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Carbon Pricing and Energy Efficiency:
Pathways to Deep Decarbonization of the U.S. Electric Sector

Marilyn A. Brown and Yufei Li

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ABSTRACT

Despite the commitment of the Paris agreement to pursue efforts to limit end-of-century global warming to 1.5°C above pre-industrial levels, few have studied mitigation pathways consistent with such a demanding goal. This paper uses a fully integrated engineering-economic model of the U.S. energy system, to explore the ability of the U.S. electricity sector to operate within a budget of 44 gigatons of CO_2 ($GtCO_2$) between 2016 and 2040 - almost 20 percent less than projected. Our modeling results suggest that carbon taxes coupled with strong energy-efficiency policies would produce synergistic effects that could meet deep decarbonization goals. Combining energy-efficiency initiatives with a \$10/tCO_2 tax rising to \$27/tCO_2 in 2040 (in \$2013) would achieve the U.S. electric sector's carbon budget with a net savings to the U.S. economy. A \$20/tCO_2 tax rising to \$53/tCO_2 in 2040 would also stay below this budget, but it would cost more if not coupled with strong energy efficiency. U.S. regions will win or lose depending on their generation mix and how carbon tax revenues are recycled.

Corresponding author:
Dr. Marilyn A. Brown
Regents Professor of Sustainable Systems
School of Public Policy
Georgia Institute of Technology
Atlanta, GA 30332-0345
Email: Marilyn.Brown@pubpolicy.gatech.edu

Forthcoming in a special issue of *Energy Efficiency* dedicated to "Demand-side policies, governance and socio-technical mitigation pathways of limiting global warming to 1.5°C"

Guest editors:
Luis Mundaca, Diana Ürge-Vorsatz, & Charlie Wilson

1. Introduction

In 2015, signatories to the Paris Agreement agreed to limit increases in the global average temperature to well below 2 °C above temperatures preceding the industrial revolution. This historic accord is the culmination of decades of climate negotiations aimed at preventing dangerous anthropogenic interference with the climate system. In addition to the 2 °C warming threshold, the Paris Agreement calls for "pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC, 2015a).

Despite this commitment, few have studied the mitigation pathways that could constrain global warming to 1.5 °C above pre-industrial levels. Clearly the achievement of such a goal will be challenging. According to the International Energy Agency (IEA, 2016), it will "require an immediate ramp-up of all low-carbon options at a rate of deployment sustained over the next 25 years that can barely be imagined from today's perspective." In the U.S, the energy system transformations consistent with limiting the global temperature increase to 1.5 °C have not been fully examined. In addition, little analysis to date has examined the kinds of U.S. policies needed to achieve such deep decarbonization, and the costs of achieving such transitions are not well understood. This paper helps to fill this gap by examining a 25-year transformation of the U.S. electric grid under an array of carbon pricing and energy-efficiency policies.

In 2010, a report by the National Academy of Sciences shifted the U.S. debate from climate goals based on annual carbon emissions to cumulative carbon budgets consistent with global warming targets. IEA (2016) estimates that to have a 50% chance of keeping global warming to 1.5 °C, the remaining global CO_2 budget from 2015 lies between 108 and 123 GTC (or 400 and 450 Gt CO_2). The IPCC Fifth Assessment Report (IPCC, 2014a) found that cumulative carbon emissions from 1870 had to remain below 615 GtC for total anthropogenic warming to not exceed 1.5 °C. Assuming that 545 GtC were emitted from 1870 through 2014, this would indicate a remaining budget from 2015 of only 70 GtC. Rogelj et al. (2015) have estimated the possibility of even smaller remaining carbon budgets (54 GtC).

More recently, Millar et al. (2017) re-examined the methodology used to estimate the magnitude of future cumulative emissions that are consistent with a 1.5 °C temperature rise in 2100 relative to 1870. They adjusted previous estimates of historic emissions to more accurately estimate the impact of natural fluctuations such as El Niño. Their updated modeling estimates a remaining carbon budget of 223 GtC from 2015 onwards, for a total anthropogenic temperature increase of 1.5 °C in 2100. In a personal communication with the principal author, Richard Millar, we learned that their global carbon trajectory would limit cumulative emissions to 256 GtC between 2016 and 2040. This limit is larger than their estimated cumulative limit through 2100 because emissions are assumed to be net negative after about 2080.

The IEA provides an illustrative case where the remaining energy sector CO_2 budget between 2015 and 2100 is well below the 2 °C case or 25% less than its 450 Scenario. Multiple emissions trajectories are consistent with this CO_2 budget. For example, one that avoids relying on global emissions turning net-negative requires energy-related CO_2 emissions to be at net-zero by around 2060. Energy-related CO_2 emissions in 2040 would need to be around 16 GtC, about 2 GtC lower than emissions in the 450 Scenario (IEA, 2016, p. 75).

The conclusion from this literature is that accelerating the pace of carbon emission reductions to meet a 1.5 °C case will require new policies. Currently, greenhouse gases (GHGs) can be emitted into the atmosphere for free in most U.S. states and indeed in most countries, but the impacts of these emissions impose real costs on society (Arent et al., 2014). This climate change externality may well be the greatest market failure the world has seen (Stern, 2007). The atmosphere belongs to everyone, and everyone should have access to the wealth created by allocating scarce access rights to it.

In the U.S., carbon taxes are one of the principal economy-wide policies currently being debated to address this climate change failure. By placing a per-unit tax on emissions of carbon dioxide, price signals can be used to move market decisions toward low-carbon choices. Prior legislative proposals suggest that the electricity sector is a viable target for a carbon tax. At the same time, research has indicated that complementary policies may be needed to address the array of additional market failures that discourage end-users from implementing energy-efficiency measures that could contribute significantly to electric sector decarbonization (Brown and Wang, 2017). In this paper, we explore the impacts of a range of carbon taxes and energy-efficiency policies, on the U.S. supply and demand for electricity, relative to a 1.5 °C warming limit.

In Section 2, we describe a framework for setting CO_2 emissions goals for the U.S. electric sector. In Section 3 we explain our focus on bundling carbon taxes with energy efficiency policies to decarbonize the U.S. electric grid. Section 4 describes our research methodology including the modeling of carbon taxes and energy-efficiency policies and provides an overview of the modeling approach. In Section 5, we present the results, focusing on CO_2 reductions, demand management, the resulting energy resource portfolios, and policy costs. The paper ends with conclusions and a discussion of policy implications (Section 6).

2. Setting a CO_2 emissions goal for the U.S. electric grid

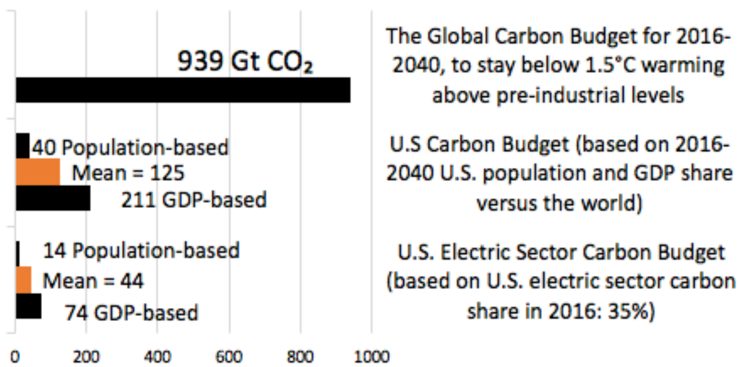
To calibrate a CO_2 emissions goal for the U.S. electric grid that is consistent with the 1.5 °C global target, we consider guidance from the Paris Conference. The "Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (UNFCCC, 2015b). In the following three steps, we arrive at a carbon goal for the U.S. electric sector (Figure 1).

First, we adopt the global carbon budget from 2016 to 2040 as identified by Millar et al. (2017). To limit global warming to less than 1.5 °C, the maximum carbon budget that global actors can emit is 256 GtC, which is equivalent to 939 Gt of CO_2. As noted earlier, this is a larger budget than has been adopted based on previous research by the IPCC and others.

Second, the U.S. carbon budget is calculated as a proportion of the global target determined by two alternative allocation principles based on the U.S. GDP or its population relative to global values. A large literature exists on distributing global emission budgets across nation-states. For example, previous studies have used different weighting metrics, viewing GDP or current emissions as "inertia" and population as "equity" (Raupach, etc. 2014). Blending these two metrics can reflect the complexities of balancing "inertia" and "equity" concerns. Because relative populations and GDP are projected to shift between 2016 and 2040, we use the midpoint values to assign an economy-wide carbon target to the U.S. Based on data and forecasts provided by the World Bank (2018) and EIA (2018), the U.S. carbon emissions target is calculated to be 40.2 Gt of CO_2 (4.3% of the global target based on population distributions) or 211.2 Gt of CO_2 (22.5% of the global target based on the GDP).

Third and finally, the U.S. electric sector target is calculated based on the proportion of total U.S. emissions in 2016 that are generated by the electric power sector. According to EIA (2017), the electric sector was responsible for 35.2 of U.S. CO_2 emissions. As a result, the CO_2 emissions target for the U.S. electric power sector ranges from 14.2 Gt of CO_2 based on population to 74.3 Gt of CO_2 based on GDP, with a midpoint of 44.25.

Figure 1. Deriving a 1.5°C Carbon Budget for the U.S. Electric System



4.1

4.2 **Cumulative Gigatons of CO_2 (2016-2040)**

4.3

3. Catalyzing energy efficiency and clean supply options

For the electricity sector, the types of low-carbon technologies and behaviors that are typically targeted by climate policies include an array of essentially "carbon-free" supply options such as wind, solar, and nuclear, a broad spectrum of energy-efficiency products and practices, and low-carbon fuels such as natural gas (Brown and Sovacool, 2014). In addition to being flawed by climate change externalities, markets for these low-carbon options often are plagued by many other market imperfections including principal-agent problems, imperfect and asymmetric information, and regulations that reward consumption over conservation (Brown and Wang, 2017). Addressing many of the problems that hinder investments in energy efficiency have been found to be particularly cost-effective and thus are examined here as possible complements to taxing CO_2 emissions.

Carbon taxes are generally seen as the least-cost economy-wide policy to reduce CO_2 emissions because they equalize the marginal cost of abatement across diverse sources, technologies, and consumers (Baumol and Oates, 1988; Carbon Pricing Leadership Coalition, 2017). Based on Pigouvian taxation principles, once the carbon tax is set to the level of damages (e.g., per ton of CO_2 emissions), carbon taxes offer flexibility by allowing sources to choose their own abatement strategies (Tol, 2017). Governments also have the ability to adjust tax levels over time as marginal social damages from climate change become stronger or weaker. Finally, the tax revenue collected can be used to improve welfare in multiple ways.

On the other hand, carbon taxes also require a great deal of information to be set optimally as is attempted in the social cost of carbon, which embodies both negative and positive externalities (Tol, 2013). Like other taxes, carbon taxes can also create undesirable equity outcomes by penalizing poorer consumers proportionately more than richer consumers, because lower income households spend a larger share of their earnings on electricity (Drehobl and Ross, 2016).

The distribution of revenue from carbon taxes can enhance policy efficiency and reduce the regressive financial burden of emissions reduction efforts (Grainger and Kolstad, 2010; Burtraw et al., 2008; Chamberlain, 2009; Shammin and Bullard, 2009). Rebating tax revenues back to households (on a per capita lump-sum basis) would be a progressive policy (Horowitz et al., 2017). Concerns about equity and appeasing targeted constituencies can also lead to tax exemptions, which generally undermine economic efficiency. Focusing exclusively on distributional goals and returning all revenue to households requires a trade-off with the efficiency gains from reducing distortionary taxes (Dinan and Rogers, 2002). Goulder and Parry (2008) suggest that it is possible to achieve both distributional and efficiency goals.

Carbon taxes have been used in five Northern European countries since the early 1990s. In 2001 the United Kingdom followed suit by implementing a Climate Change Levy (CCL), which was applied to the industrial, commercial, agricultural, public, and service sectors. Carbon taxes are used in other regions of the world as well, including British Columbia, Canada, Australia, the San Francisco Bay area, and Boulder, Colorado. The British Columbia tax started at \$10/t CO_2 in 2008, rising to \$30/t by 2012. Rather than increasing government spending, all of the tax revenues are redistributed through corporate tax cuts, personal income tax cuts, and low-income tax credits. The resulting revenue neutrality presumably creates a strong double dividend (Beck et al., 2015; Callan et al. 2009; Liu & Lu, 2015; Murray & Rivers, 2015).

An extensive academic literature suggests that macroeconomic efficiency favors a carbon tax with socially productive revenue recycling over other forms of regulation (Horowitz et al., 2017). However, carbon taxes have many opponents, with some of this resistance deeply rooted in a strong distaste for taxation, in general. At the same time, cap-and-trade programs focusing on carbon and other GHGs have taken hold in several regional programs and were the basis of EPA's proposed Clean Power Plan.
While the U.S. does have a well-honed infrastructure and vast experience with levying taxes in general, it does not have similar depth of experience with using taxation to control pollution. While carbon taxes

have been debated, the U.S. has never levied a nation-wide carbon tax and no state has yet instituted a blanket carbon tax. However, there have been carbon tax proposals, including the Carbon Dividend Plan (Feldstein, Halstead, and Mankiw, 2017). The U.S. also has some experience with carbon taxes at the local level (Chesney et al., 2016).

4. Research Design

This paper uses a computational general equilibrium model of the U.S. energy system (the National Energy Modeling System, NEMS) combined with alternative energy scenarios to explore the ability to meet significant carbon reduction goals, such as those shown in Figure 1. The dependent variable is the forecasted incremental cost of providing electric services under four carbon mitigation scenarios. These four cases are modeled using the NEMS model that generated the 2015 *Annual Energy Outlook* (EIA 2015). With modifications necessary to operate the GT-NEMS model on networked servers at the Georgia Institute of Technology, the version of NEMS used in this research is described in the standard NEMS reference manuals and documentation (USEIA, 2015).

4.1 Specification of the Reference Case and Carbon Mitigation Scenarios

The Reference Case. Our Reference Case was created by modifying EIA's 2015 Reference Case in two ways. First, we update the forecast to model U.S. legislation passed in 2015; the wind production tax credit (PTC) was extended from 1.8 cents/kWh in 2017 to 0 cents/kWh in 2020 and the solar investment tax credit (ITC) was extended from 30% in 2017 to 0% in 2022 for residential applications and from 30% in 2017 to 10% in 2022 for commercial applications. Second, the projection of installed costs per Watt-dc of distributed solar were reduced, based on a review of the literature. To illustrate, the cost of distributed commercial PV in 2030 is assumed to be $1.65 (in $2009), 26% less than the US EIA (2015a) Reference case. For distributed residential PV in 2030, the updated cost is $2.19 per Watt-dc (in $2009), 19% less than the US EIA (2015a) Reference case. See Brown, Kim, and Smith (2016) for a more detailed explanation of our solar assumptions.

Carbon Tax ("Tax"). Three levels of an electric power sector tax on CO_2 emissions are modeled, starting from $10, $20, and $40 per metric ton of CO_2 (in $2013) in 2020. The $10 and $20 taxes are increased 5% annually; thus, the $10 tax grows to $16 in 2030 and to $26 in 2040 and the $20 tax grows to $32 in 2030 and to $53 in 2040. The tax starting at $40 in 2020 increases by only 2% annually reflecting a commitment to rapid impact but a more modest tax incline, reaching $49 in 2030 and $59 in 2040. Having the carbon tax escalate over time is generally consistent with the Carbon Dividend Plan. In all of the carbon tax scenarios, we recycle all carbon tax revenues back to households on a per capita basis.

Carbon Tax with Incremental Energy Efficiency ("Tax+EE"). Three additional scenarios are created by including strong energy-efficiency policies alongside the carbon taxes defined above. The energy-efficiency policies that are modeled are summarized in Table 1 and are described in more detail in Brown et al. (2017). The Reference case reflects naturally occurring energy efficiency – that is, improvements resulting from technology advancements and market trends that occur in the baseline policy setting, also called "autonomous" energy efficiency (Thomas et al., 2012). While we model stronger policies that motivate greater investments in energy efficiency, other studies have pushed energy efficiency further with a broader array of policies and technology advancements, and their results suggest that additional investments could prove cost-effective. For example, while we model enhanced combined heat and power throughout industry, as well as process improvements in five key industries, Laitner et al. (2012) also considered supply chain integration in closed-loop systems where the waste streams from one firm become the feedstocks of another. Brown et al. (2001) modeled a more expansive array of 50 policies targeting individual economic sectors, with a strong emphasis on improved performance of energy-efficient technologies, and Hanson and Laitner (2004) modeled much stronger charges (ranging from $13 - $25/metric ton of carbon dioxide). Many studies suggest a greater potential for cost-effective energy efficiency than is modeled here, partly because of limits inherent in the GT-NEMS modeling tool, such as the inability to characterize complex systems of integrated equipment and building materials. Rather than pushing the envelope for energy efficiency to its limits, we examine in detail the impacts of a modestly strong energy-efficiency push.

Table 1. Strong Energy Efficiency Assumptions

Sector	Description
Residential Buildings	Significant improvements in appliance standards are modeled for room air conditioners as well as refrigerators and freezers. We use the 2015 NEMS updated technology assumptions for geothermal heat pumps, electric water heaters, dishwashers, and gas and electric clothes dryers. For lighting, we apply EIA's High Technology side case assumptions for costs and efficiency, improving bulb type LEDs, reflector LEDs, linear fluorescent lamps and LEDs, and LED torchieres. Miscellaneous electric uses are also made more efficient by adopting the "High Tech" side case assumptions upgrading the efficiency of home theater systems, ceiling fans, coffee makers, and dehumidifiers. Shell thermal efficiencies in single-family homes, apartments, and mobile homes are also improved, mirroring the impacts of stronger state building codes. Each of these same efficiency improvements is modeled by Hausker et al. (2014), Wang and Brown (2014) and/or by the NEMS 2014 "High Technology" side case.
Commercial Buildings	Stronger state building codes and other energy-efficiency policies are proxied by strengthening the envelope efficiency of new buildings and by using EIA's "High Tech" side case assumptions. In addition, two new high-efficiency air source heat pump technologies are added to the array of commercial HVAC options. These advanced technologies will benefit from the recent promulgation of new efficiency standards for commercial air conditioners and furnaces – the largest energy-saving building equipment standard in U.S. history[1]– that is to be implemented in two phase: in 2018 the standards will deliver a 13% improvement in the energy efficiency of new commercial units, and in 2023, an additional 15% efficiency

[1] http://energy.gov/articles/energy-department-announces-largest-energy-efficiency-standard-history

	improvement will be required. We model the new standard by eliminating noncompliant rooftop equipment in 2018 and 2023. We also decrease the discount rates used by commercial consumers of new air conditioning and lighting technologies in new and existing buildings, mirroring those used by Cox, Brown, and Sun (2013).
Industry	Stronger state energy-efficiency policies are modeled by specifying stricter energy-efficiency assumptions related to combined heat and power (CHP) and electric motors. The scenario assumes 30 percent investment tax credits for CHP through 2040, and the rate of decline for CHP system costs is increased by using EIA's High Technology assumptions. The "High Tech" case also assumed improved electric motor efficiencies. Further, we assume that policies encourage manufacturers in five industrial subsectors to reduce UEC below Reference Case projections. The reductions in energy process consumption in 2030 range from 18 percent for bulk chemicals, 23 percent for cement and refining, 40 percent for pulp and paper, and 57 percent for iron and steel, based on a literature review summarized in Brown, Cox, and Cortes (2010) and Bianco et al. (2013).

We do not model policies to further promote electric vehicles (EVs), and EVs have minimal market share through 2040 in the NEMS modeling due to outdated assumptions about the cost of a lithium-ion battery pack ($1,187/kWh in the year of 2016 compared to more recent EIA estimates of about $200/kWh).[2]

5. Results

Based on the methodologies, our key modeling results are presented and compared between the Reference Case and the different carbon mitigation scenarios. We begin by examining the ability of each scenario to meet the carbon emission reduction target. For further background, we examine the impact of each scenario on total electricity generation. Then we estimate the total costs of compliance (that is, the overall policy costs). These are presented in annual terms for 2020, 2030 and 2040, and then in cumulative terms for the 25-year period. The distributions of these costs is then examined by dividing them between utility resource costs, end-use energy-efficiency costs, and carbon tax revenue recycling. Finally, we examine the cumulative carbon reductions and costs, enabling a financial assessment of policy impacts and the ability of the alternative mitigation scenarios to meet the carbon reduction goals consistent with a 1.5 °C targeted rise in temperature.

These results explain the symbiotic effects of carbon taxes and energy-efficiency policies, suggesting a path forward to enable cost-effective energy efficiency investments that help achieve deep decarbonization.

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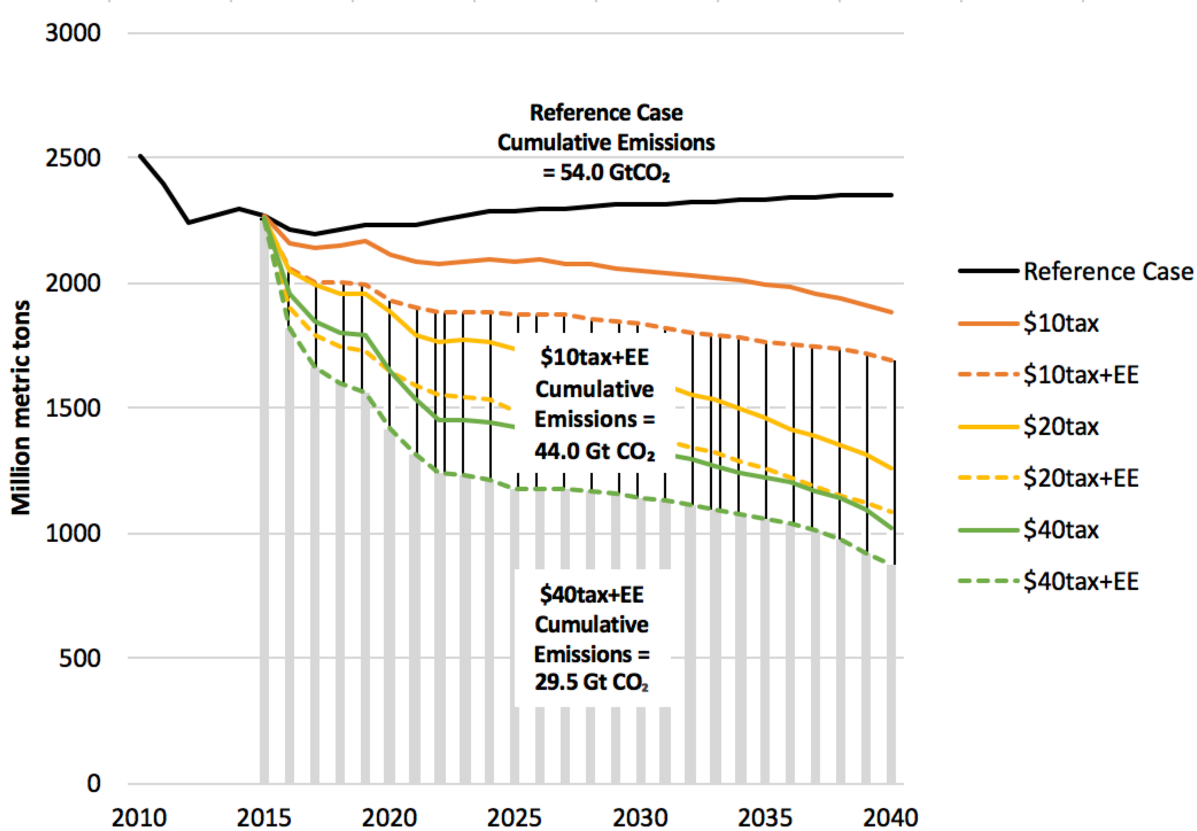
[2] Energy Information Administration, "Projecting light-duty electric vehicle sales in the National Energy Modeling System (NEMS) and World Energy Projection System plus (WEPS+)", June 2017. https://www.eia.gov/conference/2017/pdf/presentations/melisssa_lynes.pdf

5.1 Overall Effects: Carbon Emission and Electricity Generation Reductions

Before examining the cost impacts of different climate policy instruments, we first describe the effect of our scenarios on CO_2 emissions from the electric sector across mitigation scenarios. Figure 2 displays the electric sector CO_2 emissions and the total electricity generation for the Reference case and all of the six mitigation scenarios, including three levels of carbon taxation with and without additional energy-efficiency policies.

Figure 2. CO_2 Emissions from the Electric Sector Across Mitigation Scenarios (Million Metric Tons, Lower 48 States)[a]



[a] A metric ton (1,000 kilograms) is 1.10231 times larger than a short ton (2,000 pounds)

One notable feature of these trajectories is that carbon emission and electricity demand reductions both begin ahead of the implementation of the carbon taxes in the year 2020. This reflects the foresight used by GT-NEMS to realistically model investments by utility companies that periodically engage in integrated resource planning to achieve least-cost, competitive operations in light of possible future policies. This foresight allows GT-NEMS capacity planning and power demand projections to iterate through numerical projections until the expectations of demand converge with the anticipated least-cost supply investments. Thus, GT-NEMS capacity investment decisions reflect the expectation of future policy implementation, which already impacts today's U.S. power planning.

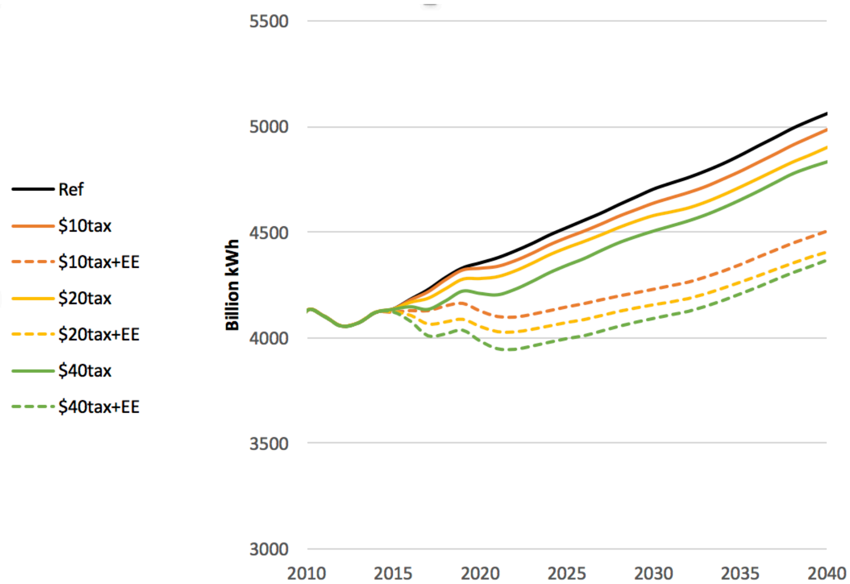
Different carbon tax scenarios trigger different carbon emission reductions depending on their starting level and rate of escalation. The higher the carbon price, the higher the level of emission reduction in 2040 relative to the Reference case, ranging from decreases of 20% for the $10tax, 33% for the $20tax and 63% for the $40tax (which increases by only 2% annually). From 2016 to 2040, the $10 tax reduces cumulative carbon emissions by 10%, the $20 tax by 27% and the $40 tax by 37%, relative to the Reference case. The $20 tax achieves more than double the reductions of the $10 tax, while the $40 tax has less than a fourfold reduction because the tax increases by only 2% annually resulting in a near convergence of carbon tax values in 2040. The abundance of abatement opportunities between $10 and $40/tCO2 – particularly low-carbon electricity generation alternatives – is well documented by mitigation supply curves (Enkvist, et al., 2010).

Energy efficiency coupled with carbon taxes drive emissions even lower. In the scenarios with energy efficiency, the $10 tax could reduce emissions by 46.4%, the $20 tax by 56.6% and the $40 tax by more than 60% lower than in the reference case, declining to about 800 million metric tons.

Figure 3 portrays the U.S. electricity generated in the Reference case and the six carbon mitigation scenarios. Overall, the demand for electricity increases across all of the scenarios for a variety of reasons including increased economic activity as well as greater electrification via heat pumps, electric vehicles, and additive manufacturing. The introduction of escalating carbon taxes beginning at $10, $20, and $40/tCO_2$ in 2020 dampens this growth by an estimated 1.5%, 3.3%, and 5.1%. These results reflect the long-term elasticity of demand for electricity, which are assumed by NEMS to start at -0.21 in 2020 and to increase slightly to -0.23 in 2035. Thus, NEMS assumes that the price elasticity of demand for electricity is relatively low, but also that it increases slightly suggesting a greater ability and willingness of consumers to reduce their electricity consumption in response to higher electricity prices over time (Brown et al., 2012). By coupling strong energy-efficiency policies with the three levels of carbon taxes, electricity demand decreases significantly more – by 10.8, 13.5, and 15.5% below the Reference Case in 2040 (Figure 3a).

Figure 3. U.S. Electricity Generation and Sectoral Demand Reductions Across Mitigation Scenarios

a. Electricity Generation



b. Sectoral Electricity Demand Reductions

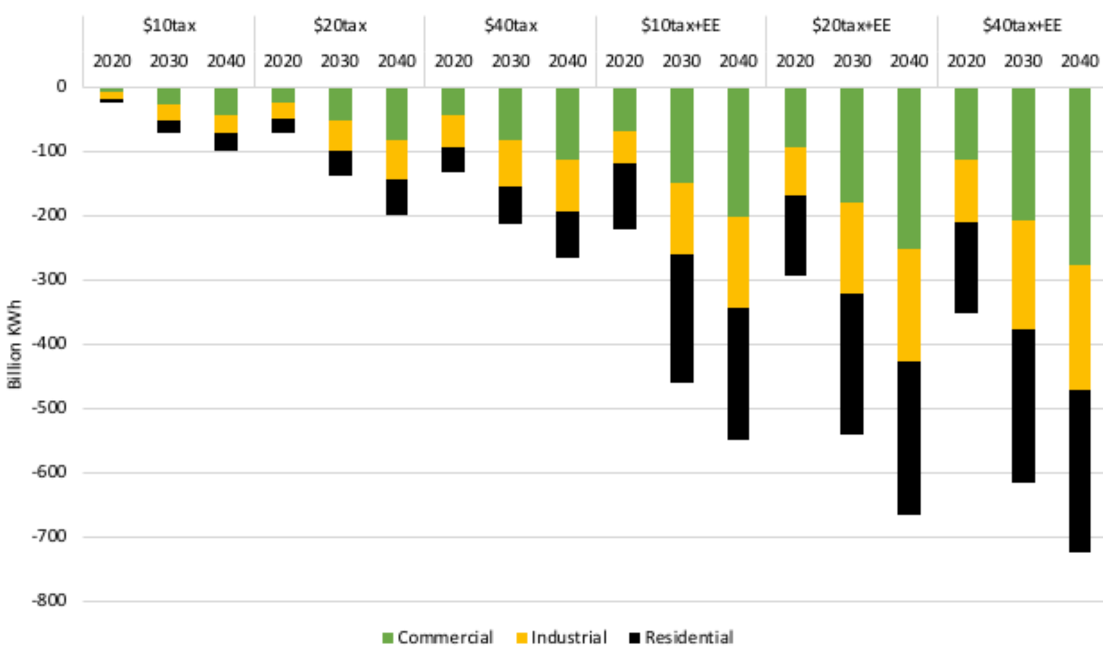


Figure 3b shows the sectoral reductions in electricity demand that result from the six carbon mitigation strategies, 2020, 2030, and 2040. Across all of the scenarios, the reduction in electricity consumption is comparable for the residential and commercial sectors, and both are slightly larger than in the industrial sector. For example, in 2030, the $10tax+EE scenario would reduce electricity generation by an estimated 149, 110, and 201 TWh, in the commercial, industrial, and residential sectors, resulting in a total reduction of 460 TWh. By 2040, the same scenario decreases electricity generation by 202, 141, and 206 TWh across the commercial, industrial, and residential sectors, resulting in a total reduction of 549 TWh. The decadal sectoral electricity demand reductions are shown in the Technical Appendix Table A.1.

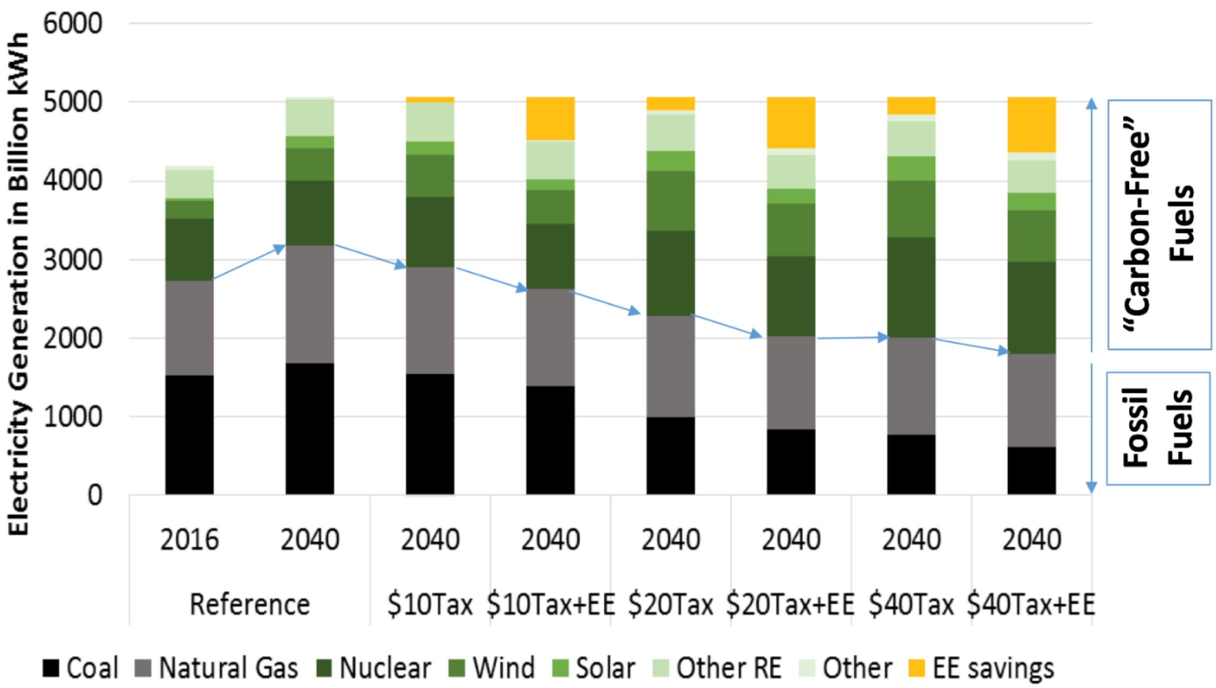
Comparing our findings with other published research on the U.S. electricity sector suggests that energy efficiency policies and technologies have the potential to deliver greater energy and CO_2 reductions. For example, Bradley et al. (2016) models the incremental energy efficiency that the proposed U.S. Clean Power Plan could prompt, using 1% to 2% growth rates that produce 347–587 TWh of electricity savings in 2030. Lashof et al. (2014) estimated that 709 TWh of cost-competitive energy efficiency could be achieved in the U.S. in 2030 by placing a price on carbon in the electricity sector. Hanson and Laitner (2004) achieved reductions of 1,508 TWh of electricity in 2040 by modeling an array of cost-effective energy efficiency policies and improvements together with a modest carbon charge comparable to those highlighted in this analysis . By mid-century, Laitner, et al. (2012, p. 57) estimate a significantly larger energy-efficiency potential from a broad array of also cost-effective policies and advanced technologies, ranging from 1,595 to 2,008 TWh below the Reference case forecast of 5,374 TWh in 2050. Thus, our scenarios clearly do not represent the full realm of energy-efficiency possibilities; rather, given the assumptions embedded in the NEMS modeling tool, they represent a least-cost energy system identified in response to the policy levers that define each scenario.

5.2 Fuel Mix and Changes to Electricity Prices and Bills

Figure 4 characterizes the U.S. electricity generation fuel mix in 2040 under various policy scenarios. With nearly 20% demand growth forecast in the Reference case by 2040, in the absence of additional policies, expansions to the fuel mix are anticipated across all of the major fuels, with the largest increase in natural gas.[3] Each of the six carbon tax scenarios would shrink coal generation significantly relative to the Reference case. To offset this decline, nuclear, wind, and solar would grow. The policy scenarios with strong energy-efficiency policies have even less fossil fuel generation.

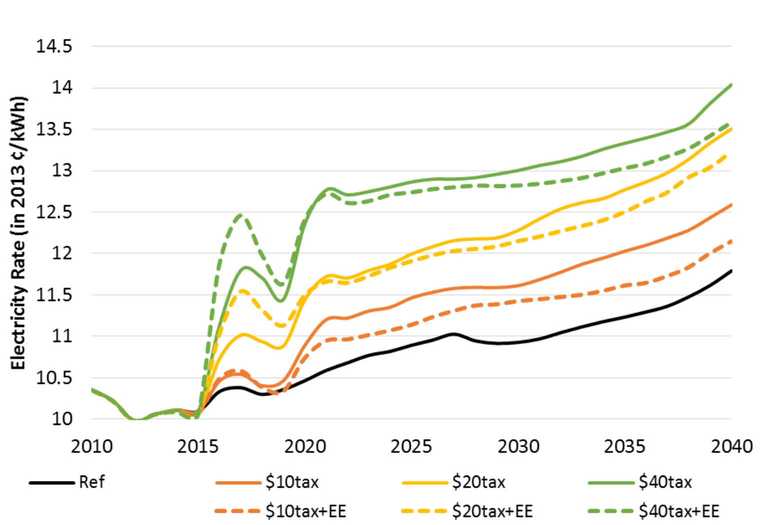
[3] Note that the modeled electricity fuel mix in 2016 shows greater coal generation than actually occurred in that year, based on the USEIA Electric Power Monthly (USEIA 2017). The actual electricity fuel mix in 2016 was reported to be 31% coal, 34% natural gas, and 20% nuclear, with nearly 6% wind, 1% solar, and 8% other renewables. The greater use of natural gas was primarily a function of natural gas prices being lower than forecast.

Figure 4. U.S. Electricity Sector Fuel Mix



The higher the carbon tax, the greater the projected shift away from coal to lower-carbon fuels. With higher carbon taxes, nuclear generation also increases. Adding strong energy-efficiency policies to the scenarios also has comparable dampening effects on overall electricity consumption, serving as the major offset source for coal generation.

Figure 5. U.S. Electricity Prices

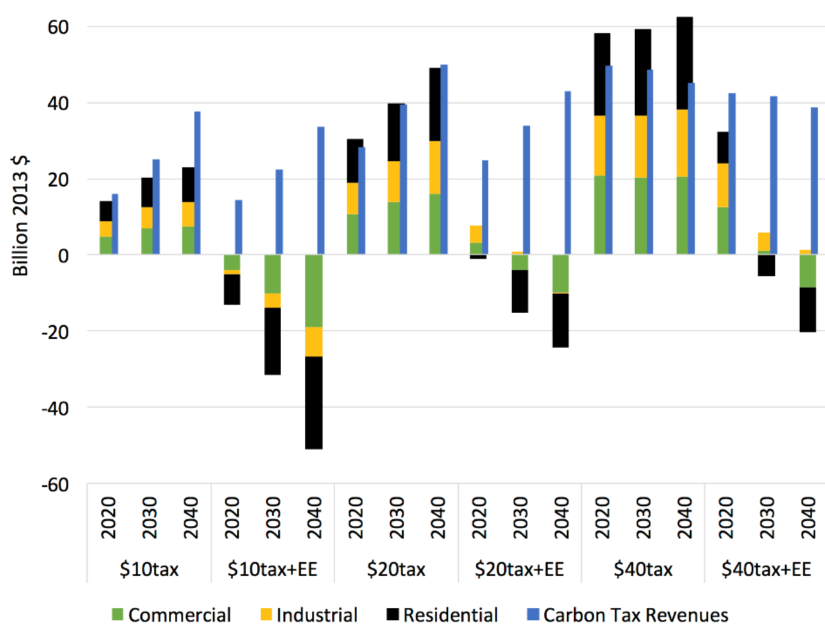


In the NEMS Reference case, electricity prices are forecast to increase from 10.3¢/kWh in 2016 to 11.8 ¢/kWh in 2040 (in $ 2013). In all six carbon tax scenarios, electricity rates are projected to increase more, rising from 12.2 ¢/kWh to 14 ¢/kWh in 2040. The higher the carbon tax, the higher the rate increases.

Energy-efficiency policies are able to moderate this rate escalation – for each of the three levels of carbon taxation, electricity prices are reduced by about 0.5 ¢/kWh in 2040 when energy-efficiency policies are modeled. At the same time, energy consumers must divert financial resources to invest in more energy-efficient technologies, as discussed below.

Some of the increases in electricity costs can be compensated by the distribution of carbon tax revenues. Figure 6 characterizes the changes in electricity bills for commercial, industrial and residential sectors under various policy scenarios. Without energy efficiency, the electricity bills will increase by the range of $14.1 billion (in 2013 $) in the $10 carbon tax scenario in 2020 to $62.6 billion in the $40 carbon tax scenario in of 2040. It shows that without energy efficiency, the electricity bills increase due to the carbon tax and the higher the carbon tax, the more the bills increase. The sectoral distribution of the extra electricity bills are similar to the baseline distribution: about 35% from residential and commercial sectors respectively and 30% from the industrial sector. When we add energy efficiency to couple the carbon tax, electricity bills can be reduced significantly. Our results show that in the short run, in 2020, $20 tax and $40 tax coupled with energy efficiency will still slightly increase electricity bills (about $7 to $32.5 billion) compared to the reference case. However, in the long run in the year of 2030 and 2040, energy efficiency scenarios will decrease the total electricity bills up to $50.8 billion in the $10 carbon tax scenarios with energy efficiency in 2040.

Figure 6. Impacts on Electricity Bills and Carbon Tax Revenues (in Billions $2013)



Carbon tax revenue recycled can compensate for the extra electricity bills paid and thus reduce the energy burden on consumers. This is the premise of the Carbon Dividends Plan (Bailey and Bookbinder, 2017; Chen and Hafstead, 2016; Horowitz et al., 2017). To characterize that effect, Figure 6 and Table 2 compare the changes in bills and carbon tax revenues. Since the carbon tax revenue are recycled to households, we calculate the savings for the residential sector and for all end-use sectors separately.

Table 2. Impacts on Electricity Bills and Carbon Tax Revenues (in Billions $2013)

	Change in Residential Electricity Bills			Change in Economy-Wide Electricity Bills			Carbon Tax Revenues			Savings for Residential Sector (Bills Minus Tax Revenues)			Savings for All Sectors (Bills Minus Tax Revenues)		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Scenarios															
$10 Tax	5.2	7.7	8.9	14.1	20.4	23.0	15.9	25.2	37.7	10.7	17.5	28.8	1.8	4.8	14.7
$10 Tax + EE	-8.1	-17.7	-24.1	-13.1	-31.6	-50.8	14.5	22.5	33.7	22.6	40.2	57.8	27.6	54.0	84.5
$20 Tax	11.3	15.1	19.2	30.5	39.8	49.2	28.3	39.5	49.9	17.0	24.4	30.7	-2.1	-0.3	0.7
$20 Tax + EE	-1.0	-11.4	-14.1	6.9	-14.5	-24.2	24.7	34.0	43	25.7	45.4	57.1	17.9	48.5	67.2
$40 Tax	21.5	22.7	24.3	58.2	59.4	62.6	49.5	48.6	45	28.0	25.9	20.7	-8.7	-10.8	-17.6
$40 Tax + EE	8.4	-5.6	-11.8	32.5	0.5	-18.8	42.4	41.6	38.6	34.1	47.2	50.4	10.0	41.1	57.4

For the scenarios with carbon tax alone without energy efficiency, residential households gain from the carbon tax revenue ranging from $10.7 to $30.7 billion. However, for all sectors, the carbon tax results in negative savings when the carbon tax exceeds $20/tCO_2$. This indicates welfare transfers from the commercial and industrial sectors to the residential sector since all sectors face higher electricity prices but only residential sector receives the carbon tax revenue. However, this effect is complex: for example, rising costs in the commercial and industrial sectors may also transfer burden to the residential households by producing higher consumer good prices. It is difficult to sort out all of the inter-sectoral welfare transfers.

In contrast, adding energy efficiency coupled with carbon tax reveals more uniformly favorable results. The residential sector benefits from higher savings and lower energy burdens ranging from $22.6 to $57.8 billion. Across all three sectors, the savings are positive, supporting the hypothesis that energy efficiency can benefit all sectors by reducing their electricity bills.

5.3 Policy Costs

The reduction of carbon emissions and the dampening of electricity demand growth are general impacts of each scenario. To examine the details, we now examine the mitigation costs. Comparing costs across different policy scenarios identifies how the policy pathways and designs influence how costs are distributed between various stakeholders. First, Table 3 presents the utility resource costs components in 2020, 2030, and 2040. These are summarized in Table 4, along with the end-use energy efficiency costs and the revenues from carbon recycling, which in total represent the costs of compliance (in other words, the policy costs).

Table 3. Utility Resource Costs: 2020, 2030, and 2040 (in Billions $2013)*

	Installed capacity			Transmission			Retrofits			Fixed O&M Costs		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Reference Case	24.65	29.53	39.45	1.26	1.69	2.37	2.68	2.42	0.15	39.77	40.58	42.61
Tax Scenarios												
$10 Tax	27.56	33.22	50.94	1.45	1.84	2.72	2.42	2.79	0.94	39.48	40.50	43.94
$10 Tax + EE	23.65	23.09	31.95	1.19	1.17	1.67	1.97	2.39	0.82	37.51	37.61	39.55
$20 Tax	36.22	49.42	90.58	1.92	2.64	4.11	2.55	2.88	1.30	38.94	41.09	47.34
$20 Tax + EE	35.01	36.53	68.39	1.91	1.99	3.00	2.06	2.36	0.95	37.13	37.51	42.42
$40 Tax	38.38	63.77	104.98	2.06	3.22	4.21	2.79	2.95	0.67	37.70	41.59	47.70
$40 Tax + EE	37.16	49.41	81.98	2.09	2.58	3.26	2.25	2.42	0.53	35.90	37.96	43.04

	Capital Additions at Existing Plants			Non-Fuel Variable O&M			Fuel Expenses			Purchased Power		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Reference Case	6.32	6.06	6.02	7.39	8.16	8.99	86.01	107.45	137.46	2.81	3.08	4.90
Tax Scenarios												
$10 Tax	6.00	5.70	5.67	6.88	7.36	8.13	86.85	102.03	118.26	2.99	3.67	5.68
$10 Tax + EE	5.46	5.18	5.13	6.08	6.05	6.56	78.86	87.94	101.45	2.96	3.72	5.40
$20 Tax	5.21	4.85	4.32	6.26	6.56	6.74	86.10	95.53	96.22	3.33	4.07	6.70
$20 Tax + EE	4.47	4.09	3.74	5.51	5.45	5.56	78.81	83.35	82.15	3.38	4.25	6.73
$40 Tax	4.54	4.08	3.66	5.93	5.91	6.61	91.94	90.92	94.10	4.05	4.88	8.64
$40 Tax + EE	4.02	3.58	3.21	5.35	4.92	5.51	84.70	78.92	78.59	4.24	4.89	7.52

Figure 7 highlights the impact of each scenario on two key utility resource costs: fuel and installed capacity expenses. Both of these costs are significantly reduced by the introduction of strong energy-efficiency policies.

Figure 7. Fuel and Installed Capacity Expenses

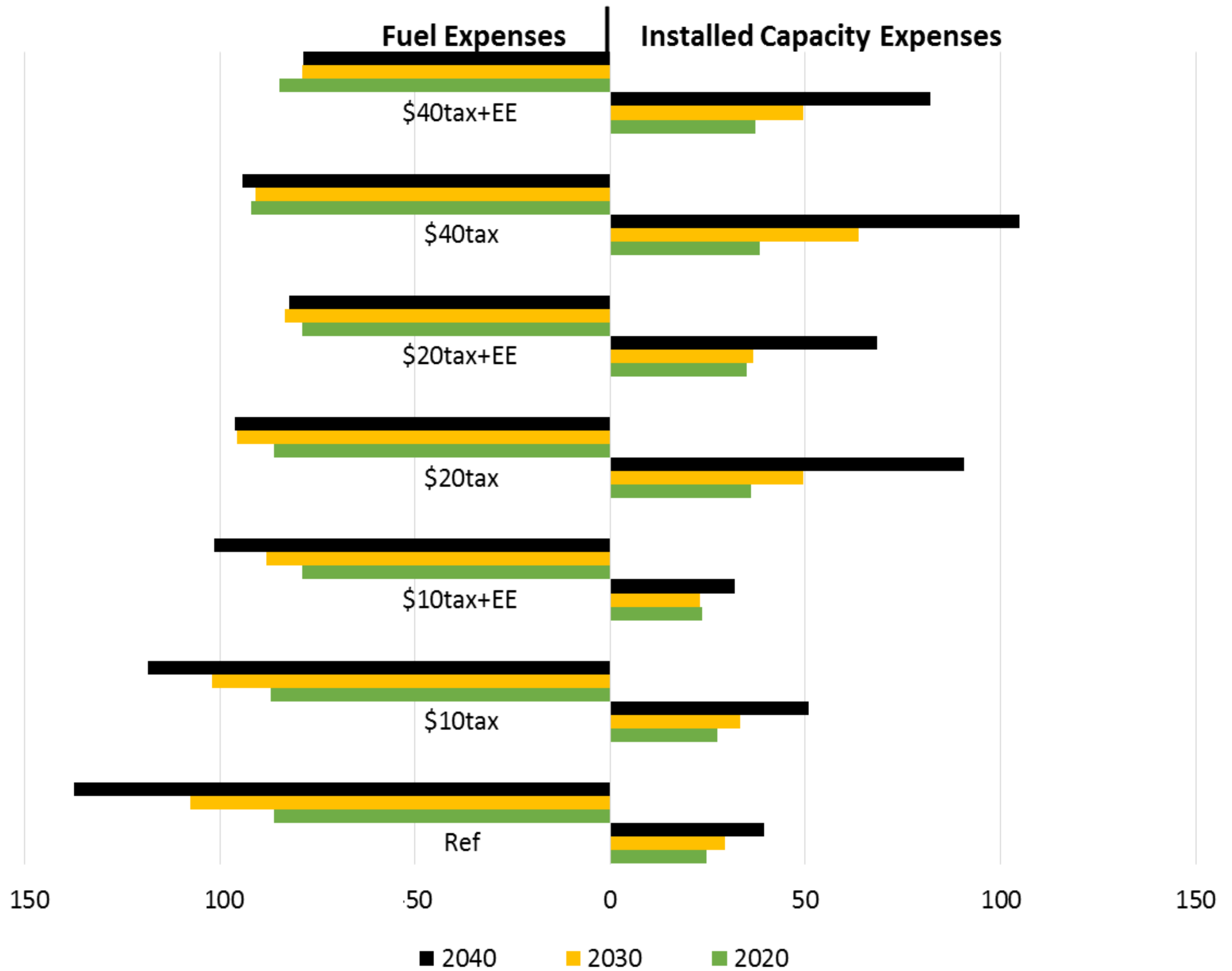


Table 4. Electricity Resource Costs Across Scenarios in 2040 ($Billions 2013)[a]

Scenarios:	Utility Resource Costs (URC) (from Table 3)			End-Use Energy Efficiency Costs[b]			Carbon Tax Recycling	Total Resource Costs (TRC)		
	Total Utility Resource Costs	Difference from Reference $B 2013	Difference from Reference %	Total EE Costs	Difference from Reference $B 2013	Difference from Reference %	$B 2013	TRC	Policy Costs (Difference from Reference) $B 2013	Policy Costs (Difference from Reference) %
Reference	241.9			79.0				321.0		
$10 Tax	274.0	32.0	13%	79.5	0.5	1%	-37.7	315.8	-5.2	-2%
$10 Tax +EE	226.2	-15.7	-6%	95.6	16.6	21%	-33.7	288.1	-32.8	-10%
$20 Tax	307.2	65.3	27%	80.3	1.3	2%	-49.9	337.6	16.6	5%
$20 Tax +EE	256.0	14.0	6%	97.8	18.7	24%	-43.0	310.7	-10.3	-3%
$40 Tax	315.7	73.7	30%	80.9	1.8	2%	-45.0	351.5	30.6	10%
$40 Tax +EE	262.3	20.3	8%	97.6	18.5	23%	-38.6	321.2	0.3	0%

[a] The estimates of utility resource costs are generated by NEMS, based on each scenario's assumptions about technology costs, demand growth, fuel prices, etc.
[b] Includes EE program administration costs.

Tables 3 and 4 provide a consistent description of how the costs of mitigation are distributed across different scenarios and over time; they also show how electricity sector costs are distributed across energy end users, taxpayers, and utilities.

Policy Costs. In the Reference case (where current policies remain and no additional policies are added), the electricity sector's total resource costs in 2040 are projected to be $321.0 billion (in $2013) (Table 4). The addition of a $10 carbon tax reduces these costs by 2%. While the total utility resource costs rise by $32 billion (due primarily to installed capacity expenses), and EE investment costs are slightly higher ($0.5 billion), the total policy costs decline as a result of the $37.7 billion of carbon tax revenues that are recycled back to households across the U.S. Policy costs decline more substantially (by $32.8 billion) when EE policies are added: total utility resource costs decline by $15.7 billion (largely because of lower fuel costs), and this more than offsets the increased EE costs ($16.6 billion) and the decline in carbon tax revenues (to $33.7 billion) because fewer tons of CO2 are available for taxing.

This pattern is mimicked across all three tax scenarios: each is estimated to have lower policy costs when incremental energy efficiency is included. Without energy efficiency, a $20 or $40 carbon tax is estimated to induce additional policy costs of $16.6 billion (in $2013) and $30.6 billion (in $2013), respectively, in the year 2040.

Utility Resource Costs. Table 3 indicates that utility resource costs under all three carbon tax scenarios would be much higher than in the Reference case in 2040. The cost premium ranges from about $30 to $70 billion, mostly resulting from increased investments in installed capacity.

Another take-away from Table 3 is the changing nature of the utility resource costs that comprise the least-cost solutions. Three components (fixed O&M, fuel expenses and installed capacity), constituting over 90% percentage of total utility resource costs, are given further attention. Other than the fixed O&M, which stays almost the same through all scenarios, there is a clear trade-off between fuel expenses and installed capacity. Figure 7 shows the fuel cost on the left and installed capacity cost on the right. Compared to the Reference Case, where fuel expenses have dominated and have increased significantly from 2020 to 2040, adding carbon pricing schemes shifts utility costs to higher installed capacity. In the $10 carbon tax case, fuel expenses still increase over the two decades and dominate the costs (although less so than in the Reference case). As the carbon tax becomes higher, for example in $40 tax scenario, fuel expenses are comparable across the two decades, but installed capacity costs more than double as utilities invest in carbon-free generation.

Incremental energy efficiency reduces investments in installed capacity and fuel expenses, lowering the utility resource costs significantly. In the $10 tax scenario, the net cost translates into $32.8 billion of savings in 2040 when incremental EE policies are added, mostly due to further reductions in fuel expenses and reduced investments in installed capacity, as well as smaller savings in transmission, fixed O&M costs, capital additions, and non-fuel variable costs.

End-Use EE Costs. Table 4 displays the incremental EE costs associated with the non-utility EE policies and programs, which are not rate-based by utilities. Across the carbon tax scenarios, consumers invest more in end-use EE, peaking at $98 billion in 2040 in both the $20 tax + EE scenario and $40 tax + EE scenarios ($19 billion more than in the reference case). Recall that the $20 tax grows 5% annually (reaching $53 in 2040), while the $40 tax grows only 2% annually (reaching $59 in 2040). Hence, their comparable EE investments in 2040 based on price elasticities of demand and the increasing competitiveness of EE. However, the magnitude of demand reduction is much greater in the $40 tax case as would be expected because of the 25-year trajectory of higher carbon taxes (see Figure 3b). The costs for administering these incremental EE policies range from $0.1 to $0.5 billion in 2040. Thus, in addition to overall cost reductions with the introduction of incremental EE policies, there is a shift of cost from rate-based utility programs paid for by all ratepayers through higher energy prices, to investments by households, businesses, and industry that purchase more efficient equipment and upgrade their buildings, structures, appliances, and manufacturing plants.

Carbon Tax Recycling. Carbon taxes are collected and recycled with different amounts for various carbon mitigation scenarios, ranging from $33.7 billion to $49.9 billion in 2040 (in 2013$). This sum is calculated by multiplying the carbon emissions by the required carbon tax per ton of emissions. Higher carbon taxes reduce the consumption of carbon fuels, thereby reducing carbon tax revenues. This causal chain explains why the $40 carbon tax scenarios recycle fewer carbon tax revenues than the $20 carbon tax scenarios.

Examining policy costs in a single year does not account for the fact that scenarios may have different trajectories of CO_2 emission reductions. The carbon budget target is the continuous carbon reduction from 2016 to 2040. Thus, we also compare cumulative CO_2 reductions with cumulative policy costs over the 2016-2040 period, for the Reference case and the all policy scenarios (Table 5).

Table 5. Policy Costs per Ton of CO_2 Reduction, Across Scenarios

Scenario:	Cumulative Incremental Total Resource Costs, 2016-2040 (Billion 2013$)					Cumulative CO_2 2016-2040 (Billion Tons)		Policy Costs of CO_2 Reductions (2013$/ Ton)
	Utility Resource Costs (URC)	Incremental Utility Resource Costs	End-Use Energy Efficiency Costs	Carbon Tax Recycling	Incremental Total Resource Costs (TRC)	CO_2 Emissions	CO_2 Reductions	
Reference	4,878.8					54.0		
$10 Tax	5,389.9	511.1	5,484	541.5	-22.6	48.5	5.5	-4.1
$10 Tax +EE	4,659.4	-219.4	9,994*	484.2	-423.3	44.0*	10.0*	-42.4
$20 Tax	5,949.7	1,070.9	14,445**	826.0	266.2	39.6**	14.4**	18.4
$20 Tax +EE	5,198.6	319.8	19,320**	710.1	-81.4	34.7**	19.3**	-4.2
$40 Tax	6,381.5	1,502.7	20,104**	1005.5	529.1	33.9**	20.1**	26.3
$40 Tax +EE	5,580.2	701.4	24,459**	857.8	159.3	29.5**	24.4**	6.5

Note: CO_2 emissions and reductions are measured in metric tons.
*Meets the median proposed U.S. electric sector's carbon budget (Figure 1).
**More reductions than needed to meet the median proposed U.S. electric sector's carbon budget (Figure 1).

A $20 and $40 carbon tax on the electricity sector would trigger higher cumulative policy costs than the Reference case. Utility resource costs rise because of the higher fuel costs, even though the carbon tax revenues are distributed back to individuals in the tax case. In contrast, the $10 carbon tax case triggers a small negative policy cost and when energy efficiency is added it triggers a sizeable policy savings relative to the Reference case. The result is cumulative reductions of CO_2 in 2016-2040 with negative or zero cost to the economy.

In sum, when strong energy efficiency policies are added to the carbon tax scenarios, cumulative policy costs drop below those in the Reference case—delivering both economic and environmental dividends.

Furthermore, Table 5 shows the symbiotic relationship between carbon taxes and energy efficiency. First of all, adding energy efficiency lowers carbon revenues recycling. However, the amount of the differences, as in the case with EE and without EE depends on the level of carbon tax. Adding EE to the $10 tax scenario will reduce the carbon tax revenue by $60 billion, compared to $150 billion in the $40 tax scenario. More importantly, coupling energy efficiency with a carbon tax will lower the overall policy cost per emission by different magnitudes: the higher the carbon tax, the less effective energy efficiency is in lowering policy costs. This highlights some of the competitive effects of carbon taxes and energy efficiency as carbon mitigation mechanisms.

Thus far, our study is simply a financial analysis assessing costs to utilities, energy end-users, and society as a whole. We do not quantify welfare losses from tax-induced higher electricity prices; however, we are able to monetize environmental ecosystem and human health benefits from the transition to cleaner energy. To roughly estimate the environmental benefits of avoided carbon emissions and co-benefits of local pollutants, we employ the estimation methods of Brown et al. (2016) (Table 6).

Table 6. Benefits of Reducing Carbon Dioxide, Sulfur Dioxide, and Nitrogen Oxides in 2016 through 2040

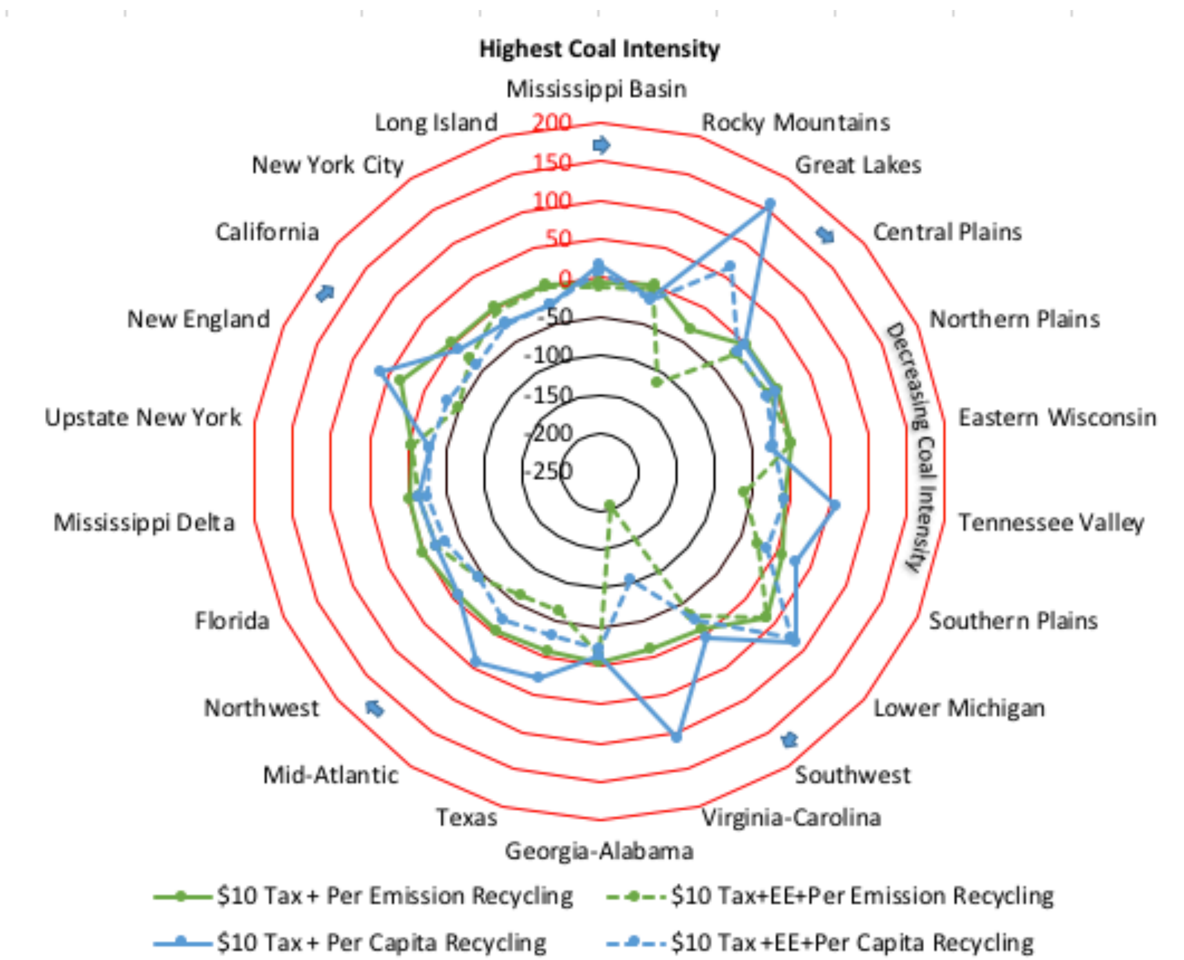
Scenario	Carbon Dioxide		Co-Benefits					Total
			Sulfur Dioxide		Nitrogen Oxide		Sub-Total	
	Avoided Emission (Billion tons)	**Total Values** (Billion 2013$)	**Avoided Emission** (Million tons)	**Total Values** (Billion 2013$)	**Avoided Emission** (Million tons)	**Total Values** (Billion 2013$)	Billion 2013$	Billion 2013$
$10tax	5.5	313	4.4	359	3.7	104	463	776
$10tax+EE	10.0	569	7.9	649	7.7	215	864	1,433
$20tax	14.4	823	11.6	954	11.7	325	1,279	2,102
$20tax+EE	19.3	1,101	15.4	1,266	15.5	430	1,696	2,797
$40tax	20.1	1,146	16.4	1,350	16.4	454	1,804	2,950
$40tax+EE	24.4	1,394	19.1	1,567	19.6	545	2,112	3,506

Notes: Note: Avoided emissions of carbon dioxide, sulfur dioxide, and nitrogen oxide are measured in metric tons. The source of pollution values is Brown et al (2016) and USEPA (2015a, b). The discount rate is 3%. The range of co-benefit estimates reflects the range of epidemiology studies for avoided premature mortality for PM2.5 and ozone. U.S. EPA and other authorities conclude that they are unable to estimate the health co-benefits associated with reduced sulfur and nitrogen oxide emission exposure directly. Accordingly, our analysis only quantifies and monetizes the PM2.5 and ozone co-benefits associated with the reductions in sulfur and nitrogen oxide emissions. Co-benefits for PM2.5 precursors are based on regional benefit-per-ton estimates. Co-benefits for ozone are based on ozone seasonal NOx emissions.

Table 6 indicates that between 2016 and 2040, the total benefits from carbon and local pollutant emission reductions range from $776 billion to $3,506 billion, which far exceed the incremental policy costs. (By comparison, the incremental policy cost ranges from negative to $529 billion.) Even the co-benefits from avoided local pollutants (from sulfur emission and nitrogen emission reductions) can be much higher than the total policy costs, ranging from $463 to $2,112 billion, about 60% of the total benefits in all scenarios.

Alternative Approaches to Carbon Tax Recycling. There are many different ways to recycle carbon tax revenues. Here we look at two strategies that can have very different regional impacts. In one case the revenues are returned to regions using per CO_2 emission recycling (the green lines in Figure 8). Thus, regions with significant amounts of coal-generated electricity would receive a proportionately higher percentage of the recycled carbon tax revenues. In the second case the tax revenues are returned to regions using per capita recycling (the blue lines in Figure 8), consistent with the proposed "Carbon Dividends Plan" (Bailey and Bookbinder, 2017; Chen and Hafstead, 2016; Horowitz et al., 2017). Thus, regions with larger populations would receive a higher proportion of carbon tax revenues.

Figure 8. Policy Costs Across Regions in 2030 (in $2013 per capita)



The $10 tax scenarios are used to exemplify the regional distribution issues posed by carbon taxes, using policy costs per capita in 2030 as an example (Figure 8). The 22 U.S. regions in this "spider diagram" are listed in clockwise descending order based on their coal generation intensity. (Starting from the top, the Mississippi Basin region is predicted to have the highest coal generation intensity of any of the NERC regions in 2030, and Long Island is predicted to have the lowest in 2030. When policy costs lie in the outer red bands, households in a region lose money ("losers"). When costs lie in the inner black bands, a region gains ("winners"). The dashed lines show the scenarios that include energy efficiency.

A $10Tax with per emission recycling would have relatively uniform and small per-capita costs across the 22 regions – never exceeding $50/capita in 2030. In contrast, there is significant regional variability in costs in 2030 using per capita recycling, with notably high costs of $150 per capita in the Great Lakes region. When energy-efficiency policies are added, overall costs are lower, but they are still variable with some notable negative costs (i.e., savings) of -$250 per capita in Virginia-Carolina but also modest costs of $40 per capita in Lower Michigan. The costs faced by different regions reflect their generation portfolios. The right-hand bulge of the “spider diagram” shows that, in general, the greater reliance on coal in a region’s generation mix, the higher the compliance cost. This figure shows that the carbon tax with different recycling strategies will create different regional winners and losers. In particular, carbon taxes with per capita recycling of tax revenues would create more extreme regional winners and losers. In general, regional differences are moderated by strong energy-efficiency policies, which also tend to have an overall cost-reduction impact.

6. Conclusions and Discussion

Our modeling suggests that carbon taxes combined with strong energy-efficiency initiatives would produce synergistic effects that could help to meet deep decarbonization goals for the U.S. electric sector. A Reference case future would emit far more carbon emissions than prescribed by the electric sector target developed in this paper (Figure 1), indicating that additional policies and transitions are needed. To comply with the goal, a U.S. tax of $10/tCO_2$ emitted from the electricity sector – introduced in 2020 and rising to $27/tCO_2$ in 2040 (in $2013) – would not be sufficient. By adding strong energy-efficiency policies, the goal can be met and the transition would be more affordable. A $20//tCO_2$ tax rising to $53/tCO_2$ in 2040 would be sufficient to keep emissions below the electric sector’s carbon budget, but without strong energy-efficiency policies it would cost more.

Our research underscores the equity issues associated with different strategies for recycling carbon tax revenues. Recycling carbon taxes back to households on a per capita basis would result in a net transfer of wealth from carbon intensive regions to the rest of the nation. Recycling taxes back to households proportionate to the carbon intensity of their regional economies would reduce such large differences between regional winners and losers while at the same time providing the price signals needed to transform electricity systems.

Two recent reviews of carbon pricing suggest that higher carbon taxes are required to achieve climate goals of 1.5 to 2°C. The highly referenced report by the IPCC (2014b) reveals scenarios that limit warming to below 2°C with high probability requires carbon prices increasing throughout the 21st century, ranging from $15 to $360/tCO_2e$ in 2030 (in $2015). Other analysts have deduced that at least $40-80/tCO_2$ by 2020 and $50-100/tCO_2$ by 2030 carbon pricing is needed to limit global temperature to below 2°C (Carbon Pricing Leadership Coalition, 2017). Similarly, estimates from IEA and IRENA (2017) indicate that global warming targets of 2°C require carbon prices to rise to $120/tCO_2$ in OECD countries by 2030.

These results tend to cover OECD countries and unlike our study, they assume that the carbon tax would be economy-wide. Limiting carbon taxes (at least in the short-run) to the electric sector takes advantage of the lower cost carbon abatement possibilities that the electric sector offers. Abatement costs and opportunities in electricity generation are consistently shown in system modelling studies to be cheaper and easier than in most end-use (housing, transport) or intermediate sectors (industry, freight, agriculture) (IPCC, 2014b). This pattern is substantiated for the U.S. by the NEMS modeling of Arora et al. (2018), which finds that an economy-wide carbon tax would have the greatest impact on emissions from electricity generation. Most 2°C modelling shows substantial decarbonization in electricity well in advance of other sectors. Similarly, national mitigation strategies typically look for faster and deepest cuts in emissions from electricity generation before other sectors.

Many prior studies focus on global carbon budgets that are smaller than ours. For example, IPCC (2014a) assumes that the remaining CO_2 budget from 2015 to 2100 is between 400 and 450 $GtCO_2$ compared to Millar et al. (2017)'s 939 $GtCO_2$ budget that we adopt. In addition, these alternative studies do not emphasize the adaptive energy-efficiency policies emphasized in our paper. Indeed, it may be that energy-efficiency improvements can be more cost-effectively achieved through policy interventions in the U.S. than in other OECD countries, partly because the level of energy efficiency in the U.S. is lower than in many other OECD countries (Kallakuri, et a., 2016). Many prior studies are based on global carbon pricing compared with our detailed examination of carbon pricing in the U.S., where energy prices are low relative to other OECD countries.

Finally, it is important to note two limitations of our research that may bias our estimates of deep decarbonization costs and emissions. First, our analysis extends only to 2040 and so does not take into account goals for 2100 and beyond. Studies suggest that mitigation costs may be underestimated if they are not embedded in a longer-term perspective to the climate change challenge (Pye et al., 2017). Second, our modeling does not deploy life-cycle assessment of the electric grid; it therefore does not consider the additional emissions that can be significant during the infrastructure phase of energy transitions (Siddiqui and Dincer, 2017).[4] Nonetheless, the economic and policy conclusions drawn from our research regarding the relative performance of carbon taxes – when coupled with alternative revenue recycling schemes and varying energy-efficiency approaches – would appear to be well-grounded even with any such overall cost and magnitude biases.

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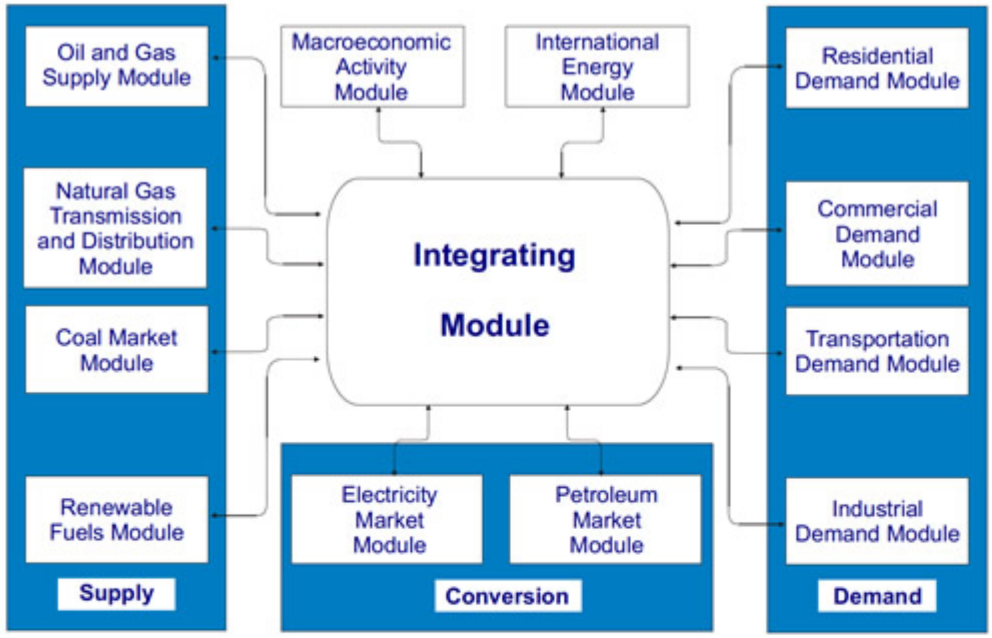
Technical Appendix A
Background on NEMS

GT-NEMS is based on microeconomic general equilibrium theory. Linear programming algorithms and other optimization techniques provide the foundation with which GT-NEMS develops forecasts of the US energy future. GT-NEMS uses twelve modules, plus a thirteenth integrating module, to simulate various sectors of the energy economy. These twelve sectors are each modeled by a respective module, and the corresponding twelve modules are: Macroeconomic Activity, Residential Demand, Commercial Demand, Industrial Demand, Transportation Demand, Oil and Natural Gas Supply, Natural Gas Transmission and Distribution, Coal Market, Renewable Fuels, Liquid Fuels (formerly the Petroleum Market Module), International Energy, and Electricity Market. Figure 1 below provides a graphical layout of the modular structure of GT-NEMS. GT-NEMS performs an iterative optimization process that results in the price and quantity that balance the demand and supply of numerous energy products. These results are intended as forecasts of general trends rather than specific predictions of future outcomes, making GT-NEMS well-suited for offering insights about alternative policy and technology scenarios.

GT-NEMS models electric power systems through a regional planning approach that makes use of one module, the Electricity Market Module, and its four constituent sub-modules (EIA 2013). The Electricity Market Module divides the US into 22 regions based on North American Electricity Reliability Corporation regional boundaries. The Electricity Market Module performs separate projections of power demand and the cost-minimizing supply necessary to meet that demand for each region. In computing estimates of cost-minimizing supply choices, the Electricity Market Module uses survey data from EIA's Form 860, 861, and 923 surveys, as well as North American Electricity Reliability Corporation projections and data from the Federal Energy Regulatory Commission's Form 1 survey. These inputs are used to characterize end-use load shapes, costs and performance of capacity types, and other key variables within the Electricity Market Module.

GT-NEMS is a computational general equilibrium (CGE) model based on the 2015 distribution of the Energy Information Administration (EIA)'s National Energy Modeling System (NEMS), which generated EIA's 2015 Annual Energy Outlook (USEIA 2015). The Annual Energy Outlook forecasts energy supply and demand for the U.S. through 2040. Other than modifications necessary to operate the NEMS model on networked servers at Georgia Tech, GT-NEMS is equivalent to EIA's National Energy Modeling System. GT-NEMS is thus documented by way of reference to the documentation manuals for NEMS (e.g., USEIA 2009; 2015). By modifying parameters and source codes within the GT-NEMS model, Georgia Tech has tested hypotheses about possible future policy and technology scenarios, ranging from advanced building codes, energy benchmarking programs, and demand response, to tax credits for industrial cogeneration, pollution from alternative coal market shifts, and employment impacts of the clean power transformation. Sensitivities to consumer discount rates, rebound effects, and shifts in end-use load shapes have also been examined. Figure A.1 is a graph of the modular structure of GT-NEMS. Selected publications are listed at the end of this overview.

Figure A.1. Graph of the modular structure of GT-NEMS



(Source: USEIA, 2009)

Linear programming algorithms and other optimization techniques provide the foundation with which GT-NEMS develops forecasts of the US energy future. GT-NEMS uses twelve modules (shown in Figure A.1), plus a thirteenth integrating module, to simulate various sectors of the energy economy. GT-NEMS performs an iterative optimization process that results in prices and quantities that balance the demand and supply of numerous energy products. These results are intended as forecasts of general trends rather than specific predictions of future outcomes, making GT-NEMS well-suited for offering insights about alternative policy and technology scenarios.

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NEMS models the demand sectors using nine Census Divisions. For buildings, appliances, industrial motors and drives, and combined heat and power (CHP) systems, NEMS adds or subtracts from the existing stock to account for new purchases, retrofits, and retirements. For mature technologies, timelines of equipment costs and efficiencies are specified by fuel type. For nascent technologies such as solid state lighting and carbon capture, sequestration and utilization, endogenous learning curves model technology performance.

For residential buildings, NEMS uses energy prices and macroeconomic indicators to estimate residential energy consumption for three building types (single-family, multi-family and mobile homes), 21 end-use services, and multiple fuel types. Logit functions assign market shares to competing technologies in ten major end-use services such as space heating, space cooling, and water heating (see Appendix). The implied discount rates are variable (ranging for space heating and cooling technologies from 15 to 42% – Wilkerson, et al., 2013). Price elasticity and rebound effects are applied to three of these end-uses (heating, cooling, and lighting) and are modeled separately for surviving equipment, replacement equipment, and new equipment using parameters that vary by equipment, housing type, and Census Division. Forecasts from commissioned reports are used for the 11 minor end-uses (U.S. Energy Information Administration, 2014b). Based on projected building and appliance stocks, the energy integrity of the building envelope is then modeled.

In the commercial sector, NEMS employs a least-cost function within a set of rules governing the options from which owners and operators of commercial buildings may choose technologies. NEMS forecasts building stocks and the energy integrity of building envelopes before forecasting the stock of end-use technologies. NEMS characterizes nearly 350 distinct types of end-use equipment and appliances in nine end-uses and eleven types of commercial buildings. Capital costs are amortized using “hurdle rates”, which are calculated for end-uses by year for different subsets of the population by summing the yield on U.S. government ten-year notes (endogenously determined) and the time preference premium of consumers (exogenous inputs to the model). Ninety percent of commercial floorspace is modeled using effective hurdle rates of 25% or more, and half employ discount rates ranging from 100% to 1000% (Cox et al., 2013). Three different decision types and three types of behavior rules are used depending on whether the technology would be a retrofit, replacement, or new addition, and if there is a change of fuel type (Wilkerson, et al., 2013). Thus, the model offers the potential for a rich examination of policy impacts and an assessment of technology choice, energy consumption, price and expenditures, carbon abatement, and pollution prevention over time and across Census divisions of the U.S.

Process energy in the industrial module is modeled separately for 16 manufacturing and 6 non-manufacturing industries, by fuel type. The energy used per dollar of shipments (called unit energy consumption or UEC) is modeled for individual industries, based on energy use per ton of throughput at each process step. Future improvements in UEC are modeled by using Technology Possibility Curves (TPCs), which reflect UECs in the initial year and annual energy intensity declines over time. The TPC rates are estimated separately for retrofitting of existing facilities and for construction of new facilities. The industrial module specifies cost and performance characteristics for a range of CHP and motor technologies (Wang and Brown, 2014).

Across these modules and regions, NEMS projects the production, imports, conversion, consumption, and prices of energy, GDP, and employment subject to assumptions about macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics (EIA 2009; 2015a).

Modeling Incremental Energy Efficiency

In the residential sector, we strengthen the representation of equipment and appliance standards in NEMS in several targeted areas. Significant improvements in appliance standards are modeled for room air conditioners as well as refrigerators and freezers. We use the 2015 NEMS updated technology assumptions for geothermal heat pumps, electric water heaters, dishwashers, and gas and electric clothes dryers. For lighting, we apply the High Tech side case assumptions for costs and efficiency, improving bulb type LEDs, reflector LEDs, linear fluorescent lamps and LEDs, and LED torchieres. Miscellaneous electric uses are also made more efficient by adopting the High Tech side case assumptions upgrading the efficiency of home theater systems, ceiling fans, coffee makers, and dehumidifiers. Each of these same efficiency improvements is modeled by Hausker et al. (2014), Wang and Brown (2014) and/or by the NEMS 2014 High Technology "side case". Consistent with the CEIP incentives to improve demand-side energy efficiency, especially for low-income communities, shell thermal efficiencies in single-family homes, apartments, and mobile homes are also improved, mirroring the impacts of stronger state building codes.

In the commercial sector, stronger state building codes and other energy-efficiency policies are proxied by strengthening the envelope efficiency of new buildings and by using EIA's High Technology "side case" assumptions. In addition, two new high-efficiency air source heat pump technologies are added to the array of commercial HVAC options. These advanced technologies will benefit from the recent promulgation of a new efficiency standards for commercial air conditioners and furnaces – the largest energy-saving building equipment standard in U.S. history[5]– that is to be implemented in two phase: in 2018 the standards will deliver a 13% improvement in the energy efficiency of new commercial units, and in 2023, an additional 15% efficiency improvement will be required. We model the new standard by eliminating noncompliant rooftop equipment in 2018 and 2023. We also decrease the discount rates used by commercial consumers of new air conditioning and lighting technologies in new and existing buildings, mirroring those used by Cox et al (2013).

In the industrial sector, stronger state energy-efficiency policies are modeled by including additional energy-efficiency assumptions related to combined heat and power and electric motors. The scenario assumes 30 percent investment tax credits for CHP through 2040, and the rate of decline for CHP system costs is increased by using EIA's High Technology assumptions. The High Tech case also assumed

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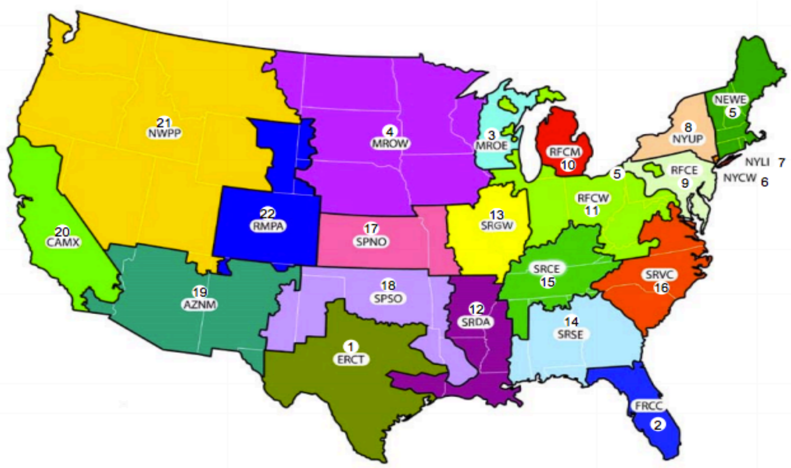
[5] http://energy.gov/articles/energy-department-announces-largest-energy-efficiency-standard-history

improved electric motor efficiencies. Further, we assume that policies encourage manufacturers in five industrial subsectors to reduce UEC below Reference Case projections. The reductions in energy process consumption in 2030 range from 18 percent for bulk chemicals, 23 percent for cement and refining, 40 percent for pulp and paper, and 57 percent for iron and steel, based on a literature review summarized in Brown, Cox, and Cortes (2010) and Bianco, et al. (2013).

Modeling Revenue Recycling

We use the *mactax*=4 revenue recycling option in NEMS, which returns revenues back to households, minus any revenue required to keep from increasing the deficit. Revenue neutral refers to legislative bills or proposals that have no net cost, such that revenues raised offset provisions that lose revenues. Deficit neutral refers to legislative bills or proposals that pay for themselves over some budget period, which is one year in NEMS. A carbon fee in NEMS assumes minimal administrative costs, so revenue neutral and deficit neutral produce almost identical rebate amounts.

Figure A.2. NERC Regions and Subregions



Number	Geographic Name	NEMS Label	Number	Geographic Name	NEMS Label
1	Texas	ERCT	12	Mississippi Delta	SRDA
2	Florida	FRCC	13	Mississippi Basin	SRGW
3	Eastern Wisconsin	MROE	14	Georgia-Alabama	SRSE
4	Northern Plains	MROW	15	Tennessee Valley	SRCE
5	New England	NEWE	16	Virginia-Carolina	SRVC
6	New York City	NYCW	17	Central Plains	SPNO
7	Long Island	NYLI	18	Southern Plains	SPPS
8	Upstate New York	NYUP	19	Southwest	AZNM

9	Mid-Atlantic	RFCE	20	California	CAMX
10	Lower Michigan	RFCM	21	Northwest	NWPP
11	Great Lakes	RFCW	22	Rocky Mountains	RMPA

Table A.1. Sectoral Electricity Demand Reductions Across Mitigation Scenarios (Billion kWh)

	$10 Tax			$20 Tax			$40 Tax		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
Commercial	-7.3	-26.7	-41.7	-22.4	-50.1	-83.2	-43.8	-80.5	-113.1
Industrial	-10.4	-24	-29.8	-27	-48.5	-59.7	-48.9	-72.4	-80.1
Residential	-6.9	-20.7	-27.3	-20.5	-38.9	-56.1	-39.2	-60.1	-72.6

	$10 Tax + EE			$20 Tax + EE			$40 Tax + EE		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
Commercial	-67.4	-149.0	-202.1	-92.5	-177.9	-250.5	-113.8	-206.6	-275.3
Industrial	-50.1	-109.7	-140.6	-75.9	-143.7	-176.5	-96.7	-168.8	-195.9
Residential	-104.3	-200.9	-206.0	-124.4	-220.1	-238.6	-141.3	-239.1	-251.7

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