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Cool Buildings:

Bundled Policies to Promote Super-efficient Space Conditioning

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ABSTRACT

Rising standards of living and global warming are increasing the demand for space cooling in buildings, creating the need for new climate adaptation and carbon mitigation strategies. The approach examined here focuses on a bundle of policies aimed at catalyzing the rapid market penetration of super-efficient heat pumps, within the context of a decarbonizing electric grid. The bundle of catalyzing policies (appliance standards, research and development, and deployment programs) is examined using the National Energy Modeling System to evaluate the likely impacts and the costs and benefits of this strategy in the U.S. We conclude that the policy bundle could significantly improve the efficiency of both space cooling and space heating systems; the significant improvements in space heating are the result of fuel switching from natural gas to electric heating, due to the uptake of heat pumps. The significant electricity savings would in turn induce a drop in electric prices, thereby extending the strategy's benefits to electricity consumers across the economy. From the private perspective, energy bill savings would exceed investment and policy administration costs by a ratio of slightly more than 2-to-1. By including the monetized benefits of CO_2 and criteria pollution reduction, this benefit/cost ratio increases to 2.5.

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1. Introduction

With rising standards of living and global warming, the demand for space cooling is growing rapidly, which is challenging energy systems across the globe. How will future energy systems meet the growing demand for air conditioning, and how will the global climate respond if this demand is met by combusting fossil fuels to generate more electricity? This dilemma is both a problem of climate adaptation and carbon mitigation. Technologies are available to address this challenge – specifically, super-efficient heat pumps powered by low-carbon electricity. A great deal of effort is currently focused on moving electricity systems toward renewable and other low-carbon resources, but much less effort has focused on the transformation of space conditioning systems to take advantage of super-efficient electric space conditioning. This paper evaluates a bundle of policies (combining appliance standards, research and development, and deployment policies) that could accelerate the market uptake of the latest generation of heat pumps. This carbon mitigation/climate adaptation strategy is evaluated using an energy-engineering methodology that considers system-wide impacts on energy prices, electric generation, energy consumption, and fuel switching..

Between 1980 and 2010, the energy used globally for heating and cooling grew by an estimated 39% and 61%, respectively, in homes and businesses. According to the Intergovernmental Panel on Climate Change (IPCC, 2014), the demand for space cooling will nearly double by mid-century. In residential buildings, the growing number of households and the increasing size of homes are contributing to this growth. In commercial buildings, the two-fold increase of global GDP is expected to expand the commercial building stock and its energy requirements. While energy-efficiency improvements are expected to reduce the energy required per square meter of building space, these improvements are not anticipated to be sufficient to offset the growing demand for cooling (IPCC, 2014).

Energy forecasts for the U.S. are consistent with these anticipated global trends. The U.S.Energy Information Administration (EIA, 2014) projects that energy usage in buildings will grow by 0.4% per year, reaching 42.4 quadrillion Btu in 2040. Over the long run, global climate change is expected to significantly increase the demand for space cooling, while slightly decreasing the demand for space heating (EIA, 2005). Because electricity is the dominant fuel for air conditioning, while heating is dominated by the direct use of fossil fuels, a warming climate is anticipated to increase the demand for electricity while decreasing the demand for natural gas and fuel oil. Hadley, Erickson, Hernandez, Broniak, and Blasing (2006) estimate that a 1.2°C increase in temperatures in the U.S. would cause primary energy use to increase by 2% in 2025. Much larger climate and cooling energy demand impacts have been projected by the middle and end of this century (Brown, Cox, Staver, & Baer, 2014; Mansur, Mendelsohn, & Morrison, 2008; Scott & Huang, 2007).

Even larger increases in peak demand for electricity are anticipated. Sathaye et al. (2013) estimate that peak electric demand in California could increase by 10-25% by the end of the century. The U.S. Environmental Protection Agency (EPA, 1989) concluded that climate change could require a 14-23% increase in electricity capacity additions between 2010 and 2055, relative to a future with no climate change. An analysis of the Western Electricity Coordinating Council region by Argonne National Laboratory (ANL, 2008) estimated that 34 GW of additional electricity capacity would be needed by 2050 to meet the region's increasing peak load requirements resulting from climate change. Such impacts pose particular stress on the electric grid, which is already vulnerable to climate-related outages. Between 2003 and 2012, severe weather caused power outages that cost the U.S. economy an estimated $18 to $33 billion (The Executive Office of the President, 2013). These costs include lost output and wages, spoiled inventory and delayed production, as well as inconvenience and damage to the electric grid. There is already evidence of climate-related stress on the grid (DOE, 2013).

Evidence to date suggests substantial regional variability in demand sensitivities. Sailor (2001), for instance, found that a 2°C temperature increase would result in an 11.6% increase in residential per capita electricity used in Florida, but a 7.2% decrease in the state of Washington. Similarly, research by Scott, Wrench, and Hadley (1994) found that climate change had a highly variable impact on commercial building energy demand across four U.S. cities. In southern states the increase in cooling would generally exceed the decrease in space heating while in northern states (those with more than 4000 Heating Degree Days per year, specifically), the opposite would likely be the case (DOE, 2013 p.13; USGCRP, 2009).

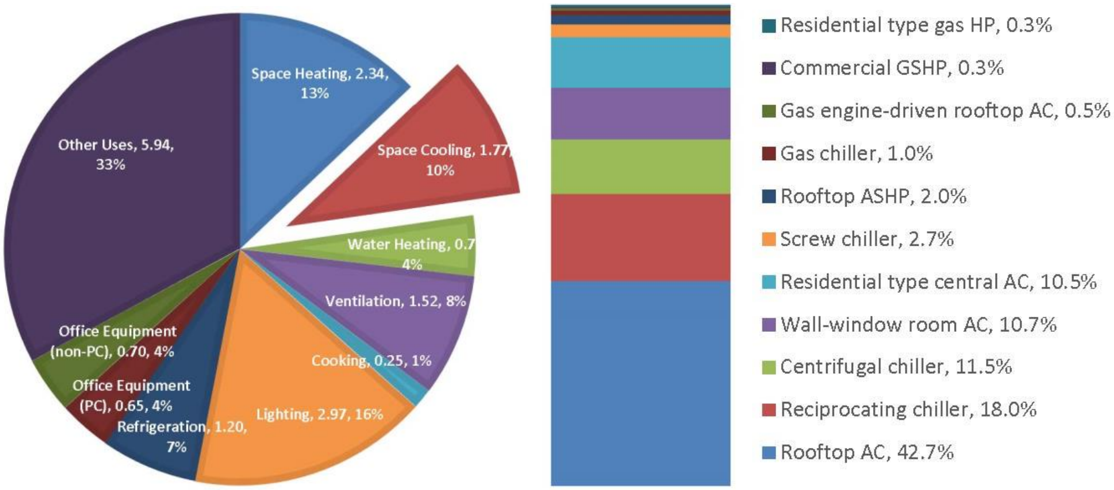
Regional differences in the fuels used for space heating make these impacts on overall energy consumption highly variable. In addition, regional differences in the extent of existing air conditioning equipment will also influence the extent that global warming impacts the use of air conditioning, at least in the short run. Where the need for cooling has largely been met by passive cooling approaches and vernacular building designs, external energy systems may need to be added in the future. Where regions are already equipped with extensive air conditioning equipment, the increase in energy for cooling requires less capital investment and can occur more rapidly.

This paper evaluates a climate adaptation/carbon mitigation strategy for industrialized economies that capitalizes on super-efficient air conditioning with a new generation of air source heat pumps. By simultaneously motivating the electrification of space heating, this climate strategy could accelerate the transition to low-carbon energy systems if accompanied by a low-carbon electric grid. Previous studies have highlighted the potential role that heat pumps could play in transitioning to low-carbon energy systems (Lowe, 2007; Sugiyama, 2012; Lucon and Urge-Versatz, 2014). A climate strategy focused on heat pumps would rely less on the direct combustion of fossil fuels for space heating and would increase reliance on electricity (Cockroft and Kelly, 2006), which has implications for the capacity of electricity systems and the stability of electric grids that warrant further assessment.

We begin with an overview of the status of air conditioning in commercial buildings in the U.S., and an overview of market trends. This paper focuses on commercial buildings because the National Energy Modeling System (NEMS), the tool selected for this analysis, has detailed technology characterizations of this sector. We then describe a three-pronged policy framework for making air conditioning more energy efficient. After describing our overall research design and modeling approach, we present our modeling results starting with estimates of the energy and carbon impacts of the scenarios as they apply to commercial buildings in the U.S. We conclude with a cost-benefit analysis of the three-pronged policy approach, and discuss the remaining research needs.

2. Rooftop air-conditioning equipment: Current status and market trends

In 2010, commercial buildings in the U.S. consumed an estimated 5.6 quadrillion Btu of energy for space heating, ventilation, and air conditioning (HVAC) (Figure 1). These HVAC services account for nearly one-third of the energy used in commercial buildings.



(Primary Energy Use in Quads)

Figure 1. Primary Energy Consumption by End-use and Space Cooling Technologies, 2010
(Source: EIA, 2014)

Rooftop units, central chillers, and wall-window ACs are the major technologies meeting most cooling demand (Figure 1). These technologies exemplify the three general types of cooling systems used in commercial buildings: packaged, central, and individual air-conditioners. Packaged systems are the most common, and they include rooftop units and split system heat pumps, where cooling is delivered directly to supply air. Central systems generate cooling service in a chiller and use chilled water as a cooling medium. Individual systems include window ACs and water-loop heat pumps. Table 1 lists the major types of AC equipment along with the heating equipment that is typically paired with it.

Table 1 Space Cooling and Heating Equipment Summary

Air-conditioning Equipment	Typical Matched Space Heating Equipment
Packaged	Various heating equipment
• **Rooftop AC**	Gas Furnace
• **Rooftop ASHP**	Heat pump
• **Gas engine-driven rooftop AC**	Gas Furnace
• **Gas engine-driven rooftop HP**	Heat pump
Central • **Centrifugal chiller** • **Gas chiller** • **Reciprocating chiller** • **Screw chiller** • **Scroll chiller** • **Residential type central AC**	Various heating equipment
Individual	Various heating equipment
• **Wall-window room AC**	Heat pump
• **Residential type gas HP**	Heat pump
• **Commercial GSHP**	
All systems except heat pumps	Unit heater
	Boiler
	Furnace

Space cooling equipment has a long life-span and is not easily replaced due to installation complexities. Naturally, innovation has focused on improving the energy performance of AC technologies. Recent technology advances in electrical refrigeration systems utilize multistage compression to improve energy performance(Afonso, 2006). In addition to novel cooling devices, energy efficiency for air-conditioning can also be improved by innovative system design, operational management, and intelligent control. For instance, the use of desiccants can reduce the energy demand for both cooling and dehumidification. Ejector systems can provide cooling and heating simultaneously from a renewable energy source; for example, solar cooling. Furthermore, intelligent air-control strategies using variable air volumes, and smart chiller sequencing methods can reduce energy consumption (Afonso, 2006; Chua, Chou, Yang, and Yan, 2013).

3. A policy framework for making air conditioning more energy efficient

For years, energy efficiency advocates have argued that bridging the energy-efficiency gap can save millions of dollars in energy consumption for consumers while improving quality of life and environmental conditions. Not doubting this premise, countless policies have been created and supported on the basis of addressing barriers to energy efficiency. Many of these policies either provide general information or attempt to change the price of goods. Despite existing efforts, the energy-efficiency gap remains: contractors build inefficient homes that people are quick to buy; people rarely replace equipment or home materials with the most efficient, cost-effective technology; and we waste energy on things that are not in use. Much of this energy-efficiency gap can be attributed to how individuals make decisions, but they also reflect principal-agent problems and other market failures (Brown & Sovacool, 2011). Principal-agent problems occur when one party (the agent) makes decisions in a market and a different party (the principal) bears the consequences. This issue was found by Prindle (2007) to be significant and widespread in many end-use energy markets in both the U.S. and other countries. In many commercial buildings, architects, engineers, and builders select equipment, duct systems, windows, and lighting for future building occupants. Similarly, landlords often purchase and maintain appliances and equipment for tenants who pay the energy bill, providing little incentive for the landlord to invest in efficient equipment (Brown, 2001).

Many policies are available to address these barriers and market failures in order to trigger higher efficiency air conditioning. Three are examined here: regulation (that is, an appliance standard), research and development (R&D) (to promote technology cost reductions), and deployment policies (so that expanded production can bring about economies of scale and learning by doing).

3.1 Regulation: A rooftop AC Appliance Standard

Appliance and equipment standards are one of the most cost-effective measures to cope with air pollution and climate change. Minimum energy performance standards (MEPS) usually impose efficiency requirements on a selected set of equipment that uses external energy sources. Many countries have implemented mandatory standards to promote more energy-efficient home appliances, building HVAC equipment, industrial motors, and other equipment. One of the first of these efforts was taken in 1974 by California, which mandated a state-wide building energy code and appliance standards. Following the National Appliance Energy Conservation Act of 1987, the federal government adopted standards for a range of appliances. At about the same time, Australia and Japan also promulgated national standards, leading to the diffusion of appliance standards to many other countries.

Policy-makers generally consider four goals in setting appliance and equipment standards, including saving energy costs, lowering energy consumption, reducing pollution, and improving energy planning with avoided investment in fossil fuels. Appliance standards are a typical command-and-control policy instrument. MEPS performance standards focus on the outcome, which is different from design standards mandating particular technologies or processes. Appliance standards have become prevalent policy approaches used by many national and state/provincial governments because they offer design flexibility and motivate innovation with well-designed programs.

The U.S. is among the earliest adopters of a nation-wide appliance standards program. The policy design involves an incremental, consensus-oriented process, generally involving key stakeholders, namely manufacturers, consumer advocates, experts, and non-profit organizations (Sachs, 2012). During the open process, manufacturers negotiate with environmental groups and other stakeholders to reach consensus agreements, which usually become the precursors of new standards. The Department of Energy (DOE) applies engineering-economics analysis to the proposed new rule, weighing the benefits and costs, including the trade-off between the increased capital costs and decreased energy costs of the more efficient appliances. The analysis process usually takes about three years before DOE issues the final rule. There is another 3-5 years before mandatory compliance so that the market has some time for adjustment (Desroches, Garbesi, Kantner, Buskirk, & Yang, 2013; Lee, Groshans, Gurin, Cook, & Walker, 2012)

Evidence has shown that appliance standards are effective in improving energy efficiency adoption and achieving energy savings. Some of the existing state and federal standards have significantly improved efficiencies for gas furnaces, central air conditioners, and refrigerators (Desroches et al., 2013). Motivated by both R&D and regulations limiting energy use, the annual energy consumption of refrigerators has declined by 70%, along with decreasing retail prices, increased capacity, and the addition of premium features (Desroches, Hafemeister, Kammen, Levi, and Schwartz, 2011). Other appliances regulated by standards have also seen significant improvement in their energy efficiency.

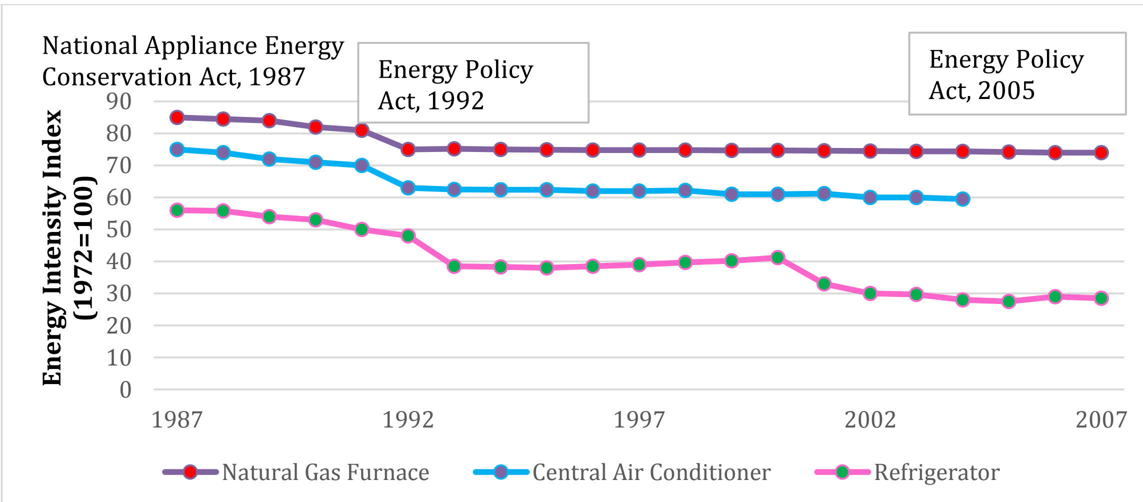


Figure 2. Illustration of Existing Federal Appliance Standards
(Adapted from Desroches et al., 2013)

Assessments of appliance standard programs usually exhibit significant energy savings (2-12%), noticeable cost savings (in the tens of billions of dollars), and significant reductions in air pollutants and greenhouse gas emissions (Desroches et al., 2013). These benefits are achieved with very limited costs – DOE only spent $0.3 billion on the appliance standards program from 1979-10. The benefit/cost ratios for such programs often exceed 100:1 (Desroches et al., 2013). Appliance standards are so attractive that DOE has promulgated new MEPS at an unprecedented rate since 2009. The volume of rulemaking makes it the biggest effort in environmental policy-making under the Obama Administration (Sachs, 2012).

Compared to market-based policy instruments such as carbon cap and trade programs, appliance standards have the advantages that (a) they can directly affect consumer behavior in investment decisions; (b) they assist the diffusion and market penetration of energy efficiency measures; and (c) they have spillover effects across state and national borders when policies are copied and diffused.

Opponents of appliance standards programs generally draw from critics of command-and-control instruments that a uniform national standard may impede innovation (Goulder and Parry, 2008). But advocates argue that standards can motivate innovation if it allows flexibility for manufacturers to develop new technologies to meet the minimum efficiency requirements. Empirical studies find it hard to quantify either innovation or policy impact. Sachs (2012) suggests viewing appliance standards as a shaper of the market, rather than a trigger of or a hurdle to innovation.

On the other hand, states that intend to set more stringent standards may find the federal standard a policy barrier. Due to the preemption rule, few states currently have adopted more stringent standards for products regulated by the federal standard. This phenomenon denotes the need for better policy design. Klass (2009) and A Chase, McHugh, & Eilert (2012) propose several approaches to accommodate states' needs for better standards: multistate standards, relaxed waiver for California, expanded subset provision, and a non-uniform approach. All four approaches involve some extent of lessening the preemption rule, to enable states to more easily pursue higher standards.

3.2 Technology learning via R&D and deployment policies

The literature on technology learning suggests that the cost of producing a manufactured item decreases regularly as a function of two influences:

- R&D, and
- cumulative production (economies of scale and learning by doing).

R&D is a powerful accelerator of knowledge. The payoff to increasing R&D focused on improved technology has been well documented. "If the electric power industry alone were to devote 2% of revenue to R&D for the next decade, the resulting $50 billion would exceed cumulative energy R&D invested since the 1970s, yet would be smaller than cumulative profits of $168 billion from 1994 to 2003 … and would be dwarfed by the $1.7 trillion forecast to be spent on new equipment and upgrades in the North American power sector from 2001 to 2030…." (Kammen & Nemet, 2007).

Cumulative production is important because it contributes to economies of scale and learning by doing. Economies of scale refer to the cost advantages that firms obtain due to lower-cost fixed capital, bulk purchasing/marketing, and financing (lower interest rate for larger projects) (Arrow, 1962). Learning by doing refers to the fact that knowledge grows over time and is a product of experience and repetitive performance. Thus, the cost of producing a manufactured item decreases regularly as a function of cumulative production of that item. Doubling the cumulative production leads to a decrease in costs by a given fraction, the learning factor.

At least two types of policies are suggested by these factors:

(1) R&D subsidies (X-prizes, tax rebates, science and technology programs, etc.), and
(2) deployment programs (training and information programs, subsidies, government procurement requirements, etc.).

Desroches et al. (2013) found that learning rates for residential central air conditioning and heat pumps averaged 18.1%. Higher rates were identified by Weiss, Patel, and Junginger (2010), who found that household appliances had learning rates ranging from 11 to 36%, but following the implementation of energy policies, learning rates increased to 33 to 49%. These studies document that energy policies can accelerate the learning process.

3.3 The link between regulation and technology learning: the Porter Hypothesis

A growing body of literature suggests that regulation can incentivize innovation. The Porter hypothesis, in particular, suggests that well-crafted environmental regulation can trigger innovation and thereby introduce cleaner technology and environmental improvements into the market. Using OECD countries panel data, Johnstone, Hascic, and Popp (2010) found a positive impact of renewable energy promoting policies, such as feed-in tariffs and renewable energy credits, on the number of renewable energy technology patents. With a similar OECD database, Lanoie and Al (2011) suggested that a more stringent environmental policy regime leads to greater corporate environmental R&D investment, indicating an increasing innovation capacity. Positive impact was also observed on the number of patents filed in response to regulations of certain criteria pollutants in the United States, Germany and Japan (Popp, 2006).

The Porter hypothesis rests on the assumption that firms engage in satisficing rather than optimizing economic behavior and use “routines” for production activities, product mix, personnel action, and R&D. Since firms are not optimizing, regulation can induce innovations that can improve economic efficiency, enhance competitiveness, and increase profits as well as social welfare (Porter and Van der Linde, 1995). Although empirical evidence is mixed regarding the relationship between environmental regulations in general and firms’ business performance (Darnall, Jolley, and Ytterhus, 2007; Feichtinger, 2005; Frondel, Horbach, and Rennings, 2007; Lanoie and Al, 2011), scholars are in agreement with the positive impact of flexible policies such as performance-based standards, as opposed to technology mandates, on both firms’ environmental and business performance (Labonne and Johnstone, 2008; Lanoie and Al, 2011). This is because rather than mandating certain technologies, flexible policies incentivize firms to “search” for customized solutions that meet the regulatory requirements and also suite their own strengths and constraints. A rooftop AC energy efficiency standard falls into the category of flexible regulations in the way that it specifies a performance standard and leaves the path to meet that standard to the discretion of equipment manufacturers.

3.4 Designing a rooftop AC standard

The energy performance of air-conditioning equipment can be measured by multiple efficiency metrics. Traditional metrics, such as coefficient of performance (COP) and energy efficiency ratio (EER), measure efficiency at a single pre-defined condition. Integrated metrics of efficiency ratios at multiple conditions have been more and more widely adopted along with the use of multistage compressors.

- **COP**: coefficient of performance, measured as the heat power extracted from the evaporator (“energy out”) divided by compressor mechanical power (“energy in”);
- **EER**: energy efficiency ratio, the efficiency metric for air conditioning equipment at full capacity;
- **IEER**: integrated energy efficiency ratio, the weighted partial load efficiency metric that combines efficiency ratios at specific load conditions (100%, 75%, 50%, and 25%)[1]. IEER measures equipment efficiencies under typical real-world working conditions.

[1] Integrated part-load value (IPLV) is another integrated efficiency metrics. It differs from IEER with regard to the different weights being put on the EERs at the four load conditions.

Minimum energy performance standards are widely used to mandate a certain level of efficiency improvement for air-conditioning equipment. The design of MEPS should avoid any significant disruption to the market and consumer experience. The principles of MEPS design are summarized as following (adapted from Sachs, 2012):

- avoid mandating the use of a particular technology;
- make sure technology is feasible;
- avoid products with very short development cycles;
- work closely with manufacturers; and
- revisit standard frequently.

The process of policy design usually involves a sophisticated analysis of technical and economic feasibility, and a collaborative process with key stakeholders. In many countries, new standards result from negotiations between manufacturers and environmental groups. Evidence suggests that the negotiation-consensus approach is more effective in improving energy efficiency than the statistical approach (eliminating a certain percent of the bottom-performers) or the top-performer approach (mandating standards equal to the efficiency of the best-performers) (Desroches et al., 2013).

The appliance standard analyzed here requires that new electric rooftop air conditioning units (rooftop ACs and rooftop air-source heat pumps) have a minimum IEER of 13, starting in 2019. This standard is similar to a proposed Notice of Proposed Rulemaking by DOE that could raise the energy performance standards for packaged terminal air conditioners (PTACs) and packaged terminal heat pumps (PTHPs). The current standard and NOPR specify efficiency requirements (measured in EER and COP) for standard size and non-standard size PTACs and PTHPs. The standard we develop acknowledges the need to adopt a partial load performance metric, IEER, to fully capture the energy-saving benefit from variable speed compressors.

3.5 Designing R&D and deployment policies

X-prizes have become increasingly popular as a way of encouraging and rewarding R&D focused on enhancing the performance of particular technologies. In January 2011, DOE initiated the High Performance Rooftop Unit Challenge to urge manufacturers to design, produce, and deliver highly energy-efficient and competitively-priced rooftop air-conditioners and heat pumps. At the same time, DOE released a design specification of 10-ton capacity commercial air conditioners. The specification requires high-performance rooftop units (RTU) to reach an IEER of 18, and to be featured with direct digital controls and operational fault detection. Units built to this specification are expected to reduce energy use by as much as 50% compared to the ASHRAE 90.1 standard. DOE encouraged manufacturers to participate in this challenge and to have their innovative products tested against the specification.

Five of America's leading manufacturers, Daikin, Carrier, Lennox, 7AC Technologies, and Rheem, are participating in this challenge. In May 2012, DOE announced the Rebel unit by Daikin to be the first winner of the rooftop unit challenge. In May 2013, the Weather Expert unit by Carrier was determined to meet DOE's specification, rising as the second winner of the rooftop challenge.

We model this X-prize approach, combined with an array of policies aimed at tackling market failures and barriers so that deployment and market penetration can accelerate. As one example, following identification of the winners of DOE's High Performance Rooftop Unit Challenge, DOE will facilitate the demonstration of winning units in big-box retailer stores, thereby lowering adoption hurdles and spurring the market adoption of high efficient rooftop air-conditioners.

The following sections introduce the modeling of a three-part policy framework: R&D combined with an appliance standard and deployment policies to accelerate economies of scale and learning by doing.

4. Methodology

4.1 Research design

This study investigates the impact of a bundled policy approach that includes an appliance standard that requiring electric commercial space cooling rooftop equipment to meet a minimum efficiency standard of IEER of 13. Experience with previous appliance standards suggests that raising the efficiency bar for a selection of technologies would not only improve the average efficiency of the particular technology families, but would also transform the market for other technologies that serve the same end-use. In this particular case, it is expected that an appliance standard for commercial rooftop air-conditioning units would remove low-performing rooftop units from the market, increase the penetration of high-efficient rooftop units, and have an impact on consumers' decision on choosing space cooling technologies that are not rooftop units (Wang & Brown, 2014).

The flow diagram of our research design therefore has several stages (Figure 3). First we introduce two super-efficient AC technologies into the product mix. We next introduce an appliance standard of 13.0 IEER for rooftop AC units. Recognizing the possibility of increased innovation and technology learning prompted by regulation (the "Porter hypothesis" discussed earlier), and deployment policies, learning effects are introduced. Finally, we explore the impact of a stricter standard, requiring that new rooftop AC units meet or exceed an efficiency of 13.5 IEER. These scenarios are described in more detail below, after first describing the modeling tool that is used. Attention then turns to the cost-benefit methodology.

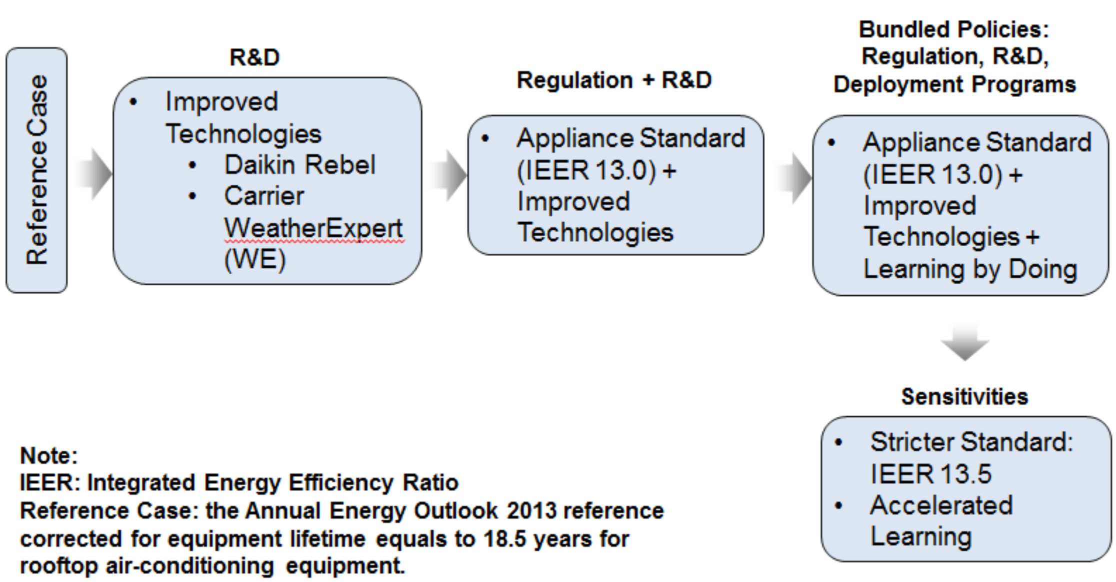


Figure 3. Flow diagram of our research design

4.2 National Energy Modeling System (NEMS)

NEMS "is arguably the most influential energy model in the United States" (Wilkerson, Cullenward, Davidian, & Weyant, 2013). Georgia Tech's version of the model (GT-NEMS) is the principal modeling tool used in this paper, supplemented by spreadsheet calculations. Specifically, we employ the version of NEMS that generated EIA's *Annual Energy Outlook (AEO) 2013,* which forecasts energy supply and demand for the nation out to 2040. NEMS models U.S. energy markets and is the modeling tool used by DOE and EIA to forecast future energy supply and demand, and to evaluate proposed energy policies.

In NEMS, twelve modules represent supply (oil and gas, coal, and renewable fuels), demand (residential, commercial, industrial, and transportation sectors), energy conversion (electricity and petroleum markets), and macroeconomic and international energy market factors. A thirteenth "integrating" optimization module ensures that a general market equilibrium is achieved among the other modules. Beginning with current resource supply and price data and making assumptions about future consumption patterns and technological development, the model carries through the market interactions represented by the thirteen modules and solves for the price and quantity of each energy type that balances supply and demand in each sector and region represented. Outputs are intended as projections of general trends rather than precise statements of what will happen in the future. As such, NEMS is well suited to evaluating how alternative assumptions about resource availability, consumer demand, and policy implementation may impact energy markets over time.

Among the thirteen modules, the Commercial Demand Module is closely examined in this study. In the module, NEMS employs a least-cost function within a set of rules governing the options from which consumers may choose technologies. 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). Among the six commercial sector sub-modules, the Forecast Commercial Floor Space Sub-module, the Service Demand Sub-module, and the Technology Choice Sub-module are particularly important.

- The **Forecast Commercial Floor Space Sub-module** provides forecasts of floor space by Census Division and building types based on population, economic effects, and historic growth patterns.

- The **Service Demand Sub-module** estimates service demand (SD) based on service demand intensity (SDI) and floor space projection for nine energy end-uses, eleven building types, and nine Census Divisions.

- The **Technology Choice Sub-module** determines the equipment chosen to meet service demand. Commercial consumers purchase equipment to meet three classes of demand: new, replacement, and retrofit. The choice of a technology in NEMS is partially determined by the discount rates employed by consumers. Then the sub-module divides service demand using three behavior rules reflecting costs, fuel choice, and equipment type. In combination, the demand class, discount rate, and behavior rule determine the technology selected to meet a given service demand.

By characterizing nearly 350 distinct commercial building technologies in nine end-uses and eleven types of commercial buildings, the model offers the potential for a rich examination of policy impacts and an assessment of technology choice, energy consumption, prices and expenditures, carbon abatement, and pollution prevention over time and across U.S. regions. The options of space cooling and heating technologies in the NEMS commercial module are numerous while also being incomplete. In the Reference scenario, twelve technology families that include 83 different technology vintages are available to be selected to meet energy demand in the space cooling end-use. Among these options, two technology families (13 vintages) are the subject of the rooftop standard studied in this paper: rooftop air source heat pump (ASHP, 6 vintages) and rooftop air conditioner (AC, 7 vintages). Together, they accounted for 44.7% of the total space cooling service demand in 2010, with rooftop AC being the most commonly used technology.

Besides space cooling, heap pump technologies like rooftop ASHPs and commercial ground source heat pumps (GSHPs) can serve both space cooling and heating energy demand. As a result, when an efficiency standard is placed on the cooling function of rooftop ASHP, it will inevitably change the technology choice for the space heating end-use, too. Therefore, the scope of this study also includes the energy use and technology choice for space heating. Table 2 presents the space heating technologies in the NEMS commercial module.

For commercial buildings, NEMS characterizes 11 technology classes for space cooling (see the stacked bar in Figure 1). In the reference case, the NEMS profile for packaged terminal air-conditioning units includes 7 vintages of rooftop ACs and 8 vintages of rooftop ASHPs (Table 2). NEMS parameters for the 15 rooftop technology vintages characterize their efficiency performance, capital cost, available years, market penetration and other market performances. Table 2 lists the main NEMS parameters for the 15 rooftop technologies from the Reference Case, and the improved technologies, Rebel and WE, from the policy scenarios. The omission of the Rebel and WE units from the NEMS technology suite illustrates one of the weaknesses of such models. As discussed by Wilkerson, et al. (2013), NEMS is not always linked to regularly updated data. Many parameters are tied to results of national energy surveys that are conducted only every four years (and sometimes longer). The hurdle rates used in NEMS, for instance, are not grounded in recent empirical literature, and the technology profiles are the result of periodic industry surveys. Our analysis fixes this latter problem with respect to HVAC equipment in the commercial sector by adding and updating several technology profiles, and by evaluating alternative technology cost and performance trajectories.

Table 2. Characteristics of Rooftop Space Cooling Technologies [a]

Technology Vintage	Capital Cost ($/kBtu/hr)	COP (Btu-out /Btu-in)	Available Years	Scenarios: Reference Case	Scenarios: Improved Technology	Scenarios: Bundled Policies	Scenarios: Stricter Standard
Rooftop AC							
2003 installed base	62.22	2.70	2003-03	√	√		
2007 installed base	70.56	2.96	2003-09	√	√		
2010 typical	88.89	3.28	2003-52	√	√		
2010 mid-range	105.56	3.52	2003-52	√	√	√	
2010 high	255.56	4.07	2010-52	√	√	√	√
2020 typical	88.89	3.37	2020-52	√	√		
2020 high	242.22	4.07	2020-52	√	√	√	√
Rooftop Air-source Heat Pump							
2003 installed base	63.89	2.73	2003-03	√	√		
2007 installed base	72.78	2.87	2007-09	√	√		
2010 typical	76.67	3.22	2003-52	√	√		
2010 high	96.67	3.52	2003-52	√	√	√	
Rebel 2014	365.75	5.89	2014-52		√	√	√
WE 2014	95.10	6.10	2014-52		√	√	√
2020 typical	76.67	3.22	2020-52	√	√		
2020 high	93.33	3.81	2020-52		√	√	√
Rebel 2020	256.03	5.89	2020-52			√	√
WE 2020	66.6	6.10	2020-52			√	√
2030 high	103.33	4.40	2025-52		√	√	√
2035 high	102.22	4.40	2030-52		√	√	√
Rebel 2035	204.82	5.89	2035-52			√	√
WE 2035	53.3	6.10	2035-52			√	√

[a] Rooftop ASHP 2030 and 2035 high will become available 5 years earlier than their names indicate under the Rooftop Standard+ scenario.

4.3 The Reference case and policy scenarios

The following four policy scenarios are designed to model the impact of the Bundled Policies compared with a "Reference case" forecast. The Reference case uses the same computer code as the published Reference case in EIA *2013 Annual Energy Outlook*. It assumes a business-as-usual world where no major technological breakthroughs and future policy interventions are assumed. The only difference between the Reference scenario and EIA's reference case is that the former assumes the average lifetime of rooftop AC and ASHP to be 18.5 years, compared to 15 years in the latter case[2].

- *Improved Technology*

  This scenario introduces two recent innovations into the NEMS technology menu: the Daikin Rebel and the Carrier Corporation's Weather Expert. Both of these technologies were winners of DOE's Rooftop Unit Challenge. The 7.5-ton Rebel was the first to win the rooftop challenge. With a variable speed heat pump and other improvements, it achieves an IEER of 20.6 and a COP of 5.89. The ASHP serves space cooling and heating, as well as water heating demands. Based on a survey of installers, the cost of a 7.5-ton Rebel is approximately $24,000 (including $10,000 for installation).

  The 8.5-ton version of Carrier Corporation's Weather Expert gas/electric unit is another winner of the DOE Rooftop Unit Challenge Award. It has an IEER = 20.8 and a COP of 6.10. Communication with the retailer indicates that Weather Expert (48LC09) costs $9,700, including installation cost, which is significantly lower than the cost of the Daikin Rebel.

  Two adjustments were made to the NEMS ventilation technology profile to reflect the improved ventilation systems that accompany these two super-efficient heat pumps.. We reduced the capital cost of variable air volume systems by 5% to reflect the cheaper cost of these integrated systems. In addition, we reduced the hurdle rate used in the Commercial Demand Module to amortize these capital costs. This was done by applying the distribution of slightly lower hurdle rates used for AC systems to ventilation systems.

- *Appliance Standard (IEER=13.0)*

  This scenario first updates the rooftop unit technology menu, and then imposes an efficiency standard of IEER=13 to the two rooftop space cooling technology families.

  In addition to the reference case, EIA also offers an alternative technology side case, the "High Technology" (High Tech) scenario, which, among many other improvements, assumes lower costs, higher efficiency, earlier market entrance, and more vintages for a number of commercial space cooling technologies. The Rooftop Standard scenario adopts this optimistic technology outlook by adding two high-efficient rooftop ASHP vintages from EIA's High Tech side cases, as shown in Table 2, increasing the efficiency of one Reference case rooftop ASHP vintage, and lowering the cost of two Reference scenario AC vintages and one ASHP vintage.

  On top of the updated technology menu, this scenario applies the efficiency floor of IEER=13, or COP=3.52 to the targeted rooftop technologies, starting from 2019. As a result, four rooftop AC and four rooftop ASHP technologies fall below the standard and will be removed from commercial consumers' choice set from 2019 onward. Table 2 presents the selection of technologies under this scenario.

- *Bundled Policies (IEER=13) (with Technology Learning)*

  Following the logic of the two-step technology learning model, we examine two types of technology learning in this paper. First, we assume that the Daikin Rebel and Carrier Weather Expert are nascent technologies that will benefit from economies of scale. In

[2] The lifetime adjustment was made based on technical advice received from DOE's Appliance and Equipment Standards Program.

particular, we introduce an exogenous learning effect that is consistent with Weiss (2010), which found a 18% learning rate for high-efficiency and Desroches (2013), which found a 30% learning rate for HVAC equipment. Specifically, we implement a step-wise cost decline combined with a cost trend function of 30% for the first doubling of service demand and 20% for the second doubling. We further assume that the Daikin Rebel and Carrier Weather Expert are subject to continuous cost reduction, so that between the periods when service demand is doubled, costs fall each year, eventually converging on the cost reductions with each doubling.

Second, we assume that rooftop AC technologies that compete with the Daikin Rebel and Carrier Weather Expert accelerate their R&D programs and introduce cost reductions more rapidly than current market forces. In NEMS, this means that the high efficiency AC units introduced in 2030 and 2035 are introduced five years earlier. In a sensitivity analysis, we advance these two technologies by an additional five years.

- *Stricter Standard (IEER=13.5) and Accelerated Learning Sensitivities*
  The introduction of the efficiency requirement of IEER equals to 13 removes the rooftop ACs and ASHPs with the lowest efficiencies from the market. However, two products with efficiencies near the cutoff line remain in the market in the Bundled Policies scenario. A stricter standard with slightly higher efficiency requirements will remove these border technologies. A scenario was developed to test the impact of a stricter standard with efficiency requirement of IEER equals to 13.5.

  In the Stricter Standard scenario, all rooftop ACs and ASHPs with IEER lower than 13.5 are removed from the market, including two previously border-line technologies with COPs of 3.52. Assumptions about the learning effect remain the same as in the Bundled Policies case. That is, Rebel and WeatherExpert experience 30% cost reductions after their first doubling of service demand followed by a 20% cost reduction initiated with the second doubling. As the Bundled Policies case, this Stricter Standard scenario also assumes that the high efficiency rooftop ASHP units (i.e., the 2030 high and 2035 high vintages) are available five years earlier than in the Reference Case.

  Another sensitivity explores the effect of an accelerated learning rate. This sensitivity examines the impact of faster learning on the cost-effectiveness of the standard. The high learning scenario is built based on the Bundled Policies scenario, assuming Rebel and Weather Expert have a 40% cost reduction for the first doubling of service demand, and a 30% cost reduction for the second doubling. In addition, the accelerated learning sensitivity assumes that the high efficiency rooftop ASHP units, the 2030 high and 2035 high vintages, are available 10 years earlier than in the Reference case. Other assumptions are the same as in the Bundled Policies scenario.

4.4 Cost-benefit analysis

The policy scenarios are evaluated from both a private and social perspective. For the private perspective, we evaluate the equipment investment costs of the improved air-conditioning equipment relative to the stream of energy-expenditure reductions to evaluate the overall cash-flow attractiveness to commercial building owners. Two metrics are emphasized: net private benefits and private benefit-cost ratio. On the benefits side of the metrics we include monetized energy savings; on the costs side, we include the equipment costs.

The cost-benefit analysis is conducted at three scales of coverage: the end-use perspective which focuses on space heating and cooling in commercial buildings, the commercial buildings sector as a whole, and the entire U.S. economy, which provides a national perspective.

The calculation of equipment investment costs is done with an Excel spreadsheet calculator that uses NEMS outputs, including estimates of service demand (SD) in each year.

- For new purchase:

$$\text{Investment Cost} = \text{SD}_{\text{new}} \times (\text{Cost}/8,760)/\text{CF}$$

where CF is the equipment-specific capacity factor

- For replacement:

$$\text{Investment Cost} = \text{SD}_{\text{replacement}} \times (\text{Cost}/8,760)/\text{CF}$$

- For retrofitting:

$$\text{Investment Cost} = \text{SD}_{\text{surviving}} \times (\text{Cost}/8,760)/\text{CF} \times 0.022/\left(\text{SD}_{\text{surviving}}/\text{SD}_{\text{total}}\right)$$

where $\text{SD}_{\text{total}} = \text{SD}_{\text{new}} + \text{SD}_{\text{replacement}} + \text{SD}_{\text{surviving}}$

Present-value calculations for the private-sector assessment were conducted using a 7% discount rate to be consistent with Office of Management and Budget guidelines (Office of Management and Budget (OMB), 2002, 2009), which recommend the use of 3% and 7% discount rates when evaluating regulatory proposals. Our use of a 7% discount rate for evaluating the private manufacturer's perspective is less than the 10% value used in some other studies such as McKinsey and Company's analysis (Granade et al., 2009).

The policies are also evaluated in terms of their net societal benefits and their social benefit-cost ratios. On the benefits side of the metrics we include monetized energy savings, CO_2 mitigation, and reductions of criteria air pollutants; on the costs side, we include both the private investments required as well as the administrative costs. In this paper, as in most detailed cost-benefit policy analysis, different benefit-cost ratios use different combinations of benefits and costs, depending on the purpose of the analysis. Present value calculations for the societal benefit-cost analysis were conducted using a 3% discount rate for valuing CO_2 emission reductions, and a 7% rate for all other costs and benefits. We estimate the financial value of reduced CO_2 emissions in a particular year by multiplying the decrement in emissions by the "social cost of carbon" (SCC) for that year. The SCC is defined as an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. The SCC used in this analysis is based on the central value estimates of the U.S. Government Interagency Working Group on the Social Cost of Carbon (U.S. Environmental Protection Agency (EPA), 2010). In this report, the central value SCC estimates rose from \$23/metric ton of CO_2 in 2011 to \$34/metric ton and \$47/metric ton in 2030 and 2050, respectively (in \$2009).

We also evaluate the avoided criteria pollutant emissions from the energy end-use and power generation sectors. The National Research Council (NRC) in its 2009 report o the *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (NRC, 2009) specified the motorized marginal damage value of pollutant emissions associated with the consumption of a variety of forms of energy in all sectors in the U.S. economy. For the commercial building sector in particular, the unit marginal damage values were estimated for SO_2, NO_x, $PM_{2.5}$, and PM_{10} emissions related to electricity generation and onsite natural gas consumption. The unit marginal damage values were then multiplied by the total amount of natural gas and electricity consumption in commercial buildings under the Reference Case and the Optimized Scenario, respectively, to calculate the total damage associated with criteria pollutant emissions. The difference between the two scenarios represents the value of avoided criteria pollutant emissions as a result of the policy.

When the cost-benefit analysis was expanded from the commercial sector to the national economy as a whole, we further included the criteria pollutants emitted in the process of industrial and residential energy consumption, in the forms of on-site natural gas, coal, and petroleum use, and electricity consumption; as well as the emissions from light vehicles and trucks. Similarly to the analysis for the commercial sector, corresponding marginal damage values associated with each type of fuel consumption were also pulled from the same NRC report and multiplied by the total amount of energy consumed under the two scenarios. The value differential indicates the monetized benefits associated with less criteria pollutant emissions due to the policy.

Finally, our cost-benefit analysis does not include a range of difficult-to-quantify costs and benefits, such as mercury pollution reduction and increased productivity.

5. Results

This section presents our results, beginning with a description of the policy scenario impacts on energy consumption, examining in particular energy used for HVAC end-uses, for the commercial buildings sector and for the economy as a whole. We also discuss how the rooftop standard would affect electricity and natural gas prices and energy expenditures. We then turn to an analysis of policy impacts on the emissions of carbon dioxide and other pollutions. Next we examine how the policy scenarios impact equipment expenditures and present our overall cost-benefit calculations. This section ends with a discussion of regional differences.

5.1 Energy impacts

Compared with the Reference case, each of the policy scenarios reduces the total consumption of electricity for space cooling and ventilation (Figure 4). The magnitude of energy savings increases over time and with the stringency of the policy scenario. Relative to the Reference case, the total primary energy consumed for space cooling and ventilation with the Bundled Policies is expected to fall by about 140 Trillion Btu (TBtu) in 2030 and 180 TBtu in 2040. This is slightly more than with the "Improved Technology" scenario and nearly a third less than with the "Stricter Standard."

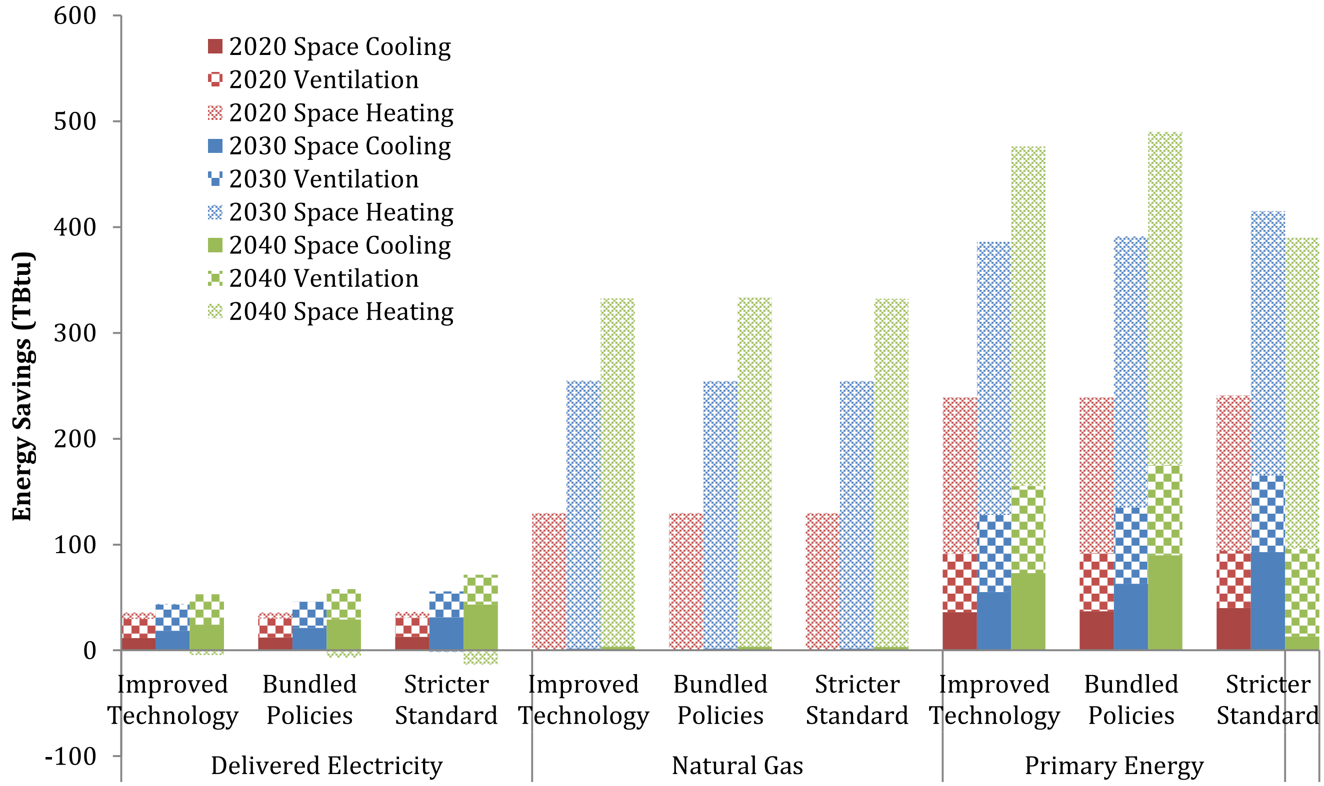


Figure 4. Energy Savings by End-Use and Fuel

(Note: Primary energy includes all fuels and electricity-related losses.)

Interestingly, the NEMS analysis suggests that the policy scenarios would have a significant fuel-switching effect on space heating. By the end of 2040, the amount of natural gas used for space heating would decrease by 23% while the electricity consumption in the same end-use would rise by 5%.

Today, approximately 80% of U.S. energy demand in space heating is met by natural gas and the rest is split between electricity and various liquid fuels. With super-efficient heat pumps and new standards with deployment policies, a large uptake in heat pump adoption would occur; more space heating demand would then also be met by electricity. The overall equipment efficiency for the space heating end-use would improve due to greater penetration of efficient heat pumps, but because the demand for electric space heating would also increase significantly, the overall electricity consumption would increase relative to the Reference case, as indicated by the "negative" delivered electricity savings for space heating shown in 2020, 2030 and 2040 in Figure 4. Nevertheless, the replaced natural gas consumption outweighs the increase in electricity consumption and as a result, the total space heating energy consumption would still decline every year from 2014 to 2040, reaching 1,635 Trillion Btu in 2040, which is a 16% reduction from the Reference case.

The impact of the high-performance ASHPs is pronounced in all three policy scenarios (Figure 5). The Improved Technology scenario increases the stock average efficiency of electric cooling (measure by COP or Btu Out/Btu In) in 2040 by 6%, compared to the Reference Case, which also sees improved COPs over time. In contrast, the Stricter Standard raises stock average COPs by 10% relative the Reference case in 2040, reaching an average stock COP of about 3.8 and an even higher average purchased efficiency.

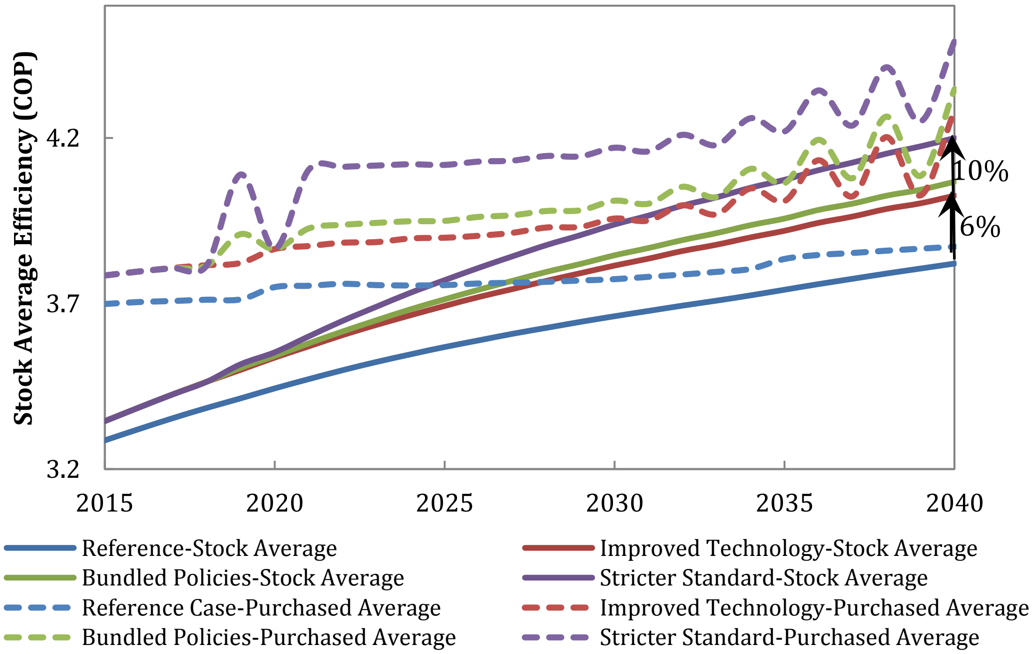


Figure 5. Improved Efficiency of Electric Cooling

There is no change in the stock average efficiency of gas-fired cooling equipment, but the heating sector experiences a significant spillover benefit in terms of improved electric-heating efficiency (Figure 6). The stock average COP for electric space heating increases by 160% from Reference case efficiencies ranging from about 1.5 in 2015 to 1.7 in 2040 to efficiencies in the policy cases ranging from 1.8 in 2015 to 4.3 in 2040. This 160% improvement in efficiency for electric space heating is similar for each of the three policy cases.

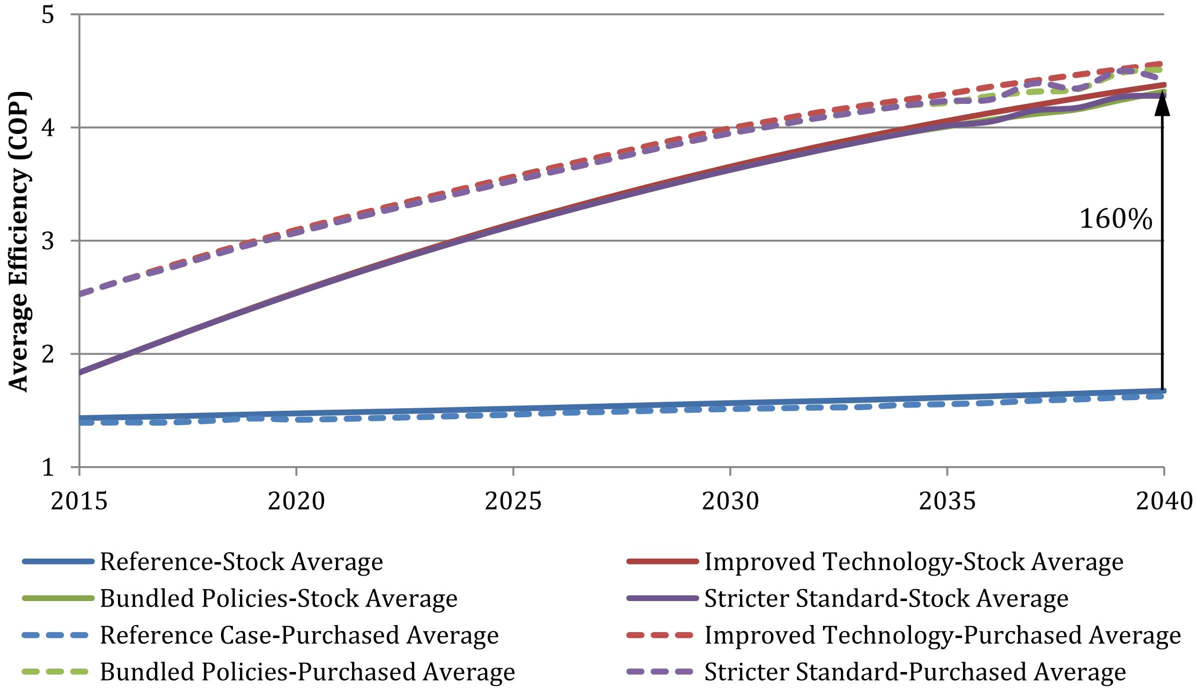


Figure 6. Improved Efficiency of Electric Space Heating

The impact of the standard and the introduction of super-efficient heat pumps do not only affect the space cooling end-use. The integrated system can provide space cooling, heating and ventilation services, which generate great energy savings for commercial buildings. The overall commercial sector energy intensity reduces steadily in the policy scenarios. For example, in 2020, the energy intensity (KBtu/ft^2) decline rate changes from 8.7% to 10% with the Bundled Policies (Figure 7). In 2040, as much as 470 Trillion Btu of energy consumption can be avoided with the implementation of the policy scenarios and the early introduction of highly efficient ASHPs. The energy intensity of other sectors of the national economy also improve in the Reference Case, but these rates are unaffected by the three policy cases.

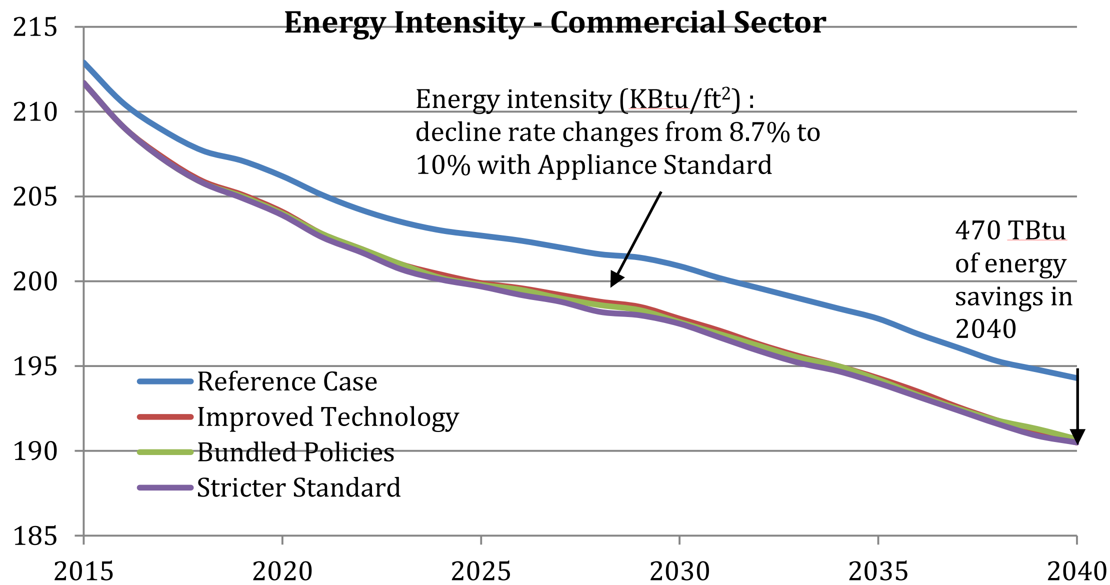


Figure 7. Energy Intensity of Commercial Buildings

Figure 8 presents the impact of the three policy scenarios on energy bills in 2020, 2030, and 2040. Billions of dollars could be saved in the energy bills of commercial building owners, growing from approximately $2.2 billion in 2020 in the Improved Technology scenario to about $7.5 billion in 2040 in the Stricter Standard scenario. These national savings are a function of changing equipment efficiencies, fuel switching, and energy prices. For the purpose of cost-benefit analysis, these annual energy bill savings need to be accumulated and extrapolated to include the savings that occur throughout the operating lifetimes of the improved equipment.

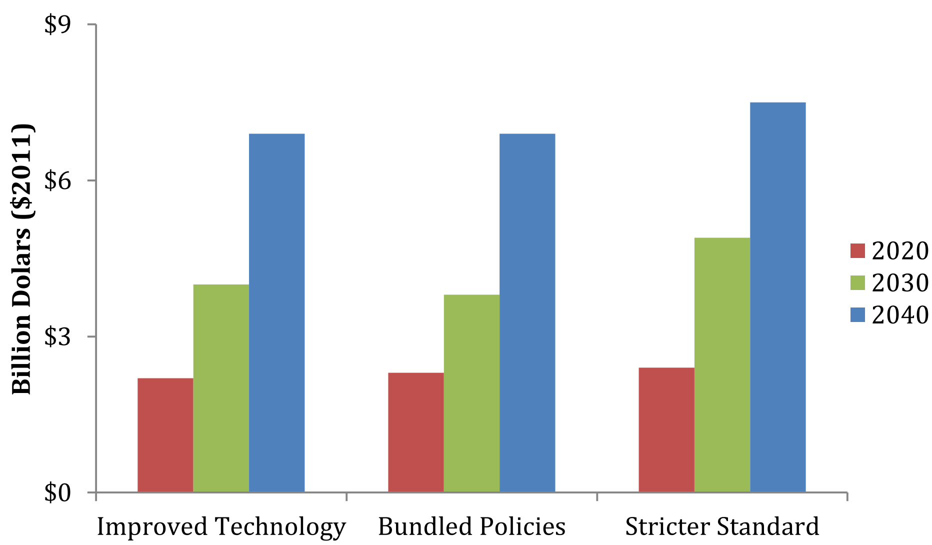


Figure 8. Estimated Energy Bills Savings from the Appliance Policy Scenarios

The accelerated energy efficiency achieved in the policy scenarios puts downward pressure on electricity rates (because less electricity is consumed) but increases natural gas prices (because more gas is consumed in the combination of space heating and electricity generation (Table 3). The statistical significance of these effects is tested using paired t-tests of the differences of the energy prices of the 22 regional entities developed by the North American Electric Reliability Corporation (NERC). The tests of differences were used to evaluate the 2020, 2030, and 2040 prices for the three policy scenarios. Four of the nine electricity price differentials and all nine natural gas price differentials are significantly different at a 0.1 level or higher, and they are uniformly lower for electricity or unchanged and they are higher for natural gas.

The literature is beginning to show that deep reductions in electricity use from energy efficiency improvement can reduce electricity prices economy-wide. With large-scale energy efficiency, competitive markets would see lower clearing prices for energy and price-regulated markets would experience lower marginal dispatch costs – in both cases, prices would benefit from decreasing reliance on the most expensive marginal generating equipment (Kim, Baer, and Brown, 2013; Kramer and Reed, 2012; Steinhurst and Sabodash, 2011). This "demand reduction induced price effect" (DRIPE) suggests that increased energy efficiency could reduce energy prices for all customer classes, generating benefits including jobs across the economy as the resulting savings are spent on goods and services that are more job-intensive than the capital-intensive industries associated with energy production.

As a result of the DRIPE effect (Table 3), energy bills in the policy scenarios would not only decline in the commercial sector, but would also drop for the residential and industrial sectors because of the significant reduction in electricity prices. This produces 470 TBtu of energy savings in 2040.

Table 3. Demand Reduction Induced Price Effect [a]

Year	Reference Rate	Change in Electricity Rate (2011 ¢/kWh)		
		Improved Technology	Bundled Policies	Stricter Standard
2020	**9.76**	**-0.01**	**-0.03**	**-0.03**
2030	**9.77**	**-0.03**	**-0.01**	**-0.07***
2040	**10.83**	**-0.08****	**-0.09****	**-0.10****

Year	Reference Price	Change in Natural Gas Price (2011 $/1000 cf)		
		Improved Technology	Bundled Policies	Stricter Standard
2020	**9.68**	**0.01****	**0.01****	**0.01****
2030	**10.95**	**0.04****	**0.05****	**0.04****
2040	**13.54**	**0.04****	**0.09****	**0.06****

[a] Paired t-tests were used to test the difference of mean energy prices between the Reference Case and each of the three policy cases, based on the 22 NERC regions.
*=Significant at the 0.1 level;
**= Significant at the 0.05 level.

The macro-economic (IHS Global Insights) model indicates that the appliance policies would have no discernable impact on gross domestic product, ranging from a reduction of $3-5 billion lower GDP per year across the 25 years of the scenario forecasts.

5.2 Carbon impacts

Strengthening the efficiency of air conditioning systems has many co-benefits, and reducing carbon dioxide emission is one of them. Changes in CO_2 emissions due to the space cooling and heating consumption of electricity and natural gas is similar to the energy consumption trend shown in Table 4. The total carbon emissions decline for both fuels in the Bundled Policies scenario. Electricity continues to be the largest source of CO_2 emissions, and these emissions would become even bigger in the Stricter Standard scenario due to the improved commercial HVAC efficiencies and greater fuel switching.

The carbon efficiency index tracks the relative carbon emission efficiency compared to the 2005 level. It projects a steady improvement in the carbon efficiency of commercial buildings relative to the base year 2005. The index characterizes the underpinning efficiency changes of carbon intensity by controlling for structural changes since 2005. Figure 9 suggests that, given no structural changes, carbon intensity in commercial buildings would decline by 13% from 2015-2040 in the Reference case. In contrast, the Improved Technology, Bundled Policies, and Stricter Standards would decrease carbon intensity by 14% over the same 25 years, reducing CO_2 emissions by 21-24 million metric tons (MMTs) in 2040.

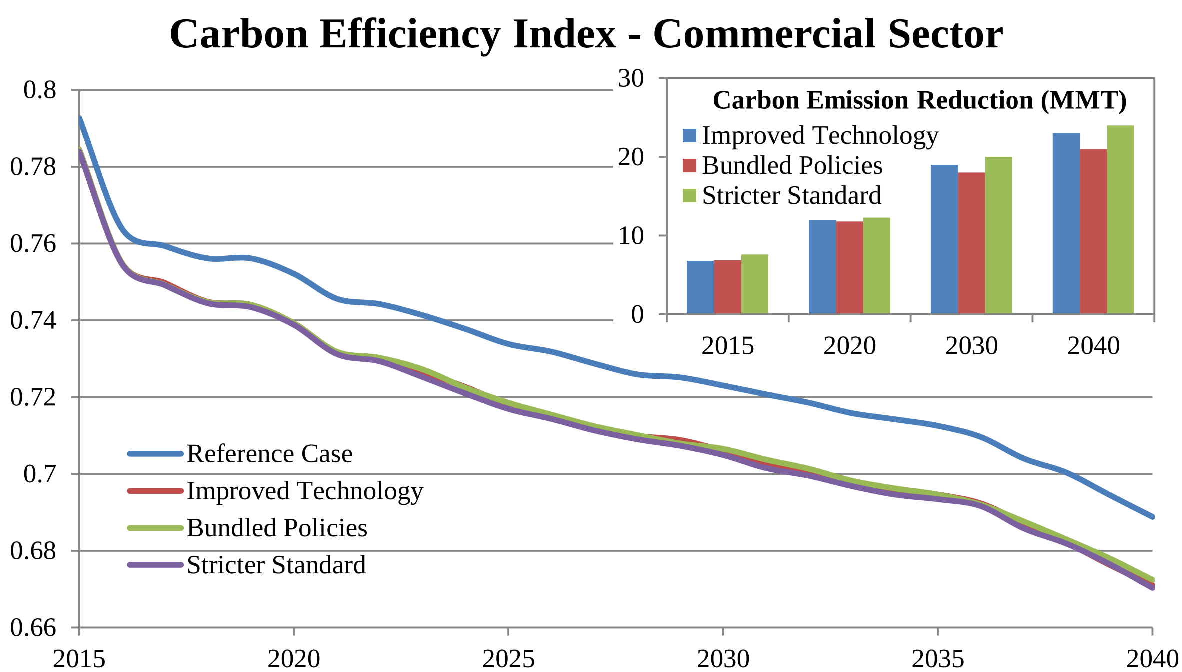


Figure 9. Carbon Efficiency Index for the Commercial Sector

5.3 Reduction of other pollutants

The values of avoided criteria pollutants SO_2, NO_x, $PM_{2.5}$, and PM_{10}, are summarized in Tables 4 and 5. The largest benefits come from the reduction of NO_x emissions (41% of the cumulative value through 2040), with $PM_{2.5}$ (at 30%) and SO_2 (at 29%). Altogether, their total impact is worth considerably less than the value of avoided CO_2.

5.4 Equipment and program administration costs

Since the capital expenditure on end-uses other than HVAC services are not meaningfully impacted by the three policy scenarios, our analysis of equipment costs focuses exclusively on HVAC equipment expenditures. By 2030, cumulative equipment expenditures with the Bundled Policies are $18.2 billion greater than in the Reference Case, and by 2040, the differential is $26.7 billion. The cumulative incremental investment costs are the same for both scales of analysis, that is, for the commercial building sector and the nationwide perspective.

The costs of administering these policies are significantly less than $1 billion in each of the policy scenarios.

5.5 Cost-benefit analysis

The cost-benefit analysis of the Bundled Policies is summarized in Table 4, both scales of coverage – the commercial buildings sector as a whole and the entire U.S. economy – and for 2030 and 2040.

In the Bundled Policies scenario, the commercial sector alone would save a cumulative $55.9 billion for investments made through 2040. The national total is slightly less because of the rebound effect. The decrease in energy consumption at the end-use level puts downward pressure on electricity prices. This, in turn, results in a rebound effect that is discernable by comparing the commercial sector and national results. There are no technology or policy initiatives modeled to offset the effect of lower bills in terms of increased energy services in homes and businesses. In estimating these energy bill savings, we assume that the savings from investments made in any given year decay 5% each year over the following 20 years of operation, which is the average lifetime of the appliances. Private savings, which result from lower energy bills account for more than two thirds of the savings. Another $19.1 billion of avoided CO_2 emissions, valued using the social cost of carbon, contribute further to the social benefits.

The higher investment costs required to purchase the high-efficient equipment in order to realize the savings are $18.2 billion cumulative through 2030 and $26.7 billion cumulative through 2040. Thus, from the private perspective using the commercial sector scale, the benefits outweigh the costs. After accounting for the social benefits from lower pollutant emissions, the Bundled Policy would result in cumulative net social benefits of more than $47.1 billion through 2040.

From the national perspective, the private energy bill savings are less than that of the commercial sector alone, because of the rebound effect in the residential and industrial sectors, resulting in slightly lower pollution reduction. The total private costs of the policy remain the same for the nation as it is for the commercial sector because only the commercial sector consumers bear the cost to upgrade their equipment stock. However, the lower private and social savings from sectors other than the commercial sector reduce the benefits by about a half billion through 2040, resulting in $46.6 billion of net social benefits through 2040.

From the private perspective, energy bill savings would exceed investment and policy administration costs by a ratio of slightly more than 2-to-1. This result holds true in 2030 and 2040, and it is true from both the commercial sector and national perspectives. By including the monetized benefits of CO_2 and criteria pollution reduction, the social benefit/cost ratios exceed 2.5 for both scales of analysis and for both time slices: 2030 and 2040.

The results of the accelerated learning sensitivity were not markedly different. Recall that this sensitivity assumes that the Rebel and Weather Expert units reduce their up-front costs by 40% with the first doubling of cumulative production, and by 30% with subsequent doublings. These higher learning rates produce only a negligible impact on energy savings in the NEMS analysis.

Table 4. Cost-benefit analysis of the Bundled Policies [a]

Commercial Buildings	Cumulative Benefits (Billions $2011)			Cumulative Costs (Billions $2011)	
	Energy Bill Savings (Private)	Value of Avoided CO_2 (Social)	Value of Avoided Criteria Pollutants (Social)	Higher Equipment Expenditures (Private)	Administration Cost (Social)
Commercial Sector					
2030 Total Impact*	36.6	12.2	1.3	18.2	0
2040 Total Impact	55.9	19.1	1.2	26.7	0
National Perspective					
2030 Total Impact*	38.9	12.8	0.9	18.2	0
2040 Total Impact	55.7	18.4	0.8	26.7	0

Commercial Buildings	Social B/C Analysis (Billions $2011)				Private B/C Analysis (Billions $2011)			
	Total Social Benefits	Total Social Costs	Social B/C Ratio	Net Societal Benefits [b]	Total Private Benefits	Total Private Cost	Private B/C Ratio	Net Private Benefit
Commercial Sector								
2030 Total Impact	48.8	19.4	2.51	29.3	36.6	18.2	2.02	18.4
2040 Total Impact	75.0	27.9	2.69	47.1	55.9	26.7	2.09	29.2
National Perspective								

2030 Total Impact	51.7	19.1	2.71	32.6	38.9	18.2	2.14	20.8
2040 Total Impact	74.1	27.6	2.69	46.6	55.7	26.7	2.09	29.0

[a] Total Impact includes the cost and savings that last until the end of the commercial HVAC equipment's lifetime. A 3% discount rate is used to calculate the net present value (NPV) of carbon emission reductions. A 7% discount rate is used for other benefits.
[b] Criteria pollutants include: NOx, SO_2, $PM_{2,5}$, and PM_{10}

5.6 Regional difference

Evidence to date suggests that climate change and mitigation strategies will have variable geographic impacts on the demand for energy in commercial buildings (Sailor, 2001; Scott, Wrench, and Hadley, 1994). This is confirmed by our modeling. The market adoption of improved rooftop air-conditioning technologies (the Rebel and Weather Expert technologies), is highly variable across regions.. Specifically, the South Atlantic division is the biggest market for super-efficient heat pumps, followed by the West South Central, and Pacific divisions. As a result, the South Atlantic (SA) division, has the most significant electricity savings (Figure 9). The electricity savings comes from efficiency improvement in space cooling due to the new air-conditioning technologies

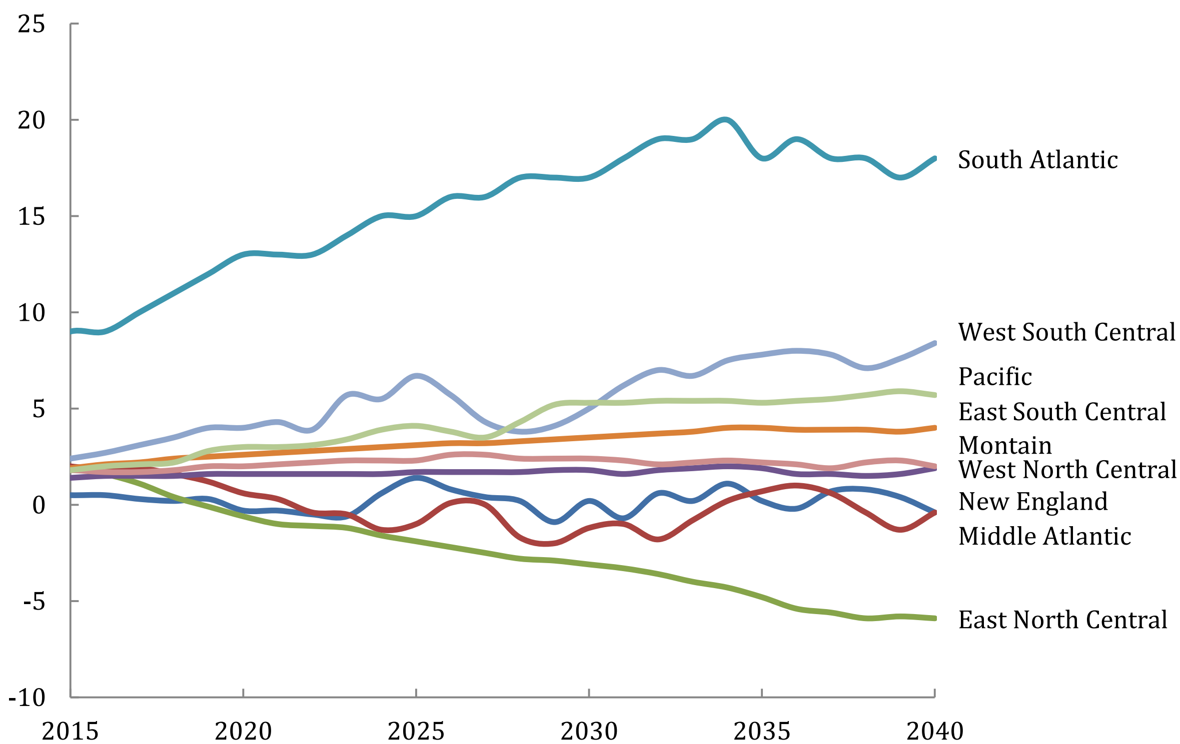


Figure 9. Electricity Savings in the Commercial Sector (TBtu)

The East North Central (ENC) division, in contrast, experiences significant increase in electricity consumption in the policy scenario. The growth in electricity demand is due to fuel switching from conventional gas heating to electric heating. Fuel switching also occurs in the Middle Atlantic (MA) and New England (NE) divisions. In these Census divisions, the electricity savings in space cooling cannot offset the increases in electricity consumption in space heating.

Figure 10 illustrates the natural gas savings in commercial buildings with the Bundled Policies. All census divisions have some amount of savings in natural gas. The significant natural gas savings in the East North Central and Middle Atlantic divisions confirms the fuel switch story described above. In addition, the South Atlanta (SA), Mountain (MTN) divisions and other Census divisions also would experience some switch from gas furnaces and boilers to the new super-efficient heat pumps.

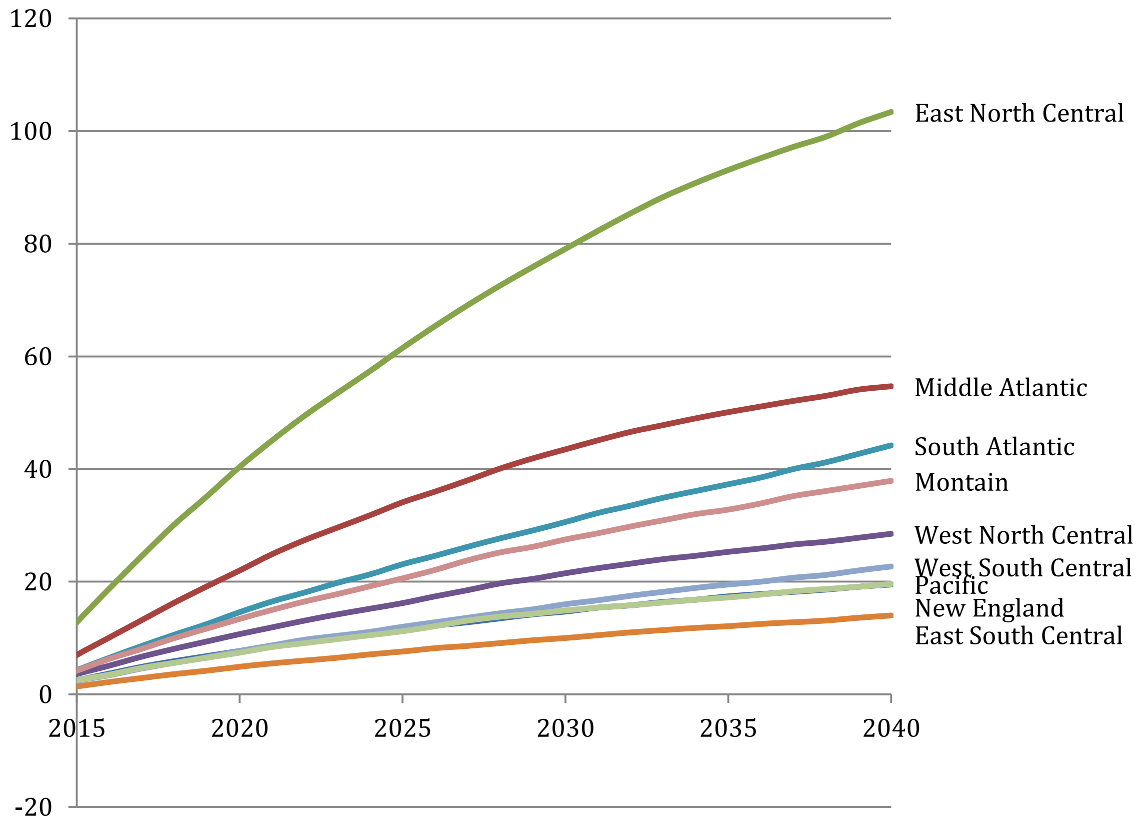


Figure 10. Natural Gas Savings in the Commercial Sector (TBtu)

6. Discussions and conclusions

The global demand for air conditioning is growing rapidly with rising standards of living and global warming. This paper describes a promising climate adaptation/carbon mitigation strategy for addressing this growing demand, capitalizing on super-efficient heat pump technologies within the context of a decarbonizing electric grid. The modeling of this strategy leads to several conclusions, which are discussed below.

The policy bundle (appliance standards, research and development, and deployment programs) has the potential to significantly improve the efficiency of both space cooling and space heating systems; the improvements in space heating are the result of fuel switching from natural gas to electric heating, due to the uptake of super-efficient heat pumps. Even with the switch to more electric space heating, there would still be sizeable electricity savings because of the more efficient heat pumping technologies. This significant electricity savings would in turn induce a drop in electric prices, thereby extending the strategy's benefits from the commercial buildings sector to electricity consumers across the economy, including households and industry.

Both the private sector and society are expected to benefit from this policy scenario. Benefits exceed costs for the commercial sector and for the nation as a whole, using both the public and private perspective. From the private perspective, energy bill savings exceed investment and policy administration costs by a ratio of slightly more than 2.0. By including the monetized benefits of CO_2 and criteria pollution reduction, social benefits exceed costs by a ratio of more than 2.5.

Finally, previous research suggests substantial regional variability in the effects of climate adaptation and carbon mitigation strategies, and this is reaffirmed here. While most regions of the U.S. would experience significant electricity savings, some regions – especially those in the northern half of the U.S. – could experience significant increases in electricity consumption as a result of the Bundled Policies. Such findings underscore the need to tailor climate adaptation and carbon mitigation strategies to the particularities of different regions.

Reference

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