The Long-Term Energy Efficiency Potential: What the Evidence Suggests

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- Advising businesses, policymakers, and program managers
- Working collaboratively with businesses, public interest groups, and other organizations
- Organizing technical conferences and workshops
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Projects are carried out by staff and selected energy efficiency experts from universities, national laboratories, and the private sector. Collaboration is the key to ACEEE's ongoing success. We collaborate on projects and initiatives with dozens of organizations including international, federal, and state agencies as well as businesses, utilities, research institutions, and public interest groups.

Support for our work comes from a broad range of foundations, governmental organizations, research institutes, utilities, and corporations.

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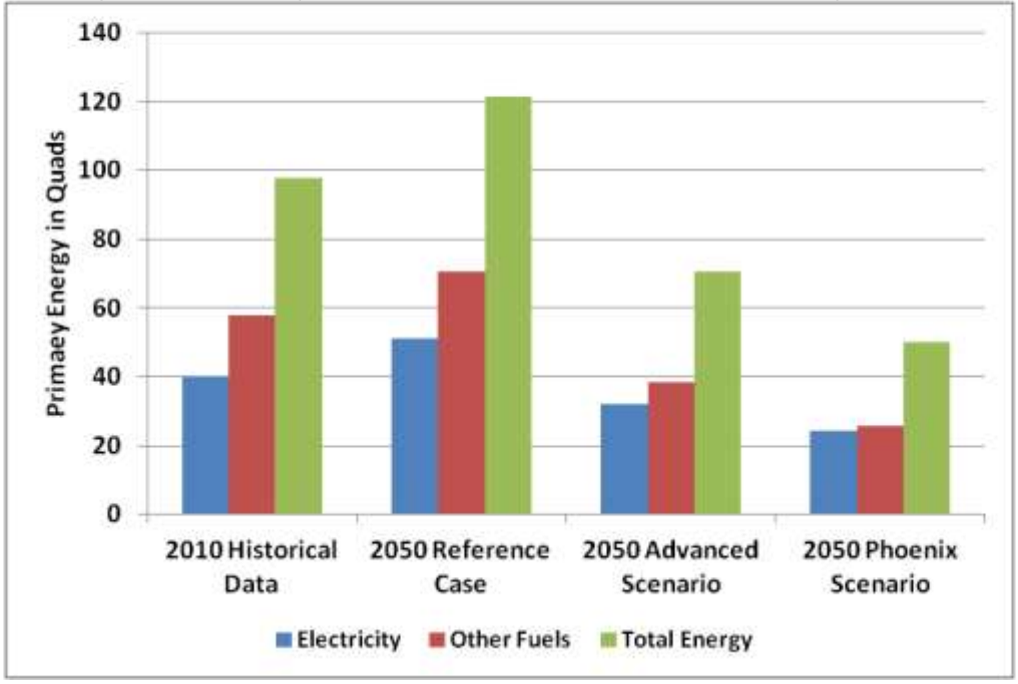
EXECUTIVE SUMMARY

In 2010 the U.S. used just under 100 Quads[1] of total energy resources to power our economy. Using the Energy Information Administration's (EIA) *Annual Energy Outlook* we project that our total energy needs might rise to about 122 quads of energy by the year 2050. In this report we explore a set of energy efficiency scenarios that emphasizes a more productive investment pattern, one that can enable the U.S. economy to substantially lower overall energy expenditures—should we choose to invest in and develop that larger opportunity. Building on the historical record of energy efficiency investments and their contribution to the nation's economic well-being, we highlight three economy-wide, long-term scenarios to explore the potential contributions that more energy-efficient behaviors and investments might play in reducing overall energy use by the year 2050. These three are:

1. Reference Case—a continuation of trends projected by EIA for the 2030-2035 period;
2. Advanced Scenario—includes penetration of known advanced technologies; and
3. Phoenix Scenario—in addition to advanced technologies, also includes greater infrastructural improvements and some displacement of existing stock to make way for newer and more productive energy efficiency technologies, as well as configurations of the built environment that reduce energy requirements for mobility.

For each scenario we separately examine the residential, commercial, industrial, transportation, and electric power sectors, and we then integrate these sectors together into a final set of impacts as shown in the chart below.

Figure ES-1. Energy Productivity and Impact on Future Energy Needs



Note: Electricity includes total energy needed to generate and distribute electricity to homes and businesses.

In total, we estimate that a more productive investment pattern might cost-effectively reduce our overall energy requirements in 2050 down to only 70 quads in the Advanced Scenario (a 42%

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[1] A *quad* is a quadrillion (10^{15}) Btu's of energy, about the amount of energy used in all sectors of the economy by the state of Arkansas, Kansas, or Oregon in a year.

savings relative to the Reference Case) and 50 quads of energy in the Phoenix Scenario (59% savings).

To achieve these savings will require major changes in how we use energy in each sector. For example, in the residential and commercial sectors we estimate reductions of space heating and cooling loads due to building shell improvements of 40% (Advanced) to 60% (Phoenix) in existing buildings and 70-90% in new buildings. We eliminate duct energy losses due to conversion to water- or refrigerant-based distribution systems, or at a minimum putting ducts within the conditioned space so that duct losses contribute toward heating and cooling. We use advanced heating and cooling systems (e.g., advanced electric, gas, and ground-source air conditioners and heat pumps; and condensing furnaces and boilers), advanced solid-state lighting, and also significantly more efficient appliances. For existing buildings achieving these savings will require major retrofits, typically at the time of building renovation. One area where we made only modest improvements was in miscellaneous/other uses such as office equipment and other “plug loads.” Data on energy use and savings opportunities for this equipment are limited. This area requires more attention in the future, since after heating, cooling, water heating, and lighting loads are reduced, these miscellaneous loads can be the majority of building energy use.

For the industrial sector, energy intensity is projected to improve in the Reference Case by about 1% per year through 2050, but leading companies have been achieving continued improvements at more than double this rate. In our Advanced Scenario we project a 2% per year improvement rate for overall industrial energy intensity, which increases to 2.75% in our Phoenix Scenario. Future energy efficiency opportunities will come less from seeking out individual sources of waste and more from optimization of complex systems enabled by advances in information, communication, and computational infrastructure. Most of the energy use in industry is in processes, not individual equipment, so improving processes represents the largest opportunity for energy intensity improvements. Current focus has been on process optimization, but we anticipate that even greater opportunities exist in the optimization of entire supply chains that may span many companies and supply chain integration that allows for efficient use of feedstocks and elimination of wasted production.

In the transportation sector, the Reference Case includes new light-duty vehicle fuel economy increases out to 2020, as mandated by the Energy Independence and Security Act of 2007, and minimal increases thereafter. Other transportation modes experience modest efficiency increases out to 2050. In the Advanced Scenario, fuel economy of conventional petroleum-fueled vehicles continues to grow while hybrid, electric, and fuel cell vehicles gain large shares, totaling nearly three-quarters of all new light-duty vehicles in 2050. Aviation, rail, and shipping energy use declines substantially through a combination of technological and operational improvements. The Phoenix Scenario assumes a shift toward more compact development patterns, greater investment in alternative modes of travel, and other measures that reduce both passenger and freight vehicle miles traveled. This scenario also phases out conventional light-duty gasoline vehicles entirely, increases hybrid and fuel cell penetration for heavy-duty vehicles, and reduces aviation energy use by 70% from the Reference Case.

While end-use electricity represents a fraction of the total energy use in the U.S. economy, currently it takes more than three units of fuel to produce a unit of electricity. The delivered efficiency of the U.S. electricity sector is projected to improve modestly in our Reference Case. Part of this increase is due to improvements in generation efficiency and reductions in transmission and distribution (T&D) losses, combined with a significant increase in the share of electricity produced by Combined Heat and Power (CHP), whose power output is predominately near its point of use thus avoiding some of the T&D losses. As we dramatically reduce the electricity use in the other sectors of the economy in our Advanced and Phoenix Scenarios, we anticipate that these reductions will result in important shifts in the generation mix in the electric sector, with many old plants retiring. We also anticipate that the delivered electricity efficiency will improve as we invest in more efficient new generation and highly-efficient CHP accounts for a greater share of the overall generation mix. We project that the delivered electric system efficiency in 2050 will increase from about 36% in the Reference Case to about 40% in the Advanced Scenario and approach 48% in the Phoenix Scenario. This improvement in overall delivered efficiency greatly reduces the losses associated with supplying electricity to other sectors of the economy.

The greater emphasis on energy efficiency would sharply reduce total energy requirements within the U.S. (especially for fuels such as natural gas and petroleum). However, we project that end-use demand for electricity will decline less than direct fuel use. The reason for this apparent difference is that the many more demands for high-quality electrical energy would hold power consumption steady as more of our economic activity is driven by a greater share of electric generation resources. By improving the delivered efficiency of electricity, we can actually hold electricity demand relatively steady and end up using significantly less total energy while meeting our overall electricity needs.

Overall, as noted previously, we estimate that energy use in 2050 can be reduced by 42% in the Advanced Scenario and 59% in the Phoenix Scenario. Savings are roughly similar in each sector. The 2050 industrial sector savings, for example, range between 36 and 51% for the two policy cases while residential and commercial buildings might realize overall energy savings from 45 to 69% savings. Transportation savings, moving closer to buildings in the scale of efficiency improvements, fall in between with suggested savings of 38 to 56%, respectively.

The levels of efficiency improvements in either the Advanced Scenario or the Phoenix Scenario will generate a productive boost to the economy. There are two primary ways in which this will happen. First, households and businesses will see lower energy bills as the level of energy efficiency improves over time. As they maintain (or even increase) their own economic activity through these productivity improvements, the growing energy bill savings will act much like an extra form of income that provides an important stimulus for other sectors of the U.S. economy. Second, and related to this first improvement, the efficiency gains will allow households and businesses to redirect the flow of spending away from the more costly energy sectors. The net result is that households and businesses will have more money available for the purchase of other goods and services. As it turns out, those other sectors of the economy tend to be more labor intensive. Hence, the increased spending, in turn, provides a larger net employment benefit for the nation's economy—we estimate that the combined effect of the efficiency investments over time, together with a growing energy bill savings, will drive a steady increase in the demand for labor so that by the year 2050 the economy will provide a net increase of 1.3 to 1.9 million jobs. Net gains to the nation's Gross Domestic Product (GDP) in 2050 are estimated to be on the order of 100 to 200 billion dollars per year. Both the employment and GDP benefits are on the order of tenths of a percent above the 2050 Reference Case. Table ES-1 highlights these and other economy-wide impacts of the two energy efficiency scenarios.

Table ES-1. Key Economic Impacts from Efficiency Improvements

Financial and Economic Indicators	Advanced Scenario	Phoenix Scenario
Energy Savings from 2050 Reference Case	42%	59%
Cumulative Financial Impacts 2012-2050 (Billion 2009 Dollars)		
Program Cost	500	1,200
Total Investments	2,400	5,300
Annual Payments on Investments	2,900	6,400
Energy Bill Savings	15,000	23,700
Net Energy Bill Savings	11,600	16,200
Net Macroeconomic Impacts in the Year 2050		
Employment (millions of jobs)	1.3	1.9
Percent from Reference Case	0.4%	0.6%
GDP (billion 2009 dollars)	100	200
Percent from Reference Case	0.3%	0.4%

Implementation of the Advanced and Phoenix Scenarios depends on our willingness to make the needed investments in higher performance buildings, equipment, industrial processes and transportation systems. At the same time, it takes money to make money. Over the period 2012 through 2050 the nation will have to provide the funding for the array of programs that will be necessary to catalyze a more productive pattern of investments. And as those investments are made over time, households and businesses will likely need to borrow the money that will enable us to upgrade the nation’s infrastructure. Hence, there will be an ongoing series of annual payments necessary to pay for those improvements.

But the good news is that the investments will generate a significant return in the form of large energy bill savings. After paying for the program costs and making the necessary investments as we pay for them over time, the economy will benefit from a net energy bill savings that ranges from 12 to 16 trillion dollars cumulatively over that 39-year time horizon (that is, a period of time that extends from 2012 through 2050). In other words, these two high-performance energy efficiency scenarios will spur an annual net energy bill savings that might range from about $297 billion to $415 billion per year (with all values expressed in constant 2009 dollars).

In effect, the two ACEEE energy efficiency scenarios highlighted in this study represent a different recipe of investments compared to the standard Reference Case. It is a recipe built on a more productive investment pattern. These investments, in turn, enable the economy to reduce overall energy expenditures in ways that also provide a greater employment benefit—again, should we choose to develop that larger opportunity. The question that remains is whether we will actually choose the more productive investment path, or will we simply “muddle through” by following the standard business-as-usual assumptions?

I. INTRODUCTION

Notwithstanding the current sluggishness of the United States economy, the standard forecasts suggest that economic activity is likely to grow at a reasonably robust level of about 2.7% annually over the next 40 years. Based on estimates published by the Energy Information Administration (EIA 2011), the nation's GDP (Gross Domestic Product) is expected to increase from about $14.6 trillion in 2010 to perhaps $41 trillion in 2050 (with all values expressed in constant 2010 dollars to eliminate the effects of inflation). This is almost a tripling of today's economy. While the increase is expected to slow compared to the expansion we witnessed in past decades (the growth in GDP averaged more than 3% in the period 1980-2005, for example), our per capita income is still expected to nearly double by 2050. This anticipated economic expansion presumes, among other things, a conventional pattern of energy production and consumption. It also presumes a straightforward extension of how we produce our goods and services. Yet the evidence suggests that without a greater emphasis on the more efficient use of energy resources, there may be as many as three jokers in the deck that will likely constrain the robustness of our nation's future economy. These include the many uncertainties surrounding the availability of conventional and relatively inexpensive energy supplies, a slowing rate of energy and therefore economic productivity, and a variety of pending climate constraints that may create further economic impacts of their own.

The first of the emerging constraints involves the many aspects of energy production and consumption. Starting prior to the recent offshore oil drilling disaster in the Gulf of Mexico (New York Times 2010), a variety of snags continue to hinder the safe and timely production of many energy resources (Elliott 2006). There is also convincing evidence we are approaching the sunset of the oil era in the first half of the 21st century (Deffeyes 2010; Rifkin 2011). Drawing on the BP *Statistical Review of World Energy* (BP 2011), we note that the global "per capita peak oil production" occurred in 1979 when we produced 15.1 barrels of oil per person compared to 2010 when we managed only 12 barrels of oil per day. Total production has already peaked in most non-OPEC countries (that occurred for the U.S. in 1970) and is expected to peak in most of the others before 2030—and this despite an assumed steady increase in world oil prices forecasted by the International Energy Agency (IEA/OCE 2011). With that inevitability, there will be a huge shift in the way most of humanity interacts with the global energy system. The realization of imminent limitations on our fossil fuel resources has generated a rush of interest in energy efficiency and renewable energy technologies while aggravating the financial and investment pressures that are necessary to maintain the integrity of the world energy market.

The second of the constraints follows from slowing growth in energy productivity. The U.S. economy has tripled in size since 1970 and three-quarters of the energy needed to fuel that growth came from an amazing variety of efficiency advances—not new energy supplies (Laitner forthcoming). Indeed, the overwhelming emphasis in current policy debates on finding new energy supplies is such that emphasis on new supplies may be "crowding out" investments and innovations that can help to achieve greater levels of energy productivity. Going forward, the current economic recovery, and our future economic prosperity, will depend more on new energy efficiency behaviors and investments than we've seen in the last 40 years (Laitner forthcoming).

The third of the three emerging problems to complicate standard growth projections is climate change. The average temperatures in the earth's atmosphere are on an upward trajectory that is largely irreversible over the next century (even if we meet ambitious emissions reduction goals). The trend is driven by the cumulative effect of rising concentrations of greenhouse gas (GHG) emissions, primarily carbon dioxide emissions (CO_2), which are generated by the combustion of fossil fuels. This trend has profound implications for the world's climate. Leading U.S. climatologist James Hansen and his colleagues (Hansen et al. 2008) say that current global CO_2 concentrations are now at about 390 parts per million (ppm) and could rise to 550 ppm or more by the year 2100 unless ambitious efficiency investments such as those recommended here occur. The IEA Chief Economist, Fatih Birol, commented on the release of the IEA's *World Energy Outlook* that "[a]s each year passes without clear signals to drive investment in clean energy, the "lock-in" of high-carbon infrastructure is making it harder and more expensive to meet our energy security and climate goals." The IEA is raising the alarm that the world is locking itself into an unsustainable energy future that would have far-reaching consequences. If left unchecked, the changing climate could seriously weaken the global and the U.S. economy (IEA/OCE 2011).

Americans may have an overly optimistic impression of how energy efficient the United States is—even as they believe in the importance of greater levels of energy efficiency (Maibach et al. 2010). Despite the enormous strides achieved in the last four decades, Ayres and Warr (2009) estimate that the U.S. economy is about 14% energy efficient, with the other 86% wasted. By way of comparison, Ayres and Warr note that Japan and several European countries are about 20% efficient, a factor of 1.5 higher than the U.S. Even so, all economies are underperforming in this regard.

At the same time that we face these critical environmental and energy challenges, the United States is on the verge of losing its competitive edge (Atkinson and Andes 2011). Competition from rapidly growing countries with employees marching up the skill ladder is a big reason for America's economic strain, but not the only one. Inspired by its uniquely democratic political culture, the U.S. economic growth miracle has been nurtured by its openness to new ideas. For over two centuries, the United States has catalyzed an array of new institutional and technological innovations. Yet, as professor of management Leon Megginson suggested, drawing on the ideas of Charles Darwin, it is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change. (Megginson 1964). Thus, it is especially troubling when a number of observers are suggesting we may be losing our resourcefulness—especially against the backdrop of these multiple challenges. As former Chief Technology Officer at Cisco Systems, Judy Estrin (2008) observes: "To be honest, we had a problem with innovation [in this country] even before the [current climate, energy, and] economic crisis. . . We're focusing on the short term and we're not planting the seeds for the future" (see also Rae-Dupree 2008, Florida 2004, and Holdren 2006). Harvard professor and award winning physicist John Holdren (1999) asks pointedly, "can we afford 'business as usual' any more?"

In the United States, and around the globe, there is a clear need for real, affordable, short-term (but also long-term) alternatives that can reduce our inefficient use of energy resources. More productive and cost-effective investments in greater levels of energy efficiency can reduce the upward pressures on and the volatility of energy prices as well as reduce the GHG emissions burden (Laitner 2009b). Furthermore, energy efficiency investments can do all this while maintaining the production of the many goods and services demanded by our economy, and according to many analyses, actually increase net employment opportunities (Laitner and McKinney 2008; Houser et al. 2010; Laitner et al. 2010).

Although energy efficiency is seen by many stakeholders as a highly effective investment, it also tends to be viewed as a short-term resource. This view is now changing. California, for example, established energy efficiency as the first choice in the loading order for new energy resources (Grueneich 2008). Other states, including Connecticut, Massachusetts, Rhode Island, and Washington, have established similar policies. This emerging perception has been instrumental in the selection of energy efficiency as a cost-effective resource for energy utilities (Molina et al. 2010). Indeed, as we show in the discussion that follows, energy efficiency may well prove to be a more dynamic and longer-term resource than many now assume (see Lovins et al. 2011 for a discussion on this issue). There is a strong historical record to suggest that energy efficiency can provide perhaps the largest single wedge of GHG emissions reductions (Laitner et al. 2010; see also Harvey 2010; Committee on America's Energy Future 2010; McKinsey 2009; Gold et al. 2009; American Physical Society 2008; Ehrhardt-Martinez and Laitner 2008; and McKinsey 2008). Yet, the question remains, just how big of a resource is energy efficiency—especially when we examine its potential over the next four decades through the year 2050?

The balance of this report seeks to accomplish three separate tasks. First, it provides an overview of the historical record on energy efficiency and discusses how that set of insights might inform our expectations of its future economic potential—specifically in the context of how energy efficiency investments might positively impact economic and climate policy outcomes. As part of this discussion it describes the critical role of energy efficiency in advancing the larger economic productivity within the United States. Second, the report highlights two economy-wide, long-term scenarios to explore the potential contributions that more energy-efficient behaviors and investments might play in reducing overall energy use by 2050. We separately examine the residential, commercial, industrial, transportation, and electric power sectors and then integrate these sectors together. As the report characterizes the future opportunities, it appears that energy efficiency writ large—including conservation behaviors, informed choices, improved devices, structural change within the economy, and more productive systems and infrastructure—might generate as much as 42 to 59% of the deep emissions reduction that most scientists agree are needed by 2050.[2] Finally, we examine the implications of this economic opportunity as it is affected by relevant policy choices.

II. THE HISTORICAL RECORD ON ENERGY EFFICIENCY

Energy efficiency has played a surprisingly enduring and critical role in our nation's economy. In the sections that follow, this report documents the past scale of the energy efficiency resource as it has powered the nation's economy. It also examines what we know about the costs and energy-saving benefits of the array of energy efficiency technologies and behaviors. The benefits include both reduced energy bills and a surprisingly large set of non-energy benefits ranging from reduced operations and maintenance costs to improved quality and speed of tasks. From there we examine how the resources that are freed up might drive a small but net positive gain benefit for the nation's unemployed or underemployed.

A. Placing Energy Efficiency into the Economic Context

As one of the richest and more technologically advanced regions of the world, the United States has expanded its economic output by more than threefold since 1970. Per capita incomes are also twice as large today compared to incomes in 1970. Notably, however, the demand for energy and power resources grew by only 50% during the same period.[3] This decoupling of economic growth and energy consumption is a function of increased energy productivity: in effect, the ability to generate greater economic output, but to do so with less energy. Having achieved these past gains with an intermittent, haphazard, and often counterproductive approach to energy efficiency and energy policy, there is compelling evidence to suggest that even greater energy productivity benefits can be achieved. Indeed, business leaders and policymakers may be surprised to learn just how big a role that energy efficiency has already played in supporting the growth of our economy over time. Indeed, Smil (2010) suggests that "sensible policies aimed at reducing wasteful energy use were completely (and indefensibly) abandoned." Figure 1 examines the historical context of efficiency gains estimated through 2010 as they compare to the development of new energy supplies since 1970. Figure 1 also illustrates the level of new energy supply that would have been needed in the absence of energy productivity gains due to efficiency measures. In effect, it compares the projected level of energy consumption in 2010 to that which might have been necessary had the economy continued to rely on 1970 technologies and market structure.[4]

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[2] Drawing on the emerging scientific evidence, for example, a 2009 declaration by the leaders of the G8 nations called for an 80% or more reduction of aggregate greenhouse gas emissions by 2050 in developed countries compared to 1990 or more recent levels (G8 Leaders 2009).

[3] These and other economic and energy-related data cited are the authors' calculations as they are drawn from various resources available from the Energy Information Administration (EIA 2011a, 2011b).

[4] Strictly speaking, the term energy efficiency as used here can be more broadly defined as a reduction in energy intensity; that is, a reduction in the number of Btus needed to support a dollar of economic activity. This change results from two key drivers. The first is a change in market structure as we move away from energy-intensive industries as a source of income to higher value-added services. The second is what we typically think of as energy efficiency—more efficient lighting and consumer products, greater fuel economy in our vehicles, and more efficient power plants and industrial processes. The United States has benefited from both economic drivers; both were made possible by a combination of behaviors, innovations, and productive technology investments. From a macroeconomic perspective the evidence suggests that anything we can do that positively reduces energy use while maintaining incomes and economic prosperity can be termed "energy efficiency." It is in that larger sense that the term is used in this report.

In 1970 Americans consumed an estimated 68 quadrillion Btus (quads) for all uses of energy.[5] These different uses of energy run the gamut from heating and cooling our homes, schools, and businesses to powering our many industrial processes and transporting both people and freight to the various places they needed to go. If we converted all forms of energy consumed in 1970 to an equivalent gallon of gasoline—whether coal, natural gas, or electricity, it turns out that the U.S. economy required about 2,700 gallons of gasoline equivalent for each man, woman, and child living in the U.S. at that time. Had the United States continued to rely on 1970 market structure and technologies to maintain its economic growth, in 2010 we would have consumed an estimated 210 quads of energy resources. In per capita terms, that would be equal to roughly 5,400 gallons of gasoline per person. But in fact, the actual level of consumption estimated for 2010 appears to be just short of 98 quads of energy (in rounded numbers). Again on a per capita basis, this means that the U.S. economy now requires no more than about 2,500 gallons of gasoline per resident—about 200 gallons less than needed in 1970.

In examining these numbers more closely, however, several important observations deserve to be highlighted. First, although we currently enjoy a much broader set of goods and services in today's economy, we have been able to achieve this expanded level of economic output while maintaining constant levels of energy use per capita. This has been achieved through investments in energy efficiency. Second, although the same level of goods and services hypothetically could have been achieved through the consumption of 210 quads of energy per year, we have been able to achieve this level of output with less than half that amount of energy. In effect, investments in energy efficiency have allowed us to reduce total energy use by the equivalent of 112 quadrillion Btus in 2010 (relative to what our energy use would have been without those efficiency gains). Even when we make adjustments to reflect the large number of goods and services that have been imported—things that required energy outside our borders to produce and ship those goods into the United States, the demand for energy services is still 203 quads in 2010. That means energy efficiency has "fueled" about 106 quads, or roughly three-fourths of the *new* growth for energy-related services since 1970. The conventional energy resources, on the other hand, satisfied only one-quarter of the new demands (or about 30 quads, shown as the difference in Figure 1 between the 2010 consumption of 98 quads compared to the 1970 consumption of 68 quads).[6]

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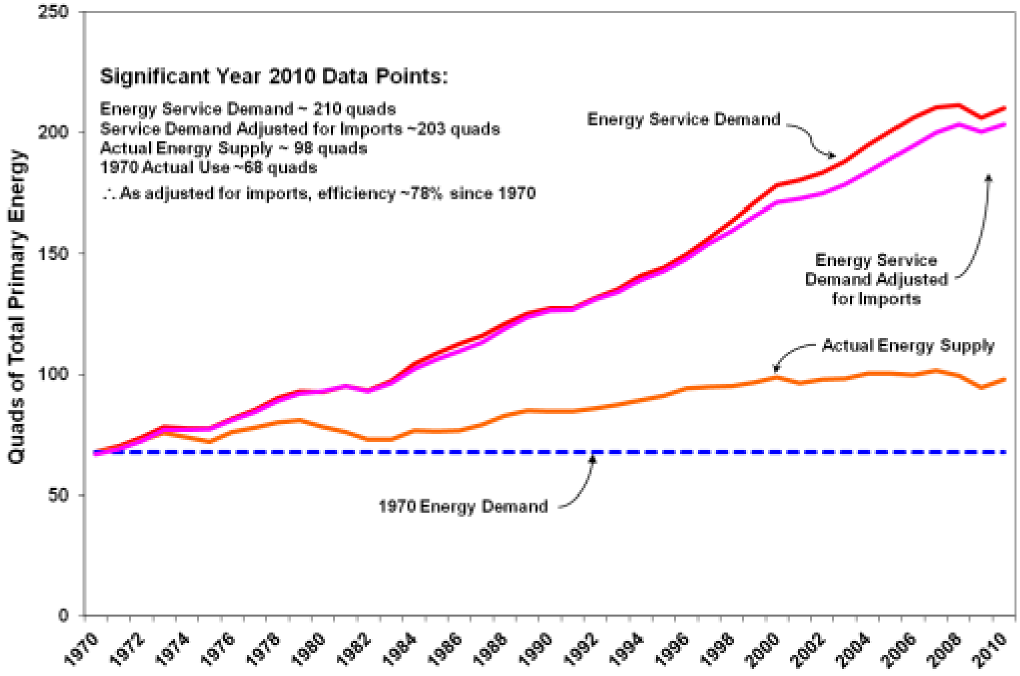
[5] One quadrillion British thermal units is 1,000,000,000,000,000 Btus (10 to the fifteenth power). In today's markets, one quad is the amount of energy contained in 8 billion gallons of gasoline. One quad is sufficient energy to power more than 15 million cars in the U.S. for one year (at today's average fuel economy and typical driving distances). One quad contains sufficient heat to also provide the total energy needs for more than 5 million homes in the U.S.

[6] As one of our reviewers (David Goldstein) suggested, it would be interesting to try to reconstruct what a 210 Quad economy would look like. What would we have invested in nuclear energy to get there and what would electricity prices have been? What would world oil prices have been and where would the oil have come from? While this would, indeed, be a very useful exercise, it is beyond the scope of this particular inquiry. Still, we might speculate that without the very large historical efficiency gains, energy supplies might be significantly tighter and energy costs would likely be higher and much more volatile than we've seen to this point. This, in turn, would likely have constrained our nation's economic productivity and resulted in a smaller level of economic activity than we've seen to date. One important conclusion from this thought experiment is that today's economy would likely have not been possible but for the historical gains in efficiency as we've previously discussed.

Figure 1. U.S. Energy Service Demands, Energy Efficiency Gains, and Energy Supplies



Source**:** ACEEE calculations based on data from the Energy Information Administration (2011a)

One often unappreciated aspect of the growth in energy consumption is what might have been had we previously chosen to develop our energy efficiency resources more completely. For example, a minimum attention to greater energy productivity in the last decades might have kept current energy demands closer to the 1970 level of consumption—even with a growth in both the population and the size of the economy. In that case, the historical growth in high efficiency improvements might have kept total energy demand closer to 70 quads by 2010.[7] Perhaps more interesting is the set of the many previous studies that have suggested we might have done (and might still do) even better. We explore these past studies in the section that follows.

B. Where Energy Efficiency Might Have Taken Us and Where We Might Head

The market tends to be more dynamic than policy assessments generally concede, especially when given an appropriate mix of policies and guidance. In the late 1970s, as the United States was assessing its various energy options following the 1973-1974 Oil Embargo, the National Research Council published an authoritative report called *Energy in Transition 1985–2010* (NRC 1979). It was one of the more thorough assessments of its time, but certainly not atypical of the many past studies that explored future technology. The report suggested that, if one assumed a doubling in the size of the U.S. economy, and if energy prices (adjusted for inflation) stayed roughly the same, U.S. energy consumption would rise from about 72 quads in 1975 to about 135 quads by 2010. The NRC study further indicated that if real energy prices were to double instead, then U.S. energy demand might grow to only 94 quads by 2010. The demand pattern that actually emerged since 1975 provides an especially useful insight as policymakers and business leaders turn their attention to the growing problems of climate change and energy security.

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[7] This so-called “Historical High Efficiency” scenario is generally patterned after a series of low range energy efficiency that explored such possibilities over the period 1975 through 2010. For more details, see DOE (1980) and the discussion that accompanies Figure 2.

As it turned out, the economy didn't doubled, but nearly tripled in volume over the last 35 years. And while energy prices did not remain at the 1975 levels, neither did they double in size. In fact, it appears that real energy prices since 1975 have grown on average by only 70% compared to the comparable prices seen in 1975. And what of the nation's actual use of energy? Returning to the data in Figure 1, the latest forecast from the Energy Information Administration (EIA 2011b) suggests that total energy use this year will be just under 100 quads. So we've grown the economy much bigger than we anticipated and energy prices have less than doubled, but as Figure 2 below suggests, total energy demand has stayed closer to what analysis in the mid-1970s thought would be an unlikely low energy future. What is the difference? The evidence suggests two very big factors have made the economy more energy efficient than anticipated in the 1970s. The first is that we have deployed more productive technologies than we thought possible from a 1970s vantage point. But a further investigation also suggests that more informed behaviors and a more dynamic market also played critical roles.

One interesting comparison to emerge from Figure 2 (below) is an early attempt at characterizing just how the energy consumption might look in the event that emerging energy efficiency technologies developed significant market share. Based on a review of 20 earlier studies that explored that same possibility, the U.S. Department of Energy (DOE 1980) provided what it termed an "approximate envelope of low energy futures." As illustrated by the solid green line in Figure 2, the envelope of projections extended all the way out to the year 2050. The projection peaked roughly in 2005 at a little more than 90 quads and then sloped gently downward. The overall conclusion of the study was that "if these efficiency improvement measures could be widely and rapidly adopted across all sectors of the economy, the combined and cumulative effects are estimated by most of the studies reviewed to result in negative future growth in U.S. primary energy use—possibly approaching 60 quads."[8]

Figure 2 also provides two other important comparisons. The first is a line representing the standard forecast assumption before 1980 with an indication that energy use by the year 2000 might reach as much as 150 quads. The irony here is that, both for expected and for unexpected reasons, the nation's actual energy consumption (highlighted by the jagged red line in Figure 2) more closely reflected what was characterized in 1980 as a "low energy future." In other words, the combination of technology investments, informed behaviors, and supportive energy policies enabled a more dynamic market response than energy modelers anticipated in previous years. Perhaps even more compelling, the economy itself also proved to be more robust than the modelers originally thought likely.

As a final comparison highlighted in Figure 2, the *Annual Energy Outlook 2011* projection for total primary energy (EIA 2011b)—extended to 2050 by incorporating additional data from Economy.com (2011)—nicely splits the difference between the pre-1980 forecasts and what DOE in 1980 referred to as an envelope of low energy futures. The question for policymakers is whether there are opportunities to close the gap between the current projection of business-as-usual and that low energy future first suggested by the 20 studies reviewed in 1980.[9] As we examine next, the evidence continues to underscore that possibility—if we choose to act on the full set of opportunities to increase our nation's energy productivity.

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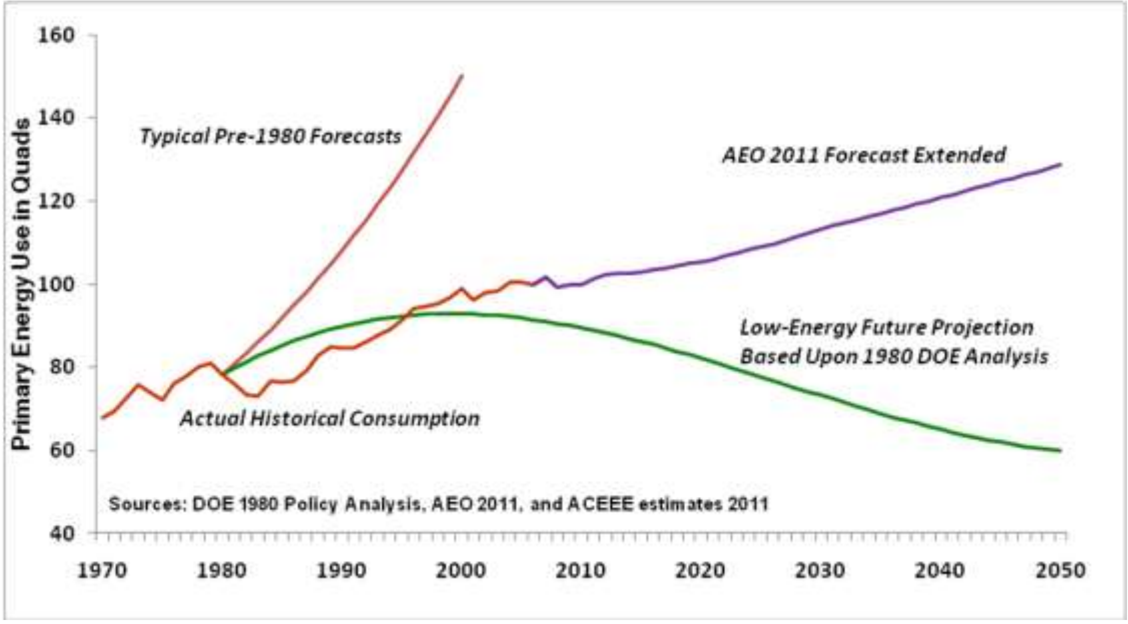
[8] An interesting side note is that the 1980 DOE report specifically excluded from its more in-depth analysis a 1979 study with a projection of 33 quads in 2050 "because it assumes major lifestyle changes."

[9] Not to be lost in the comparison, the gap between the pre-1980s projections and what actually occurred by the year 2000 is approximately the same magnitude as the comparison between the extended AEO 2011 forecast for the year 2050 and the 60-quad low energy future.

Figure 2. Energy Scenarios: Differences in Technology and Behavioral Assumptions?



Sources: DOE 1980 Policy Analysis, AEO 2011, and ACEEE estimates 2011

Since the useful compendium and analysis provided by DOE in 1980, there have been a number of other studies that have further explored the feasibility of greater investments in the nation's energy productivity. Two significant studies include *America's Energy Choices* (AEC 1991) and *Energy Innovations* (Interlaboratory Working Group 1997). These two highly detailed studies, sponsored by a association of nonprofit organizations and research groups, suggested that—with the right mix of policies and investments—it was technically and economically possible to reduce the nation's total primary energy consumption to between 60 and 70 quads by the year 2050. Harvey (2010) provides almost encyclopedic detail that further reinforces such prospects. In effect, these past assessments of long-term energy efficiency improvements envisioned the substitution of innovation and productive capital as a smart substitution for the inefficient use of energy. Two major studies by a consortium of the nation's national energy laboratories generally reinforce these finding although over a shorter time horizon (see Interlaboratory Working Group 1997, 2000).

C. Cost-Effectiveness of the Efficiency Resource

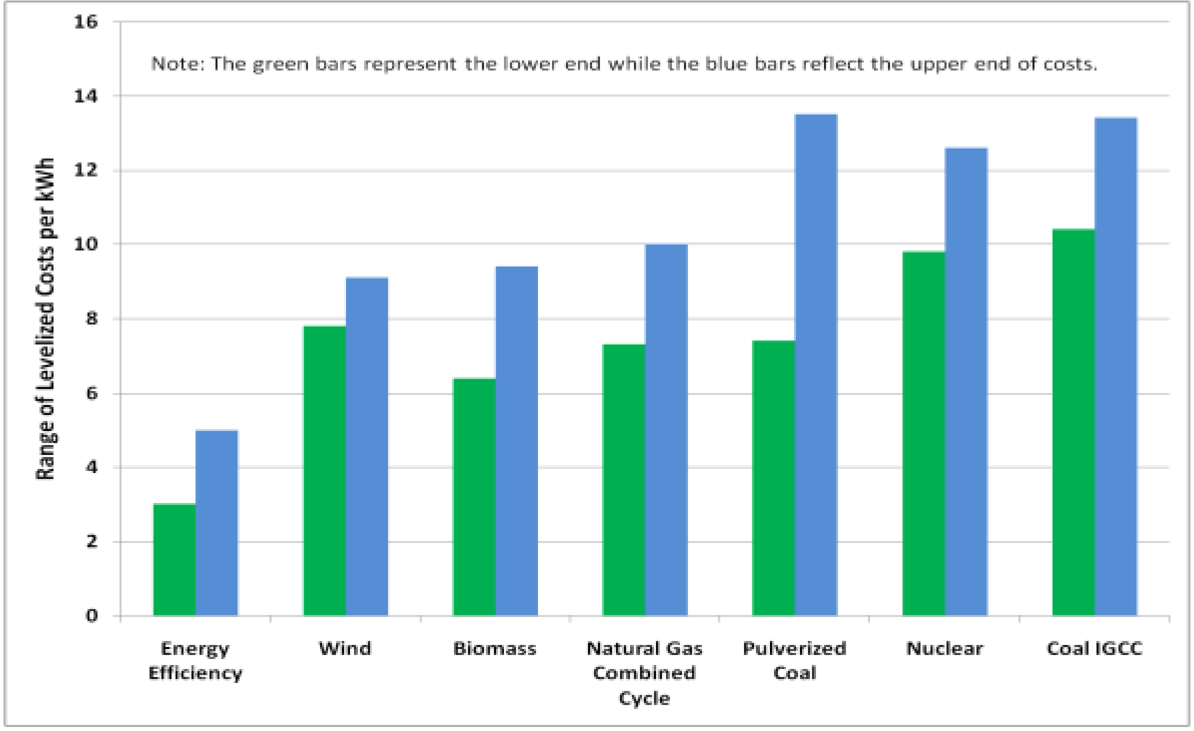
The question at this point becomes one of cost-effectiveness. Can the substantial investments that might be required in the more energy-efficient technologies save money for businesses and consumers? In the subsections that follow, we again turn to the evidence as we first explore what we might call the engineering estimates of energy efficiency compared to conventional energy resources. We then examine how these costs might progress over time. Finally we explore the reality of energy efficiency costs compared to the standard and more narrowly defined range of cost estimates.

1. Engineering-Economic Cost Estimates

Figures 3 and 4 offer two initial but different assessments of the "first cost" comparison of energy efficiency compared to other investments. Lazard (2009) presented a mix of levelized costs—that is, the cost of investments as they are amortized and operated over time—associated with electricity generation expenditures. These are summarized in Figure 3 as they cover the annual costs associated with a variety of new power plants. The left green bars represent the lower end of the costs while the right blue bars represent the higher end of the estimated costs. Included are estimates for conventional coal-fired power plants, coal units that rely on integrated gasification combined cycle technologies or IGCC, nuclear units, and natural gas combined cycle power plants. Also shown are costs for wind and biomass systems together with both Lazard and ACEEE estimates for the range of costs associated with energy efficiency measures (including program-operator and end-user costs).

With efficiency costing the equivalent of 3-5 cents per kilowatt-hour of electricity service demand, the resulting electricity savings are clearly the more cost-effective option.[10]

Figure 3. The Range of Costs Associated with Electricity Generation



Sources: Lazard (2009); Friedrich et al. (2009)
Note: For energy efficiency this includes both utility and customer costs.

Figure 4 provides a different look, comparing energy efficiency investments to other opportunities for generating investment returns. This is done in two ways. The first is an annual return on investment. The second is an examination of risk associated with a given investment opportunity. In exploring the prospective returns on investments in efficiency upgrades, McKinsey & Company (2008) reviewed an array of energy efficiency options that had at least a 10% return on the investment dollar. When spread out globally over an annual $170 billion energy efficiency market potential, McKinsey suggests an average 17% return might be expected across that spread of annual investments. Rather than a return on investment, we can also explore the amortized cost of electricity, for example, and determine a prospective return compared to the expected average cost of electricity.

At five cents per kWh, we might envision the spending of 36 cents upfront to save one kWh each year for perhaps 15 years. When amortized over the life of that one-time investment, at a real 7% interest rate, the annual cost is estimated as $0.04/kWh. If we think of the time it takes for that investment to pay for itself, and if we know the monthly electricity cost is 9 cents per kWh, we might then suggest the investment would pay for itself over four years. In that case, the investment is approximated to have the equivalent of a 25% annual return. As shown on the vertical axis in Figure 4, a typical range of efficiency investments is suggested as having one of the more durable and better annual returns compared to other investments—whether in treasury bills or common stock. Even more interesting is the stability of the investment as shown on the horizontal axis. Although data is not collected on risk

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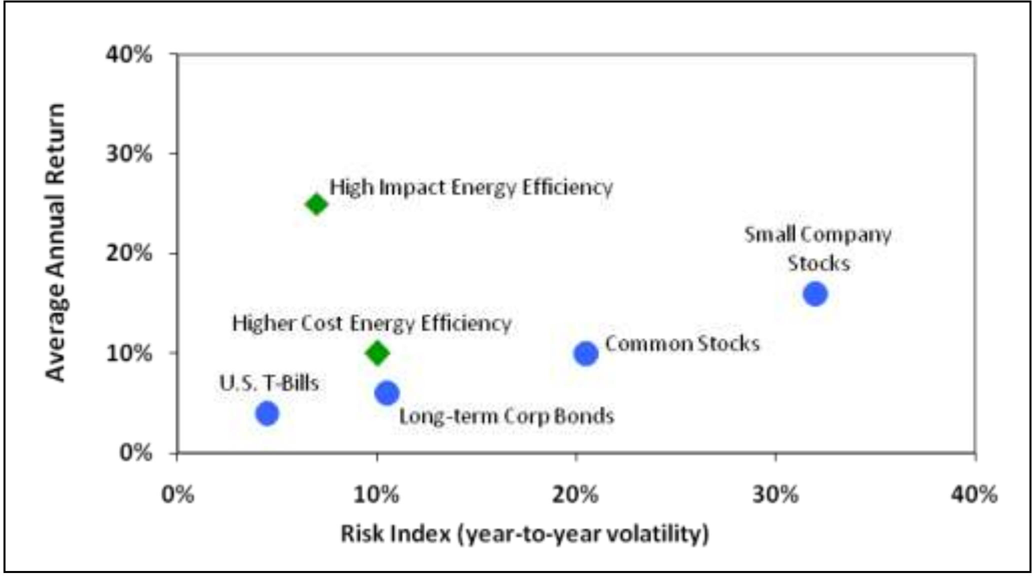
[10] Not included in Figure 3 is a significant supply of negative cost measures. These are essentially measures that rely on changes in procedures that require no capital outlays. In effect, they are so-called "housekeeping" improvements that only require things to be done differently.

associated with institutional investments in energy efficiency in any systematic way, it appears to provide a more stable investment opportunity compared to normal market instruments. [11]

Figure 4. Comparing Risk and Return on Investment Opportunities



Source: Author estimates based on a variety of published sources and data

We can extend this issue of cost effectiveness even further to examine policy rather than discrete technologies. Laitner and McKinney (2008) provided a meta-review of 48 past policy studies that were undertaken primarily at the state or regional level. The set of studies included in this assessment generally examined the costs of economy-wide efficiency investments made over a 15-25 year time horizon. The analysis found that even when both program costs and technology investments were compared, the savings appeared to be twice the cost of the suggested policies.

In a similar way, the AEC (1991) and the Energy Innovations (1997) reports show a benefit-cost ratio that also approached two to one. More recently, the Union of Concerned Scientists (Cleetus, Clemmer & Friedman 2009) published a detailed portfolio of technology and program options that would lower U.S. heat-trapping greenhouse gas emissions 56% below 2005 levels in 2030. The result of their analysis indicated an annual $414 billion savings for U.S. households, vehicle owners, businesses, and industries by 2030. After subtracting out the annual $160 billion costs (constant 2006 dollars) of the various policy and technology options, the net savings is on the order of $255 billion per year. Over the entire 2010 through 2030 study period, the net cumulative savings to consumers and businesses was calculated to be on the order of $1.7 trillion under their so-called Blueprint case.

2. The Progression of Cost Estimates

Figure 5 highlights yet another aspect of the cost-effectiveness of energy and climate policy—the so-called marginal abatement cost curves.[12] Many economic modelers are uncomfortable with the idea

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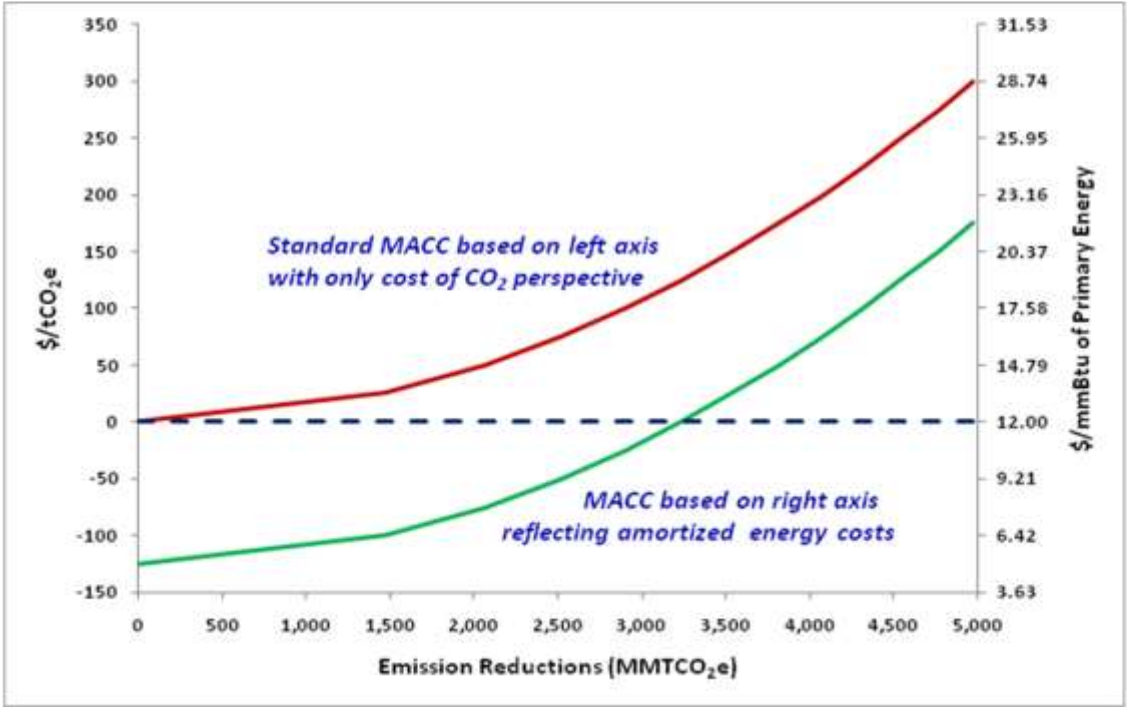
[11] Peretz (2009) has a useful paper that further explores the scale of the investment potential in energy efficiency and the need for financial metrics that might help the market improve its evaluation of such investment opportunities.

[12] What one of us (Laitner) sometimes refers to as "the Big MACC." While the curves in Figure 5 are not drawn to any specific set of technologies, the red abatement curve reflects the approximate scale of the more conventional policy models that assume no returns from investments in abatement technologies. The green abatement curve generally reflects an assumption that as much as 40% of the emissions might be reduced with a net savings—given today's technologies and prices. Presumably, greater investments in research and development, coupled with greater levels of innovation over time, might shift both curves to the right.

of negative costs and tend to assume that all abatement measures have only positive costs. This implies that marginal abatement cost curves must, therefore, start at zero and can only rise as more of the abatement opportunities are used up. The figure illustrates, however, the availability of a large supply of emission reductions that could be achieved today at negative cost; that is, with economic savings that result from the value of reduced energy expenditures, based on currently available technology and current costs. Of further interest is that when one compares the cost of carbon dioxide reductions with the cost of energy, in fact, there is no negative cost as such. Any investment in an energy efficiency technology has a positive energy cost, as suggested earlier by the data in Figure 3. The difference is that the levelized cost of the technology is less than the purchased price of energy. Hence, what appears as a negative cost on the left or Y1 axis of Figure 5 is really an amortized cost of energy efficiency on the right of the Y2 axis.

Figure 5. Interpreting the Marginal Abatement Cost Curve



Source: Author's illustration of supply curves showing comparability of CO_2 on the Y1 or left axis costs with equivalent energy costs on the Y2 or right axis.

There are two final aspects of the evidence to briefly review. The first is associated with the non-energy benefits that typically accrue to energy efficiency investments. The second reflects the changes one might normally expect in the cost and performance of technologies over time. The evidence for these two added benefits is summarized next.

When energy efficiency measures are implemented in industrial, commercial, or residential settings, several "non-energy" benefits such as maintenance cost savings and revenue increases from greater production often result in addition to the anticipated energy savings. Often, the magnitude of non-energy benefits from energy efficiency measures is significant. These added savings or productivity gains range from reduced maintenance costs and lower waste of both water and chemicals to increased product yield and greater product quality. In one study of 52 industrial efficiency upgrades, all undertaken in separate industrial facilities, Worrell et al. (2003) found that these non-energy benefits were sufficiently large that they lowered the aggregate simple payback for energy efficiency projects from 4.2 years to 1.9 years. Unfortunately, these non-energy benefits from energy efficiency measures are often omitted from conventional performance metrics. This omission leads, in turn, to overly modest payback calculations and an imperfect understanding of the full impact of additional efficiency investments.

Several other studies have quantified non-energy benefits from energy efficiency measures and numerous others have reported linkages from non-energy benefits and completed energy efficiency projects. In one, the simple payback from energy savings alone for 81 separate industrial energy efficiency projects was less than 2 years, indicating annual returns higher than 50%. When non-energy benefits were factored into the analysis, the simple payback fell to just under one year (Lung et al. 2005). In residential buildings, non-energy benefits have been estimated to represent between 10 to 50% of household energy savings (Amann 2006). If the additional benefits from energy efficiency measures would be captured in conventional performance models, such figures would make them more compelling.

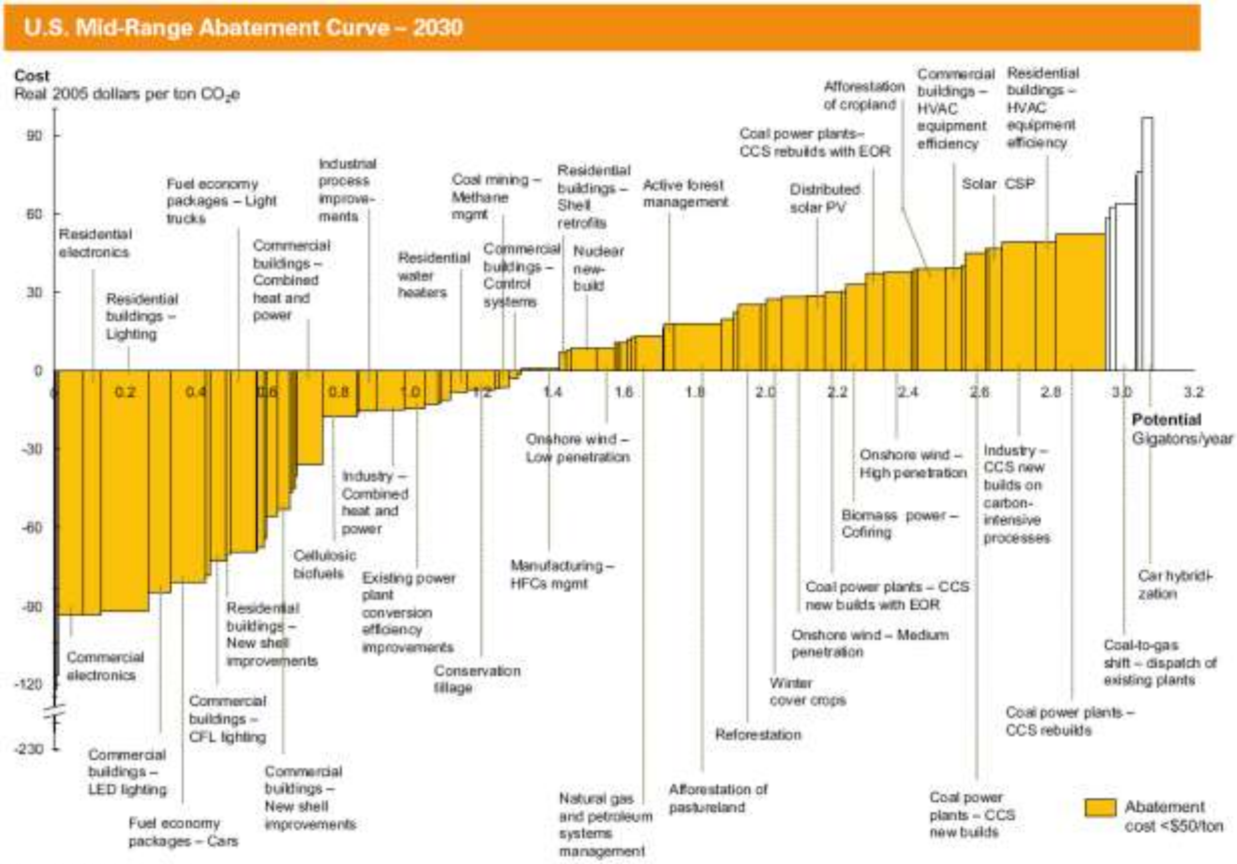
As a strong complement to the likelihood of large-scale non-energy benefits typically omitted from most energy policy assessments, there is also a significant body of evidence that indicates that technology is hardly static and non-dynamic. Laitner and Knight (Forthcoming), for example, cite more than three dozen examples of recent technologies with noteworthy declines in prices coupled with increased technology performance. Their review covers a multitude of end-uses including transportation, appliances, and consumer electronics. The rapid technological change seen especially in semiconductor-enabled technologies has led to cheaper, higher performing, and more energy-efficient technologies (Laitner et al. 2009). The increasing penetration of information and communication technologies interacting with energy-related behaviors and products suggests that energy efficiency resource may become progressively cheaper and more dynamic as the 21st century moves on (Laitner and Ehrhardt-Martinez 2008).

3. The Reality Versus Theory of Cost Estimates

Standard economic policy models have been a favorite methodological approach to evaluate energy and climate policy dating back to the 1970s and before. These models represent linkages among the many sectors of the economy as well as between the supply and demand for energy as well as other goods and services. While these models can provide some insights, in particular in elucidating the indirect effects of policies, in many ways they are inherently biased against the type of bold energy and climate policies that are consistent with sound economic policy and necessary to avoid the most deleterious impacts of global warming. They fail to value the many co-benefits associated with climate solutions, such as those we have discussed as being associated with energy efficiency measures, i.e., improved energy security, air quality, and public health. But this is a common limitation that the current analysis does not seek to remedy. More to the point, most of the standard economic policy models operate under an optimality assumption that obscures a range of important sub-optimal behaviors. Essentially, these models assume that people, firms, and markets are perfectly rational, and that markets are perfectly competitive (Laitner 2009c).

In fact, because of a range of market imperfections and market barriers, real world behavior leaves substantial room for public policy to induce behavior changes that produce economic benefits. The entire negative cost range of reductions found in the well-known McKinsey abatement cost curve exists because price signal alone is not enough. Carbon pricing, the correction of the current under-pricing of fossil fuel-based energy due to the failure of our current economic system to account for the costs of greenhouse gas emissions (i.e., internalization of the current carbon pollution externality), is a necessary but not sufficient condition for the most cost-effective package of policies. Without a robust set of complementary policies, in particular ones targeting energy efficiency gains, a host of negative and low cost emission reductions will be missed. The more stylized “top-down economic models” fail to illuminate this important lesson for policymakers.

Figure 6. The McKinsey Carbon Abatement Cost Curve



Source: McKinsey analysis
Note: The McKinsey report only examines a scenario through 2030. NRDC recommends a goal of 80 percent emissions reductions by 2050.

One classic example is the misaligned incentive that exists for those living in rental units when the renter pays the energy bills but the landlord purchases the large appliances such as refrigerators and water heaters. In this case, the purchaser of the durable good does not reap the benefits of greater energy efficiency. The Market Advisory Committee of the California Air Resources Board (2007) provides a nice short overview of key market failures.[13] A deeper exploration of the types of market barriers is beyond the scope of this report, but others have done work to map this terrain (Levine et al. 1995; Brown 2001; Levinson and Niemann 2004; Sathaye and Murtishaw 2004; Murtishaw and Sathaye 2006; Geller et al. 2006; Natural Resources Defense Council 2009; Brown et al. 2009).

It is worth noting that some economists cling to their belief of the magic of the market—and tend to dismiss the amount of negative cost emission reductions available (Goldstein 2007; Levine et al. 1995). That said, this is hardly a monolithic view. Other economists certainly do recognize the significance of market failures and imperfections beyond the lack of a price on carbon. The importance of reflecting policies that might be directed at market failures was explored, in part, by

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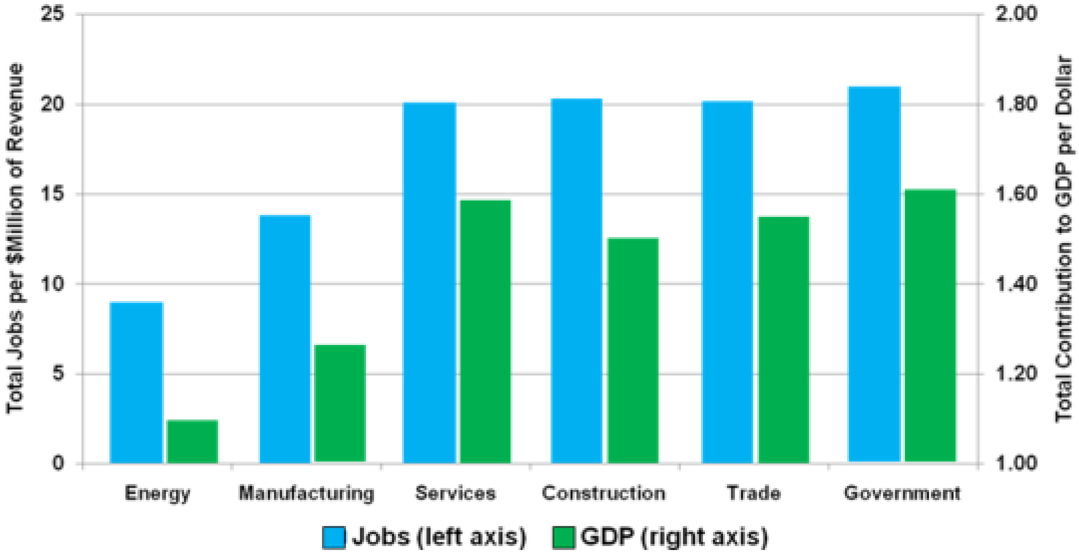
[13] Following are examples of important market failures: (1) Step-Change Technology Development—where temporary incentives will be needed to encourage companies to deploy new technologies at large scale to the public good, because there is otherwise excessive technology, market, and policy risk. Examples of remedies are renewable portfolio obligations, biofuel requirements, and the Low-Carbon Fuel Standard. (2) Fragmented supply chains—where economically rational investments (for example, energy efficiency in buildings) are not executed because of the complex supply chain. Examples of remedies are building codes. (3) Consumer behavior—where individuals have demonstrated high discount rates for investment in energy efficiency that is inconsistent with the public good. Examples of remedies are vehicle and appliance efficiency standards and rebate programs (California Air Resources Board 2007, p.19).

Hanson and Laitner (2004). In one of the few top-down models that explicitly reflects both policies and behavioral changes as a complement to pricing signals, they found that the combination of both price and non-pricing policies actually resulted in a significantly lower carbon permit price to achieve the same level of emissions reductions.

D. Evidence for the Larger Economy-Wide Benefits

As one might imagine, providing significant energy bill savings through cost-effective energy efficiency improvements would clearly benefit the economy. At the same time, it turns out that redirecting resources away from energy into almost any other sector of the economy will also amplify the number of jobs and even boost overall economic activity. So the good news, as we discuss below, is that if we do it smart, we might promote an even more robust economic future even as we dramatically increase overall energy productivity.

Figure 7. Employment and GDP Contributions for Key Economic Sectors



Source: 2009 IMPLAN data set for the U.S. economy (IMPLAN 2011)

Figure 7, above, shows two sets of economic impact coefficients for the United States. The first, looking at the vertical axis on the left, is the total number of jobs directly supported by spending within six major sectors of the U.S. economy. For example, revenues received by the different energy sectors require on average only 9 total jobs per million dollars of spending. All other sectors support a larger number of direct and indirect jobs for that same one million dollars of spending. The second, now looking at the vertical axis on the right, is the rate of the value-added or contribution to GDP that is supported for each of the major sectors of the economy. Here the data show each dollar spent on energy contributes about $1.13 cents of GDP return while all other sectors show a larger value-added benefit (see Appendix B for a more complete review of these sectoral differences and their implication for the national economy given changes in overall spending).

The state of California has had the most comprehensive and aggressive energy efficiency policies for decades. As a result, while per capita energy use has increased since 1970 in the rest of the country, in California it has fallen 18% below 1970 levels and the state's per capita electricity consumption is about 40% less than the country as a whole (Next 10 2009). Despite relatively high electricity rates, California has the fifth lowest electricity bill in the country as a fraction of Gross State Product. University of California Professor David Roland-Holst has investigated the historical macroeconomic effects of these policies. He concludes that California's efficiency programs from 1972 onward have created about 1.5 million full-time jobs with a payroll of over $45 billion and saved households $56 billion in energy costs over that same period. One causal factor is the same shift from energy-intensive economic activity to labor-intensive economic activity due to efficiency investments that we document in this work (Roland-Holst 2008). This work is also consistent with the meta-review of four dozen state and regional impact assessments completed by ACEEE (Laitner and McKinney 2008).

With the evidence highlighted in this discussion, together with other documented assumptions described in the remaining part of this report and the accompanying appendixes, we can evaluate how changed investment and spending patterns might positively impact energy production and consumption patterns for the U.S. economy as a whole.

III. LONG-TERM ENERGY EFFICIENCY

At this point we now lay out a range of energy efficiency opportunities as they might be driven by productive investments and smart energy policies for the U.S. In this exercise we take a long view by examining the set of energy efficiency improvements as they might impact our nation's residential and commercial buildings and our industries as well as our transportation system and energy infrastructure by the year 2050. We build on both the *Annual Energy Outlook 2010* and the *Annual Energy Outlook 2011* published by the Energy Information Administration (EIA), extending its forecast from the 2035 end-year that it now reflects out to the year 2050. This business-as-usual or **Reference Case** scenario reflects more than 50 key variables that affect total energy use in the United States—including growth of the economy (measured in constant dollars as Gross Domestic Product), the set of prices that affect specific demands for energy (measured in constant 2009 dollars to reflect the base year of the model—further described in Appendix B), and the end-use or delivered energy that might be required or demanded by household and business consumers.[14] We provide two distinct scenarios for the four end-use sectors. The first scenario, referred to as the **Advanced Scenario**, assumes only the penetration of known but advanced technologies. The second scenario, which we call the **Phoenix Scenario,** incorporates other changes—including greater infrastructural improvements and some displacement of existing stock to make way for newer and more productive energy efficiency technologies. We are not saying that the Phoenix Scenario represents the limits of energy efficiency—for example, Goldstein (2009) discusses how even higher efficiency savings may be possible.

A. The Residential Sector

Our definition of the *residential sector* is that of the *Residential Energy Consumption Survey* (RECS, EIA 2005c). It includes all housing units occupied as primary residences, whether single-family, multi-family, or mobile homes. Basically, our Advanced Case technology scenario assumes very substantial changes in the performance of the building shell, its equipment, and the appliances and devices in the living space. These changes are constrained to high penetration levels of products and processes available today. In contrast, the *Phoenix Scenario* assumes foreseeable improvements not yet commercially available.

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[14] There is one important caveat to be kept in mind when examining the emerging findings of these various sector reviews. Our sector assessments only "benchmark" to the EIA *Annual Energy Outlook* (AEO). We did not actually run the EIA's National Energy Modeling System to generate an exact match of the Reference Case assumptions typically found in the AEO. First, as noted, the AEO extends only out to the year 2035 rather than 2050. Nor does it have the capacity to integrate the kinds of changed technology assumptions and characterizations envisioned here. For these and other reasons, we looked to the AEO as a means to generate an internally consistent set of energy consumption patterns within each sector that are also linked to an expected set of economic and engineering variables. This, in turn, provides us with reasonable set of Reference Case outcomes that—given the kinds of changes we describe elsewhere in this study—enable us to compare the two alternative high efficiency energy scenarios with the business-as-usual projection. In this way we are able to evaluate the impacts of the high efficiency paths for their potential benefits to the larger economy (see Appendix A for a further discussion of this perspective). Consistent with the philosophy of Stanford University's Energy Modeling Forum (Huntington et al. 1982), we are modeling for insights rather than exact numbers—or in this case, evaluating reasonable differences between sector assumptions as we explore possible benefits to the U.S. economy.

For example, we assume that the remaining heating loads in both scenarios are met with advanced equipment and improved distribution systems (see Table 1).

Table 1. 2050 Advanced Technology and Phoenix Case Heating Technologies

	2050			
	Advanced		Phoenix	
Parameter	**Gas**	**Electric**	**Gas**	**electric**
Average AFUE	1.0		1.3	
Electric heat effectiveness		3.0		4.0
Relative system efficiency	1.5	3.8	2.0	5.0
Source Quads to meet 2010 loads	2.1	0.3	1.6	0.2
Heat Provided				
Market Share (%)	40%	60%	30%	70%
HVAC by fuel (quads)	0.4	0.4	0.2	0.5
Total heating (quads)	0.8		0.6	

Notes: AFUE is a measure of the annual efficiency of a heating season, averaged over different operating conditions. "Electric heat effectiveness" is analogous to a system coefficient of performance (COP). "Relative system efficiency" includes distribution efficiency, load following, etc.

Notice that the 2050 heating market moves from a 40%/60% share in the gas/electric mix in the Advanced Scenario, to a 30%/70% share in the Phoenix Scenario. Where gas is used, we stipulate combination gas space and water heating equipment with performance equivalent to today's condensing equipment (that is, equipment that provides useful services from more than 90% of the heat value). For Phoenix, we use a higher criterion, performance that could be achieved by gas heat pumps (engine driven or absorption), comparable to a COP of about 1.3 for gas-heated houses (COP means Coefficient of Performance, the unit-less ratio of output energy to input energy). In both , we achieve dramatic electric heat savings by eliminating resistive heating, instead using advanced air source and ground source heat pumps in the two . We did not assume any residential gas air conditioning, for either scenario.

The overall approach in the residential sector begins with estimating the housing stock changes that might be anticipated over the study time horizon, in this case 2012 through 2050. These changes include increases in the total number of households as well as the numbers of single family, multifamily, and mobile homes for both the Advanced and Phoenix . From this, we look at the building energy loads and explore feasible changes in both new construction and in retrofits to existing homes.

We start with building shell load reductions, stipulated as in Table 2.

Table 2. Percent Shell Load Reduction Relative to Today's Practice

	Heating		**Cooling**	
	New	Existing	New	Existing
Advanced	70%	40%	70%	40%
Phoenix	90%	55%	90%	60%

These large shell load reductions leave us to be relatively indifferent about the actual ratios of single-family to multi-family: As the fraction of shared walls rises, the dependency on actual insulation levels decreases, Intuitively, for the same floor space per household, given the complexities of large multifamily systems, there is probably little difference between highly efficient single family detached, town houses at 15–20 per acre, and multi-story multifamily buildings.

We postulate large improvements in the energy use of products governed—or likely to be governed—by efficiency standards. Table 3 shows our estimates of improvements in energy needed for these functions, as a fraction of our baseline.

After establishing the likely 2050 patterns for the projected housing stock (number, type, and size of homes), we then consider technologies to meet the small residual loads. Throughout, we allow ourselves to extrapolate modestly from today's emerging technologies and practices, and provide examples of technologies that could meet those needs in a more energy-efficient manner.

Some key assumptions:

- We have not changed the total number of housing units from those found in the EIA projections. In contrast, we did reduce Phoenix commercial space by 20%.
- In both , we have moved half of the present mobile home population into single family or multifamily units—effectively postulating that the pre-2030 or so mobile homes are replaced by units built to the same performance specifications as single family and multi-family homes. These could be very efficient mobile homes, or other manufactured housing. This should be possible, since the expected life of mobile homes is shorter than the other stocks. Note that we have not assumed any specific average housing density, but only that shell loads are reduced enough that it matters relatively little whether the boundaries of housing are other units or ambient air and solar loads.
- We assume different load reduction fractions associated with the building shell or envelope in the Advanced and Phoenix Scenarios, making an appropriate distinction between both new and existing housing (Table 2, above).

1. Further Details

Our analysis of the residential end-use sector begins with ACEEE's estimate of the 2050 housing stock as an extrapolation from the EIA projections for 2035. For both, we moved half the mobile home stock into single family, and half into multifamily. The mobile home stock turns over relatively quickly, so we assumed that the remaining mobile homes were built to the same shell efficiency standards as the other categories—that is, the obsolete HUD Code has given way to a proper and more efficient set of building codes. The mix of high-rise and small multi-family and their respective energy intensities is taken from the Department of Energy's Building Energy Data Book (BEDB) (DOE 2009). For the single family housing stock only, we estimate that median house size reverts to the 2010 median from the extrapolated 2050 value, but this is subsumed in the appropriate adjustments to the building shell loads.

Internal gains. Internal gains reflect heat dissipation by people, pets, appliances, lighting and all the entertainment and information equipment in the house. We have moderately reduced this in both . This assumes that further improvements in the efficiency of appliances (refrigerators, clothes washers, etc.) will be offset in part by new energy uses, such as greater use of electronic devices (such as voice-activated energy management systems).

Shell loads. For both , we could have justified starting with the assumption that all housing in 2050 was built or retrofitted to roughly "Passivhaus" standards, which imply 90% reduction in total energy use (Klingenberg et al. 2008). Instead, we reserved the "Passivhaus" assumption for new construction in the Phoenix Scenario:

To achieve these reductions in the shell load in existing houses, we assumed external insulation would be required in some houses. However, the most common, post-war, types of residential units could generally be done with proper internal work to insulate walls and all other edges of the thermal envelope. We explicitly assume that there are no ducts or other energy carriers external to the building shell in 2050. These changes reduce shell loads to a fraction of or small multiple of the internal gains from lighting, appliances, other electricity-using gear, and people. Note that internal gains/loads reduce heating energy required, but add to cooling energy required to remove the internal loads and maintain comfort.

With today's construction and retrofit technologies, and current energy prices, the aggressive new construction and retrofit technologies we assume might have paybacks measured in scores of years. Thus, our assumptions rest on some future combination of three assumptions: (a) higher energy prices that are perhaps due to carbon constraints or the simple depletion of high-grade natural resources; (b) other benefits, discussed below, that go a long way to offset the higher energy efficiency premium cost; and (c) a re-invention of the construction industry that generates significant cost savings. Other benefits can be substantial and include improved occupant comfort from homes without drafts and cold spots, easier-to-clean windows, and reduced fabric fading as new windows generally reduce ultraviolet light that causes fading. Cost savings can be readily visualized for new construction, where "stick-built" homes will give-way to "mass customization" using industrial processes which lead to "installer-proof," high-performance, building shells that require relatively little equipment to satisfy comfort needs. For existing construction, we anticipate great savings from economies of scale as the industry learns the least-cost ways to achieve high performance for all the different building stocks.

Non-energy code end uses. We made estimates based on trends and best available current technologies for loads covered by present or anticipated energy standards (refrigeration, cooling, dryers, freezers, lighting, clothes washers, dishwashers, TVs, set-top boxes, PCs and related), and for "other miscellaneous uses." Together, these groups are projected to need 9 quads, almost ¾ of the total estimated use in 2050. Of this, "other" or "miscellaneous loads" is 5 quads by itself, about 40% of the total of 13 quads. "Other uses" includes set-top boxes, televisions, other audio and video equipment, ceiling fans, coffee machines, microwave ovens, portable electric spas, rechargeable electronics, and security systems (TIAX 2006). It would also include hobby equipment (power tools, sewing machines, home ceramic kilns), and hot tubs.

Heating, ventilating, and air-conditioning. We assume that gas and electricity are both still used as "prime movers" for space conditioning and water heating, in both scenarios in 2050. All equipment, whether gas or electric, is multi-function (e.g., ventilation + space and water heating; space conditioning and water heating. All has variable output to match loads with minimum cycling. In general, modulation improves equipment efficiency by giving larger effective heat exchanger surface areas at loads lower than the design peak. As important, in 2050 there are no longer any low-performance ducts in any buildings. Ductwork has been brought inside the thermal envelope or abandoned in favor of hydronic equipment (with local fan-coil units) or "multi-splits" that carry energy via refrigerant phase-changes.

We implicitly assume that multi-function appliances are prevalent by 2050, with gas appliances providing space and service water heating where natural gas is used. Electric heat pumps provide air conditioning, as well. The incremental savings from reduced equipment cycling for combo appliances do not show up in the granularity of this analysis. For the Advanced Scenario, the equivalent seasonal heating efficiency moves from <0.81 today (including distribution losses) to 1, reflecting abandonment of non-condensing heat appliances, with some penetration of triple-function gas heat pumps. The Phoenix Scenario assumes widespread use of advanced gas HP with an equivalent 1.3 AFUE (Annual Fuel Utilization Efficiency),[15] Similarly, resistance electricity is essentially completely replaced by advanced heat pumps, both air-source and ground-source. We assume "fleet" average for the Advanced and Phoenix Scenarios that are respectively 3.0 and 4.0 times higher than the current electric fleet consumption, with its high penetration of resistance heat (including electric furnaces).

By 2050, distribution energy losses have been essentially eliminated primarily due to a fairly large shift from duct work to energy delivery in hydronic and refrigerant-based (multi-split) systems. With

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[15] AFUE (Annual Fuel Utilization Efficiency) is the federal efficiency metric. It is a seasonal value.

greatly reduced shell loads, energy distribution to avoid hot and cold spots is less important, but we visualize both multi-split and fan-coil of zoned hydronic heat pump systems as handling energy distribution in most housing units. The remaining ducted systems are entirely within the thermal envelope by design or from retrofits to the existing stock.

Traditionally, houses used window-opening and spot fans (bath and kitchen) for ventilation. New energy standards require or credit mechanical ventilation. Today, (excess) ventilation is considered to account for 1/3 to ½ of average annual HVAC cost. Tightening buildings and installing mechanical ventilation will reduce this cost significantly, but the effect is implicitly included in our HVAC treatment.

Furnace fans & pumps. These move energy and introduce ventilation air. For 2050, we greatly reduce the fraction of houses with forced-air distribution systems. To compensate, water-based energy distribution almost doubles, and “other” systems increase greatly. This reflects large expected growth of energy distribution by refrigerants/phase changes (multi-split systems). This will proceed because the systems require less space in the house, perform well, and have no distribution losses (more specifically, distribution energy is fully reflected in the efficiency rating). In addition, it is much easier to abandon ductwork in favor of hydronic and refrigerant energy distribution, because the latter systems have much smaller size and “footprint” in the building, facilitating installation with minimum décor disruption.

Water heating. We assumed gas, electricity, and solar contributions for water heating. For gas use, we are implicitly considering integrated space and water heating appliances, with EF (Energy Factor) of condensing appliances in the Advanced Case (EF 0.85 from a mixture of tank and tankless approaches), and gas heat pumps in the Phoenix Case (EF 1.3). We assign an effective EF of 5 to solar, corresponding roughly to a solar fraction of 0.8.

Our water heating energy treatment also includes significant improvements in distribution efficiency, that is, the losses of hot water energy in the distribution pipes of a house. We use conservative values (in the range of 80%), with different values for new construction than for the existing stock. Similarly, we assume moderate further improvements to fixture (faucet, showerhead) efficiency, using the EPA WaterSense requirements as our basis. Note that we are assuming no significant market penetration of hot water uses that are not prevalent today, such as heated indoor lap pools, or much wider use of hot tubs. In both, we implicitly assume that most new construction includes drainwater heat recovery from showers, a promising heat recovery application.

What’s missing? We did not explicitly include solar space heating. Passive (solar) gains are implicit in advanced glazing and overhangs where appropriate for shading, but we do not explicitly offset the small fuel requirements with a solar fraction. Given the magnitude of the residual shell loads of very well-constructed houses, we find little justification for the use of active solar systems.

2. Reference Case

With this background, we can consider how energy is used in the Reference Case. The Reference Case is based on the EIA 2010 *Annual Energy Outlook* (EIA 2010a), but since this does not extend past 2035, ACEEE has estimated energy use to 2050 by extrapolating from the growth rate over the 2030-2035 period. Table 3 builds up energy use and energy use intensity (Btu/sf) for 2050, based on this extrapolation. We have done the extrapolation by energy service (heating, cooking, etc), and the color codes isolate “Energy Code” (tan), “Standards” (pale green), and “Unregulated” (pale yellow) loads.

Table 3. Residential Building Energy Use, by Service, 2010 and 2050

Service:	Reference Case (Quads) 2010 total	Reference Case (Quads) 2050 Total	EUI, Btu/sf-yr 2010	EUI, Btu/sf-yr 2050	EIA Growth Factor
Space Heating	5.4	4.9	28,000	13,200	-52.9%
Space Cooling	2.4	3.4	12,500	9,100	-27.2%
Water Heating	3.0	3.1	15,200	8,400	-44.7%
Ventilation (not in RECS)	0.0	0.0	-	-	
Refrigeration	1.2	1.4	6,000	3,700	-38.3%
Cooking	0.6	0.8	3,000	2,100	-30.0%
Dryers	0.9	1.1	4,800	3,100	-35.4%
Freezers	0.3	0.3	1,300	800	-38.5%
Lighting	2.3	1.3	11,800	3,500	-70.3%
Washers	0.1	0.1	500	200	-60.0%
Dish Washers	0.3	0.4	1,500	1,100	-26.7%
Television & Set-Top Boxes	1.2	1.8	6,100	4,900	-19.7%
PCs and Related	0.6	0.7	3,100	1,900	-38.7%
HVAC Fans & Pumps	0.5	0.7	2,400	1,800	-25.0%
Other Uses	3.0	5.9	15,400	16,000	3.9%
Subtotals					
"Energy Code" Loads	14	13	69,900	36,000	
"Standards" Loads	5.1	7	26,300	17,800	
Other Uses	3.0	6	15,400	16,000	
Grand Total	22.1	21.7	111,600	69,800	

The "Quads" columns are per-service expectations. "EUI" columns divide total energy by EIA 2010 total residential square footage (sf) and the ACEEE extrapolation for 2050. The right-most column, "EIA Growth Factor," reflects and extrapolates the EIA judgment of the effects of technology changes on the specific energy use category, divided by EIA's stipulation of residential building floor area and the ACEEE extrapolation. For example, space heating loads decrease from 28,0200 Btu/sf in 2010 to 13,200 in 2050.

Consider the "energy code" loads, highlighted in tan. The extrapolation from EIA 2035 indicates aggressive efficiency improvements in the baseline energy use: 27% (cooling) to 70% (lighting), resulting from EIA's assumptions on technology changes. Similarly, EIA projects large changes in the "standards" loads for equipment and appliances regulated by DOE (highlighted in light green): the typical improvements reduce energy use by one third, with much more (60%) for dryers. Only "other uses" grow modestly. This category may include water treatment and delivery, and certainly includes all of the electronics and "hobby" loads that are not subject to regulation by DOE.

3. Advanced Scenario

Table 4 presents ACEEE estimates for the Advanced Scenario. In these estimates we use today's best available technologies and those readily foreseen as commercially viable for all residential buildings. This implies an aggressive, mandatory, retrofit program to bring all existing buildings up to the level of performance shown in Table 2 by 2050. Such a program might be financed by a PACE-type mechanism,[16] with investments amortized on the property tax bill and any residual obligation at time of sale transferred with title.

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[16] PACE is Property Assessed Clean Energy and refers to a mechanism to lend money to homeowners and have

Table 4. Code, Standards, and Other Loads in the Advanced Scenario

Service	Reference Case (Quads)		Advanced Case (Quads) 2050 total	% of 2050 Reference Case
	2010 total	2050 Total		
Space Heating	5.4	4.9	0.47	10%
Space Cooling	2.4	3.4	0.54	16%
Water Heating	3.0	3.1	2.32	75%
Refrigeration	1.2	1.4	1.03	75%
Cooking	0.6	0.8	0.72	90%
Dryers	0.9	1.1	0.17	14%
Freezers	0.3	0.3	0.23	75%
Lighting	2.3	1.3	0.42	33%
Washers	0.1	0.1	0.06	71%
Dish Washers	0.3	0.4	0.37	91%
Television & Set-Top Boxes	1.2	1.8	0.84	46%
PCs and Related	0.6	0.7	0.30	42%
HVAC Fans & Pumps	0.5	0.7	0.28	42%
Subtotals				
"Energy Code" Loads	14	13	3.6	27%
"Standards" Loads	5.1	7	4.1	62%
Other Uses	3.0	5.9	5.34	90%
Grand Total	21.7	25.9	13.1	51%

Building code loads. The first observation is that about 90% of **space heating loads** are eliminated. The combination of outstanding building shells and advanced technologies allows almost all buildings to be heated by internal gains, combination water heating equipment, and other advanced technologies. We essentially eliminate duct losses by placing ducts in conditioned spaces or in favor of heat transport by refrigerants and water, dramatically reducing inefficiencies. As a corollary, the percentage **space cooling** reduction is smaller, since the internal loads of houses still must be dissipated. In this scenario, space cooling and space heating are about equal at ½ quad per year, while heating is twice as large in 2010. Conversely, we reduce water heating energy use relatively little, to 75% of the EIA extrapolation. Our Advanced Scenario looks at large-scale replacement of electric resistance with heat pump water heaters, but there are much smaller changes in the transition from atmospheric to condensing gas.

Standards loads, in our advanced projections, drop to 62% of the Base Case. Lighting loads decrease 67% from universal replacement of today's incumbent technologies with solid state lighting. In the residential sector, we do not assume additional savings from major changes in lighting "ambience." For example, we do not assume diffuse glowing ceilings providing ambient lighting, supplemented by task lighting as desired. We note that residential lighting may "turn over" more quickly than water heating or space conditioning. Dryers also improve by a remarkable 86%. In this case, was are assuming transitions to modulating gas burners and complete replacement of resistance electric dryers with heat pumps. We do *not* require "solar dryers," also known as clothes lines.

Other loads. We reduce the EIA projections for these miscellaneous energy uses by 10% in the Advanced Scenario. We can likely produce more efficient lawnmowers, electronic games, hobby equipment, and the like, but for now as a conservatism, have only included limited such changes in

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the loan payment be included in property taxes.

our analysis. Additional savings in these areas can be used to make-up for areas where a reader may feel we have been too aggressive in our savings assumptions.

4. Phoenix Case

Table 5 presents ACEEE estimates for residential energy use in the Phoenix Scenario. The Phoenix Scenario deviates from the Advanced one in a few respects: First, we reduce weatherized (heated) floor space to 85% of the value used in the Base and Advanced Cases, assuming that smaller households (and more expensive energy) will reduce the fraction of very large houses. Second,, we assume more efficient technologies, such as gas heat pumps. This includes virtual elimination of equipment outside the thermal envelope (except condensers), and reduction of distribution losses to *de minimus.* For this, we substitute hydronic and refrigerant energy distribution for ducts and fans. Small fans and ducts are only used for ventilation and some air movement for comfort.

Table 5. Residential Energy Use Components in the Phoenix Scenario

Service	**Reference Quads**		Quads **total**	**% of EIA 2050**
	2010 total	**2050 total**		
Space Heating	5.4	4.9	0.2	5%
Space Cooling	2.4	3.4	0.3	10%
Water Heating	3.0	3.1	1.0	31%
Ventilation (not in RECS)	0.0	0.0		
Refrigeration	1.2	1.4	0.7	50%
Cooking	0.6	0.8	0.6	70%
Dryers	0.9	1.1	0.1	11%
Freezers	0.3	0.3	0.2	50%
Lighting	2.3	1.3	0.4	33%
Washers	0.1	0.1	0.1	71%
Dish Washers	0.3	0.4	0.4	91%
Television & Set-Top Boxes	1.2	1.8	0.8	46%
PCs and Related	0.6	0.7	0.3	42%
HVAC Fans & Pumps	0.5	0.7	0.2	28%
Subtotals				
"Energy Code" Loads	14	13	1.7	13%
"Standards" Loads	5.1	6.6	3.5	53%
Other Uses	3.0	5.9	4.8	80%
Grand Total	21.7	25.9	10.0	39%

Building code loads. The loads are dramatically reduced, with aggressive assumptions that include:

- “Perfect” building envelopes and more shared-wall construction that reduce heating loads to little more than the internal gains of the housing.
- Complete elimination of energy distribution in air (except as part of ventilation); this is replaced by refrigerant and hydronic energy distribution.
- All gas space and water heating is built around “combo” gas heat pumps that provide both services; electric space and water heating also uses multifunction heat pumps. We implicitly include solar hot water boost supplemented with point-of-use water heating, just by the aggressive efficiency multipliers we use.
- Lighting is completely solid state, and meets or exceeds 165 lumens/watt (compared to the best fluorescent lighting systems sold today which are around 100 lumens per watt.

For the "standards" loads, we take varying approaches, as shown in the table. We assume very large reductions in cooking and refrigeration, in part technology driven and also assuming increased use of foods that have been irradiated and pre-cooked, which do not require refrigeration for preservation, or conventional cooking preparation. On the other hand, we will still want some refrigeration for food that tastes better cold or frozen (ice cream, ice, white wine, orange juice). Note that we allow a margin of error by not reducing freezing energy relative to the EIA extrapolation. We assume that much of the cooking will be microwave—but that households will still have stoves for special food preparation.

Miscellaneous loads. In the Phoenix Scenario, we decrease these from the Base Case by 20%, as contrasted with the 10% reduction in the Advanced Scenario. We are conservative because we are confident that many of the existing loads (service station and medical equipment, for example) can be made more efficient, but over four decades we anticipate a host of new "other" energy consuming appliances and equipment. While these new other loads are included in the Reference or Base Case, our conservative estimate of savings here allows room for potential additional growth in miscellaneous loads.

5. Discussion

Our analysis suggests a potential reduction in residential energy use by an estimated 49 to 61% for the Advanced and Phoenix Scenarios, respectively.[17] These savings estimates are larger than are typically found in most nearer-term assessments, but with nearly 40 years to implement these, more systematic changes are possible. Actual energy use could be much higher if the policy environment and energy prices do not force major changes in how buildings are constructed, and enable deeply retrofitting the existing stock.

Figure 8 illustrates these changes as stacked bars, as labeled. The first set, EIA 2010, is the set of initial conditions. The three other bars are 2050 cases. "EIA" is ACEEE's extrapolation from the 2035 EIA projection. "Advanced" and "Phoenix" Cases are our study cases. On each bar, the uppermost (light green) segment or band represents "Standards" loads, those that are or can be regulated by standards for equipment and appliances, whether boilers or computers. Standards loads drop by 38% and 47% in the respective cases.

The middle band represents the loads regulated by building energy codes. It accounts for most of the changes in energy consumption in our cases, with 73% and 87% reductions. These are the direct result of our assumptions about improved envelope quality, and large changes in space conditioning and hot water services (including delivery). These changes are large in comparison with those in current energy codes that are considered aggressive, such as the IECC 2012. However, our estimates are not constrained by current cost-effectiveness but reflect our judgment of technical and economic feasibility at a large scale, given enough time. In context, they are less stringent than the current Passivhaus specification, which requires 90% reductions in *total* building energy use (Klingenberg, Kernagis, and James 2008).

Finally, note that the lowest bar segment, "miscellaneous" loads, only modestly changes—and the changes are exogenously forced by our model inputs. As discussed above, these are poorly understood and highly variable residential loads and we use conservative assumptions to allow for potential new loads not yet a part of American homes. We can characterize them as everything that has a plug, but is not a regulated appliance. Notable examples include "set-top boxes" that interface televisions and computers to high bandwidth connections (evolved from cable "boxes"), advanced game consoles, heated fish tanks (and other pet gear), battery chargers, and innumerable types of hobby and home business equipment. Thus, in the Advanced Case these miscellaneous loads are about half of residential energy consumption, and 60% in the Phoenix Case. Clearly, these areas

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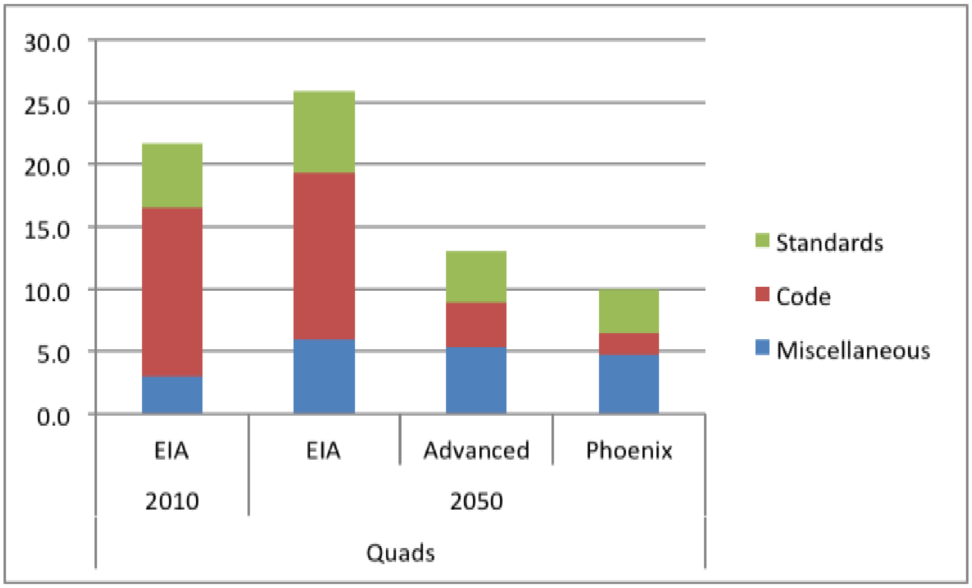
[17] Please note that these values are different from the values reported in Table 17 since the values reported here do not include improvements in the efficiency of the electricity generation, transmission and distribution system while the values in Table 17 do include electric system improvements.

require much further study, and the creation of mechanisms to assure that their energy use (active, standby, and off) is commensurate with their value to consumers.

Figure 8. Projected Residential Energy Use by Category in the 2010 and 2050 Cases



B. The Commercial Sector

This section provides an overview of the methods used for estimating energy use for commercial buildings in the Reference Case, in the 2050 Advanced Case and the Phoenix Case. We first extrapolate from the 2035 Energy Information Administration (EIA) forecast to 2050 (our baseline scenario), to understand the assumptions about technology improvements and other changes built into EIA's National Energy Modeling System (NEMS). Based on technology assumptions for the Advanced Scenario, we then change the energy intensity of the technology services for each end use. For the Phoenix Scenario we further adjust total expected commercial sector floor area to reflect a change in the expected demands for energy services. We also apply different improvement coefficients for some specific end-use service applications in both.

Our definition of the *commercial sector* is that of the *Commercial Building Energy Consumption Survey* (CBECS, EIA 2008). It includes all commercial buildings, in classes including education, food sales, food service, health care, lodging, mercantile, office, public assembly, public order and safety, religious worship, service, warehouse and storage, and others. Basically, our *Advanced Case* technology scenario assumes very substantial changes in the performance of the building shell, its equipment, and the appliances and devices in the living space. These changes are constrained to high penetration levels of products and processes available today. In contrast, the *Phoenix Scenario* assumes foreseeable improvements not yet commercially available.

For example, we assume that the remaining heating loads in the Advanced Scenario are met with combination gas space and water heating equipment with performance equivalent to today's condensing equipment (that is, equipment that provides useful services from more than 90% of the heat value, including latent heat, of the fuel). For Phoenix, we use a higher criterion, performance that could be achieved by gas heat pumps (engine driven or absorption), comparable to a COP of about 1.3. In both, we achieve dramatic electric heat savings by eliminating all resistive heating, instead using advanced and even more advanced (air source and ground source) heat pumps in the two . We did not assume any gas air conditioning, for either scenario.

1. Some Key Assumptions

Building characteristics. As discussed in the Methods section below, we aggregate the eight size classes and fifteen building use types of EIA (2005b) into three building categories: Small, medium, and large. In the Advanced Case, the total floor space is based on extrapolation from the NEMS 2035 estimate to 2050, as used throughout this project. For the Phoenix Case, we reduce total commercial space from 71,700 million square feet to 57,400 million sf, or 80% of the Advanced Case value. We also modestly redistribute floor area fractions among the size classes, allocating relatively more space to medium-sized, community-scale buildings than to the largest ones. This change corresponds to expected "densification" of commercial space in response to an energy- and carbon-constrained world. Some might argue that current trends in "telecommuting," and internet purchases instead of "brick and mortar" stores would allow a larger change in the projected commercial building space. They might point out trends in religious attendance decreasing that sector, and large expected changes in education as also impacting space needs. We have chosen to not make these assumptions, noting that they would allow additional savings beyond those calculated here. Table 6 summarizes our assumptions.

Table 6. 2050 Commercial Building Characteristics

Floor Area and Technology Assumptions			
Class by size	**Small, <5000 sf**	**Medium, 5000 to ~35,000 sf**	**Large, > ~35,000 sf**
Number in size class (thousands)	2600	1900	400
Percent of total buildings	54%	39%	8%
Floor area (millions of square feet)	6900	24400	40400
Floor space distribution, Advanced	10%	34%	56%
Floor space distribution, Phoenix	10%	45%	45%
New building construction	SIP-like facades or exterior insulation, super windows or restricted glazing area		
HVAC	"Residential"	Unitary	Built-up
Ventilation	HRV-ERV	HRV-ERV	Advanced
Service water heating	POU	POU	Varies
Number of floors	1 or 2	1 or 2	Multi
% of floor area with daylighting, new & existing buildings	0.6	0.5	0.1
Artificial lighting, lumens/Watt	165	165	165

Notes: 2050 Advanced Scenario uses the baseline floor area and space distributions. Changes in Phoenix Scenario noted in table. "SIP" is "Structural Insulated Panel, a well-established residential technology with analogues for larger commercial buildings. "HRV-ERV" means Heat Recovery or Energy Recovery Ventilator, depending on whether latent heat recovery is included. "POU" means point of use water heater, as contrasted with central system with distribution piping.

According to the Federal Energy Management Administration (FEMA), "[t]he effective life of an office building is 20 to 30 years, after which major renovation and updating is normally necessary" (FEMA 2004). There is certainly a "long tail" of commercial buildings that are not renovated this frequently, such as houses of worship and commercial buildings in distressed areas. We infer that short service lives between major renovations are normative. Thus, our working assumption is that commercial buildings can be brought to very high performance levels by 2050. For existing buildings, this is demonstrably feasible in almost all cases with exterior insulation of exposed walls. New buildings, even high rise, can also include exterior insulation that is thermally isolated from the structure (Lstiburek 2007).

How big is this "long tail"? For this question, we examine the "AEO 2010 Extended to 2050" Reference Case. Table 7 summarizes the calculations:

Table 7. Estimates of New Construction as Fraction of the Total 2050 Commercial Building Stock

New Construction		
Since	Billion sq. ft.	% of 2050 stock
2010	97.3	73%
2020	77.5	58%
2035	40.9	31%

For this study, we have assumed that the 2050 stock is 46% post-2028 (and hence subject to our new construction assumptions), and 54% is existing. We further assume that major retrofitting has been done by 2050 on the existing stock, so its shell loads are only 20% greater (per unit of floor space) than those of the best codes for new construction. This leads to savings in the "[building] codes" loads of 59% in the Advanced Scenario, and 66% in the Phoenix Scenario.

HVAC and ventilation. We assume a characteristic HVAC system type for each building size class: "residential" for buildings up to about 5000 sf, "unitary" (principally roof-top units today) for medium buildings, and "applied" or built-up for buildings larger than about 35,000 sf. In both , air-based energy distribution is largely replaced by some combination of hydronic, hydronic/electric (water-source heat pump), and refrigerant-based (VRV, multi-split, etc). Roof-top units as we know them today vanish from the U.S. building stock. For our purposes, we subsume ventilation within heating and cooling. Moving air through ducts is limited to ventilation needs. In general, ventilation still requires moving air with fans, but it may also benefit from major changes in technologies. Examples include gas-phase air filtering, used in some casinos today, and liquid desiccants for latent control, particularly in humid climates (Sachs et al. 2009).

Building envelopes. We assume that we can make envelopes so good that there is no longer need for dedicated space heating, in any size of building.[18] That is, the total commercial building heating requirement is met by internal loads from lighting, people, and installed equipment. We build such a scenario around optimized advanced glazing, excellent infiltration control, and appropriate insulation of the surfaces for each building size classes. For small buildings, this is readily done, as with the PassivHaus methods successfully deployed in over 10,000 buildings in Europe (Klingenberg, Kernagis, and James 2008).

As buildings become larger, in general the surface area to volume ratio decreases, so internal heat gains meet an ever larger fraction of heating needs. Today's largest buildings combine perimeter heat losses with excessive core heat gains, so better facades and energy distribution will reduce their heat losses to values lower than the internal heat gains. So, as a first order approximation, heating energy can be driven to zero.

On the other hand, such a zero-heating building still may have significant cooling loads to dissipate the internal heat gains and residual solar gain through windows. Thus, the cooling energy requirement in an Advanced Scenario depends on changes in envelope gains and internal loads. As noted above, we assume that existing buildings have 20% higher "code" or shell loads than new buildings (see Table 7).

Other building loads. "Miscellaneous" loads that are not now subject to either building codes or equipment standards account for one-fourth of today's commercial building energy use, and more than one-third of the total in our 2050 Base Case (extrapolation from EIA 2035). As discussed below,

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[18] Of course, this is not true for the smallest buildings, those in the 1000–5000 sf range. Although numerous, they are less than 10% of total commercial floor space (EIA 2008Table A1), and 11% of space heating energy use (EIA 2008, Table C1).

these loads have not been studied carefully, but include things as varied as "water services" (the embodied energy in water supply, distribution, and treatment for commercial buildings) and miscellaneous small-scale manufacturing in commercial buildings. The category inherently includes amenity and productivity loads that are pervasive by 2050, although not even thought of today. To keep these loads from dwarfing the "regulated" loads addressed by codes and standards, we have exogenously forced growth limits on these categories. We assume that these loads are 80% of the EIA 2050 extrapolation in the Advanced Scenario. For Phoenix, we decrement this by the 80% total commercial building floor area assumed for that scenario, so other loads are about two-thirds of the EIA extrapolation. These categories warrant much more study.

Lighting. Typical commercial lighting today might operate with 80 lumens per watt. We assume that the DOE solid state lighting goal of 165 lumens per Watt is achieved, and that lighting this good or better is ubiquitous. This seems feasible, particularly with our conservative assumptions about the penetration of daylighting. In addition, we do not explicitly require widespread adoption of low ambient/high task lighting strategies. With these assumptions, we do not need to worry about the "long tail" of obsolete lighting in commercial buildings, or the special needs of retail display.

Investments. We do not apply any benefit-cost test in this study. Instead, we assume that exogenous factors (resource scarcity, carbon policy, etc) increase the effective price of energy, and thus warrant major investments in redevelopment, deep retrofits, and new approaches to construction that design in quality (and efficiency) instead of attempting to "inspect in" at the job site. And as we gain better experience with deep retrofits, we will find the most cost-effective techniques, allowing these retrofits to be cost-effective at times of major building renovations, aided with advanced financing such as property-tax-based loans, as discussed in the residential section.

2. Methods

Classes of commercial buildings. In the EIA *Commercial Building Energy Consumption Survey* (CBECS), commercial buildings are divided into eight size categories from less than 5,000 square feet to more than 500,000 square feet (sf). For purposes of this assessment, we aggregated the buildings into three size-based categories as shown previously in Table 6.[19]

We should note that more than half of the commercial buildings are very small, less than about twice the size of the typical new house. Conversely, more than half of the total commercial floor space is in "skyscrapers," buildings with floor area greater than 500,000 square feet (about 11 acres) (EIA 2005b).

Although the boundaries between classes are not extremely sharp, this classification exploits some fundamental differences in building characteristics:

- Small buildings are generally low-rise, built like residential structures, and served by residential-type HVAC and water heating equipment. We doubt that many have mechanical ventilation systems, but instead they generally rely on window-opening for ventilation.
- Medium buildings are also generally low-rise (so a large fraction can install roof-based daylighting), but use unitary or applied HVAC equipment, typically "RTUs" (roof-top units).
- Large buildings are generally mid- to high-rise, and served by "applied" or "built-up" HVAC systems, typically with chillers as the prime energy converters. Because they are multi-story, there is much less daylighting potential—only perimeter areas and the top floor.

Clearly, this oversimplifies the world of commercial buildings. For example, "big box" buildings and warehouses are typically in the large size category, but can adopt daylighting where needs justify it, and are generally served by RTU HVAC systems. Conversely, a large number of elementary and

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[19] We have divided number of buildings and total area in the 25,000 to 50,000 square foot CBECS class equally between the medium and large size classes.

other school buildings in the medium size category have built-up HVAC for its assumed lower life-cycle costs and integrated ventilation.

Commercial buildings also include fifteen principal activities (EIA 2005b). We have not attempted to differentiate needs separately among activity types at the level of analysis appropriate for this four decade projection.

3. The EIA Base Case

In this analysis, we examine building loads in the same aggregated categories as EIA in its National Energy Modeling System (NEMS), that is,

- Space Heating
- Space Cooling
- Water Heating
- Ventilation
- Cooking
- Lighting
- Refrigeration
- Office Equipment (personal computing and information processing)
- Other Office Equipment (servers, copiers, etc)
- Other Uses, principally service sector equipment and light manufacturing in commercial buildings, but also ATMs and telecommunications switches, etc.

For the forty year period of interest, these can logically be broken into three categories:

- "**Energy code**" loads. These are loads covered in the IECC, ASHRAE 90.1, and similar energy codes that offer prescriptive and/or performance paths for mandatory minimum energy efficiency. These codes include:

    - Envelope characteristics. Glazing, insulation, and infiltration.
    - HVAC and water heating equipment and systems.
    - Lighting, both indoor and outdoor. We implicitly include display and other retail lighting.

- "**Standards" loads**. These include appliances and equipment that can have energy standards as free-standing products. We emphasize currently regulated products, but include our estimates for products that could be regulated and for which regulations could be enforced. Examples include:

    - Refrigeration. Food service and sales, as well as conventional refrigerators. Both cooling and ice-making equipment.
    - Office equipment, notably personal computers and displays.

- **"Other" loads**

    - Water and wastewater distribution and treatment energy.
    - Elevators and escalators.
    - Medical equipment such as X-Ray and MRI.
    - ATMs, telecommunications switches, small data centers in office, education, or research spaces.
    - Service station equipment (lifts, air compressors), and analogous service industry equipment (large laundry equipment).
    - Light manufacturing in commercial spaces, such as small print shops.

To a large extent, the "energy code" and "standards" categories are subject to reasonable forecasts of efficiency improvements: Equipment in common use will asymptotically approach its thermodynamic limits. Furnaces and boilers can't exceed 100% higher heat value efficiency, and are approaching that now. Gas heat pumps probably cannot realistically expect efficiencies greater than 135–150% without going to more stages than can be justified on either space or cost. Similarly, there are foreseeable limits for all kinds of compressor-based equipment, and little on the horizon for "breakthroughs" On the other hand, large system efficiency improvements are feasible. These begin with moving from air-based energy distribution (pervasive forced air systems) to water- and phase-change energy distribution, generally with dedicated outdoor air systems for ventilation. This facilitates energy recovery, moving heat from where it is rejected to where it is needed.[20]

In contrast, "other loads" represent a very large challenge, because they are very heterogeneous and many are not necessarily proportional to total commercial square footage.

The core issue is that all of these enumerated loads, including the imputed water services, add up to one fourth of today's energy use assigned to the commercial sector. Because we do not know what they are in any detail, but we greatly reduce other loads in our projections for the Advanced and Phoenix Scenarios, *these miscellaneous loads are half of the 2050 energy use in these .*

Finally, total energy use is the product of energy use intensity multiplied by total square footage. The difference between our Advanced and Phoenix Scenarios includes different assumptions of total commercial sector space. In the Advanced Scenario, we use NEMS assumptions. In Phoenix, we allow total area and the distribution of area among building size classes to change, responding to assumed modest "densification" of both residential and commercial space in response to an energy- and carbon-constrained world.

4. The EIA 2050 Extrapolation

With this background, we can consider how energy is used in the EIA Reference Case. The EIA Reference Case does not extend past 2035, so ACEEE has estimated energy use to 2050 by extrapolating from the growth rate over the 2030–2035 period. Figure 9, at the end of this chapter, summarizes our Base Case and projections.

Table 8 below provides additional detail on energy use and energy use intensity (Btu/sf) for 2050. These data underlie Figure 9.

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[20] This is one key to the high performance of ground-source heat pump systems that use a circulating water loop to move energy. It is also feasible with other systems, including chilled beam and 4-pipe.

Table 8. Commercial Building Energy Use Reference Case, by Service, 2010 and 2050

	Quads			EUI, Btu/sf-yr		
Service:	**EIA 2010**	**Baseline 2050**	**Percent of 2010 Baseline**	**EIA 2010**	**Baseline 2050**	**Percent of 2010 Baseline**
Space Heating	2.4	2.1	90%	29,200	15,800	54%
Space Cooling	1.6	2.3	141%	20,000	17,100	86%
Water Heating	0.8	1.0	125%	9,500	7,200	76%
Ventilation	1.6	2.3	138%	20,100	16,800	84%
Lighting	3.3	3.9	119%	40,400	29,000	72%
Cooking	0.3	0.3	133%	3,100	2,500	81%
Refrigeration	1.2	1.3	104%	15,400	9,700	63%
Office Equipment (PC)	0.8	0.8	101%	9,800	6,000	61%
Office Equipment: Non-PC	0.8	1.6	192%	10,400	12,100	116%
Other Uses	6.0	12.8	215%	73,600	95,600	130%
Subtotals						
"Energy Code" Loads	9.7	11.5	119%	119,200	85,900	72%
"Standards" Loads	2.3	2.4	107%	28,300	18,200	64%
Office Equipment + Other Uses	6.0	14.4	215%	73,600	95,600	130%
Grand Total	17.9	28.3	158%	221,300	199,800	90%

Note: 2010 numbers from EIA 2010. 2050 numbers projected by ACEEE based on trends from 2030-2035 in EIA 2010. "Other uses include water services, vertical transportation (elevators and escalators), medical equipment, non-road electric vehicles (fork lifts, etc.), distribution transformers, and the myriad of specialized equipment used in laundries, automobile service, etc. These loads are very diverse: The named categories from water services to distribution transformers account for only 23% of the 2050 baseline energy use of 12.8 quads.

Discussion of the 2050 Base Case. Each of the energy code and standards loads is projected to decrease, with a range from 15% to 45% of the 2010 intensity in the Base Case scenario. In contrast, the "other" loads *increase significantly*—about 30%. This limits the total savings available from current and anticipated regulations, since efficient energy code, standards, and listed "other" energy uses are only about half the NEMS 2050 energy use.

Envelope considerations (insulation, glazing) are not treated explicitly in space heating or in space cooling. We infer that EIA internalizes all expected envelope improvements as changes in heating and cooling loads. Further, note that there is no significant difference in the "growth factor" for ventilation and that for space cooling. From this we infer that NEMS does not project substantial changes in the penetration of mechanical ventilation into small buildings (which would increase loads), or that they are compensated by improvements in the technologies.

The scale of uncertainties in this kind of estimation is suggested by comparing the "energy code loads" above (119,200 Btu/sf) with other estimates. In particular, ASHRAE estimates from CBECS 2003 that the weighted average commercial building used about 90,000 Btu/sf in 2003,[21] vs. the CBECS reported energy code loads here of 119,000 Btu/sf.

The figures in Table 8 can be placed in the context of other work. Griffith et al. 2007[22] simulated the CBECS 2003 building stock, and explored the possible improvements with today's and foreseeable technology. They found:

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[21] Cited in 2010 ASHRAE Energy Targets Report to the Board, p. 5

[22] Cited in 2010 ASHRAE Energy Targets Report to the Board.

- New buildings can reduce energy use per square foot (Energy Use Intensity—EUI) 43% on average (across types) without employing photovoltaics or ground source heat pumps, but using integrated design.
- Retrofitting the existing building stock to current standards would cut EUI to 70 kBtu/sf. This may be only the "energy code" loads.
- Similarly, the "MaxTech" would be about 40.3 kBtu/sf, again presumably for energy code loads.

5. Energy Use in the Advanced and Phoenix Scenarios

Figure 9 at the end of this section summarizes our projections of aggregated energy use to meet shell loads, lighting and standards-regulated equipment, and miscellaneous loads.

Table 9 presents ACEEE estimates for the Advanced Scenario.[23] In these estimates we use today's available technologies and those readily foreseen as commercially viable for all buildings. This implies an aggressive, mandatory, retrofit program to bring all buildings to within 20% of the performance of the most recent code available in 2050. Such a program might be financed by a PACE-type mechanism,[24] with investments amortized on the property tax bill and any residual obligation at time of sale transferred with title.

Table 9. Code, Standards, and Other Loads in 2050 in the Advanced Scenario

Advanced Technology	Quads		EUI, Btu/sf-yr	Advanced		
				Values		% of 2050 Baseline
Service:	EIA 2010	Baseline 2050	Baseline 2050	Quads	EUI	Quads
Space Heating	2.4	2.1	15,800	0.34	4,200	16%
Space Cooling	1.6	2.3	17,100	0.85	10,500	37%
Water Heating	0.8	1.0	7,200	0.42	5,200	43%
Ventilation	1.6	2.3	16,800	0.90	11,100	40%
Lighting	3.3	3.9	29,000	1.77	21,800	45%
Cooking	0.3	0.3	2,500	0.30	3,700	90%
Refrigeration	1.2	1.3	9,700	0.78	9700	60%
Office Equipment (PC)	0.8	0.8	6,000	0.40	5,000	50%
Office Equipment: Non-PC	0.8	1.6	12,100	1.62	19,900	100%
Other Uses (Ref. Case. Comm)	6.0	12.8	95,600	10	126,700	80%
Subtotals						
"Energy Code" Loads	9.7	11.5	85,900	4.29	52,800	37%
Adjusted Energy Code Loads	9.7	11.5	85,900	4.75	58,500	41%
"Standards" Loads	2.3	2.4	18,200	1	18,400	61%
Office Equipment + Other Uses	6.8	14.4	27,800	11.9	146,600	82%
Total	18.8	28.4	211,900	18.1	217,800	64%

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[23] As noted earlier in the residential discussion, the savings described below for commercial buildings are different from the values reported in Table 17 since the values reported here do not include improvements in the efficiency of the electricity generation, transmission and distribution system while the values in Table 17 do include electric system improvements.

[24] PACE is Property Assessed Clean Energy. PACE would finance energy efficiency upgrades with money repaid as part of the property tax. The justification is that improvements remain with the real property—and that this would give access to low interest rates commensurate with the low risks of these investments and municipal bonds.

The first observation is that **space heating** loads are reduced to about one-quarter of the baseline, due to greatly reduced shell losses combined with continuing internal gains. The residual heating loads are small because all resistive heating has been eliminated, substituting heat pumps in smaller buildings and heat recovery in larger buildings. In this scenario, we do not introduce gas heat pumps, which will penetrate the market in the Phoenix Scenario. However, no non-condensing gas equipment remains to provide heating services. In the smallest buildings that have some residual heat load that cannot be recovered from waste heat, combination gas appliances serve both space and water heating loads.

Space cooling loads are cut by almost two-thirds, but not eliminated. Loads remain relatively large because of internal gains from people (60–100 watts/person), advanced lighting, and the sum of other "standards" and "other" loads. Forced air energy distribution is eliminated throughout the sector, replaced by refrigerant phase change (mini-split and multi-split) in smaller buildings and water-based energy distribution in larger ones (technologies including 4-pipe terminal units, water-loop and ground-source heat pumps, and chilled beams for cooling.

Ventilation, decreases less than cooling loads, but is reduced by more than half. That is interpreted as residual internal loads offsetting the need to heat ventilation air (assuming appropriate heat exchange and distribution strategies), while substantial amounts of air still must be cooled and dehumidified in the cooling season.

Lighting, in the Advanced Scenario, uses less than half as much energy as forecast in the baseline NEMS extrapolation. This is a very conservative estimate, since we only assume that all commercial lighting will work at 1.0 w/sf, half of our assumption of present practice.[25] The additional reduction forecast results from more daylighting than in the Advanced Scenario, and occupancy controls, the former as applicable for the small and medium size classes, and the latter for all categories.

"Standards." Cooking, refrigeration, and office equipment all drop from readily foreseeable technology improvements. For refrigeration, our estimates may be conservative, if (for example) room-temperature of irradiated foods supplants refrigeration for preservation (so refrigerators preserve leftovers and provide amenities (ice, chilled food).

Miscellaneous or "other" loads. We have made some assumptions about the potential for improvement of the named "other uses," typically for a 33% system efficiency improvement. These are attributed to more efficient drives and controls, and (for water services) reduced demand attributable to more efficient fixtures (low-flow showers, waterless urinals, better housekeeping methods). We derive the savings from a sensitivity analysis by Ecos Consulting and the New Buildings Institute (Heller, Heater, and Frankel 2011). Much more attention is needed to better understand these "other uses" and then to develop techniques and approaches for reducing this energy use.

In contrast, for the large loads that are not accounted for elsewhere in the tables, we have made reasonable but arbitrary assumptions about efficiency improvements and changes in service demand. In the Advanced Case, we reduce these loads to 80% of the value in the Reference case. Some parts may have large changes. For example, advanced textiles may require much less in laundry services; less printing may be required for commerce, including advertising—but this promise has not been met in the past decades.

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[25] The ratio of watts per square foot calculated from CBECS data is about 3.7 w/sf, but this includes display lighting, and seems to include outdoor lighting. We assume 2.0 w/sf as our baseline. For the Advanced Case we assume overall lighting efficiency of 1 W/sf, comparable to today's codes.

6. Energy Use in the Phoenix Scenario

Table 10 presents ACEEE estimates for building floor space in the Phoenix Scenario. The Phoenix Scenario deviates from the Advanced Scenario in two respects: First, we alter the relative amounts of space in small, medium, and large buildings. Second, we reduce the overall amount of commercial space to 80% of the EIA forecast (and Advanced Scenario), to reflect anticipated life style changes in response to very high carbon or energy prices. These include greater density of residences and commercial structures, and less expansive spaces for merchandising, warehousing, and assembly. These changes are summarized in the table below:

Table 10. Space Allocations Among Size Classes in the Advanced and Phoenix

	Class by size	**Small, <5,000 sf**	**Medium, 5,000 to ~35,000 sf**	**Large, > ~35,000 sf**	**Total**
Adv. Tech	Millions of sf	6,900	24,400	40,400	71,700
	Percent	10%	34%	56%	
Phoenix	Millions of sf	5,700	25,800	25,800	57,400
	Percent	10%	45%	45%	

Notes: Advanced Scenario uses the extrapolated EIA floor space estimates, while Phoenix reduces total commercial building space by 20% from that projection, and slightly redistributes the classes, allocating relatively more space to medium-sized, community-scale buildings than to the largest ones.

With these changes in place, we can project energy use by service for the Phoenix Scenario. This follows in Table 11 below.

Table 11. Energy Use in the Phoenix Scenario

Phoenix	**Quads**		**EUI, Btu/sf-yr**	**Phoenix**		
				Values		**% of 2050 Baseline**
Service:	**EIA 2010**	**Baseline 2050**	**Baseline 2050**	**Quads**	**EUI**	**Quads**
Space Heating	2.4	2.1	15,800	0.15	1,900	7%
Space Cooling	1.6	2.3	17,100	0.62	7,700	27%
Water Heating	0.8	1.0	7,200	0.62	7,700	64%
Ventilation	1.6	2.3	16,800	0.72	8,900	32%
Lighting	3.3	3.9	29,000	1.70	21,000	44%
Cooking	0.3	0.3	2,500	0.19	2,300	56%
Refrigeration	1.2	1.3	9,700	0.52	6,400	40%
Office Equipment (PC)	0.8	0.8	6,000	0.32	4,000	40%
Office Equipment: Non-PC	0.8	1.6	12,100	1.29	16,000	80%
Other Uses (Ref. Case. Comm)	6.0	12.8	95,600	8	101,300	64%
Subtotals						
"Energy Code" Loads	9.7	11.5	85,900	3.82	47,200	33%
Adjusted Energy Code Loads	9.7	11.5	85,900	4.23	52,300	37%
"Standards" Loads	2.3	2.4	18,200	1.03	12,700	42%
Office Equipment + Other Uses	6.8	14.4	27,800	9.5	117,300	66%
Total	18.8	28.4	211,900	14.8	182,300	52%

7. Differences Between Advanced and Phoenix

As in the Advanced Scenario, **space heating** loads are virtually eliminated. In the Phoenix Scenario, we adopt gas heat pumps. Of course, no non-condensing gas equipment remains to provide heating services. However, even though we reduced heating loads from 15,800 Btu/sf (EIA) to 1800 in the Advanced Scenario, the further reduction to 1100 Btu/sf in this scenario saves relatively little additional energy, since so little is used.

Space cooling loads are cut to 27% of the EIA projection, but not eliminated.

Ventilation, as in the Advanced Case, tracks closely with cooling loads.

in the Advanced Scenario, **lighting** uses about 4% as much energy as forecast in the Reference Case. Unspecified but expected further technology advances move lighting beyond 165 lumen/watt, and we expect less retail display space and lighting in the Phoenix Sector. Together these factors give a modest further improvement of 20%, in energy per square foot.

The "**standards**" loads (**cooking, refrigeration**, and **office equipment**) all drop from the readily foreseeable technology improvements of the Advanced Scenario. For refrigeration and cooking, our estimates may be conservative, if (for example) room-temperature storage of irradiated foods displaces significant refrigeration for preservation.

We have made more aggressive (but largely unsubstantiated) assumptions about the potential for improvement of the named "other uses." These changes are attributed to more efficient drives and controls, and (for water services) additional demand reduction attributable to more efficient fixtures (low-flow showers, waterless urinals, better housekeeping methods), and to new infrastructure.

In contrast, for the large loads that are not accounted for elsewhere in the tables, we have simply asserted an efficiency improvement and/or changes in service demand that reduces these to 2/3 of the Reference case loads. Some parts may have larger changes.

8. Discussion

It is plausible and feasible over four decades to greatly upgrade the building stock. "Code" loads for HVAC and lighting can be cut by a factor of three. We can readily reduce the loads of equipment not now covered by standards by one-third. However, without much more work to uncover the nature and technical potential of the loads that are not now accounted for, we cannot reduce overall energy consumption by much more than 50% in the Phoenix Scenario.

By way of comparison, we also note a study published by the National Renewable Energy Laboratory (Griffith et al. 2007) which suggested that if all commercial buildings were rebuilt by applying a comprehensive package of energy efficiency technologies and practices, they could reduce their typical energy use by 60%. This implies that our Phoenix Scenario, while aggressive, it not pushing the envelope.

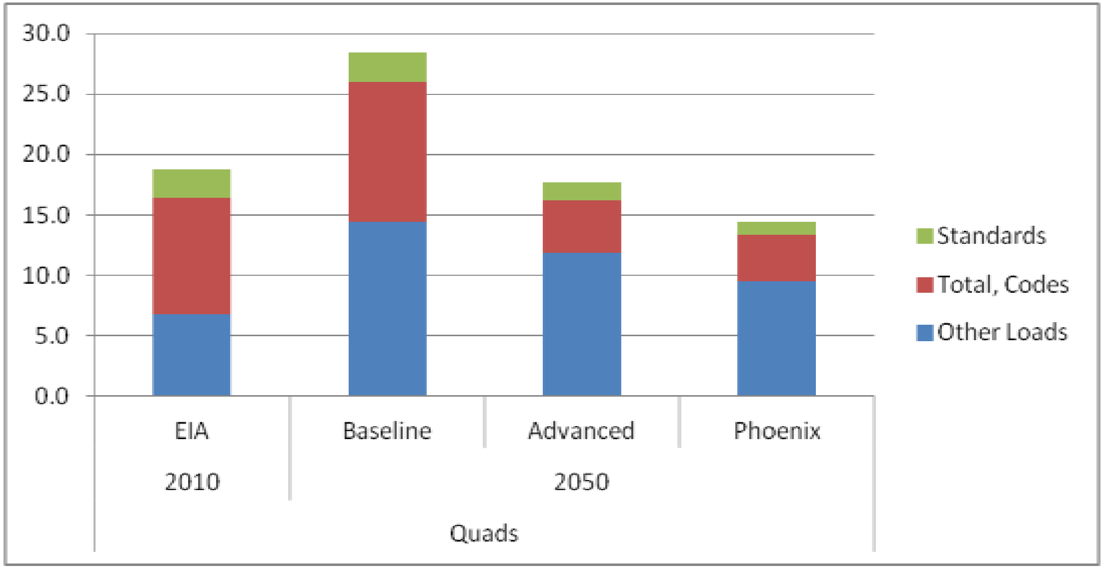
Figure 9 illustrates these changes as stacked bars. The first set, EIA 2010, is the set of initial conditions. The three other bars are 2050 cases. "Baseline" is ACEEE's extrapolation from the 2035 EIA projection. "Advanced" and "Phoenix" Cases depict our study case outcomes. On each bar, the uppermost (light green) segment or band represents "Standards" loads, those that are or can be regulated by standards for equipment and appliances, whether boilers or computers. These loads drop by 43% and 53% in the respective cases. Interestingly, because we change the size mix of commercial buildings in the Phoenix Scenario, the lighting results are virtually the same in both cases (1.7 v. 1.77 Quads): larger buildings use less daylighting, for example.

The middle band represents the loads regulated by building energy codes. It also accounts for much of the changes in energy consumption in our cases, with 39% and 58% reductions. These are the direct result of our assumptions about improved envelope quality, and large changes in space conditioning and hot water services (including delivery). These changes are large in comparison with those in current energy codes that are considered aggressive, such as the IECC 2012. However, our estimates are not constrained by current cost-effectiveness but reflect our judgment of technical and economic feasibility at a large scale, given enough time. In context, they are less stringent than the current Passivhaus specification, which requires 90% reductions in *total* building energy use (Klingenberg, Kernagis, James, 2008).

Finally, note that the lowest bar segment, "miscellaneous" loads, only show changes that are exogenously forced by our model inputs. As discussed above, these loads are very poorly understood and highly variable. Notable examples include Non-PC office equipment (printers, copiers, and faxes; servers and telecommunications equipment; elevators and escalators; and distribution transformers that convert mains to building supply voltages. Several other categories warrant mention: food services for restaurants; medical equipment (since hospitals, clinics, and medical/dental offices are commercial buildings), non-road electric vehicles (fork lifts, office robots), and process equipment for service stations, laundries, and similar commercial uses.

Thus, in both cases these miscellaneous loads are about 60% of commercial building energy consumption, which is astounding. Clearly, these areas require much further study, and the creation of mechanisms to assure that their energy use (active, standby, and off) is commensurate with their value to society.

Figure 9. Projected Commercial Buildings Energy Use by Category in the 2010 and 2050 Cases



Notes: Graphic representation of data from Table 11. Standards includes equipment and lighting), Codes refers to shell loads met by HVAC, and water heating. Other loads are numerous and include everything from elevators to service station equipment.

C. The Industrial Sector

The economic activity and resulting energy use within the industrial sector is largely driven by the demand for products from other sectors of the domestic economy and exports, much as the freight sub-sector of transportation is driven by demand for shipment of goods. This sector analysis will focus on domestic demand to simplify the analysis rather than attempt to address exports explicitly. From a global perspective, the exported products would be produced somewhere else so resources used and emissions produced would be similar, if not greater, whether they were manufactured here or overseas.

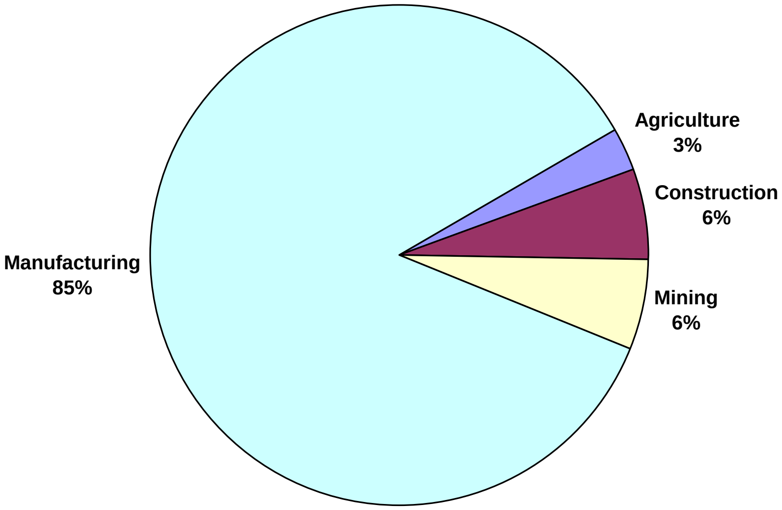
Since the other sectors of the economy drive the demand for industrial products, whether they are food, construction materials or consumer goods, our analysis of the industrial sector focuses on changes in energy intensity,[26] reflecting the amount of energy required to produce a unit of industrial output. For purposes of this analysis, we look at energy per value of shipments as the basis for our intensity calculations, because this is the unit of intensity that EIA has chosen for its analyses and data reporting. We use these intensities to estimate future industrial energy consumption based on the projected value of shipments from our extended AEO forecast (EIA 2010b).

1. Characterizing the Industrial Sector

The industrial sector comprises an array of complex and diverse activities which currently consume about 30% of U.S. total energy demands. It includes agriculture, construction, mining and manufacturing (Figure 10). As the figure notes, in 2010 manufacturing accounts about 85% of total energy consumption within the industrial sector and about 75% of value of shipments (EIA 2010b). Even within manufacturing, energy use is highly varied, ranging from diverse thermal and electrolytic processes to mechanical drive and chemical separation.

Because of this diversity in energy needs, it is more useful to think about process integration than it is to think about discrete technologies. This concept applies both within industrial plants and extends to the idea of entire supply chains. A focus on systems does not say that technologies—both process and product—are unimportant, but rather that it is the interaction and optimization of the application of these technologies that define to a greater extent the energy intensity of the industrial sector rather than the intrinsic efficiency of the technology alone.

Figure 10. 2010 Industrial Consumption by Subsector (30 Quads)



Source: EIA 2010

Investments and new processes in the industrial sector have driven declining energy intensity for as long as we have collected data. However, total industrial energy consumption has increased because growth in industrial sector output has exceeded that rate of declining energy intensity. Looking at the data over the past four decades, we can clearly see this trend (Figure 11), with periods of rapid

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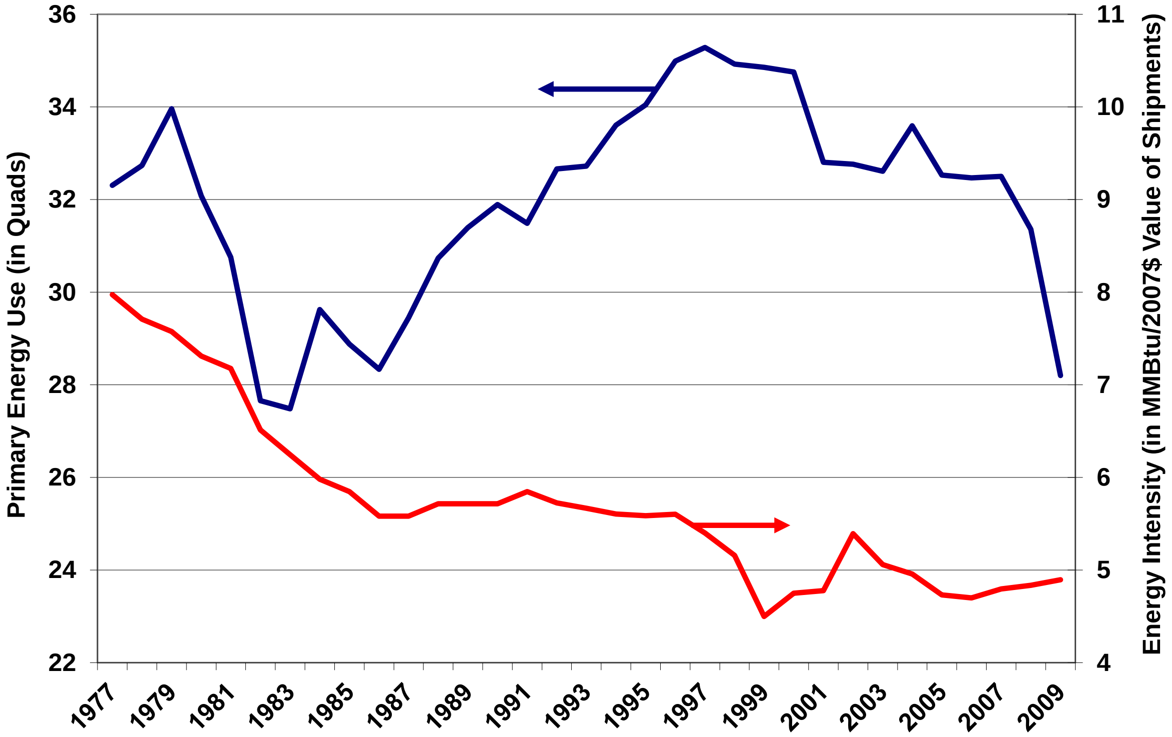
[26] While simple in concept, the term "energy intensity" embodies a rather complex set of interrelated metrics throughout the entire production chain within the industrial sector. It is anchored to the numerous steps within the production process, from the extraction of materials, chemical feedstocks, and energy resources themselves to the processing and fabrication of the final goods demanded by other sectors of the economy. An excellent discussion of this topic can be found in the 1995 EIA report *Measuring Energy Efficiency in the United States' Economy: A Beginning* http://tonto.eia.doe.gov/ftproot/consumption/0555952.pdf.

decline in intensity following energy price shocks and during periods of major capital investments. During the late 1970s and early 1980s the intensity declined at above 3% per year. During the late 1980s and early 1990s, the intensity improvements stalled as low energy prices and economic downturns slowed investment in manufacturing capacity. Since the mid-1990s we have seen industrial energy intensity resume its decline at a rate of about 1% per year.[27] EIA (2010) projects that this rate of intensity decline will continue into the future, once the economy recovers from its current slow-down.

Figure 11. Historical Industrial Energy Intensity and Consumption



Source: ACEEE from EIA data

Because of the effects of the declining energy intensity, total industrial consumption remained about constant during the period shown in the graph. Manufacturing output expanded by 71% from 1997 to 2006, before the economy began to see the effects of the coming economic slowdown. Looking forward, EIA projects intensity will decline at an annual rate of 0.96% while manufacturing economic activity will grow at an average annual rate of 1.13% (from 2012-2035, after the economy is projected to recover), so overall manufacturing consumption is projected to increase as well since economic activity grows faster than intensity declines.

The energy intensity of the major industrial sub-sectors varies significantly, with manufacturing being the most energy intensive (see Figure 12).

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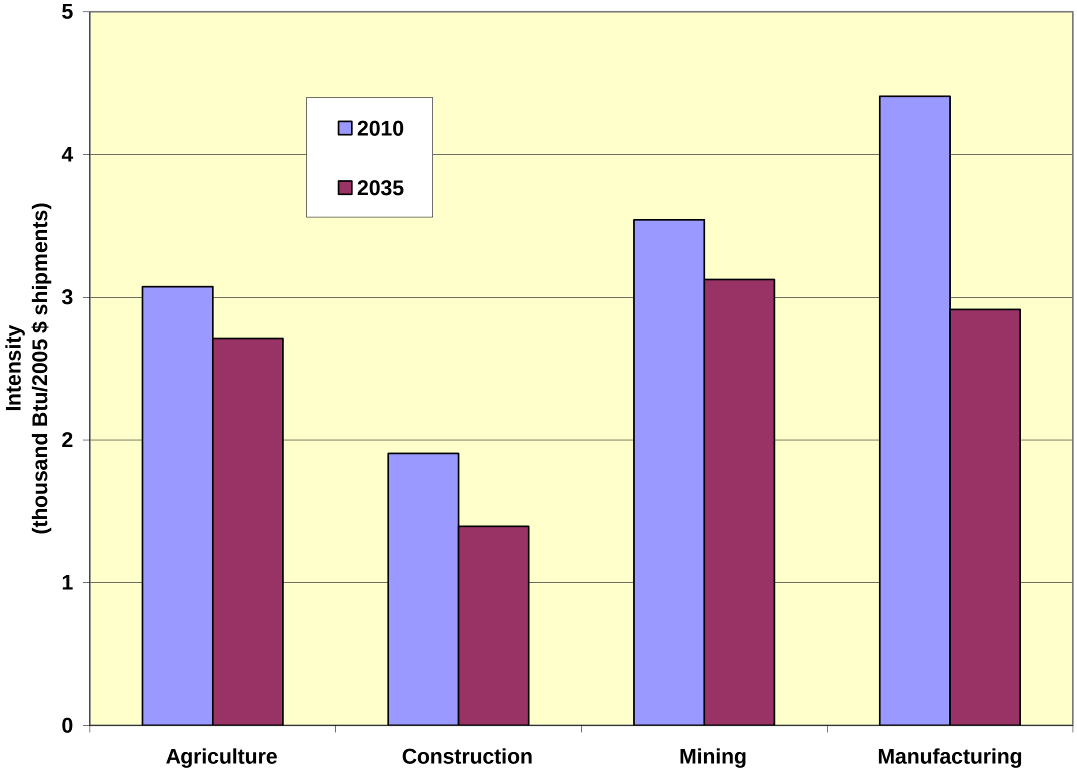
[27] It is worth noting that the modest increase in the intensity seen is attributable to the recession that began in 2008, manifested both by the rapid drop in consumption and substantially reduced rates of investment in new technologies. During period of high manufacturing activity, intensity decreases because of increased capacity utilization of facilities allowing fixed energy use to be spread over more production.

Figure 12. Energy Intensity by Industrial Sub-Sector 2010 and Projected 2035



Source: EIA 2010

2. Relationship between Industrial Sector and other Economic Sectors

Industrial energy use is largely driven by the demands for goods and materials in other sectors of the economy and exports, including demand for energy resources. If we become more efficient in other sectors or use less material because of changes in the way we live, the demand for industrial goods will fall more or less proportionately. Since much of the fuels consumed in the U.S. come from our own industrial sector, reduction is fuels use from efficiency in other sectors will reduce the need for energy use by the industrial sector in their production. Fuel production in the U.S. includes both extraction (e.g., mining, oil and gas extraction) and transformation (e.g., refining).

This relationship between consumption and production however is not a one-way street, because innovation in the products and materials produced by the industrial sector is key to enabling energy efficiency in other sectors of the economy. For example, lightweight, high-strength materials developed by the manufacturing sub-sector have enabled significant energy efficiency improvements in the transportation sector by light-weighting cars, trucks and aircraft. In addition, other changes in the marketplace, such as a shift to more manufactured buildings systems may result in reductions in waste in the construction sub-sector thus requiring less construction materials production from mining, forestry and manufacturing.

The industrial sector thus plays a unique, dual role of both consuming technologies and products, but also producing products, materials and fuels for other sectors of the economy. As the structure of our overall economy shifts, we are likely to see shifts in the products that are produced by the industrial sector, such as renewable energy or efficiency products. Some of these products may be more energy intensive to produce, so there may be some net reduction in energy savings as savings in other sectors of the economy are offset by some increased industrial energy savings. This second order effect is not considered in this analysis, because the uncertainties in the first-order effects are so great as to mask any effects from the lesser effects.

3. Opportunities for Greater Energy Efficiency in the Industrial Sector

In contrast with other sectors of the economy, a bottom-up analysis has proven more difficult for the industrial sector because of the complexity and interconnectedness of the industrial sector (Cleetus et al. 2003). Most industrial energy is consumed in processes rather than by discrete systems making a technology focus challenging. In addition, because of changes in markets, product and technologies the opportunities for energy efficiency evolve in ways that cannot be clearly discerned—at least in the longer term. An ACEEE study (Shipley and Elliott 2006) found that the **identified** opportunities for industrial energy efficiency remained largely the same order of magnitude over the period from 1980 to 2000 in spite of significant realized energy savings in the sector. As known efficiency techniques were adopted, new energy savings opportunities were identified (e.g., the "fruit" grew back on the tree). Equally important, the study found that the nature of the identified savings changed because of new technologies, improved understanding of efficiency opportunities and better awareness. As the report concluded, the identified opportunities were as much about learning what energy efficiency "fruit" looked like as it was about re-growing the fruit with new technology.

While quantifying the magnitude of the technical and economic potential for energy efficiency in industry is challenging, what can be said is that the projected and realized opportunities for energy efficiency in the industrial sector are very large. A wide range of studies ASE, et al. 1997, Interlaboratory Working Group 1997, Plunket et al. 2003, McKinsey Global Institute 2009) have identified a large technical and economic efficiency opportunity at a very low cost. These findings are reinforced by experiences of companies in realizing significant and sustained energy efficiency savings (Prindle 2010). In addition, many of these companies have found that the non-energy benefits of energy efficiency investments exceeded the direct energy savings by a factor of greater than two (Elliott, Laitner & Pye 1997; Worrell et al. 2003; Lung 2005).

So with the complexities in industrial energy efficiency, where are the large savings opportunities likely to come from? Below we will give several examples of large systemic opportunities that are likely to contribute.

Recycled feedstocks and materials substitution. A major use of industrial energy is for materials transformation—the conversion of a raw material into a refined materials that can be used to produce goods. As we continue to extract raw materials from the earth, the quality of these raw materials decline so more energy is required to refine the materials into the building blocks of manufactured goods. If we shift from using virgin feedstocks, such as iron and aluminum ore and petroleum, to recycling existing materials, we can avoid a significant fraction of the energy required to transform a virgin feedstock (Elliott 1994; Elliott et al. 2006). We have seen recycling levels increase dramatically over the past two decades, particularly for metals to the extent that there are now robust global markets for scrape metals. However, significant opportunities remain to increase these levels further by designing products for recyclability.

The manufacturing sector also uses hydrocarbon fuels as feedstocks to produce chemicals that are used to produce other products. Significant among these are plastics, which account for 4% of manufacturing energy use. Recycling of plastics to produce plastics represents another large energy savings opportunity. The U.S. recycles only a fraction of the plastics, in contrast to Europe, which is achieving much higher rates (Elliott et al. 2006).

In addition to increasing use of recycled feedstocks, there are opportunities for substitution of less energy intensive materials. Among the examples of materials substitutions are:

- rubberized asphalt that lasts twice as long and requires half the volume of conventional asphalt (Elliott et al. 2006)

- use of pozzolans[28] to displace Portland cement in structural concretes (Malhotra 1983)
- use of non-Portland cements in structural concretes
- use of waste products from manufacturing processes as feedstocks for other product production, such as has been seen in Kalundborg, Denmark where enterprises buy and sell waste products such as steam, dust, gases, heat, slurry or any other waste product in a closed loop (Kalundborg 2011).

In all these cases, the energy input for the materials use to produce goods and products is dramatically reduced by shifting to a less energy intensive feedstock.

Transformative processes. New processes might transform what we manufacture and how we manufacture these materials. For example, direct iron reduction[29] reduces the energy and carbon emissions that result from the reduction of iron from iron ore. Similar technologies are on the horizon for many other key materials such as organic chemicals and industrial gasses. In another example, the adoption of the submerged combustion melting process promises to reduce fuel use by 20% in the melting of glass and metals (ITP 2006).

In addition many of these new production processes allow the manufacture of materials that could not otherwise be produced. Examples of these new materials are some of the ultra-high-strength steels that are being produced that are already being used in the automotive industries (Ford Motor Company 2011). Research into glass offers the promise of producing materials with strength of more than 50% greater than current glass. This glass could be used to reduce the weight of products from containers to cars to buildings, while enabling applications of glass that can only be imagined today. In addition, high-strength glass fibers could enable lightweight composites at a favorable cost and energy of manufacture relative to carbon fiber (GMIC 2009; Spinosa 2009).

***Smart* manufacturing and supply chain integration**. Shipley and Elliott (2006) found that one of the major changes between 1980 and 2000 in the energy efficiency opportunity was the share of potential attributable to “sensors and controls.” Advances in sensor, communication and computation have enabled levels of simulation and system optimization that were not envisioned three decades ago. The National Science Foundation (NSF) has supported research into this topic that suggests we are just starting to realize the transformative opportunities that this area may offer (SMLC 2011). We have seen automation and control progress from equipment level optimization to process line optimization. We are beginning to see systems deployed that optimize the operation of an entire plant, and are beginning to optimize across an entire company and even to an entire supply chain.

The energy efficiency improvements from smart manufacturing techniques result from optimization of multiple systems that eliminate energy waste, which allows for better process control that further reduces waste and improves product quality, and that better matches production levels and product mix to customer demands. ACEEE estimates that supply chain optimization could result in as much as 40-60% intensity reductions relative to current practice (Shipley and Elliott 2006).

Similarly, managing system processes can reduce waste throughout a supply chain. Food distribution is a prime example of the savings opportunity. It is estimated that about half of the food produced in the U.S. is wasted due to spoilage (Jones 2004). While some is lost in the supply chain, much is lost at the retail and consumer levels, with all of the energy embedded in the food wasted as well. By evaluating the food supply system from farm to table, there are opportunities to significantly reduce this waste by changing the processing, handling, packaging and delivery systems so that a fresher,

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[28] A pozzolan is a material which, when combined with calcium hydroxide, exhibits cementitious properties. Pozzolans are commonly used as an addition (the technical term is "cement extender") to Portland cement concrete mixtures to increase the long-term strength and other material properties of Portland cement concrete, and in some cases reduce the material cost of concrete (Wikipedia 2011).

[29] A process where iron is produced from iron ore using a reducing gas without the need to produce coke.

better quality and more stable product is delivered to the consumer—with fewer energy requirements. We are already seeing such products emerge such as individually quick frozen fruits, vegetables and meats that preserve product quality for longer and convenience products such as individually packaged chicken parts that allow the consumer to prepare portions of the right size. While the embedded energy per unit may increase, if these changes reduce system waste then the net energy savings can be significant (Pollan 2006). These supply chain measures will likely need to be complemented with educational and communications outreach that further enhance adoption of new practices and recipes which offer variable ingredient portions for different number of servings.

4. Summary of Opportunities

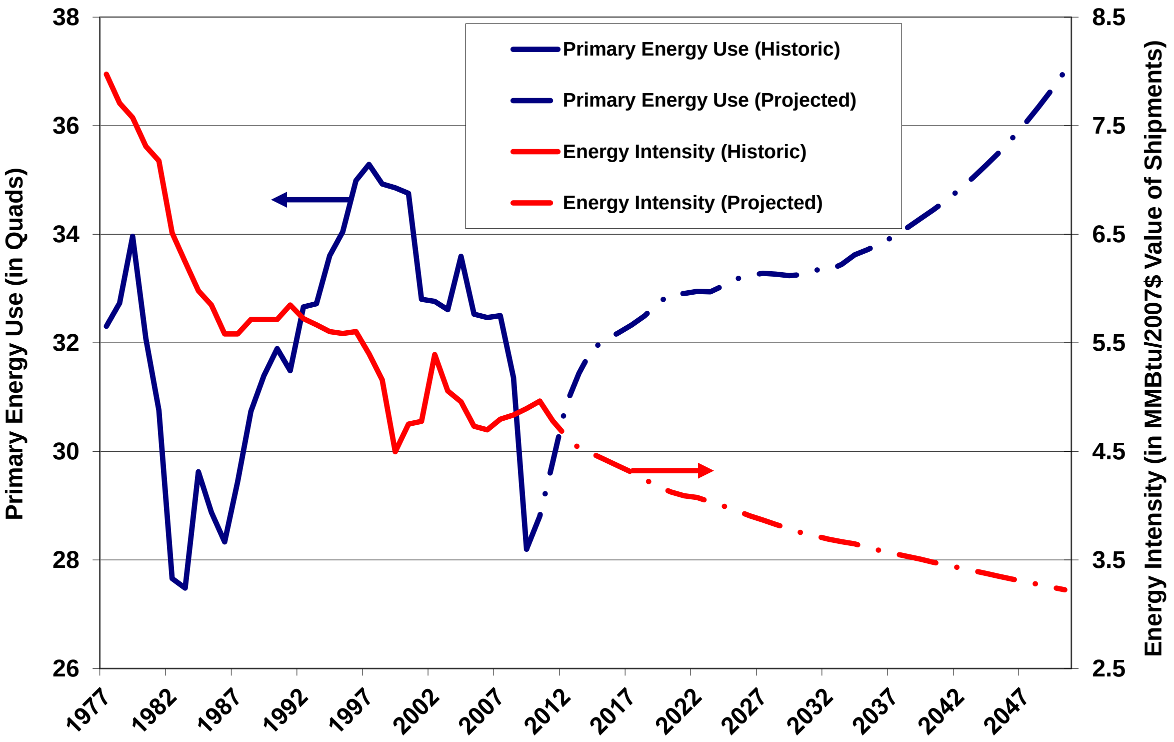
While we may not know how industrial processes and products will evolve over the next four decades, looking back we can see that changes will likely hold great promise for far greater efficiency. The more we look for opportunities, the more we find. Increasingly, the opportunities will come less from seeking out individual sources of waste and more from optimization of complex systems enabled by advances in information, communication and computational infrastructure.

5. Analytical Approach

As discussed above, we have seen two competing trends play out in industrial energy use: declining energy intensity and increasing economic activity in the sector. As a result, we have focused on the intensity of the industrial sector as the basis for our analysis, and then applied the intensity to the economic activity, in this case the value of shipments to project the level of energy consumption in the sector.

In the Reference Case, we project a declining intensity of 0.96% per year from 2010 to 2050, continuing the trend we have seen in this sector over the decades since data has been collected (see Figure 13). As noted above, the 0.96% rate is EIA’s latest projection for the 2011-2035 period. This intensity decline results in a decrease in sector intensity of 27.2% in 2035 and 32.0% in 2050 relative to 2010. During this period, the value of shipments from the industrial sector increases 60.8% by 2035 and 88.9% by 2050, and as a result, the total industrial energy consumption increases by 17.0% in 2035 and 28.4% in 2050 relative to 2010.

Figure 13. Historic and Reference Case Industrial Consumption and Intensity



For our policy case we vary the rate of decline in industrial energy intensity reflect the changes in technology, products, and materials discussed above. More details are provided in the discussion that follows.

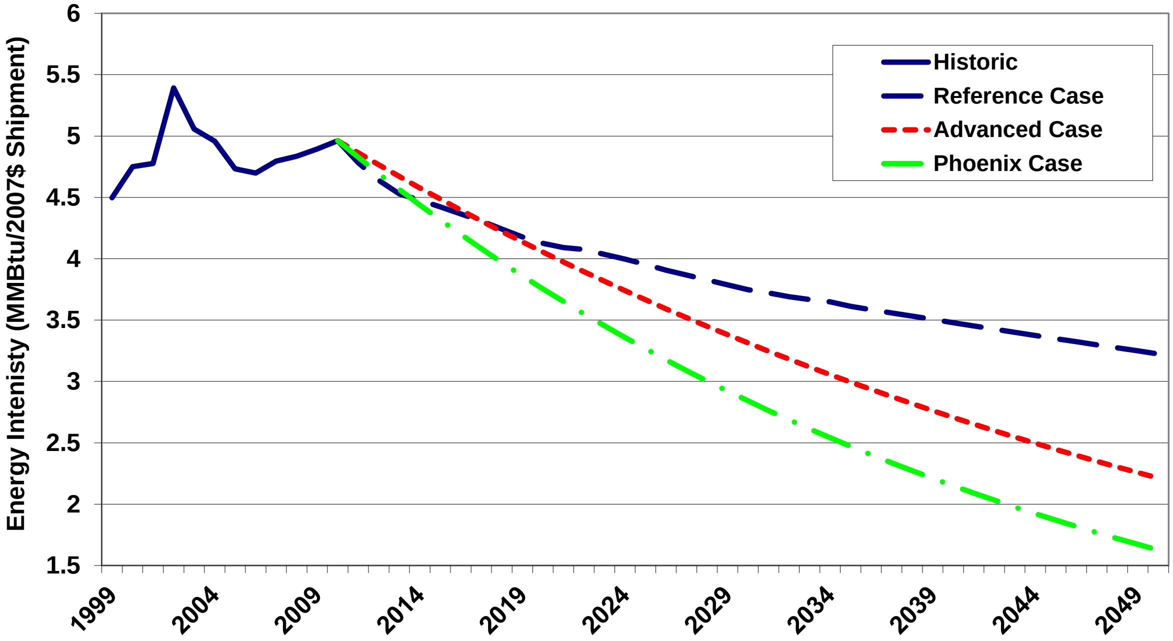
In addition to changes in industrial energy intensity, we will look separately in a later section at expanding opportunities for Combined Heat and Power (CHP) in the industrial sector.

6. Advanced Scenario

In this scenario, we assume that the overall energy intensity of the industrial sector declines at 2% per year, compared with 0.96% per year in the Reference Case. The 2% per year rate represents a rate of decline that McKinsey (2009) identified as a rate of intensity that could be sustained in the industrial sector. This rate of decline is lower than was experienced during the late 1970s and well into the 1980s. A number of the leading firms, such as 3M, Dow, UTC and Alcoa have been achieving reductions in intensity well above this level for over a decade (Prindle 2010). While some, more technically mature industries such as steel may not be able to achieve this rate at least in the near term, many others will be able to achieve even more aggressive results.

In this scenario, we do not consider any major structural changes such as major substitutions of new materials for current materials choices, or shifts in products that are produced in response to changes in consumer demands. Rather, we see continued improvements in product and process technologies, as well as continued improvements from the system optimization trend we have seen emerge over the past two decades. We also hold the ration of electricity to fuel constant at the level in the Reference Case. While our analysis estimates that the improvements in intensity are smooth and continuous (see Figure 14), in reality the changes will likely be more lumpy, much as has been seen in the historic data (see Figure 8) due to the periodicity of economic cycles, investments and technology introductions.

Figure 14. Projected Industrial Energy Intensities for Reference and Policy Cases



While it may appear that these efficiency improvements would likely occur under business-as-usual conditions, in reality a number of barriers to investment in efficiency have been identified (Elliott, Shipley & McKenney 2008):

1. Need for new technologies, products, and processes
2. Access to industry-specific technical expertise, assessments, and training for workers
3. Availability of a trained and capable workforce
4. Access to capital required to implement process investments needed to realize energy productivity opportunities

In the United States, both the public and private sectors have under-invested in all of these categories over the past 30 years. We also need to address these four general barriers is required if we are to achieve the savings suggested in this scenario.

7. Phoenix Scenario

In this scenario, we increase the annual rate of decline in intensity to 2.75% from the Reference Case. This rate of intensity reduction is consistent with the reductions that were seen during the 1980s and with the changes we have seen in the steel industrial during the peak of their reinvestment period from the mid-1990s until the mid-2000s.

In this scenario we assume that we see more aggressive modernization and technology advances than are envisioned in Advanced Scenario*.* These advances result from more concentrated and expanded R&D by government and industry, and more favorable tax treatment of process investments that encourage greater investments in production capacity. In this scenario we see transformative process technologies such as submerged combustion melting, which can reduce energy use for melting by a quarter,[30] coming to market sooner than in the Advanced Scenario. In

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[30] See http://www.osti.gov/glass/Glass%20R&D%20Project%20Factsheets/Energy%20eff%20glass%20melter%20next%20gen.pdf.

addition we see more dramatic shifts in materials available for production of consumer goods, such as high strength glass that can reduce the amount of material used in consumer containers by a quarter, while enabling products that cannot not be envisioned with existing materials. We also see shifts to alternative materials and feedstocks, such as biologically produced plastic monomers or non-Portland cement concretes that are far less energy intensive and may have performance characteristics beyond the conventional materials. We have seen such a transformation over the past 20 years in the steel industry that is now producing new, high-strength steels, many largely from recycled feedstocks, that are able to compete with aluminum and fiber reinforced composites on a weight and performance basis. These new materials enable new products, such as lightweight cars that in turn use less energy in their application.

These changes will not come easily, but will require a major commitment to research and education to insure that manufacturing has the knowledge, workforce and infrastructure needed to realize this transformed sector. These changes will also require a significantly higher level of investment in productive capacity by the industrial sector than we have seen over the past 30 years.

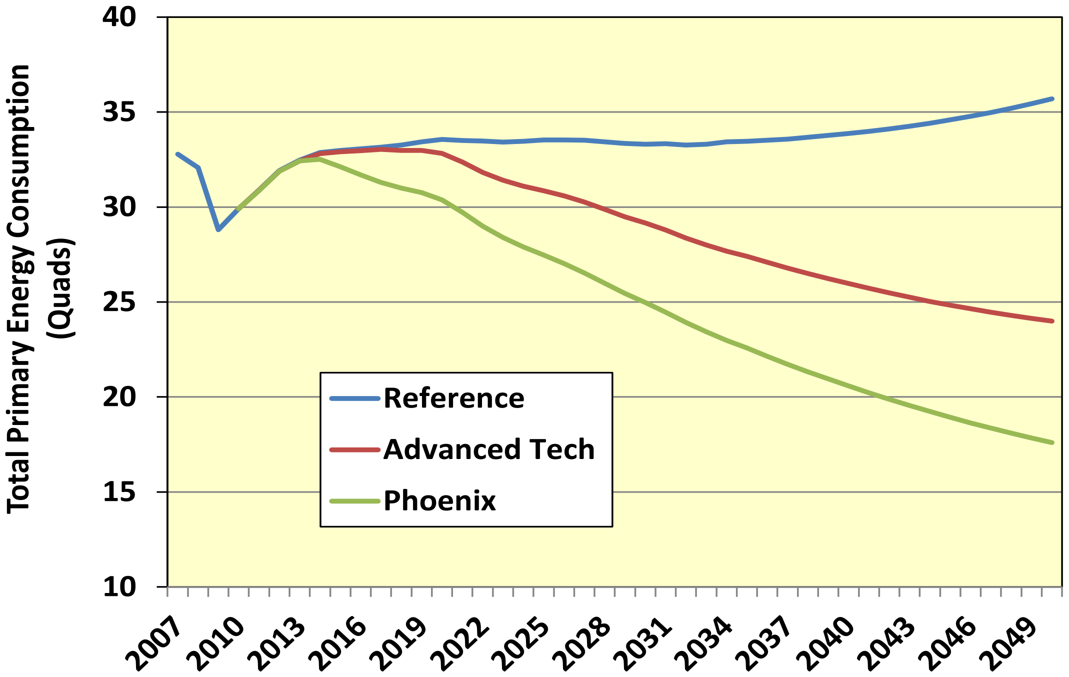
8. Sector Impact Results

We project that value of shipments in the Reference Scenario for the industrial sector is $10,850 billion for the U.S. in 2050, an increase of almost 90% over the 2010 value of shipments. In our Reference Scenario we project that the total primary energy in the industrial sector would increase 19% from the estimated 2010 level (see Table 12 and Figure 15).

Table 12. End-Use and Primary Industrial Energy Consumption in Quads for Reference and Energy Efficiency Scenarios

	2010 Actual Data	2050			Change from 2050 Reference Case	
		Reference Case	Advanced Case	Phoenix Case	Advanced Case	Phoenix Case
Industrial Sector						
Delivered Energy						
Electricity	3.2	3.4	2.3	2.3	-33%	-33%
Other Fuels	20.6	25.9	17.4	12.3	-33%	-53%
Subtotal Delivered	23.8	29.2	19.6	14.5	-33%	-50%
Electricity Losses	6.1	4.0	1.6	1.7	-60%	-59%
Total Primary Energy	29.9	33.2	21.3	16.2	-36%	-51%

Figure 15. Industrial Energy Consumption in the Reference Case and for the Advanced and Phoenix Scenarios



In the Advanced Scenario, primary energy use actually decreases 29% relative to 2010 energy while the value of shipments is held constant. This represents a 36% reduction in primary energy consumption relative to the 2050 Reference Scenario estimates. The ratio between end use electricity and other fuels was maintained across these two , with the Advanced Scenario focusing on improvements in efficiency of the technologies alone.

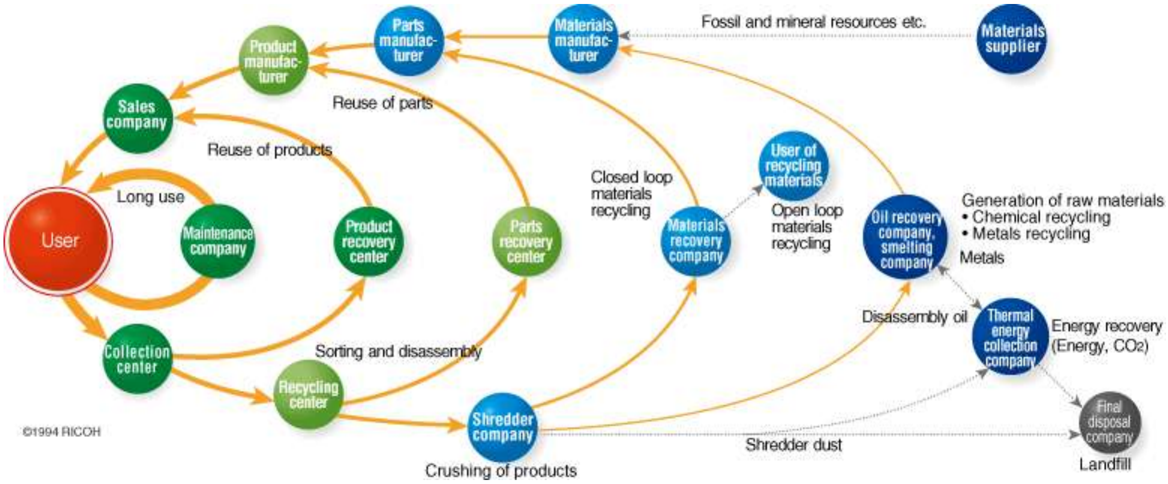
In the Phoenix Scenario, total primary energy falls to 46% below the 2010 level for the same level of value of shipments, representing a 51% reduction of energy use relative to the 2050 Reference projections. In this case, we see electricity use remaining at about the same level as in the Advanced Scenario, with other fuels decreasing by over half relative to the Reference case. This distribution in savings results from a shift to more electric technologies as has been suggested in several analyses, such as Seryak et al. (2011).

9. Discussion

The industrial sector is projected to continue on a path of decreasing energy intensity that dates back as to before the second World War. Rather than a dramatic change in direction for energy use in this sector, we see the potential for incrementally increasing the rate of intensity reductions, which promise to result in significant reductions in primary energy use in 2050. Total energy use in the industrial sector is not driven internally to the sector, but rather results from the combination of the energy intensity of the sector and the overall demand for industrial goods, as is the demand for freight transport as discussed in the transportation section. To the extent that changes in the structure of the economy reduce demand for goods due to changes in consumption behavior, the reductions in industrial primary energy offer even greater opportunities to reduce energy use in the sector.

Increased use of CHP in the industrial sector represents an important efficiency opportunity, primarily to reduce wasted energy in the electric power sector. Our analysis focuses on meeting electricity needs within the industrial sector, due to fact that most manufacturing is not co-located with energy demands in other sectors of the economy. If we were to see a shift toward distributed manufacturing, creating symbiosis opportunities allowing for sharing of energy infrastructures and waste streams among various industrial and the community, as have been accomplished over the past three decades in Kalundborg Denmark (Kalundborg 2011). Fully implemented, the producers and consumers are integrated allowing for reuse, recycling and waste minimization not possible without integration of consumption with production of goods. This concept is embodied in the Ricoh "Comet Circle" (Ricoh 2011), shown in Figure 16. A number of technology changes such as a shift to flexible manufacturing, a concept of a plant that can produce multiple products on demand, are needed to realize this shift (see Ford Motor Company 2011).

Figure 16. Ricoh Comet Circles Reflecting Waste Reduction



Source: Ricoh 2011

A shift to local manufacturing does result in some important interactions with the freight transportation sector, some resulting in reductions in energy use while others potentially increasing energy use. By increasing the level of local resource utilization, we can reduce both the tons of products shipped and the distance they are shipped. However, the shift to local, short-haul freight reduces the opportunity for modality shifts from less efficient trucks to more efficient long-haul trucks and to even more efficient rail transport. The exploration of this topic is beyond the scope of this report, but represents an area of future research.

D. The Transportation Sector

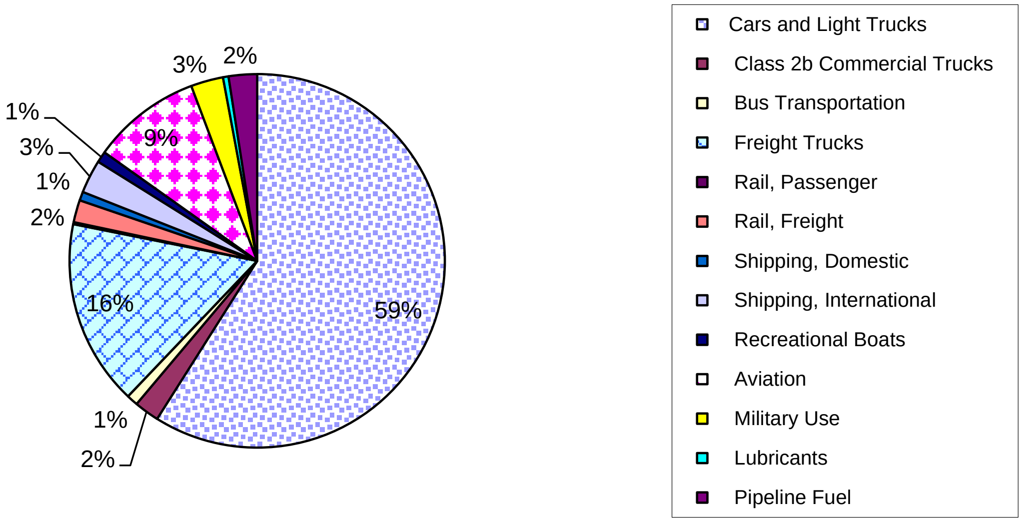
1. Introduction

The transportation system in the U.S. provides vital support to the U.S. economy and public life but is responsible for 66% of U.S. oil consumption (EIA 2011c). The transportation sector is almost entirely dependent on petroleum based fuels. It also contributes more than a quarter of U.S. annual greenhouse gas emissions (GHG). This sector in 2009 generated 31% of the total carbon dioxide (CO_2), which was second to electricity generation that contributed 39% of the total CO_2 (EPA 2011, EIA 2011c). Energy consumption in transportation has followed an increasing trend over the last three decades (Greene and Plotkin 2011), although it experienced a rare decline in 2008-2009 due to the recession and high gas prices during that period. Recently-adopted fuel economy standards will cause fuel consumption to flatten for the next 15 years, but Increasing travel activity, as projected by the Energy Information Administration (EIA), will cause fuel use to rise again thereafter absent new initiatives. Reducing transportation energy use will require a comprehensive approach encompassing increased vehicle efficiency, reduced personal and freight vehicle miles, and attractive alternative modes of transport.

Sector Description

According to the EIA, total energy consumption in the transportation sector in 2010 was 27.47 quadrillion Btu (Quads) (EIA 2011b). Transportation energy use in EIA's Reference Case will increase to almost 32 Quads in 2035, an annual increase of 0.6%. It will rise to almost 36 Quads in 2050 if this trend continues. The transportation sector is dominated by light- and heavy-duty on-road vehicles, followed by aviation and shipping. Light-duty vehicles including cars and light trucks consumed 16.2 Quads or 60% of the total transportation energy, while heavy-duty vehicles including tractor-trailers, vocational trucks, and buses consumed 5.3 Quads or 20% of the total transportation energy in 2010. Sub-sector energy consumption in 2010 is illustrated in Figure 17.

Figure 17. U.S. Transportation Energy Use in 2010



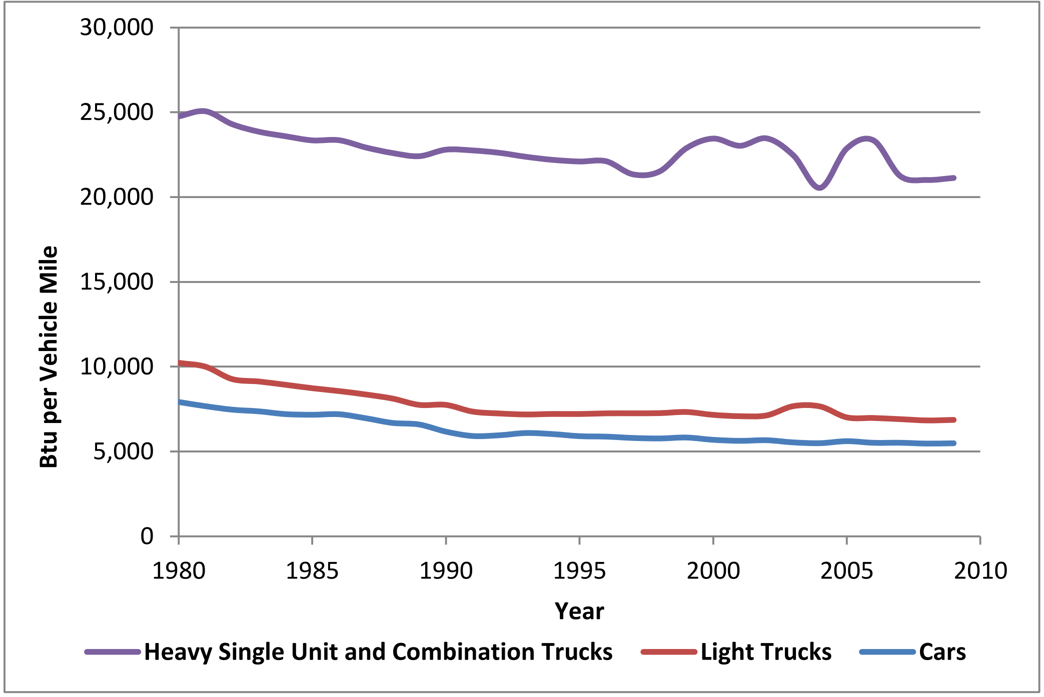
Source: EIA (2011b)

2. Reducing Energy Use in Transportation

Reducing transportation sector energy consumption will reduce GHG emissions and enhance energy security by reducing oil dependence, and could contribute to economic growth as well. However, the task will require major technology advances as well as changes to travel and development patterns.. The International Energy Agency identified in a 2010 report modal shift, efficiency improvement, and use of alternative fuels as the primary means to reduce transportation GHG emissions and fuel consumption in Organization for Economic Cooperation and Development (OECD) countries including the U.S. (IEA/ETP 2010). Accordingly, this analysis will examine the scope and range of improvements that are technically feasible in those areas and how they can best contribute to reducing energy use in transportation. We examine highway vehicles, rail, shipping and aviation. We did not consider energy used by the military, in lubricants, or in pipelines.

Fuel efficiency improvement. With the advent of the Corporate Average Fuel Economy (CAFE) program in 1975, passenger vehicle fuel efficiency increased dramatically into the late 1980s. Fuel economy improved very little over the succeeding two decades, however, as fuel economy standards were essentially unchanged during this period. Historical on-road fuel efficiency in Btu per vehicle mile is shown in Figure 18. Car and light truck energy consumption per mile declined by almost 32% on average from 1980 to 2009 while freight truck fuel consumption decreased by 15% during the same time (DOE 2011).

Figure 18. Vehicle Fuel Efficiency from 1980 to 2009



Source: ACEEE with data from DOT (2011)

There have been several major changes in fuel efficiency standards in recent years. The Energy Independence and Security Act of 2007 mandated light-duty CAFÉ levels of at least 35 miles per gallon by 2020 and set a timetable for the first fuel efficiency requirements for medium- and heavy-duty vehicles. In 2010, the Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) adopted fuel economy and GHG standards for light-duty vehicles that will increase the average CAFE value for new light-duty vehicles to 34.1 miles per gallon in 2016 (EPA and NHTSA 2010). The agencies recently proposed a rule that would further increase light-duty fuel economy to 49.6 miles per gallon by 2025 (EPA and NHTSA 2011a).

Heavy-duty vehicles will soon be regulated for fuel efficiency and GHG emissions for the first time. A fuel efficiency and GHG emissions rule adopted in 2011 by EPA and NHTSA for model years 2014 to 2019 will require tractor-trailers to reduce fuel consumption per ton-mile by 10-24% in 2017 from 2010 levels, depending on their configurations (EPA and NHTSA 2011b). Vocational vehicles, such as refuse, delivery, dump and utility trucks and transit buses will reduce fuel use by 6-9% during the same time frame. Fuel consumption of gasoline and diesel work trucks (heavy pickups) will decrease by 11% and 16%, respectively, by 2018. These initial standards do not reflect the full range of efficiency technology available today. The National Academy of Science (NAS) Committee to Assess Fuel Economy Technologies from Medium and Heavy-Duty Vehicles found that fuel consumption for all heavy-duty vehicles, including tractor trailers, transit buses and other vocational vehicles, and work trucks, could be reduced by 33-46% by 2020, compared to 2010 levels (NAS 2010). These gains were based on vehicle technologies including aerodynamic features, reduced rolling resistance, reduced idling and accessory loading; powertrain technologies, including engine improvements, hybrid technology, and efficient transmissions; and intelligent driving. The NAS analysis relied upon technologies that were either already available or under development. Some of the technologies considered may not yet be cost-effective, especially for vocational vehicles and work trucks, which have relatively low annual mileage. However, hybridization in particular has large potential for several important vocational vehicle segments in the medium term.

Fuel efficiency improvement in aviation will combine engine advances, including geared turbofans and compressor optimization at low speed, drag reduction, and increased operational efficiency (EPA

2010). Material substitution and design changes to reduce aircraft weight will also reduce fuel consumption (Greene and Plotkin 2011). The National Aeronautics Research and Development Plan (NARDP) of the White House's National Science and Technology Council, envisions "N+2" aircraft in the next 5-10 years that will reduce fuel consumption by at least 40% compared to a 1997 Boeing 777 aircraft with GE-90 engines. These aircraft will use revolutionary configurations such as hybrid wing body, small supersonic jets, cruise-efficient short takeoff and landing, and advanced rotorcraft (NSTC 2010). Research from other agencies also projected 40-50% reduction by 2030 in aviation fuel consumption with improvements in engines, ground operation and air traffic management, and reductions in airframe weight and drag (EPA 2010; NSTC 2007). The NARDP also set a goal of developing "N+3" aircraft and engines in the next 25 years that will reduce fuel consumption by up to 70% compared with a 1998 B737 aircraft with CFM 56 engines. This goal assumes significant advances in aerodynamics, engine performance, propulsion/airframe integration, and material (NSTC 2010).

Passenger and freight rail fuel efficiency has improved steadily over the past two decades, Rail freight energy intensity (Btu per ton-mile) declined by 17% in the decade from 2000 to 2009 (Davis et al. 2011, Table 9.8). Additional opportunities for improvement exist in this sector, through increased load factor, improved engine and locomotive efficiency, reduced frictional and braking energy, aerodynamic improvement, and increased operational efficiency (EPA 2010). Adoption of electric or hydraulic hybrid locomotives in line-haul operation can have fuel savings of 15% in the next 15 years (EPA 2010). Other researchers have estimated that rail energy consumption could be reduced by 40% in 2050 utilizing technological and operational potential in full (Greene and Plotkin 2011).

Shipping and recreational boating energy consumption could also be reduced by almost 40% by 2030, according to an EPA estimate the agency describes as "very aggressive" (EPA 2010). This reduction would be accomplished by technology retrofits including engine optimization, reduced ballast, reduced hull friction, and propeller design optimization on existing ships, improved technology or design concept including increased capacity, hull and superstructure design, and hybridization of new ships, and operational improvements for all ships. The IEA's 2009 analysis estimated that shipping energy consumption could be reduced by as much as 60% in OECD countries by taking full advantage of available and potential opportunities in vessel design, propulsion system, and operation management (IEA/SPT 2009).

Advanced technology. Hybrid technologies, both electric and hydraulic, will be important to improving fuel efficiency in several transportation subsectors. Full hybridization of light-duty vehicles has the potential to reduce per-mile fuel consumption by 50% (IEA/ETP 2010). Hybrid systems will also contribute to reducing energy consumption in the rail and shipping sectors. EPA estimates 15% improvement in fuel economy from grid-capable hybrid locomotives by 2030 if they are introduced in 2015-16 and a similar improvement from shipping with the introduction of hybrid propulsion systems (EPA 2010). According to other estimates, hybrid locomotives can achieve a 50% gain in fuel efficiency (Greene and Plotkin 2011).

Battery electric vehicles are typically far more fuel efficient in use than even the most efficient internal combustion engine vehicle. Given the large energy losses in the production and transmission of electricity, however, the energy efficiency competition between an electric vehicle and a hybrid, for example, is much closer on a "well-to-wheels" basis. Hence, while vehicle electrification will clearly reduce oil consumption, net energy savings will depend heavily on the particulars of the vehicles being compared. However, increases in power generation efficiency are expected in all scenarios considered in this report, as discussed below. Especially in the Advanced and Phoenix Scenarios, these increases are sufficient to ensure that vehicle electrification will result in substantial net energy savings, even given the further improvements expected in the efficiency of hybrid vehicles.

These advanced technologies are not suited to meet all transportation needs. Hybrid systems provide most benefit in urban driving, where idle-off and regenerative braking provide the most benefit. They do not offer large benefits for long-haul freight truck operation, for example. Plug-in vehicles are also best suited to city and local operation, at least until a network of fast charge and battery swap stations has been established in extensive areas. Battery capacity and cost also will slow the market penetration of these vehicles. Fuel cells will have to overcome high upfront costs and infrastructure challenges to ensure access to hydrogen (H_2).

The 2009 NAS study, *Transition to Alternative Transportation Technologies—Plug-in Hybrid Electric Vehicles,* projected approximately 106 million PHEVs by 2050 in a "probable penetration" scenario. However, this number could sharply rise to approximately 240 million by 2030 in a "maximum possible scenario"—over 70% of the light-duty fleet—with strong policy intervention, including mandates to manufacturers, subsidies, and increased taxes on fuel (NAS 2009). The IEA 2009 report envisioned plug-ins, electric vehicles, and fuel cell vehicles capturing nearly 80% of the light-duty market in 2050. For heavy-duty vehicles, the report estimates 30% penetration for fuel cells and plug-ins plus 20% penetration for natural gas technology in 2050 (IEA/ETP 2010). Natural gas and biofuels may play an important role in the transportation sector in the future, but they do not bring an intrinsic energy efficiency gain and will not be further discussed explicitly here.

Reduced travel activity and modal shift. The dominant surface transportation modes, cars and trucks, are among the least efficient transportation modes. They have achieved their high shares of passenger and freight trips by virtue of the provision of infrastructure for them—roads and highways and parking—as well as taxation and land use policies that made them the preferred choice for most families, not their energy efficiency. They are well-suited to the dispersed development patterns that have emerged since the 1950s as the result of federal state, local, and private-sector policies and regulations that have resulted in enormous growth in vehicle miles traveled, as well as the more recent just-in-time delivery demands on freight carriers. Yet congested roadways and high fuel prices and the high cost of personal transportation, approaching 20% of household expenditures, among other concerns, have given rise to many efforts to reinvest in alternative transportation modes and to better integrate land use and transportation planning.

Modal shifts in urban travel to public transit and non-motorized modes and in long distance travel to high speed trains can deliver energy savings, since these alternative modes are typically much more efficient than personal vehicles or short-distance air travel. However, mass transit now serves less than 1% of the total passenger miles. While more flexible transit systems, including IT-enabled paratransit and bus rapid transit, may increasingly attract suburban users, major reductions in vehicle miles traveled will require that new development occur in compact, mixed use, transit-oriented communities and that existing suburbs be retrofitted to greater walkability and higher density. Such development and redevelopment patterns not only facilitate higher usage of alternative travel modes but, even more importantly, reduce the distances that people and goods must travel to reach their destinations. Compact communities would be consistent with, though by no means assured by, the residential sector Phoenix Scenario trend toward smaller homes. A substantial reduction in vehicle miles traveled can be promoted through pricing policies as well. These often can be designed to be revenue-neutral, as in the case of pay-as-you-drive insurance, although net revenues from a pricing measure might be needed to fund alternatives to driving.

The 2009 study *Moving Cooler* found that it would be possible to achieve reductions in on-road GHG emissions of up to 24% relative to expected levels in 2050 through land use changes, investments in alternative modes, and local and regional pricing measures, along with operational improvements and freight strategies (Cambridge Systematics 2009a). All measures employed would yield proportional reductions in fuel use. Additional reductions could be brought about through economy-wide pricing measures. The Moving Cooler results form the basis for the transportation system efficiency component of the Phoenix Scenario below.

Trucks are at present the preferred mode for nearly all short-haul and much long-haul freight transport, since roads are everywhere and shipping by truck is faster than other surface modes. Air freight's share also has grown steadily in recent decades. However, shifting from less fuel-efficient truck and aviation freight to more fuel-efficient rail or waterborne freight can save money and generate significant fuel savings. Such a shift would face numerous challenges, including infrastructure, flexibility, time constraints, and time and resources involved in transferring freight between modes. Investment in intermodal facilities could yield greater use of less energy-intensive freight modes, however, especially in the face of increasing in fuel prices and traffic congestion.

Integration of transportation and land use planning can reduce freight as well as passenger energy use by increasing the feasibility of alternatives to trucking. Establishment of “freight villages” at intermodal nodes, where value-added activity and IT-enabled logistics systems would be based, could provide system efficiency gains for multiple shippers and carriers. On the other hand, the Industry section above contemplates a rise in distributed manufacturing, which could limit the viability of rail and water freight modes by dispersing origins and destinations and encourage the use of smaller, less-efficient freight trucks. At the same time, this trend could dramatically reduce the distances that certain goods would travel. The net transportation energy impacts of distributed manufacturing are unclear and will depend upon the design of, and motivations for, such operations.

3. Scenario Analysis

Reference Case. The Reference Case for transportation, as for the other sectors, is based on an extrapolation of AEO 2010 projections through 2035 out to 2050. For highway vehicles, an extrapolation of AEO 2010 is already implemented in Argonne National Laboratory’s VISION model (ANL 2010), and we adopt the VISION Base Case for our Reference Case for these vehicles. VISION projections to 2050 are based on growth rates derived from AEO 2010, together with other sources for population and GDP growth (ANL 2010).

Because our Reference Case is based on AEO 2010 (via VISION), it is somewhat outdated. It reflects the CAFE goal of 35 miles per gallon in 2020 established in EISA 2007, rather than the subsequent fuel economy rules. Fleet average fuel economy of light-duty vehicles in the Reference Case increases from 27.8 miles per gallon in 2010 to 40.9 miles per gallon in 2050. The Reference Case also does not include the heavy-duty fuel efficiency standards adopted in August 2011. Finally, our Reference Case reflects the growth in vehicle miles traveled projected in AEO 2010, which averages 1.75% per year between 2010 and 2035, and the VISION extrapolation to 2050. While these projections show a declining growth rate, reaching 0.7% per year by 2050, they may nonetheless overstate future VMT growth. Changing trends in household income, congestion, exurban housing construction, and workforce participation, for example, could lead to slower growth than reflected in our Reference Case.

Advanced Scenario. The Advanced Scenario, by definition, relies entirely on technological progress in vehicles. For light-duty vehicles, this scenario reflects both the CAFE rule for model years 2012 through 2016, resulting in average fuel economy of 34.1 miles per gallon in 2016, and the rule proposed in 2011 by EPA and NHTSA for model years 2017 to 2025, which is projected to increase fuel economy to 49.6 miles per gallon in 2025 (EPA and NHTSA 2011a). Fuel economy values for light-duty vehicles are stated throughout this discussion in terms of regulatory CAFE values, rather than in terms of the adjusted values shown on vehicle labels, which are substantially lower. Major, further improvements to conventional vehicles, considerable weight reduction, high penetration of advanced hybrids, and modest penetration of plug-in hybrids and battery electric vehicles are the principal elements of the likely pathways to reach that CAFE target.

After 2025, we assume modest further increases in the fuel economy of conventional gasoline vehicles, rising to 65 miles per gallon for cars and 47.7 miles per gallon for trucks, or 57.9 miles per gallon combined, by 2050. Penetration of plug-in vehicles will increase and fuel cell vehicles will begin to appear in the market. We assume that 44% of new cars in 2050 will be EVs, plug-in hybrids, or fuel cell vehicles. We also assume 30% penetration for hybrid vehicles in 2050 compared to 11% penetration for them in the Reference Case. For trucks, we assume a lower penetration of EVs, plug-in hybrids, or fuel cell vehicles, about 22% in 2050. Using VISION assumptions regarding the in-use fuel efficiencies of plug-in hybrid, electric, and fuel cell vehicles relative to conventional vehicle fuel efficiency leads to an average new light-duty vehicle fuel economy of 77 miles per gallon. This value falls between the Mid and High Mitigation case new light-duty fuel economy values for 2050 in Greene and Plotkin (Greene and Plotkin 2011). We note also that other analysis suggests that considerably higher levels are achievable by that time. For example, DeCicco projected that an average light-duty fuel economy for gasoline-powered vehicles of 74.4 miles per gallon could be reached by 2035 (DeCicco 2010).

For heavy-duty on-road vehicles, the Advanced Scenario includes both the fuel efficiency gains of EPA and NHTSA's standards for model years 2014 to 2019 and additional improvements from technologies evaluated by the National Academy of Sciences panel (NAS 2010). Based on largely on the panel's report, we estimate that the fuel efficiency of tractor-trailers could double in 2050 from 2010 levels with improvements from engines, transmissions, aerodynamics, and other vehicle technologies. As a result, fuel efficiency of a tractor-trailer would reach 13.3 mpg in 2050, compared to 6.2 mpg in 2010. We estimate that fuel efficiency of medium-duty vocational vehicles could rise from 7.7 miles per gallon in 2010 to 20 miles per gallon in 2050 with advanced engines, transmissions, and aerodynamics. They will also benefit from hybrid technologies, including hydraulic hybrids.

The Advanced Scenario assumes that shipping, aviation, and rail will also experience moderate to high efficiency gains in this timeframe. We estimate that rail, shipping, and aviation, using technology and system efficiency improvements, can reduce fuel consumption by 50%, 49%, and 43%, respectively, from the 2050 extended Reference Case. This range of improvement is reasonable considering estimates by EPA and other researchers (Stodolsky 2002; EPA 2010; IEA/ETP 2010).

This scenario assumes no changes in development patterns or modes of transportation relative to the Reference Case. This by no means reflects a view that changing development patterns or mode split is beyond the realm of an Advanced Scenario; it simply follows from defining the Advanced Scenario throughout this report as an advanced technology scenario. Transportation energy consumption under the Advanced Scenario is presented in Table 13. Energy consumption in 2050 under this scenario is 25% lower than the 2010 AEO level and 43% lower than 2050 Reference Case consumption.[31]

Table 13: Energy Consumption in Quads from Transportation in Advanced Scenario

	2010 AEO	2050 Reference Case	2050 Adv Scenario
Light-Duty Vehicles (below 10,000 lbs. Gross Vehicle Weight)	16.75	19.47	11.64
Heavy-Duty Vehicles	4.68	8.22	4.45
Rail	0.58	0.84	0.42
Shipping	1.26	1.62	0.82
Aviation	2.58	3.76	2.14
Total	**25.85**	**33.91**	**19.47**

Note: The total energy consumption shown in this table does not include energy use associated with military use, lubricants and pipeline fuel.

Phoenix Scenario. The Phoenix Scenario is based on a substantial reduction in on-road vehicle travel, both passenger and freight, relative to the other , as well as some operational improvements. It also includes greater penetration of hybrids, plug-ins, and fuel cells than in the Advanced Scenario in both the light- and heavy-duty sectors. For on-road passenger and freight travel, we adopt the Moving Cooler study's Long Term/Maximum Results bundle of measures, assuming Aggressive Deployment (stopping short of Maximum Effort Deployment), together with pay-as-you-drive insurance and a per-mile travel fee (Cambridge Systematics 2009a). The study finds savings of 22% by 2050 from these measures. The reductions are achieved through land use strategies, enhancement of alternative modes, parking policies, transportation systems operations strategies, and multimodal freight

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[31] These percentages are slightly different from those shown later in Table 17 as the Table 17 values also include changes in the efficiency of electricity generation and distribution.

improvements, as well as pricing measures. The land use strategies are characterized by the assumption that, between now and 2050, at least 64% of new development is "in compact, pedestrian- and bicycle-friendly neighborhoods with high-quality transit." (Cambridge Systematics 2009b).

In this scenario, we also assume that there will be no market share for conventional gasoline or diesel technologies in light-duty vehicles in 2050. Instead, we take IEA's projection of 30% hybrid-electric vehicles, 50% plug-ins vehicles, and 20% fuel cell vehicles in the Blue Map scenario (IEA/SPT 2009). Using the same advanced technology fuel economies assumed in the Advanced Scenario results in average fuel economy of 97.8 miles per gasoline gallon equivalent for light-duty vehicles. These technology shifts in combination with fewer vehicle miles traveled will reduce light-duty vehicle energy consumption by 60% from the Reference Case, to 8.15 Quads.

The heavy-duty sector will also experience higher penetration of hybrids and fuel cells compared to Advanced Scenario. This is in line with IEA's estimate of 20% fuel cell and 5-10% penetration of plug-ins in heavy trucks for its Blue Map scenario (IEA/SPT 2009). VMT from these vehicles would also decline as a result of increased development of compact neighborhoods, which will also promote local production and consumption. Use of mass transit will increase relative to the other due to mode shift, but we assume this will be offset by higher efficiency of mass transit, including operating at higher passenger loads. Combining these factors results in about 60% savings for heavy-duty vehicles relative to the Reference Case level to 3.08 Quads in 2050, where VMT reduction contributed 0.8 Quads in savings. The light and heavy-duty vehicle analysis was performed using the VISION Model, with modification to the heavy-duty template in order to accommodate advanced technology trucks including fuel cells and plug-ins in the heavy-duty fleet.

We assume that energy consumption in aviation could be reduced by 70% from the Reference Case level in 2050, combining technological and operational efficiency improvement and reduced travel (NSTC 2007; Greene and Plotkin 2011). This falls between Greene and Plotkin's Mid and High Mitigation , based on engine and airframe improvements, operational efficiency improvements, and a modest reduction in vehicle travel. They point out that past improvements in the first category alone have delivered a two-thirds reduction in energy per passenger mile since 1970. This reduction occurred without substantial improvements to aircraft operating procedures, including air traffic control, over the last 30 years (NSTC 2007). Fundamental changes to aircraft operation and system improvement including expanding individual aircraft capacity, maximizing arrivals and departures at airports, and mitigating adverse impacts of weather would be required to achieve the 70% reduction assumed in this scenario (NSTC 2007).

For freight rail and shipping, we assume the same energy usage as in the Advanced Scenario. Some goods transported by truck or by air would shift to rail or water in this scenario. However, the use of coal, which accounted for 43% of rail tonnage in the U.S. in 2004 (CBO 2006), will be greatly reduced in the Phoenix Scenario (see Electricity Supply Sector, below). We assume this factor, together with operational improvements, will be sufficient at least to keep energy use for these alternative modes from rising. Table 14 presents energy consumption under the Phoenix Scenario. Energy consumption from transportation declines by 60% from the Reference Case and by 47% from the 2010 AEO level.

Table 14: Energy Consumption in Quads from Transportation in Phoenix Scenario

	2010 AEO	2050 Reference Case	2050 Phoenix Scenario
Light-Duty Vehicles (below 10,000 lbs. Gross Vehicle Weight)	16.75	19.47	8.15
Heavy-duty Vehicles	4.68	8.22	3.08
Rail	0.58	0.84	0.42
Shipping	1.26	1.62	0.82
Aviation	2.58	3.76	1.13
Total	**25.85**	**33.91**	**13.6**

E. Combined Heat and Power (CHP) and Clean Distributed Energy

In addition to changes in industrial energy intensity, expanding CHP in the industrial sector represents a further opportunity for greater efficiency. CHP systems, also known as cogeneration, generate both electricity and useful thermal energy in a single, integrated system. In some existing generation systems, additional equipment can be installed to recover energy that would otherwise be wasted (this is known as “recycled energy”). CHP is more energy efficient than separate generation of power and thermal energy because heat that is normally wasted in conventional power generation is recovered as useful energy (Shipley et al. 2008). This recovered energy is used to satisfy an existing thermal demand of an industrial plant or even the heating and cooling of nearby buildings or water supply facilities. CHP and district energy factor heavily into the concepts of industrial symbiosis discussed earlier (Kalundborg 2011). CHP systems can save customers money and reduce net overall emissions by displacing utility fuel use and emissions.

CHP is not restricted to the industrial sector, though industrial CHP does constitute the majority of the installed capacity in the U.S. A number of larger commercial and institutional consumers represent good markets for CHP including universities, hospitals, government campuses, military bases, and large hotels. These non-industrial systems account for approximately one-sixth of installed capacity (Shipley et al. 2008).

EIA (2010b) reports that the U.S. has 75,672 MW of CHP capacity representing about 7% of total electricity capacity in the country. CHP has represented an increasing share of total U.S. generation (as is shown in Figure 19) since the mid-1980s, as the impact of the Public Utilities Regulatory Policy Act of 1978 (PURPA) has enabled CHP in the marketplace.[32] The current level of CHP generation represents a fraction of the share of generation seen in many other industrialized countries. CHP provides 30% or more of the electricity in countries such as the Netherlands, Russia, Finland, and Denmark. The U.S. Department of Energy has projected that CHP could provide 20% or more of U.S. electricity by 2030 (Shipley et al. 2008).

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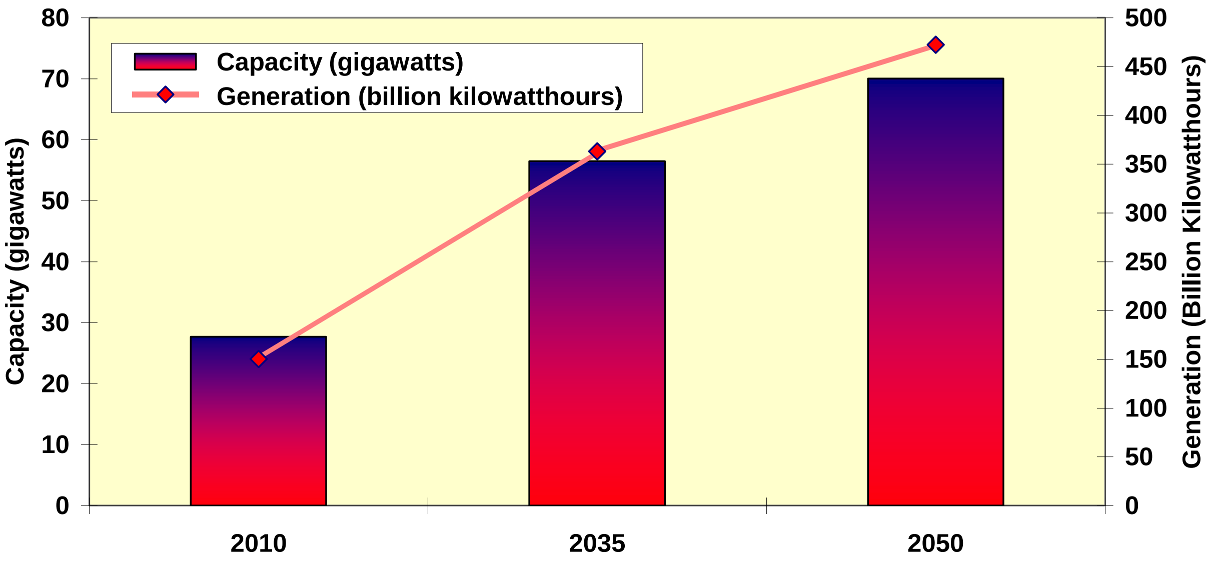
[32] For a discussion of the impacts of PURPA on CHP, see Elliott and Spurr (1999).

Figure 19. CHP as a Percentage of U.S. Annual Electricity Generation

Source: Shipley et al. (2008)

EIA (2010a) projects that the generation from CHP is likely to continue to increase (see Figure 20). By 2025, installed capacity is projected to double with electricity generation from CHP increasing by 142%. ACEEE has extended the EIA forecast to 2050 by applying the growth rate for 2030-2035 to growth beyond 2035. In this extended projection, the CHP capacity would increase 152% and generation from CHP would increase 214%, representing an important energy efficiency resource to the economy in the Reference Case.

Figure 20. Projections of CHP Capacity and Generation to 2035 (Extended to 2050 by ACEEE)



Source: EIA 2010 extended to 2050 by ACEEE

1. Industrial Combined Heat and Power (CHP)

Many people focus on the power output from the CHP system. However, for efficiency benefits to be realized from CHP there must be a thermal load that can be displaced by the output from the system as well. As the overall intensity of industry decreases, the thermal load that is available to be displaced by CHP systems decreases, limiting the amount of CHP than can be supported by the thermal load. Because of the diverse nature of the industrial sector it is not reasonable to assume that all thermal loads could be met through CHP, so we constrain the available thermal load to 20% of total thermal load.[33] We thus assess the available thermal load to support CHP, and limit the CHP installed if it exceeds the available thermal load.

Since EIA projects significant additions to capacity in its Reference Case, it is not clear that it is reasonable to increase the capacity beyond our Reference Case, because this represents a larger share of the total electricity consumed in the industrial sector. In reality, a significant fraction of the electric output from many CHP facilities will be sold into the wholesale electricity marketplace. For simplicity of accounting and analysis, we assume that the output from industrial CHP is netted against electricity consumption in the industrial sector. The share of industrial electricity increases significantly in the two efficiency scenarios (see Table 15). The available thermal load in the industrial sector in the Advanced Scenario is sufficient to support the projected CHP capacity in the Base Case. However, in the Phoenix Scenario, there is insufficient thermal load as a result of the reduced energy use and shift to electricity in manufacturing to fully support the CHP capacity in 2050 in the Reference Case, so the capacity is reduced by about 30% relative to the Advanced Case.

Table 15. Net Electric Output and Capacity from CHP

	2010		2035		2050	
	Generation (BKWh)	% Industrial Electricity	Generation (BKWh)	% Industrial Electricity	Generation (BKWh	% Industrial Electricity
Industrial CHP						
Reference	150	16%	363	36%	472	48%
Advanced	150	NA	363	52%	472	71%
Phoenix	150	NA	363	56%	333	50%
Capacity (GW)						
Reference & Advanced	27.7 GW		56.5GW		70.0 GW	
Phoenix	27.7 GW		56.5 GW		49.7 GW	
Non-Industrial CHP						
Reference	20		30		50	
Advanced & Phoenix	20		50		100	
Capacity (GW)						
Reference	3.7 GW		4.7 GW		7.4 GW	
Advanced & Phoenix	3.7 GW		7.8 GW		14.8 GW	

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[33] The total thermal load is estimated by using EIA (2010b) estimates for fuels available for heat and power, summing estimates for LPG for heat and power, residual fuel oil, petroleum coke, natural gas for heat and power, industrial coal, and biofuels for heat. Based on its experience analyzing CHP system opportunities, ACEEE estimates only a fifth of that total thermal load is assumed to be available for displacement by CHP. The balance of the thermal load is assumed to be technically or economically infeasible for displacement by CHP because the loads are too small, a mismatch on temperature not readily collocated with a CHP facility.

2. CHP Outside of Industrial Sector

In the Reference Case, we project that CHP outside of the industrial sector will contribute 50 Billion kWh to meeting electricity demand, up from 20 Billion kWh in 2010 (see Table 15). In the Advanced and Phoenix Scenarios, we assume that electricity from non-industrial CHP is doubled. Electric generation from non-industrial CHP was not increased further in absolute terms in the Phoenix Scenario because as energy use efficiencies reduce electric and thermal demand in this scenario, we are concerned that capacity would exceed demand for both the thermal and electric output, similarly to our bounding of industrial CHP.

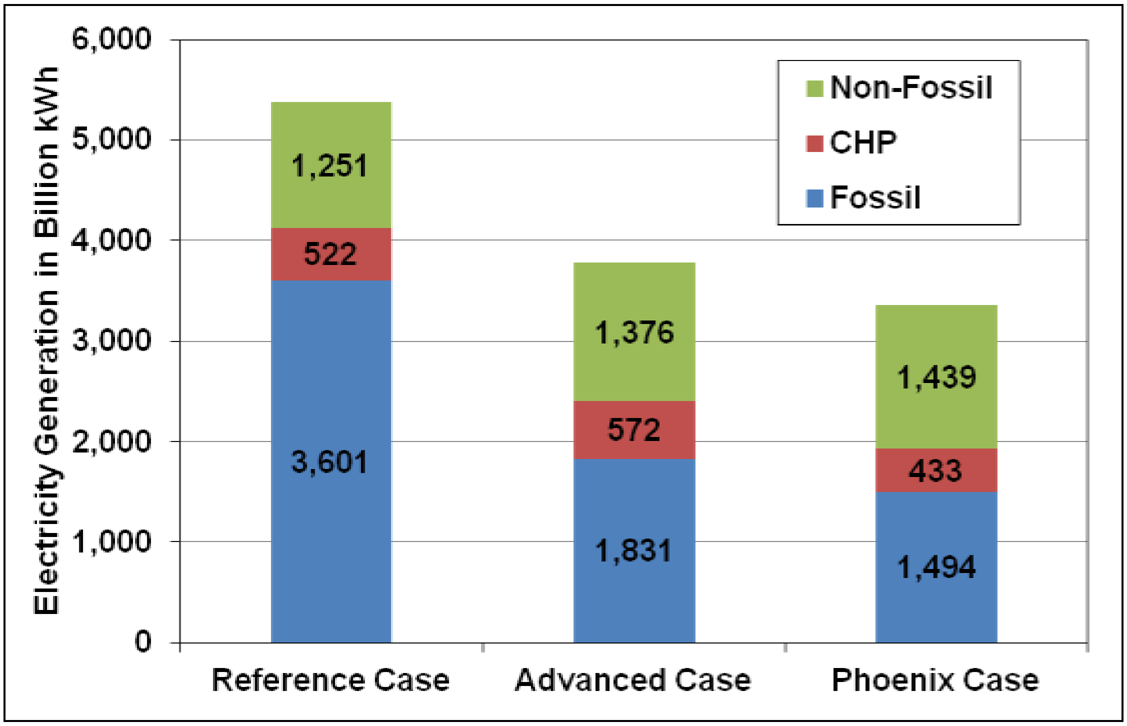
F. The Electricity Supply Sector

The production and distribution of electricity requires a number of steps starting with the actual generation of electricity at a power plant. From the power plant, electricity is sent out through a series of high-voltage transmission lines to the load centers where it is actually needed and then finally to the many distribution systems that serve individual facilities, commercial buildings, homes, industrial plants, and transportation vehicles. Over the last several decades, the efficiency with which electricity has been generated and distributed has hovered at about 31% efficiency (EIA 2011a). That is to say, for every one unit of energy that is transformed into electricity that is used in a home or business, about two units of energy are lost as waste heat. In 2010, for example, total demand for electricity—whether supplied by the utilities or generated onsite by the customers themselves—was estimated at 3,699 billion kWh. On a heat equivalent basis this represents 12.6 quads of energy, but 39.3 quads of energy inputs were required in generate this electricity. With a typical efficiency conversion at the power plant of about 34%, an additional 6% may be either used to support the operation of the power plant or lost in the transmission and distribution (T&D) of electricity to the ultimate customers. The overall system efficiency would be estimated at about 32%. The implication is that a full accounting of energy that is delivered as electricity must also include the energy in both generation and T&D, as well as the energy as it actually reaches the end-user.

For purposes of this analysis, we have divided electricity generation into utility fossil fuel (i.e., coal, natural gas, and petroleum), non-fossil (i.e., renewables and nuclear) sources, and CHP from industrial and non-industrial sources (as discussed in the previous section). Currently fossil fuels account for about two-thirds of electric generation. In 2050, in the Reference Case, total reliance on fossil fuels for electric generation is projected to increase modestly.

As the demand for electricity falls significantly in the Advanced Technology and Phoenix Cases, we anticipate that the generation mix will shift from a fossil fuel dominated mix to a more balanced mix in the Phoenix Case, as can be seen in Figure 21. As demand for electricity is reduced, we assume that this will result in substantial retirements of old coal units, thereby avoiding substantial environmental compliance costs for some of these units and also reducing emissions of greenhouse gases. We assume a significant decline in fossil generation as coal plants retire, resulting in natural gas assuming a dominate role in fossil generation, as has been suggested by several recent analyses such as the recent MIT (MITEI 2011) study. The share of non-fossil utility generation increases from about 23% in the 2050 Reference Case to 32% and 40% in the Advanced and Phoenix Cases, respectively. Great uncertainty exists as to the relative mix of non-utility generation, as renewable technologies compete with nuclear generation. Because of the uncertainty, we assume that all non-fossil resources—nuclear or otherwise—have the same heat rate as the typical fossil resource in the same period. This assumption is consistent with the treatment of non-fossil assets in EIA's *Annual Energy Review 2010* (EIA 2011a)

Figure 21. Electricity Generation in 2050 by Source



Source: ACEEE analysis from this report

The share of electricity generated from CHP will also increase as the overall electricity demand falls in the enhanced efficiency cases, though in the Phoenix Case the CHP generation declines in absolute terms and in overall share from the Advanced Case because the available thermal load declines with improved efficiency in the industrial sector combined with an increase in electrification of industrial processes, as is discussed in the prior section.

We also anticipate increases in the efficiency of generation technologies. We project modest improvements in delivered electricity efficiency will occur in the Reference Case, with efficiency levels rising from slightly above 32% in 2010 to about 36% in 2050. We suggest that even greater efficiencies could be obtained with the best individual power plants expected to push design efficiency levels to 55-60% by 2050 (Harvey 2010). For example, new combined cycle generation systems offer efficiencies above 60%, while maintaining efficiency over a wider range of operating loads than were practical before (GE Energy 2011). CHP systems can achieve even higher incremental electric efficiencies, approaching 80% (Elliott et al. 2009).

We also anticipate modest decreases in T&D losses as a result of improved transmission system equipment through the deployment of technologies such as super conductors and high-efficiency transformers. In addition, the greater use of distributed resources, in this case represented by CHP and some renewable sources, will reduce T&D losses as the distance between generation and use is decreased.

Combining improvements in equipment and T&D efficiencies with the shift in the generation mix described above, we project that the delivered electric system efficiency in 2050 would increase from about 36% in the Reference Case to about 40% in the Advanced Case and approaching 48% in the Phoenix Case (see Table 16). We caution that these are rough estimates and are subject to substantial uncertainty with respect to generation mix and technology development.

Table 16. Electric Generation and Delivered Efficiency by Resource

Metrics	2010 Actual Data	2050 Reference Case	2050 Advanced Case	2050 Phoenix Case
Total Delivered Electricity (Billion kWh)	3,749	5,375	3,779	3,366
Utility Fossil Generation	2,437	3,601	1,831	1,494
Utility non-Fossil Generation	1,142	1,251	1,376	1,439
CHP	170	522	572	433
Delivered Electricity System Efficiency				
Utility Generation	31.3%	34.1%	37.1%	45.0%
CHP	71.6%	71.6%	75.2%	79.2%
Overall Electric System Efficiency	**32.1%**	**35.9%**	**40.2%**	**47.7%**

G. Adding It All Up

With the detail now provided for each of the separate end-use sectors, we now have a complete profile of how the nation's energy demands might look in the year 2050—assuming the right policies and investments decision drive these energy productivity improvements. Figure 22 and Table 17 on the following pages summarize this detail for the benchmark or historical data for 2010, and across each of the three cases that we examine for the year 2050 in this analysis: (i) the extended AEO Reference Case, (ii) the Advanced Case, and (iii) the Phoenix Case, as they have all been described in the earlier sections of this report. The data are reported for each of these four cases by end-use sector, including their anticipated electricity and other energy needs, and also including the anticipated losses in the production of electricity for the entire United States.

The very last row of Table 15 gives us the first summary of the four cases. In 2010 the U.S. economy consumed a total of 98 quads (rounded) to support the production of goods and services. Under standard assumptions and economic projections this will rise to about 122 quads of total energy.[34] Under both the Advanced Case and the Phoenix Case, the energy efficiency of the economy would improve significantly. For comparable levels of economic activity as in the Reference Case, consumers and businesses would require a total of only 70 and 50 quads of energy in 2050 for the Advanced Case and the Phoenix Case, respectively. As shown in the last two columns of Table 17, this reflects a 42% and a 59% savings in 2050 for these same two cases as a result of the increased energy efficiency investments. Again, as we discuss more fully later in this report, the good news is that the economy will continue to maintain the same level of goods and services in these two policy cases as in the 2050 Reference Case. Indeed, as we discuss in the next section, the larger economy may, in fact, turn out to be even more robust as a result of the efficiency investments implied within each of the policy cases. The reason is that energy efficiency investments provide a much lower cost of energy services that increases the larger productivity of the American economy.

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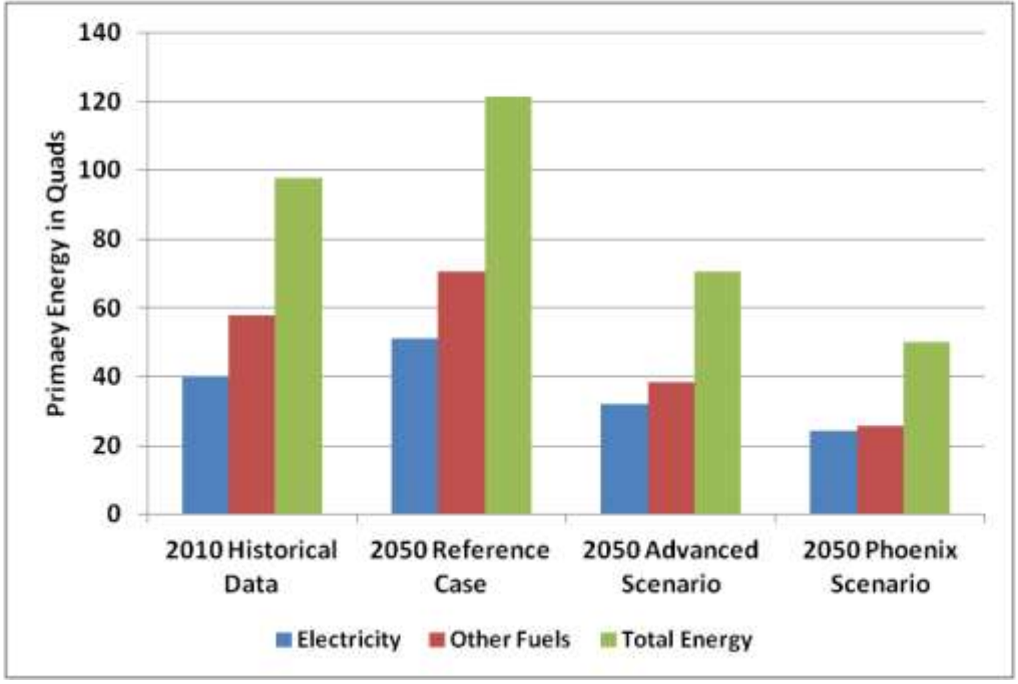
[34] As a historical footnote, the most recent projections for energy use both in the 2010 benchmark data and the 2050 projections (as we've extended them here) have changed dramatically from even just a few years ago. As an example, the AEO 2005 forecast for the year 2010 (EIA 2005a) suggested that we might consume closer to 111 quads compared to the estimated 98 quads that we actually used in that year. More intriguing, extending the EIA (2005a) forecast to 2050 in the same way as done for this analysis would have suggested that we would be using more like 180 quads of energy rather than the 122 quads shown in Table 17. The weaker and a slightly more energy-efficient economy accounts for this very big difference in the EIA (2005a) and the EIA (2011a) extended Reference Cases. Looking out to the year 2050, the extended AEO 2011 Reference Case shows a 3% higher population, with a 22% lower per capita income and a 14% lower energy intensity. These three factors translate into a 31% lower energy requirement for the 2050 Reference Case energy that sets the stage for the two policy cases discussed in this report.

Figure 22. Energy Productivity and Impact on Future Energy Needs



Note: Electricity includes total energy needed to generate and distribute electricity to homes and businesses.

Moving from the summary chart shown in Figure 22, Table 17 provides a number of other interesting perspectives that emerge from this assessment.[35] Perhaps the most immediate observation is the huge variability in the range of savings among sectors and end-uses. People may be surprised to see that industry already tends to be more energy efficient than imagined. So while there are significant improvements still to be tapped within the variety of industrial sectors, industry generally has smallest scale of improvement. On the other hand, buildings have significant potential to cost-effectively reduce overall energy use while still providing the desired level of amenities and services as in the Reference Case projections. The 2050 industrial sector savings, for example, range between 36 and 51% for the two policy cases while residential and commercial buildings might realize overall energy savings from 45 to 69% savings. Transportation savings, moving closer to buildings in the scale of efficiency improvements, fall in between with suggested savings of 38 to 56%, respectively. Interestingly, the transportation sector actually increases some electricity use as a means of reducing larger sector energy consumption. In other words, increasing electricity consumption for the nation's vehicle fleet can actually reduce total transportation energy use. Finally, and especially in the case of the electricity sector, moving toward much more efficient generation technologies, such as combined heat and power, greatly increases the thermal efficiency of electricity production (see the discussion on this point in the write-up of the efficiency gains in the industrial sector). Again, the result is that any savings in end-use demand for electricity is amplified by further savings driven by increased performance in the production and distribution of electricity throughout the economy.

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[35] Readers might note that the data for sector totals in Table 17 might differ slightly from totals reported in the building sector analysis. The reason is an assumption of reference case system electricity efficiencies in driving the buildings assessment. Table 17 incorporates the revised Advanced Case and Phoenix Case electric system efficiencies as they might otherwise impact the primary energy data in the buildings data. See Appendix A for a further discussion of reconciling the differences.

Table 17. Energy Use by Scenario and by Sector (with all values in Quads)

	2010 Historical Data	2050			Change from 2050 Reference Case	
		Reference Case	Advanced Case	Phoenix Case	Advanced Case	Phoenix Case
Residential Sector						
Delivered Energy						
Electricity	4.97	6.66	3.95	3.23	-40.7%	-51.5%
Other Fuels	6.47	6.20	1.80	0.80	-71.0%	-87.1%
Subtotal Delivered	11.44	12.86	5.75	4.03	-55.3%	-68.7%
Electricity Losses	10.59	12.88	6.70	3.94	-48.0%	-69.4%
Total Primary Energy	22.03	25.74	12.45	7.97	-51.6%	-69.0%
Commercial Sector						
Delivered Energy						
Electricity	4.60	7.96	5.60	4.66	-29.7%	-41.5%
Other Fuels	3.90	4.97	0.79	0.52	-84.1%	-89.5%
Subtotal Delivered	8.50	12.93	6.39	5.18	-50.6%	-59.9%
Electricity Losses	9.82	15.14	9.04	5.36	-40.3%	-64.6%
Total Primary Energy	18.32	28.07	15.43	10.54	-45.0%	-62.4%
Industrial Sector						
Delivered Energy						
Electricity	3.20	3.36	2.25	2.25	-32.8%	-32.8%
Other Fuels	19.89	25.86	17.38	12.25	-32.8%	-52.6%
Subtotal Delivered	23.09	29.21	19.63	14.50	-32.8%	-50.4%
Electricity Losses	6.82	4.01	1.62	1.66	-59.6%	-58.5%
Total Primary Energy	29.91	33.23	21.25	16.17	-36.0%	-51.3%
Transportation Sector						
Delivered Energy						
Electricity	0.02	0.36	1.09	1.34	202.8%	272.2%
Other Fuels	27.42	33.55	18.38	12.26	-45.2%	-63.5%
Subtotal Delivered	27.44	33.91	19.47	13.60	-42.6%	-59.9%
Electricity Losses	0.05	0.70	1.85	1.64	165.6%	135.0%
Total Primary Energy	27.49	34.61	21.32	15.24	-38.4%	-56.0%
Economy-Wide Totals						
Delivered Energy						
Electricity	12.79	18.34	12.89	11.48	-29.7%	-37.4%
Other Fuels	57.68	70.58	38.35	25.83	-45.7%	-63.4%
Subtotal Delivered	70.47	88.92	51.24	37.31	-42.4%	-58.0%
Electricity Losses	27.28	32.73	19.21	12.61	-41.3%	-61.5%
Total Primary Energy	97.75	121.65	70.45	49.92	-42.1%	-59.0%

IV. MACROECONOMIC IMPACTS OF ENERGY EFFICIENCY INVESTMENTS

At this point we have established that the U.S. economy can go a very long way to improve its overall energy efficiency. That is, the nation has the wherewithal to provide an expanded set of goods and services, and to do so using considerably less energy. What lessons might we draw from the larger perspective of the macroeconomy? To generate some meaningful insights in that regard we now turn to an analysis of the macroeconomic impacts of these scenarios. To do this, we mapped the suggested 2050 energy savings into ACEEE's proprietary **D**ynamic **E**nergy **E**fficiency **P**olicy **E**valuation **R**outine, or DEEPER modeling system.

Although we have not evaluated the individual cost of the efficiency upgrades characterized in the earlier part of this report, the model contains a number of algorithms that can provide working computations to generate such information. In particular, we build on work of Cleetus et al. (2003) and Dahl (2006) to generate a set of capital costs associated with different levels of energy savings in the different end-use sectors of the economy. As explained in Appendix B, for example, a 10% savings might generate a cost that requires three or four years for the investment to pay for itself through the energy bill savings. On the other hand, a 50% savings might require nine or ten years before the investment is paid back. These results are broadly consistent with results summarized in Laitner et al. (2006) and Hanson and Laitner (2004).

Once we know both the costs and the likely energy bill savings, DEEPER can then transform the data to match changes in consumer and business spending with the appropriate sector labor and income coefficients. This, in turn, allows us to generate information on the net employment benefits associated with energy efficiency improvements. This also allows us to assess the contributions to household income and the nation's Gross Domestic Product. Again, Appendix B provides more detail on the DEEPER modeling system.

Following this analysis, we briefly discuss the potential for a macroeconomic rebound effect that could modify our results somewhat.

A. Providing Jobs and Income

Earlier in this report, reflecting on the historical record for energy efficiency improvements (see Section II), we noted that the economy would likely benefit from any improvement that was cost-effective. Indeed, the evidence pointed to a large number of studies suggesting net savings from accelerated investments in the more productive use of energy. Yet, few assessments of policy have been completed that reflect as deep of a penetration of efficiency improvements as suggested by the findings in Section III—a 42% energy savings for the Advanced Case and a 59% energy savings for the Phoenix Case, all by 2050. Hence, there is the need to map those savings into the DEEPER model to provide us with a sense of likely outcomes.

At this point we offer a note of caution as we first describe the mapping of a large-scale energy savings into any macroeconomic model, and as we then characterize the net impacts. Recall that the point of the exercise in Section III of the report was to evaluate the potential for energy efficiency improvements for a single year in time. In this case we examined the outcomes in the year 2050 so that we might determine how changes in the nation's infrastructure might accommodate significant productivity gains. But the very large improvements that might be possible for the year 2050 will be the result of decisions, behaviors, and investments that will have to be made beginning next year and continuing right on through 2050. As it turns out, mapping the kind of changes that have to be made over time can take any number of paths. In this case, we assume a slow ramp up of activity so that more than half of the program effort and investment occurs in the last ten years of the time horizon. In other words, while the activity begins very slowly in 2012, it doesn't reach full stride until the period 2040 through 2050. Table 18 provides the highlights of impacts given that trajectory.

Table 18. Indicative Macroeconomic Impacts

Financial and Economic Indicators	Advanced Case	Phoenix Case
Energy Savings from 2050 Reference Case	42%	59%
Implied Cost of Technology		
Simple Average Payback 2012	3.5	3.6
Simple Average Payback 2050	5.6	9.9
Cumulative Financial Impacts 2012-2050 (Billion 2009 Dollars)		
Program Cost	$500	$1,200
Total Investments	$2,400	$5,300
Annual Payments on Investments	$2,900	$6,400
Energy Bill Savings	$15,000	$23,700
Net Savings	$11,600	$16,200
Net Present Value at 5% Discount Rate	$3,000	$3,900
Total Resource Cost Ratio at 5% Discount Rate	2.8	2.1
Net Macroeconomic Impacts in the Year 2050		
Employment (millions of jobs)	1.3	1.9
Percent from Reference Case	0.4%	0.6%
GDP (billion 2009 dollars)	100	200
Percent from Reference Case	0.3%	0.4%

The first critical assumption reflected in Table 18 is the assumed cost of the energy efficiency improvements. Here we simplify that idea by using the payback metric. In other words, if an efficiency measure is installed, how many years will it require for the energy bill savings to pay for the installed cost of that improvement? From the DEEPER algorithms it generally appears that in the very first year of activity (that is, year 2012), the first technologies on average will pay for themselves in just over three years. Some very simple efficiency upgrades may pay for themselves in less than a year while others might take many more years than that. With most technologies having a life of well over a decade, and in many cases more than 20 or 30 years, this implies a very positive return. At the same time, as the easier upgrades are completed it become more costly to implement efficiency improvements. In the Advanced Case the payback rises closer to a 6-year average—with some measures perhaps exceeding 7 or 8 years while others perhaps only 3 or 4 years. In the Phoenix Scenario, however, the economy is being pushed harder and the new efficiency enhancements in 2050 might rise to an average 9.9-year payback. While still roughly the equivalent of a 10% average annual return, it becomes less cost-effective compared to the easier installations.

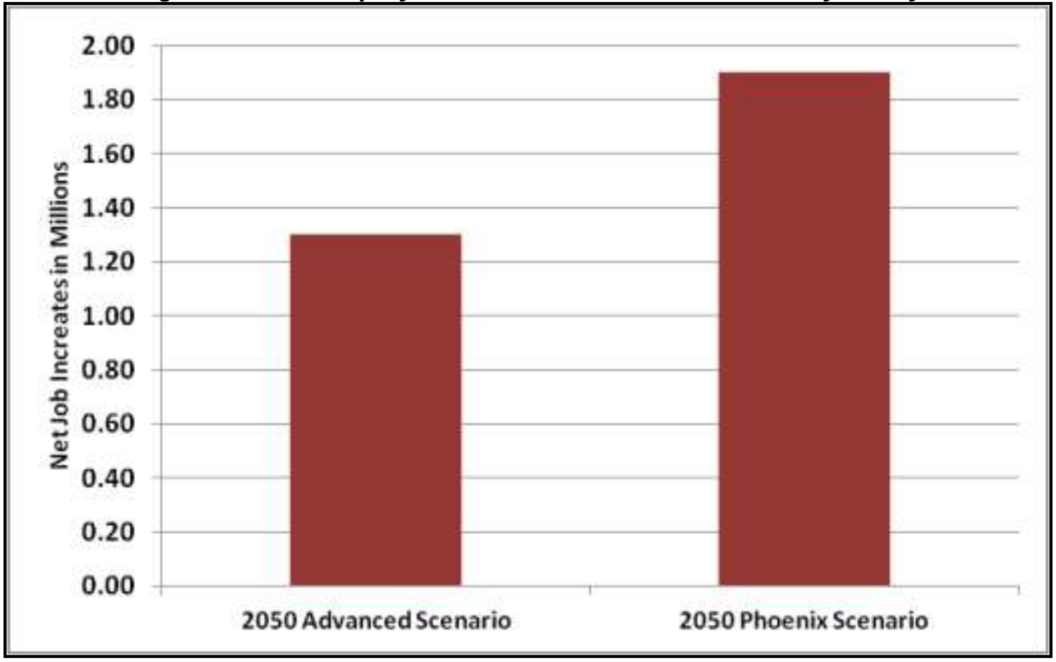
A second observation from Table 18 is the assumption that policies cost money to implement. This is true whether we are talking about private sector activities or government-initiated efforts. Such expenditures include efforts to train key personnel, to market and promote the critical ideas, to inform consumers and businesses about the opportunities, and to evaluate overall success so that appropriate adjustments can be made in overall program design and outreach. In DEEPER the working assumption—based on the evaluation of other policy initiatives—is that program costs will start at about 25% of the first efficiency investments. As more and more marketing experience builds and as the market itself is slowly transformed, the program costs are assumed to drop to about 15% of the total investment by 2050.

As one might expect, lower payback means lower upfront or capital costs. Table 18 suggests the cumulative investments in the efficiency upgrades for the Advanced Case will about $2.4 trillion over the 39-year period 2012 through 2050 (with all financial values reported in constant 2009 dollars). The significantly greater magnitude of efficiency changes in the Phoenix Case, together with the higher costs per unit of improvement, increases the cumulative investments to $5.3 trillion in that same period of time. This seems like a lot of money until we realize that the economy will likely invest something like an average of $4.6 trillion per year each year over the 2012 through 2050 time horizon. In other words, while energy efficiency appears to be significantly more costly in the Phoenix Scenario, it is still roughly the equivalent just one year's routine investment spread out over a 39-year period.

DEEPER also assumes that most of the upgrades will be financed over time rather than paid for directly by businesses and consumers. Here we implement the conservative assumption of a 7% nominal interest rate that is paid for on average for a five-year period. Because the improvements are paid for over time, this results in annual payments that are less in a given year than the new investments that are made. Cumulatively, the total payments are shown to be $2.9 and $6.4 trillion over the entire 39-year period for the Advanced Case and the Phoenix Case, respectively. But the good news is that these investments generate a cumulative energy bill savings of $15 trillion in the Advanced Case, which increases dramatically to $23.7 trillion in the Phoenix Case. This larger cumulative savings in the latter scenario is the result of both a deeper level of savings that also occurs earlier in time.

The net consumer and business savings—reflecting energy bill savings less both the program costs and the annual payments for the upgrades—run to a total of $11.6 and $16.2 trillion for the two cases, respectively. When discounted at 5% over the entire 39-year period, the net present value falls to $3.0 and $3.9 trillion for the Advance Case and the Phoenix Case, respectively. The benefit-cost ratio shows a net positive 2.8 and 2.1 for the Advanced Case and the Phoenix Case, in that order.

Figure 23. Net Employment Benefits from the Efficiency Policy



The big news is the significant and sizeable impact of these investments—and especially as those efficiency upgrades pay for themselves over time and drive a significant increase in net employment (see Figure 23 above). The Advanced Case shows about 1.3 million net jobs in the year 2050. Surprisingly, the Phoenix Case, benefiting from a larger investment and net energy bill savings, grows to 1.9 million net jobs (rounded) in 2050. The triple bottom line, including a significant net energy bill savings, a sizeable boost in the job market, and (although not shown here) a substantial reduction in air pollution and greenhouse gas emissions, confirms that the U.S. economy would be greatly revitalized under either of these two investment-led productivity .

B. The Impact of Rebound on Overall Energy Consumption

A number of policy analysts have recently written about the “rebound effect.” Traditionally this term has been used to refer to potential increases in demand for energy services, as a result of efficiency improvements. For example, consumers may drive longer distances because they know their cars are more efficient and cost less to operate. Our analysis of energy savings in the transportation sector includes these impacts. In the buildings sector, a variety of field studies have shown such a rebound effect to be minimal (see, for example, Nadel 1993 and Ehrhardt-Martinez and Laitner 2010a). More recently, growing attention has been paid to a “macroeconomic rebound effect,” meaning that as costs of energy services decline, resources are freed up that enable both people and equipment to amplify their level of effort and economic activity. This allows the economy to expand, which, in turn, will tend to pull energy use back up to a slightly higher level to support that added output.

If the economy is more productive as the result of the very large net energy bill savings, as suggested by the DEEPER modeling runs discussed above, the logical question is how might this affect the nation’s overall energy use. Unfortunately, DEEPER is not presently set up to answer this question, but we are exploring ways to incorporate such feedback into DEEPER and hope to write a paper on this subject once we do. We note that DEEPER estimates a 0.3% and 0.4% higher GDP in the Advanced and Phoenix Cases. As a rough approximation, if the economy is 0.4% larger, than energy use might also be on the order of 0.4% higher, raising energy use by about a fourth of a quad relative to the values shown in Table 17.

V. COMPARISON TO OTHER STUDIES: FURTHER DISCUSSION AND REVIEW

Ours is not the first study to look at energy efficiency opportunities out to 2050. In this section we compare our results to five other studies—Lovins et al. (2011), the California Council for Science and Technology (CCST 2011), Harvey (2010), IEA/ETP (2010), Goldstein (2009), and Laitner (2009a).

First, physicist and noted author Amory Lovins and his team at the Rocky Mountain Institute (RMI) released a book in September 2011, *Reinventing Fire: Bold Business Solutions for the New Energy Era*. In that extensive review, the RMI investigation suggested that a business-as-usual energy scenario might increase the nation’s demands for primary energy to about 117 quads by 2050. This compares to our Reference Case assumption of 122 quads, which is a larger number that is likely affected by growth assumptions for the U.S. economy. While the Lovins team assumed a 158% expansion of the American economy by 2050, our assumption—based on the data extrapolated from the AEO 2011—was that the expansion of GDP might be closer to 180% by 2050.

By unleashing smart business investments at all levels of the economy, RMI found that systematic energy efficiency improvements could bring the energy consumption down to 71 quads by 2050. This is on the same order of the Advanced Case 70 quads suggested by our report, but significantly higher than the 50 quads found in the Phoenix Case. At the same time, Lovins and RMI found a very large number of system upgrades that, although not formally quantified into their main scenario, are likely to reflect a savings that would reduce total energy use much closer to 50-quad estimate reflected in our Phoenix Case. More important, they concluded “we can run the same 2050 economy . . . but with half the delivered energy, with less risk, and for $5 trillion less” (expressed in 2010 net present value dollars). When that net savings of $5 trillion is adjusted for the differences among the several scenarios and key assumptions, this compares favorably with the findings in our assessment in which we find a net present value savings that range from $3.0 to $3.9 trillion (in 2009 dollars) that are cumulative over the period 2012 through 2050 (shown in Table 18 above).

Although from a slightly different perspective, the International Energy Agency released an analysis in 2010 that also explored alternative energy futures in the year 2050. The emphasis was on reducing energy-related carbon dioxide emissions globally (IEA/ETP 2010). At the same time, however, the global scenario integrated many of the same technology perspectives reflected in the main body of this report, and it contained a separate analysis that was done for the United States in a way that makes it possible to compare those results with both this evaluation and the Reinventing Fire assessment. In short, the IEA analysis suggested that a mix of carbon abatement options might enable the U.S. to cost-effectively reduce energy-related carbon dioxide emissions by 82% compared to standard projections for the year 2050. According to the IEA report, clean energy options like nuclear and renewable energy technologies might account for 45% of the potential reductions but that various forms of energy efficiency might provide 55% of the total reductions. To better underscore the cost-effective opportunities to increase our nation's energy productivity, we can compare both the IEA/ETP and the Reinventing Fire analyses with the ACEEE Advanced and Phoenix Cases—all over the period 2010 through 2050. Table 19 below highlights the key metrics from this comparison.

Table 19. Key Metrics from Year 2050 Alternative Future Studies

	Year 2050 Impacts			
Metric	ACEEE-Advanced	ACEEE-Phoenix	IEA ETP	Reinventing Fire
BAU GDP Index (2010 = 1.00)	2.79	2.79	1.95	2.58
BAU Energy Use (2010 = 1.00)	1.24	1.24	1.05	1.27
Efficiency Scenario Energy Use (2010 = 1.00)	0.72	0.51	0.47	0.69
Investment (Trillion 2009 Dollars)	2.9	6.4	5.9	4.5
Savings (Trillion 2009 Dollars)	15	23.7	15.1	9.5

Note**:** Both the investments and savings data in the last two rows of the table reflect cumulative values in constant dollars over the period 2010 through 2050.

A number of insights begin to emerge with even a cursory review of the table above. First, despite wide variations in expected performance of the U.S. economy—building on the forecasts published by the Energy Information Administration (EIA 2011b), the ACEEE scenarios anticipate a "business-as-usual" (BAU) 2050 economy that is nearly three times as large as it is in 2010. The IEA suggests a much smaller growth trajectory while Reinventing Fire falls between ACEEE and the IEA. But all three suggest the potential for large gains in energy efficiency. ACEEE, for example, suggests that improvements by 2050 could see energy use that is somewhere between 51% and 72% of the 2010 consumption levels. IEA and Reinventing Fire suggest improvements that are 47% and 69% of 2010 levels. All four scenarios indicate the need for significant upfront cumulative investments that range from about $3 to $6 trillion (rounded) over the period 2010 through 2050. At the same time, all four also suggest the potential for a very large future energy bill savings as the size of the nation's energy bills shrink.[36]

Other assessments generally confirm these magnitudes and opportunities for efficiency improvements show in the table above. University of Toronto professor L. D. Danny Harvey (2010), for example, published an extensive 600-page volume, *Energy Efficiency and the Demand for Energy Services*, which provided a highly detailed assessment of the energy efficiency resource both in North America and globally. While focusing on stabilizing atmospheric concentrations of carbon dioxide emissions at lower levels, Harvey explored a range of economically feasible rates of reduction in the global primary energy intensities over the next 40-100 years. Depending on the assumptions affecting population growth and per capita incomes, his scenario assessments suggested that a wide variety of

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[36] This larger energy bill savings suggested by ACEEE is, in significant part, because the EIA/ACEEE estimate of the Base Case GDP is higher, providing larger nominal energy and energy bill savings, especially in the ACEEE Phoenix Case. In the Phoenix Case, for example, ACEEE suggests a 70 quad energy savings by 2050. The IEA and Reinventing Fire suggest an average 55 quad savings. As this larger savings accumulates over time, the energy bill savings would be proportionately larger as well.

efficiency improvements could reduce carbon dioxide emissions by more than 40% by 2050 and as much as 80% by 2100. As he acknowledges, however, the deeper efficiency gains would require an aggressive set of behaviors and policies implemented in a persistent way over a long period of time.

Moving from a global to a state perspective, the California Council for Science and Technology (CCST) released a May 2011 report entitled *California's Energy Future: The View to 2050*. The study was motivated by both legislation and an executive order that were designed to push California total greenhouse gas emissions to 80% below their 1990 levels by the year 2050. The approach was two-fold. First, the Council wanted to establish an "existence proof." In effect, it was asking the question, can it be done? And what needs to change to allow California to get there? Second, its focus was on "technology, GHG emissions and other impacts, not economics." The conclusion was that, yes, California can achieve 80% cuts in total GHG emissions and still meet its energy needs. But the Council noted that the state might get only ~60% of the reduction cuts with technology that we largely know about today. The remaining 20% will have to come from new technologies and revised behaviors. This is not an especially daunting conclusion, since in 1970 we were arguing about whether even a 5% savings in national energy use was feasible by 2010 and we now see the very large savings that have unfolded since that time. Imagine what a forecast of computer technology 40 years ago would have failed to predict. Based on the 60% interim target, CCST identified efficiency opportunities that might help the state achieve more than half of the needed reductions.

In 2009 Physicist David Goldstein released a book entitled *Invisible Energy: Strategies to Rescue the Economy and Save the Planet (*Goldstein 2009). Following an extensive review of the efficiency potential in a full array of technologies, he concluded that "energy efficiency can produce savings of 35 to 50% in the next 20 to 40 years." At the same time, however, he suggested that savings of 80 to 90% are possible in the major uses of energy. Of most interest, Goldstein estimates that "implementing the opportunities already available with current technologies could save more than $10 trillion [for the American economy] over the next 40 years." This amount includes $4 trillion through energy savings measures plus $5 trillion in reduced energy prices. He also suggests there would likely be additional trillions in secondary non-energy benefits that result from efficiency measures.

Finally, in an investigative comparison of many typical policy models as they might assess the economic impacts of climate legislation, Laitner (2009a) set up an independent diagnostic model in a report entitled *The Positive Economics of Climate Change Policies: What the Historical Evidence Can Tell Us*. In that assessment he examined the impact of an 86% reduction in energy and non-energy greenhouse gas emissions by the year 2050. Many of the typical models, he noted, might achieve only a 72% reduction of total emissions with energy efficiency providing just 15% of those reductions, and clean energy supply (e.g., some combination of nuclear, renewable, and coal-fired electricity with carbon capture and sequestration) providing another 29%. Domestic and international offsets were expected to provide more than half of the needed reductions. All of this was at a very high cost with a negative impact on the economy. On the other hand, when energy efficiency was properly mapped into the policy solution, the diagnostic modeling exercise found that a much larger 86% emissions reduction is not only possible, but also cheaper by comparison. Energy consumption declined from 129 quads in the Reference Case to as little as 64 quads in the Policy Case. That 65-quad savings falls roughly halfway between the 50-quad savings identified in the Advanced Case and the 70-quad savings in the Phoenix Case.

VI. CONCLUSIONS AND MOVING FORWARD

Based on our nation's previous track record and the available evidence, two critical details emerge from this assessment. The first is that the larger well-being of the economy has been powered in good measure by historical gains in our nation's overall level of energy efficiency. The second is that the prospect for future improvements is very large. Perhaps more critically, our nation's larger prosperity will depend on our ability to secure those large-scale efficiency improvements. At the same time, the capacity for such improvements is larger than the public and most policymakers understand or believe.

In 1970 our economy required 15,900 Btus of energy to support a dollar of economic activity. By 2010 this ratio had fallen by more than half—to 7,300 Btus per dollar (where economic activity in measured in constant 2005 dollars). The annual rate of decline in the nation's energy intensity was about 1.9% even as our economy grew by 2.9% per year. The better part of those annual growth rates occurred in the years through 2006. Since 2006 and right on through this year, however, it appears the annual rate of energy efficiency improvement dropped to 0.7% per year, even as the nation's economy expanded by just 0.5% per year. In a working paper prepared for this assessment, the data underscores the vital link between efficiency improvements and a robust economy. Simply stated, it actually does require energy to power the economy but the energy that is at work within the economic process must be cost-effective relative to the cost of labor and other investments needed within the economy. And the cheapest form of energy has actually been the steady increase in our nation's energy efficiency (Laitner forthcoming).

In the Reference Case benchmarked to the *Annual Energy Outlook 2011* (EIA 2011b) and extended out to the year 2050, the annual rate of efficiency improvement is projected to be just under 2.0% per year over the period 2012 through 2050. In the Advanced and Phoenix Cases, that rate of improvement grows to 3.3% and 4.3%, respectively. If we choose to invest in the large-scale energy efficiency resource, the data in Table 17 imply a net energy bill savings that ranges from $2.6 to 4.0 trillion cumulative over the same time horizon of 2012 to 2050. Lovins et al. (2011) suggest that same scale of net savings, noting a $5 trillion net savings through 2050 (with all three estimates of net energy bill savings based on a net present value assessment). In other words, as Lovins notes and our own study suggests, we can run the same 2050 economy, but with 40% to 60% less energy, with less cost and less risk, and with a substantial net boost to employment—from 1.3 to 1.9 million jobs (about 0.5% above Reference Case). And as Lovins et al. (2011), the California Council of Science and Technology (CCST 2011), and other studies have all underscored, we have the technical and behavioral capacity to move in this direction, but it will require a set of policies and choices, all made possible by more productive investments.

Jacobson and Delucchi (2009) have noted that "society has achieved massive transformations before." They cite the World War II transition when "the U.S. retooled automobile factories to produce 300,000 aircraft, and other countries produced 486,000 more." Or as Laitner (2004) previously noted, rather than practical limits on further efficiency gains, it might be more the limits of public policy to encourage the needed innovations and investments (see also CCST 2011). In effect, the ACEEE energy efficiency scenarios highlighted in this study merely represent a different recipe of technology investments compared to the standard Reference Case, but it is one that emphasizes a more productive investment pattern that can enable the U.S. economy to substantially reduce overall energy expenditures—should we choose to invest in and develop that larger opportunity. The question is will we choose to make those more productive investments?

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APPENDIX A: OVERVIEW OF THE ASSESSMENT METHODOLOGY

This assessment was generally carried out in various stages over a two-year period beginning in late 2009. Our intent was to compare a 2050 reference case for each of the end-use sectors with what we might anticipate as cost-effective energy efficiency improvements, also by the year 2050. Hence, the focus was on changes, or what we might call the 2050 deltas, from a suggested business-as-usual (BAU) energy consumption for residential buildings, commercial buildings, industrial processes, and transportation services. We also included the potential energy savings from improvements in the supply-side operations of electricity generation, transmission and distribution.

Staff Leads for Sector Analysis

Harvey Sachs provided the lead on residential and commercial buildings in collaboration with Steve Nadel. Neal Elliott was the lead analyst for industry while Siddiq Khan provided the transportation sector analysis with active support from Therese Langer. Both Skip Laitner and Neal Elliot developed the set of assumptions on the potential for supply-side efficiency improvements in the electric utility sector. Laitner was the lead analyst for the macroeconomic assessment, and working with Steve Nadel, he provided the overall integration of the individual sectors as all of the individual analyses converged into the main report.

An Overview of End-Use Assessments

While we generally benchmarked to the Energy Information Administration's *Annual Energy Outlook* 2010, we also made an effort to update some key benchmarks to the AEO 2011. At the same time, each group of analysts used specific techniques appropriate to their end-use sectors which generated minor differences from the Annual Energy Outlook. In the building sectors, for example, we used an equivalent stock model that reflected different assumptions about the typical square footage of a building, its level of occupancy, and the mix of end use services which included everything from space heating and cooling, lighting, and a full array of equipment and appliances.

Industry, on the other hand, is an incredibly diverse group of agricultural, mining, construction, and manufacturing services that produces everything from aspirin tablets and pounds of fruit and vegetables to tons of copper and millions of new homes and cars. The Bureau of Labor Statistics, for example, tracks more than 9,000 producer price indexes for individual products and group of products each month (see, generally, www.bls.gov/ppi). With that enormous diversity as a backdrop, we chose to model the efficiency improvements as sector-wide changes in energy intensities over time per million constant dollars of shipments.

For transportation services we relied on the Argonne National Laboratory's VISION model (ANL 2010). This allowed us to reflect the level of energy services (for example, the number of miles traveled or ton-miles of freight that might be hauled) together with the mix and fuel economy with an evolving stock of both new and existing vehicles that might be needed to meet given demands for transportation services.

In the case of evaluating the efficiency gains in electricity generation we took the anticipated or projected demands for electricity services and produced a working estimate of how much of the electricity demands might be met through distributed generation, and at what overall system efficiencies might be anticipated with best practices associated with reasonably known generation, transmission, and distribution technologies. We also provide estimates (as suggested in Figure 21) of what the more energy-efficient, supply-side technologies might imply for the use of fossil fuels, non-fossil fuel resources (as nuclear energy and renewable energy technologies), and combined heat and power technologies, and what they, in turn, might also imply about the larger "system efficiency" of generating and distributing the electricity that might be demanded.

Against this back drop one might quickly imagine the differences which materialize when compared, for example, to the integrated National Energy Modeling System (NEMS) used by the Energy

Information Administration. As but one example of potential differences, the Annual Energy Outlook indicates a total primary energy use that is just under 98 quadrillion Btus of energy in 2010. More significantly, under the standard or BAU assumptions of normal efficiency improvements and economic growth, extending the NEMS forecast to 2050 might indicate a growth to perhaps 126 quads of energy in that same year. On the other hand, adding up the different sector assessments, we find that the total energy use might grow to only 122 quads of energy by 2050. Much of that four-quad difference appears to be the result of a divergence of assumed system efficiencies in the economy-wide production of electricity. Extending the AEO assumptions in the reference case seems to indicate an improvement of overall system efficiency from about 32% in 2010 to only 34% in 2050. Our own judgment suggests a reference case that might be closer to 36% by 2050. That small difference translates into a roughly three-quad difference. Differences in rounding and other small assumptions account for the remaining quad of BAU energy consumption.

As we have integrated the individual sector assessments for both the Advanced Case and the Phoenix Case (as defined in the main report), we find that working from an assumed 122 quad Reference Case in 2050, the individual sector savings results in an aggregate total savings of 51 and 72 quads, respectively. These integrated results are summarized in Table 17.

Future Areas of Research

While the prospects for large-scale enhancements in energy efficiency are very real, both time and resource constraints prevented us from undertaking a fully integrated macroeconomic assessment of that economic potential. This is particularly true as we evaluate the long-term economics of the suggested efficiency measures and system improvements, and as we might examine the positive environmental and climate benefits that are likely to follow from greater levels of energy productivity. For example, one specific area that we think would be useful to explore is the so-called macroeconomic rebound effect. As we've noted in the main body of the report, that impact is likely to be minimal but the issue merits further and a more systematic review.

In a related set of topics, we also believe that additional insights might be gained about the energy efficiency resource potential by integrating the human and social elements of technology development and deployment—especially as they might enable a more positive economic outcome to emerge. Here we might extend our previous work on what we call "people-centered initiatives" (Ehrhardt-Martinez and Laitner 2010b) to explore more cost-effective ways that increase energy savings. Finally, the evidence suggests that if we do not boost our nation's energy productivity well-above the historical rates of improvement, the economy may follow a less robust growth trajectory. It may turn out, for example, that a weakened energy and economic productivity may support fewer jobs than we now anticipate. In that case, rather than simply a net gain 1.3 or 1.9 million more jobs compared to the reference case, we might find that accelerating the deployment of the full energy efficiency potential might also preserve millions of existing jobs.

APPENDIX B: KEY ECONOMIC AND TECHNOLOGY ASSUMPTIONS

As implied in the main part of this report, the impact assessment described here is really an examination of how changed behaviors and investment flows might reasonably characterize an alternative and perhaps a more productive energy and economic future. As business leaders and policymakers first think about the policy implications of suggested climate change legislation, they may conclude that the implied transition to a less carbon-intensive economy will end up costing more. On the other hand, when all system costs are properly included and balanced, it can be shown—on a net basis—that the alternative future or the enacted policy may actually cost less.

In a format consistent with a number of other past studies that inform this debate (see, for example, McKinsey 2009; CCS 2008; Laitner and McKinney 2008; Barrett et al. 2005; Laitner et al. 2006; Lovins et al. 2004; Interlaboratory Working Group 2000), this appendix highlights the major analytical assumptions that underpin the assessment described in the main part of the report.

The assumptions generally fall into four major categories: prices, quantities, investment flows, and input-output modeling. Each of these categories is subscripted by sector and by end-use energy or fuels. The analytical tool used to evaluate the energy and climate policy impacts is the DEEPER Model, which is described next. This is then followed by the major price, cost, income, and demand assumptions that underpin the results summarized in the main body of the report.

The DEEPER Modeling System

The **D**ynamic **E**nergy **E**fficiency **P**olicy **E**valuation **R**outine—the DEEPER Modeling System—is a 15-sector quasi-dynamic input-output model of the U.S. economy.[37] Figure A-1 on the following page contains a block diagram of the model that highlights many of the key features discussed in this appendix. Although updated model with a new name, the DEEPER model has a 19-year history of use and development. See Laitner, Bernow, and DeCicco (1998) for an example of an earlier set of modeling results.[38] Laitner and McKinney (2008) also review past modeling efforts using this modeling framework. The model is used to evaluate the macroeconomic impacts of a variety of energy efficiency, renewable energy, and climate policies at both the state and national level. The timeframe of the model for evaluating policies at the national level is 2010 through 2050, or in the case of evaluating the Long-Term Energy Efficiency Outlook characterized in this report, for the single year impact for 2050. In its current implementation, the model iterates for the net impacts across the sectors of the economy to evaluate gains and losses in jobs, income and contribution to GDP compared to a previously defined Reference Case.

Although not used in this particular assessment, the model includes a representation of both energy-related CO_2 emissions and all other greenhouse gas emissions as well as emissions reduction opportunities. The DEEPER Model focuses, in particular, on the use of energy in all sectors of the economy, electricity production, and energy-related CO_2 emissions as well as on the prices, policies, and programs necessary to achieve the desired emissions reductions. The DEEPER Model is an Excel-based analytical tool with three linked modules combining approximately two dozen interdependent worksheets. The primary analytic modules are: (i) the Energy and Emissions Module,

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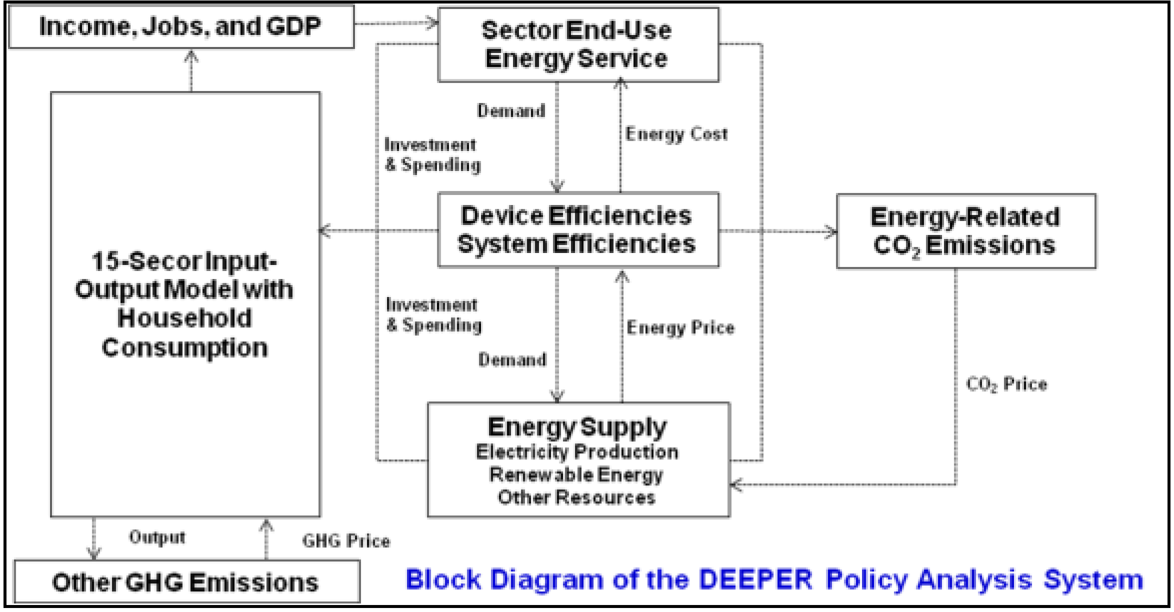
[37] There are two points that might be worth noting here. First, the model solves recursively. That is, the current year set of prices and quantities is dependent on the previous years' results. As the model moves through time, there are both secular and price-quantity adjustments to key elasticities and coefficients within the model. Second, there is nothing particularly special about this number of sectors. The problem is to provide sufficient detail to show key negative and positive impacts while maintaining a model of manageable size. If the analyst chooses to reflect a different mix of sectors and stay within the 15 x 15 matrix, that can be easily accomplished. Expanding the number of sectors will require some minor programming changes and adjustments to handle the larger matrix.

[38] When both equilibrium and dynamic input-output models use the same technology assumptions, both models should generate reasonably comparable set of outcomes. See Hanson and Laitner (2004) for a diagnostic assessment that reached that conclusion.

(ii) the Electricity Production Module, and (iii) the Macroeconomic Module. The block diagram of the DEEPER Modeling System on the following page lays out the analytical framework of the model.

Figure B-1. Block Diagram of the DEEPER Policy Analysis System



The model outcomes are driven primarily by the demands for energy services and alternative investment patterns as they are shaped by changes in policies and prices. A key feature of the model is one that also allows consumer behaviors to also adjust to changing preferences. This follows the logic outlined in Laitner, DeCanio, and Peters (2000), and fits within the framework outlined by Ehrhardt-Martinez (2008). The changes are implemented in what we call a price-preference ratio following Laitner (2009b) and Laitner and Hanson (2006). The functional form of the price-preference ratio is computed as an index of price divided by the consumer's implicit discount rate. This is a rate that reflects a desired return on investment. For example, if a consumer chooses not to adopt a technology, for whatever reason, unless it pays for itself over a 2-year period, that suggests a 50% discount rate; or said differently, a desire to earn at least a 50% return on his or her investment in an energy-efficient technology. All else being equal, either a doubling of prices or a 50% reduction in the implicit discount rate (or some equivalent combination of the two) will have the same impact on the various elasticities within the model.[39]

Although the DEEPER Model is not a general equilibrium model, it does provide sufficient accounting detail to match import-adjusted changes in investments and expenditures within one sector of the economy and balance them against changes in other sectors. As shown in the block diagram above, the demand for energy-related services is the starting point for policy-induced changes. Both price and non-price policies—including standards, technical assistance, financial incentives, research and development (R&D), or general information and labeling programs (e.g., the EPA and DOE ENERGY STAR programs)—can shift consumer preferences and the availability of technologies. Implementation of these policies stimulates an array of changes in prices, investments, and expenditures. These changes include program costs and incentives that might be needed to shift behaviors and investments so that the energy and emissions targets are satisfied. As changing demands confront a changing mix of energy resources, GHG prices (in constant dollars per metric ton of avoided CO_2-equivalent emissions) and energy prices (in constant dollars per million Btus of energy) are likely to change in response. The combination of new policies and induced changes in

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[39] One nice feature of this functional form is that it is less important to determine the "right" starting implicit discount rate as it is to show what a shift in the size of that rate might matter.

prices stimulates changes in investments and other consumer behaviors. These changes in investments and consumer behaviors drive the final results that emerge from application of the DEEPER Model.[40] With this preliminary characterization of the model, the sections that follow describe the three major modules within DEEPER.

Energy and Emissions Module: The DEEPER Model is benchmarked to the most current version of the *Annual Energy Outlook* (EIA 2011b), which now extends out through 2035. Based on data available from other sources like Economy.com (2010), which now goes out to 2041, we must make a reasoned estimate of how the economy might grow through the year 2050 in a "Business-as-Usual" or Reference Case scenario, and how that will, in turn, affect energy use, fuel and electricity prices, and greenhouse gas emissions. The key benchmark data for the Reference Case are highlighted in Table A-1, below.

Table B-1. Key Reference Case Data for Benchmark Years

Indicator	2010	2025	2050	Annual Growth Rate 2010-2050
Population (millions)	310.8	358.1	442.0	0.88%
Total Energy Use (Quads)	97.7	107.8	124.6	0.61%
Per capita Income (2005 dollars)	42,535	55,899	83,796	1.71%
US GDP (billion 2005 dollars)	13,221	20,015	37,042	2.61%
Energy Intensity (kBtu / 2005 $GDP)	7.39	5.38	3.36	-1.95%
Average End Use Energy Price (2009 $/MBtu)	16.58	19.08	21.42	0.64%
Total Energy Expenditures (Bln 2009 dollars)	1,168	1,503	1,949	1.29%

The main Reference Case assumptions shown in the above table are for the key benchmark years of 2010, 2025 and 2050. In general the economy is expected to grow at a rate of about 2.6% annually; total end-use energy consumption will grow 0.6% per year. Rising average annual end-use energy prices (with all values in 2009 dollars) will increase at a rate of about 0.6% annually. Because of the expected growth in overall energy use, the nation's total energy bill (across all sectors and all fuels) will grow about 1.3% per year—escalating from an estimated $1.2 trillion dollars in 2010 to about $1.9 trillion by 2050.

Some of the important inputs derived from this module that feed into the macroeconomic model described below include:

- The policies and measures that are phased in over time;
- The stringency of the emissions reduction target;
- The rates of growth in energy-related prices;
- The pattern of consumer and investor decisions concerning the adoption of new technologies; and
- The resulting innovations that lead to new technologies and/or changes in demands for services.

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[40] As noted in Hanson and Laitner (2004), a combination of price and non-price policies can generally produce a much more cost-effective policy resolution than either type of policies would induce by itself. The resulting deployment of new technologies depends on the assumed effectiveness of programs that might be implemented and the incentives being offered. Implementation of these policies—along with the resulting deployment of new technologies—strengthens the ability of the market to respond to the price signal. In this context, prices act as a signal for necessary changes, rather than as a punishment for consumers and producers.

Table B-2. Employment, Compensation, Value-Added, and Total Output by Sector 2009

Economic Sector	Employment (Million Jobs)	Millions of Dollars Employee Compensation	Value-Added	Output
Agriculture	3.39	40,503	130,286	346,793
Oil & Gas Extraction	0.78	46,901	176,602	341,321
Coal Mining	0.10	7,454	16,339	32,410
Other Mining	0.17	9,696	30,974	60,026
Electric Utilities	0.51	58,070	205,868	327,468
Natural Gas Utilities	0.11	13,206	63,725	182,788
Transportation, Other Utilities	3.46	150,949	263,638	576,688
Construction	9.87	378,245	573,984	1,216,251
Manufacturing	11.96	820,545	1,498,632	5,191,447
Refining	0.08	12,619	122,653	699,919
Trade	23.57	886,527	1,653,055	2,216,415
Services	100.73	4,621,345	7,322,787	10,768,655
Finance	15.81	630,575	1,962,162	3,090,895
Government	1.85	136,505	98,395	310,579

Macroeconomic Module: This set of spreadsheets contains the "production recipe" for the U.S. economy for a given "base year." For this study, the base year used was 2009. The input-output data, or sometimes referred to as the I-O data, currently purchased from the Minnesota IMPLAN Group (IMPLAN 2011), is essentially a set of economic accounts that specifies how different sectors of the economy buy (purchase inputs) from and sell (deliver outputs) to each other. Further details on this set of linkages can be found in Hanson and Laitner (2009). For this study, the model was run to evaluate impacts of the selected policies upon 15 different sectors, including: Agriculture, Oil and Gas Extraction, Coal Mining, Other Mining, Electric Utilities, Natural Gas Distribution, Construction, Manufacturing, Wholesale Trade, Transportation and Other Public Utilities (including water and sewage), Retail Trade, Services, Finance, Government, and Households.[41] To provide the reader with a sense of scale for these major sectors, Table A-2, above, provides sector employment (in millions of jobs and the individual sector wages and value-added contributions to the nation's gross domestic product (GDP) as well as the total economic output of the U.S. economy (with all of the dollar values in millions of 2009 dollars). As described below, examining the job and value-added intensities of the different sectors in this table provides early insights of likely scenario outcomes.

The principal energy-related sectors of the U.S. economy are not especially job-intensive. For example, taking total employment for electric utilities and dividing it by the total number of revenues received by those that sector, it turns out that the nation's electric utility industry in 2009 supported only 1.6 direct jobs for every one million dollars of revenue received in the form of annual utility bill payments. The rest of the economy, on the other hand, supports about 6.8 direct jobs per million dollars of receipts. *Thus, any productive investment in energy efficiency that pays for itself over a short period of time will generate a net energy bill savings that can be spent for the purchase of goods and services other than energy.* The impact of a one million dollar energy bill savings suggests there may be a net gain of about 5.4 jobs (that is, 6.8 jobs supported by a more typical set of consumer purchase compared to the 1.6 jobs supported by the electric utilities). Depending on the sectoral interactions, however, this difference may widen or close as the changed pattern of spending works its way through the model, and as changes in labor productivity changes the number of jobs needed in each sector over a period of time.[42]

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[41] While there are only 14 sectors shown in the table above, household spending is allocated to each of the sectors using the personal consumption expenditure data provided with the IMPLAN data set.

[42] As we will see later in this appendix, DEEPER does capture sector trends in labor productivity. That means the

Based on the mapped into the Energy and Emissions module, the set of worksheets in the Macroeconomic Module translates the selected energy policies into an annual array of physical energy impacts, investment flows, and energy expenditures over the desired period of analysis. Using appropriate technology cost and performance characterization as it fits into the investment stream algorithm discussed below, DEEPER estimates the needed investment path for an alternative mix of energy efficiency and other technologies (including efficiency gains on both the end-use and the supply side). It also evaluates the impacts of avoided or reduced investments and expenditures otherwise required by the electric generation sector. These quantities and expenditures feed directly into the final demand worksheet of the module. The final demand worksheet provides the detailed accounting that is needed to generate the implied net changes in sector spending. Once the mix of positive and negative changes in spending and investments have been established and adjusted to reflect changes in prices within the other modules of DEEPER, the net spending changes in each year of the model are converted into sector-specific changes in final demand. This then drives the input-output model according to the following predictive model:

$$X = (I-A)^{-1} * Y$$

where:

X = total industry output by sector
I = an identity matrix consisting of a series of 0’s and 1’s in a row and column format for each sector (with the 1’s organized along the diagonal of the matrix)
A = the matrix of production coefficients for each row and column within the matrix (in effect, how each column buys products from other sectors and how each row sells products to all other sectors)
Y = final demand, which is a column of net changes in spending by each sector as that spending pattern is affected by the policy case assumptions (changes in energy prices, energy consumption, investments, etc.)

This set of relationships can also be interpreted as

$$\Delta X = (I-A)^{-1} * \Delta Y$$

which reads, a change in total sector output equals the expression $(I-A)^{-1}$ times a change in final demand for each sector.[43] Employment quantities are adjusted annually according to exogenous assumptions about labor productivity in each of the sectors within the DEEPER Modeling System (based on Bureau of Labor Statistics forecasts; see BLS 2009). From a more operational standpoint, the macroeconomic module of the DEEPER Model traces how each set of changes in spending will work or ripple its way through the U.S. economy in each year of the assessment period. The end result is a net change in jobs, income, and GDP (or value-added).

For each year of the analytical time horizon (i.e., 2012 to 2050 for the climate policy assessment in this report), the model copies each set of results into this module in a way that can also be exported to a separate report. For purposes of this separate report, and absent any anomalous outcomes in the intervening years, we highlight the decadal results in order to focus attention on the differences in results emerging from various alternative policy assumptions. For a review of how an I-O framework might be integrated into other kinds of modeling activities, see Hanson and Laitner (2009). While the DEEPER Model is not an equilibrium model, we borrow some key concepts of mapping technology representation for DEEPER, and use the general scheme outlined in Laitner and Hanson (2006). Among other things, this includes an economic accounting to ensure resources are sufficiently available to meet the expected consumer and other final demands reflected in different policies.

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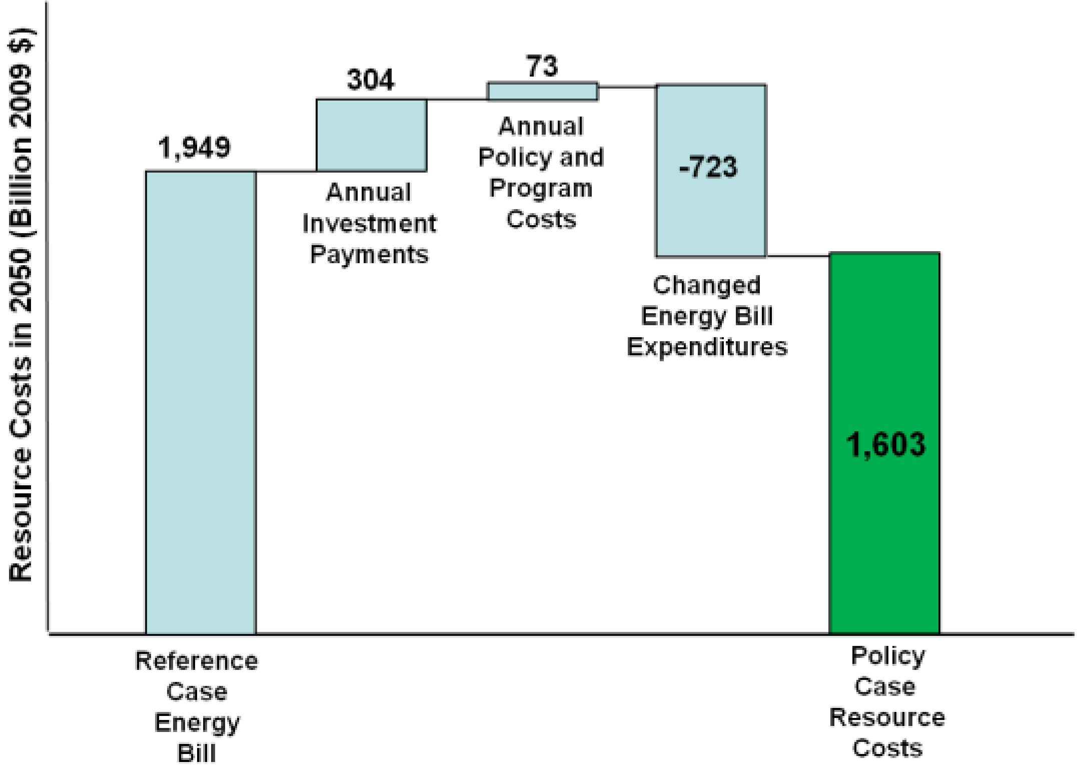
number of jobs needed per million dollars of revenue will decline over time.

[43] Perhaps one way to understand the notation $(I-A)^{-1}$ is to think of this as the positive or negative impact multiplier depending on whether the change in spending is positive or negative for a given sector within a given year.

Figure B-2 on the following page offers a diagram that illustrates the way DEEPER tracks changes in expenditures to evaluate the macroeconomic impacts of policy. In this case the example is drawn a typical diagnostic run of the Advanced Case Policy Scenario for the year 2050. The Base Case energy expenditures are estimated to be $1,949 billion (in 2009 dollars) for 2050. The enhanced energy efficiency provisions require an outlay of $304 billion in combined energy efficiency investments together with payments to the market for borrowing the necessary funds. The entire case is driven by an estimated $73 billion in various public and private program spending to catalyze the investments and more energy-efficient behaviors. The economy-wide energy bill savings are estimated to be $723 billion in 2050. The bottom line is a net reduction from the Reference Case energy bill so that businesses and consumers are paying only $1,603 billion for energy as a result of the improved efficiency gains.

Figure B-2. Changes in the 2050 Resource Costs from Adoption of Efficiency Policies



Source: DEEPER Diagnostic Run for Advanced Policy Case Impacts

Energy Prices

The sector prices for electricity and fuels are typically shaped by the change in demand for energy and any potential cost of CO_2 emissions as a function of their carbon intensities. In this analysis, however, we follow the Reference Case prices for energy by fuel and by sector through the year 2050. Table B-1 highlights the kinds of pricing changes that might be expected within the economy.

Technology Investment Streams

As previously noted, the investment costs are estimated for three different categories of emissions reductions: energy efficiency investments, low-carbon energy supply technologies, and non-CO_2 emissions reductions. The key set of assumptions for each of the major sources of investment flows is summarized below.

Energy Efficiency

One critical piece of information needed to evaluate the impact of these is the cost of investment in energy efficiency technologies. To derive this information, we adapt the structure of the Long-Term Industrial Energy Forecast or LIEF model (Cleetus et al. 2003). The key relationship in this model is the current gap between average and best energy efficiency technology or the best efficiency practice.

The assumption in the LIEF model is that as a sector moves closer and closer to best practice or best technology (sometimes referred to as the production frontier), the cost of efficiency investment per unit of energy saved will increase. The rate of that potential cost increase depends on the energy prices, the elasticity of the efficiency supply curve, and the discount rate. It also depends on how innovations and R&D policies might shift the best technology or best practice frontier. As used in this exercise, the investment cost is shown as:

$$\text{Investment per Unit Energy Savings} = \left[\frac{1-G_0}{1-S}\right]^{(1/A)} * \left[\frac{P}{C}\right]$$

where:

P = price of energy in the base year
C = capital recovery factor (CRF) or sector implicit discount rate for the given year
A = an elasticity that reflects the magnitude of the investment response to changes in price levels or the capital recovery factor
S = percent of sector energy savings in current year compared to base year consumption
G_0 = the energy intensity gap, or the difference between best and average practice

In many ways this can be thought of as the energy savings that should be economically viable in the base year, but have not been realized.

By way of example, the data might suggest that today there is a current energy intensity gap of 25% based on the potential for long-term efficiency gains through the year 2050, a long run efficiency substitution elasticity of 0.6, and an implicit discount rate of 20%.[44] If energy prices of a given sector are, say, $12.19 per million Btu in 2010, these assumptions suggest an average payback of about 3.7 years for a 10% efficiency gain based on prices in 2010. This rises to a 10-year payback for a 50% efficiency gain by 2050. Based on the much higher Reference Case prices in 2050, these paybacks would decline over time to 1.4 and 3.7 years. These results are broadly consistent with results summarized in Laitner et al. (2006) and Hanson and Laitner (2004).[45]

At the same time, the DEEPER Model uses a modified accounting function for each of the end-use sectors and fuels as they are impacted by the American Power Act provisions, out to 2030. Using estimates from McKinsey & Company (2009), Committee on America's Energy Future (2010), Gold et

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[44] This adaptation of the LIEF equation ignores the autonomous time trend component. In other words, as used here, the assumption of an efficiency gap remains static and there is only movement toward best practice or best technology rather than improvement in the base year representation of best practice or best technology. As the historical record suggests, the gap may actually grow to 50%—if the U.S. chooses to invest in greater innovation and energy productivity improvements. Hence, the use of a fixed 25% gap for purposes of estimating investment costs will tend to overstate the cost of the new efficiency gains.

[45] Although this is not emphasized in either the report or appendix, DEEPER also can explore changes in costs needed to drive a final result. For example, as it is now configured, if investments cost 20% less than now projected for the year 2050, the net gain in jobs shown in the main report increase by about 3.5%. On the other hand, if the investments run about 50% more than now suggested, the net increase in jobs might decline by about 9%. But this would continue to be a highly positive net gain in 2050. The significance of this finding is that the framework of the American Power Act framework—especially if it includes a greater emphasis on energy productivity benefits—is likely to generate a robust outcome for the American economy for all the reasons described earlier in the report.

al. (2009), and Eldridge et al. (2009), among others, each of the cost curve functions was adjusted by sector to reflect both the current and anticipated technology costs and performance reflected in those various studies. In the modeling characterized in this report, the payback periods typically begin at about 2.5 to 3 years in 2013, and depending on policy assumptions, R&D, changes in implicit discount rates, and how quickly efficiency is “used up,” the payback periods in 2050 might range from 5 to 9 years. On the other hand, to the extent that that are innovations and economies of scale and scope that tend to lower technology costs, we might expect to see paybacks that remain closer to 5 years. For this working assessment, however, we generally allow DEEPER to move toward the higher technology costs since we are more interested in highlight the potential of energy efficiency rather than evaluating a specific set of policy over time. In this regard we are then maintaining a conservative (i.e., higher cost) focus in completing this particular assessment for 2050.

Policy and Program Costs

One of the working assumptions in this review is that that policies and programs are needed to drive the requisite investments. In generating an estimate of what these incremental costs might look like, we borrow from a study by Amy Wolfe and Marilyn Brown, *Estimates of Administrative Costs for Energy Efficiency Policies and Programs* (Interlaboratory Working Group 2000, Appendix E-1). In that study the average administrative cost is assumed to be $0.60 per million Btu of efficiency gains. In Eldridge et al. (2009) and McKinsey & Company (2009), these program costs were generally assumed to run about 15-20% of the annual investments in efficiency gains. In Table 4 of this main report, comparing the program cost totals with the annual payments for investments, the range is shown to be approximately 24% in the early years as program activity and R&D investments scale up early in the scenario. Under the current assumptions this declines to about 18% by 2050.