166] Zhu and Zhu, “Corporate innovation and economic freedom.”

[167] Jie (Jack) He and Xuan Tian, “Institutions and Innovation,” *Annual Review of Financial Economics,* Vol. 12, 377-398, 2020.

- The presence of activist hedge funds
- The presence of short sellers
- The availability of laws that protect intellectual property
- Laws that limit non-practicing entities (NPEs) from enforcing patents
- Laws that protect minority shareholders
- Laws that protect contracts
- Low personal and corporate taxes
- The impartiality of the political system
- Effective but not overly burdensome accounting rules
- The absence of laws mandating disclosure of portfolio holdings
- Lower frequency of mandatory reporting by regulated firms

Many of these factors are features of "economic freedom." Others are related to economic freedom, such as the appropriateness and cost-effectiveness of regulation. For example, complex stock market regulations, limitations on "accredited investors," and many other financial market regulations impede the ability of companies to raise equity capital.[168] Meanwhile, banking regulation impedes competition among suppliers of credit (for example, deregulation of interstate banking increased competition, leading to an increase in the availability of credit and consequent increase in investment in R&D[169]). Furthermore, some of the "cultural" factors are indirectly related to economic freedom. For example, managerial quality is affected by the market for corporate control, which is in turn affected by antitrust laws (arbitrary restrictions on mergers, for example, reduce incentives for managers to respond to shareholder pressure to invest in R&D).

These findings suggest that policy changes that increase a jurisdiction's level of economic freedom will improve the prospects for innovation, which in turn will increase the rate of decline in emissions of GHGs per unit of output.

---

[168] Lars Hornuf and Armin Schwienbacher, "Should securities regulation promote equity crowdfunding?" *Small Business Economics,* Vol. 49, 2017, 579–593. https://link.springer.com/article/10.1007/s11187-017-9839-9

[169] Mario Daniele Amore, Cédric Schneider, and Alminas Zaldokas, "Credit supply and corporate innovation," *Journal of Financial Economics,* Vol. 109, 2013, 835-855.

In the 2020 Economic Freedom of the World Index, the U.S. ranked sixth overall, with a score of 8.22 out of 10.[170] As such, the U.S. is clearly one of the most economically free countries in the world. However, it is worth noting that the U.S. has fallen in the ranks over the past two decades. In 2000, it was ranked third, with a score of 8.67.[171] Specifically, the U.S.' scores on "size of government," "legal system and property rights," and "freedom to trade internationally" have worsened somewhat over that time. Policies directed at improving the U.S.' performance on these metrics would be expected to improve the nation's prospects for innovation. The Fraser Institute also ranks U.S. states on economic freedom, which also offers insights into potential state-level changes that might improve the prospects for innovation.[172]

> *In the 2020 Economic Freedom of the World Index, the U.S. ranked sixth overall, with a score of 8.22 out of 10.*

While there is insufficient space in this study to detail all the changes to U.S. policy that might result in increased innovation, it is worth briefly outlining some broad changes that would likely have a positive effect both on innovation in general and in relation to energy specifically. Of particular importance are changes to regulations and taxes, which currently have widespread negative effects on innovation and could thus be productively reformed, as discussed below.

9.1.2 REFORM REGULATION

Adam Thierer, an economist at the Mercatus Center, has argued persuasively that top-down regulatory controls are a major deterrent to innovation and argues instead for "permissionless innovation," which entails a shift away from such top-down regulations toward bottom-up approaches to problems associated with externalities, public goods, and

---

[170] Gwartney et al. *Economic Freedom of the World Annual Report 2020*, Vancouver, B.C.: Fraser Institute.

[171] Ibid.

[172] Ibid.

informational asymmetries.[173] To address new problems, Thierer proposes policy solutions including:[174]

- Relying on existing legal solutions and the common law to solve problems.
- Waiting for insurance markets and competitive responses to develop.
- Pushing for industry self-regulation and best practices.
- Promoting education and empowerment solutions and be patient as social norms evolve to solve challenges.
- Adopting targeted, limited legal measures for truly hard problems.

In addition, Thierer argues that extant regulations that primarily serve as barriers to entry and innovation should be identified and removed, and that regulatory policies should be evaluated and re-evaluated to ensure they are only retained if their benefits exceed their costs.

During the COVID-19 crisis, the federal government and some state governments partially relaxed numerous regulations that were impeding the supply of important goods and services, including novel tests and treatments. The result seems to have been an increase in access to those goods and services, with no dramatic adverse effects. Maintaining and extending these relaxations would shift the U.S. in the direction of permissionless innovation.[175]

Reform Federal Regulation

If Thierer's proposals were fully adopted, innovation in the U.S. would likely rise dramatically. While the Administration, Congress and state legislatures should be encouraged to adopt such an approach, even more-incremental reforms can have significant benefits. Such an approach was advocated in 2014 by the Business Roundtable,

---

[173] Adam Thierer, *Permissionless Innovation: The Continuing Case for Comprehensive Technological Freedom, revised and expanded edition,* (Arlington, VA: Mercatus Center, 2016).

[174] Adam Thierer, *Permissionless Innovation and Public Policy: A 10-Point Blueprint*, (Arlington, VA: Mercatus Center, 2016). https://permissionlessinnovation.org/wp-content/uploads/2016/04/PI_Blueprint_040716_final.pdf

[175] Patrick A. McLaughlin, Matthew D. Mitchell, and Adam D. Thierer, *A Fresh Start: How to Address Regulations Suspended During the Coronavirus Crisis,* (Arlington, VA: Mercatus Institute, Special Edition Policy Brief, 5 May 2020). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3593010

which suggested some specific actions that could help reduce unnecessary federal regulatory burdens, including:[176]

- Congress should codify key principles of Executive Order 12866 to establish the basic requirements for sound Cost-Benefit Analyses (CBA). These requirements (which, when codified, would be judicially enforceable) include identifying a compelling public need for new regulatory action; assessing the costs and benefits of a proposed regulatory action and reasonable alternatives using the best available scientific, technical, and economic information (with quantification if feasible); and proceeding with a regulation only upon a reasoned determination that the benefits justify the costs. Codification could be accomplished in multiple ways, such as (1) including requirements in future authorizing statutes for agencies to follow these principles when proposing any major regulation issued under these statutes or (2) incorporating cost-benefit requirements into a more comprehensive regulatory reform bill.
- Congress should extend CBA and OMB review requirements to independent regulatory boards and commissions.
- OMB should require regulatory agencies to provide additional justification for major rules in which ancillary benefits comprise more than 50% of the expected benefits.
- OMB should ensure that regulatory agencies conduct sensitivity and uncertainty analyses to the extent they are required under Circular A-4.
- Congress and OMB should promote replicability of CBAs through increased transparency and well-documented methodologies, thereby enhancing the ability of qualified and credible third parties to review agency analyses and conduct their own analyses using alternative assumptions.
- Congress and OMB should encourage regulatory agencies to focus retrospective reviews on rules that impose large socio-economic costs or that stakeholders and the public identify as problematic.
- Congress should provide the Office of Information and Regulatory Affairs with additional staff resources.

---

[176] *Using Cost-Benefit Analysis to Craft Smart Regulation: A Primer and Key Considerations for Congress and Federal Agencies*, (Washington, D.C.: Business Roundtable, December 2014).

Remove Energy-Specific Regulatory Barriers to Competition and Innovation

Competition is a key driver of innovation, yet as noted in Part 7, most energy markets in the U.S. suffer from a lack of competition. While there are many causes, incumbent regulated monopolies play a substantial role. Quarantining these monopolists, in much the way Texas did, may offer the best hope for promoting genuinely competitive markets in electricity (and other forms of energy subject to utility regulation), leading to disruptive competition with associated innovation.[177]

Competition is a key driver of innovation, yet as noted in Part 7, most energy markets in the U.S. suffer from a lack of competition. While there are many causes, incumbent regulated monopolies play a substantial role.

In addition to top-down regulation of energy systems, there are currently numerous regulatory barriers to the development and implementation of new technologies in the realm of energy generation and supply. Some of these barriers are specific to energy, such as regulation by state public utility commissions and the Nuclear Regulatory Commission. Others, such as NEPA, apply more generally but have a particularly pernicious effect on energy technologies. Reducing these barriers would enable more rapid deployment of existing low-carbon technologies at lower cost, while also incentivizing the development of innovative low-carbon technologies. Ideally, legislators would apply the principles of permissionless innovation (see above), but if that is not feasible, then implementing more incremental reforms (for example, expediting reviews under NEPA and APD, as discussed in subsection 8.10.3) would reduce costs and enable more experimentation and innovation.

---

[177] Here I am combining the concept of "creative destruction" coined by Joseph Schumpeter (a noted economist), with the term "disruptive innovation" coined by Clay Christensen (a noted management consultant).

In addition, federal and state governments could do more to shift regulatory burdens away from inefficient standards-based approaches that have dominated rulemakings for decades and toward market-based approaches such as emissions trading systems (of the kind that were adopted following the Clean Air Act Amendments in 1990 in respect of emissions of sulfur). Such market-based approaches reward those plants that are able more cost-effectively to reduce emissions, while enabling higher-cost legacy plants to continue operations. However, when designing such systems it is important to ensure that they do not lead to adverse local health and/or environmental outcomes.[178]

9.1.3 REFORM TAXES

The U.S. federal tax system is, by any measure, vastly complicated. One measure of its complexity is the number of pages of the code: 15,361 in 2020.[179] This poses a heavy burden on individuals and businesses. In 2016, the Tax Foundation estimated that 8.9 billion person-hours were spent complying with IRS tax filing requirements.[180] That is an average of over 24 hours per person. Meanwhile, these filing requirements cost the U.S. economy approximately $409 billion, or about 0.2% of U.S. GDP. Analysis by the National Taxpayers Union found that compliance costs fell slightly following the 2017 reforms but still amounted to $367 billion in 2020.[181]

But the complexity of the U.S. tax system has another cost: much of it arises from the enormous number of tax expenditures (including deductions, exemptions, credits, deferrals, and preferential tax rates), which have the effect of distorting investment and spending toward those items that are given preferential treatment. The scale of these distortions is gigantic: federal tax expenditures totaled approximately $1.5 trillion in 2018, compared

---

[178] H. Ron, Chan, et al., "The Impact of Trading on the Costs and Benefits of the Acid Rain Program," *Journal of Environmental Economics and Management,* Vol. 88, 2018, 180-209.

[179] U.S. Government Publishing Office. Code of Federal Regulations, Title 26, 2020. https://www.govinfo.gov/app/collection/cfr/2020/

[180] Scott A. Hodge, *The Compliance Costs of IRS Regulations*, (Washington, D.C.: Tax Foundation, 2016). https://files.taxfoundation.org/legacy/docs/TaxFoundation_FF512.pdf

[181] Demian Brady, "Tax Complexity 2020: Compliance Burdens Ease for Second Year Since Tax Reform," National Taxpayers Union, April 15, 2020. https://www.ntu.org/foundation/detail/tax-complexity-2020-compliance-burdens-ease-for-second-year-since-tax-reform

with total federal tax receipts of around 3.3 trillion.[182] In many, perhaps most, cases such distortions lead to investments that are less productive than alternatives that would have occurred without the expenditure. As Steven Entin of the Tax Foundation noted in a 2013 paper,

> *A more neutral tax base, combined with lower tax rates, would be a powerful engine for economic growth. Labor costs are expensed. Capital costs are not. Fixing the distortion in the tax base by moving toward expensing of capital outlays would redress some of the punitive treatment current law imposes on capital-intensive industries and the blue collar jobs they provide. It would end the tax bias against long-lived assets such as plants, commercial buildings, and multifamily housing in favor of short-lived assets or intellectual property. Lower corporate tax rates on the resulting, better-defined income would add a further boost to all types of innovation and expansion. Combined, they would break the economy out of its current sluggish pattern of inadequate investment and job creation.*[183]

“*But the complexity of the U.S. tax system has another cost: much of it arises from the enormous number of tax expenditures (including deductions, exemptions, credits, deferrals, and preferential tax rates), which have the effect of distorting investment and spending toward those items that are given preferential treatment.*”

---

[182] Robert Bellafiore, “Tax Expenditures Before and After the Tax Cuts and Jobs Act,” Tax Foundation, December 18, 2018. https://taxfoundation.org/tax-expenditures-pre-post-tcja/

[183] Steven J. Entin, *The Tax Treatment of Capital Assets and Its Effect on Growth: Expensing, Depreciation, and the Concept of Cost Recovery in the Tax System,* (Washington, DC: Tax Foundation, Background Notes Number 67, April 2013). https://files.taxfoundation.org/legacy/docs/bp67.pdf

9.1.4 REFORM SUBSIDIES

In addition to tax expenditures, both federal and state governments provide direct subsidies of various kinds. Proponents argue that direct subsidies to "renewable energy" technologies are necessary due to the incomplete appropriability of rents from investments in innovation (that is to say, some of the benefits of innovation accrue to parties other than the innovator), which leads to an undersupply of such investments.[184] There are several problems with such arguments.

First, it is impossible to know beforehand the optimal level of investment in any specific technology. Take the examples of energy technologies in Part 7: it is not obvious which technology or sets of technologies will lead most cost-effectively to reductions in carbon emissions. As such, it is not possible to know how much to invest in which technologies. Attempting to correct for this assumed "market failure" in the supply of investment through direct subsidies therefore tends to result in significant misallocation of resources.

Second, many innovations are the result of attempts to solve concrete, incremental problems that are known only to the specific firms (or, sometimes, groups of firms) attempting to solve those problems. But governments do not have access to the firm-specific information that would be necessary to identify the problems being addressed. As such, they cannot know how best to allocate subsidies between firms, even if they knew what kinds of technologies in general would be worth supporting.

A 2014 study published in the *American Economic Review* that looked at the effect of subsidies and tax expenditures targeted at renewable energy concluded that "despite tax revenue losses of $10 billion per year in 2010, these provisions have a very small impact on GHG emissions and, in some cases, may actually increase emissions."[185]

Third, there are several other ways to solve the appropriability problem, including:

---

[184] Matteo Deleidi, Mariana Mazzucato, and Gregor Semieniuk, "Neither crowding in nor out: Public direct investment mobilising private investment into renewable electricity projects", *Energy Policy,* Vol 140, May 2020. https://www.sciencedirect.com/science/article/abs/pii/S0301421519307803

[185] Brian C. Murray, et al., "How Effective are US Renewable Energy Subsidies in Cutting Greenhouse Gases?" *American Economic Review: Papers & Proceedings,* 104 (5), 2014, 569–574.

- **First mover advantage**. In many cases, innovators are able to appropriate a considerable portion of the rents from an innovation by rapidly scaling up before others are able to copy it.
- **Investment in related products**. In many cases, much of the rents from a technology accrue either upstream products (i.e. commodities or intermediate inputs necessary for the production of the technology) or downstream products (i.e. technologies that utilize the technology). As such, innovators can appropriate a greater portion of the rents from their technologies by investing in upstream and/or downstream products.
- **Intellectual property**. Where the marginal cost of copying an innovative technology is low relative to the costs of development, rents can be appropriated by others who are able quickly to copy the technology. This is especially the case when innovators are not able to obtain a substantial first mover advantage and are unable to capture some of the rents through vertical control (i.e. investments in upstream and downstream products). In some cases, intellectual property protections (including trade secrets and patents) can overcome the problem by prohibiting appropriation by others for a period of time.

“Given the inefficiency associated with both subsidies and tax expenditures, the first best solution would simply be to scrap all subsidies and tax expenditures.”

Given the inefficiency associated with both subsidies and tax expenditures, the first best solution would simply be to scrap all subsidies and tax expenditures. However, if that is not possible politically, then subsidies should be reformed so that they more effectively achieve their desired ends. One way to do this would be to switch the funds currently dedicated to subsidies and tax expenditures into prizes and pre-commitments that would be available only for technologies that meet specific criteria.

While prizes and purchase pre-commitments are not without their own problems, they have been successfully used to incentivize the development of numerous technologies that have had significant economic, social, and environmental benefits.[186] For example, a series of rewards offered by the British government for better ways to measure longitude led to the development of a more accurate clock that worked at sea, enabling more precise navigation using astronomical charts, and dramatically reducing the loss of life and property at sea.[187] More recently, government purchase pre-commitments led to more-rapid development of several COVID-19 vaccines.[188] There are also numerous examples of private sector prizes, including some with environmental applications, such as the Wendy Schmidt Oil Cleanup XCHALLENGE, which resulted in the development of an oil cleanup system that was more than three times as efficient as previous best practice methods.[189]

The Department of Energy already uses prizes to some extent. Unfortunately, these prizes are generally technology-specific rather than outcome-specific (i.e. they support improvements in the performance of a specific technology, such as wave power or solar power[190]), so they continue to suffer from the allocation problem. Shifting all tax expenditures and subsidies to prizes and pre-commitments that are outcome-specific would likely result in a considerable increase in the efficiency and effectiveness of such government disbursements.

9.1.5 REDUCE TRADE BARRIERS

Trade restrictions drive up costs, reducing both supply and demand. In the case of U.S. energy, restrictions on exports have reduced the price of oil and gas in the U.S., leading both to excessive domestic consumption and lower output.[191] Removing such trade barriers

---

[186] Michael Kremer, Jonathan Levin, and Christopher M. Snyder, "Advance Market Commitments: Insights from Theory and Experience," *American Economic Association Papers and Proceedings,* Vol. 110, 2020, 269-273.

[187] Dava Sobel, *Longitude*, (London: Bloomsbury, 2010).

[188] Claire Felter, *A Guide to Global COVID-19 Vaccine Efforts,* (New York: Council on Foreign Relations, March 1, 2021). https://www.cfr.org/backgrounder/guide-global-covid-19-vaccine-efforts

[189] XPrize, *Removing Oil from the Sea. Xprize Challenge Oil Cleanup - Wendy Schmidt,* https://www.xprize.org/prizes/oil-cleanup

[190] DOE Wave Energy Prize, Department of Energy, https://www.challenge.gov/toolkit/case-studies/wave-energy-prize/; and DOE Solar Energy Sunshot Prize, Department of Energy, https://www.energy.gov/eere/solar/about-sunshot-prize

[191] EIA, *Effects of Removing Restrictions on U.S. Crude Oil Exports*, (Washington, DC: U.S. Energy Information Administration, 2015). https://www.eia.gov/analysis/requests/crude-exports/

would lead to a small increase in prices in the U.S., which would incentivize increased energy efficiency, while at the same time stimulating investment in the development of oil and gas reserves.

In a sense, all these policies really amount to “getting the institutions right”—but it is worth emphasizing some of the specific barriers to energy-specific competition, innovation, and trade because of the outsize role they play in impeding the development of lower-carbon technologies.

9.2 RETURNING TO THE HYPOTHETICAL

Given the foregoing, it seems reasonable to ask how plausible is the hypothetical projection of future GHG emissions discussed in Part 3? Specifically, how likely is it that present trends in energy intensity and decarbonization will continue, leading to a dramatic decline in carbon emissions between 2030 and 2060? Unfortunately, the author of this study is merely an economist, not a soothsayer. Nonetheless a few observations are merited.

First, it seems clear that the likelihood of such a trajectory materializing would be greatly increased if governments remove the impediments to decarbonization detailed in this study, including unnecessary (and often counterproductive) regulations, subsidies, taxes, and tax expenditures. By removing such impediments, the full throttle of the free market would be unleashed, leading to all manner of innovations, many of which would contribute to reductions in carbon emissions.

Second, unfortunately many governments are unlikely to make the necessary reforms in the short to medium term. As such, at the global level the trajectory is probably overly optimistic.

Third, while the trajectory may be overly optimistic, it nonetheless seems plausible that decarbonization could occur quite rapidly toward the end of the century, driven by innovations occurring initially in a smaller set of countries and subsequently adopted in other countries.

ABOUT THE AUTHOR

Julian Morris has been researching and writing on the economics of climate change for 30 years. He is a Fellow of the Royal Society of Arts in the UK, a Senior Fellow at Reason Foundation, and a Senior Scholar at the International Center for Law and Economics. He is also a member of the editorial board of Energy and Environment, and a member of several non-profit boards. He was previously a vice president at Reason Foundation and before that founded and ran International Policy Network.