The Value of Advanced Technologies in the U.S. Buildings Sector in Climate Change Mitigation

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ABSTRACT

There is a wide body of research addressing the potential of advanced technologies to reduce energy consumption in buildings. How such improvements relate to global climate change is less clear, due to the complexity of the climate change issue, and the interactions within the energy system as a whole that need to be considered. This study uses MiniCAM, an integrated assessment model, to examine the potential contribution of advances in four groups of buildings technologies in meeting a national carbon emissions constraint from 2005 to 2095. The constraint is part of a global policy to mitigate climate change by stabilizing atmospheric CO_2 concentrations at 450 ppmv. Technology groups analyzed include building shells, heat pumps for HVAC and water heating, solid-state lighting, and miscellaneous electric equipment. In a scenario with all technology groups advanced and no emissions constraint, the buildings sector energy consumption is reduced by 28% in 2095. Advanced heat pumps and energy-efficient miscellaneous electric equipment are responsible for the greatest energy reductions seen in this analysis, but all technology groups are important for reducing future buildings sector energy consumption. With an emissions constraint, the buildings sector tends to switch to electricity, while the electric power sector dramatically lowers the carbon intensity of electricity generation through carbon capture and storage, and expanded nuclear and renewable energy. In a scenario with advances in all buildings technology groups analyzed, total discounted costs of carbon abatement are reduced by 17%. Advanced heat pumps are especially important for facilitating fuel switching towards electricity.

Introduction

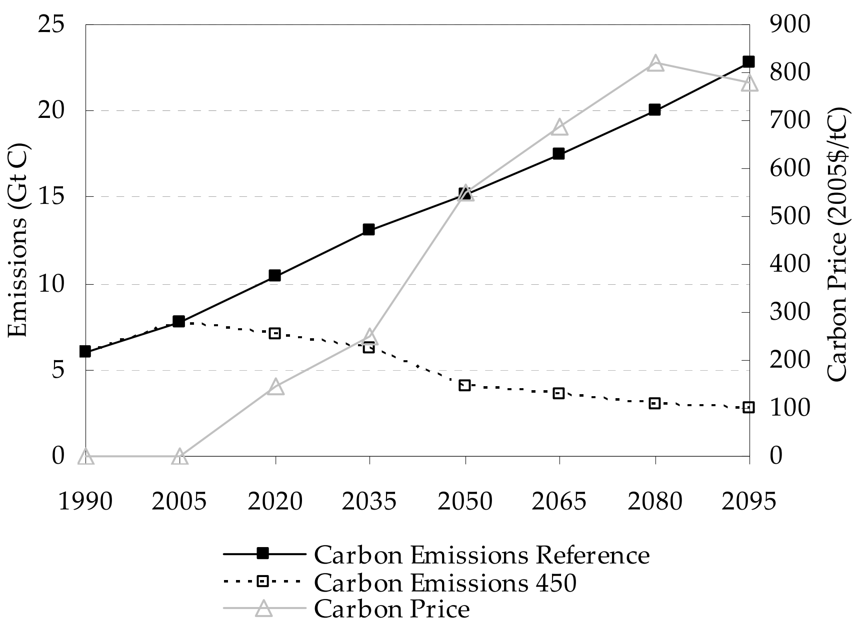
Consumers in the United States demand goods and services currently supplied by technologies that use fossil fuels, whose combustion releases emissions that contribute to increasing atmospheric greenhouse gas concentrations and global climate change. Mitigation of climate change will require comprehensive strategies that simultaneously consider many aspects of the energy and climate system, and the relevant analytical time frame is longer than that of most other policy issues. As interest in addressing climate change has grown in the past several decades, a number of integrated assessment models have been developed to compare long-term, global strategies (for review see Nakicenovic et al. 2000, Clarke et al. 2007). To date, integrated assessment models have tended to focus their technological detail on the supply side of the energy sector, treating end-use demand in aggregate fashion, generally as regional buildings, industrial, and transportation sectors. The analysis presented in this study was conducted using the MiniCAM model (Edmonds et al. 2004), recently enhanced to incorporate a high level of detail in end-use sectors (the ObjECTS framework; Kim et al. 2006). Therefore, while this study focuses primarily on the U.S. buildings sector, and secondarily on the U.S. electricity sector, the model also incorporates sub-models of the global energy system (Edmonds and Reilly 1985;

Edmonds et al. 2004), agriculture and land use (Sands and Leimbach 2003), and atmospheric gas concentrations and climate change (the MAGICC model; Wigley and Raper 2002).

The goal of the United Nations Framework Convention on Climate Change is the stabilization of atmospheric concentrations of greenhouse gases at levels that avoid dangerous anthropogenic interference with the climate system (UNFCCC 1992, Article 2). Because of uncertainty in the response of climate to increasing greenhouse gases, the stabilization levels that would achieve this goal are not known. Still, stabilization of any greenhouse gas at any concentration will require that global emissions are ultimately balanced by terrestrial and oceanic uptake. Reducing emissions will incur economic costs; the purpose of this study is to investigate the role of buildings technologies in reducing costs associated with CO_2 stabilization.

Figure 1 shows global carbon emissions in a reference scenario (no climate policy), and with a constraint on fossil and industrial carbon emissions that leads to stabilization of atmospheric concentrations of CO_2 at 450 parts per million by volume (ppmv). The emissions pathway is characterized by increasingly stringent reductions over time (as seen by the departure from the reference emissions in Figure 1), to minimize the retirement of existing capital stock, and to benefit from future technologies that reduce carbon abatement costs. These reductions are achieved by a price on carbon emissions (implicit or explicit), also shown in Figure 1.

Figure 1. Global Fossil and Industrial Carbon Emissions with and without a 450 ppmv CO_2 Stabilization Constraint, and Carbon Prices with the Constraint



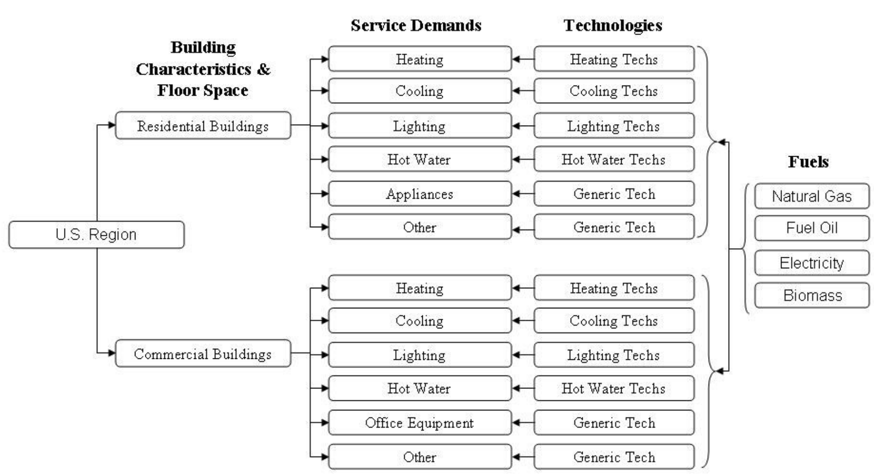
In this study, the carbon price pathway generally follows Peck-Wan-Hotelling (Peck and Wan 1997), increasing at an assumed long-term discount rate until the stabilization target is approached, after which the price levels also stabilize or decline. The carbon price adds to the market price of a fuel in proportion to its carbon content. These cost increases influence technology choice and service demand levels. Note that secondary fuels such as electricity and refined liquid fuels can be produced from several different primary fuels with different carbon contents; their carbon emissions intensity in the future is not fixed.

The U.S. Buildings Sector and the Energy System

Buildings in the U.S. accounted for 40% of delivered energy consumption in 2005, and are large consumers of electricity, driving daily and seasonal electric load cycles. In recent decades, electricity has accounted for an increasing share of delivered energy in the buildings sector: 25% in 1975, 39% in 1990, and 48% in 2005 (DOE 2006). This fuel switching has been driven by a number of technological and demographic factors, and is expected to continue in the near future (DOE 2007). This has important implications for emissions, due to the large amount of emissions from the electricity sector. In 2005, for instance, direct carbon emissions from the buildings sector were approximately 150 Mt, whereas emissions from generating the electricity consumed by buildings were approximately 450 Mt.[1]

This shift towards electricity underscores an important aspect of the buildings sector: the services demanded evolve over time. While the heating service remains the largest energy consumer of the residential services, accounting for 45% of delivered energy to the residential sector in 2005 (DOE 2007), its relative share of delivered energy has decreased substantially since the 1970's (DOE 2001). In contrast, miscellaneous electric-powered services, such as office equipment, televisions, and appliances, have taken increasing shares of building energy for the past several decades. Further growth of these services in the future seems likely, and, independent of improvements in energy efficiency, such changes in service demands are important drivers of the quantities and types of fuels demanded by the buildings sector.

Figure 2. Conceptual Structure of the U.S. Buildings Sector in MiniCAM



[1] This figure is calculated from the average carbon intensity of electric generation for all end uses. Because it does not account for the timing of the demand, and peak load electricity is generally more carbon-intensive than off-peak, this figure may under-estimate the actual electricity-related emissions of the buildings sector.

Overview of the U.S. Buildings Module

The U.S. buildings module in MiniCAM is detailed in Clarke et al. (in review), and is shown schematically in Figure 2. Buildings are separated into residential and commercial sectors, each represented in terms of floorspace. Each unit of floorspace demands a range of services, which are supplied by technologies that consume fuels. This separation between services and technologies is important for isolating the effects of technological improvement from changes in service demand.

In the future, growth in floorspace is driven by population and per-capita GDP (income). Levels of service demands depend primarily on floorspace, but are also influenced by a "saturation" parameter, which captures accelerated future demand in services whose growth is expected to outpace that of floorspace. Furthermore, heating and cooling demands take into account internal gains, or heat released into the building envelope from operating equipment. During the fraction of the year that heating and cooling equipment are operational, the internal gains are subtracted from heating service demands, or added to cooling service demands.

Technology and Technology Choice

Technologies in MiniCAM compete for service provision according to total costs, which are calculated based on exogenous non-fuel costs, exogenous efficiencies, and model-derived fuel costs. Technologies are discrete: in any period, each has an assumed stock average efficiency, and a non-fuel cost that consists of the sum of levelized capital and operating costs. Future technology non-fuel costs and efficiencies are scenario variables; they can be altered to test various future possibilities of technology evolution.

Technologies in MiniCAM compete according to a logit formulation (Clarke and Edmonds 1993), which allocates market shares to competing technologies based on their relative costs, and an assumed cost distribution of each technology. This approach ensures that more costly technologies still gain some share of the market, consistent with actual market observations (McFadden 1981). Finally, technologies in MiniCAM are assigned a calibration parameter, calculated from base year market shares, to parameterize non-economic technology preferences. Calibration parameters of competing technologies are generally assumed to converge at some point in the future, allowing competition for market shares to be based purely on relative economics.

Scenarios and Assumptions

The socioeconomic and technology backdrop for the scenarios presented here are documented in Clarke et al. (2008 update of Clarke et al. 2006). In summary, U.S. population grows from 296 million persons to 523 million between 2005 and 2095, and per-capita GDP grows from $39,000 to $124,000 (2005 USD). In the U.S. buildings sector, per-capita residential floorspace grows from 750 square feet to 1100 square feet in 2095, and per-capita commercial floorspace grows from 300 square feet in 2005 to 440 square feet in 2095. In aggregate, this amounts to a doubling of the total amount of building floorspace in the U.S. between 2005 and 2095. Service demands are generally assumed to be 100% saturated in 2005; exceptions are residential appliances (90%), residential other services (80%), commercial office equipment (80%), and commercial other services (80%). All are assumed to reach 100% saturation by 2050.

Table 1. Residential Technology Efficiencies in 2005, and Reference and Advanced Technology Assumptions in 2050 and 2095

			Reference		Advanced	
	Measure	**2005**	**2050**	**2095**	**2050**	**2095**
Shell efficiency	Indexed	1.00	1.29	1.53	1.53	1.91
Gas furnace	AFUE	0.82	0.88	0.91		
Gas heat pump	COP	n/a	n/a	n/a	1.72	2.19
Electric furnace	AFUE	0.98	0.99	0.99		
Electric heat pump	HSPF	7.32	8.43	8.76	9.23	9.80
Fuel oil furnace	AFUE	0.82	0.85	0.87		
Wood furnace	AFUE	0.58	0.64	0.66		
Air conditioning	SEER	10.7	15.3	18.0	18.8	23.9
Gas water heater	EF	0.56	0.62	0.64		
Gas heat pump water heater	EF	n/a	n/a	n/a	1.69	1.86
Electric resistance water heater	EF	0.88	0.93	0.96		
Electric heat pump water heater	EF	n/a	n/a	n/a	2.79	2.97
Fuel oil water heater	EF	0.55	0.56	0.58		
Incandescent lighting	lumens/watt	14	16	16		
Fluorescent lighting	lumens/watt	60	76	81		
Solid-state lighting	lumens/watt	n/a	117	121	156	183
Gas appliances	Indexed	1.00	1.09	1.12		
Electric appliances	Indexed	1.00	1.22	1.27	1.39	1.53
Gas other	Indexed	1.00	1.12	1.25		
Electric other	Indexed	1.00	1.05	1.08	1.40	1.54
Fuel oil other	Indexed	1.00	1.12	1.25		

Tables 1 and 2 show the specific technology stock average efficiencies in the residential and commercial sectors in 2005, and for the reference and advanced scenarios in 2050 and 2095 (for documentation see Kyle et al. 2007; Clarke et al. 2008); a brief summary follows. Reference stock average efficiencies are generally consistent with DOE (2007) for the near term, with steady improvement, where feasible, over the long term. The advanced case efficiencies improve at a more rapid rate, informed by current best available practice and theoretical maximum efficiencies. Year 2005 non-fuel costs are generally calculated from NCI (2004), and are assumed to decrease in the future at a modest rate. The following technologies have rapid future cost decreases in the advanced scenarios, such that their non-fuel costs are comparable to competing (less energy-efficient) technologies by 2050: gas heat pump, electric heat pump, gas heat pump water heater, electric heat pump water heater, and solid state lighting.

Study design. This study presents twelve scenarios (see Table 3), consisting of six technology scenarios with and without national emissions constraints, imposed as part of a global CO_2 stabilization policy. Technology scenarios represent accelerated advancement in four groups of technologies that provide buildings services, along with a reference scenario, and an all-advanced scenario. Discounted policy costs of meeting the U.S. emissions constraints are then calculated as the cumulative discounted sum of additional costs to the whole economy, incurred as a result of meeting the emissions constraints.[2]

[2] This is the same as the area under the marginal abatement cost curve in each time period. This figure can be divided by the amount of carbon abated to calculate the carbon price in each period.

Table 2. Commercial Technology Efficiencies in 2005, and Reference and Advanced Technology Assumptions in 2050 and 2095

			Reference		Advanced	
	Measure	**2005**	**2050**	**2095**	**2050**	**2095**
Shell efficiency	Indexed	1.00	1.30	1.45	1.33	1.77
Gas furnace/boiler	AFUE	0.76	0.83	0.86		
Gas heatpump	COP	n/a	n/a	n/a	1.72	2.19
Electric furnace	AFUE	0.98	0.99	0.99		
Electric heatpump	HSPF	10.58	12.23	12.70	13.37	13.88
Fuel oil furnace	AFUE	0.77	0.81	0.84		
Wood furnace/boiler	AFUE	0.58	0.64	0.66		
Air conditioning	SEER	10.6	15.2	17.8	17.1	20.1
Gas water heater	EF	0.82	0.93	0.93		
Gas heatpump water heater	EF	n/a	n/a	n/a	1.69	1.86
Electric resistance water heater	EF	0.97	0.98	0.98		
Electric heatpump water heater	EF	n/a	n/a	n/a	2.79	2.97
Fuel oil water heater	EF	0.76	0.80	0.82		
Incandescent lighting	lumens/watt	14	16	16		
Fluorescent lighting	lumens/watt	76	97	103		
Solid-state lighting	lumens/watt	n/a	117	121	156	183
Office equipment	Indexed	1.00	1.27	1.35	1.66	1.83
Gas other	Indexed	1.00	1.14	1.17		
Electric other	Indexed	1.00	1.14	1.17	1.41	1.65
Fuel oil other	Indexed	1.00	1.14	1.17		

Table 3. U.S. Buildings Sector Modeling Scenarios

REF	Reference technology assumptions
SHELL	Advanced shell efficiency only
HP	Advanced heat pump technologies only: gas heat pump, electric heat pump, air conditioning, gas water heater, gas heat pump water heater, and electric heat pump water heater
SSL	Advanced solid-state lighting only
MISC	Advanced miscellaneous electric technologies only: residential appliances, commercial office equipment, and "other" technologies in the residential and commercial sectors
ALL_ADV	All technologies advanced
REF_450	Reference technology assumptions with 450 ppmv stabilization policy
SHELL_450	Advanced shell efficiency with 450 ppmv stabilization policy
HP_450	Advanced heat pump technologies with 450 ppmv stabilization policy
SSL_450	Advanced solid-state lighting with 450 ppmv stabilization policy
MISC_450	Advanced miscellaneous electric load technologies with 450 ppmv stabilization policy
ALL_ADV_450	All technologies advanced with 450 ppmv stabilization policy

Results

No Emissions Constraint

Delivered energy by service for the REF and ALL_ADV scenarios are shown in Figure 3. In the REF scenario, delivered energy to all buildings grows over time, reaching 29.7 EJ in 2095, 47% greater than the energy consumed in 2005. While this is substantially less than the floorspace growth (100%), the technology level in this scenario nevertheless does not increase as fast as service demands. The ALL_ADV scenario diverges from the REF scenario starting in 2020. In 2095, energy consumption is 28% less than in the REF scenario, and only 6% greater than the delivered energy in 2005.

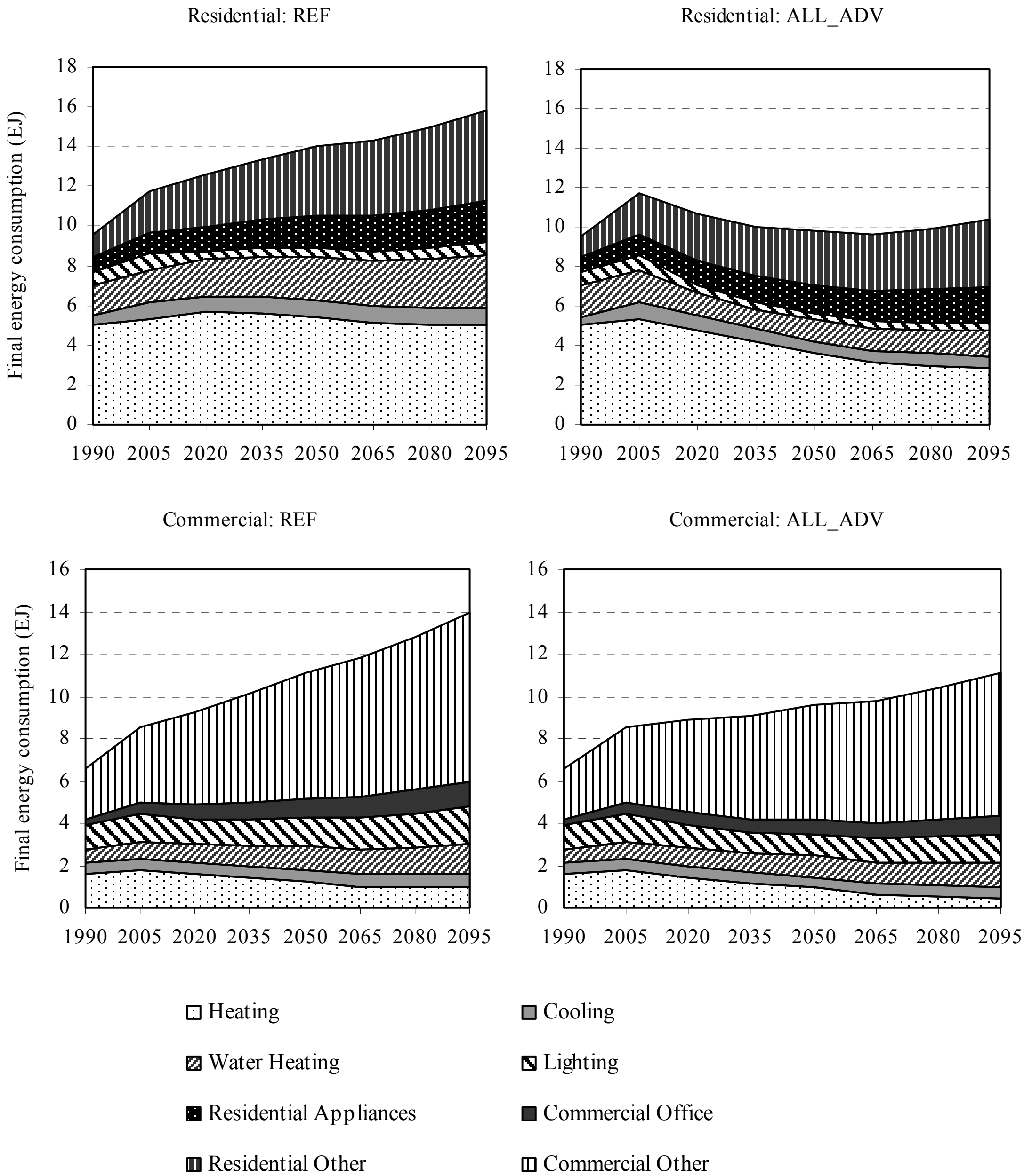
By end use service, the largest energy savings in the ALL_ADV scenario relative to the REF scenario are in heating and “other” services, for both the residential and commercial sectors. The heating energy reductions are the result of the combination of more efficient heating technologies (technological improvement) and enhanced building shells that better retain the output of heating technologies and internal gains (reduced service demand).

Energy demand reductions in each of the single-group advanced technology scenarios are shown in Figure 4; Figure 4B assigns the energy reductions shown in Figure 4A to the relevant buildings services. The advances in the HP scenario are responsible for the largest energy use reduction of any of the technology groups analyzed, mostly driven by space heating and water heating services. This is because heat pumps are currently a small or non-existent part of the service provision (particularly for water heating), and use substantially less final energy in supplying services. However, note that these figures do not consider the fuel inputs to electricity generation.

Savings in the MISC scenario are also relatively large, particularly in later time periods, both due to the growing service demands in this area, and due to the relatively long lifetimes of the technologies providing commercial “other” services. This category includes infrastructural technologies, such as distribution transformers and water treatment and pumping. In addition to having low projected near-term improvement in efficiency (TIAX 2006), stocks of these technologies will be slower to turn over than other building technologies. The same is true of building shells, and the SHELL scenario is likewise characterized by low near-term energy savings and higher long-term savings. Note also that the energy savings in the SHELL scenario are driven mostly by heating demand reductions; cooling demands are barely reduced. This is because more efficient building shells simultaneously enhance retention of internal gain energy while also reducing the losses of cooling service energy to the outside, effects which nearly balance each other in this scenario.

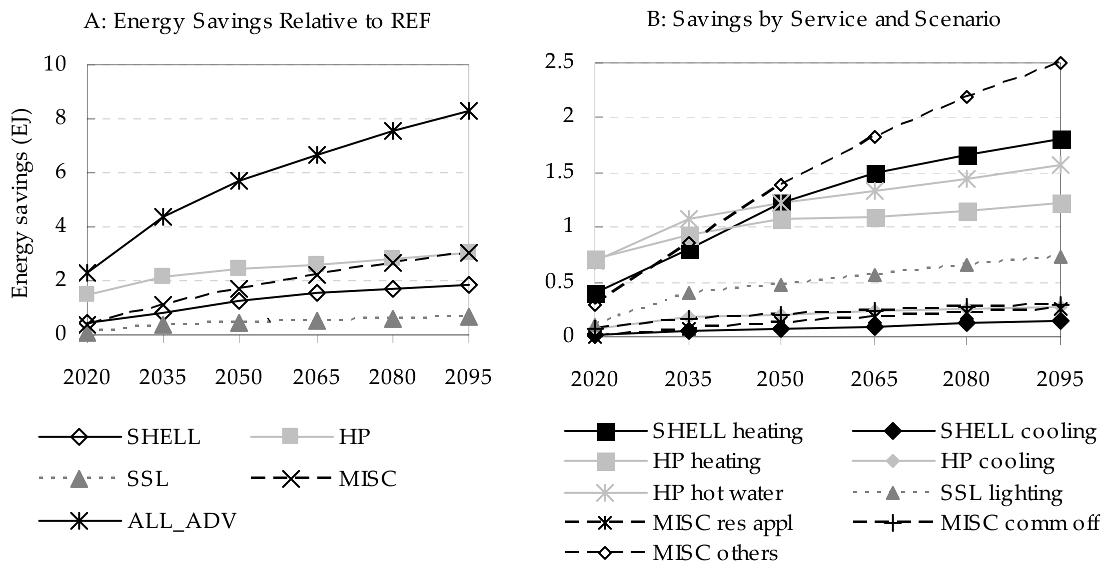
The SSL scenario leads to a 30% reduction in lighting energy consumption in 2095; in this year, solid-state lighting accounts for 82% of the lighting service output, compared with 9% in the REF scenario. This reduction in energy use in the SSL scenario should be seen in the context of the efficiency gains already present in the REF scenario. All scenarios in this study assume a near phase-out of incandescent lighting starting in the first future time period (2020), as the Energy Independence and Security Act of 2007 is assumed to marginalize incandescent lighting in the future. Had the REF scenario maintained a comparable share of incandescent lighting to the market share in the base years (90% of lighting energy in the residential sector and 32% in the commercial sector; NCI 2002), the SSL scenario would have shown greater energy savings relative to the REF.

Figure 3. Building Final Delivered Energy by Service in the REF and ADV Scenarios, Residential and Commercial Sectors



The total amount of energy saved in 2095 in the ALL_ADV scenario relative to the REF scenario—8.3 EJ—is only slightly less than the sum of the energy reductions in each of the four intermediate scenarios (8.7 EJ). This indicates little redundancy in the energy-saving effects of the four technology areas, a point that will be revisited in the following section, which analyzes the impacts of an emissions reduction policy.

Figure 4. U.S. Buildings Sector Energy Savings by Scenario, and Energy Savings by Service Demands within Scenario



CO_2 Stabilization Policy: 450 ppmv

In all CO_2 stabilization scenarios, the emissions constraint induces large-scale technology switching in the electricity sector. Absent a climate policy, electricity is generated mostly by fossil fuels in all future time periods. While advances in efficiency of generation technologies and growth of renewable electricity reduce the carbon emissions intensity from 45 kg C/GJ in 2005 to 23 kg C/GJ in 2095 (0.77 and 1.5 kwh/lb CO_2, respectively), emissions from electricity are still about 600 Mt C in 2050, and 650 Mt C in 2095 in the reference (no policy) case. The climate policy case leads to large-scale deployment of carbon capture and storage (CCS) with coal and gas power; 47% of electricity generated in 2095 is fossil-CCS. Nuclear power expands, accounting for 27% of generation in 2095, as do wind, solar and geothermal (together 20% of generation). This technology switching lowers the average carbon intensity of electricity to 1 kg/GJ in 2095 (34 kwh/lb CO_2); emissions are 36 Mt C in 2050 and 30 Mt C in 2095.

Policy-induced fuel switching for the buildings sector in the REF technology scenario is shown in Figure 5. Without a policy, the dominant fuel in the future is electricity, which accounts for 57% of energy delivered to the buildings sector in 2050, and 65% in 2095. The CO_2 stabilization policy increases these fuel shares to 71% and 78%, respectively. The total emissions (including fuel inputs to electricity generation and liquid fuel refining) by fuel in the buildings sector are shown in Figure 6, for the REF and REF_450 scenarios. The reduced emissions from electricity generation account for 84% of the total emissions reductions from the buildings sector, in 2050 and in 2095. Where total emissions from the buildings sector were about 600 Mt C in 2005, this is reduced to about 100 Mt C in 2095 in the 450 stabilization scenario.

There were only minor deviations from these fuel trends across the scenarios analyzed. Advanced technologies did reduce costs of mitigation, however, shown in Figure 7. The ALL_ADV_450 scenario shows a 17% decrease in total policy costs relative to REF_450, or a decrease in $312 billion (2005 USD). The technology group associated with the greatest cost decrease is HP_450. This is because (a) the relatively short lifetimes of the equipment allow for fast stock turnover when new technologies enter the marketplace, reducing costs in early time periods (important for lowering discounted costs), and (b) these technologies facilitate switching from fossil fuels to electricity, which in these policy scenarios is an affordable, low-emissions fuel. Also of note, the policy cost savings (relative to the reference) of each single-group advanced technology scenario (SHELL_450, HP_450, SSL_450, and MISC_450) add up to $317 billion, only slightly greater than ALL_ADV_450.

Figure 5. Energy Consumption by Fuel in the U.S. Buildings Sector, with and without a CO_2 Stabilization Policy (REF and REF_450 Scenarios)

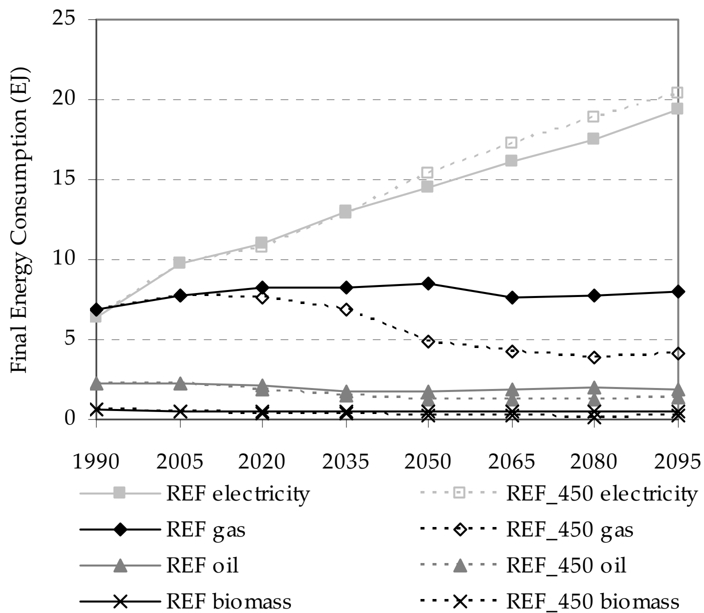


Figure 6. Total U.S. Buildings Sector Emissions, including Emissions from Electricity Generation and Oil Refining (REF and REF_450 Scenarios)

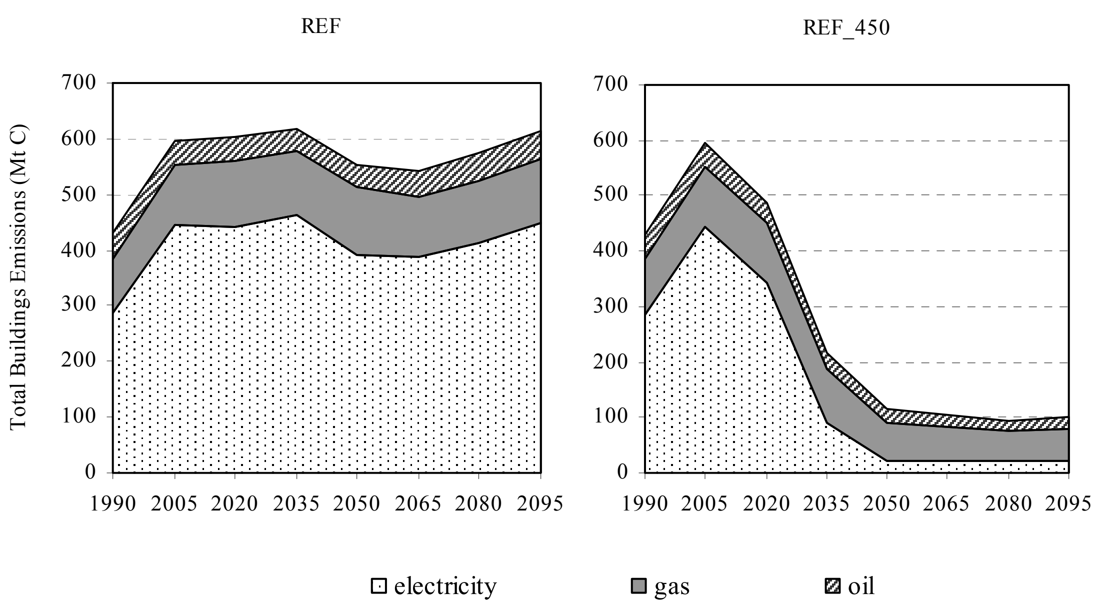
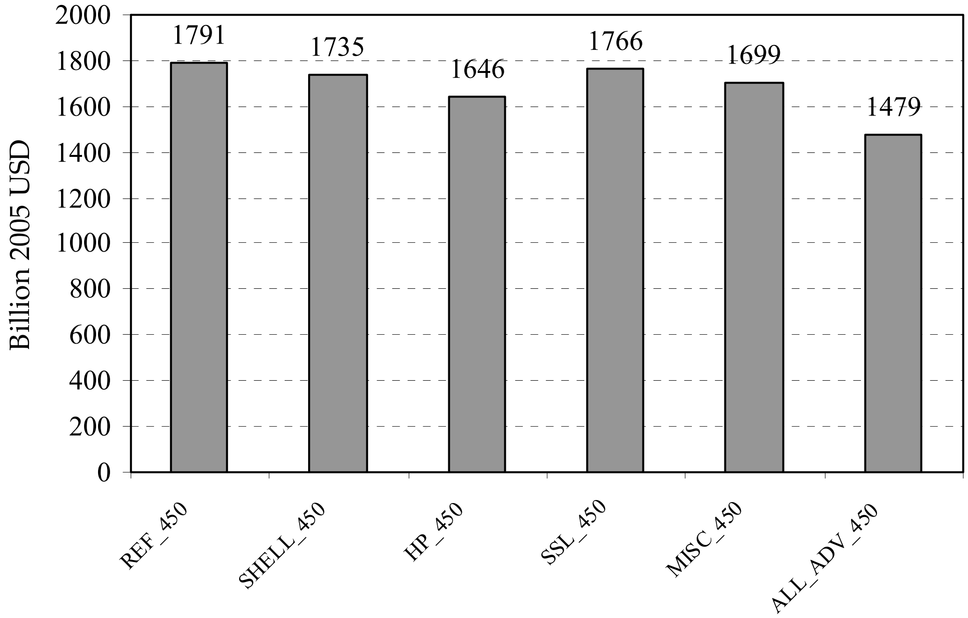


Figure 7. Total Discounted Costs by Scenario to meet 450 ppmv Stabilization Policy Targets



Conclusions

This study emphasizes the importance of an integrated approach to developing strategies to address climate change. We find that the technological response of the buildings sector to a carbon-constrained economy is to switch to electricity where possible, in conjunction with large-scale deployment of emissions-reduced generation technologies in the electric power sector. Therefore, technologies that enable electrification are important for facilitating this process. But switching to electricity in the buildings sector alone does not constitute a viable strategy to reduce emissions. In fact, without an emissions constraint, the average carbon intensity of electricity in 2095 (23 kg C/GJ) is greater than that of natural gas (14.2) or fuel oil (19.6).

This study also finds that each group of advanced buildings technologies leads to comparable policy cost savings whether in isolation or as part of an integrated, sector-wide deployment of all available advanced technologies. The implication is that the development of advanced technologies in one area are not redundant with advances in other areas. This underlines the importance of a multi-faceted approach to buildings sector research, development, and deployment.

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