From Risk To Return

Investing in a Clean Energy Economy

RISKY BUSINESS

A Product of the Risky Business Project

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RISKY BUSINESS

Executive Summary

In our 2014 inaugural report, "Risky Business: The Economic Risks of Climate Change in the United States," we found that the economic risks from unmitigated climate change to American businesses and long-term investors are large and unacceptable. Subsequent scientific data and analysis have reinforced and strengthened that conclusion. As a result, we, the Co-Chairs and Risk Committee of the Risky Business Project, are united in recognizing the need to respond to the risk climate change poses to the American economy.

Now we turn to the obvious next question: *how* to respond to those risks. Seriously addressing climate change requires reducing greenhouse gas emissions by at least 80 percent by 2050 in the U.S. and across all major economies. We find that this goal is technically and economically achievable using commercial or near-commercial technology. Most important, we find that meeting the goal does not require an energy miracle or unprecedented spending.

The transition to a cleaner energy economy rests on three pillars: moving from fossil fuels to electricity wherever possible, generating electricity with low or zero carbon emissions, and using energy much more efficiently. This means building new sources of zero- and low-carbon energy, including wind, solar, and nuclear; electrifying vehicles, heating systems, and many other products and processes; and investing in making buildings, appliances, and manufacturing more energy efficient.

Meeting these targets requires a large-scale shift away from ongoing spending on fossil fuels and toward up-front capital investments in clean energy technologies. Many of those, such as wind and solar, have little or no fuel cost once built. Given an appropriate policy framework, we expect these investments to be made largely by the private sector and consumers, and to yield significant returns. Because of the large capital investments and the long-term savings in fuel costs, this shift presents significant opportunities for many American investors and businesses. Notably, shifting the U.S. to a low-carbon, clean energy system presents not just long term benefits but also immediate, near-term opportunities, particularly for those actors best positioned to capitalize on these trends.

Our Modeling

Our conclusions are based on a sophisticated energy, economic and infrastructure planning model that compares scenarios through 2050. Each of the four pathways we modeled would achieve an 80 percent reduction in carbon emissions by 2050, and would do one of the following:[1]

- Rely heavily on renewable energy;
- Significantly expand reliance on nuclear power;
- Include a substantial amount of fossil fuel power plants with carbon capture and storage; or
- Generate electricity from a relatively even mix of these three zero- and low-carbon resources (the Mixed Resources pathway).

Each pathway also assumes a different combination of transportation fuels (electricity, biofuels, and fossil fuels).

For each of these pathways, we modeled changes in nationwide and sectoral energy use, electricity use, fuel use, carbon emissions, and investment. We do not endorse any specific pathway.

1 Our modeling was limited to carbon emissions (CO_2) which represent 81 percent of total U.S. GHG emissions. We did not model pathways that would achieve the needed reductions in the other greenhouse gases (methane, nitrous oxide, and fluorinated gases).

Capital Investment Needs

Under our Mixed Resources pathway, we found that the total additional capital investment necessary to cut carbon emissions 80 percent economy-wide by 2050 would be[2]:

- $220 billion per year from 2020 to 2030
- $410 billion per year between 2030 and 2040
- $360 billion per year between 2040 and 2050

These capital investments would significantly reduce fuel costs, with the savings growing every decade. The savings would be[3]:

- $70 billion per year from 2020 to 2030
- $370 billion per year from 2030 to 2040
- $700 billion per year from 2040 to 2050

The largest additional investments would be in power generation ($55 billion per year); advanced

2 Results presented here are decadal averages for the Mixed Resources pathway that incorporates a variety of low-carbon energy sources, one of four pathways analyzed. All modeling results are expressed in 2014 dollars unless otherwise noted.

3 Fuel savings are based on a U.S. government "business-as-usual" projection of fossil fuel prices in which: oil prices are $79/bbl in 2020, escalating an average of 3.4% per year out to 2050; natural gas prices are $5/Mbtu in 2020, escalating at an average of 2.7% per year out to 2050; and coal prices are $1.9/Mbtu in 2020, escalating at an average of 1.4% per year out to 2050. The analysis also explores a scenario in which a global shift to clean energy results in lower fossil fuel prices as demand decreases.

Figure ES-1.

Average Annual Additional Capital Investments and Fuel Expenditures by Decade

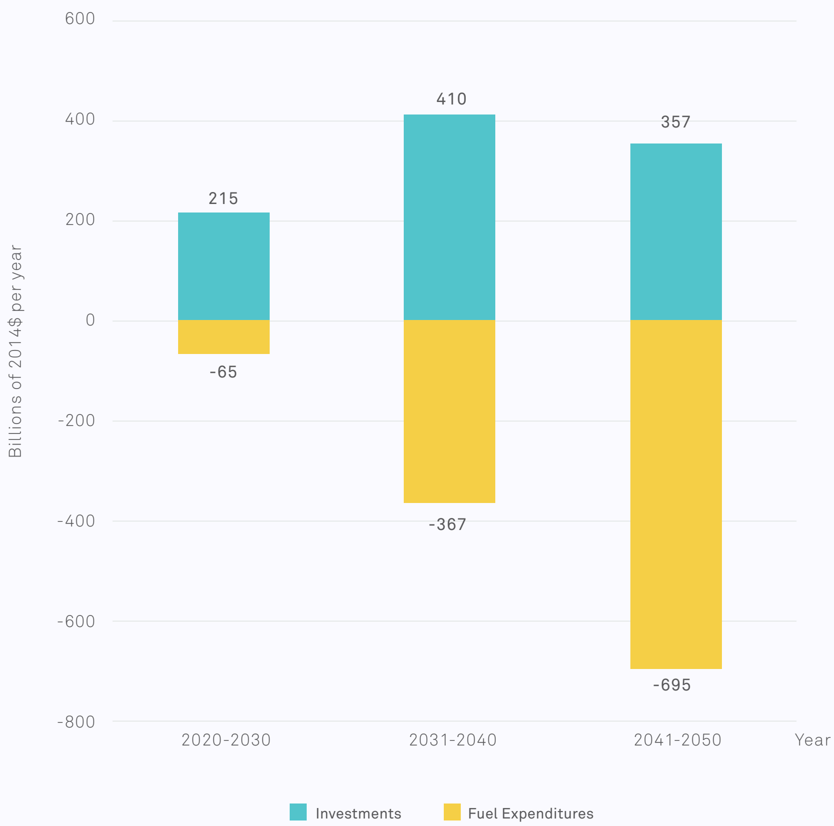


Figure ES-1 depicts the annual changes (from reference case levels) in investments and fuel expenditures averaged over three decadal periods for the Mixed Resources pathway.

biofuels ($45 billion per year); purchases of advanced light duty vehicles ($75 billion per year); and energy efficiency measures ($16 billion per year). Businesses that become leaders in these sectors could see large increases in revenue in the years ahead, while those that lag behind risk being left with stranded assets.

The investment needs of a transition to a clean energy economy are manageable, especially when compared to the costs that would be imposed by unmitigated climate change and continued fossil fuel dependence. They are also comparable to other recent investments, such as in unconventional oil and gas production, and in computers and software. Those investments have transformed the American economy, yielding huge returns to those businesses that led in the development of new technologies and products.

Regional and Sectoral Impacts

Investment needs and business opportunities will vary considerably by region. For example, in our Mixed Resources pathway, new nuclear plants would likely be built in the mid-Atlantic and southern regions, while wind power would grow fastest in the windy central region, investments in solar power would be greatest in the sunny western and southern regions, and revenue from biomass feedstocks would be greatest in the Midwest.

Overall, the increased investment would boost manufacturing and construction across the U.S. Roughly 460,000 additional construction jobs could be created by 2030, with the number rising to 800,000 by 2050. At the same time, reductions in fossil fuel use would further constrain coal, oil, and natural gas exploration and production. The number of coal mining and oil- and gas-related jobs could decline by more than 130,000 by 2030 and 270,000 by 2050, disproportionately affecting the specific geographic regions that currently depend heavily on these industries.

We know innovation will continue as American businesses develop and deploy new technologies. Many economic sectors and communities will also respond to the challenges and opportunities presented by the transition to a clean energy economy in new and surprising ways. We can project how the costs of current technologies are likely to decline as they are developed and deployed, but we can't predict which new technologies will emerge in the next 35 years—though we're confident new innovations will be made. The costs of creating a clean energy economy are thus likely to be lower—and the benefits greater—than we project.

Critical Role of Policy

The private sector alone cannot solve the climate change problem. We know from our collective business and investment experience that the private sector will take action at the necessary speed and scale *only* if it is given a clear and consistent policy and regulatory framework. That framework must send a clear, consistent, and long-term market signal on the necessity of climate action, provide incentives for innovation and deployment of clean energy systems, and help society adapt to climate impacts that are inevitable due to past and current emissions.

We are united in believing that the real costs of carbon emissions must be incorporated into economic decision-making in both the public and private sector, for instance, through putting a price on carbon. Government investment must also be coordinated and streamlined—and must not subsidize or exacerbate climate-related risks and economic activities that contribute to climate change (e.g., tax incentives for fossil fuel extraction or subsidized flood insurance in high-risk areas). Policies should also help those Americans hurt by the clean energy transition, as well as those who are most vulnerable to climate impacts.

America has a responsibility to lead by example. Ultimately, however, U.S. actions must be integrated into a larger global commitment to shift toward a cleaner energy economy. U.S. policies also must ensure that the competitiveness of U.S. business is not harmed. This may require border adjustments and other mechanisms to prevent other countries from seizing unfair advantages.

With the right policy framework, we are confident that America can reduce the economic risks from climate change while seizing new market opportunities. But businesses must also start now to factor climate risks into their investment decisions. Whenever capital assets reach the end of their productive lives, they should be replaced with energy efficient and low-carbon alternatives wherever possible and prudent. All businesses, especially those making regular long-term, place-based infrastructure and supply chain investments, should also conduct detailed analyses of climate risks they face, build internal capacity, develop concrete action plans to address these risks, and disclose their risks and actions.

The transition to a clean energy economy is already underway, but must be accelerated to avoid unacceptable risks from climate change. In the past, transformative investments in such areas as highways, rural electricity, and telecommunications have unleashed the power of innovation and American business. Investing in clean energy can ensure American economic security and competitiveness for decades to come. But to substantially reduce the growing risks of climate change, and to take maximum advantage of the opportunities in a clean energy economy, we must act now.

> “We can reduce climate risks with existing clean technologies. We don’t need an energy miracle.”
>
> – Henry M. Paulson, Jr.

A clean energy economy
is coming.

Contents

1. Introduction

1.1 From Risk to Return: Investing in a Clean Energy Economy

We formed the Risky Business Project to better understand the specific economic risks businesses and investors face from unmitigated climate change. Our first report, released in June 2014, took a traditional business risk assessment approach to the issue, including analysis of both likely impacts and risks, and less likely but potentially more severe risks. The report found that while the physical risks vary across region and sector, the likely economic impacts to key sectors such as real property, agriculture, and energy are enormous.

In order to avoid these serious economic consequences, the best available science suggests that U.S. greenhouse gas (GHG) emissions need to be reduced by 80 percent or more by 2050. Similar cuts must be made across all major economies. Achieving these reductions will require a transition to an economy powered almost entirely by low- and zero-carbon energy sources.

With the scale and urgency of such a transition in mind, this new report summarizes the findings of recent research and analysis on pathways to achieve a clean energy economy in the United States. We combine a literature review with new modeling to analyze four feasible pathways to reduce carbon emissions across the U.S. economy by 80 percent. These pathways use different mixes of energy technologies, including renewable energy sources, nuclear, and fossil fuels with carbon capture and storage. They are designed to ensure that American businesses and consumers will have access to at least as much energy as they would if the nation continued to rely on the current mix of high-carbon energy sources.

We believe this large-scale transition is urgently necessary to maximize the chance of avoiding the potentially devastating impacts of climate change on our economy. Making a convincing case for such a major transition, however, requires answering key questions, including:

- Is creating a clean energy economy technologically and economically feasible?
- What are the investment needs of this transition and how might specific economic sectors and regions be affected?
- What are the opportunities and challenges for business?
- What is the role of policy in this transition?

1.2 Risky Business: The Economic Risks of Climate Change

Before describing the possible pathways for achieving a clean energy economy, it is important to understand why such a transition is necessary. Our 2014 report did not estimate the costs of climate change to the entire American economy, but it did calculate the likely economic impacts in four key areas: coastal property, commodity agriculture, energy demand, and worker health and productivity. We found that the financial toll from rising seas, steadily increasing heat, and more frequent and extreme storms will likely add up to hundreds of billions of dollars in direct costs to both the public and private sectors over the coming decades. For example:

- Rising seas and more powerful storm surges are expected to more than double the average cost of coastal storms to $3.5 billion per year along the Eastern Seaboard and the Gulf of Mexico within 15 years.
- Yields of corn, wheat, and other crops in the Midwest and South are likely to drop by more than 10 percent in the next five to 25 years absent adaptation—and could decline by more than 20 percent in some counties.
- Some regions of the U.S., especially the Southwest, Southeast, and upper Midwest, will likely see several months each year with temperatures of 95°F or above. Extreme heat could make working outdoors or living without air conditioning a serious and potentially fatal health hazard.

These are the impacts and risks that are *likely* to occur over the next few decades—that is, those impacts with more than a 2-in-3 chance of occurring given the emissions that have already been released into the atmosphere. The risks at the tail end of the distribution of possible impacts, which would become likely impacts without action to combat climate change, are even more severe. For example, while it is likely that between $66 billion and $106 billion worth of existing coastal property will be below sea level nationwide by 2050, there is a 1-in-20 probability that this value will reach $701 billion by 2100 if we stay on our current emissions trajectory, with another $730 billion worth of property at risk during high tide. There is also a 1-in-100 chance that cities like New York, Norfolk, Virginia, and Honolulu will experience more than 6.9 feet of sea level rise by 2100.

As the 2014 report concluded, some of these physical impacts from climate change are already being felt across the U.S. today. In response, many businesses and local governments are already adopting adaptation plans or making investments that bring greater resilience to extreme weather and other climate change impacts. But the most severe climate impacts we modeled are not inevitable, and can be avoided with strong public and private sector action to cut emissions. To that end, we strongly recommended—and continue to urge—that business leaders take action now across all industries to measure and manage climate risk within their own companies and encourage policymakers to seriously address this issue.

1.3 New Science, Market Trends, and Policies Change the Equation for Business

The risk assessment model we used in 2014 anticipated changing conditions, including new climate science[4]. Since that time, the likelihood of severe risks from climate change has continued to grow. Indeed, every year that goes by without reductions in GHG emissions increases both the likelihood and potential magnitude of future climate change impacts. Since 2014, new scientific research has suggested that the likelihood of rapid sea level rise and sustained, higher temperatures has increased, underscoring the expected severity of climate impacts and the urgency of action[5].

With the benefit of this new research, we now believe our 2014 numbers were too conservative.

The financial risks of investments in the high-carbon fuels driving climate change are also growing. One example is the significant devaluation of publicly listed U.S. coal stocks in the past several years.

4 Our 2014 report used modeling and analysis that is open source and available to anyone interested in identifying specific physical risks to their businesses or investments. Since its publication, many businesses, as well as public and private sector investors (including the federal government), have adopted and built on this methodology.

5 The following sources are not exhaustive provide a solid sampling of recent research on the increasing effects of climate change: See Jessica Blunden and Derek S. Arndt, Editors, "State of the Climate in 2015," Bulletin of the American Meteorological Society 97 no. 8 (2016), https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/ ; Robert M. DeConto and David Pollard, "Contribution of Antarctica to past and future sea-level rise," Nature 531 (2016): 591–597, http://www.nature.com/nature/journal/v531/n7596/full/nature17145.html;

Christopher Harig and Frederick J. Simons, "Ice mass loss in Greenland, the Gulf of Alaska, and the Canadian Archipelago: Seasonal cycles and decadal trends," Geophysical Research Letters 43 no. 7 (2016): 3150-3159, https://www.researchgate.net/publication/301632663_Ice_mass_loss_in_Greenland_the_Gulf_of_Alaska_and_the_Canadian_Archipelago_Seasonal_cycles_and_decadal_trends;

WMO Statement on the Status of the Global Climate in 2015, http://library.wmo.int/pmb_ged/wmo_1167_en.pdf; Flavio Lehner, Clara Deser, and Benjamin M. Sanderson, "Future risk of record-breaking summer temperatures and its mitigation," Climatic Change (2016), http://link.springer.com/article/10.1007/s10584-016-1616-2; Thomas R. Karl, et al., "Possible artifacts of data biases in the recent global surface warming hiatus," Science 348 no. 6242 (2015):1469-1472, http://science.sciencemag.org/content/348/6242/1469; Catherine M. O'Reilly, et al., "Rapid and highly variable warming of lake surface waters around the globe," Geophysical Research Letters 42 no. 10 (2015): 10,773–10,781, http://onlinelibrary.wiley.com/doi/10.1002/2015GL066235/full; Jeremy S. Pal and Elfatih A. B. Eltahir, "Future temperature in southwest Asia projected to exceed a threshold for human adaptability," Nature Climate Change 6 (2016): 197–200, http://eltahir.mit.edu/wp-content/uploads/2015/08/Paper.pdf

A combination of citizen pressure, compliance costs associated with public health and environmental regulations, and the declining costs of renewable energy and natural gas led to a 12 percent drop in domestic coal consumption in 2015 alone, bringing coal's share of U.S. electricity generation to its lowest level since 1982. As a result, coal mining companies such as Peabody, Arch, and Alpha Natural Resources have filed for bankruptcy, and across the industry workers and shareholders have faced significant losses as the industry contracts[6,7].

Investors are also recognizing that the risks of investing in other fossil fuel sectors are increasing as governments consider policies, such as carbon pricing and emissions curbs, that would reduce fossil fuel consumption along with emissions. Meanwhile, zero-carbon sources of renewable energy are becoming increasingly cost competitive. BlackRock, the world's largest asset manager, noted in a recent report that investors with the longest time horizons are the most sensitive to these risks: "The longer an asset owner's time horizon, the more climate-related risks compound. Yet even short-term investors can be affected by regulatory and policy developments, technological disruption or an extreme weather event.[8]"

6 Inti Landauro, "Engie Pushed to Loss by Hefty Write-Downs," The Wall Street Journal, last modified February 25, 2016, http://www.wsj.com/articles/engie-pushed-to-loss-by-hefty-write-downs-1456384071; "Major step in ENGIE's transformation to reach its ambition to be leader of the world energy transition," ENGIE.com, February 25, 2016, http://www.engie.com/en/journalists/press-releases/major-step-transformation/

7 Camila Domonoske, "U.S. Coal Giant Peabody Energy Files for Bankruptcy," NPR.org, April 13, 2016, http://www.npr.org/sections/thetwo-way/2016/04/13/474059310/u-s-coal-giant-peabody-energy-files-for-bankruptcy

8 BlackRock, "Adapting portfolios to climate change", September 6, 2016. Available at: https://www.blackrock.com/institutions/en-us/insights/markets/climate-change

Some large investors have begun to reduce risks in their own portfolios through greater diversification or by explicitly "decarbonizing" their investments. For example, the Investor Network on Climate Risk, a network of more than 120 institutional investors with more than $14 trillion in assets, has committed to addressing climate change, including by investing in low-carbon energy and technologies.

Even absent a price on carbon, governments at all levels are working to reduce greenhouse gas emissions and to encourage the growth of clean energy. Their actions and policies are having an impact on business practices across the country. To cite just a few examples, dozens of U.S. cities (many of them members of the Global Covenant of Mayors for Climate Change & Energy) have committed to reducing their emissions by 80 percent or more over the next few decades. California and a number of New England states have capped emissions from specific sectors, thus putting a de facto price on carbon. Twenty-nine U.S. states and the District of Columbia have renewable portfolio standards, which require a specific percentage of electricity to be generated from renewable sources [9]. Nearly every state uses building codes to encourage or require improvements in energy efficiency.

At the federal level, the U.S. EPA has promulgated rules under the Clean Air Act that require the power sector to cut carbon emissions 32 percent below 2005 levels by 2030. And at the international level, 197 nations around the world agreed to reduce GHG emissions and increase support for clean energy and energy efficiency in the 2015 Paris Agreement,

9 "Renewable Portfolio Standard Policies," DSIRE, last modified August, 2016, http://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2014/11/Renewable-Portfolio-Standards.pdf

which went into effect in late 2016. This evolving policy landscape is putting increasing pressure on companies to cut their own emissions. It also means that companies must include a range of carbon constraints and costs in their future planning in order to reduce their potential financial risks.

However, and this cannot be said strongly enough: taken as a whole, current government policies cannot achieve the needed emissions reductions to avert the worst impacts of climate change. Moreover, these policies are inconsistent across cities, states, and nations, creating an uncertain business and investment environment. Finally, policies remain in place both nationally and internationally that subsidize or otherwise encourage climate risk, including favorable tax treatment for fossil fuel production and consumption, and publicly-funded insurance for high-risk real estate investments.

This fast-changing policy landscape creates new risks and opportunities for business. If momentum continues to build for a transition to a clean energy economy, businesses face the risk of falling behind in the global competition for market share and technological leadership. If climate action stalls, those businesses establishing a leadership position now may not benefit from moving first. But even in the absence of consistent government policy on climate and clean energy, almost all businesses will be forced to adapt to some climate change impacts.

1.4 Moving from Risk Measurement to Risk Management

Many U.S. business leaders, including members of our Risk Committee, believe that moving to a low-carbon energy economy is necessary if business—and the U.S. overall—is to avoid severe climate-related economic impacts. To reduce current and future risks from climate change, businesses must begin taking specific steps now to transform the economy away from its current dependence on carbon-intensive fuels, processes, and products.

We know that most businesses and investors operate on a shorter time horizon than some of the key steps in the transition discussed here. Ultimately, for business to act with the necessary speed and scale to address climate change, government must put in place a strong policy framework that supports the transition and rewards first movers. This is a matter not only of risk reduction but also of basic competitiveness: As the rest of the world starts moving toward a clean energy economy, our innovators and investors can lead the way.

There are other important economic benefits: For example, renewable energy sources can reduce fuel price risk for businesses with considerable exposure to fossil fuel price volatility. This transition could also stimulate innovation and create new jobs across multiple industries. But such a transition will have costs, both to companies and workers, and its benefits will likely be unevenly distributed.

In order to assess the economic and technical feasibility of this transition and to identify the most significant costs and opportunities for business, the Risky Business Project commissioned this new report, "From Risk to Return: Investing in a Clean Energy Economy."

Methods and modeling approach

Our analysis relies predominantly on the PATHWAYS** model, a bottom-up, stock rollover model with similar structure and inputs as the National Energy Modeling System (NEMS) maintained by the U.S. Energy Information Administration. PATHWAYS projects the energy system costs (and CO_2 emissions) associated with meeting an exogenous demand for energy services. The modelers choose to deploy technologies over time within a specified pathway in a way that meets that demand, both in terms of specific technological characteristics and how they would interact within the entire energy system.

A key strength of the PATHWAYS model is the very granular level of detail it brings to modeling of the energy system as a whole, and to the electricity sector in particular. PATHWAYS builds new generation, transmission, and distribution infrastructure to meet reliability needs in each of the nine census regions, and dispatches generation resources to balance supply and demand in each of the three main interconnection regions in the U.S. The model has several options for maintaining load balance in the case of high levels of variable renewable generation.

The model estimates the changes in investments, fuel expenses, and other operating expenses of low-carbon pathways relative to what we label the "High-Carbon Reference Case." Investments can be estimated annually on an "as spent" basis, and they can be annualized over the lifetime of the investment. PATHWAYS combines changes in annualized investments, fuel costs, and operating expenses to estimate the annual net cost of a pathway, i.e., the "change in total energy system cost" for any given year (one of the key cost metrics of the model). The Appendix provides additional details about the PATHWAYS model. Appendix can be found at www.riskybusiness.org.

Notably, PATHWAYS does not model the effects of price on supply and demand. It is not a partial or general equilibrium economic model, nor is it an optimization model. It is not designed to project macroeconomic impacts or to determine which clean energy pathway is "best" in terms of the narrow criterion of cost-effectiveness. Nevertheless, the model's estimates of changes in investment, fuel costs, and total energy system cost illuminate the key questions of economic feasibility and affordability.

We gained additional insights into macroeconomic impacts by reviewing a study using PATHWAYS and the Policy Insight Plus model, a macroeconomic model developed by the Regional Economic Models, Inc. (REMI). Using outputs from PATHWAYS (changes in energy use and investments) as inputs, the REMI model can project how those changes would affect the U.S. economy relative to a reference case. A 2015 study using PATHWAYS and REMI in this way modeled very similar clean energy pathways with reduction goals for CO_2 emissions of 80 percent by 2050 from 1990 levels. The macroeconomic projections from that study are presented here.

Uncertainties abound in any modeling exercise that looks 35 years into the future. We explored two key uncertainties as part of this study:

- If the global economy succeeds in making a transition to clean energy, fossil fuel prices are likely to decrease significantly. We developed a plausible price scenario reflecting this, and explored the implications.
- Rapid advances in Autonomous Vehicle (AV) technologies suggest that AVs could revolutionize how we conceive of and provide "personal mobility." We explored a scenario in which AVs expand rapidly in the decades ahead.

In addition to the modeling using PATHWAYS and REMI, we critically reviewed more than a dozen studies that examine the technical and economic feasibility of achieving major reductions in greenhouse gas emissions (see Appendix), and also developed seven case studies on key aspects of a clean energy economy, such as energy storage technologies and transportation advances.

** PATHWAYS was originally built by Energy and Environmental Economics, Inc. (E3) and used to model the U.S. as part of the Deep Decarbonization Pathways Project (http://deepdecarbonization.org/). Evolved Energy Research (EER) further developed the model and we engaged EER to apply it for this study ("EnergyPATHWAYS" is currently the official name of the model).

2. Report Findings: The Clean Energy Economy

Seriously addressing climate risk requires reducing carbon emissions by at least 80 percent by 2050 in the U.S. and across all major economies. We find that meeting this goal is both technically and economically feasible using commercial or near-commercial technology. It requires a transition to an economy powered by clean energy. Our research leads to the following general findings:

1. Shifting to a cleaner energy economy requires three major changes: switching from fossil fuels to electricity wherever possible; generating electricity with low or zero carbon emissions; and using energy more efficiently.
2. These changes involve substantial capital investments up front, but these investments will be offset by fuel savings. Essentially, the shift substitutes up-front capital investment for long-term fuel spending.
3. The largest increases in investment in the 2020-2030 period would be in vehicles of all types ($75 billion per year); power generation ($55 billion per year); advanced biofuels such as renewable diesel ($45 billion per year); and energy efficiency measures ($16 billion per year). The total additional capital investment would average about $200 billion per year from 2020 to 2030, and then average about $400 billion per year between 2030 and 2050. (Results are for the Mixed Resources pathway, one of four modeled—see textbox on page 21.)
4. The investment needed to transition to a clean energy economy is likely less than either the economic costs of unmitigated climate change or the projected spending if the U.S. continues to rely primarily on fossil fuels. This level of investment is also comparable in scale to other recent investments that have transformed the American economy. For example, with advances in unconventional oil and gas production, investment in fossil fuel production has increased to an average of $130 billion per year over the past decade, from less than $30 billion in 2000. An average of $350 billion per year has been invested over the past decade in computers and software, more than tripling the annual investment levels of the early 1990s. These investments have yielded solid returns to those businesses willing to lead.
5. These up-front capital investments would bring large reductions in fuel costs, because renewable electricity generation requires little or no fossil fuels, and electric vehicles and

other new systems would bring major gains in energy efficiency. The savings would grow from an average of $65 billion per year between 2020 and 2030, to $400 billion per year between 2030 and 2040, and to an average of about $700 billion per year from 2040 to 2050.

6. The higher levels of capital investment needed for the clean energy economy would boost manufacturing and construction in the U.S., stimulate innovation, and create new markets. Roughly 460,000 new construction jobs could be created by 2030, with the number rising to 800,000 by 2050. However, dramatically reducing the use of fossil fuels would obviously hurt industries and regions that now depend heavily on coal, oil, and natural gas. It could decrease the number of coal mining and oil- and gas-related jobs by more than 130,000 by 2030 and 270,000 by 2050, with job losses concentrated in the Southern and Mountain states. Transition assistance and job training would be needed to ease these economic dislocations.

7. Because of regional differences in energy consumption and renewable energy resources, each region of the U.S. would see different amounts of job growth and industry gains. Wind power would grow fastest in the windy central region, and investments in solar power would be greatest in the sunny western and southwestern regions. Revenue from biomass feedstocks would be greatest in the Southeast and the Midwest. New nuclear plants would be concentrated in the mid-Atlantic and southern regions, where renewable resources are less abundant and the regulatory framework for vertically integrated utilities is more conducive to such plants.

We modeled four distinct pathways that could achieve economy-wide reductions in CO_2 emissions of 80 percent below 1990 levels, and compare results to a "business-as-usual" pathway we call the High-Carbon Reference Case. Three of these pathways each rely significantly on one of the three major types of low- and zero-carbon electricity: renewable energy, nuclear power, and fossil fuel power with carbon capture and storage (CCS). The fourth, labeled the "Mixed Resources" pathway, relies on a balanced blend of these three types of clean electricity. Each pathway also includes a different mix of low- and zero-carbon transportation fuels and technologies. We focus primarily in this summary report on the results for the Mixed Resources pathway, but full results are available in the Appendix for the other pathways: High Renewables, High Nuclear, and High CCS. The Appendix also provides additional details on the design of the pathways. The Co-Chairs and the Risk Committee of the Risky Business Project do not endorse any one specific pathway.

2.1 The Three Pillars of a Clean Energy Economy

The transition to a clean energy economy is critical if we are to reduce risks from the impacts of climate change. It is also economically feasible and offers opportunities for many U.S. businesses. The transformation to a clean energy economy will rely on three pillars:

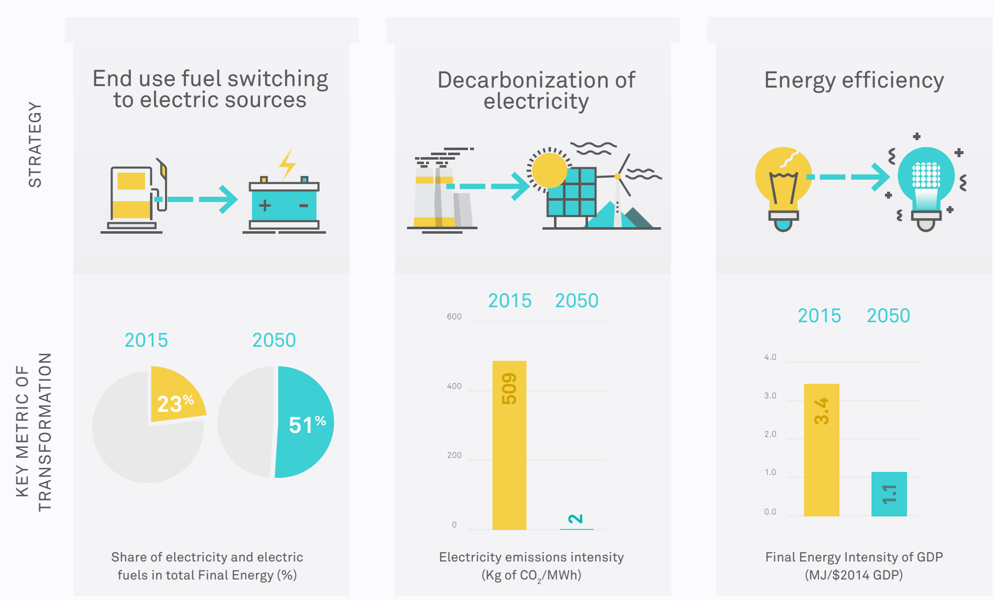
- A widespread electrification of the economy, substituting electricity for fossil fuels[10].
- A transition to low- and zero-carbon electricity generation sources and away from fossil fuels.
- Major progress in using energy more efficiently across all sectors.

Together, these steps will result in a large-scale substitution of capital for fossil fuel use, requiring increased private investment in the economy (Figure 1).

10 This includes both the direct substitution of electricity for fossil fuel use and using electricity to produce hydrogen and synthetic methane that substitute for fossil fuels.

Figure 1.

Three Pillars of a Clean Energy Economy: Strategies and Metrics



Mixed Resources Pathway

Figure 1 illustrates the three pillars and presents key metrics of transformation (2015 to 2050) for the Mixed Resources pathway:

- The share of electricity as a portion of total final energy use more than doubles, from 23 to 51 percent[11]. The remaining 49 percent comes from low-carbon biofuels (expand from 3 to 18 percent), and from direct fossil fuel combustion (decreasing from 74 to 31 percent).
- The CO_2 emissions intensity of generating electricity decreases from 509 to 2 kg of CO_2/MWh.
- The final energy intensity of GDP (reflecting energy productivity) decreases by about two-thirds, from 3.4 to 1.1 megajoules per dollar of GDP. This rate of change corresponds to a reduction in final energy intensity of about 3 percent per year, compared to a reduction of about 2 percent per year in the High-Carbon Reference Case[12].

Electrification of the Economy. Electrifying the economy, if electricity is generated with low- or zero-carbon sources, would significantly reduce CO_2 emissions. Electricity would replace fossil fuels across a variety of end-uses. In buildings, electric heat pumps for space heating and cooling and water heating would replace oil and gas furnaces. Cars, light trucks and buses, and other types of vehicles would use electric battery drives to reduce gasoline use, with the additional benefit of lower maintenance costs. Hydrogen and synthetic natural gas produced from electricity could also come into the vehicle fuel mix. Electricity, hydrogen, and synthetic gas would also substitute for fossil fuels in many industrial applications. However, airplanes and many industrial processes are much harder to electrify, and therefore still likely to be largely powered by fossil fuels.

Low- and Zero-Carbon Electricity Generation. Electrifying the economy achieves climate benefits only if the electricity itself is generated using low- or zero-carbon sources. These can come in several forms: renewable energy, nuclear power, and fossil fuel power with carbon capture and storage (CCS). Because of continuing innovation and declining costs for technologies like wind (the cost of wind energy has decreased 41 percent from 2009 to 2016) and solar (installed costs have dropped 64 percent since 2008), continued expansion of renewable energy is now both technically possible and economically feasible. Unlike some forms of renewable energy, nuclear power and CCS have not significantly decreased in cost in recent years; however, assuming improvements in cost effectiveness, both could provide sources of baseload power in the future[13].

11 Includes electricity used to produce hydrogen and synthetic methane.

12 Energy intensity is not the same as energy efficiency, although they can be related. Energy intensity can vary because of changes in the structure of the economy. With exogenous demand for energy services, PATHWAYS assumes the structure remains the same.

13 U.S. Department of Energy, Revolution Now: The Future Arrives for Five Clean Energy Technologies. September 2016. http://energy.gov/sites/prod/files/2016/09/f33/Revolutionâ€Now%202016%20Report_2.pdf.

Greater Energy Efficiency. The potential for improved energy efficiency—doing more with less—remains huge despite steady gains over many decades. A National Academy of Sciences study concluded that the U.S. could cost-effectively reduce energy use by 25 to 31 percent by 2030, applying discount rates ranging from 7 to 15 percent[14]. Indeed, many steps to improve energy efficiency, such as insulating buildings or upgrading heating and cooling systems, have energy savings over the lifetime of the investments that are far greater than the initial investment costs. Unfortunately, the payback periods and rates of return for these projects often preclude widespread adoption. Long-recognized problems of imperfect information, high transaction costs, and the misaligned incentives of principals and agents[15] also pose obstacles to greater investments in energy efficiency[16].

14 National Academy of Sciences, Real Prospects for Energy Efficiency in the United States, Washington, DC: National Academies Press, 2010. Available at: https://www.nap.edu/catalog/12621/real-prospects-for-energy-efficiency-in-the-united-states.

15 An example of misaligned incentives would be the apartment building owner who pays for efficiency improvements but doesn't get the benefits if tenants pay individual electricity bills. This misplaced incentive problem also occurs in commercial and industrial installations.

16 In some cases, electrification and increased efficiency can work together to bring greater reductions in overall costs, because efficient technologies can reduce initial capital costs as well as save energy over their lifetimes. For example, a light and aerodynamic all-electric vehicle requires a smaller, cheaper electric motor and fewer batteries than a more conventional all-electric design, both cutting initial capital costs and reducing future energy use. This type of integrated whole system design can bring savings in many sectors. Buildings can rely on smaller

2.2 The Cost of the Clean Energy Transition and Impacts on the Economy

Our modeling of clean energy pathways paid close attention to the useful lifetimes of many types of capital assets (Figure 2). In general, the cost of the transition to a clean energy economy would be lower if companies and consumers can avoid early retirement of capital assets. Consequently, each of our four pathways assumes average fixed asset turnover rates. For instance, hot water heaters, space heating equipment, and light-duty vehicles would be replaced two to three times between now and 2050. Longer-lived assets such as heavy-duty vehicles, industrial boilers, and some power plants would be replaced only once. Buildings last many decades and our modeling does not assume any replacements before 2050. It is important to note that companies and consumers sometimes hold onto capital assets longer than their average or recommended life, and that incentives may be required to keep to a recommended turnover schedule.

heating and cooling systems if better insulated, while industry can use smaller pumps and motors with better piping design. See Chapter 6 of Jonathan Koomey, Cold Cash, Cool Climate: Science-based Advice for Ecological Entrepreneurs (Burlingame, CA: Analytics Press, 2012), 89-122; Rocky Mountain Institute, "10xE: Factor Ten Engineering," accessed August 22, 2016, http://www.rmi.org/10xE; and Stansinoupolos, Peter, Michael H. Smith, Karlson Hargroves, and Cheryl Desha. 2008. Whole System Design: An Integrated Approach to Sustainable Engineering. New York, NY: Routledge.

Figure 2.

Replacement Opportunities for Selected Equipment and Facilities

Infrastructure Replacement:
Opportunities between 2015 and 2050

Infrastructure	Replacement Opportunities
Hot water heater	3
Space heater	2
Light duty vehicle	2
Heavy duty vehicle	1
Industrial boiler	1
Gas combined-cycle plant	1
Residential building	0

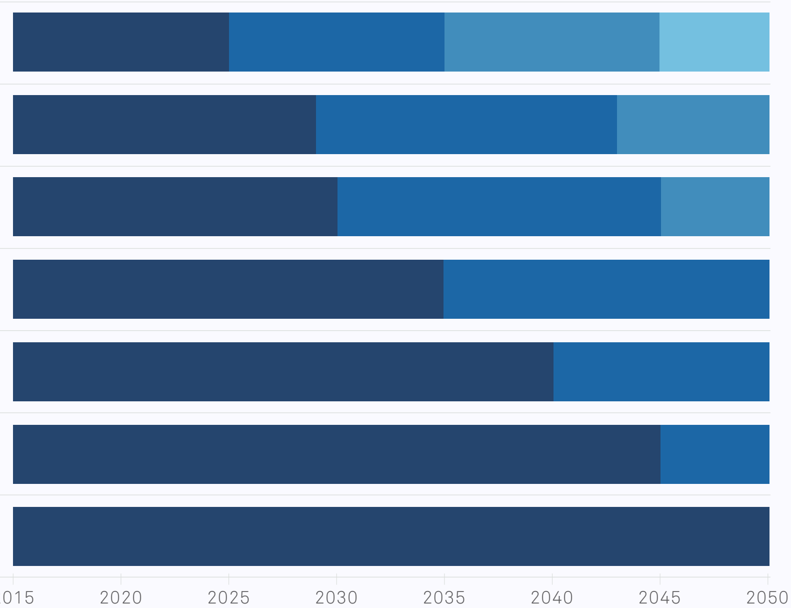


Figure 2 presents the number of replacements that PATHWAYS assumes from 2015-2050. Modeling assumes that replacements of energy-using equipment and facilities would occur on a timeline consistent with their normal turnover or lifetimes. Due to their long lifetimes, residential and other buildings are not replaced in our modeling. However, buildings' HVAC, lighting, and other systems can be made more efficient.

As noted earlier, we used the PATHWAYS model to estimate the changes in investments, fuel expenses, and other operating expenses of our low-carbon pathways relative to the High-Carbon Reference Case. We present below three perspectives on the costs of the clean energy transition:

- **As-Spent Cost Estimates.** This perspective looks at annual expenditures on capital and on fuel and other operating costs. Some refer to this as "cigar box" accounting.
- **Total Energy System Costs.** This perspective annualizes the capital costs over the lives of the investments, by translating these costs into a series of annual payments.[17] Then it combines those annualized costs with fuel and other operating costs. This perspective provides yearly cost estimates that are closer to what businesses will experience as they provide returns to equity and debt holders, and to what consumers will experience in energy costs and related purchases.
- **Macroeconomic Impacts.** A 2015 study using PATHWAYS and the macroeconomic REMI model[18] modeled clean energy pathways very similar to those in this report. The projections of impacts on GDP and employment from that study are useful indicators of the macro impacts of our pathways, and are presented here.

17 In financial analysis, one can annualize a capital investment cost by calculating a series of equal annual payments over the lifetime of the asset. The present value of the series of payments (using the appropriate discount rate) is equal to the initial capital costs. Annualization is sometimes called "equivalent annual cost" and is calculated by applying a Capital Recovery Factor to the initial capital investment.

18 REMI is a widely used macroeconomic model. See: http://www.remi.com/the-remi-model.

Below, we apply each of these three perspectives in examining the net cost to the U.S. economy between 2020-2050 of the transition to a clean energy economy relative to a "business-as–usual" scenario, which we call the High-Carbon Reference Case[19].

As-Spent Cost Perspective

Our first perspective on cost can be viewed in terms of as-spent cost estimates. A clean energy economy would require substantial shifts—and major net increases—in capital investments, while reducing overall spending on coal, oil, and natural gas fuels and related capital equipment. Under our Mixed Resources pathway, net U.S. investments in new clean energy technologies (after subtracting avoided investments in fossil fuel power plants) would grow annually until roughly 2030-2035, and then plateau at $400 billion per year more than in the High-Carbon Reference Case (Figure 3). Fuel and investment savings would grow slowly but steadily offset these costs, exceeding clean energy investments by the mid- to late 2030s. By 2050, fuel savings alone would be about $800 billion annually. Spending on natural gas would increase through the mid-2030s, and then begin to decrease. These changes in investments and fuel costs affect both businesses (e.g., for power plants and associated fuel) and consumers (e.g., for vehicle and gasoline purchases).

19 "Net cost" used here means the difference in cost to the economy of moving from the High-Carbon Reference Case to a clean energy pathway. Results presented focus on the Mixed Resource pathway.

Figure 3.

Net As-Spent Investments and Fuel Expenditures: Changes from High-Carbon Reference Case

Annual Net Costs: Mixed Resources Pathway

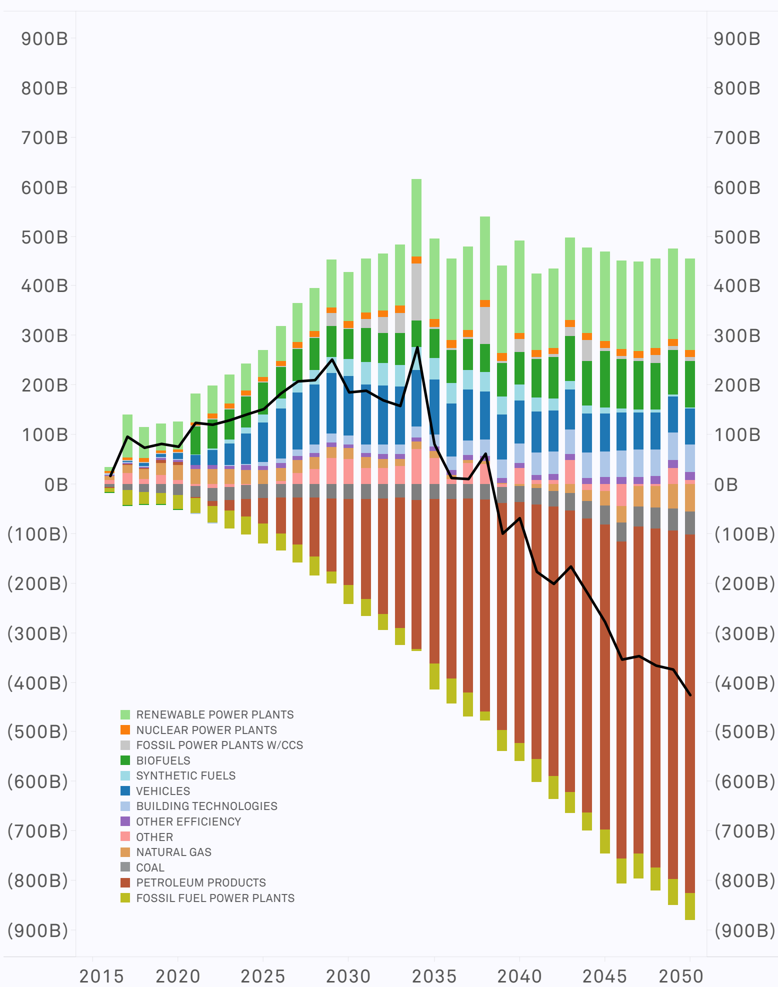


Figure 3 depicts the annual changes in as-spent investments and fuel expenditures in the Mixed Resources pathway, relative to the High-Carbon Reference Case.

- Investments and spending on clean energy, consistent with our Mixed Resources pathway, are shown as positive numbers in the upper portion of the figure. These include:
  - renewable and nuclear power plants, fossil plants with CCS;
  - production plants for biofuels, hydrogen and synthetic gas;
  - incremental investments in vehicles, buildings, other efficiency measures and other infrastructure (e.g., grid and pipeline expansion).
- Fuel savings and decreased investments in fossil fuels resulting from taking the Mixed Resources pathway are shown as negative numbers in the lower portion of the figure. These include decreased investment in coal, petroleum products, and fossil plants without CCS.
- The black line indicates the "as-spent" net cost, largely the difference between the clean energy investments and the fossil fuel savings from a simple "cash drawer" accounting perspective (with relatively small changes in non-fuel operating costs also accounted for).

Between 2020-2030, we project average yearly investment to increase, as compared to the High-Carbon Reference Case, for the following areas:

- Electricity sector: $55 billion per year
- Vehicles: $75 billion per year
- Biofuels: $45 billion per year
- Energy efficiency: $16 billion per year

Notably, a greater percentage of energy spending is likely to stay in the U.S. under any of our clean energy pathways. Today, more than 60 percent of the money America spends on energy is used to purchase petroleum products to fuel cars, trucks, buses, trains, and planes, and about one-quarter of that fuel is imported.[20] In a clean energy economy, the bulk of this spending will be redirected to clean power plants, production of hydrogen and synthetic gas, biofuels production facilities, biofuels feedstocks, and energy efficiency investments. Though some capital stock necessary for the clean energy transformation will likely be imported, overall a greater percentage of energy-related spending would remain in the domestic economy.

20 EIA, Primary Energy, Electricity, and Total Energy Expenditure Estimates, 2014. Accessed September 12, 2016: http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_sum/html/sum_ex_tot.html&sid=US and http://www.eia.gov/tools/faqs/faq.cfm?id=32&t=6.

Total Energy System Cost Perspective

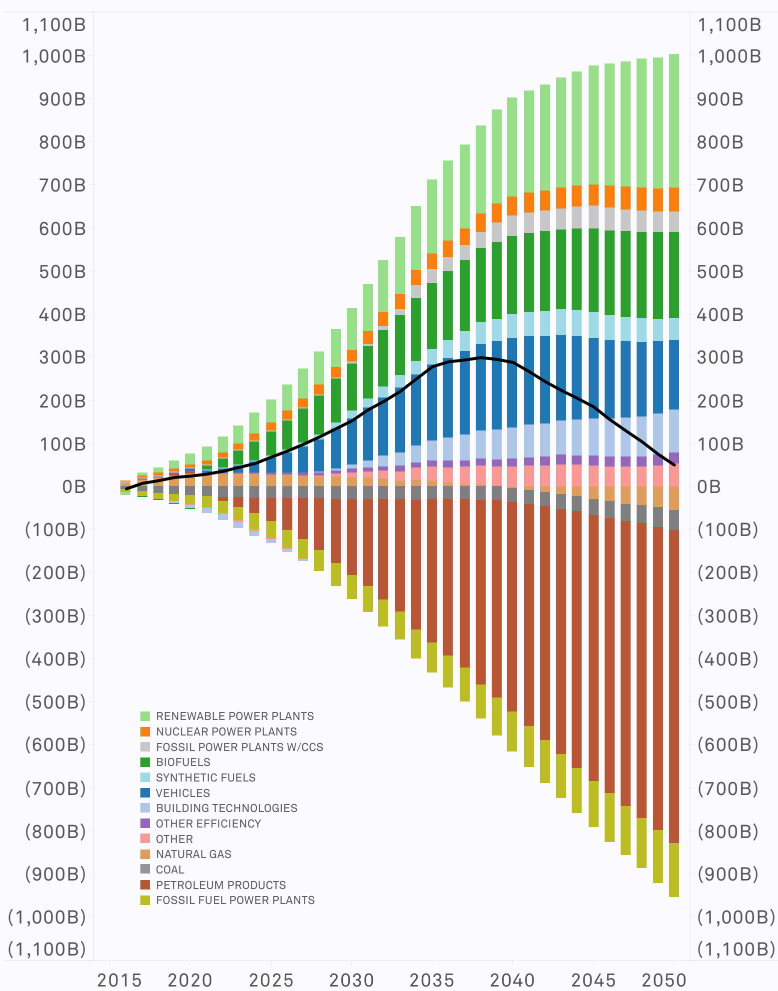
The second perspective on cost is the "total energy system cost." This viewpoint annualizes the investments over the lifetimes of the assets. Annualizing investments smooths out bumpy patterns of investment and can better reflect the actual cash flows (including interest) that businesses and consumers experience as they invest in or purchase power plants, new buildings, vehicles, and other facilities and goods.

From this perspective, investment costs grow more slowly than in the "as-spent" perspective. The annual net cost associated with the transition to a clean energy economy (the change in total energy system cost) peaks in the late 2030s at less than $300 billion per year (Figure 4).

Figure 4.

Total Energy System Cost: Net Changes from High-Carbon Reference Case

Levelized Net Costs: Mixed Resources Pathway



In Figure 4, the black line indicates the net change in total energy system cost, estimated as changes in annualized investment costs plus changes in fuel costs. It also includes small changes in other operating costs. Individual cost components are the same as described for Figure 3.

To put these numbers in context, total investments by government, businesses, and consumers currently exceed $3 trillion per year. The U.S. GDP is more than $18 trillion. The increases in investment needed for the Mixed Resources pathway would therefore increase annual economy-wide investment as a percentage of GDP by 0.4 to two percent over the period 2020-2050, with GDP growing to roughly $40 trillion in 2050. Total economy-wide investment would be 19-20 percent of GDP between 2020 and 2050, compared to 18-19 percent in the High-Carbon Reference Case. Our definition of investment includes business investments in plant and equipment, as well as incrementally higher costs for consumers in purchases of vehicles and appliances. Similarly, the conventional definition of economy-wide investment includes consumer purchases of new homes[21].

Similar increases in investment have occurred in other industries when opportunities are offered by market conditions and/or technology innovation. Over the past 15 years, for example, innovation in drilling and hydraulic fracturing technology led to increased annual investment in fossil fuel production, growing from less than $30 billion in 2000 to more than $170 billion in 2014. Fossil fuel investment increased to roughly 12 percent of total private investment, yet remained less than two percent of GDP as a whole[22].

The U.S. has also seen explosive growth in investments in computers and software. From 1980 to 1985, annual investments more than doubled, from $33 billion to $73 billion. Annual investment then topped $100 billion in 1990, $200 billion in 1997, $300 billion in 2000, and $400 billion in 2015. In total over the past 20 years, the U.S. has invested $6 trillion in computers and software. In similar fashion, U.S. investment in communications equipment and infrastructure stayed fairly level, at roughly $50 billion per year, until the early 1990s. With the creation of the Internet and cellular phones, growth increased, reaching $100 billion in 1998. Since 1994, the U.S. has invested more than $2 trillion in communications equipment and infrastructure. In yet another example, the Interstate Highway System was a major infrastructure investment totaling roughly half a trillion dollars (in today's dollars), spread out over roughly four decades. Historically, investment has fluctuated between 16 and 21 percent of GDP, as some sectors grow and some sectors decline in their capital needs.

21 These comparisons refer to economy-wide investment as understood in the conventional formula in which GDP = C + I + G + (Ex - Im), where "C" equals spending by consumers, "I" equals investment by businesses (and in residential structures), "G" equals government spending and "(Ex - Im)" equals net exports.

22 Bureau of Economic Analysis, "Table 2.7. Investment in Private Fixed Assets, Equipment, Structures, and Intellectual Property Products by Type," http://www.bea.gov (converted to 2014$ using GDP deflator). Business Insider, "Crashing Oil Prices Will Be Terrible Only For A Tiny Part Of The US Economy," December 14, 2014. http://www.businessinsider.com/energy-investment-a-small-share-of-gdp-2014-12.

Impacts on GDP and Employment

The third perspective on cost examines macroeconomic impacts on GDP and employment. While less relevant to individual companies and investors, these impacts are of particular interest to policymakers working across jurisdictions and economic sectors. As noted earlier, PATHWAYS can estimate investment needs, fuel savings, and changes in total energy system costs. PATHWAYS is not a macro-economic model that explicitly forecasts GDP and employment, but there is additional literature that can provide insights into likely GDP and employment impacts. In 2015, ICF International conducted a study that provides a good indication of possible impacts on GDP and employment from our Mixed Resources pathways (see text box).[23]

ICF found that at the national level, GDP would increase by 0.6 percent above reference case levels in both 2030 and 2050 (by $157 billion and $199 billion respectively). The REMI model projected that employment would increase by 0.5 percent in 2030 and 0.4 percent in 2050. However, regional impacts (discussed on page 42) would vary, and there would likely be winners and losers in the shift to a clean energy economy.

23 NextGen Climate America commissioned the study: ICF International, Economic Analysis of U.S Decarbonization Pathways: Summary of Findings, November 15, 2015. Available at: https://nextgenamerica.org/wp-content/uploads/2015/11/ICF-Study-Decarb-Econ-Analysis-Nov-12-2015-Final3.pdf. See also Williams, J.H., B. Haley, F. Kahrl, J. Moore, A.D. Jones, M.S. Torn, H. McJeon (2015). Pathways to Deep Decarbonization in the United States. The U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. Revision with technical supplement, Nov 16, 2015. Available at http://deepdecarbonization.org/countries/#united-states.

PATHWAYS and the REMI Macroeconomic Model

ICF International estimated GDP and employment by using PATHWAYS and the Policy Insight Plus model, a macroeconomic model of the economy developed by the Regional Economic Models, Inc. (REMI). ICF used PATHWAYS output from a 2015 study conducted for the Deep Decarbonization Pathways Project (DDPP) that also had reduction goals for U.S. CO_2 emissions of 80 percent by 2050 from 1990 levels.

ICF used outputs from PATHWAYS (changes in energy use and investments) as inputs to the REMI model to project how those changes would affect the U.S. relative to the REMI reference case. Outputs included increased investments in constructing new electricity generation facilities, transmission lines, hydrogen and synthetic gas production facilities, electric vehicle charging stations, and hydrogen fueling stations, along with decreases in fossil fuel energy use and investment.

Table 1.

Change in GDP and Employment Projections from 2015 ICF Study

	2020	2025	2030	2035	2040	2045	2050
Change in GDP (billion 2014$)	26.3	75.1	156.8	200.1	190.0	189.5	199.0
% Change in GDP	0.1%	0.3%	0.6%	0.8%	0.7%	0.6%	0.6%
Change in Employment (thousands)	288	610	1,008	1,147	955	938	963
% Change in Employment	0.2%	0.3%	0.5%	0.6%	0.5%	0.5%	0.4%

Source: ICF International, Economic Analysis of U.S. Decarbonization Pathways: Summary of Findings, November 15, 2015. Results for Mixed Resources pathway. Additional output details provided to Risky Business by ICF, and GDP adjusted to 2014$.

These numbers must be put in context: for instance, some economists also argue that economies tend to gravitate toward full employment, meaning that long-term creation or loss of jobs from investments in one set of activities or sectors is unlikely. Moreover, the U.S. economy, and indeed the global economy, continues a profound shift toward mechanization and automation in general, including in some of the key manufacturing and construction industries discussed here. This shift will certainly lead to job losses across some industries accompanied by job growth in other industries, regardless of the direction of our energy investments.

Keeping these larger economic trends in mind, the key takeaway from the ICF study is that a major substitution of electricity and capital for fossil fuels would have a small positive effect on GDP and employment. All economic modeling exercises of this nature have multiple layers of uncertainty. For instance, the modest but reasonable GDP growth rate in our High-Carbon Reference Case would lead to a $40 trillion economy in 2050. The REMI modeling indicates that shifting several hundred billion dollars annually away from fossil fuels and to clean energy would have a modest and positive effect on GDP.

Positive macro-economic impacts are plausible for several reasons. Fewer dollars would go overseas for oil imports, and more dollars would remain circulating in the domestic economy. Construction, operation, and maintenance of power plants, and retrofitting millions of American homes with insulation and more efficient heating and cooling systems, would likely require a larger labor force than producing coal and oil.

The labor needed to construct, operate, and maintain various facets of the clean energy economy would be domestic by nature. Trends in manufacturing jobs are more uncertain, as there are already global markets for power plant components, wind turbines, and solar PV cells. The market shares of U.S. manufacturers and the impacts on employment will be determined by many factors, including global supply chains and broader trends towards increased automation. Nevertheless, major technological transitions reward innovation and entrepreneurial risk-taking, which are key strengths of American business.

2.3 Sector Impacts

The transition to a clean energy economy would have markedly different impacts on different sectors. This section examines impacts on five key sectors: electric power, transportation, fossil fuel exploration and production, manufacturing, and buildings.

Electric Power Sector

Electrifying the economy would create a major opportunity for utilities and other electricity providers by addressing one of their biggest problems: a stagnant market. Electricity demand was flat in the U.S. from 2007 to 2014, even as the economy grew eight percent in real terms.[24] That lack of growth has reduced revenues and bottom lines, causing layoffs and power plant retirements. Putting millions of electric and fuel cell vehicles on the road, switching to electricity for most heating and cooling, and using electricity to produce hydrogen and synthetic methane would roughly double electricity demand between now and 2050 (Figure 5). A clean energy economy could lead to a long period of growth for the utility industry.

24 Hirsh, Richard F., and Jonathan G. Koomey. 2015. “Electricity Consumption and Economic Growth: A New Relationship with Significant Consequences?” The Electricity Journal. vol. 28, no. 9. November. pp. 72-84. http://www.sciencedirect.com/science/article/pii/S1040619015002067

Figure 5.

Total Power Generation and Generation Mix in 2050

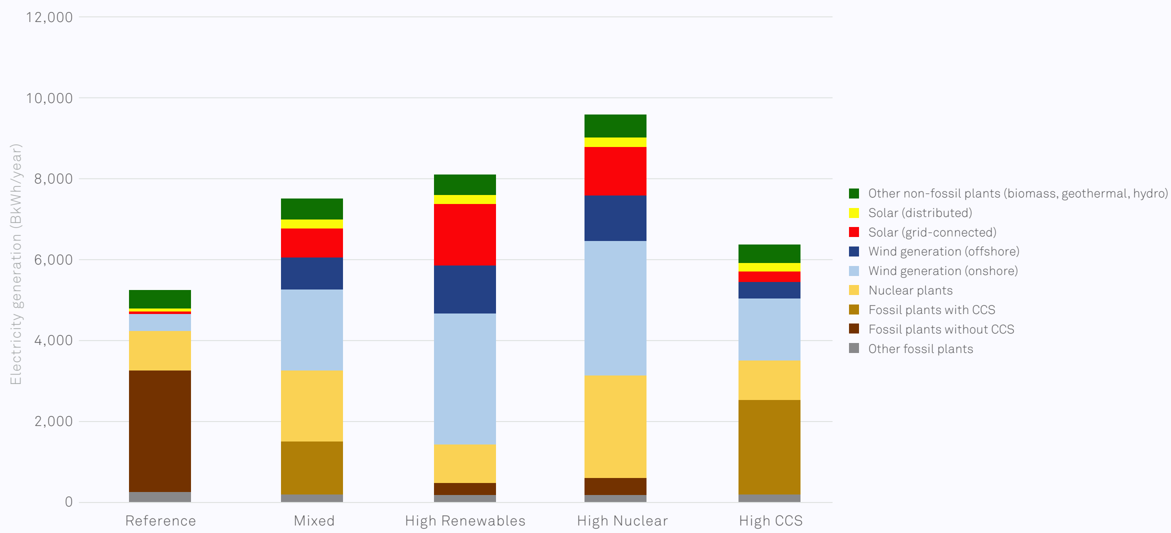


Figure 5 depicts total power generation and the mix of generating sources in 2050 in the High-Carbon Reference Case and the four clean energy economy pathways. In the Mixed Resources pathway, total electricity generation increases to nearly 8,000 billion kWh from a High-Carbon Reference Case level of roughly 5,000 billion kWh, more than doubling from today's 4,000 billion kWh. Demand would increase as electricity replaces fossil fuels in vehicles, buildings, and industry.[25] In the High-Carbon Reference Case and High Renewables and High Nuclear pathways, fossil fuel power plants do not use CCS. In the Mixed Resources and High CCS pathways, the vast majority of fossil fuel power plants use CCS. Also, generation varies significantly across pathways due to variation in production of hydrogen and synthetic gas (see Transportation section).

25 Nearly all clean energy studies project increased electricity demand. One exception: Rocky Mountain Institute's *Reinventing Fire* (2011) examined several pathways to a clean energy economy and in one ("Transform"), overall electricity demand actually declined because of major efficiency gains—despite rapid adoption of electric vehicles. Studies also vary substantially in projecting the portion of electricity that would come from large-scale generation, such as utility-scale solar, large wind farms, and/or nuclear plants vs. the portion that would come from smaller scale distributed generation, such as rooftop solar, combined heat and power (CHP), and fuel cells, thus requiring less investment in new transmission compared to a central power generation path.

These added investments would also boost markets all along the power sector supply chain, benefiting polysilicon manufacturers, transmission line builders, inverter suppliers, and wind turbine maintenance firms, among others. There would also be many opportunities for innovation, such as new devices to reroute power on transmission lines; large-scale batteries and other energy storage technologies; smart meters in most homes and businesses; and sophisticated micro-grid technologies.

Creating a low-carbon economy will likely accelerate the emergence of new utility business models, as companies increasingly sell energy management services instead of, or in addition to, selling electricity as a commodity. New and emerging markets include managing demand response services, conducting energy audits and retrofits, developing new smart grid technologies, and building and operating charging networks for electric vehicles. In addition, one major trend is rapid growth in distributed generation in the form of community solar plants and rooftop solar on homes and commercial buildings. Distributed generation is perceived as a threat to the traditional utility model of large centralized power plants, but some utilities are seeing opportunities to invest in and/or own such distributed capacity.[26] There is a rich literature on the challenges and opportunities for the power sector in a clean energy transition. We discuss these in Section 3 and in the Appendix.

26 Julia Pyper, "Utilities See Distributed Generation as a Challenge—and Owning It as the Solution," Greentech Media, February 18, 2016, http://www.greentechmedia.com/articles/read/utilities-see-distributed-generation-as-a-challenge-and-owning-it-as-the-so

Electrifying the economy is an ambitious goal. Timing is critical. Conventional power plants typically operate for 30-60 years or more once they come online (depending on the type of plant and the regulatory framework they operate in), which means that decisions made today will shape the U.S. electricity system at mid-century and beyond.

Transportation

The transportation sector would experience perhaps the largest shift in the clean energy transition. Multiple vehicle types and their manufacturers, including businesses operating across the transportation sector supply chain, have the opportunity to move away from traditional fossil fuels and toward electricity, biofuels, or other low-carbon fuels. There is also an opportunity to redesign cities to prioritize public transit and new technology solutions such as shared vehicles and rides, autonomous vehicles, and inter-city rail, all of which could reduce vehicle ownership and GHG emissions. All of these are important parts of the transportation transformation; however, we focus here on light-duty cars and trucks, because they are responsible for 16 percent of U.S. GHG emissions[27] and present major economic opportunities for innovation in manufacturing and deployment.

27 U.S. EPA, Fast Facts U.S. Transportation Sector: Greenhouse Gas Emissions, EPA-420-F-16-020, June 2016. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100ONBL.pdf

Figure 6.

Total Transportation Energy Use and Fuel Mixes in 2050

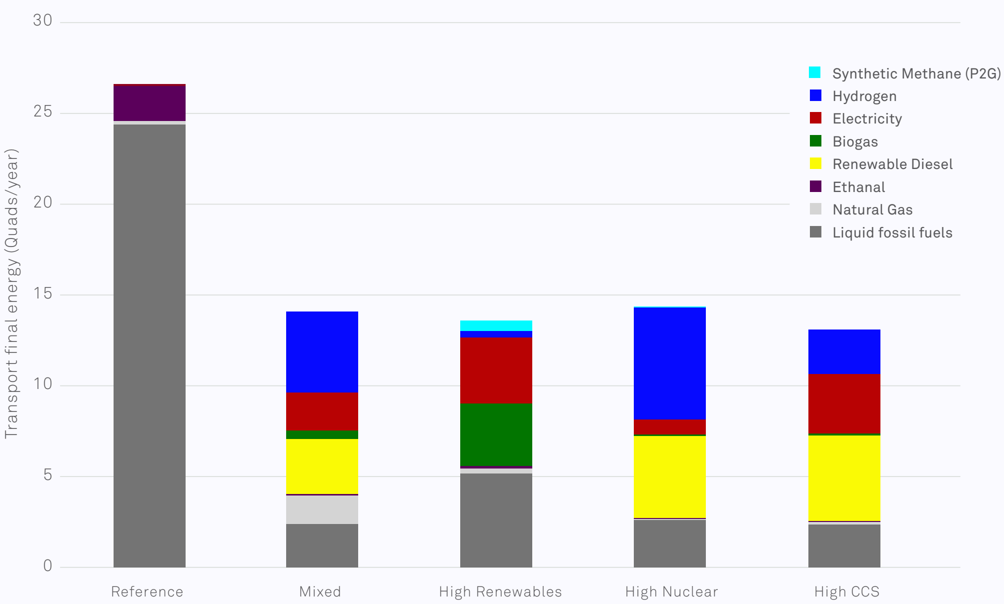


Figure 6 depicts how the four pathways would meet transportation demand in 2050. The four pathways exhibit a diverse mix of low- and zero-carbon fuels, while all retain liquid fossil fuel components for aviation and freight transport. All four pathways increase the efficiency of vehicles and other transportation modes so total energy use is less than 15 quads (quadrillion BTU) per year. In each pathway, electricity plays two roles in different proportions: 1) charging batteries in electric vehicles, and 2) producing hydrogen and synthetic methane gas.

A clean energy economy would create a mixture of opportunities and risks for vehicle manufacturers. There are more than 250 million cars and light trucks on the road in the U.S. and millions more buses and tractor-trailer trucks. The transition described in our modeling would require auto manufacturers to redesign their offerings and retool their assembly lines. Given vehicle lifetimes, the current light-duty vehicle fleet could turn over two to three times between now and 2050, while the heavy-duty fleet will likely turn over only once.

All of our pathways envision a major transformation for vehicles within the transportation sector, including a very different and diverse mix of vehicle technologies, fuels, and fueling infrastructure than currently exists. In particular, the transportation transformation would require that the transportation and power sectors become much more integrated. Our modeling explored four diverse pathways that reflect this integration. In the High Renewables pathway, for example, surplus power would be used to charge electric vehicles and produce synthetic methane for heavy-duty vehicles. In the High Nuclear pathway, excess generation would be used to produce hydrogen for fuel cell vehicles. Over time, our modeling assumes that electric vehicle battery costs would decrease and driving range would increase; it also assumes that more charging stations would be installed.

This transition could create significant opportunities for vehicle manufacturers that make early investments in electric and hybrid vehicles. In fact, electric drive vehicles—including battery electric, plug-in hybrid, and potentially fuel cell vehicles—are projected to become a $430 billion to $550 billion annual market by 2030 in our Mixed Resource pathway.

Our modeling shows the average low- or zero-emissions vehicle initially would be more expensive than today's average gasoline-powered vehicle. For example, PATHWAYS assumes that in 2020, an all-electric car would carry a price premium of roughly $10,000 over a conventional car. The price premium for an all-electric light truck would be roughly $15,000. Over time, our relatively conservative modeling assumes the price premium for electric vehicles would decline as vehicle manufacturers move up the learning curve and achieve economies of scale in production. By 2030, the price premiums would be roughly $4,000 and $8,000 for all-electric cars and trucks, respectively, and by 2050 the price premium would be essentially zero. As with the energy transition as a whole, initial investment in these vehicles will ultimately be offset by lower fuel costs.[28]

As with the overall energy transition, the transportation transformation will create opportunities and challenges for various businesses. For example, electric vehicles could pose a major challenge to the business model of auto dealers and auto repair shops, which rely heavily on maintenance and repairs for their revenues and profits. Electric cars do not require oil changes or many other routine maintenance measures. Brakes also last longer because of regenerative braking. At the same time, widespread switching from liquid fuels to electricity would mean that many of today's parts—e.g., camshafts and catalytic converters—would become niche products, while the U.S. would see the rise of companies focused on new components such as electric motors, batteries (and/or fuel cells), electricity management systems, and charging stations.

28 Our modeling used cost projections for various vehicle types drawn from: National Research Council, Transitions to Alternative Vehicles and Fuels, Washington DC: National Academies Press, 2013. Available at: https://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels.

More difficult to predict are the opportunities that may arise from changes in the future roles and capabilities of the automobile. Our modeling retained the assumption from a U.S. government forecast of modest growth in vehicle-miles-traveled per capita out to 2050.[29] However, there are signs of shifting preferences to live in cities rather than suburbs, which would likely increase demand for public transit. Increased investment in, and use of, public transit could serve a greater portion of all urban and suburban mobility needs in the decades ahead. There are other possible trends that could reshape how we supply personal mobility: Will cars increasingly become part of a shared service instead of a privately owned product? Will driverless, or autonomous, vehicles become the norm? The emergence and growth of Autonomous Vehicles (AVs) could alter the timing of changes in the composition and performance of the light-duty vehicle (LDV) fleet, which would, in turn, affect investment costs, electricity demand, and final energy demand.

Many companies are already working to create visions of a different transportation future, as companies test self-driving vehicles, invest in ride-hailing companies, and create new car-sharing services.30 A truly different transportation system of this sort has the potential to significantly reduce the cost of mobility and the total cost of transitioning to a clean energy economy.

Electricity is not the only alternative fuel in our models. We also look at the potential for biofuels to replace fossil fuels in specific cases. This is not a new idea: Biofuel in the form of ethanol is currently added to gasoline, providing roughly 10 percent of the total volume sold.[31] Our modeling shows that biofuels could supply key fuel needs in the clean energy transition, e.g., for tractor-trailers and airplanes, which are difficult to electrify using current technology. Our pathways include use of renewable diesel and biogas made from non-food sources, such as agricultural waste, municipal waste, and dedicated energy crops such as switchgrass (when grown on lands not in agricultural use). Use of such non-food sources reduces the controversy that surrounds ethanol made from corn, because they do not compete with land dedicated to food production. However, there are significant environmental and economic concerns about increasing the use of biofuels, and current market trends are not encouraging.[32]

29 U.S. Energy Information Administration, Annual Energy Outlook 2015, with Projections to 2040. Washington, DC: U.S. Department of Energy. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf. AEO 2015 projected a growth in VMT per capita of 14 percent between 2015 and 2050.

30 Kirsten Korosec, "GM, Lyft Deepen Partnership with Short-Term Car Rental Service," Fortune, March 15, 2016, http://fortune.com/2016/03/15/gm-lyft-rental-service/

31 EIA, "Almost all U.S. gasoline is blended with 10% ethanol," http://www.eia.gov/todayinenergy/detail.cfm?id=26092

32 See case study: Biofuels: Promise Dimmed by Market and Policy Trends, but Niche Markets Remain.

Fossil Fuels

Any major expansion in the electricity sector with an eye toward electrification of the economy will necessarily be paired with major contractions in the coal mining and oil and gas industries. Businesses that are directly dependent on coal mining and oil and gas production will see economic contraction and job losses.

Notably, however, fossil fuels could still play a limited role in a clean energy economy (Figure 7). For example, the High CCS pathway would preserve a role for fossil fuel generation, while sequestering 90 percent of the associated CO_2 emissions.

Aviation would still rely on jet fuel, while natural gas would retain a role in power generation, industry, and transportation, whichever path we choose.

Nevertheless, as the demand for fossil fuels declines, some businesses will shrink or exit the market. Strategic companies have the opportunity to adapt and grow—for instance, some oil and gas firms are already investing in CCS, biofuels, and other advanced technologies that are essential to a clean energy economy.

Figure 7.

Energy Use in 2015 and 2050

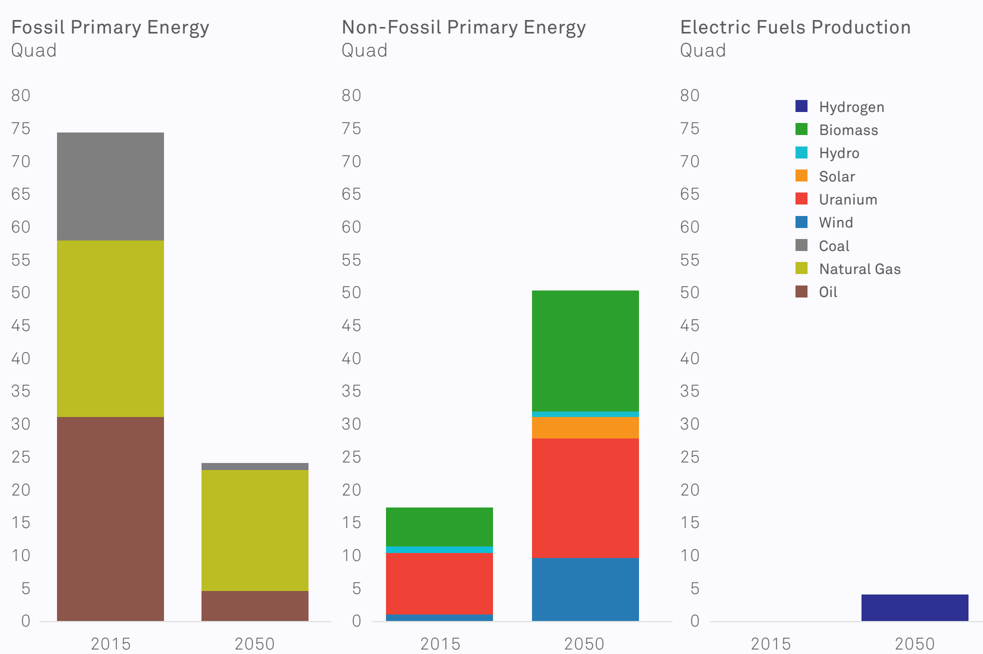


Figure 7 depicts the transition away from fossil fuels in the Mixed Resources pathway. Use of coal, oil, and natural gas decreases from the current combined level of about 75 quads to less than 25 quads. In this pathway, coal use in the energy system would be nearly eliminated by 2050. Oil consumption would decrease substantially, as electricity, hydrogen, synthetic gas, and biofuels replace gasoline and diesel use by vehicles. Significant use of natural gas would continue, mostly in industry and power generation.

Manufacturing

The additional capital investment inherent in a transition away from fossil fuels will create opportunities for American manufacturers. It would increase demand for many material components, equipment, and products, such as concrete, steel, wind turbine blades, transmission wire, solar panels (and mounts), heat pumps, LED lighting, and batteries. Many of these goods could be manufactured domestically, especially if domestic demand increases to provide large markets for these products, and if new carbon emission-reduction policies in the U.S. or elsewhere include protections to ensure we are not meeting the needs of the clean energy transition with goods made in countries that have not adopted similar policies.

In addition, there is increasing evidence that as manufacturing becomes more advanced, it is more important for firms to locate near the source of product innovation.[33] Today, the U.S. is the global leader in clean technology innovation, based on venture capital investment and patents held. [34] Moreover, the earthquakes in Japan in 2016 that disrupted the supply chains of Toyota and others are reminders that natural disasters, including increased climate impacts from sea level rise and increased heat, may require manufacturing to move closer to innovation and markets as part of an overall risk-reduction strategy.

33 Gary P. Pisano, "The U.S. Is Outsourcing Away Its Competitive Edge," Harvard Business Review, October 1, 2009. Available at https://hbr.org/2009/10/the-us-is-outsourcing-away-its.html.

34 PR Newswire, "U.S. Leads World in Clean Tech Innovation, Investment & Electric Vehicles, Earns Poor Marks for High Energy Consumption & Emissions," May 18, 2015. http://www.prnewswire.com/news-releases/us-leads-world-in-clean-tech-innovation-investment--electric-vehicles-earns-poor-marks-for-high-energy-consumption--emissions-300084423.html.

Manufacturers are also major energy users. But our modeling shows that energy-intensive industries would see small changes in overall energy demand and fuel mix under a clean energy transition, because most U.S. firms are already relatively energy efficient. In addition, some high-temperature processes cannot be fully electrified, though some fuel switching is still possible: In iron and steel production, for example, electric arc furnaces could further expand their share of production, reducing the share of basic oxygen furnaces (thus reducing use of coking coal and refinery gas intensive processes common for basic oxygen furnaces) and allowing for increased replacement of new steel production with steel recycling. Some heating and steam production could also be electrified in a number of energy-intensive industries.

Buildings

In a transition to a clean energy economy, total energy use in buildings would decline while electricity would play a larger role in heating and cooling.[35] Currently, buildings represent about 40 percent of total U.S. energy demand, split about equally between direct fossil fuel combustion and use of electricity. In the Mixed Resources pathway, total energy use in buildings would decrease by slightly less than half (from 21 to 14 quads) despite economic and population growth, while the fossil fuel portion would decrease to 3 quads, from 10.

35 Our High-Carbon Reference Case does not account for various factors that could affect energy demand, e.g. the possibility that electricity demand in the buildings sector could increase as air conditioning needs increase in a warming climate.

Electricity would replace natural gas for most building uses, such as space heating and water heating. Meanwhile, energy efficiency would increase substantially through improvements in lighting (e.g. LEDs), building insulation, and efficiency of heating, ventilation and cooling (HVAC) systems and appliances. By 2050, the electricity use as a share of total building energy use would increase to more than 75 percent.

Utilities are finding better ways to help customers improve energy efficiency in existing buildings.[36] For new buildings, the challenge is to incorporate maximum efficiency—and perhaps power generation—in the initial design and construction.

Efficiency improvements in buildings can catalyze job creation and stimulate innovation along the entire supply chain.[37] Building materials are often manufactured near where they are used (rather than being imported from overseas), which would tend to keep more money in local economies; building efficiency projects also create significant construction jobs for local workers.

36 See case study: Breaking Down Barriers to Energy Efficiency.

37 Bell, Casey J., Understanding the True Benefits of Both Energy Efficiency and Job Creation, March 2014. Available at: http://www.frbsf.org/community-development/files/cdir_vol10issue1-Understanding-the-True-Benefits-of-Energy-Efficiency-and-Job-Creation.pdf.

2.4 Regional Impacts

Just as most economic sectors will see specific challenges and opportunities in a transition to a clean energy economy, regions will also experience the transition differently. Energy is fundamentally a local issue, and will become even more so in a transition away from fossil fuels that are shipped from concentrated geological deposits in particular states, to a system of more locally-generated renewable energy sources.

Figure 8.

Nine U.S. Census Divisions

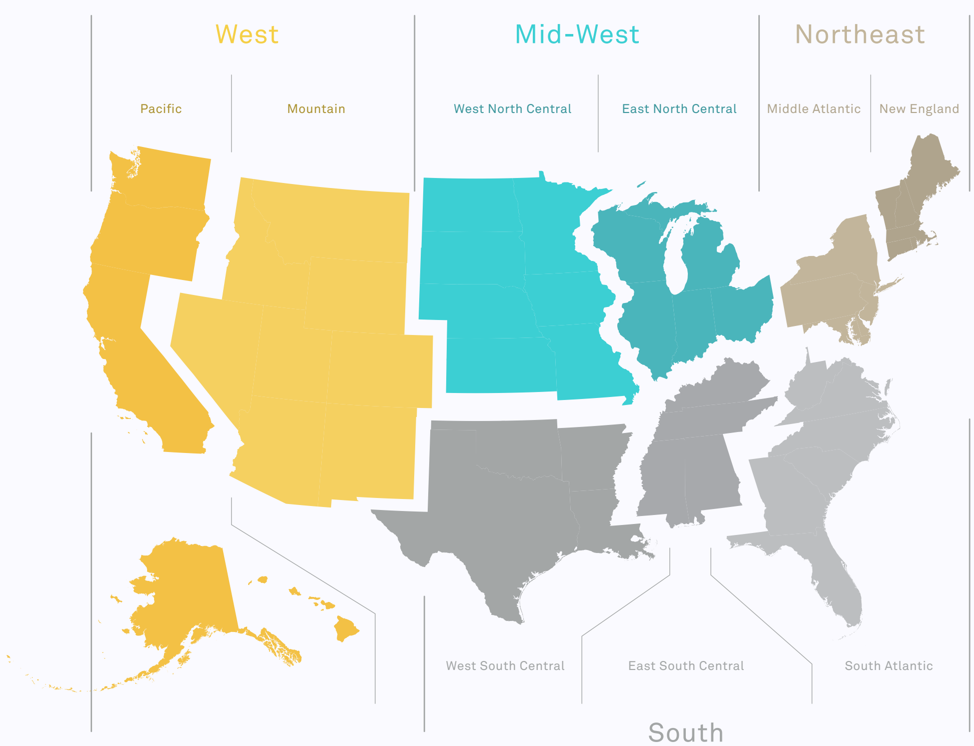


Figure 9.

Regional Generation Investment

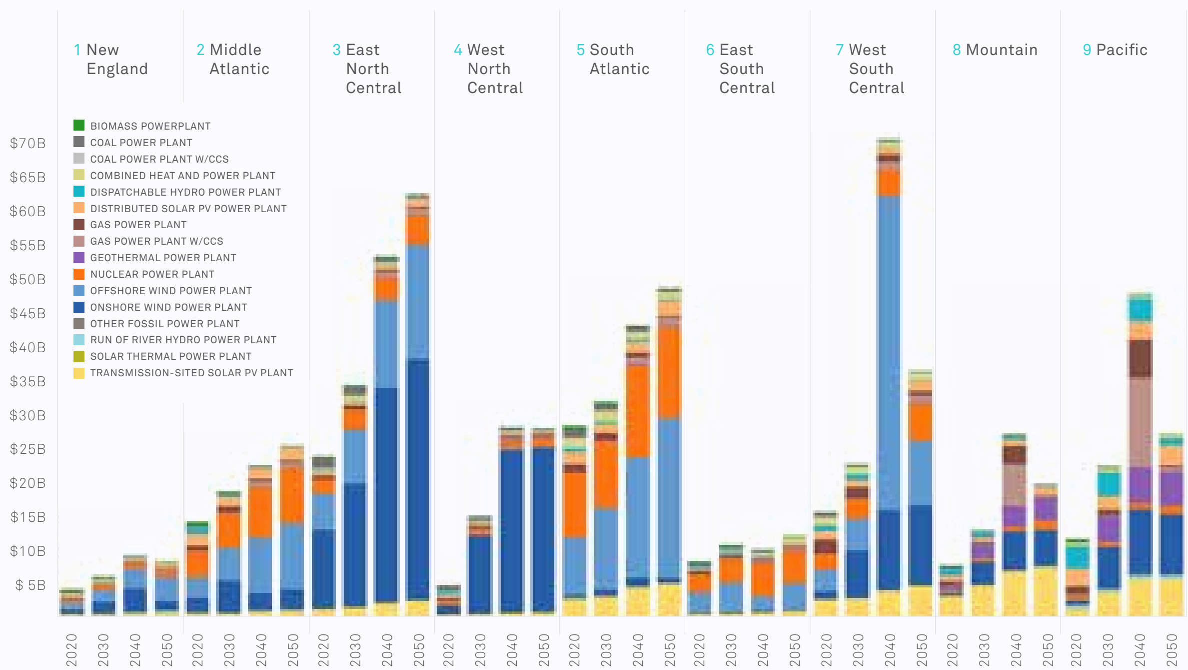


Figure 9 presents power generation investments by type and by region from 2020-2050 for the Mixed Resources pathway.

PATHWAYS provides output for both the U.S. as a whole and for the nine U.S. census divisions, offering insights into how specific states may experience the clean energy transition. The above example (Figure 9) relates specifically to the Mixed Resources pathway. It highlights different opportunities across the census regions. For example, new nuclear plant additions would be concentrated in the mid-Atlantic and southern regions, where the regulatory framework for vertically integrated utilities is more conducive to such plants. Wind power would grow fastest in the windy central region, and investments in solar power would be greatest in the sunny western and southern regions. Revenue from biomass feedstocks (not shown in the figure) would be greatest in the Southeast and the Midwest.

Our modeling shows regional investment rather than the macro-economic impacts on jobs or regional economies of a clean energy transition. To better understand the latter we used the 2015 ICF study cited earlier. This study shows that seven of the nine regions would experience positive effects on GDP and employment in a very similar Mixed Resource pathway. The two exceptions are the West South Central and Mountain regions, which represent a large share of current U.S. fossil fuel production. ICF estimated that employment would decrease by 0.1-0.6 percent relative to the Reference Case in 2030 and 2050 in the West South Central and Mountain regions where those industries are concentrated.

Table 2.

Regional Change in GDP Projections from 2015 ICF Study: Mixed Resources Pathway (Billion 2014$)

	2020	2025	2030	2035	2040	2045	2050
New England	2.1	5.4	13.2	16.0	15.2	16.1	22.1
Middle Atlantic	2.8	9.2	24.1	30.9	23.8	29.2	47.2
South Atlantic	12.6	31.1	43.3	55.0	50.7	46.2	72.8
East North Central	8.3	22.4	37.5	41.2	31.3	29.7	28.8
East South Central	3.2	8.3	14.4	19.7	17.6	17.4	16.2
West North Central	1.4	5.8	14.5	17.4	16.2	16.8	13.7
West South Central	-4.1	-5.6	-4.2	0.5	5.0	-2.2	-31.4
Mountain	-2.8	-6.6	-2.9	-2.1	-1.7	2.5	-13.3
Pacific	2.8	5.1	16.8	21.6	32.0	33.8	42.9
Total U.S.	**26.3**	**75.1**	**156.8**	**200.1**	**190.0**	**189.5**	**199.0**

Source: ICF International, Economic Analysis of U.S. Decarbonization Pathways: Summary of Findings, November 15, 2015. Results for Mixed Resources pathway. Additional output details provided to Risky Business by ICF, and GDP adjusted to 2014$.

Table 3.

Regional Change in Employment Projections from 2015 ICF Study: Mixed Resources Pathway (thousands)

	2020	2025	2030	2035	2040	2045	2050
New England	16	35	79	87	76	80	113
Middle Atlantic	23	66	149	169	121	163	257
South Atlantic	132	270	303	330	248	180	339
East North Central	74	159	215	207	122	116	101
East South Central	32	67	93	109	73	63	39
West North Central	13	38	84	88	71	68	36
West South Central	-17	-36	-35	-8	0	-33	-182
Mountain	-21	-43	-10	0	19	50	-52
Pacific	34	53	131	166	225	251	312
Total U.S.	**288**	**610**	**1,008**	**1,147**	**955**	**938**	**963**

Source: ICF International, Economic Analysis of U.S. Decarbonization Pathways: Summary of Findings, November 15, 2015. Results for Mixed Resources pathway. Additional output details provided to Risky Business by ICF.

Climate risks and impacts will also vary according to geographic locations, and will have different impacts on regional energy needs. For example, the Southeast and Texas in particular will experience an increase in electricity demand due to an increase in air conditioning use in periods of extreme heat by the middle of the century, a factor that is not accounted for in our modeling.

2.5 Co-Benefits of a Clean Energy Economy

Our analysis of the direct economic consequences of a transition to a low-carbon, clean energy economy, including direct job benefits, only represents part of the overall impact. The transition also brings important co-benefits. Holding global temperatures down by cutting emissions worldwide would significantly reduce the risks—and the costs to business—from extreme weather, rising seas, and the other physical impacts of climate change. Our 2014 research found that these impacts will have significant economic consequences if the U.S. continues on its current high-emissions path. For example, the incidence of extreme weather is expected to rise. By mid-century, the number of days with temperatures greater than 95°F is expected to triple compared to a 1981-2010 baseline. While extreme heat both would threaten public health and reduce the productivity of outdoor workers, it would also lead to rising demand for electricity for air conditioning.

Our 2014 report looked at the risks posed by climate change to only a few key sectors, not to the economy as a whole. Other economists have argued about the magnitude of the costs of not acting to curb climate change, with estimates ranging as low as 0.25 percent of GDP (about $45 billion for the U.S.) to as high as 20 percent of GDP ($3.6 trillion) if average temperatures rise by 4.5 to 5.4 degrees Fahrenheit (the differences are driven mainly by different assumptions about discount rates)[38].

38 John Carey, "Calculating the True Cost of Global Climate Change," Environment 360, January 6, 2011, http://e360.yale.edu/feature/calculating_the_true_cost_of_global_climate_change/2357/.

Another analytical approach has been to try and calculate the actual cost of continuing to produce GHG emissions at current rates, which would include health impacts, shortened lives due to pollution, and a host of other economic and social factors. These numbers vary due to assumptions about the speed and scale of technology advancement, the adaptation rates of various industries to change, the discount rate used in the analysis, and other factors. But what is clear is that overall undiscounted costs in the future, and thus the benefits of emissions reductions, are very large.

Building a clean energy economy is likely to improve the health of American citizens. A recent analysis by researchers at Duke University and the NASA Goddard Institute for Space Studies estimates that cutting GHG emissions (and thus pollution from fossil-fuel burning) could prevent 295,000 premature deaths in the U.S. by 2030. Near-term annual health benefits are estimated to be $250 billion per year[39].

39 Drew T. Shindell, Yunha Lee & Greg Faluvegi, "Climate and health impacts of US emissions reductions consistent with 2 °C," Nature.com, February 22, 2016. http://www.nature.com/nclimate/journal/v6/n5/full/nclimate2935.html. An earlier study that documented the full social costs of pollution in the US economy is Muller, Nicholas Z., Robert Mendelsohn, and William Nordhaus. 2011. "Environmental Accounting for Pollution in the United States Economy." American Economic Review vol. 101, no. 5. August. pp. 1649–1675. Available at:https://www.aeaweb.org/articles.php?doi=10.1257/aer.101.5.1649.

Replacing coal, oil, and natural gas with clean electricity would also have non-climate related environmental benefits. Those benefits include fewer oil spills; fewer incidences of mercury contamination from coal combustion or contaminated streams from coal mining; and reduced chances of groundwater pollution or induced earthquakes from hydraulic fracturing and waste injection wells associated with gas drilling.

On the other hand, low-carbon energy can also have environmental costs. These include radioactive waste associated with nuclear power and the mining of rare-earth minerals for solar panels, wind turbines, and electric car batteries. However, these potential negative impacts are likely less severe than the well-documented, and already observed, effects of conventional air pollutants. They can also be addressed over time with technology improvements.

Creating a clean energy economy that reduces the risks of climate change is economically and technologically feasible.

3. Implementation Challenges

Creating a clean energy economy that reduces the risks of climate change is economically and technologically feasible. But the clean energy transition cannot be accomplished simply by adding solar panels, wind farms, and other low-carbon resources on the margins of the existing electricity system. Instead, the most promising pathways require doubling the total amount of electricity generated while also shifting primarily to low- and zero-carbon sources. This transition also means switching to low- and zero-emission cars and trucks while making buildings and industry more efficient.

These challenges are difficult and daunting, but they can be overcome with the right policy framework combined with a strong commitment from U.S. businesses to effect this transition in their own companies and industries. The bottom line is that this transition is not optional: It is something that must be done to combat the major economic threat of climate change to our businesses and overall American competitiveness.

3.1 Scaling Up Production and Construction

All four potential pathways to a clean energy economy require building many new clean power plants, across every region of the U.S. (Figure 10)[40]. This will provide opportunities for jobs and local economic stimulus, and the level of overall investment appears feasible. However, the power sector would likely face real challenges in the siting, permitting, and construction of this new infrastructure.

40 Our 2014 modeling also pointed to the need for new power plants to address the higher net energy demand caused by higher heat levels across the U.S.

Figure 10.

Average Annual Rate of Construction of Generation Capacity (2020-2050)

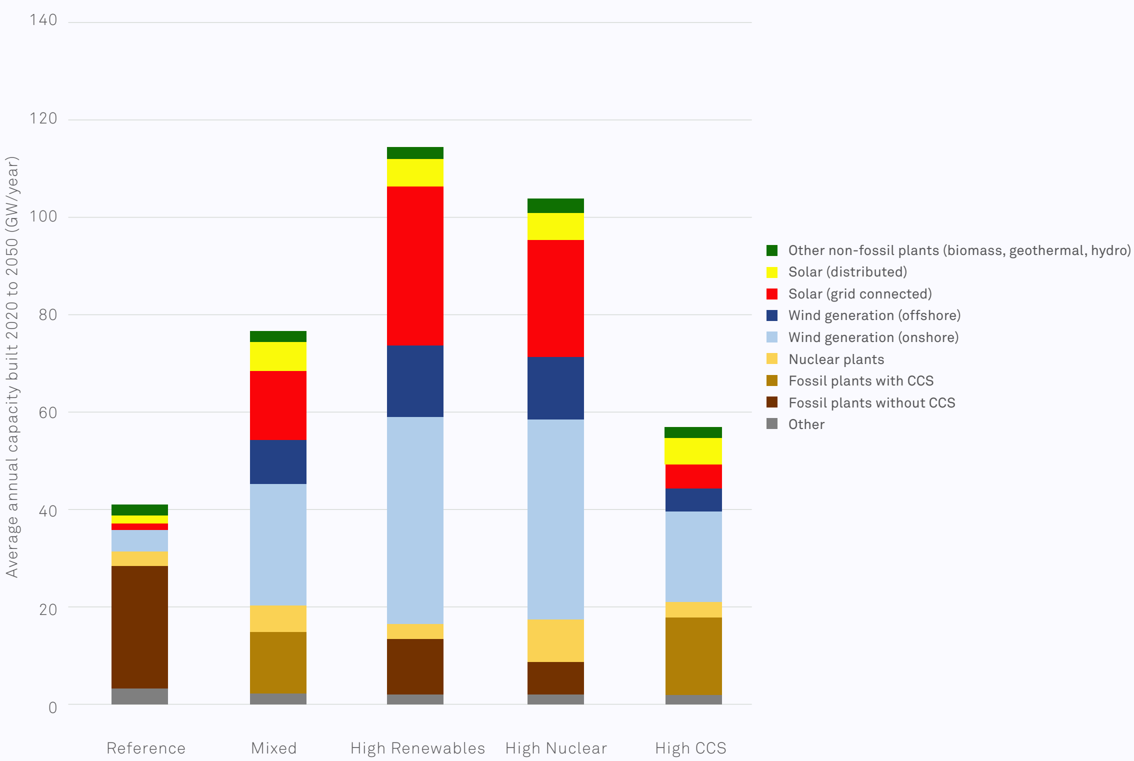


Figure 10 shows average annual capacity additions of different types of generation for 2020-2050 for the four clean energy pathways and the High-Carbon Reference Case.

Our modeling shows that building a clean energy economy would require constructing power plants at a rate nearly two times the rate in the High-Carbon Reference Case (for the Mixed Resources pathway) and nearly three times that rate in the case of the High Renewables pathway. For some renewable technologies, this would require plant construction at a rate *two to five times* higher than average historical rates. (For details by technology, see Appendix.) The Mixed Resources pathway would require the nuclear industry to build new plants at a rate roughly 17 percent higher than the historical rate from 1970-1990. The High Nuclear pathway would require a build rate roughly 80 percent higher than the 1970-1990 rate. Achieving these rates would require a much more accelerated siting, permitting, and construction process than that in use today.

3.2 Ensuring a Reliable Grid

Renewable Integration

One of the major technical issues with dramatically scaling up renewable energy is the variable nature of these energy resources. The power generated by wind turbines drops when the wind dies. Solar PV output dips during cloudy days and is zero at night. This variability is one of the defining features of renewable power, and requires careful minute-by-minute balancing between load centers and electricity generating units. Yet fossil-fired electricity generating units may have somewhat variable output as well—for example, through forced outages, scheduled maintenance, or transmission constraints on generation—making the integration of variable electricity generation resources not a fundamentally new problem for the utility industry. However, accommodating high levels of renewable power in a clean energy economy would create new operational challenges.[41] A grid powered with a high percentage of variable renewable energy would have to be highly flexible, and be able to handle variable power outputs on shorter time scales and with less predictability than grids powered largely by fossil fuel and nuclear plants.

Extensive studies of these challenges, and observation of specific states and countries that have moved forward with grid integration plans, make clear that high levels of renewable power can be cost-effectively integrated into the grid without threatening reliability.[42]

41 Timothy P. Duane and Kiran H. Griffith, “Legal, Technical, and Economic Challenges in Integrating Renewable Power Generation into the Electricity Grid,” 4 San Diego Journal of Climate & Energy Law 1-68, Spring 2013.

42 Integration challenges are discussed in more detail in the Appendix.

In our PATHWAYS modeling, much of the load balancing is achieved through production of hydrogen and synthetic natural gas[43]. These facilities would be oversized in production capacity in order to allow them to operate flexibly and absorb excess power generation. However, we expect that to integrate higher levels of renewable generation, grid operators would likely use an array of tools for maintaining the match between supply and demand. In fact, they are already adept at predicting and managing big, rapid changes in load. Tools include dispatchable resources, diverse types of resources, geographic diversity in generation, and the use of energy storage and demand response resources. All of these tools would likely grow in importance as renewable power expands.

A diverse portfolio of wind and solar plants allows for more consistent power supply, as some of the plants can still operate when winds slow or clouds cut solar output in specific locations. Denmark has successfully integrated 39 percent of its total electricity generation from wind power, but its interconnection with Germany has proved critical for balancing periods of surplus or insufficient Danish wind generation[44]. Renewable sources are

43 Williams, J.H., B. Haley, F. Kahrl, J. Moore, A.D. Jones, M.S. Torn, H. McJeon (2014). Pathways to Deep Decarbonization in the United States. The U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. Revision with technical supplement, Nov 16, 2015, p. 37 Available at http://deepdecarbonization.org/countries/#united-states

44 The Danish Experience with Integrating Variable Renewable Energy. Study on behalf of Agora Energiewende. September 2015.

best integrated when the grid covers a larger and more diverse geographic footprint [45]. Building more transmission lines can therefore be important to integrating renewable power on the grid [46].

Integrating renewable power on the grid also requires large-scale energy storage [47]. Parts of California already generate more solar power than can be used during the afternoon on some days [48]. As a result, California has mandated that utilities add 1.325 GW of storage to the grid by 2020 to capture the excess solar power and to increase flexibility [49]. Meanwhile, advances in batteries and other storage technologies have caused prices to decline significantly, making them cost-effective for some applications [50]. Large battery installations in places like Moraine, Ohio, and Elkins, West Virginia, are already being used to manage power quality and short-term fluctuations on regional grids [51].

More flexibility can also come from applying information technology to grid operation, creating a "smart grid" which can give customers more ability to match energy use to times when the grid is not already overloaded [52]. Such technologies will also facilitate the adoption of electric vehicles, allowing the grid to charge these vehicles at times when renewable power is available. Electric vehicles can ultimately serve as a form of energy storage for renewable power, as can space and water heating systems. Ultimately, it should be possible to draw power from connected electric vehicles when needed [53], though this technology is still in its infancy.

https://www.agora-energiewende.de/filead-min/Projekte/2015/integration-variabler-er-neuerbarer-energien-daenemark/Agora_082_Deutsch-Daen_Dialog_final_WEB.pdf

45 Timothy P. Duane and Kiran H. Griffith, "Legal, Technical, and Economic Challenges in Integrating Renewable Power Generation into the Electricity Grid," 2013, San Diego Journal of Climate & Energy Law, 4, 1-68., Spring 2013. National Renewable Energy Laboratory, Western Wind and Solar Integration Study, 2010, available at http://www.nrel.gov/grid/wwsis.html., Western Governors' Association, Meeting Renewable Energy Targets in the West at Least Cost: The Integration Challenge, 2012. Available at http://www.uwig.org/variable2012.pdf.

46 Duane and Griffith 2013

47 See case study: Energy Storage: Indispensible to a Cleaner, More Resilient Electricity Grid.

48 See Appendix A-3 for discussion of the "Duck Back" curve for net load

49 The 1.325 GW is only a pilot project and would cover only about 10% of the total ramping capability projected by CAISO to be needed by 2020. Increased flexibility in other resources may be less expensive than added storage, however, so CAISO is developing a variety of tools (including market mechanisms and expansion) to manage the shift in the net load profile.

50 See Appendix Section X for cost data

51 "Deployments," AES Energy Storage webpage, http://aesenergystorage.com/deployments/

52 See case study: Information Technology Meets the Electricity Grid.

53 Nelder, Chris, James Newcomb, and Garrett Fitzgerald. 2016. Electric Vehicles as Distributed Energy Resources. Old Snowmass, CO: Rocky Mountain Institute. http://www.rmi.org/pdf_evs_as_DERs

Transmission and Distribution

In each of our four pathways, a clean energy economy requires significant new investment in transmission and distribution (T&D).[54] However, different pathways require different T&D approaches. For example, a future that relies more on large utility-scale renewable generation requires more long-distance high-voltage transmission lines than does a distributed generation system.

The expansion of the transmission system faces similar obstacles as does building new power plants. Proposed projects typically face local opposition, permitting issues, and regulatory questions around rate recovery and siting authority. Wind and solar projects have been slowed because the transmission lines needed to get their power to markets have yet to be built.

Meanwhile, utilities have been reluctant to invest in the local distribution systems that enable more roof-top solar panels and other distributed generation to send power back to the grid, since under the current utility business model, these distributed systems cut utility electricity sales and revenues.

54 The investment costs of the needed T&D investments are already included in the PATHWAYS model in two ways: (1) general increases in T&D investment for the entire system are proportionate to increases in peak load, while (2) additional technology-specific transmission costs are incorporated into the levelized cost of energy (LCOE) for each renewable technology in the analysis. The projected costs of electricity from solar PV, for example, include the costs of building transmission lines to bring the solar power to market.

The utility model should evolve to reward such investment based on the added value provided by these investments, and states such as New York are taking on this issue.[55] This would require a supportive policy environment to allow these companies to stay profitable given new capital outlays necessary for the transition. (Possible approaches to create such incentives for utilities are explored in the Appendix.)

3.3 Transforming Transportation

A clean energy economy would require major transformation in the transportation sector. Our four clean energy pathways include a major shift from oil to combinations of electricity, hydrogen, synthetic gas, and biofuels to power the nation's cars and trucks, along with continuing improvements in design and materials that reduce vehicle weight.[56] This transformation would cut the overall energy used in transportation in half by 2050 compared to the High-Carbon Reference Case.

55 See for example: New York PSC, "DPS – Reforming the Vision," http://www3.dps.ny.gov/W/PSCWeb.nsf/All/CC4F2EFA3A23551585257DEA007DCFE2?OpenDocument.

56 See case study: Lighter Vehicles Bring Fuel Savings – and Higher Sales

One of the challenges to achieving this transformation is overcoming auto manufacturers' basic chicken-and-egg problem: manufacturers will not produce new vehicle types without sufficient expectations of demand, and customers can't buy cars that manufacturers don't offer. Retooling takes time and money, and most of these companies operate on debt without the cash on hand for major capital investments in their facilities. New materials are also expensive when first deployed, thus impeding the widespread adoption that would drive down costs. Electric charging stations and hydrogen fueling depots are also far less numerous than conventional gas stations, but their numbers won't increase substantially until many more EVs or hydrogen-powered cars are sold. And finally, there is the economic reality that many consumers hold onto their vehicles longer than the recommended lifespans of these capital investments, meaning that turnover rates can be slower than anticipated in our modeling.

What may speed the transition are the advantages that electric cars offer to consumers. In addition to lower fuel costs, even at 2016's low oil and gasoline prices, electric cars offer better performance, greater reliability, and lower maintenance costs, since they don't require oil, coolant, transmission fluid, or many other complex systems found in conventional internal combustion engine vehicles.[57] In some cases, maintenance is as simple as downloading a software patch.

57 U.S. Department of Energy, "EV Everywhere: Electric Car Safety, Maintenance, and Battery Life," http://energy.gov/eere/eveverywhere/ev-everywhere-electric-car-safety-maintenance-and-battery-life.

Those advantages, along with supportive policies such as state and federal tax credits and rising fuel economy standards, explain why manufacturers are making significant investments in electric vehicles. Bloomberg New Energy Finance forecast that global sales of electric vehicles will hit 41 million by 2040, which would represent 35 percent of new light duty vehicle sales.[58] Manufacturers along with some utilities are working to increase deployment of electric charging stations; however, these require additional upfront capital expenditures.

Our modeling of clean energy pathways assumes the same continued modest growth in vehicle-miles-traveled per capita as in the High-Carbon Reference Case. However, demographic trends and supportive policies could reduce that growth and make emission targets easier to achieve. Meanwhile, better information and communication technology can improve traffic flow. For example, drivers are already alerted to traffic jams—and offered alternative routes—by GPS mapping and cell phone apps.

58 "Electric Vehicles to be 35% of Global New Car Sales by 2040," Bloomberg New Energy Finance, February 25, 2016, http://about.bnef.com/press-releases/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/

3.4 Timing and Coordinating Investments

Creating a clean energy economy does not require an energy miracle. It can be accomplished by deploying existing (and near-commercial) technologies, while incorporating improvements and innovations as they become available. But the timing of new investments is critical in every clean energy economy pathway.

As we noted earlier, investments in clean energy technologies make the most sense when businesses replace obsolete technologies at the end of their lives, rather than prematurely retiring assets while they remain cost-effective to operate. Investments over the coming decade are critical, as they will lock the nation into an energy system made up of long-lived infrastructure that will continue to operate for decades to come. Ideally, businesses should make the right choices each time an asset is fully amortized and can be economically replaced.

One challenge to smart capital stock replacement, though, is that businesses often evaluate energy efficiency and renewable energy projects using high hurdle rates (20 percent or more) rather than the lower expected returns that may be acceptable in other areas of corporate investment. Such practices limit many cost-effective investments in energy efficiency and clean energy technologies. A project may offer a reasonable payback within five to 10 years, but that may not be competitive against a high hurdle rate. So there is a risk that many of the investments that our analysis shows are cost-effective will not be made despite their clear benefits from a climate risk-reduction perspective. Ensuring access to low-cost capital for such projects and overcoming both internal and external impediments to those investments is therefore critical in the coming decade.

The transition to a clean energy economy requires not just the right timing of investments, but also coordinating these investments across several sectors that have historically not been closely coupled: energy, transport, buildings, and manufacturing. Powering millions of electric cars, for example, requires building new power plants at a rate that matches the growth in vehicle numbers (in addition to the expansion of clean energy generating sources to decarbonize electricity generation). The electricity and transportation systems also need to be better integrated to manage the complexity of more low-carbon sources (which ultimately can include plugged-in vehicles that send power to the grid when needed).

If investments in each area are not complementary, there is a real risk of both companies and the country going down a “dead end” pathway that reduces emissions for 10-20 years but constrains the options for reductions over 30-40 years. That’s why both the public sector and the private sector must play a role—through a realignment of both investment strategies and government policies—ultimately ensuring that businesses have the right information and incentives to invest in the combination of technologies that make the most economic and technological sense.

3.5 Maintaining Momentum Through the Transition

One paradox of the transition to a clean energy economy is that, if this transition is successful, it may lead to lower fossil fuel prices and resulting higher demand for fossil fuels—thus slowing momentum. In the absence of supportive policies for clean energy investment and deployment, lower fossil fuel prices will make it harder for solar, wind, and other clean energy to compete. For example, low gasoline prices in 2015 and 2016 (caused in part by lower demand due to gains in vehicle fuel efficiency) have contributed to increases in sales of less fuel efficient vehicles, causing gasoline demand to grow again.

Recognizing this dynamic, we explored a scenario in which a global clean energy transition leads to a significant drop in global fossil fuel prices.[59] PATHWAYS projects that this would save the U.S. economy at least $100 billion per year in lower fossil fuel costs beginning in the early 2020s (in the Mixed Resources pathway). However, it would also diminish the fuel savings from each additional deployment of clean energy technologies. This highlights the need for policies that support the long-term transition to a clean energy economy. A carbon price could be particularly effective in this context. The price could be set to make up for some or all of the drop in fossil fuel prices (or be set even higher). That would ensure that after-tax prices remain high even as market forces drive the pre-tax prices down. PATHWAYS projects some decreases in the costs of clean energy technologies in the coming decades, but probably understates the likely cost reductions. However, such decreases alone may not be enough to counter the effect of falling fossil fuel prices.

59 See Appendix for details.

Similarly, rapid growth in renewable generation would reduce the marginal value of adding more new installations. In typical wholesale power markets, when more solar or wind power is added to the grid (with a marginal cost to the generator of zero or near-zero), the market-clearing, short-term price of power decreases. This downward pressure on the wholesale power price (as the supply of renewable generation increases) can reduce the rate of return on existing plants and reduce investors' expected returns on new plants. This effect could slow the momentum for new power plant construction in those states that have restructured their utilities and rely on wholesale markets for generation, and points to the need for improved market design by regulators.[60]

These perils of success increase the importance of a strong and consistent policy framework to support and maintain momentum for the clean energy transition.

60 This particular problem does not arise in states with traditional vertically integrated utilities.

Investments over the coming decade are critical, as they will lock the nation into an energy system made up of long-lived infrastructure...

“Coal is dying because cheaper and cleaner forms of energy are replacing it. This transition is both saving lives and saving us money, and the faster we can accelerate it, the better off our country will be.”

– Michael R. Bloomberg

4. The Crucial Role of Policy

In the previous chapters, we laid out the case for a clean energy transition to reduce climate risk. This transition is both economically necessary and technically feasible. Now we turn to the key operational question: how do we get it done?

We believe businesses must act to reduce their climate risk and help to slow the march of climate change. Indeed, the clean energy transition can happen *only* if the private sector invests in clean energy and efficiency, deploys low-carbon technologies, and continues to innovate.

But the private sector, in turn, will take these actions at the necessary speed and scale *only* if they can do so on the back of a clear and consistent policy and regulatory framework that provides incentives for innovation and deployment of clean energy systems, and helps business adapt to those climate impacts that are inevitable due to past emissions.

A strong policy foundation sets the stage for strategic climate-related decisions by executives and boards. And in fact it is a core responsibility of government to take the long view, and to provide support for the infrastructure, innovation, and investments that will underpin the clean energy economy across every region and sector of this country.

4.1 Policy Principles

With this understanding, we recommend establishing legislative or regulatory policies that promote the clean energy transition, avoid actively subsidizing economic activities that increase climate risk, and avoid negative economic and social impacts in the future.

These policies must:

- Internalize the true costs of carbon pollution through legislation or regulation, e.g. through a mechanism that puts a price on carbon emissions.
- Avoid actively subsidizing activities that increase climate risk, e.g., tax incentives for fossil fuel extraction or subsidized flood insurance in high-risk areas.
- Coordinate and streamline government investment in research and development, infrastructure, and education and workforce training to provide consistent and comprehensive support to the clean energy transition.
- Lower regulatory and financing barriers to clean energy projects.
- Require corporate disclosure of material climate-related risks.
- Include measures to help those Americans negatively affected by the clean energy transition as well as those who are most vulnerable and least resilient to the physical and economic climate impacts that are no longer preventable.

Across all policies, the U.S. must consider its position in the international context, in a manner that maintains and increases the global competitiveness of U.S. firms. The Paris Agreement, signed by 197 countries that committed to addressing climate change through domestic policy, provides a basis for international action. The Paris Agreement would not have happened, and will not be implemented effectively, without U.S. leadership. The U.S. may have a small percent of the world's population, but it accounts for one-fifth of the global economy, produces more than one-sixth of global GHG emissions, and has outsized influence on global policy. It is therefore this country's job to lead by example, both in the public and private sectors.

We have no doubt that the U.S. can reduce its overall economic risks from climate change by investing in a clean energy economy, and encouraging other countries to do the same. Business will play a critical role in this transition, as it has in the past. But, as in the past, government must provide the underlying policy framework to support innovation and to encourage the transition. It must also reduce the negative impacts on those workers and communities most dependent on the status quo, and provide support for those who are most vulnerable to the climate impacts that are already inevitable.

We have no doubt that the U.S. can reduce its overall economic risks from climate change by investing in a clean energy economy...

The impacts of climate change are happening now, faster and stronger than expected.

5. How Business Can Lead: A Call to Action

If the government's role is to establish a clear policy framework to accelerate the transition to the clean energy economy, it is the role of the private sector to take on the hard work of implementation through capital investments, innovation, and deployment of clean technologies.

We recognize that a policy framework is necessary for businesses to act at the speed and scale required to meet the climate challenge, but that does not mean businesses and investors should sit back and wait to act, especially as the impacts of climate change are happening now, faster and stronger than expected.

The decisions businesses and governments make today — this week, this month, this year — are crucial. They will impact not just the size of the threats from climate change, but also the overall security of the U.S. economy, affecting countless businesses, jobs, and homes. As the Sustainability Accounting Standards Board found, 71 of 79 industries in the economy are already affected by climate risk. Businesses from nearly every sector have a stake in this transition and need to be active participants in shaping policy and in making operational decisions to reduce their own carbon emissions and climate risk.

We recommend businesses take the following specific actions even in the absence of a strong policy framework for energy transition, while recognizing that some companies will not be able to put meat on the bones of these recommendations without that framework:

- Conduct a detailed analysis of the risks that climate change poses to operations, facilities, supply chains, and markets. These risks include both the physical impacts of climate change — such as sea level rise and increased heat — and the potential for rapid changes in technology and markets as governments and businesses act to reduce greenhouse gas emissions.
- Build internal capacity to address climate risks by engaging experts who can analyze the fast-growing set of climate science and risk data available to businesses.
- Develop and implement concrete action plans, including putting an internal price on carbon, to reduce these risks. Putting an internal price on carbon can help identify revenue opportunities and risks, and anticipate future government action. Setting a specific price will also make this issue real to companies and their investors, and affect corporate business decisions in a way that a general commitment to sustainability will not.
- Create, publicize, and implement plans to significantly reduce or even eliminate company-wide emissions by a set future date. Ideally, these emission reduction goals should consider not only direct and indirect emissions from facilities, but also emissions associated with business travel and employee commuting. Moreover, supply chain management represents the largest emissions reduction opportunity for many businesses. Setting ambitious "stretch" goals will help identify profitable emissions reductions opportunities that may not be obvious when looking only for modest reductions.
- Provide investor-facing information on how the company is dealing with climate risks and opportunities. This includes improving disclosure of climate factors in SEC filings that go beyond boilerplate language and include specific analysis of material climate-related risks.
- Push governments at all levels to provide policy frameworks that are necessary to achieve the speed and scale required for the transition to a clean energy economy. Businesses and their trade associations should actively engage, individually or through collective action, in shaping effective, efficient, and internationally consistent policies. Multinational businesses working with multiple governments across jurisdictional boundaries can be particularly effective in pushing for this kind of policy change.

The decisions businesses and governments make today — this week, this month, this year — are crucial.

“Now, more than ever, business must lead this transition for the sake of our climate, our country and our economic security.”

– Thomas F. Steyer

6. Conclusion: The Time to Act is Now

This is a pivotal moment in human history. The risks from climate change are growing and pose major threats to the entire economy and every individual's quality of life. With the right policy framework in place, American businesses can dramatically reduce these risks and seize important new economic opportunities by actively participating in the transition to a clean energy economy. That transition is already underway, but must be accelerated to avoid the most serious impacts of climate change.

Our earlier report on the economic risks from unmitigated climate change, and the vast amounts of new climate data since that report's release, demonstrate that a clean energy transition is critically necessary. We know from the analysis in this report that such a transition is technically feasible and affordable for the economy as a whole. And we know from our decades of work with the American business community that the private sector can lead in identifying and scaling up the key technologies and practices that will accelerate the clean energy transition.

In particular, this report calls for three major economic shifts to address the looming threat of climate change: electrification of the economy; de-carbonization of that electricity; and increases in energy efficiency. These shifts, while dramatic, are entirely technically feasible with current commercial technologies. With the right policies in place, businesses and investors can drive these changes, not only for the U.S. but for the rest of the world as other countries embrace the clean energy transition.

We are firmly convinced that American business is up to this enormous challenge. The same ingenuity that put billions of transistors on a silicon chip and a smartphone in every pocket can also bring clean, reliable, and affordable electricity to every American home; boost energy efficiency; and create long-range, affordable low-carbon transportation options. But we also know that this transition cannot happen without government policy to level the market playing field and accurately account for both the costs of carbon pollution and the benefits of forward-looking action.

At the time of this writing, the country lacks the political consensus needed to enact legislation to establish this kind of comprehensive clean energy policy. That fact, while sobering, cannot change the fact that we *must* address the real threat of climate change. One critically important role for business is to clearly sound the alarm and push our policymakers to rise above partisan bickering and act in the country's best interest.

The nation has seen how past transformative investments, in such areas as railroads, highways, rural electricity, and telecommunications, have unleashed the power of innovation and American business. Investing in a clean energy economy will do the same, protecting the nation from the impacts of climate change while keeping the economy strong and competitive. But to substantially reduce the growing risks to business and society from climate change, and to take maximum advantage of the business opportunities in a cleaner future, we must act now.

Notes

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The U.S. economy faces significant risks from unabated climate change. Every year of inaction serves to broaden and deepen those risks. Founded by co-chairs Michael R. Bloomberg, Henry M. Paulson, Jr., and Thomas F. Steyer, the Risky Business Project examines the economic risks presented by climate change and opportunities to reduce them.

Is creating a clean energy economy technologically and economically feasible?

What are the investment needs of this transition?

What are the opportunities and challenges for business?

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