★★★★★★

Chapter 6

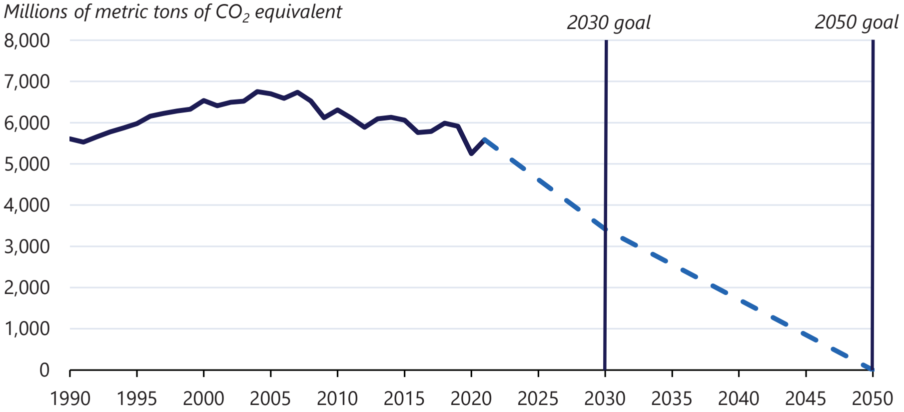
Accelerating the Clean Energy Transition

The clean energy transition is under way. Its end goal is an innovative, cutting-edge U.S. economy powered by cheap, reliable, and secure clean energy sources and technologies. In this future, various aspects of the economy—the electricity that powers it, the cars and planes that move people and goods, the products and foods we consume—will be provided without the harm of air pollution and climate change. The production of clean energy will also create new sources of economic growth, employment, and prosperity, furthering American competitiveness throughout the 21st century to meet global demand for clean energy technologies.

Contrast this future with the Nation's past reliance on fossil fuels, a dependence that has come at significant costs. The use of fossil fuels—responsible for 68 percent of total historical human-induced carbon dioxide emissions—has given rise to climate change (Friedlingstein et al. 2020). The global average temperature has already risen more than 1 degree Celsius (1.8 degrees Fahrenheit) since the preindustrial period, and is projected to reach 2.4 to 5 degrees Celsius (4.3 to 9 degrees Fahrenheit) by 2100 if no further action is taken (Kriegler et al. 2017; IEA 2023a).

The cost of inaction is high, with damage from climate change already starting to mount. In 2023, the United States experienced an unprecedented 28 weather- and climate-related disasters with losses of at least $1 billion each (NOAA 2024). Some insurers are starting to pull out of home insurance markets due to the high costs of covering climate-related disasters (CEA 2023a). Additional warming is expected to further damage human health, productivity, living standards, and food security, driving mass migration and

Figure 6-1. U.S. Net Total Greenhouse Gas Emissions, with Emissions Reduction Goals



Council of Economic Advisers

Sources: U.S. Environmental Protection Agency; CEA calculations.

Note: Dotted segments represent pathways to achieving 2030 and 2050 emissions reduction goals. The measure "millions of metric tons of CO_2 equivalent" scales each gas by its global warming potential relative to CO_2.

2024 Economic Report of the President

worsening social and political instability, among other social and economic outcomes, and inequities therein (Carleton et al. 2022; Burke, Hsiang, and Miguel 2015; Schlenker and Roberts 2009; Hsiang et al. 2013, 2023; Marvel et al. 2023). This is further compounded by the harmful health consequences of local air pollution due to continued burning of fossil fuels (Lelieveld et al. 2019). To avoid these costs, policymakers must induce a rapid energy transition from fossil fuels to clean energy sources.

Decarbonizing the U.S. economy is an immense undertaking. A combination of private and public investments triggered by Federal, State, and local climate policies are already moving in this direction (CEA 2023a; White House 2022; OMB 2023; California Legislature 2023; NYC Department of Buildings 2023). Between 2005 and 2021, U.S. greenhouse gas (GHG) emissions fell by 17 percent, as shown in figure 6-1 (UNFCCC 2023), a remarkable annualized rate for a major industrial economy during a period of economic growth (OECD 2023).[1] Yet this pace is still not fast enough

---

[1] GHG emissions also fell across the European Union during this period, but under a regulated declining cap on emissions (UNFCCC 2024b; European Environment Agency 2023).

to meet Paris Agreement commitments seeking to limit global warming to 1.5 degrees Celsius (UNFCCC 2024a). To achieve the midway goal of a 50 percent emissions reduction relative to 2005, the United States must lower its annual emissions by 6 percent on average between 2021 and 2030, and must further accelerate emissions reductions after 2030.[2]

Achieving decarbonization rapidly enough to avoid growing physical damage from climate change will require deploying commercially available clean energy technologies—like solar and wind power, electric vehicles, and heat pumps—at even faster rates (IEA 2023b). To reach net zero emissions by 2050, the United States will need to act across all sectors of the economy. For example, the United States may need to double its share of electricity generated by non-carbon-emitting sources to roughly 75 percent by 2030 (National Academies 2021). Furthermore, more than half of global emissions reductions by 2050 will need to come from technologies that are yet to be invented or commercialized (IEA 2023b).

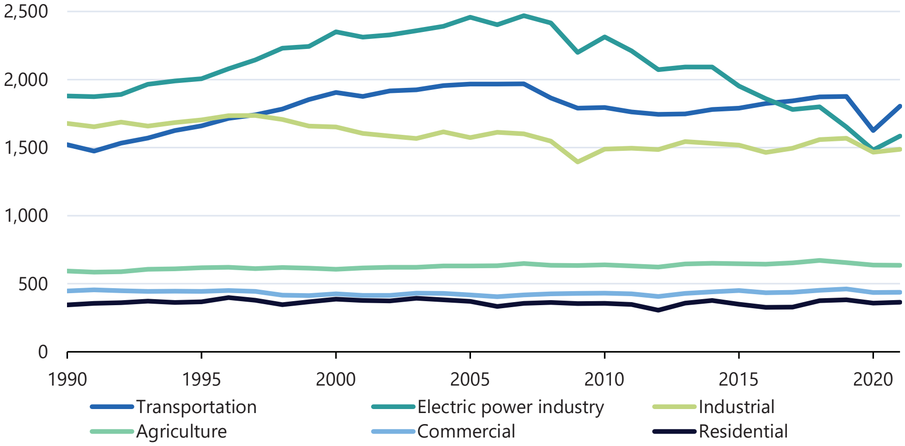
Faster decarbonization can be achieved in part by accelerating two complementary recent developments. First, the electricity sector needs to shift away from fossil fuels. Much of recent U.S. GHG reduction comes from the electricity sector (dark teal line, figure 6-2). A large share of emissions reductions in the electricity sector to date have been the result of displacing coal-fired generation with clean energy and natural gas (figure 6-3). The electricity sector must now accelerate its transition from using fossil fuels, including natural gas, to clean energy. At the same time, given a cleaner source of electricity, a shift toward electrification in other sectors—such as the transportation, industrial, commercial, and residential sectors—would be an effective way to help lower emissions across the economy. Both tasks are long-term shifts in the type of energy that powers the U.S. economy.

---

[2] This CEA calculation assumes a constant-percentage annual GHG emissions decline between observed 2021 U.S. GHG emissions and the Administration's 2030 U.S. GHG emissions target.

Figure 6-2. U.S. Emissions per Sector, 1990–2021

Millions of metric tons of CO_2 equivalent

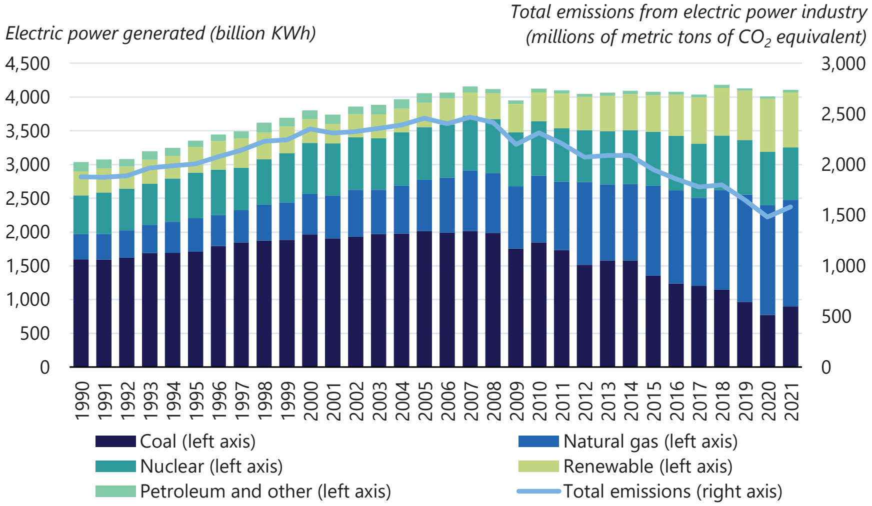


Council of Economic Advisers

Source: U.S. Environmental Protection Agency (2023).

2024 Economic Report of the President

Figure 6-3. U.S. Electricity Generation by Energy Source, 1990–2021



Council of Economic Advisers

Sources: U.S. Energy Information Administration; U.S. Environmental Protection Agency.

2024 Economic Report of the President

Economists characterize such broad transitions as structural change: long-term evolutions in an economy's composition, whether through inputs or outputs, from an established set of economic activities to a set of emerging ones. Structural change underlies many major moments in economic development; past examples include the transition from agriculture to manufacturing during the Industrial Revolution and the more recent shift from manufacturing to services in advanced economies. The clean energy transition—moving an economy primarily based on fossil fuels to one powered by clean energy sources and technologies—can also be viewed through this lens.

The structural change perspective provides a foundation for understanding the forces that will determine the direction, pace, and endpoint in the transition from one energy system to another. It also offers a lens for identifying the specific investments needed for accelerating the transition from an energy system based on fossil fuels to one based on clean energy. For example, in the electricity sector, the decline in capital costs for clean energy has increasingly made it competitive with fossil-based electricity, yet some new electricity capacity still uses natural gas (Lazard 2023; EIA 2023a). This is in part because some types of clean electricity, such as solar, require complementary technologies, like batteries, to be available during all parts of the day. A structural change perspective highlights how the transition can be accelerated through complementary investments in battery storage, along with lowering siting and transmission costs, enabling renewable energy to better substitute for fossil fuels by supplying electricity throughout the day.

Also embedded in a structural change perspective is the notion of path dependence. Fossil fuels dominate today's market not only because they have historically been cheaper, due in part to Federal policies and subsidies implemented in the past, but also because they have accumulated historical economic advantages that are difficult for emerging clean energy technologies to surmount. However, this path dependence cuts both ways. Policies that provide a sufficient push for clean energy technologies to overcome fossil fuels' historically accumulated advantage can alter the need for future government intervention. That is, putting the economy on a clean energy path will make it easier to achieve long-term decarbonization. As that happens, policy interventions need not be permanent: Once an economy has built up sufficient economic advantage in clean energy, private market incentives can sustain the clean energy transition.

By considering a subset of clean energy sources and technologies—including wind, solar, electric vehicles (EVs), and batteries—through the economics of structural change, this chapter provides a framework for understanding the clean energy transition and the policies that can accelerate it.[3] However, this framework, like any, is not comprehensive, and does not address every element of the Biden-Harris Administration's whole-of-government approach to climate policy. It is also an incomplete account of the benefits of the clean energy transition, such as avoiding climate damage, lowering air pollution and energy prices, creating high-quality jobs, and fostering economic competitiveness. Instead, the narrower task of this chapter is to offer an economic lens for understanding the path toward the clean energy transition and how it can be achieved.

The chapter's first section provides an overview of structural change and how economists have applied the framework to explain important moments in economic development. It then provides a taxonomy of the various factors that can push or pull against structural change and thus determine the direction, rate, and end point of long-term transitions. The section then discusses market failures and economic frictions under which government intervention may be needed when the direction and pace of market-driven structural change are not in line with society's goals.

---

[3] This framework also applies to nuclear, hydropower, and technologies such as carbon capture and storage and direct air capture that lower net GHG emissions.

The second section applies the structural change framework to the clean energy transition, discussing various ways in which the transition represents a distinct case of structural change—and the ensuing set of unique challenges and opportunities. The push-and-pull factors discussed in the first section are then mapped onto specific issues in the clean energy transition.

The third section describes how specific policies enacted by the Biden-Harris Administration are strategically targeting these push-and-pull factors to accelerate the clean energy transition. These and other efforts can build a U.S. clean energy economy that benefits workers and communities, avoiding the worst economic consequences of climate inaction.

The Economics of Structural Change

This section introduces structural change as a broad economic concept and delineates the various push-and-pull forces that determine the direction and speed of structural change. Market failures and other economic frictions may inhibit the socially optimal direction and rate of structural change, justifying government intervention. The structural change lens shows how policy interventions, if successful, need not be permanent; once properly directed, an economy has the momentum to carry forward that transition on its own.

What Is Structural Change?

The transition to a net zero economy requires structural change. Structural change refers to long-term (as opposed to short-term, cyclical) changes in the composition of an economy, from an established activity to an emerging one. Of particular interest are the direction and the pace of this change, as well as the final composition of the economy. Embedded in a structural change perspective is the notion of path dependence: that historical economic dependence continues to exert influence today (Nelson and Winter 1985). Once the process of structural change begins, it can gather momentum on its own without much further impetus.

History is rich with examples of structural change, many of which were considered important turning points in economic development. For instance, structural change in the allocation of labor from agricultural to industrial activity characterized the Industrial Revolution (Nurkse 1952; Rao 1952; Lewis 1954; Ranis and Fei 1961). Similarly, much attention has been given to the shift in labor shares from industrial to service-oriented activities during the latter half of the 20th century (Autor, Levy, and Murnane 2003; Acemoglu and Autor 2011).

Redirection of capital—both physical and financial—also characterizes major historical transitions. During World War II, economies around the world redirected domestic production from consumer durables—such as automobiles and home appliances—to tanks, airplanes, and artillery. From February 1942 until the end of the war, U.S. commercial auto production ceased, and auto assembly lines were repurposed to produce 80 percent of U.S. tanks and more than half of all aircraft engines (Gropman 1996). From 1940 to 1943, U.S. national defense gross investment rose from $13.2 billion to $517.9 billion (in 2022 dollars), representing an enormous financial reallocation.[4] Such redirection of resources transformed the trajectory of U.S. innovation for decades thereafter (see box 6-1).

These and other historical examples have led to a rich intellectual tradition in economics examining the drivers and consequences of structural change (Johnston 1970; McMillan and Rodrik 2011; Autor, Dorn, and Hanson 2013; Herrendorf, Rogerson, and Valentinyi 2014). Unlike more static frameworks, this literature focuses on transitional dynamics and their drivers. In doing so, it builds on macroeconomic models, but with an added focus on understanding the composition of an economy and how it changes.

Determinants of Structural Change

The structural change framework focuses on understanding the forces that shape—or reshape—the composition of an economy, whether through inputs, outputs, or both. These forces can push or pull against structural change, the balance of which determines the direction, speed, and end point of an economy's transition from an established activity to an emerging one. This section details such push-and-pull forces.

Productivity spillovers arise under many circumstances. Spillovers within a sector can occur at the individual level in the form of learning-by-doing (Arrow 1962; Lucas 1988) or at the sectoral level through technological or knowledge spillovers (Romer 1990; Acemoglu 2002; Acemoglu et al. 2012). Regardless of the mechanism, productivity spillovers within a sector favor the established economic activity and allow that advantage to strengthen over time, making the emerging economic activity increasingly unlikely to replace the established activity. Spillovers across sectors can, however, accelerate structural change, particularly when knowledge and technologies developed for an established sector can be applied to an emerging sector (Bloom, Schankerman, and Van Reenen 2013). Government-supported research efforts during the World War II mobilization effort, for example, had spillovers onto postwar innovation that enabled the

---

[4] This is from CEA calculations using data from the Bureau of Economic Analysis.

Box 6-1. World War II and Technological Change

The U.S. government has played a critical role in enabling past periods of rapid technological change, including during World War II, when the Federal Government established the Office of Scientific Research and Development (OSRD), an expansion of the then–recently created National Research Defense Committee and a predecessor to the National Science Foundation. This new office would eventually invest more than $9 billion (in 2022 dollars) in research and development (R&D) between 1940 and 1945 to develop innovations in radar technology, military weapons, and pharmaceuticals, among other sectors. Unlike previous models of public investment in R&D, the OSRD's novel approach channeled investments to hubs of applied research while facilitating partnerships and collaborations between public, private, and academic researchers (Gross and Sampat 2023a). Despite its brief existence, the OSRD bent the path of U.S. technical innovation for decades to follow, as a potential template for the clean energy transition.

Many of the technological advancements generated by OSRD support had direct civilian applications despite originally being intended for military use. For example, while penicillin cells were discovered in 1928, neither industry nor government had pursued their use as an antibiotic until the OSRD began investigating them for military applications in the early 1940s. After demonstrating its success in the military, the government released penicillin for commercial use in 1945 (Quinn 2013).

Recent evidence on the large-scale shock to research activity during World War II from the OSRD program suggests that public investment can have a sustained, long-term impact on subsequent innovation. Technology hubs that received the greatest R&D investment from the program during World War II realized 40–50 percent more patent-based innovation activity per year by 1970 (Gross and Sampat 2023a). World War II–era Federal investment in industrial activity and the ensuing mobilization also led to a sectoral shift in the composition of manufacturing activity toward industries like lumber, chemicals, rubber, stone, metals, machinery, and transportation equipment (Jaworski 2017).

These effects on future innovation were primarily driven by spillovers and agglomeration economies, in which co-located firms mutually benefit from the sharing of ideas, infrastructure, and other assets (Duranton and Puga 2004). Gross and Sampat (2023a) find that these effects were approximately double in clusters centered on a highly ranked university. That firms and other research institutions (including government labs) later located in these hubs also suggests spillover benefits from regionalized innovation activity. Roughly 40 years after World War II, industrial clusters that received the OSRD's R&D investment saw 90 percent higher employment in those manufacturing industries as well as additional manufacturing business formation (Gross and Sampat 2023a).

The research demands necessitated by World War II are similar in scope to those required to address climate change. Gross and Sampat (2023b) argue that unlike the Manhattan Project or the Apollo Program—which were focused on singular technological goals for singular customers—World War II demanded a portfolio-based approach to technological innovations for a variety of end users. In this regard, the authors note a parallel between the R&D investment approach of the OSRD and the scope of today's energy transition needs. But while the challenges are similar in scope, the broad-based structural transformation necessary to address climate change may require investment at an even greater scale.

development of information technologies and biomedical advances (see box 6-1).

An economy's composition may reflect *relative input prices* between established and emerging inputs. These include both the price of the input itself and any complementary capital, land, or other material inputs associated with the input of interest. Relative adoption tilts toward the input with lower contemporaneous prices. But in the presence of within-sector productivity spillovers, that tilt may be muted. For a new input, technology, or sector to become dominant, lower relative contemporaneous prices may not fully overcome the productivity advantage the established activity has built up over time. For example, high efficiencies in some forms of fossil fuel use from decades of experience would lead to lower adoption of renewables even if electricity from renewables were cheaper today than from fossil fuels.

Factor mobility can also accelerate structural change. Factor mobility refers to the ease with which factors of production—labor, capital equipment, or materials—can be allocated across different economic activities. For example, when workers in established sectors have skills that are attractive in emerging sectors, these workers can switch jobs across sectors—and relocate geographically if moving costs are low—without acquiring much additional education or retraining. Likewise, capital that can be redeployed readily across established and emerging sectors—for example, if a factory can shift from being powered by fossil fuels to clean energy—can help accelerate structural change. But when factors of production cannot be easily reallocated, the rate of structural change may be slow.

Structural change is often shaped by the degree of *substitutability* between existing technologies and those replacing them. Emerging economic activity must compete for consumers with existing activity. When an emerging sector's output perfectly substitutes for that of an established sector, consumers will more readily adopt goods from the new sector (Acemoglu 2002). However, when the new product is not a direct substitute, complementary investments are necessary to ensure the new good has similar—if not better—attributes than the established good. For example, complementary investments in battery storage alongside clean energy sources for electricity will enable electricity supplied from clean sources at all hours of the day, as is currently provided by the established electricity generation mix (IRENA 2019).

New goods can also offer *quality or attribute improvements* that induce added demand. In many sectors, the adoption of new product categories is hastened in part by consumer demand for improved attributes, new use cases, or simply novelty.

Market Failures and Policy Implications

Policymakers and the public may in some cases decide that structural change is occurring in the wrong direction or too slowly. This is justified in the presence of canonical market failures. Externalities, for instance—whereby economic activity imposes costs and benefits onto others without consequences for the actor generating the activity—can lead markets to underprovide a public good (e.g., innovation) or overprovide a public bad (e.g., pollution or GHG emissions). Sector-level economies of scale that require coordination across complementary inputs may also prevent emerging sectors from overcoming the initial hurdle of competing with established sectors.

Policymakers can address these market failures with familiar economic policy tools, including input and output taxes designed to "internalize" the externality, along with subsidies and public research-and-development (R&D) investments. But government interventions differ in one fundamental way when structural change dynamics are at play: They can create lasting change via path dependence. As such, to the extent that these interventions are successful, they need not be permanent. Provided that an intervention is sufficiently large to redirect an economy toward a more socially desirable composition, the intervention may no longer be needed once enough momentum has been built (Acemoglu 2002; Acemoglu et al. 2012, 2016; Meng 2023).

Structural change's key implication—the ability to use policy interventions to permanently alter the direction of change toward a different composition of the economy—may be attractive from a political economy perspective. But because path dependence cuts both ways, it also places added importance on well-targeted policy interventions that direct the economy toward an efficient use of cost-effective inputs. Policies that promote costly technologies may lead to a locking in of those technologies, making a future redirection toward more cost-effective alternatives harder to accomplish. The momentum inherent in economies undergoing structural change amplifies the importance of correctly promoting cost-effective technologies.

Structural Change and the Clean Energy Transition

The structural change framework and the push-and-pull forces articulated in the first section provide a lens to understand opportunities and challenges for accelerating the clean energy transition. Energy is an essential input for nearly every form of economic activity, and it has undergone various transitions over the past few centuries. As society invents new technologies, energy sources—and the form energy takes—change. Before the Industrial Revolution, labor—both human and animal—was the primary energy input for the production of goods and services. The Industrial Revolution unleashed a new and disembodied source of energy: fossil fuels. And the introduction of steam-powered, and then electricity-powered energy brought a transition in how the economy utilized fossil fuels (Devine 1982).

To lay out how the clean energy transition can be viewed through a structural change lens, this section examines the various push-and-pull forces that can accelerate or delay the clean energy transition. While these forces are explored in isolation, policies must target these economic forces simultaneously to achieve the required speed and scale of an economy-wide clean energy transition, as discussed in the third section.

The Costs of Fossil Fuels

Fossil fuels—coal, oil, and natural gas—provide energy through combustion, and in doing so release air pollutants, toxins, and climate-damaging greenhouse gases such as carbon dioxide (CO_2) and methane. In 2021, 92 percent of U.S. anthropogenic CO_2 emissions could be attributed to the combustion of fossil fuels (EIA 2023b).

Understanding the economic challenges of transitioning from fossil fuels to clean energy sources begins with understanding how fossil fuels came to be dominant and deeply embedded in the global and U.S. economies. Because energy is central to both national and economic security, fossil fuel providers benefited from government subsidies to secure strategic geopolitical alliances beginning in the late 19th century. U.S. government support, itself the result of political lobbying, aided fossil fuels in becoming the primary sources of American energy (Victor 2009) (see box 6-2). This is not a uniquely American phenomenon: Fossil fuels became a relatively cheap source of energy globally in part because they have been heavily subsidized.

In addition to government support, the technical characteristics of fossil fuels and their availability further shaped the energy system that emerged in the global economy. Fossil fuels are abundant, energy-dense, and found in many parts of the world. They are also transportable carriers of energy: A piece of coal can be mined in one location and shipped elsewhere to readily meet that location's energy demand, leading to global markets for many fossil fuels and associated infrastructure as well as competitive price pressures. Additional technical qualities aid fossil fuels' competitiveness even when they are not the final energy carrier. For instance, use of some fossil fuels, like natural gas, can be readily ramped up and down for electricity generation, helping balance aggregate electricity supply and demand nearly instantaneously (EIA 2012).

Clean Energy Opportunities and Challenges

Fossil fuels are not the only energy source, and they are far from the most abundant one; sunlight and wind are freely available around the planet. Aside from their critical role in mitigating GHG emissions and air pollution, clean energy technologies have many economic and national security benefits. Because they do not rely on costly fuel inputs, these technologies have

Box 6-2. Fossil Fuel Subsidies

A key challenge for the clean energy transition is the cost competitiveness of renewable energy sources compared with the fossil fuel sources they are replacing—a challenge made particularly difficult because the U.S. government has long subsidized fossil fuel production. These subsidies have largely been enacted through the tax code. Since the introduction of the modern Federal income tax in 1913, fossil fuel producers have received unique deductions, effectively shifting risk and losses from oil and gas producers to taxpayers.

The largest fossil fuel subsidies focus on defraying the risks of investment for producers. One major provision involves the deduction of intangible drilling costs—which include wages and preparatory work conducted to drill an oil well—amounting to 60–80 percent of total drilling costs, according to one estimate. Oil producers may deduct 70 percent of these costs immediately, rather than over the lifetime of the well, as is common with standard business expenditures (CRFB 2013). Also subsidized are the costs to explore new wells, despite novel technologies that significantly reduce the risks of drilling unprofitable or nonproducing wells. As recently as 2004, the Federal Government introduced new tax instruments to support investment in drilling capacity (U.S. Congress 2004).

Production is also subsidized, for instance, in the form of a percentage depletion. Independent oil producers are permitted to write off 15 percent of gross income on the first 1,000 barrels they produce a day, and this deduction rises to 25 percent for marginal wells during periods of low prices. Because this deduction is based on gross income, its value can exceed the total value of the producer's investment in the well (CRS 2021). While these provisions target independent producers (those without integrated refining capacity), this represents over 80 percent of U.S. crude oil production (Golding and Kilian 2022).

While estimates vary, one valuation assesses the total producer benefit from the Federal Government's fossil fuel subsidies at $62 billion, on average, annually (Kotchen 2021). This benefit substantially incentivizes production and the entry of new fossil fuel producers at the margin, particularly when oil prices are low, and the subsidies' total contributions to domestic production are estimated to be substantial (Erickson et al. 2017). Over the past 20 years, these subsidies have fueled the development of unconventional projects through the shale boom, with potential benefits to oil producers of up to $4 a barrel (Erickson and Achakulwisut 2021). One study estimates that at oil prices of $50 per barrel, fossil fuel subsidies could be responsible for up to 20 percent of U.S. crude oil production through 2050, while contributing 6 billion metric tons of CO_2 emissions (Erickson et al. 2017).

These subsidies to fossil fuels, both direct and indirect, have greatly promoted domestic production of natural gas and oil for more than a century. Their scope and longevity demonstrate both the Federal Government's ability to support energy production and the extent to which the oil and gas sectors have benefited from such support. As the country looks to accelerate the adoption of nonemitting energy sources, fossil fuel subsidies are also an obstacle to a rapid clean energy transition. As such, President Biden has repeatedly urged Congress to remove these subsidies, most recently in his 2024 budget proposal, in order to recover billions for taxpayers while winding down policy interventions that slow the clean energy transition (OMB 2023).

near-zero marginal costs of generation and can, in the long run with continued technological advances, lower energy prices. Due to its cost advantages, solar is already the fastest growing source of energy in the United States and in the world (EIA 2024a; IEA 2023c). Clean energy technologies can also reduce volatility in energy markets and enhance energy security (Cox, Beshilas, and Hotchkiss 2019). Studies have also shown clean energy to be more resilient than fossil fuels in the event of a natural disaster (Chang 2023; Esposito 2021).

And yet, despite the benefits of clean energy and the need to transition away from fossil fuels to address climate change, many parts of the world have been slow in adopting clean energy technologies that produce energy from these abundant and free resources—or have not adopted them at all (IRENA 2023). In some cases, this may be because clean energy technologies require inputs that are costly or exhibit low mobility. In other settings, complementary technologies are needed for clean energy to serve as a better substitute for fossil fuels. To understand what may accelerate or delay the clean energy transition, this section maps the push-and-pull forces—productivity spillovers, input prices, factor mobility, and substitutability—articulated abstractly in the chapter's first section, onto specific features of the clean energy transition.

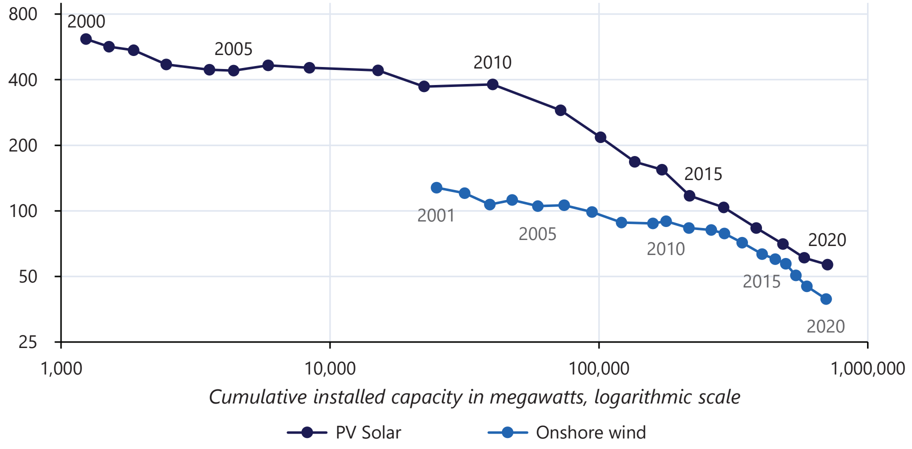
Productivity spillovers and declining capital cost curves. Technologies tend to become cheaper as experience with their production increases, consistent with the presence of productivity spillovers. This dynamic likely characterizes the clean energy sector. Despite high initial costs, increased manufacturing capacity and deployment of clean energy technologies have been associated with lowering costs as a result of learning and investments in process innovation (Nemet 2019).

The role of path dependence in productivity spillovers and declining capital cost curves can be illustrated through the history of clean energy technologies over the past century. In a number of cases, despite having near-zero marginal costs, high capital costs—alongside ongoing government subsidies for fossil fuels—made clean energy more expensive than energy derived from fossil fuels. For example, while in the early 20th century, electric wind turbines were common across rural America, in the two decades after President Roosevelt's rural electrification programs brought cheaper fossil-fuel-based electricity to rural areas, every American wind power company went out of business (Pasqualetti, Righter, and Gipe 2004). Solar photovoltaic (PV) panels, first developed in the 1950s to power space satellites, were unable to compete commercially for decades, and were restricted to niche applications such as calculators and solar-powered radios (Nemet 2019). Electric vehicles enjoyed an early boom around the turn of the 20th century, after the discovery of electromagnetism and the invention of the rechargeable battery allowed them to capture 38 percent of the (albeit very small) U.S. automotive market. However, advances in the combustion engine and the growing cost-competitiveness of fossil fuels—a result partially of public subsidies—quickly led to the dominance of internal combustion engine vehicles (Guarnieri 2012).

In the future, as clean energy technologies develop and disseminate, costs are likely to decline as a result of economies of scale and

Figure 6-4. Capital Cost Curves for PV Solar and Onshore Wind, 2000–2020

2020 dollars per megawatt-hour, logarithmic scale



Council of Economic Advisers

Sources: International Renewable Energy Agency (2023); Nemet (2019).

Note: Logarithmic scale shows the relationship between a 50 percent drop in capital costs and a 1,000 percent increase in installed capacity.

2024 Economic Report of the President

learning-by-doing. Economies of scale will move clean technologies down the average cost curve while learning-by-doing will shift down the average cost curve itself as productivity increases. Together, these forces should lead to lower costs at higher levels of output. However, if new technologies cannot compete with existing energy technologies, they will be unable to advance to mass production and experience the cost declines associated with scale economies and learning effects (Hart 2020). This could result from a lack of policies to spur demand, the competitiveness of established technologies, or some combination of both. Indeed, as shown in figure 6-4, it was not until the start of this century that clean energy's capital costs began declining dramatically, coinciding with when many governments around the world began supporting its deployment (Nemet 2019).

Land, transmission, and supply chain costs. Capital costs of clean energy for electricity have fallen dramatically over recent decades and are now often lower than those of fossil fuels (Lazard 2023). These cost advantages notwithstanding, there are other inputs incurred when changing from a fossil-fuel-based to a clean-energy-based system. Electricity from renewable energy has different land use requirements, necessitates investments in transmission infrastructure, and relies on different raw materials than fossil-fuel-based electricity. This implies that the total input cost of clean energy relative to fossil fuels may still not be low enough for markets on their own to deliver a structural transition.

Clean energy electricity generation can be more land-intensive than fossil fuel generation, even after accounting for land used in fossil fuel extraction and distribution (Gross 2020; Van Zalk and Behrens 2018). Utility-scale solar and land-based wind power generation requires large quantities of contiguous land. By one estimate, the capacity necessary to complete the U.S. net zero transition with current technologies could take over 250,000 square miles, roughly the area of Texas (Nature Conservancy 2023). While some of this renewable capacity can be installed on existing land uses—as in the case of rooftop solar—replacing the fossil-fuel-based energy system will likely require repurposing land specifically for clean energy. Siting, the process of picking locations for projects, can also incur political risks. Local interest groups have sued and taken political action against renewable projects, with opposition rising rapidly in recent years, raising the cost of installation (Bryce 2023; Brooks and Liscow 2023).

Siting clean energy installations on cheaper land away from population centers can mitigate these concerns, but may prompt an additional cost: the need to transmit renewable energy generation to load centers. Current transmission regulations also create an externality: The cost of adding a marginal transmission line is often borne by the marginal generator connecting onto the grid—even though the extra transmission line benefits all connected generators (Sankaran, Parmar, and Collison 2021). One recent analysis argues that inadequacies in the current U.S. transmission system—which in some parts of the country fails to connect regions with high solar and wind potential—may lower renewable energy adoption by 65 percent by 2030 (Jenkins et al. 2022). And for planned renewable generation that can connect to existing transmission lines, the average wait time for grid connection is currently 3.5 years (RMI 2022).

Clean energy technologies require different inputs than do fossil fuel technologies, which may be less raw-material-intensive in the construction of generation facilities but require ongoing fuel supplies (IEA 2023b). Wind generation uses over 5 metric tons of zinc per new megawatt of generation capacity, while solar PV uses about 4 metric tons of rare earth metals. By contrast, a new megawatt of natural gas generation capacity uses only about 1 metric ton of metal. Similarly, EV production requires over six times the critical minerals compared with what is needed for producing internal combustion engines, owing primarily to the large quantities of graphite, cobalt, nickel, and lithium used in batteries, though that difference will narrow as battery recycling programs ramp up (IEA 2023b; Riofrancos et al. 2023). Global supply chains can drive down input costs for clean energy technologies, but that may require government intervention. While the United States is currently developing domestic capacity in this area, mining these materials and transporting them requires, in some cases, creating new supply chains and forming new trade relationships (IEA 2023b).

Labor mobility. The clean energy transition will require a shift in the labor market, with workers leaving fossil fuel jobs and entering clean energy jobs. The extent to which labor is mobile across locations and sectors will play an important role in the clean energy transition. These frictions are not unique to the clean energy transition; they affect any process of structural change.

The clean energy sector will require more highly skilled workers (IEA 2022). Globally, about 45 percent of energy workers were in occupations requiring tertiary education as of 2019, compared with only about one-quarter across the U.S. economy. In 2022, more than 80 percent of U.S. clean energy employers reported at least "some difficulty" finding qualified workers (DOE 2023a), compared with about 75 percent of firms across the economy (Manpower Group 2022). In an industry survey, 89 percent of U.S. solar companies reported difficulties finding skilled labor, citing competition, small applicant pools, and applicants' lack of training, experience, and technical skills (IREC 2022). Demand for workers in clean energy sectors continues to increase (DOE 2023a). Indeed, in some sectors, such as transportation, manufacturing clean energy technologies may be more labor-intensive than manufacturing fossil-fuel-based counterparts (Cotterman, Fuchs, and Whitefoot 2022), but that may not apply in all cases.

Geographic immobility may also slow transitions from fossil fuel to clean energy jobs (Lim, Aklin, and Frank 2023). While some fossil fuel and clean energy skills overlap (IEA 2022), fossil fuel and clean energy jobs are often not in the same places. For instance, approximately one-third of recently laid-off coal miners in Appalachia—some of them third-generation employees—have not moved since job displacement, despite the lack of clean energy job opportunities nearby (Greenspon and Raimi 2022; Weber 2020).

This clean energy labor demand presents an economic opportunity, but also requires overcoming skill mismatch with the current workforce. Some of this demand may be met by workers currently employed in fossil fuel sectors. But so long as these workers are able to find employment more generally in an economy as large as the United States', a one-to-one match between fossil and clean industries' labor pools may not be needed (Curtis, O'Kane, and Park 2023). The likelihood of working at a clean firm conditional on having worked for a fossil fuel firm in the previous year was extremely low as of 2019, suggesting an important potential role for workforce development programs and place-based incentives (Colmer, Lyubich, and Voorheis 2023).

Finally, fossil fuel extraction also has local fiscal effects (Raimi et al. 2023). Excise and royalty taxes on fossil fuel extraction provide a major source of local tax revenue, supporting employment in local schools, hospitals, and other public services. An important consideration is whether and how revenue from local fossil fuel taxes can be replaced by proceeds from investments in clean energy or other industrial sectors.

Substitutability. Electricity from clean energy sources like wind and solar is not available at all times of the day, unlike electricity from fossil fuels. This variability of renewable energy can be solved through complementary investments in battery storage and other solutions—including nuclear and hydropower—which makes electricity from clean energy a better substitute for electricity from fossil fuels. For example, to make clean energy dispatchable at all hours of the day, battery storage can be deployed in a manner that incentivizes batteries to be charged when renewables are abundant and discharged when they are not.

Likewise, electric vehicle range—though it is improving rapidly—can present a barrier to EV adoption. To date, most EVs have a lesser range than cars powered by internal combustion engines. Recent surveys show that the majority of EV owners have a second, nonelectric vehicle—and drive that second vehicle more (Davis 2023). As a result, actual EV usage is less than half of what State regulators typically assume (Burlig et al. 2021). While there remain challenges for the substitution of EVs for internal combustion engine vehicles, solutions already exist and more are emerging. These include carmakers installing larger battery packs, improvements in battery technology, and progress on the building out of a robust EV charging network, which is currently under way.

In the extreme case of no substitutability between energy technologies, demand can fail to materialize. Solar PV cells present an early case study of missing demand. When silicon solar cells were first developed by Bell Labs in 1954, they were too expensive for many commercial applications. The U.S. government long remained their main buyer for use in satellites and defense applications (Nemet 2019). Today, hydrogen as an energy feedstock faces similar challenges in industrial settings, where some existing equipment and processes for using fossil fuels cannot be used for hydrogen. Complementary capital investments will be needed to generate demand for hydrogen as an energy feedstock (CEA 2023b).

Financing the Speed and Scale of the Clean Energy Transition

While past structural changes have tended to move on their own timelines, the biggest challenges for the clean energy transition are the required speed and scale. As noted above, global temperatures are already rising and the economic damage is growing. The United States and other countries need to decarbonize across their economies through the rapid deployment of existing clean energy technologies and investments in new technological solutions.

The energy transition has significant financing needs that require accelerating private sector investments. Private investments in clean energy technologies have grown in recent years (White House 2023). However, as a result of impediments common to structural change, they can be riskier and less profitable than alternative investments. Removing such obstacles to rapid structural change in the energy sector can accelerate the pace at which financial markets fund the energy transition on their own. Conceptually, this financing issue is not distinct from other challenges for the clean energy transition discussed above; rather, it is a consequence of many of these impediments existing simultaneously.

On the supply side, novel clean energy technologies can have difficulty accessing traditional capital markets relative to other industries because of greater perceived credit risk (Armitage, Bakhtian, and Jaffe 2023). Novel technologies may experience large cost uncertainties as a result of construction timing and delays, uncertainty about future revenue streams, and manufacturing cost overruns due to a lack of production experience. Traditional financial institutions may also have less capacity to assess risk for nascent technologies, making them reluctant to underwrite projects (IEA 2021c).

Clean energy projects confront an additional set of challenges: They must demonstrate initial commercial viability before being widely adopted. Early-stage financiers are often unable or unwilling to provide the substantial initial capital this demonstration requires (Ghosh and Nanda 2010). Financing risks can further limit early-stage investment. Nanda, Younge, and Fleming (2015) document how energy projects' financing needs and profiles are riskier and more capital-intensive than those in other high-growth industries, such as software and information technology. Potential early-stage investors may refrain from investing in clean energy companies if they anticipate that the technology will likely not receive mid-stage financing in the "valley of death," whereby market demand is insufficient for large-scale deployment (Nanda and Rhodes-Kropf 2016).

Demand-side factors can also slow financing for the energy transition. For example, investors in venture-financed energy start-ups have historically realized fewer exit opportunities compared with those in industries like biotechnology, semiconductors, and information technology, where established markets exist for start-up firms even before they have demonstrated commercial viability for their products (Ghosh and Nanda 2010). Energy companies and utilities have in the past often been reluctant to acquire start-ups with unproven technologies (Nanda, Younge, and Fleming 2015). Even as venture capital investment in clean energy has increased over time (CTVC 2023), venture capital firms may remain hesitant to invest in capital-intensive energy projects when the exit opportunities are limited in the short run, because such investments may require repeated capital injections over long periods of time to see a product through to market (Van den Heuvel and Popp 2022; Fontana and Nanda 2023). Creating a more favorable exit environment for start-ups can help mobilize private sector investment in these sectors.

In the transition to a new energy system, uncertainty about the broader market for clean energy can inhibit private sector investment, creating an opportunity for the public sector to send a durable demand signal. Lerner and Nanda (2020) argue that understanding market demand is an important prerequisite for early-stage companies to succeed. According to the authors, software and service-based businesses have shorter development timelines, and technological advancements allow these types of companies to ascertain market demand faster. Compared with software- and service-based businesses, clean energy companies may have more difficulty forecasting or demonstrating the demand certainty that would make them attractive to investors.

In summary, the balance of the economic push-and-pull forces affecting the clean energy transition today may limit private sector investment from reaching the necessary scale required to meet decarbonization goals, even as progress has been made. The next section turns to the role that government can play in catalyzing a faster transition to the net zero economy.

The Role of the Public Sector

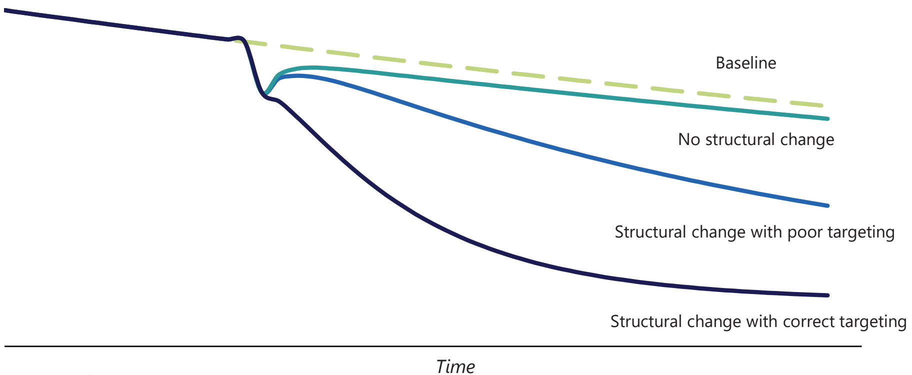
Due to the market failures and economic frictions discussed in the first section, government intervention is necessary to reach net zero emissions. Governments have long made investments in developing clean energy technologies, though not always with the intent of reducing GHG emissions. In the 1970s, large-scale public investments in wind and solar R&D, which came about primarily in reaction to shortages and high prices in the oil market, were major forays into this space (Pirani 2018; CRS 2018; Nahm 2021). Since then, governments around the world have amplified support for clean energy, increasingly to accelerate the transition to a net zero economy.

Government intervention is critical to solving classic market failures, such as pollution and knowledge externalities. When it comes to structural change, such interventions are fundamentally about changing the direction and pace of transitions. Because economic incentives do not yet fully encourage replacing the existing, fossil-fuel-based energy system with one based on clean energy, government intervention can alter such incentives. But importantly, from a structural change lens, those interventions need not be permanent; once sufficient momentum builds in favor of the clean energy transition, the private sector could continue the transition, even without continued government involvement (see box 6-3).

Figure 6-5 illustrates this argument. Emissions in the absence of a policy intervention are shown as the dashed green line, declining—as in the case of recent U.S. GHG emissions—albeit not fast enough to meet net

Figure 6-5. Schematic: GHG Emissions with and without Structural Change Dynamics

Greenhouse gas emissions



Council of Economic Advisers

Source: CEA calculations.

Note: GHG = greenhouse gas. In the absence of structural change dynamics, a temporary policy intervention would lower GHG emissions but not their growth rate (solid teal line) relative to the no-policy trajectory (dashed green baseline). In the presence of structural change, a temporary policy would lower the growth rate of GHG emissions. The added decline in GHG emissions is faster when the policy correctly targets technologies (solid dark navy line) than when targeting is poor (solid lighter blue line).

2024 Economic Report of the President

zero goals. Consider first an economy without structural change dynamics. A temporary policy intervention lowers the level of GHG emissions over time but not the growth rate, as illustrated by the solid teal line. As a consequence, emissions continue changing at the same pace as before the policy. For such an economy, achieving net zero emissions requires permanent policy intervention. This trajectory contrasts with an economy featuring structural change dynamics, as shown by the solid blue lines in the figure. A policy under this scenario can permanently lower emissions' growth rate by building path dependence into clean energy sources, generating momentum that maintains the clean energy transition even after the policy is lifted. That is, under structural change, long-term decarbonization can be achieved with policy interventions that eventually allow private market incentives to sustain the clean energy transition without continued government intervention.

The rate at which emissions decline depends on how well the policy targets cost-effective technologies and GHG reduction options that can compete with fossil-fuel-based technologies to become self-sustaining. Policies that target poorly (the solid light blue line in the figure) may lead to lock-in of more costly technologies, ultimately making the economy's redirection toward the adoption of clean energy technologies more difficult and expensive than with better targeting (solid navy line).

This path dependence can emerge from economic conditions, but can also have political origins. A growing literature has documented that climate policies can help strengthen economic and consumer interest groups

Box 6-3. The Public Sector's Role in Accelerating Structural Change: The Case of South Korea

The transformation of South Korea's heavy and chemical industries (HCI) sector since the 1970s is an example of export-led structural change. After the devastation of the Korean War of the early 1950s, South Korea turned to a broad export-based economic strategy in the 1960s and early 1970s, giving preferential trade policy treatment to any exporting firm. In 1973, in response to defense concerns, the South Korean government restricted this policy to HCI firms, providing extensive loan subsidies from domestic financial institutions. The state additionally instituted performance standards for subsidy recipients, relying on export targets and eschewing financial indicators of firm performance. Although this policy system was short-lived, lasting only until 1979, it had a sharp effect on South Korean industrial production in the decades that followed (Lane 2022).

This sector-specific public intervention resulted in a steep increase in the productivity of HCI firms, both during the 1973–79 period of direct industrial strategy and afterward (Lane 2022). The share of HCI exports remained above pre-1973 levels well after 1979, and remains above those levels today (Lane 2022; Choi and Levchenko 2021; OEC 2023). Major present-day South Korean exports—such as Samsung semiconductors and Hyundai cars—were first produced between 1973 and 1979, and production grew sharply through the 1980s.

Government policies during this period helped spur structural change, which had previously stalled due to frictions and market failures. Before the intervention, South Korea's HCI sector suffered from a financing problem: Western financial institutions were reluctant to provide loans to Korean plants (Amsden 1992). The South Korean government spurred investment with subsidized loans that resemble the investment tax credits underlying modern clean energy investment. And because local demand was not sufficient to sustain growth in the targeted industries, the South Korean government then supported exports, allowing cheaper capital and privileged regulatory status for exporting firms. The government's last intervention was to build human capital—essential due to the complexity of HCI manufacturing—by developing and promoting an extensive engineering education pipeline (Amsden 1992).

The success of South Korea's HCI sector can be linked to the country's industrial strategy during this period. The government's temporary intervention was sufficient to shift the direction of investment and establish comparative advantage over the long term in a previously undistinguished industry. Today, many of the component industries of the HCI drive, such as motor vehicles and shipbuilding, remain pillars of the South Korean economy. The program's success suggests that public intervention can be critical to overcoming obstacles to rapid structural change.

that make policies more difficult to reverse. For instance, policies that yield widespread economic benefits, such as by creating new industrial sectors and sources of employment, can be politically costly to reverse and therefore are more likely to stay in place across administrations (Meckling and Nahm 2021; Meckling et al. 2015). Conversely, the absence of policy certainty will lead to underinvestment if potential entrants become unsure of the subsidies or taxes they may encounter years down the road (Noailly, Nowzohour, and van den Heuvel 2022). Studies have documented that frequent expirations of renewable energy production and investment tax credits—as well as short-term extensions—have a negative impact on the development of a domestic wind industry (Lewis and Wiser 2007; DOE 2022a).

Finally, public sector interventions work best when governments directly support desired outcomes rather than require firms to adopt specific processes or market behaviors (Rodrik 2014). For example, to increase renewable energy adoption in the power sector, government interventions would ideally either subsidize renewable energy or tax fossil fuel emissions—without mandating where, how, or what type of renewable energy is built, as in the case of technology-neutral tax credits. Furthermore, to meet research and development goals—which may otherwise face private financing challenges—governments could invest in well-diversified portfolios covering large suites of potential new technologies rather than pick a handful of firms and products, anticipating that some technologies may ultimately fail while others succeed. These interventions can provide certainty to the private sector while allowing flexibility for new innovations. They can help mitigate the potential effects of incomplete information, particularly during a transition to emerging technologies, and address the difficulty of acquiring accurate information in the face of rent-seeking by firms.

In order to accelerate the clean energy transition, the supply- and demand-side policies highlighted below take account of these considerations. These interventions must also be coordinated because they are part of a broader, multipolicy approach that simultaneously enhances the push forces and removes the pull forces behind the clean energy transition.

Supply-Side Policies

Enhancing productivity spillovers. Government can induce the creation of new technologies. Basic research can lead to breakthrough technologies that generate high economic returns (National Research Council 2001), but because private returns are significantly smaller than public returns, private investors tend to underinvest in basic research (Lucking, Bloom, and Van Reenen 2020). This pattern is particularly pronounced in the energy sector, where the private sector has historically underinvested in basic R&D (Nemet and Kammen 2007).

The U.S. government has therefore long supported basic research, and remains the world's largest funder of energy research (IEA 2023d; Sandalow et al. 2022). The Bipartisan Infrastructure Law (BIL)—enacted as the Infrastructure Investment and Jobs Act (Public Law 117-58), along with the 2020 Energy Act (Public Law 116-260, div. Z)—more than triples the Department of Energy's annual funding for energy programs and includes a significant expansion of funds for R&D (DOE 2022b). Such public investments in research will yield global knowledge and productivity spillovers that can accelerate the energy transition (Berkes, Manysheva, and Mestieri 2022). Nonetheless, current public investments in energy R&D still fall short of the levels required to meet climate targets, given that key technologies needed to reduce costs and decarbonize industrial sectors have yet to become commercialized (see box 6-4). Current U.S. public energy R&D spending remains below the amount spent in the aftermath of the oil crises of the 1970s (Gallagher and Anadon 2022).

Lowering capital, land, and transmission costs. Certain clean energy technologies, like solar PV cells, have already seen significant declines in capital costs. However, newer technologies—such as grid-scale battery storage, hydrogen electrolyzers, carbon capture and storage, direct air capture, and advanced modular nuclear reactors—still face high capital costs (DOE 2023c).

Public sector interventions, including loan guarantees, can lower capital costs for clean energy technologies. The Department of Energy's Clean Energy Financing Program, which provides loan guarantees for innovative clean energy technologies—and which was recently scaled up under the Inflation Reduction Act (IRA) of 2022 (Public Law 117-169)—is an example of such a public sector intervention. Such programs can lower the future cost of renewable technologies through learning-by-doing (Arkolakis and Walsh 2023) and by encouraging complementary private investments required to achieve the net zero economy (Heintz 2010; Juhász, Lane, and Rodrik 2023). Loan guarantees can lower the risks inherent in financing clean energy projects, thereby increasing the availability of capital (Bachas, Kim, and Yannelis 2021; CRS 2012). They can also provide an information signal to private financiers to further de-risk projects and "crowd in" private capital—shortening the time frame by which clean energy technologies become bankable (DOE 2023e). One analysis of the Department of Energy's early-stage grants to high-tech clean energy start-up firms finds a positive effect on future financing from the private sector (Howell 2017). Another study finds that young firms in Germany that received public investment were more likely to access bank loans, and that this effect was particularly pronounced in sectors that were "information-opaque" (Hottenrott, Lins, and Lutz 2017).

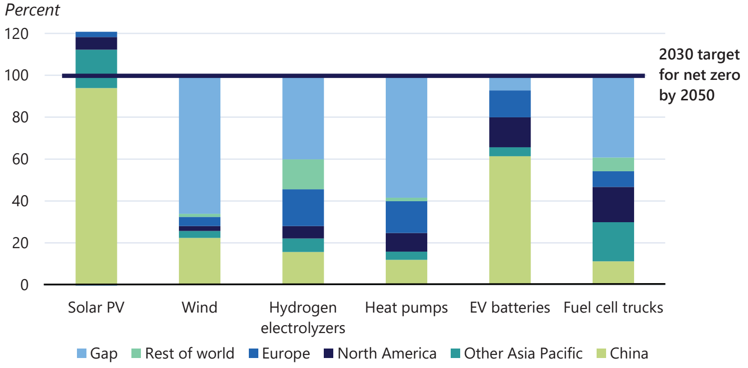
Box 6-4. The Need for Global Climate Collaboration

Solving climate change is an inherently global challenge, for which the United States' clean energy transition is only one part of the solution. The world will avoid dangerous climate change only if other countries also undertake similar structural transformations. In 2022, the United States accounted for 14 percent of global GHG emissions; China's share was 31 percent. Collectively, major powers have the potential to substantially curb emissions: The United States, China, the EU-27, Brazil, Russia, and India together accounted for more than 60 percent of global emissions in 2022 (Friedlingstein 2023).

U.S. investments in clean energy technologies could drive down global production costs (Way et al. 2022; Larsen et al. 2023) and encourage innovation worldwide (Berkes, Manysheva, and Mestieri 2022). But even accounting for these investments and their global spillovers, the world is projected to fall short of the manufacturing and deployment capacity necessary to meet global climate goals. For example, while the world is expected to develop sufficient or near-sufficient manufacturing capacity for EV batteries and solar modules by 2030 to stay on track for global net zero emissions by 2050 (IEA 2021a), global manufacturing capacity of wind turbines, heat pumps, and other key technologies is likely lagging behind the necessary pace to meet decarbonization goals (figure 6-i).

There is an urgent need for other governments to join the United States in rapidly accelerating their clean energy transitions. In the United States and elsewhere, strategic public sector intervention to remove impediments to structural change in the energy transition can generate the necessary buy-in from the private sector to yield clean energy technologies that will be cheaper than their carbon-emitting counterparts.

Figure 6-i. Projected and Target Global Manufacturing Capacity, 2030



Council of Economic Advisers

Sources: International Energy Agency; CEA calculations.

Note: "Manufacturing capacity" refers to the maximum rated output of facilities for producing a given technology, as distinguished from the capacity of the technologies themselves once deployed. Capacity is stated on an annual basis for the final product.

2024 Economic Report of the President

However, lowered capital costs for clean technologies may be insufficient if other input costs remain high. The land requirements of some clean energy technologies imply added costs—and often this demand occurs in agriculturally productive areas (van de Ven et al. 2021). Governments can help navigate this trade-off, especially in the case of wind farms. Each turbine has a relatively small footprint (Denholm et al. 2009), and incentivizing the use of arable space between wind turbines for agriculture dramatically lessens a wind farm's land requirements. Likewise, policies can encourage solar co-location with agriculture. While growing crops under solar PV is still a nascent practice, tax breaks and direct subsidies could scale it up (Boyd 2023), potentially through the resources provided by the IRA for the U.S. Department of Agriculture's Rural Energy for America Program.

High land prices can also be mitigated by building renewable energy generation away from agriculturally productive areas. But these locations tend to be far from population centers where electricity demand is highest, and new renewables projects are limited by the transmission capacity of the section of the grid to which they are connected. Expanding transmission is therefore an important complement to building new clean energy generation capacity. New transmission is needed both within and across regions of the country (DOE 2023d). The BIL allocates $2.5 billion to specific projects to this end. Absent such investment in transmission as well as in distribution, increased electrification will strain the existing grid.

Increasing labor mobility. Governments can play a central role in removing labor market frictions that could otherwise impede the clean energy transition (CEA 2021). Initiatives that address both skill needs and mismatch in the labor market, along with geographic immobility, are particularly necessary to accelerate the energy transition.

Workforce development programs are needed to train the next generation of workers in the clean energy sector and to retrain workers transitioning from the fossil fuel industry. Government initiatives that standardize education to include training on clean energy technologies are critically important—particularly for multicraft work like rooftop solar installation, which requires knowledge of carpentry, roofing, metal work, electrical, and information technology (IREC 2023). Programs that create pathways between education, training, entry-level jobs, and long-term careers are necessary to ensure long-term job quality and retention. Recent Federal policies reflect the importance of establishing a pipeline from apprenticeships to entry-level jobs. The IRA, for instance, introduced a bonus adder on top of a wide range of tax credits in the power, manufacturing, and transportation sectors for eligible firms that provide prevailing wages and employ qualified apprentices for certain construction, alteration, and repair work. Moreover, the creation of new apprenticeship programs provides an opportunity to accelerate economic growth by ensuring that workers—and in particular women—who have been historically underrepresented in the energy sector have access to the jobs of the future. Women represent less than 20 percent of employed workers in both the clean and fossil fuel sectors (Colmer, Lyubich, and Voorheis 2023).

Government interventions in retraining programs can support workers currently in the fossil fuel sector, retraining them for either the clean energy sector or other industries (Katz et al. 2022; Hanson 2023). Hyman (2022) provides evidence that deliberately targeting labor immobility during market disruptions can increase the likelihood that workers will switch industries—and improve workers' outcomes. In the context of the clean energy transition, estimates for the costs of retraining programs vary (Louie and Pearce 2016), but may be minor relative to the overall costs of the transition (Vanatta et al. 2022).

Government programs addressing geographic immobility can complement workforce development programs. Such programs can provide funding to construct clean energy manufacturing facilities close to their fossil-fuel-based counterparts, or provide moving allowances to help workers relocate (Vanatta et al. 2022; Pollin and Callaci 2016). The Department of Energy, for instance, announced $15.5 billion in funding for the conversion of existing automotive manufacturing facilities to support the EV supply chain (DOE 2023b). Policies can also support communities where local tax revenues have historically depended on fossil fuel industries (International Renewable Energy Age 2023).

Demand-Side Policies

Boosting demand over longer horizons. Because private investors are reluctant to fund the commercialization of new energy technologies, government interventions can create a long-term demand signal. Such interventions can prevent novel clean energy technologies from being stranded in the "valley of death" (Nemet 2019).

Production and investment tax credits for clean energy installations can boost demand for these technologies. The United States has employed some form of a production tax credit since 1992 to generate demand for a wide variety of renewable energy technologies, all without favoring specific firms (CRS 2020). Under the IRA, production and investment tax credits for clean energy will be technology-neutral by 2025—production of any type of energy with sufficiently low emissions will receive the same tax breaks. Both subsidies are available without a total tax expenditure limit until 2032, or when U.S. GHG emissions from electricity reach a certain threshold, creating a durable market signal incentivizing the use of renewable energy for electricity.

Such policies have proven effective in mobilizing private sector financing in other contexts. One paper finds that such demand-side policies shore up durable market demand and help mobilize private sector investments—particularly venture capital—toward clean energy innovation (van den Heuvel and Popp 2022). And in the pharmaceutical industry, demand-side policies (also known as "demand-pull" policies) have helped to mobilize biomedical R&D when market incentives to do so are weak (Glennerster and Kremer 2000; Global Trade Funding n.d.). Likewise, advance market commitments have enabled greater production of pharmaceutical products—such as vaccines—in markets without mature market demand (Kremer, Levin, and Snyder 2020; Berndt et al. 2006).

Improving substitutability. In the power sector, battery storage technologies provide one avenue for alleviating variability concerns and making renewable energy a better substitute for fossil fuels. Grid-connected battery storage is rapidly increasing in the United States. In 2023, the United States deployed 16 gigawatts (GW) of grid-connected battery capacity, with another 15 GW planned for 2024 (EIA 2024b). To meet net zero goals, the United States needs about 131 GW of grid-scale storage by 2050, according to models (Narich et al. 2021). Policies encouraging additional deployment are likely to lower costs further (NREL 2023). These policies include investment tax credits for battery adoption and production tax credits for battery manufacturing—both of which are provided under the IRA.

Batteries installed on electricity grids should be charged when wholesale electricity prices are low and discharged when these prices rise. Assuming the marginal electricity generator uses renewable energy when prices are low and fossil fuels when prices are high, tax incentives for batteries will result in reduced GHG emissions by replacing electricity from fossil fuels with electricity from renewables. If low electricity prices instead coincide with deriving marginal electricity from fossil fuels, battery incentives could lead to increased GHG emissions (Hittinger and Azevedo 2015; Pimm et al. 2019; Beuse et al. 2021). Policies that tie investment tax credits for batteries only to grids with a positive within-day correlation between wholesale prices and marginal emissions would ensure that battery expansion coincides with GHG reductions.

Better substitutability between clean energy and fossil fuels also ensures that clean energy subsidies deliver both lower electricity prices and GHG reductions. This is because clean energy subsidies have composition and scale effects (Baumol and Oates 1988). They make clean energy cheaper relative to fossil fuels, tilting the composition of electricity toward clean energy and lowering GHG emissions, all else remaining equal. Clean energy subsidies also increase the overall scale of electricity consumption by making electricity cheaper, increasing all energy inputs, including fossil fuels, and thus possibly GHG emissions, all else remaining equal (Casey, Jeon, and Traeger 2023). When clean energy and fossil fuels are better substitutes, as with greater battery deployment, the composition effect dominates over the scale effect and clean energy subsidies both reduce emissions and lower electricity prices (Hassler et al. 2020; Casey, Jeon, and Traeger 2023).

Likewise, policies that make EVs more substitutable with internal combustion engines—either by improving range or increasing charging convenience—can accelerate their adoption. The IRA's production tax credit for battery manufacturing is aimed at driving down the cost of production, which can improve range. The investment tax credit for household adoption of battery storage under the IRA and the $7.5 billion allocated for building a national high-speed EV charger network under the BIL are designed to increase charging convenience.

Coordinating Supply and Demand

The necessary scale and speed of the clean energy transition requires coordinating supply and demand policies. Demand for clean energy technologies often requires complementary and simultaneous supply-side investments in different technologies and supporting infrastructure. As noted above, EVs are dependent on a charging infrastructure. Some consumers are reluctant to invest in EVs before an adequately convenient supply of chargers is installed, while investments in chargers are unprofitable before consumers collectively purchase a sufficient fleet of EVs (Li et al. 2017). Prior research has suggested that supply-side investments—such as subsidies for the EV charging infrastructure—should be developed in tandem with direct EV subsidies (Cole et al. 2023; Rapson and Muehlegger 2022; Dimanchev et al. 2023).

Similar network effects and coordination problems exist in the switch to new fuels, like clean hydrogen, which require investments in the technologies for both production and demand (Armitage, Bakhtian, and Jaffe 2023). In addition to retrofitting facilities to use hydrogen as a feedstock, midstream infrastructure, including pipelines and storage, will be essential for maturing the clean hydrogen industry—in addition to investments in the technology used for hydrogen production (U.S. Department of Energy 2023c). The current short-term availability of infrastructure to transport, store, and distribute hydrogen is often cited as a constraint on industry growth, especially given the challenges of co-locating production and end use (Zacarias and Nakano 2023).

The public sector can play a significant coordinating role, incentivizing demand while ensuring adequate supply to establish new markets. When future demand is uncertain, firms may find investing in the necessary production technology or infrastructure more challenging, in part because financing is more difficult to obtain under such conditions. However, in the absence of adequate supply, investments in technologies and infrastructure to create demand are often also difficult to justify. Policy interventions can resolve such coordination challenges. For example, offtake contracts—to purchase an agreed-upon quantity at a price often determined ahead of production—are often a prerequisite for project financing. Loan underwriters therefore commonly ask to see offtake contracts before approving debt financing (Global Trade Funding n.d.). The Department of Energy is currently establishing a demand-side support program that provides offtake certainty—through contracts with, for instance, hydrogen producers and buyers—for projects in the Regional Clean Hydrogen Hubs program funded by the BIL (U.S. Department of Energy 2023).

Conclusion

Decarbonizing the global economy—in addition to mitigating the effects of climate change—provides new economic opportunities. The shift to clean energy can lower energy prices, offer greater energy security, reduce volatility in energy markets, mitigate local air pollution, and create new sources of employment in emerging sectors. Switching to clean energy also offers a generational opportunity for the United States to further its economic competitiveness in the innovative sectors of the 21st century. This chapter has explained in detail how to achieve these objectives through structural change, presenting an economic framework for understanding the factors that can accelerate the clean energy transition. It has further highlighted specific government interventions that can remove obstacles to the transition and create opportunities for the private sector to drive new sources of green growth.

The Biden-Harris Administration is strategically targeting these high-return investments. On the supply side, examples of this approach include the Department of Energy's expanded funding for energy programs and R&D through the BIL, which serves to accelerate innovation spillovers and drive down capital costs for emerging technologies where private sector investments are still insufficient. Similarly, the IRA includes loan guarantees for innovative clean energy technologies to mitigate risk for clean energy projects and to unlock new private financing. Both the BIL and the IRA support the construction of new clean energy manufacturing facilities in communities with preexisting fossil fuel industry presence, thereby reducing labor market frictions by helping workers transition to the clean energy sector (U.S. Department of the Treasury 2023).

On the demand side, the IRA, among many other of its provisions, employs tax credits for renewable energy installation and for household adoption of electric vehicles, renewable energy generation, and heat pumps. The duration of these tax credits boosts demand for clean energy technologies over longer time horizons sufficient for enabling scale economies and learning-by-doing. Battery incentives under the IRA can also accelerate the clean energy transition in the power sector by making renewable energy sources less variable and thus a better substitute for fossil fuels. By simultaneously pursuing these interventions, the clean energy agenda of the Biden-Harris Administration is jointly addressing the supply- and demand-side challenges needed to ensure a rapid clean energy transition.

Although the scale and urgency of the clean energy transition present unique challenges, this transition ultimately shares many features with prior government- and market-led transformations. In the process of reaching net zero emissions, both governments and private actors will need to grapple with how to transform an economy powered by fossil fuels to one powered by clean energy. A structural change framework helps illuminate how to achieve this shift, through targeted government investments that lower the cost of clean energy and their complementary inputs and technologies, as well as through programs that enable the transition to help both workers and their communities. Such successful interventions could pay large dividends for decades to come, putting the U.S. economy on a path toward a future where energy is clean, cheap, reliable, and secure.

★★★★★★

References

Chapter 6

Acemoglu, D. 2002. “Directed Technical Change.” *Review of Economic Studies* 69, no. 4: 781–809. https://doi.org/10.1111/1467-937X.00226.

Acemoglu, D., P, Aghion, L. Bursztyn, and D. Hemous. 2012. “The Environment and Directed Technical Change.” *American Economic Review* 102, no. 1: 131–66. https://doi.org/10.1257/aer.102.1.131.

Acemoglu, D., U. Akcigit, D. Hanley, and W. Kerr. 2016. “Transition to Clean Technology.” *Journal of Political Economy* 124, no. 1: 52–104. https://doi.org/10.1086/684511.

Acemoglu, D., and D. Autor. 2011. “Chapter 12: Skills, Tasks and Technologies—Implications for Employment and Earnings.” In *Handbook of Labor Economics*, 4B, ed. O. Ashenfelter and D. Card. Amsterdam: Elsevier Science. https://www.sciencedirect.com/science/article/abs/pii/S0169721811024105.

Amsden, A. 1992. *Asia’s Next Giant: South Korea and Late Industrialization*. Oxford: Oxford University Press. https://doi.org/10.1093/0195076036.001.0001.

Arkolakis, C, and C. Walsh. 2023. *Clean Growth*. NBER Working Paper 31615. Cambridge, MA: National Bureau for Economic Research. https://doi.org/10.3386/w31615.

Armitage, S., N. Bakhtian, and A. Jaffe. 2023. *Innovation Market Failures and the Design of New Climate Policy Instruments*. NBER Working Paper 31622. Cambridge, MA: National Bureau for Economic Research. https://doi.org/10.3386/w31622.

Arrow, K. 1962. “The Economic Implications of Learning by Doing.” *Review of Economic Studies* 29, no. 3: 155–73. https://doi.org/10.2307/2295952.

Autor, D., D. Dorn, and G. Hanson. 2013. “The China Syndrome: Local Labor Market Effects of Import Competition in the United States.” *American Economic Review* 103, no. 6: 2121–68. https://doi.org/10.1257/aer.103.6.2121.

Autor, D., F. Levy, and R. Murnane. 2003. “The Skill Content of Recent Technological Change: An Empirical Exploration.” *Quarterly Journal of Economics* 118, no. 4: 1279–333. https://doi.org/10.1162/003355303322552801.

Bachas, N., O. Kim, and C. Yannelis. 2021. “Loan Guarantees and Credit Supply.” *Journal of Financial Economics* 139: 872–94. https://www.sciencedirect.com/science/article/abs/pii/S0304405X20302361.

Baumol, W., and W. Oates. 1988. *The Theory of Environmental Policy*. Cambridge: Cambridge University Press. https://books.google.com/books?hl=en&lr=&id=32-r0N8l9BgC&oi=fnd&pg=PR7&dq=baumol+and+oates+1988&ots=P3N0jyJZwI&sig=sZmDlJUPsVMTaFFUm6PqZVRqKHA.

Berkes, E., K. Manysheva, and M. Mestieri. 2022. “Global Innovation Spillovers and Productivity: Evidence from 100 Years of World Patent Data.” Working paper, Federal Reserve Bank of Chicago. https://www.chicagofed.org/publications/working-papers/2022/2022-15.

Berndt, E., R. Glennerster, M. Kremer, J. Lee, R. Levine, G. Weizsäcker, and H. Williams. 2006. “Advance Market Commitments for Vaccines against Neglected Diseases: Estimating Costs and Effectiveness.” *Health Economics* 16, no. 5: 491–511. https://doi.org/10.1002/hec.1176.

Beuse, M., B. Steffen, M. Dirksmeier, and T. Schmidt. 2021. “Comparing CO2 Emissions Impacts of Electricity Storage Across Applications and Energy Systems.” *Joule* 5, no. 6: 1501–20. https://doi.org/10.1016/j.joule.2021.04.010.

Bloom, N., M. Schankerman, and J. Van Reenen. 2013. “Identifying Technology Spillovers and Product Market Rivalry.” *Econometrica* 81, no. 4: 1347–93. https:// doi.org/10.3982/ECTA9466.

Boushey, H. 2023. “The Economics of Public Investment Crowding in Private Investment.” White House Blog. https://www.whitehouse.gov/briefing-room/blog/2023/08/16/the-economics-of-public-investment-crowding-in-private-investment/

Boyd, M. 2023. “The Potential of Agrivoltaics for the U.S. Solar Industry, Farmers, and Communities.” U.S. Department of Energy Solar Energy Technologies Office Blog. https://www.energy.gov/eere/solar/articles/ potential-agrivoltaics-us-solar-industry-farmers-and-communities.

Brooks, L., and Z. Liscow. 2023. “Infrastructure Costs.” *American Economic Journal: Applied Economics* 15, no. 2: 1–30. https://doi.org/10.1257/app.20200398.

Burke, M., S. Hsiang, and E. Miguel. 2015. “Global Non-Linear Effect of Temperature on Economic Production.” *Nature* 527, no. 7577: 235–39. https://doi.org/10.1038/nature15725.

Burlig, F., J. Bushnell, D. Rapson, and C. Wolfram. 2021. “Low Energy: Estimating Electric Vehicle Electricity Use.” *AEA Papers and Proceedings* 111: 430–35. https:// doi.org/10.1257/pandp.20211088.

Bryce, R. 2023. “Renewable Rejection Database.” https://robertbryce.com/ renewable-rejection-database/.

California Legislature. 2023. “An Act Making Appropriations for the Support of the Government of the State of California and for Several Public Purposes in Accordance with the Provisions of Section 12 of Article IV of the Constitution of the State of California, Relating to the State Budget, to Take Effect Immediately, Budget Bill, Senate Bill No. 101, 2023.” https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202320240SB101.

Carleton, T., A. Jina, M. Delgado, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, R. Kopp, K. McCusker, I. Nath, J. Rising, A. Rode, H. Kwon Seo, A. Viaene, J. Yuan, and A. Zhang. 2022. “Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits.” *Quarterly Journal of Economics* 137, no. 4: 2037–105. https://doi.org/10.1093/qje/qjac020.

Casey, G., W. Jeon, and C. Traeger. 2023. *The Macroeconomics of Clean Energy Subsidies*. CESifo Working Paper 10828. https://www.cesifo.org/en/publications/2023/working-paper/macroeconomics-clean-energy-subsidies.

CEA (Council of Economic Advisers). 2021. “Innovation, Investment, and Inclusion: Accelerating the Energy Transition and Creating Good Jobs.” https://www.whitehouse.gov/wp-content/uploads/2021/04/Innovation-Investment-and-Inclusion-CEA-April-23-2021-1.pdf.

______. 2023a. “Chapter 9: Opportunities for Better Managing Weather Risk in the Changing Climate.” In *Economic Report of the President*. Washington: U.S. Government Publishing Office. https://www.whitehouse.gov/wp-content/uploads/2023/03/erp-2023.pdf.

———. 2023b. “The Economics of Demand-Side Support for the Department of Energy’s Clean Hydrogen Hubs.” https://www.whitehouse.gov/cea/ written-materials/2023/07/05/ the-economics-of-demand-side-support-for-the-department-of-energys-cleanhydrogen-hubs/.

Chang, R. 2023. “Renewable Energy Is the Key to Building a More Resilient and Reliable Electricity Grid.” Center for American Progress. https://www.americanprogress.org/article/ renewable-energy-is-the-key-to-building-a-more-resilient-and-reliable-electricity-grid/.

Choi, J., and A. Levchenko. 2021. *The Long-Term Effects of Industrial Policy*. NBER Working Paper 29263. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w29263.

Cole, C., M. Droste, C. Knittel, S. Li, and J. Stock. 2023. “Policies for Electrifying the Light-Duty Vehicle Fleet in the United States.” *AEA Papers and Proceedings* 113: 316–22. https://doi.org/10.1257/pandp.20231063.

Colmer, J., E. Lyubich, and J. Voorheis. 2023. “Nice Work If You Can Get It? The Distribution of Employment and Earnings During the Early Years of the Clean Energy Transition.” https://api.semanticscholar.org/CorpusID:266525460.

Cotterman, T., E. Fuchs, and K. Whitefoot. 2022. “The Transition to Electrified Vehicles: Evaluating the Labor Demand of Manufacturing Conventional versus Battery Electric Vehicle Powertrains.” Working paper, Carnegie Mellon University. https://dx.doi.org/10.2139/ssrn.4128130.

Cox, S., L. Beshilas, and E. Hotchkiss. 2019. “Renewable Energy to Support Energy Security.” National Renewable Energy Lab. https://www.nrel.gov/docs/fy20osti/74617.pdf.

CRFB (Committee for a Responsible Federal Budget). 2013. “The Tax Break-Down: Intangible Drilling Costs” https://www.crfb.org/blogs/ tax-break-down-intangible-drilling-costs.

CRS (Congressional Research Service). 2012. “Loan Guarantees for Clean Energy Technologies: Goals, Concerns, and Policy Options.” https://crsreports.congress.gov/ product/pdf/R/R42152.

———. 2018. “Renewable Energy R&D Funding History: A Comparison with Funding for Nuclear Energy, Fossil Energy, Energy Efficiency, and Electric Systems R&D.” https://crsreports.congress.gov/product/pdf/RS/RS22858/17.

———. 2020. “The Renewable Electricity Production Tax Credit: In Brief.” https://sgp.fas.org/crs/misc/R43453.pdf.

______. 2021. “Oil and Gas Tax Preferences: In Brief.” https://crsreports.congress.gov/product/pdf/IF/IF11528.

CTVC. 2023. “Insights: CTVC by Sightline Climate.” https://www.ctvc.co/tag/insights/.

Curtis, E., L. O’Kane, and R. Park. 2023. *Workers and the Green-Energy Transition: Evidence from 300 Million Job Transitions.* NBER Working Paper 31539. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w31539.

Davis, L. 2023. “Electric Vehicles in Multi-Vehicle Households.” *Applied Economics Letters* 30, no. 14: 1909–12. https://doi.org/10.1080/13504851.2022.2083563.

Denholm, P., M. Hand, M. Jackson, and S. Ong. 2009. “Land Use Requirements of Modern Wind Power Plants in the United States.” National Renewable Energy Lab, Technical Report TP-6A2-45834. https://www.nrel.gov/docs/fy09osti/45834.pdf.

Devine, W. 1982. *An Historical Perspective on the Value of Electricity in American Manufacturing.* Technical Report ORAU/IEA-82-8(M). Oak Ridge: Institute for Energy Analysis, Oak Ridge Associated Universities. https://doi.org/10.2172/6774921.

Dimanchev, E., S. Fleten, D. MacKenzie, and M. Korpås. 2023. “Accelerating Electric Vehicle Charging Investments: A Real Options Approach to Policy Design.” *Energy Policy* 181. https://doi.org/10.1016/j.enpol.2023.113703.

DOE (U.S. Department of Energy). 2022a. “Wind Energy: Supply Chain Deep Dive Assessment.” https://www.energy.gov/sites/default/files/2022-02/Wind%20 Supply%20Chain%20Report%20-%20Final%202.25.22.pdf.

———. 2022b. “DOE Optimizes Structure to Implement $62 Billion in Clean Energy Investments from Bipartisan Infrastructure Law.” https://www.energy.gov/articles/ doe-optimizes-structure-implement-62-billion-clean-energy-investments-bipartisan.

———. 2023a. “United States Energy and Employment Report 2023.” https://www.energy.gov/sites/default/files/2023-06/2023%20USEER%20REPORT-v2.pdf.

———. 2023b. “Biden-Harris Administration Announces $15.5 Billion to Support a Strong and Just Transition to Electric Vehicles, Retooling Existing Plants, and Rehiring Existing Workers.” Press release.

———. 2023c. “Pathways to Commercial Liftoff: Clean Hydrogen.” https://liftoff.energy. gov/.

———. 2023d. “National Transmission Needs Study.”

———. 2023e. “Building a Bridge to Bankability.” https://www.energy.gov/sites/default/files/2023-05/DOE-LPO22-PPTv03_LPO-Overview_May2023.pdf.

Duranton, G., and D. Puga. 2004. “Chapter 48: Micro-Foundations of Urban Agglomeration Economies.” In *Handbook of Regional and Urban Economics*, no. 4: 2063–2117. https://doi.org/10.1016/s1574-0080(04)80005-1.

EIA (U.S. Energy Information Administration). 2012. “Today in Energy.” https://www.eia.gov/todayinenergy/detail.php?id=7590.

———. 2023a. “Electricity Monthly Update: December 2022.” https://www.eia.gov/electricity/monthly/update/archive/february2023/.

———. 2023b. “Energy and the Environment Explained Where Greenhouse Gases Come From.” https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php.

———. 2024a. “Solar and Wind to Lead Growth of U.S. Power Generation for the Next Two Years.” https://www.eia.gov/todayinenergy/detail.php?id=61242.

———. 2024b. “U.S. Battery Storage Capacity Expected to Nearly Double in 2024.” https://www.eia.gov/todayinenergy/detail.php?id=61202.

Erickson, P., and P. Achakulwisut. 2021. “How Subsidies Aided the U.S. Shale Oil and Gas Boom.” Stockholm Environmental Institute. https://www.sei.org/publications/subsidies-shale-oil-and-gas/.

Erickson, P., A. Down, M. Lazarus, and D. Koplow. 2017. “Effect of Subsidies to Fossil Fuel Companies on United States Crude Oil Production.” *Nature Energy* 2, no. 11: 891–98.

Esposito, D. 2021. “Meta-Analysis of Clean Energy Policy Models.” Energy Innovation Policy & Technology LLC. https://energyinnovation.org/wp-content/

uploads/2021/09/Studies-Agree-80-Percent-Clean-Electricity-by-2030-WouldSave-Lives-and-Create-Jobs-at-Minimal-Cost.pdf.

European Environment Agency. 2023. “Total Net Greenhouse Gas Emission Trends and Projections in Europe.” https://www.eea.europa.eu/en/analysis/indicators/ total-greenhouse-gas-emission-trends?activeAccordion=546a7c35-9188-4d2394ee-005d97c26f2b.

Fontana, S., and R. Nanda. 2023. “Innovating to Net Zero: Can Venture Capital and StartUps Play a Meaningful Role?” In *Entrepreneurship and Innovation Policy and the Economy, Volume 2*, ed. B. Jones, and J. Lerner. Chicago: University of Chicago Press. https://doi.org/10.1086/723236.

Friedlingstein, P., M. O’Sullivan, M. Jones, R. Andrew, J. Hauck, A. Olsen, G. Peters, et al. 2020. “Global Carbon Budget 2020.” *Earth System Science Data* 12, no. 4: 3269–340. https://doi.org/10.5194/essd-12-3269-2020.

Friedlingstein, P., M. O’Sullivan, M. Jones, R. Andrew, D. Bakker, J. Hauck, P. Landschützer, et al. 2023. “Global Carbon Budget 2023.” *Earth System Science Data* 15: 5301–69. https://doi.org/10.5194/essd-15-5301-2023.

Gallagher, K., and L. Anadon. 2022. “Database on U.S. Department of Energy (DOE) Budgets for Energy Research, Development, & Demonstration (1978-2023R).” Harvard Kennedy School. https://www.belfercenter.org/publication/ database-us-department-energy-doe-budgets-energy-research-developmentdemonstration-1.

Ghosh, S., and R. Nanda. 2010. *Venture Capital Investment in the Clean Energy Sector*. Working Paper 11-020, Harvard Business School. https://www.hbs.edu/ris/Publication%20Files/11-020_0a1b5d16-c966-4403-888f-96d03bbab461.pdf.

Glennerster, R., and M. Kremer. 2000. “A Better Way to Spur Medical Research and Development.” *Regulation* 23: 34. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=235870.

Global Trade Funding. No date. “Offtake Agreements, Project Finance Document Critical for Loan Approval.” https://globaltradefunding.com/project-finance/projectfinance-documents/offtake-agreements/.

Golding, G., and L. Kilian. 2022. “Don’t Look to Oil Companies to Lower High Retail Gasoline Prices.” Federal Reserve Bank of Dallas. https://www.dallasfed.org/research/economics/2022/0510.

Greenspon, J., and D. Raimi. 2022. *Matching Geographies and Job Skills in the Energy Transition*. RFF WP 22-25. Washington: Resources for the Future. https://media.rff.org/documents/WP_22-25_PnkcURf.pdf.

Gropman, A. 1996. “Mobilizing U.S. Industry in World War II: Myth and Reality.” Institute for National Strategic Studies. https://apps.dtic.mil/sti/tr/pdf/ADA316780. pdf.

Gross, D., and B. Sampat. 2023a. “America, Jump-Started: World War II R&D and the Takeoff of the US Innovation System.” *American Economic Review* 113, no.

12: 3323–56. https://doi.org/10.1257/aer.20221365.

———.2023b. “The World War II Crisis Innovation Model: What Was It, and Where Does It Apply?” *Research Policy* 52, no. 9: 104845. https://doi.org/10.1016/j.respol.2023.104845.

Gross, S. 2020. “Renewables, Land Use, and Local Opposition in the United States.” Brookings Institution. https://www.brookings.edu/articles/ renewables-land-use-and-local-opposition-in-the-united-states/.

Guarnieri, M. 2012. “Looking Back to Electric Cars.” https://ieeexplore.ieee.org/xpl/conhome/6480931/proceeding.

Hanson, G. 2023. “Local Labor Market Impacts of the Energy Transition: Prospects and Policies.” In *Economic Policy in a More Uncertain World*, 155–99. Washington: Aspen Economic Strategy Group. https://www.economicstrategygroup. org/wp-content/uploads/2022/12/Hanson-chapter.pdf.

Hart, D. 2020. “The Impact of China’s Production Surge on Innovation in the Global Solar Photovoltaics Industry.” Information Technology & Innovation Foundation. https://itif.org/publications/2020/10/05/ impact-chinas-production-surge-innovation-global-solar-photovoltaics/.

Hassler, J., P. Krusell, C. Olovsson, and M. Reiter. 2020. “On the Effectiveness of Climate Policies.” Working paper, Institute for International Economic Studies at Stockholm University.

Heintz, J. 2010. “The Impact of Public Capital on the US Private Economy: New Evidence and Analysis.” *International Review of Applied Economics* 24, no. 5: 619–32. https://doi.org/10.1080/02692170903426104.

Herrendorf, B., R. Rogerson, and A. Valentinyi. 2014. “Chapter 6: Growth and Structural Transformation.” In *Handbook of Economic Growth*, ed. P. Aghion and S. Durlauf, 855–941. Amsterdam: Elsevier Science. https://www.sciencedirect.com/science/article/abs/pii/B9780444535405000069.

Hittinger, E., and I. Azevedo. 2015. “Bulk Energy Storage Increases United States Electricity System Emissions.” *Environmental Science & Technology* 49, no. 5: 3203–10. https://doi.org/10.1021/es505027p.

Hottenrott, H., E. Lins, and E. Lutz. 2018. “Public Subsidies and New Ventures’ Use of Bank Loans.” *Economics of Innovation and New Technology* 27, no. 8: 786–808. https://doi.org/10.1080/10438599.2017.1408200.

Howell, S. 2017. “Financing Innovation: Evidence from R&D Grants.” *American Economic Review* 107, no. 4: 1136–64. https://doi.org/10.1257/aer.20150808.

Hsiang, S., M. Burke, and E. Miguel. 2013. “Quantifying the Influence of Climate on Human Conflict.” *Science* 341, no. 6151: 1235367. https://doi.org/10.1126/science.1235367.

Hsiang, S., S. Greenhill, J. Martinich, M. Grasso, R. Schuster, L. Barrage, D. Diaz, et al. 2023. "Ch. 19: Economics." In *Fifth National Climate Assessment*, ed. A. Crimmins, C. Avery, D. Easterling, K. Kunkel, B. Stewart, and T. Maycock. Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH19.

Hyman, B. 2022. "Can Displaced Labor Be Retrained? Evidence from Quasi-Random Assignment to Trade Adjustment Assistance." Working Paper, U.S. Census Bureau, Center for Economic Studies. https://www2.census.gov/ces/wp/2022/CES-WP-22-05.pdf.

IEA (International Energy Agency). 2021a. "Net Zero by 2050: A Roadmap for the Global Energy Sector." https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

———.2021b. "The Role of Critical Minerals in Clean Energy Transitions." In *World Energy Outlook*. https://www.iea.org/reports/ the-role-of-critical-minerals-in-clean-energy-transitions.

———. 2021c. "The Cost of Capital in Clean Energy Transitions." https://www.iea.org/articles/the-cost-of-capital-in-clean-energy-transitions.

———. 2022. "World Energy Employment." https://iea.blob.core.windows.net/assets/a0432c97-14af-4fc7-b3bf-c409fb7e4ab8/WorldEnergyEmployment.pdf.

———. 2023a. *World Energy Outlook*. Paris: IEA. https://www.iea.org/reports/ world-energy-outlook-2023.

———. 2023b. "A Renewed Pathway to Net Zero Emissions." https://www.iea.org/reports/ net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach/arenewed-pathway-to-net-zero-emissions.

———. 2023c. "Solar PV: Overview." https://www.iea.org/energy-system/renewables/solar-pv.

———. 2023d. "Energy Technology RD&D Budgets Data Explorer." https://www.iea.org/data-and-statistics/data-tools/energy-technology-rdd-budgets-data-explorer.

Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization. 2023. "Revitalizing Energy Communities: Two-Year Report to the President." https://energycommunities.gov/wp-content/uploads/2023/04/IWGTwo-Year-Report-to-the-President.pdf.

International Renewable Energy Agency. 2023. "Renewable Power Generation Costs in 2022." Report. https://energycommunities.gov/wp-content/uploads/2023/04/IWG-Two-Year-Report-to-the-President.pdf.

IREC (Interstate Renewable Energy Council). 2022. "National Solar Jobs Census 2021." https://irecusa.org/wp-content/uploads/2022/07/National-Solar-JobsCensus-2021.pdf.

———. 2023. “Cultivating a Diverse and Skilled Talent Pipeline for the Equitable Transition.” https://irecusa.org/wp-content/uploads/2023/02/ Alliance-Report-2.23-Interactive-compressed.pdf.

IRENA (International Renewable Energy Agency). 2019. “Utility-Scale Batteries: Innovation Landscape Brief.” https://www.irena.org/-/media/Files/IRENA/Agency/ Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf.

———. 2023. “Renewable Capacity Statistics 2023.” https://mc-cd8320d4-36a1-40ac83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Mar/IRENA_RE_Capacity_Statistics_2023.pdf?rev=d2949151ee6a4625b65c82881403c2a7.

Jaworski, T. 2017. “World War II and the Industrialization of the American South.” *Journal of Economic History* 77, no. 4: 1048–82. https://doi.org/10.1017/S0022050717000791.

Jenkins, J., J. Farbes, R. Jones, N. Patankar, and G. Schivley. 2022. “Electricity Transmission Is Key to Unlock the Full Potential of the Inflation Reduction Act.” Rapid Energy Policy Evaluation and Analysis Toolkit Project, PowerPoint presentation. https://repeatproject.org/docs/REPEAT_IRA_Transmission_2022-09-22. pdf.

Johnston, B. 1970. “Agriculture and Structural Transformation in Developing Countries: A Survey of Research.” *Journal of Economic Literature* 8, no. 2: 369–404. https://www.jstor.org/stable/2720471.

Juhász, R., N. Lane, and D. Rodrik. 2023. “The New Economics of Industrial Policy.” National Bureau of Economic Research. https://drodrik.scholar.harvard.edu/sites/scholar.harvard.edu/files/dani-rodrik/files/the_new_economics_of_ip_080123.pdf.

Katz, L., J. Roth, R. Hendra, and K. Schaberg. 2022. “Why Do Sectoral Employment Programs Work? Lessons from WorkAdvance.” *Journal of Labor Economics* 40, no. S1: S249–91. https://doi.org/10.1086/717932.

Kotchen, M. 2021. “The Producer Benefits of Implicit Fossil Fuel Subsidies in the United States.” *Proceedings of the National Academy of Sciences* 118, no. 14: e20119691 https://www.pnas.org/doi/10.1073/pnas.2011969118.

Kremer, M., J. Levin, and C. Snyder. 2020. “Advance Market Commitments: Insights from Theory and Experience.” *AEA Papers and Proceedings* 110: 269–73. https://pubs.aeaweb.org/doi/pdfplus/10.1257/pandp.20201017.

Kriegler, E., N. Bauer, A. Popp, F. Humpenöder, M. Leimbach, J. Strefler, L. Baumstark, et al. 2017. “Fossil-Fueled Development (SSP5): An Energy and ResourceIntensive Scenario for the 21st Century.” *Global Environmental Change* 42: 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015.

Lane, N. 2022. “Manufacturing Revolutions: Industrial Policy and Industrialization in South Korea.” University of Oxford, Department of Economics. http://dx.doi.org/10.2139/ssrn.3890311.

Larsen, K., H. Pitt, M. Mobir, S. Movalia, A. Rivera, E. Rutkowski, and T. Houser. 2023. “Global Emerging Climate Technology Diffusion and the Inflation Reduction Act.” Rhodium Group. https://rhg.com/research/ emerging-climate-technology-ira/.

Lazard. 2023. “Levelized Cost of Energy Analysis +.” PowerPoint presentation. https://www.lazard.com/media/2ozoovyg/lazards-lcoeplus-april-2023.pdf.

Lelieveld, J., K. Klingmüller, A. Pozzer, R. Burnett, A. Haines, and V. Ramanathan. 2019. “Effects of Fossil Fuel and Total Anthropogenic Emission Removal on Public Health and Climate.” *Proceedings of the National Academy of Sciences* 116, no.
15: 7192–97. https://doi.org/10.1073/pnas.1819989116.

Lerner, J., and R. Nanda. 2020. “Venture Capital’s Role in Financing Innovation: What We Know and How Much We Still Need to Learn.” *Journal of Economic Perspectives* 34, no. 3: 237–61. https://doi.org/10.1257/jep.34.3.237.

Lewis, J., and R. Wiser. 2007. “Fostering a Renewable Energy Technology Industry: An International Comparison of Wind Industry Policy Support Mechanisms.” *Energy Policy* 35, no. 3: 1844–57. https://doi.org/10.1016/j.enpol.2006.06.005.

Lewis, W. 1954. “Economic Development with Unlimited Supplies of Labour.” *Manchester School* 22, no. 2: 139–91. https://doi.org/10.1111/j.1467-9957.1954. tb00021.x.

Li, S., L. Tong, J. Xing, and Y. Zhou. 2017. “The Market for Electric Vehicles: Indirect Network Effects and Policy Design.” *Journal of the Association of Environmental and Resource Economists* 4, no. 1: 89–133. http://dx.doi.org/10.1086/689702.

Lim, J., M. Aklin, and M. Frank. 2023. “Location Is a Major Barrier for Transferring U.S. Fossil Fuel Employment to Green Jobs.” *Nature Communications* 14: 5711. https://doi.org/10.1038/s41467-023-41133-9.

Louie, E., and J. Pearce. 2016. “Retraining Investment for U.S. Transition from Coal to Solar Photovoltaic Employment.” *Energy Economics* 57: 295–302. https://doi.org/10.1016/j.eneco.2016.05.016.

Lucas, R. 1988. “On the Mechanics of Economic Development.” *Journal of Monetary Economics* 22, no. 1: 3–42. https://doi.org/10.1016/0304-3932(88)90168-7.

Lucking, B., N. Bloom, and J. Van Reenen. 2020. “Have R&D Spillovers Declined in the 21st Century?” *Fiscal Studies* 40, no. 4: 561–90. https://doi. org/10.1111/1475-5890.12195.

Manpower Group. 2022. “The United States’ 2022 Talent Shortage.” https://go.manpowergroup.com/hubfs/Talent%20Shortage%202022/MPG_2022_TS_Infographic-US.pdf.

Marvel, K., W. Su, R. Delgado, S. Aarons, A. Chatterjee, M. Garcia, Z. Hausfather, et al. 2023. “Ch. 2: Climate Trends.” In *Fifth National Climate Assessment*, ed. A. Crimmins, C. Avery, D. Easterling, K. Kunkel, B. Stewart, and T. Maycock. Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH2.

McMillan, M., and D. Rodrik. 2011. *Globalization, Structural Change and Productivity Growth.* NBER Working Paper 17143. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w17143.

Meckling, J., N. Kelsey, E. Biber, and J. Zysman. 2015. “Winning Coalitions for Climate Policy.” *Science* 349, no. 6253: 1170–71. https://doi.org/10.1126/science.aab1336.

Meckling, J., and J. Nahm. 2021. “Strategic State Capacity: How States Counter Opposition to Climate Policy.” *Comparative Political Studies* 55, no. 3: 493–523. https://doi.org/10.1177/00104140211024308.

Mendell, R., M. Einberger, and K. Siegner. 2022. “FERC Could Slash Inflation and Double Renewables with These Grid Upgrades.” Rocky Mountain Institute. https://rmi.org/ferc-could-slash-inflation-and-double-renewables-grid-upgrades/.

Meng, K. 2023. *Estimating Path Dependence in Energy Transitions*. NBER Working Paper 22536. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w22536.

Nahm, J. 2021. *Collaborative Advantage: Forging Green Industries in the New Global Economy*. Oxford: Oxford University Press. https://global.oup.com/academic/product/collaborative-advantage-9780197555361.

Nanda, R., and M. Rhodes-Kropf. 2016. “Financing Risk and Innovation.” *Management Science* 63, no. 4: 901–18. https://doi.org/10.1287/mnsc.2015.2350.

Nanda, R., K. Younge, and L. Fleming. 2015. “Innovation and Entrepreneurship in Renewable Energy.” In *The Changing Frontier: Rethinking Science and Innovation Policy*, ed. A. Jaffe and B. Jones, 199–232. Chicago: University of Chicago Press. https://www.nber.org/system/files/chapters/c13048/c13048.pdf.

Narich, C., D. Kammen, M. Stark, T. Powers, B. Budiman, J. Szinai, and P. Hidalgo-Gonzalez. 2021. “The Role of Storage in the Path to Net Zero.” Accenture and University of California-Berkeley Renewable and Appropriate Energies Lab. https://www.accenture.com/content/dam/accenture/final/a-com-migration/r3-3/pdf/pdf-144/accenture-path-to-net-zero-pov.pdf.

National Academies of Sciences, Engineering, and Medicine. 2021. *Accelerating Decarbonization of the U.S. Energy System.* Washington: National Academies Press. https://doi.org/10.17226/25932.

National Renewable Energy Lab. 2023. "Annual Technology Baseline: Utility-Scale Battery Storage." https://atb.nrel.gov/electricity/2023/ utility-scale_battery_storage.

National Research Council. 2001. *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000*. Washington: National Academies Press. https://doi.org/10.17226/10165.

Nature Conservancy. 2023. "Power of Place National Executive Summary." https://www.nature.org/content/dam/tnc/nature/en/documents/FINAL_TNC_Power_of_Place_National_Executive_Summary_5_2_2023. pdf?itid=lk_inline_enhanced-template.

NCEI (National Centers for Environmental Information). 2024. "Billion-Dollar Weather and Climate Disasters." https://www.ncei.noaa.gov/access/billions/overview/.

Nelson, R., and S. Winter. 1985. *An Evolutionary Theory of Economic Change*. Cambridge, MA: Harvard University Press. https://www.hup.harvard.edu/books/9780674272286.

Nemet, G. 2019. *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation*. Oxford: Routledge. https://www.routledge.com/How-Solar-Energy-Became-Cheap-A-Model-for-Low-Carbon-Innovation/Nemet/p/book/9780367136598?utm_source=cjaffiliates&utm_medium=affiliates&cjevent=ced8fe67678411ee8168008b0a82b82a.

Nemet, G., and D. Kammen. 2007. "U.S. Energy Research and Development: Declining Investment, Increasing Need, and the Feasibility of Expansion." *Energy Policy* 35, no. 1: 746–55. https://doi.org/10.1016/j.enpol.2005.12.012.

Nemet, G., V. Zipperer, and M. Kraus. 2018. "The Valley of Death, the Technology Pork Barrel, and Public Support for Large Demonstration Projects." *Energy Policy* 119: 154–67. https://doi.org/10.1016/j.enpol.2018.04.008.

NOAA (National Oceanic and Atmospheric Administration). 2024. "Billion-Dollar Weather and Climate Disasters." https://www.ncei.noaa.gov/access/billions/overview.

Noailly, J., L. Nowzohour, and M. van den Heuvel. 2022. *Does Environmental Policy Uncertainty Hinder Investments Towards a Low-Carbon Economy?* NBER Working Paper 30361. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w30361.

NREL (National Renewable Energy Laboratory). 2023. "Utility-Scale Battery Storage." https://atb.nrel.gov/electricity/2023/utility-scale_battery_storage.

Nurkse, R. 1952. "Some International Aspects of the Problem of Economic Development." *American Economic Review* 42, no. 2: 571–83. https://www.jstor.org/ stable/1910629.

NYC Department of Buildings. 2023. "Solar Electric Generating Systems Tax Abatement

Program." https://nyc-business.nyc.gov/nycbusiness/description/ solar-electric-generating-systems-tax-abatement-program.

OEC (Observatory of Economic Complexity). 2021. "South Korea." https://oec.world/en/profile/country/kor.

OCED (Office of Clean Energy Demonstrations). 2023. "OCED Funding Opportunity Announcements." https://oced-exchange.energy.gov/Default.aspx#FoaId3c3d8e7f-1839-45fc-8735-c0caf87408ef.

OECD (Organization for Economic Cooperation and Development). 2023. "Greenhouse Gas Emissions." https://stats.oecd.org/Index.aspx?DataSetCode=air_ghg.

OMB (U.S. Office of Management and Budget). 2023. "Budget Exposure to Increased Costs and Lost Revenue Due to Climate Change: A Preliminary Assessment and Proposed Framework for Future Assessments." White Paper. https://www.whitehouse.gov/wp-content/uploads/2023/03/climate_budget_exposure_fy2024. pdf.

Pasqualetti, M., R. Righter, and P. Gipe. 2004. "History of Wind Energy." In *Encyclopedia of Energy*, ed. C. Cleveland, 419–33. Cambridge: Academic Press. https://www.researchgate.net/publication/265594973_History_of_Wind_Energy.

Pimm, A., E. Barbour, T. Cockerill, and J. Palczewski. 2019. "Evaluating the Regional Potential for Emissions Reduction Using Energy Storage." In *Proceedings of 2019 Offshore Energy and Storage Summit*, 1–6. https://ieeexplore.ieee.org/document/8867357.

Pirani, S. 2018. *Burning Up: A Global History of Fossil Fuel Consumption*. London: Pluto Press. https://www.jstor.org/stable/j.ctv4ncp7q.14?typeAccessWorkflow=login&seq=10.

Pollin, R., and B. Callaci. 2016. "The Economics of Just Transition: A Framework for Supporting Fossil-Fuel-Dependent Workers and Communities in the United States." Working paper, *Labor Studies Journal*. https://peri.umass.edu/publication/ item/762-the-economics-of-just-transition-a-framework-forsupporting-fossil-fuel-dependent-workers-and-communities-in-the-united-states.

Quinn, R. 2013. "Rethinking Antibiotic Research and Development: World War II and the Penicillin Collaborative." *American Journal of Public Health* 103, no. 3: 426–34. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3673487/.

Raimi, D., E. Grubert, J. Higdon, G. Metcalf, S. Pesek, and D. Singh. 2023. "The Fiscal Implications of the U.S. Transition Away from Fossil Fuels." *Review of Environmental Economics and Policy* 17, no. 2: 295–315. https://doi.org/10.1086/725250.

Ranis, G., and J. Fei. 1961. “A Theory of Economic Development.” *American Economic Review* 51, no. 4: 533–65. https://www.jstor.org/stable/1812785.

Rao, V. 1952. “Investment, Income and the Multiplier in an Under-Developed Economy.” *Indian Economic Review* 1, no. 1: 55–67. https://doi.org/10.1177/0019466220080205.

Rapson, D., and E. Muehlegger. 2023. *The Economics of Electric Vehicles*. NBER Working Paper 29093. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w29093.

Riofrancos, T., A. Kendall, K. Dayemo, M. Haugen, K. McDonald, B. Hassan, M. Slattery, and X. Lillehei. 2023. “Achieving Zero Emissions with More Mobility and Less Mining.” Climate and Community Project. https://www.climateandcommunity.org/more-mobility-less-mining.

RMI. 2022. “FERC Could Slash Inflation and Double Renewables with These Grid Upgrades.” https://rmi.org/ ferc-could-slash-inflation-and-double-renewables-grid-upgrades/.

Rodrik, D. 2014. “Green Industrial Policy.” *Oxford Review of Economic Policy* 30, no. 3: 469–91. https://doi.org/10.1093/oxrep/gru025.

Romer, P. 1990. “Endogenous Technological Change.” *Journal of Political Economy* 98, no. 5: S71–102. https://www.jstor.org/stable/2937632.

Sandalow, D., M. Meidan, P. Andrews-Speed, A. Hove, S. Qiu, and E. Downie. 2022. “Guide to Chinese Climate Policy 2022.” Oxford Institute of Energy Studies, chap. 21: “Clean Energy R&D.” https://chineseclimatepolicy.oxfordenergy.org/book-content/domestic-policies/clean-energy-rd/.

Sankaran, V., H. Parmar, and K. Collison. 2021. “Just & Reasonable? Transmission Upgrades Charged to Interconnecting Generators Are Delivering System-Wide Benefits.” American Council on Renewable Energy. https://acore.org/ wp-content/uploads/2021/10/Just_and_Reasonable.pdf.

Schlenker, W., and M. Roberts. 2009. “Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change.” *Proceedings of the National Academy of Sciences* 106, no. 37: 15594–98. https://doi.org/10.1073/pnas.0906865106.

UNFCCC (United Nations Framework Convention on Climate Change). 2023. “2023 Voluntary Supplement to the U.S. Fifth Biennial Report.” https://unfccc.int/sites/default/files/resource/US_BR_Voluntary_Suplement_2023.pdf.

———. 2024a. “The Paris Agreement.” https://unfccc.int/process-and-meetings/ the-paris-agreement.

———. 2024b. “What Is the Kyoto Protocol?” https://unfccc.int/kyoto_protocol.

U.S. Congress. 2004. “H.R.4520: American Jobs Creation Act of 2004.” https://www.congress.gov/bill/108th-congress/house-bill/4520.

U.S. Department of the Treasury. 2023. “New U.S. Department of the Treasury Analysis:

Inflation Reduction Act Driving Clean Energy Investment to Underserved Communities, Communities at the Forefront of Fossil Fuel Production.” https://home.treasury.gov/news/press-releases/jy1931.

Van den Heuvel, M., and D. Popp. 2022. *The Role of Venture Capital and Governments in Clean Energy: Lessons from the First Cleantech Bubble*. NBER Working Paper 29919. Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w29919.

Van de Ven, D., I. Capellan-Peréz, I. Arto, I. Cazcarro, C. de Castro, P. Patel, and M. Gonzalez-Eguino. 2021. “The Potential Land Requirements and Related Land Use Change Emissions of Solar Energy.” *Scientific Reports* 11. https://doi.org/10.1038/s41598-021-82042-5.

Vanatta, M., M. Craig, B. Rathod, J. Florez, I. Bromley-Dulfano, and D. Smith. 2022. “The Costs of Replacing Coal Plant Jobs with Local Instead of Distant Wind and Solar Jobs across the United States.” *iScience* 25, no. 8. https://doi.org/10.1016/j.isci.2022.104817.

Van Zalk, J., and P. Behrens. 2018. “The Spatial Extent of Renewable and Non-Renewable Power Generation: A Review and Meta-Analysis of Power Densities and Their Application in the U.S.” *Energy Policy* 123: 83–91. https://www.sciencedirect.com/science/article/pii/S0301421518305512.

Victor, D. 2009. “The Politics of Fossil-Fuel Subsidies.” Working paper, Global Studies Initiative. https://dx.doi.org/10.2139/ssrn.1520984.

Way, R., M. Ives, P. Mealy, and J. Farmer. 2022. “Empirically Grounded Technology Forecasts and the Energy Transition.” *Joule* 6, no. 9: 2057–82. https://doi.org/10.1016/j.joule.2022.08.009.

Weber, J. 2020. “How Should We Think about Environmental Policy and Jobs? An Analogy with Trade Policy and an Illustration from U.S. Coal Mining.” *Review of Environmental Economics and Policy* 14. no. 1. https://doi.org/10.1093/reep/rez016.

White House. 2022. “Federal Budget Exposure to Climate Risk.” https://www.whitehouse.gov/wp-content/uploads/2022/04/ap_21_climate_risk_fy2023.pdf.

Zacarias, M., and J. Nakano. 2023. “Exploring the Hydrogen Midstream: Distribution and Delivery.” Center for Strategic and International Studies. https://www.csis.org/analysis/exploring-hydrogen-midstream-distribution-and-delivery.