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Reducing U.S. Residential Energy Use and CO_2 Emissions: How Much, How Soon, and at What Cost?

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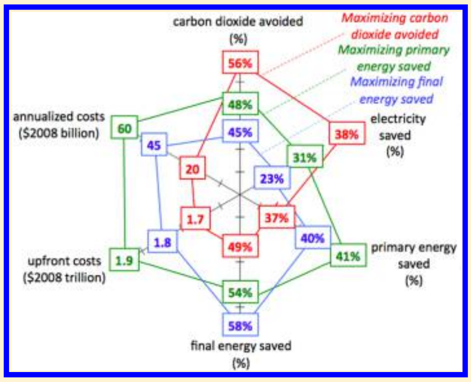
S Supporting Information

ABSTRACT: There is growing interest in reducing energy use and emissions of carbon dioxide from the residential sector by deploying cost-effectiveness energy efficiency measures. However, there is still large uncertainty about the magnitude of the reductions that could be achieved by pursuing different energy efficiency measures across the nation. Using detailed estimates of the current inventory and performance of major appliances in U.S. homes, we model the cost, energy, and CO_2 emissions reduction if they were replaced with alternatives that consume less energy or emit less CO_2. We explore trade-offs between reducing CO_2, reducing primary or final energy, or electricity consumption. We explore switching between electricity and direct fuel use, and among fuels. The trade-offs between different energy efficiency policy goals, as well as the environmental metrics used, are important but have been largely unexplored by previous energy modelers and policy-makers. We find that overnight replacement of the full stock of major residential appliances sets an upper bound of just over 710 × 10^6 tonnes/year of CO_2 or a 56% reduction from baseline residential emissions. However, a policy designed instead to minimize primary energy consumption instead of CO_2 emissions will achieve a 48% reduction in annual carbon dioxide emissions from the nine largest energy consuming residential end-uses. Thus, we explore the uncertainty regarding the main assumptions and different policy goals in a detailed sensitivity analysis.



1. INTRODUCTION

Energy efficiency must be an important part of any cost-effective strategy to curb energy consumption and achieve a large reduction in the emission of greenhouse gases in the United States.[1−10] In the United States, the residential sector accounts for 37% of national electricity consumption, 17% of greenhouse gas emissions, and 22% of primary energy consumption.[11,12] As shown in Figure S0.1 in the Supporting Information (SI), the largest contributors to carbon dioxide emissions in the residential sector are heating (~360 Mt in 2009), hot water (~140 Mt), lighting (~140 Mt), and cooling (~135 Mt).[11,12]

Energy and carbon dioxide emissions savings achieved through refrigerator and other appliance efficiency standards suggest that large future savings should be possible.[1,13] While there is no U.S. federal climate policy, federal energy legislation has pursued efficiency goals. For example, the Energy Policy Act of 2005[14] and the Energy Independence and Security Act of 2007[15] both tightened a number of energy efficiency standards, and $11 billion of the American Recovery and Reinvestment Act were directed to projects designed to improve energy efficiency. Yet, despite these and other developments, the Energy Information Agency (EIA) *Annual Energy Outlook of 2011* reference case scenario, estimates that total energy consumption in the residential sector will increase from ~22 × 10^{18} Joules (21 quads) in 2008 to ~24 x10^{18} Joules (23 quads) in 2035.[11] There is wide acknowledgment that the residential sector provides an opportunity for large energy and greenhouse gas savings. However, realizing this potential continues to pose a major challenge, and the following questions have not yet been definitively answered:

1. What is the technically feasible potential for primary and final energy reductions, carbon dioxide emissions avoided and electricity consumption reductions that can be derived from energy efficiency investments?
2. What percentage of this technical potential is cost-effective?
3. Households, utilities, and governments have a diverse set of efficiency technologies to choose from. Given that, what potential trade-offs exist across differing policy objectives that have the following goals: primary energy savings, delivered energy savings, CO_2 emissions avoided, and minimizing costs?

Clearly, any progress in reducing residential energy demand will result in a variety of environmental consequences beyond changes in the emissions of carbon dioxide. Depending on the

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local generation mix, such reductions may result in significant changes in the emissions of criteria air pollutants.[16] At a global scale, they will also have a variety of impacts on net radiative forcing.[16−19] However, because the focus of most of the literature on energy efficiency has been on carbon dioxide emissions[1,6,16] and because assessing the wider range of other local and global impacts would entail a very different set of analysis and analytical methods, here we have retained the narrower focus.

This paper addresses these questions for the U.S. residential sector. We start by describing methodological considerations in Section 2, and in Section 3, we describe the data and methods used in this work. In Section 4, we present results and analysis and in Section 5, we discuss policy implications.

2. METHODOLOGICAL CONSIDERATIONS

We use a *bottom-up* or engineering-economic model described below. Bottom-up models use data on technological costs to construct economic estimates on a technology-by-technology basis,[9] for which the results are generally presented in terms of the incremental costs of specific measures or interventions.

A standard method for reporting estimates of the potential to achieve energy efficiency is in terms of energy efficiency supply curves. Such curves were first introduced by Rosenfeld and Meier.[15−23] According to Rosenfeld, before the acceptance of the representation of energy efficiency as depicted in supply curves, "one of the drawbacks of seeing energy efficiency as an alternative to additional electricity generation was [and is] the inability of easily comparing both the economics and the scale of conservation with the new energy supplies."[23] The solution he and his colleagues provided was a new investment metric, the *cost of conserved energy*, and a graphical display of the potential energy savings as a conservation supply curve. Rosenfeld et al.[22] estimate the cost of conserved energy as the annualized payment divided by the annual energy savings. In this approach, the cost of conserved energy (CCE) is computed as follows:

$$\mathrm{CCE} = [\text{annualized investmentcos } t] / [\text{annual energy savings}]$$

The annualized investment cost is given by the initial investment multiplied by the capital recovery rate (CCR), with CCR = $d/(1 - (1 + d)^{-n})$, where d is the discount rate and n the number of years over which the investment is amortized. As Meier[15] explains:

> *"[A conservation supply curve] consists of a series of steps, each of which represents a conservation measure. The width of each step is the annual energy that could be saved...by the implementation of the measure within the time horizon specified... To decide which conservation measures are economic, one must compare their CCE to the price of new energy supplies during the time horizon."*

We considered using other decision-making metrics, such as NPVs, IRR, or payback periods, instead of using levelized annual cost (LAC). However, LAC was chosen because it accounts for differences in useful lifetimes across energy efficiency strategies, it can be used to evaluate mutually exclusive projects, and it takes into account time value of money.

Energy efficiency supply curves (or carbon marginal abatement cost curves) provide the path for potential energy efficiency (or carbon mitigation) investments, under particular sets of assumptions. Since Rosenfeld and Meier first developed the approach, several studies have assessed potential energy efficiency savings and related costs using bottom-up analysis.[1,3−5,15−35] Detailed overviews of the findings of these previous studies can be found in Urge-Vorsarz[36] and Brown.[29]

Energy efficiency or carbon mitigation supply curves can be used to prioritize measures and guide policy recommendations. Supply curves generally characterize only one dimension of efficient technology: net annualized cost (or benefit). Such curves do not necessarily provide the lowest cost options. That depends on the quality of the technology characterization used in the models, the types of fuels considered, the sectors being included, and the choice of measures considered. Nor are such supply curves intended to provide a tool that forecasts how much energy savings *will* be achieved. Instead, they indicate how much *could* be saved if the least costly path shown in the curve is undertaken in order to achieve a particular level of energy savings or greenhouse gases (GHG) mitigation.

Researchers in economics, in psychology, and in other fields have tried to understand the reasons why the optimal level of energy efficiency is not achieved, that is, why the actual technology choices made by consumers differ from the choices one would expect when using engineering-economic models such as the ones that result in energy efficiency supply curves. One reason is that energy prices to not reflect the environmental and health costs associated with externalities from energy.[37] Also, consumers may not have access to financing mechanisms that allow them to pursue energy efficiency strategies. Brown argues that uncertainty in the future price of electricity or other fuels also plays a role[38] and Anderson and Claxton[39] mention that energy related decisions are not as important as other decisions to consumers. Finally, Golove and Eto[40] note that improved energy efficiency often is inseparable from other unwanted features in products.

The potential for energy/carbon efficiency and respective cost per unit of energy saved, or unit of CO_2 or pollutant avoided, almost always depends on the period of analysis, region, the economic agent being considered, and the assumptions made about technology replacement and market turnover. The shape of the efficiency supply curve also depends on the discount rate that is assumed and on whether the energy fuel costs to run the technologies are incorporated in the estimate of the costs per unit saved.

Efficiency supply curves are by definition static representations and typically do not capture technical evolution, rebound effects, abrupt changes in fuel prices, or similar factors. The annualized cost of energy efficiency investments is generally compared to an average fuel price over the lifetime of the efficiency measure. Alternatively, the economic potential is defined as the energy or emissions savings that can be achieved at a cost lower than retail energy or electricity prices. To the extent that the evolution of technology is considered, it is embedded in the baseline assumptions of capital turnover.

There are several other limitations to consider when using the supply curves approach. For example, Stoft,[41] details the conceptual challenges of assessing the cost of conserved energy as follows:

The crucial step in the construction [of a conservation supply curve] is the calculation of the marginal cost of conserved energy (CCE), which is computed by dividing the total cost of conservation (TCC) by the total energy savings (E). The difficulty with the concept of the cost of conserved energy is in knowing to what it applies. Clearly, to compute E, we must consider two production technologies, one before and one after the conservation measure. But, conservation measures are usually defined in such a way that one does not know either the starting or ending technology, but only the change in technology. For example, a measure might specify an increase in ceiling insulation from four inches to eight inches, without specifying the efficiency of the building's furnace.

In our work, we have overcome these issues by using a detailed technology characterization and the efficiency improvements estimates from the Energy Information Administration Annual Energy Outlook 2008 (EIA-AEO) reference case. The speed with which the U.S. energy system is changing and decarbonizing is slow and uncertain. Thus, we restricted our focus to assessing the potential that was available under 2009 conditions. However, in the sensitivity analysis section, we provide how sensitive our results are to the carbon intensity of the U.S. electric grid.

We estimate how much energy and emissions of carbon dioxide could be reduced, if we replaced current appliances and end-use devices with the most energy efficient model—thus providing an upper bound technological potential. We then estimate the subset of energy efficiency measures that would save consumers money, while maximizing energy or carbon dioxide reductions. Finally, we discuss what the feasible reductions would have been when accounting for the natural rate of turnover of the capital stock.

3. DATA AND METHODS

The results we report here were generated using the Regional Residential Energy Efficiency Model (RREEM), a model developed at Carnegie Mellon University, in collaboration with Resources for the Future. This model estimates energy efficiency and greenhouse gas emissions reductions as a function of varying policy goals and displays the results as energy and carbon dioxide mitigation supply curves. For a reference year of analysis, these curves report the cost-effectiveness of energy efficiency investments as a function of the energy saved or greenhouse gases emissions avoided. RREEM uses a bottom-up approach, providing energy and carbon dioxide supply curves that are based on engineering-cost estimates of specific end-use equipment.

Joint work between Carnegie Mellon University and Resources for the Future led to an inferred set of annual estimates and projections for unit energy consumption, stock, capital costs, new purchases and replacements, by end-use, region, technology type, and technology class based on tables provided by the EIA-AEO.[12] A list of technologies and a summary of the stock, capital costs and site energy consumption are provided in SI, S1.

In this work, all the analysis and results reported refer to year 2009 and are for the residential sector and all costs are in 2008 dollars. The residential end-uses included in the efficiency supply curves are heating and cooling systems, clothes washers and dryers, dishwashers, hot water heaters, stoves and ovens, refrigerators, freezers, and lighting. For clothes washers and dishwashers we do not include the water-heating portion of the load. We limit our analysis to end-use appliances and devices, and do not include adding or enhancing building insulation. The fuel types that can power this end-use equipment include direct use of natural gas, kerosene, wood, geothermal, coal, solar, distillate, and LPG. Electricity is generated with the region-specific mixes of natural gas, steam coal, nuclear power, renewable energy, distillate fuel oil, and residual fuel oil, as projected by AEO 2008 reference case scenario, in the nine census division level regions (Pacific, West South Center, East South Central, South Atlantic, Middle Atlantic, New England, East North Central, West North Central, and Mountain). Electricity imports or exports between census division regions are assumed to have average 2008 national carbon intensity (0.63 t CO_2/kWh). A comparison of the baseline energy consumption in RREEM and in AEO 2008 is shown in SI, S3 "Data and data quality assessment". The assumptions used for the carbon intensity of direct fuel use and electricity are presented in SI, S4 "Carbon emissions factors,"

For each region, our estimates include the technology characterization, the primary energy consumption, final energy consumption, electricity consumption and carbon dioxide emissions of equipment (in units of Joules/unit per year, kWh/unit per year and tonnes of CO_2/unit per year respectively). In each case, we consider only direct energy use, and scope 1 and 2 CO_2 emissions (which account for the bulk of emissions).

We estimate efficiency supply curves by optimizing different metrics (primary or final energy saved, electricity saved, CO_2 emission reductions, cost savings, and annualized costs) using a single central decision maker who optimizes objective functions on behalf of consumers. This approach allows us to explore the implications of different policies with different incentives and objectives.

For each technology in the baseline stock, we determine the best available replacement technology (e.g., the one that provides the largest savings while providing a similar energy service) given the particular outcome of interest (e.g., final energy, primary energy, electricity, carbon dioxide emissions, capital cost, annualized cost) from the list of technologies shown in Table S.1.1 of the SI. In each region, AEC, the baseline annual energy consumption (or baseline CO_2 emissions) is estimated by multiplying the stock size of a specific technology type in that region by the average unit energy consumption (or unit carbon emissions):

$$\mathrm{AEC} = \mathrm{Stock}_{\mathrm{year,region,end\,use,tech\,type}} \times \mathrm{UEC}_{\mathrm{year,region,end\,use,baseline,tech\,type}} \quad (1)$$

The unit with the lowest consumption (or emissions, depending on the optimization goal) from that set is selected as the best available technology. The annual energy saved (or CO_2 emissions avoided), $\mathrm{AES}_{\mathrm{tech\ type}}$, is then computed as:

$$\mathrm{AES}_{\mathrm{tech\,type}} = \mathrm{Stock}_{\mathrm{year,region,end\,use,tech\,type}=i} \times (\mathrm{UEC}_{\mathrm{year,region,end\,use,tech\,type}=i} - \mathrm{UEC}_{\mathrm{year,region,end\,use,tech\,type}=j}) \quad (2)$$

where Stock is the number of units of equipment of a certain type in 2009 for the region and specified end-use, and UEC is the corresponding annual unit energy consumption (or carbon dioxide emissions). To address the issues raised in Stoft[41] (discussed above in Section 2), we explicitly assess the impact of changes in technologies from a specified baseline. The

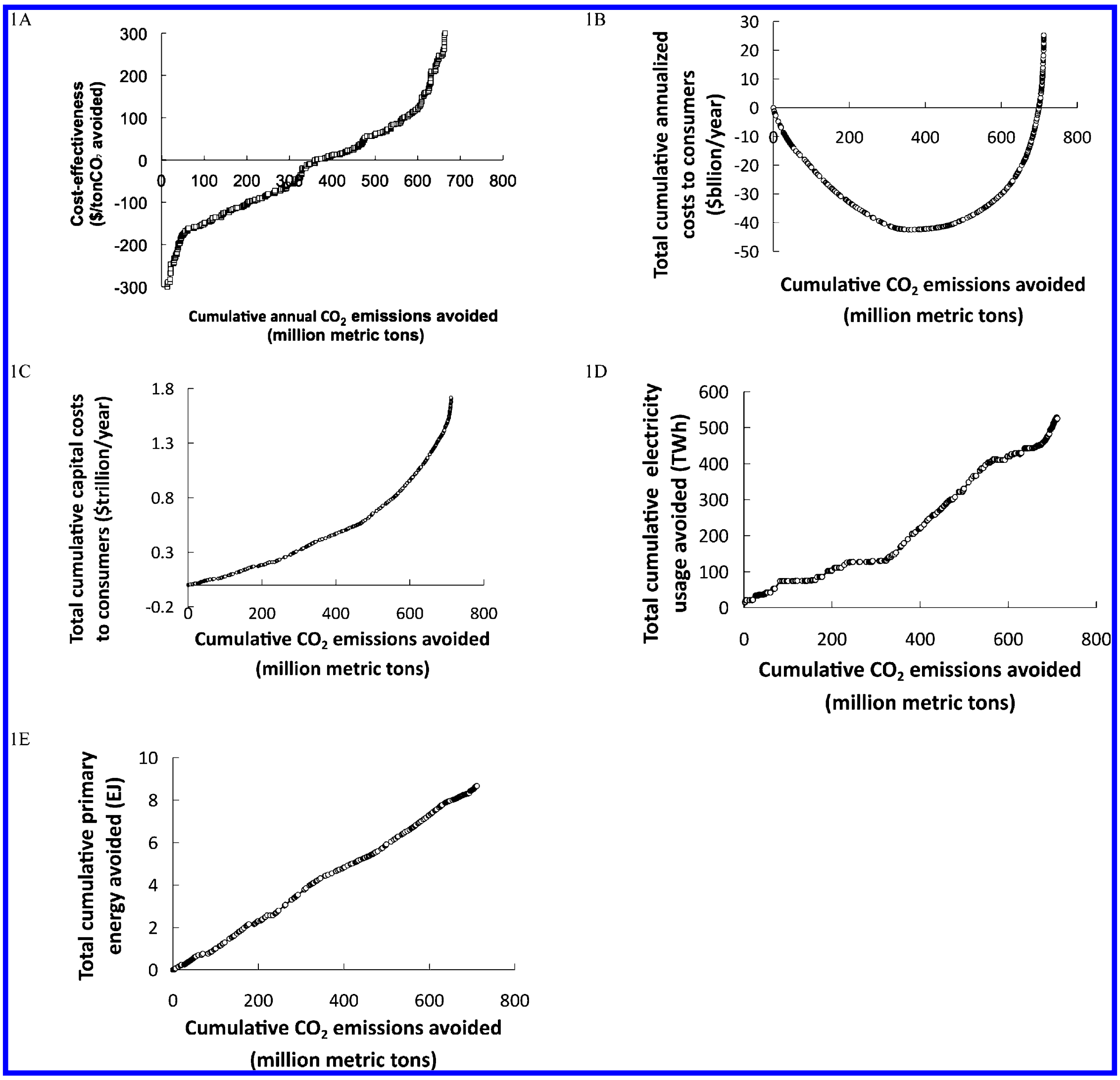

Figure 1. Carbon dioxide mitigation supply curves estimated with the RREEM model for the U.S. residential sector in 2009. A real discount rate of 7% (accounting for inflation) is assumed. The results are obtained by maximizing the amount of CO_2 savings, and by ranking the cost-effectiveness of residential equipment from lowest to highest. In all cases, the *x*-axis displays the annual carbon dioxide emissions avoided due to investments in energy efficiency. Panel 1A is a carbon dioxide mitigation supply curve: the *y*-axis displays the net cost-effectiveness of those energy efficiency measures in \$2008 per tonne CO_2; the line in Panel 1A is the carbon mitigation supply curve from energy efficiency investments costs to consumers. Panel 1B shows the total cumulative annualized cost to consumers (i.e., the integral of the curve in Panel 1A). Panel 1C shows the total cumulative upfront capital costs that would have been required in 2009 to achieve these energy efficiency savings. Panel 1D shows the total cumulative electricity saved in 2009 (in TWh). Panel E shows the total cumulative primary energy saved in 2009 (in EJ). All costs are in 2008 dollars.

technology type "*i*" is the technology in place in that baseline, and the technology "*j*" is the best available replacement technology. Then the total energy saved (or carbon dioxide avoided) for each end-use "e", or $\text{AES}_{\text{end use}}$ is computed as:

$$\text{AES}_{\text{end use}=e} = \sum_{\text{tech type}=1}^{i} [\text{Stock}_{\text{year,region,end use,tech type}} \times (\text{UECC}_{\text{year,region,end use,,tech type}} - \text{UEC}_{\text{year,region,end use,tech type}=j})] \quad (3)$$

The total annual energy saved or carbon dioxide avoided in a specific year and region, or $\text{AES}_{\text{total}}$ is computed as

$$\text{AES}_{\text{total}} = \sum_{\text{end use}=1}^{x} [\text{AES}_{\text{end use}}] \quad (4)$$

For each pair of baseline-efficient technologies "*i*" and "*j*", the levelized annual cost is estimated using the general expression:

$$\text{CCE}_{\text{tech type}} = \frac{I_j \frac{d}{(1-(1+d)^{-n})} + (\text{Fuel Price}_j \times E_j) - I_i \frac{d}{(1-(1+d)^{-n})} - (\text{Fuel Price}_i \times E_i)}{E_i - E_j} \quad (5)$$

$\text{CCE}_{\text{tech\_type}}$ is the annualized cost of conserved energy (or electricity or CO_2 emissions depending on the metric used by the decision-maker to compare the cost-effectiveness of energy efficiency policy goals) in \$/GJ (or \$/kWh or \$/tonne CO_2 avoided), *I* is the investment or retail cost (in \$/unit), Fuel Price is the price of the fuel used by the technology, *d* is the discount rate, and *E* is the annual energy (or electricity or carbon dioxide emissions) consumed by the technology in one

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year. Again, "i" corresponds baseline technologies and "j" represents the efficient technology.

The expression above for $CCE_{\text{tech type}}$ is appropriate when estimating the costs of equipment that has reached the end of its lifetime and needs to be replaced, or that is added to meet new demand. For the scenario where equipment might be retrofitted, the decision becomes whether to keep current appliances or invest in new ones, and the opportunity cost is to do nothing (i.e., continue using the inefficient technology until it reaches the end of its useful lifetime). In this case, the cost of conserved energy (or electricity or carbon dioxide emissions) becomes

$$CCE_{\text{tech type}} = \frac{I_j \frac{d}{(1-(1+d)^{-n})} + (\text{Fuel Price}_j \times E_j) - (\text{Fuel Price}_i \times E_i)}{E_i - E_j} \quad (6)$$

After computing the economic costs, and energy and carbon dioxide savings using the equations above, we rank the efficiency options in terms of their cost-effectiveness. In the efficiency supply curve representation, efficiency options are displayed from the most cost-effective to the least cost-effective along the y-axis of the curve. We estimate such ranking in terms of relevant units: \$/GJ (for primary and delivered energy), \$/tonne CO_2 or \$/kWh (in this later using only that subset of end-uses and technologies that use electricity).

4. RESULTS

All results refer to the year 2009, and all cost figures are reported in 2008 dollars. In 2009, the residential sector accounted for 1260 million metric tons of CO_2, used 1400 TWh of electricity, was responsible for 23 EJ of primary energy, and for 12 EJ of final energy consumption.[11,12] Our technology database includes the nine largest residential energy end-use services (heating and cooling systems, clothes washers and dryers, dishwashers, hot water heaters, stoves and ovens, refrigerators, freezers, and lighting), which in 2009 we estimate accounted for 12 EJ of primary energy, 9 EJ of delivered energy, and 887 TWh of electricity. We use carbon dioxide emission factors specific to each for the nine census division regions as shown in the Supporting Information. Using these factors, we estimate that the annual CO_2 emissions from the nine energy end-use services modeled in RREEM account for 950 million metric tons of CO_2 annually. Given the uncertainty on carbon factor estimates and the resulting implications for decision-making, later in this section, we provide a sensitivity analysis.

We estimate the potential for energy efficiency that would maximize carbon dioxide savings. We consider two bounding scenarios: retrofit the full stock of residential equipment shown in Figure 1A–E, or only replace the equipment that reached the end of its useful lifetime in 2009 and meet new equipment demand with the technologies that would minimize carbon emissions (discussed jointly with other scenarios in Figure 3, and also shown in Figures S4C and S4D in SI). In SI, S4, we also show the results for the cases where we include a fuel switching constraint, which means that we assume that all stock that is currently using electricity will need to be substituted by new equipment using electricity, all stock that is currently using natural gas will need to be substituted by new equipment using natural gas, and so forth.

The scenario in Figure1A–E display the savings that would be achieved if consumers were to invest in the technologies that minimize carbon dioxide emissions while providing a similar level of energy services. That is, we follow the taxonomy from the National Academies report on the "Real Prospects from Energy Efficiency", where "[the] economic potential, includes those technologies that are judged to be economically attractive.[1]

While the scenarios are estimated to maximize carbon dioxide emissions reductions while delivering a similar level of energy services, energy savings are obviously also achieved. However, the energy and electricity savings obtained in this case are lower than if the simulation were performed with the objective of maximizing energy or electricity savings. These trade-offs are explored in the section below.

The solid line in Figure 1A reports the carbon mitigation supply curve using a real discount rate (accounting for inflation) of 7%. We assume that all inefficient appliances are replaced overnight with the least carbon emitting technologies (from the technology list presented in SI, S1). The x-axis reports the resulting annual carbon dioxide emissions avoided, and y-axis shows the cost-effectiveness in \$/tonne CO_2 avoided (\$2008), computed using levelized annual costs. Negative cost-effectiveness values mean that consumers would realize net benefits (i.e., save money) by making such investments, whereas positive values represent options that entail net costs to consumers.

In Figure 1, we use a scenario where we allow switching between sources of energy or fuel. This involves substituting the baseline technology installed in 2009 with the technologies listed in SI Table S1.1 in that has the lowest annual CO_2 emissions. We do so for each Census Division regions (the heating technology with lowest annual CO_2 emissions in New England may not be the same as in the Pacific region, for example, due to different electricity mixes and usage patterns).

Figure 1B reports, for the same scenario as in Figure 1A, the cumulative annualized costs in \$billion per year to consumers of investments that maximize reductions in CO_2 emissions. Again, the negative values in the y-axis reflect net benefits to consumers. Because cumulative annualized costs include the capital costs, and capital availability might prevent some of these investments from occurring, we believe that it is important for policy makers to consider this metric when setting energy efficiency goals. In order to assess the magnitude of capital investment that would have been needed in 2009 to achieve these different levels of carbon dioxide emissions reductions, in Figure 1C we report the cumulative upfront capital costs associated with achieving the potential emissions reductions shown in Figure 1A. Figure 1D and E report cumulative annual savings in electricity and primary energy that would be achieved by following the strategy shown in Figure 1A, all in 2008 dollars.

Technological Potential with a Stock Retrofit. We find the upper bound technological potential for U.S. residential CO_2 reduction, if all of the nine modeled energy end-use services in RREEM were replaced with their least carbon intensive alternatives, would be 711 million metric tons of CO_2 (see Figure 1). Under this very optimistic scenario, 56% of total residential CO_2 emissions in the U.S. could be avoided, together with a reduction of 6,000 PJ in delivered energy (or 49% of residential delivered energy consumption), 8670 PJ of primary energy (or 41% of residential primary energy consumption) and 525 TWh reductions in electricity

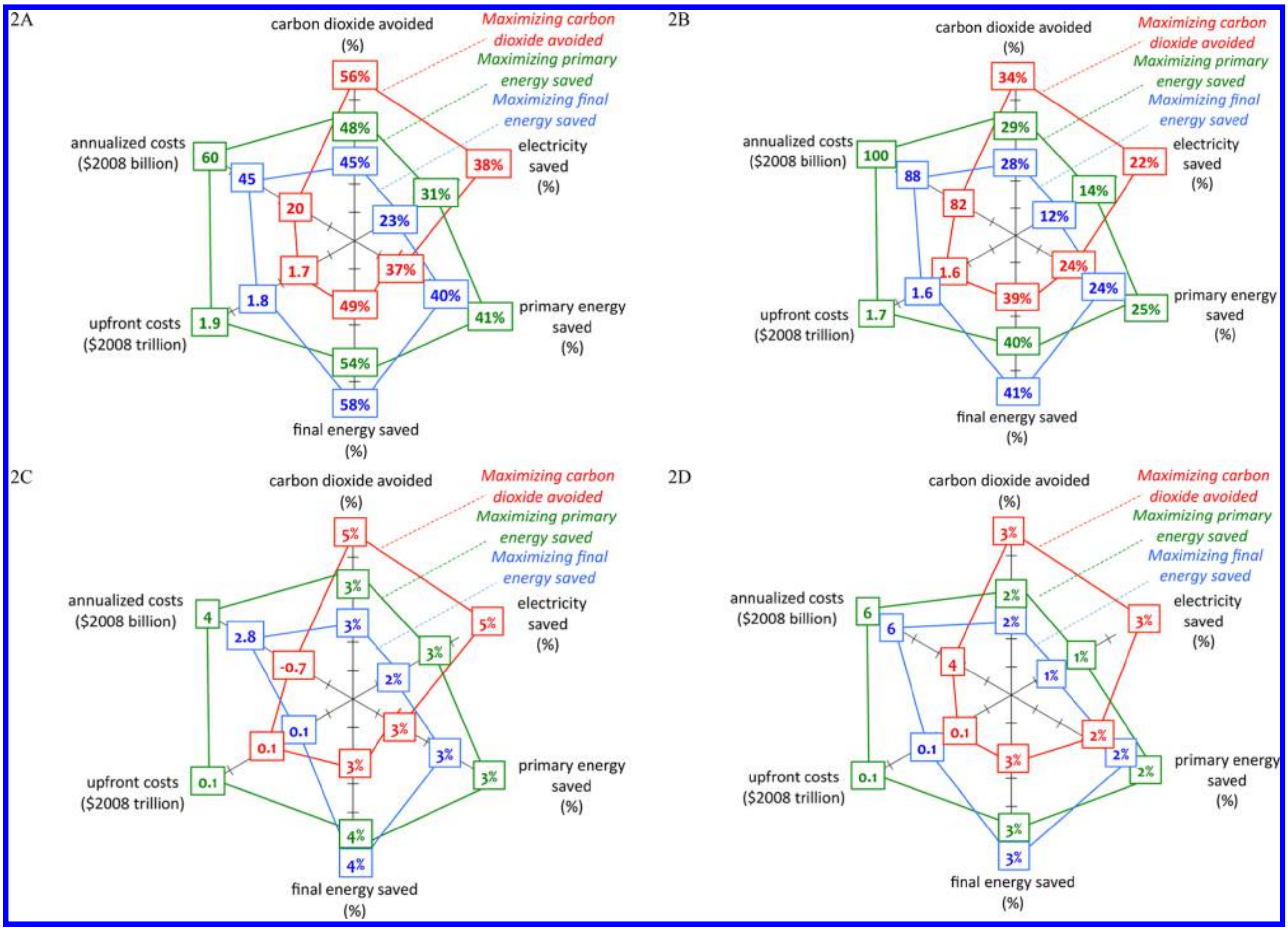

Figure 2. Results from several simulations with the RREEM model for the year 2009 run with different optimization objectives, assuming a discount rate of 7%. Each figure shows the results for optimizations that would maximize either carbon dioxide avoided, primary energy saved or final energy saved, so that the maximum technological potential is attained in each case. In Panel 2A, the full stock of equipment is available for immediate replacement, and fuel switching is allowed. In Panel 2B, the full stock of equipment is available for immediate replacement, but no fuel switching occurs. In Panel 2C, only purchases of new equipment in 2009 to replace equipment at the end of its life and meet population growth is considered, and fuel switching is allowed. Panel 2D is the same but without fuel switching. Axis in Panels 2A–2D are all at scale, except in the case of the annualized costs in Panel C where we had to represent a negative value.

consumption (or 38% of residential electricity consumption). Achieving this "technological potential" would result in an annual net cost to consumers of $20 billion (or an average of approximately $64 per capita per year). However, the initial capital cost of such investments would be close to $1.7 trillion (or an average of approximately $5400 per capita). This cost is already included in the levelized annual costs, but also estimated separately in order to understand the dimension of the investments required to achieve such potential.

Economic Potential with a Stock Retrofit. More realistically, considering only those options that could be achieved with a net cost-effectiveness in \$/tonne of CO_2 avoided that is less than zero (therefore providing net benefits to consumers), Figure 1A shows that 357 million metric tons of CO_2 emissions (or 28% from total residential CO_2 emissions) could be avoided by implementing measure that would also save consumers' money.

Achieving this net economic potential would correspond to a net annual benefit of $42 billion to consumers (or a net benefit of $135 per capita per year), but requires an investment of $415 billion of upfront costs in energy efficient measures (i.e., an investment cost of $1330 per capita). In this case, 3980 PJ of final energy, 4440 PJ of primary energy, or 172 TWh of electricity would be saved. While consumers would benefit from investments in energy efficiency that have positive net benefits, many of these investments do not occur because upfront costs are high, and market or behavioral barriers prevent their widespread adoption or because consumers must choose among many investments, only some of which improve energy efficiency.

Note that this is a conservative estimate of the cost-effective potential, given that we are implicitly assuming a \$0/tonne CO_2 price for carbon (i.e., we are not including environment and health externality valuation in this assessment). This means that if we assume, for example, a social cost of carbon (i.e., the benefit derived by society from avoiding a marginal ton of CO_2 emissions) of about \$20/tonne of CO_2 (which is within the range of the values reported by the Interagency Working Group on Social Cost of Carbon),[42] the optimal level of investment for society would be to pursue energy efficiency strategies up to the level where the y-axis in Figure 1 is \$20/tonneCO_2.

In Figure 2 each figure shows the results for optimizations that would maximize either carbon dioxide avoided, primary energy saved or final energy saved, so that the maximum technological potential is attained in each case. In 2A, the full stock of equipment is considered, and fuel switching is allowed.

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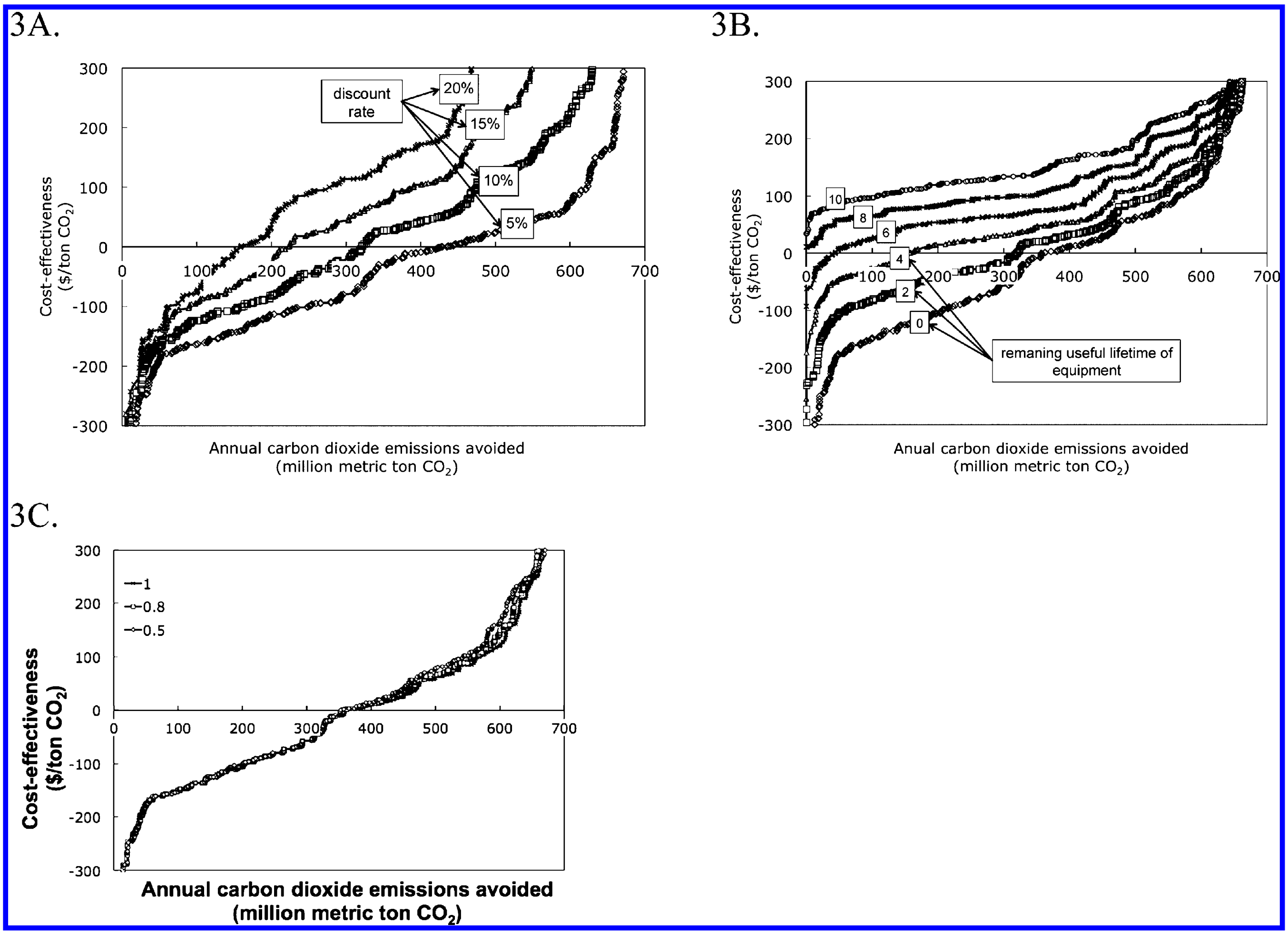

Figure 3. Sensitivity analysis for the carbon dioxide mitigation supply curve estimated for the U.S. residential sector in 2009 assuming a full stock replacement and allowing for fuel switching (i.e., the base-case shown in Figure 1). Panel 3A reports sensitivity analysis for the discount rate. Panel 3B reports sensitivity analysis for the remaining useful lifetime of the equipment to be replaced (remaining lifetime is varied from by 0 to 10 years).Panel 3C reports sensitivity analysis with respect to the carbon intensity of electricity generation.

In Figure 2B, the full stock of equipment is considered, but no fuel switching occurs. In Figure 2C, only purchases of new equipment in 2009 to replace equipment at the end of its life and meet population growth is considered, and fuel switching is allowed. Figure 2D is the same as Figure 2C, but with no fuel switching.

Trade-Offs among Different Goals. The order in which efficient technologies are adopted, and the amount of reduction in CO_2 emissions or energy use that is achieved depends on the policy goal. Overnight replacement of the full stock of major residential appliances sets an upper bound of 711 × 10^6 tonnes/year of CO_2 or a 56% reduction from baseline residential emissions. A policy designed to minimize primary energy consumption while maintaining energy services, achieves only a 48% reduction in CO_2 emissions from the baseline. Only replacing appliances at the end of useful life achieves only a 5% reduction. If policy is designed to minimize primary energy consumption, then a 3% reduction is achieved.

Fuel Constraints. For the results shown in Figure 2A, no restriction on fuel changes is considered. Thus, the red line (labeled "*Maximizing carbon dioxide avoided*") in Figure 2A summarizes the results displayed in greater detail in Figure 1. In Figure 2B, we include the additional constraint in the optimization that the fuel being used to provide each end-use service remains the same as in the business as usual scenario (i.e., the share of stock currently using electricity will keep on using electricity). In the latter case, we find that, when the simulation for reducing CO_2 emissions is performed, carbon dioxide emissions would be reduced by 34%, electricity consumption by 22%, and primary energy and final energy by 24% and 39%, respectively. This would require a capital investment cost of $1.6 trillion in 2009 (or $5140 per capita), and result in $82 billion in annualized costs to consumers (or $260 per capita per year). This cost does not include the cost of building new natural gas infrastructure.

Only Replacing Equipment at End of Life. While an assumption that customers can replace all inefficient appliances and switch between energy sources or fuels overnight provides an upper bound on potential reductions. More realistic scenarios limit the rate at which replacement occurs and/or limit changes in which fuels are used to power such end-uses. Figures 2C (with fuel switching) and 2D (without fuel switching) display scenarios that only consider purchases of new equipment in 2009 that are made to replace equipment that has reached the end of its life or is needed to meet population growth. In this case, consumers make investments in new equipment since their old equipment has reached the end of its useful lifetime. The decision is whether to invest in a baseline technology or an efficient one. Here we use incremental capital costs, as shown in eq 5.

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When there are no fuel constraints, the simulation for maximizing carbon dioxide savings shows a reduction in baseline emissions of 5% (or 52 million metric tons CO_2 annually), a 3% reduction in final and primary energy, and a 5% reduction in electricity consumption. This would provide net benefits to consumers of \$0.7 billion (or \$22 per capita per year), but would require \$129 billion of upfront costs (or \$414 per capita of initial investments).

In the most constrained set of optimizations (Figure 2D) which only allow end of life replacement and market growth, but without fuel switching, the simulation for carbon dioxide savings finds a reduction in 3% of current residential carbon dioxide emissions, electricity saved or final energy, and a 2% reduction in primary energy, could be achieved. This would provide net costs to consumers of \$3 billion (or about \$10 per capita per year), and would require an investment of \$112 billion in upfront costs.

In SI, S4, we show the energy efficiency supply curves for the subset of scenarios shown in Figure 2 where we maximize CO_2 emissions avoided.

Sensitivity Analyses. Figure 3 presents a set of sensitivity analysis for the scenario allowing for full stock replacement, and allowing for fuel switching. The sensitivity analysis is performed on discount rates, remaining useful equipment lifetime, and the regional carbon intensity of the electric grid.

Discount Rate. Empirical studies of consumer choices often imply effective implicit discount rates of 20% or more when choosing efficient technologies.[43−45] Figure 3A displays the sensitivity of our results as the discount rate goes from 5 to 20%. The amount of carbon dioxide emission that can be avoided with net benefits to consumers (i.e., with a cost-effectiveness of <0\$/tonne CO_2) when a 20% discount rate is assumed is approximately 160 million metric ton CO_2 per year.

Remaining Useful Lifetime of the Equipment. In Figure 3B, we assess the implications of remaining useful lifetime for the existing equipment. We assume that new equipment has a lifetime of n years when it is purchased, and that existing equipment has a remaining useful lifetime of y years ($0 \leq y \leq n$). The consumer can wait for the existing equipment to reach the end of its useful life, or can change to a new technology at any time, $t < n$. Section S5 in SI details the equations that were used. In Figure 3B, we report the effect of assuming a remaining lifetime for the existing equipment of between $t = 0{-}10$ years, for cost-effectiveness values that range between 300 and 300 \$/tonne CO_2 avoided. The amount of carbon dioxide that can be avoided without consumers' net benefits drops to zero when remaining lifetime exceeds approximately 7 years.

Finally in Figure 3C we display the sensitivity to the carbon intensity of electricity generation. In this case, we reduce the carbon intensity in each of the nine census division regions by a factor of 0.5 and 0.8 from what was assumed in the base-case (see Table S3.2 in the SI for the base-case regional grid emission factor assumptions). Because of the large role played by nonelectric heating (SI Figure S0.1), the impact of reducing that intensity by up to 50% is very modest.

5. DISCUSSION

While analysis of energy saving potential at the regional level would benefit from better data on the distribution of equipment and associated usage, the data now available supports some clear insights. Foremost is that the technologies and strategies that energy efficiency policy should target depends on whether the goal is to reduce primary energy, delivered energy consumption, electricity consumption or carbon dioxide emissions. While a proposed policy may be targeted at one of these objectives, to avoid unintended outcomes it should be evaluated in terms of its effect on all four measures.

In recent years, efforts by behavioral economists, psychologists and others social scientists have explored the reasons why consumers do not choose the most cost-effective energy efficient strategies. While this is an important area of study, such behavioral issues are not considered in this study (except for the issue of how high implicit discount rates affect the results, as shown in Figure 3A). Based on a recent paper by Huntington,[46] readers can make a first order assessment of their impact by dividing the savings by approximately a factor of 2.

Assessments of energy and monetary savings from energy efficiency are particularly difficult to gauge, not just because of the vagaries of the assessments of direct effects on efficiency measures, but also due to indirect effects. If efficiency measures save money for consumers, those consumers may then spend the money saved on other goods and services, thereby increasing demand and inducing less-than-proportional reductions in energy use.[47,48] Greening et al.[48] suggest that the size of the rebound effect for residential consumers ranges from 0 to 50%, expressed as "a percentage increase in consumption estimated to result from a 100% increase in efficiency" and some of our own work in this topic suggest that rebound effects for residential energy efficiency end-uses are more likely to be in the range of 5−15%.[49] Given the considerable uncertainty about the magnitude of rebound, we have not considered it in the results we report here, although we continue to explore these issues in other work.

Finally, this paper has focused on the costs of implementing energy efficiency measures and the amount of CO_2 and energy that would be avoided. We do not estimate changes in other gases that would change radiative forcing, such as black carbon, methane,[50,51] nitrous oxide, ozone precursors, and sulfates.[52,53] We assess the costs of investment in energy efficiency technologies, not the social benefits derived from efficiency such as the avoided health and environmental impacts.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

In S1, we provide a detailed characterization of the technology used in the analysis. In S2, we describe the data used and provide a data quality assessment. In S3, we provide the carbon emissions factors assumed for all fuels and for electricity. In S4, we report the efficiency supply curves for all scenarios (full stock replacement or end of life replacements; with and without fuel switch) where we maximize CO_2 savings.This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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