Prioritizing Climate Change Mitigation Alternatives: Comparing Transportation Technologies to Options in Other Sectors

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Prioritizing Climate Change Mitigation Alternatives: Comparing Transportation Technologies to Options in Other Sectors

by

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ABSTRACT

Governments worldwide and in the U.S. are enacting a variety of measures to mitigate greenhouse gas emissions (GHG) from various economic sectors. Tools to prioritize these measures are generally lacking in analytical rigor. On the other hand, the research literature continues to proliferate with assessments of energy efficiency and GHG mitigation options that can be adapted to the policy evaluation process. This dissertation formulates an analytical method to better prioritize future climate change policy actions.

A framework is developed to integrate current research on climate change mitigation technology alternatives from all sectors of the U.S. economy on an equal footing. Applying consistent economic assumptions, a multi-benefit cost-effectiveness accounting tool is developed that simultaneously evaluates the technology costs, lifetime energy saving benefits, and GHG reductions in a single cost-per-tonne-reduced metric. The framework synthesizes the disparate studies' data to compare and prioritize options across sectors as well as determine the aggregate impacts from multiple sectors' GHG mitigation actions.

A broad portfolio of cost-effective technologies is available from each major sector of the economy. The findings indicate that there are many net-beneficial "no regrets" climate change mitigation technologies – where the energy savings of the technologies outweigh the initial costs – and most of these technologies are not being widely adopted. Transportation technologies are found to represent approximately half of the "no regrets" mitigation opportunities and about one-fifth of the least-cost GHG mitigation measures to achieve the benchmark 1990 GHG level. With the adoption of known near-term technologies, GHG emissions by 2030 could be reduced by 14% with net-zero-cost technologies, and emissions could be reduced by about 30% with technologies that each have net costs less than \$30 per tonne of carbon dioxide equivalent reduced.

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1. INTRODUCTION

The eleven-year period since the adoption of the Kyoto Protocol of the United Nations Framework Convention on Climate Change in 1997 has been a time of flux and uncertainty for U.S. climate change policy. As the international community has sought to re-engage the U.S. in cooperative global climate change action with mandatory emission reductions, the U.S. federal government has rebuffed any such effort in favor of voluntary industry initiatives and greenhouse gas emission intensity reduction targets. Complicating matters, many U.S. state and local governments and multi-national corporations have taken action to mitigate greenhouse gas emissions. Such a critical mass of bottom-up climate change mitigation action has amassed that it now appears inevitable that some form of federal climate change policy will be enacted to at least coordinate, and perhaps strengthen, the mitigation efforts.

Although climate change policy uncertainty has prevailed in the U.S., there is a silver lining to the years of federal inaction on climate change mitigation in the U.S. In the interim years from international rebuff to inevitable comprehensive federal policy, many steps that are supportive of the formulation of cost-effective climate change policy have been taken. Many state and city level emissions mitigation policy experiments have been enacted, and these initiatives continue to promote the emergence and wider adoption of greenhouse gas emission-reducing technologies. The development and deployment of emissions mitigation technologies (e.g., energy efficiency and renewable fuels) that the mitigation policies are directed at now have tangible results in terms of their demonstrations of feasibility, emissions impacts, and costs. Resolve to support climate change policy actions, shown by public polling on climate change and the manifest actions by governments, has solidified and decision-makers are following suit.

Just as state government commitment and popular resolve on mitigating climate change emissions strengthens, so too does the consensus of the climate change science community's understanding of the impacts of anthropogenic climate change and the climate change mitigation research communities' understanding of the mitigation options, their impacts, and their costs. This convergence of government action, climate science consensus, and mitigation research has made for the opportune timing to synthesize the varied climate change puzzle pieces to assess and quantify the potential emission reduction and cost impacts of the prospective federal U.S. policy actions on climate change. This study draws from current policy process in the U.S. toward climate change mitigation, literature on emissions abatement cost-effectiveness tools, and the wealth of technical data on climate change mitigation options to develop a framework to aid in the prioritization of U.S. climate change mitigation actions.

Following this introduction chapter, the layout of this dissertation goes as follows. Chapter 2 provides a policy background on sub-federal climate change mitigation initiatives in the U.S. In so doing, the chapter provides the prime motivations for the research presented in this dissertation. The chapter investigates the trends in increasing U.S. involvement – city-by-city, state-by-state, and through multi-government coalitions – in climate change mitigation and how these actions have essentially committed the U.S. to national climate change action, despite the federal inaction in terms of comprehensive climate change legislation.

In Chapter 2, it is shown that the accumulation of sub-federal action, at a minimum, commits the U.S. to a broad pervasive patchwork of multi-sectoral climate change mitigation options. These early actions might also lay the foundation for the sector-by-sector mitigation programs and cap-and-trade mechanisms that will ultimately form the basis for federal policy. The chapter also addresses the potential limitations of the sub-federal policy making and the remaining concerns for the states' ability to meet their emission reduction goals with their chosen mitigation policies.

After the Chapter 2 investigation of the status of U.S. policies on climate change, Chapter 3 delves into the methods in use by state governments in formulating their climate change action plans and the policy assessment tools of environmental policy literature. Strengths and limitations in the analytical policy assessment tools are highlighted. A gap is found between actual government assessment practices and best practices in the literature. Methodological advancements are proposed for the cost-effectiveness accounting of marginal greenhouse gas emission abatement policies. The result is the method to evaluate and prioritize climate change mitigation efforts that is applied in the subsequent chapters of this dissertation.

The following Chapters, 4 through 8, use the methodology that is developed in Chapter 3 to quantify the cost-effectiveness of alternatives to reduce greenhouse gas emissions from each sector of the U.S. economy. Finally, Chapter 9 brings the individual sectoral results together to compare, combine, and discuss the cumulative impacts, costs, and benefits of multi-sector GHG mitigation action in the U.S. Chapter 10 discusses the implications of this research, and Chapter 11 summarizes the research findings.

2. BACKGROUND ON U.S. CLIMATE POLICY

Climate change is often referred to as a global "commons" problem, whereby individuals are unlikely to take responsibility for global accumulation of atmospheric greenhouse gases.[1] This "commons" problem implies that top-down international treaties will ultimately be required to achieve substantial climate change mitigation. Yet, increasingly lower level governments within the U.S. are enacting their own climate change policy targets and greenhouse gas (GHG) emission mitigation regulations.

Over the past decade, the federal and state governments have diverged in their awareness and willingness to act on climate change in the U.S. Federal policy related to climate change has, through 2007, stopped short of mandatory emission reduction goals. The prevailing federal climate change mitigation goal in the U.S. is to reduce the national greenhouse gas emission intensity by 18% over the 10-year period from 2002 to 2012 (U.S. EPA, 2008a). This targeted reduction in GHG emission intensity – measured as greenhouse gas emission divided by the gross domestic output – sets a goal to slow the growth in national GHG emissions. The federal government has focused on research and development partnerships and voluntary programs while lower level governments have intensified their emissions mitigation actions.

The growing number of local and state level actions, including new energy efficiency funding mechanisms, aggressive renewable fuel requirements, and regulatory standards, contrast with the relative inaction at the federal level. State and local governments are utilizing policy levers available to them to act on climate change and, in part, to help encourage or influence more widespread federal action. The April 2007 U.S. Supreme Court ruling in the case of *Massachusetts v. EPA* (U.S. Supreme Court, 2007), could begin to put to rest many of the legal challenges against sub-national climate change initiatives. The numerous actions at lower levels of government can now more solidly by considered the first steps of the U.S. toward climate change mitigation. Local, regional, and state governments are now following a prescribed pattern of inventorying their emissions, establishing climate change action plans, setting emission reduction targets similar to those of the Kyoto Protocol, enacting state-level regulations and standards explicitly targeting greenhouse gases, and forging multi-government alliances to reinforce and support their actions. As more climate change mitigation efforts take shape, significant nationwide emission reductions may result. These first steps by governments concerned about climate change provide templates for national initiatives.

2.1. Sub-Federal Climate Policy

This Chapter 2 builds upon Rabe's (2004) careful categorization and cataloguing of state climate change policy and subsequent elaboration since (see e.g., Rabe, 2006; PCGCC, 2007; U.S. EPA, 2007a; Byrne et al., 2007). This chapter adds a quantification component by estimating the cumulative potential impacts of lower level government actions in the U.S. In

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[1] A version of this chapter is published as "America's bottom-up climate change mitigation policy" in *Energy Policy* (Lutsey and Sperling, 2008)

analyzing the potential impacts of state and local climate change mitigation policy, the advantages and limitations of the decentralized "bottom-up" approach are examined more broadly to provide a the background policy context for this dissertation research.

The relative merits of the power balance of environmental federalism – toward central federal authority or toward lower-level constituent political units – are well discussed in the literature (see, e.g. Buzbee, 2005; and Adler, 2005). Benefits of more decentralized regulatory action include allowing more experimentation by more policy-makers, local tailoring of specific actions to fit more aptly the environmental preferences of constituents of various states and locales, testing the political response of innovative regulatory and policy actions, and gaining the benefit of local expertise and experience in enforcing programs and policies.

However, enactment of state and local environmental policy initiatives may overlap and interact with one another in negative ways: patchwork regulatory programs pose additional administrative burden on industry, duplicative enforcement results in a waste of regulatory resources, and cross-boundary mismatch between pollution sources and impacts. Also, the pitfall of uneven performance by the various jurisdictions can have unintended consequences such as to encourage "shuffling," whereby companies redirect their low-carbon products (such as hydro-electricity) to jurisdictions with stringent rules and high-carbon products (such as coal-based electricity) to areas with weaker or non-existent rules. Finally, the issue of jurisdictional confusion over which level of government is responsible for a given environmental issue can be especially problematic in its potential to encourage inaction by decentralized lower level governments. This problem is highlighted by Adler (2005): "one cannot reasonably expect states, acting alone, to adopt welfare-enhancing environmental protections as the regulating state will bear a disproportionate share of the costs from such regulation with no guarantee of reaping proportionate benefits."

Considerable criticism has been directed at the current trend toward lower-level U.S. climate policy. Victor et al. (2005) generally favor the approach of early bottom-up policy action with later cooperation to control emissions, but they downplay these various lower level actions as lacking the necessary institutional leverage to amount to serious action on climate change. They cite as an example the 10 states with emission targets that only encompass 14% of the U.S. electric sector. Wiener et al. (2006) favor an international cap-and-trade market regime to coordinate all of the local actions, arguing that the ability of bottom-up local policies to move from "uncoordinated autarchy to the accretion of shared norms and informal cooperation" will be difficult and will have little chance of engaging other climate change mitigation partners.

On the other hand, several researchers have underscored the growing importance of lower level U.S. government action in the formation of federal U.S. climate change policy and on U.S. reengagement in international climate change policy. Rabe (2004) finds that U.S. state initiatives could help promote the development of federal U.S. climate policy in a bottom up fashion. Other researchers predict that future U.S. federal climate policy will evolve from and be motivated by major state and regional U.S. climate policy adoption trends (Selin and VanDeveer, 2007). Purvis (2004), on the general practice of the U.S. "to act first at home, and then to build on that approach at the international level," suggests that present environmental developments in the U.S. could eventually spur a new international climate change regime (i.e., post Kyoto Protocol) in which the U.S. would participate. Bang et al. (2007) find that the domestic "push" of lower level U.S. government actions could offer an alternate path toward international climate engagement for the U.S.; they conclude that two preconditions for U.S. participation in any global climate regime are the gathering of more experience and the crystallization of U.S. policy preferences. Perhaps most importantly, lower level engagement is key to real, long term progress. There must be a local commitment, down to individuals, to accomplish the type of economic and societal transformations that will be necessary to achieve very large reductions in carbon. The more engaged and the more powerful the commitment, the more likely it is that actual change will occur.

In this Chapter, trends in U.S. climate change policy actions are reviewed and their effects quantitatively measured. With an eye to what the lower level government actions could tell us about eventual federal climate change policy, quantification is offered on several questions: Just how committed is the U.S. toward emissions reductions in future years? What percentages of the U.S population and U.S. GHG emissions are covered by the current lower level climate policy actions? How much net reduction in national emissions can be gained by fully implemented lower level GHG mitigation initiatives? Based on this quantitative analysis, drawbacks of decentralized environmental policy action are examined, and critiques that current U.S. climate policy does not amount to serious action are assessed. Also discussed is the critique that lower level governments lack sufficient institutional leverage, and that these actions have little potential for wider engagement.

2.2. Potential Impacts of Current U.S. Policy

In the following sections, three types of GHG policy actions that are being employed by sub-national U.S. governments are investigated. First, the impacts of "top-down" state- and city-level GHG emission reduction targets (e.g., reducing state emissions to 1990 level by the year 2020) are analyzed. Second, acknowledging that there is little guarantee or binding regulation to assure that these top-level targets are achieved, specific "bottom-up" sector-specific GHG mitigation policies (e.g., emission standards for vehicles) that are directed at achieving those targeted reductions are looked at more closely. Third, multi-government activities that connect these mitigation efforts are explored.

The quantification of these measures requires the compilation of numerous government data sources that will be discussed below. To perform these calculations, a database was constructed with baseline characteristics, including GHG emissions, population, number of vehicles, and GHG-related policies, for each state. By inputting which states have adopted given policy actions alongside the emissions characteristics in the database, policy options are toggled "on" and "off" to examine impacts of "policy" and "no policy" scenarios, respectively. In addition, the dates of policy adoption are inputted to graphically analyze trends. The impacts on GHG emissions are explored based on the states' current chosen policies. Expanded state adoption of the policy measures is considered, beyond the states that have currently committed to such policies. Finally, the 50 states' GHG emissions – in varying policy adoption scenarios – are summed to determine the total potential national impact of the GHG mitigation policies.

2.1.1. Trends in emission reduction target-setting in the U.S.

Regional, state, and local greenhouse gas reduction actions have been chronicled by numerous researchers and organizations (Rabe, 2004; U.S. EPA, 2007a; PCGCC, 2007; Ramseur, 2007). As late as 2004, U.S. climate change policy efforts could be characterized as an uncoordinated patchwork of disparate initiatives. Now, in 2007, a more systematic strategy with a consistent set of actions is being undertaken by state governments. States that engage in climate change policy generally follow the steps of inventorying greenhouse gas emissions in the state, establishing a GHG registry, formulating a GHG mitigation action plan, and initiating programs and regulations to bring about GHG reductions in future years. Numerous governments are engaged in each of these climate change action steps (PCGCC, 2007; WRI, 2007b). These governments are guided by a variety of non-government and government agencies (Prindle et al. 2003; U.S. EPA, 2006a). States are routinely following similar paths for mitigation actions. At least twenty-six states have used, or are using, consistent methods to prioritize similar GHG mitigation actions (CCS, 2007).

Table 1 provides a summary of the current status of state and city climate policy actions with the current (as of mid-2007) levels of U.S. involvement, quantified by number of governments and percentages of the population and national GHG emissions associated with each action. In the table, U.S. population involvement percentages are calculated, based on which states and cities have undertaken the actions (from PCGCC, 2007; U.S. EPA, 2007a; U.S. MCPA, 2007), the total population in those jurisdictions (from U.S. Census Bureau, 2007), and the states' GHG emissions (from U.S. EIA, 2006 and WRI, 2007a).

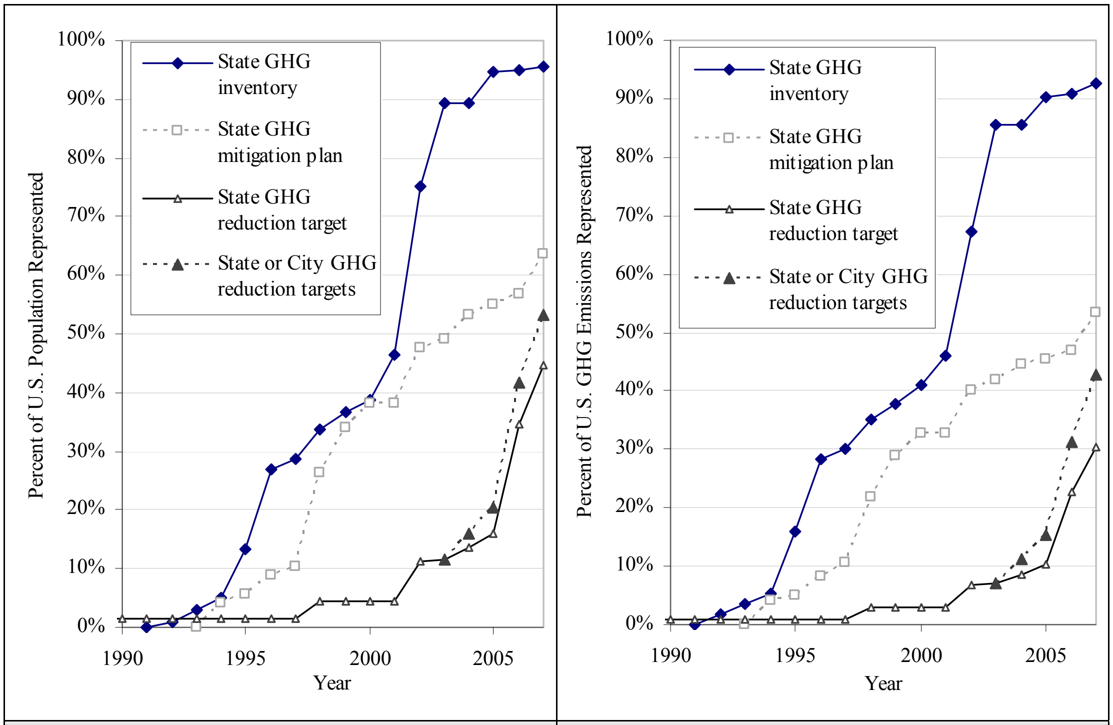
Shown in Table 1 are the percentages of the 2007 U.S population that are in states that are currently GHG inventoried (96%), have state climate change action plans (64%), and have state-wide GHG emission reduction goals (45%). The additional impact of the city-level targets (for the 285 cities that are *not* in states with emission targets) is also shown; these city targets increase the proportion of the U.S. population in regions with GHG emission-reduction targets to 53%. Perhaps more important than the population involvement is the representation of those government actions in terms of their portion of U.S. GHG emissions. State-level inventories cover 93% of the nation's GHG emissions; state mitigation plans, 53%; and state GHG emission targets, 30%. In the absence of city-specific emissions data, the impact of the cities' initiative on emissions is estimated based on average GHG-per-person data for each of the respective states, which likely overestimates emissions for larger cities and undercounts for the smaller cities. Also, the U.S. GHG emissions representation percentages in the far right column are lower than percentages for the U.S. population mostly because the more active climate action states tend to have lower GHG-per-person intensities than states that are undertaking fewer mitigation actions.

Table 1. Involvement in climate change actions by U.S. states and cities

Climate change action	Description of climate change action	Area represented by climate change action	Percent of 2007 U.S. population [a]	Percent of 2007 U.S. GHG emissions [b]
City GHG emission reduction target	Target to reduce cities' GHG emissions to 7% below 1990 GHG levels by 2012	684 U.S. cities, including Chicago, Dallas, Denver, Los Angeles, New York [c]	26%	23% [e]
State GHG emission reduction target	Targets to reduce state GHG to specific emission levels in future years (generally to 1990 GHG levels by 2020)	17 U.S. states: AZ, CA, CT, FL, HI, IL, ME, MA, MN, NH, NJ, NM, NY, OR, RI, WA [e]	45%	30%
City or state GHG emission reduction target	Targets to reduce cities' and states' GHG emissions to specific levels in future years	17 states plus the 284 target cities that are *not* in the 17 target-setting states	53%	43% [e]
State GHG action plan	State plan that identifies and evaluates feasible and effective policies to reduce GHG emissions	30 states [d]	64%	53%
State GHG inventory	State data collection report that quantifies GHG emissions by states sources and sectors	42 states [d]	96%	93%

[a] *based on U.S. Census Bureau, 2007;* [b] *based on U.S. EIA, 2006 and WRI, 2007a;* [c] *U.S. MCPA, 2007;* [d] *based on PCGCC, 2007 and EPA,2007;* [e]*based on cities' state average per capita GHG emissions because city-level GHG emissions were not widely available for the 684 initiative-participating cities*

In Figure 1 the time dimension is added to show adoption trends of GHG inventory completion, GHG action plan formulation, and GHG target-setting. The first two precursors to state GHG mitigation, inventories and climate change action plans, both experienced large increases in U.S population involvement and U.S. GHG coverage from 1994 to 2007. The growth in enactment of emission reduction targets, from about 5% to 53% of the population in less than six years, is important for several reasons. The target-setting commits policy-makers to delivering substantive emission reductions, and they provide a firmer framework than plans and mitigation assessment studies. Furthermore, the rapid ramp-up of target setting, from 2001 to 2007, for governments serving over half the population, reveals an expanding enthusiasm that may inspire other state policy-makers to proceed beyond simply conducting inventories and mitigation plans.



U.S. Population

U.S. GHG Emissions

Figure 1. Trends in U.S. involvement in climate change actions, 1990-2007

Table 2 shows the results for the overall U.S. impact of the lower level government target-setting on future U.S. GHG emissions, assuming for now that all target reductions are achieved. The U.S. DOE *Annual Energy Outlook 2007* (U.S. EIA, 2007) forecast is used as a baseline for U.S. energy and emissions characteristics. The states with GHG goals generally aim to reduce emissions to 1990 levels by 2020, and in some cases to 10% below 1990 levels by 2020. Some have more aggressive goals beyond 2020, but only the impact of the 2020 goals is shown. City targets are most commonly set to reduce emissions to the U.S. Kyoto Protocol level of 7% below 1990 levels by 2012, and these cities' emissions are then assumed to hold constant at that level through 2020. All other (i.e. non-target-setting) states and cities are assumed to continue on their general emission growth trends, according to the U.S. EIA (2007) baseline outlook. The current cities' initiative, if all the cities achieved their goals, would equate to a 7% reduction of U.S emissions from the 2020 baseline. The cities' and states' goals, if both achieved, would reduce U.S. emissions by about 13%. This 13% reduction from the baseline would be equivalent to 47% of the total U.S. emission reduction that would be required to meet the benchmark of the 1990 U.S. emission level. The result of the state and city initiatives would be to approximately stabilize U.S. GHG emissions at their 2010 levels until the year 2020, after which increases resume due to business-as-usual increases in the non-climate-action states' GHG emissions.

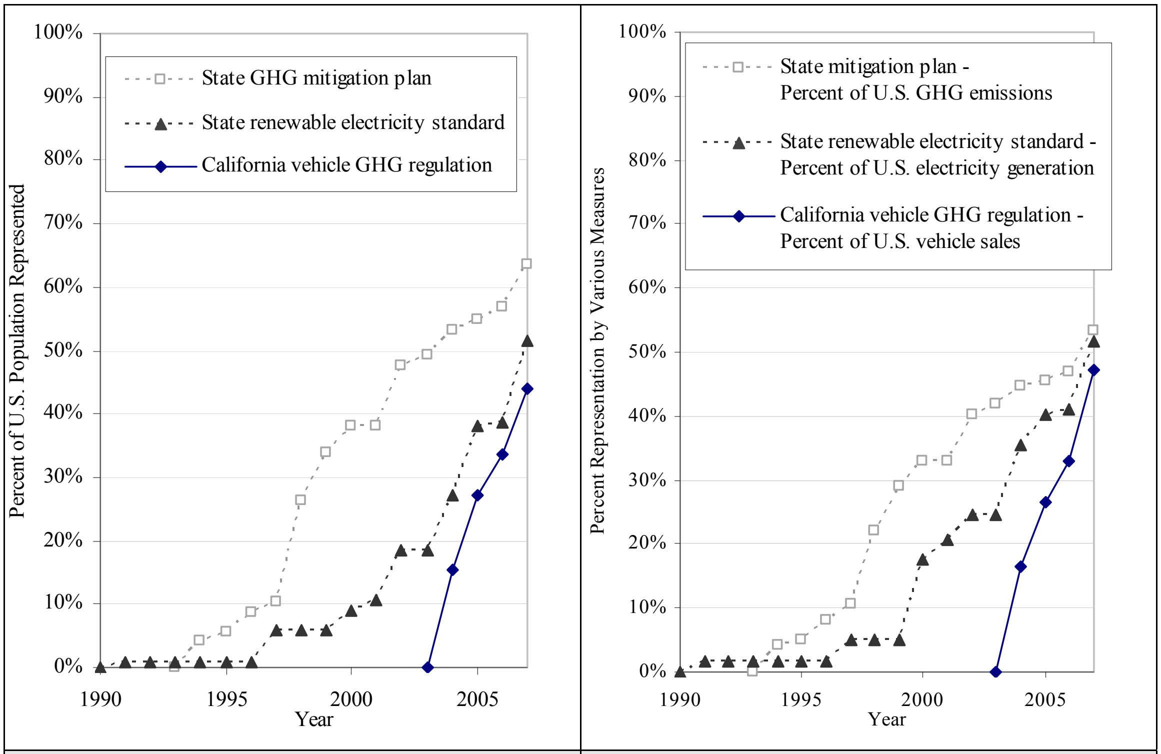
Table 2. Emission reduction impact of state and local climate policy in the U.S.

Scenario	Areas of GHG reductions	2020 emissions (MMT CO2e)	2020 reduction (MMT CO2e)	Percent reduction from baseline	Percent of reductions to meet 1990 emissions level in 2020
Baseline - no state GHG reduction targets achieved (US EIA, 2007)	None	8,146	0	0%	0%
Target-setting cities reach 7% below 1990 GHG levels by 2012	684 U.S. cities representing 26% of the U.S. population	7,549	597	7%	27%
Target-setting states achieve their target reductions	17 U.S. states representing 45% of U.S. population	7,418	728	9%	33%
Target-setting cities and states reach GHG target reductions	17 states plus the 284 cities that are not in the 17 target-setting states	7,168	1041	13%	47%
U.S. 1990 GHG emissions	-	5,910	2,237	27%	100%

2.1.2. Trends in sector-specific GHG mitigation actions in the U.S.

Many state and city policy-makers have backed up their "top-down" GHG emission target-setting directives by enacting sector-specific policy mechanisms. The largest GHG emissions contributors are power plants and vehicles, which represent 39% and 32% of U.S. GHG emissions, respectively (U.S. EIA, 2007). Many states are now targeting these sources with mitigation policies (PCGCC, 2007; CCC, 2007; Nadel, 2006). Other targets for state actions include residential energy usage (with appliance standards) and agricultural and forestry sequestration. Local mitigation action areas include land use, transportation planning, building codes, and waste reduction policies. This subsection focuses on the impact of major policies in the two largest GHG sectors and therefore does not comprehensively discuss the full array of GHG policy options being undertaken. For example, this research does not attempt to analyze the potential impacts of the implementation of states' vehicle travel reduction measures.

In this subsection, trends in the two foremost climate change action areas – light duty vehicles and renewable electricity – are investigated for their ability to deliver U.S. GHG emission reductions in future years. Figure 2 shows the extent of GHG regulations for vehicles and renewable electricity standards by summing the individual states according to when they engaged in the climate actions. Measured in terms of both population and the units that these programs operate on (light duty vehicle sales and electricity generation), each of these initiatives cover about half of the U.S. The increased involvement in the California vehicle standard is more abrupt – from 2004 to the present – on account of the other (i.e. non-California) states only legally being able to follow California's 2004 regulatory adoption, whereas states have had the ability to adopt renewable electricity targets as they wish since the early 1990s.



U.S. Population | U.S. GHG Emissions

Figure 2. Trends in U.S. involvement in climate change actions plans, vehicle GHG regulation, renewable electricity standard, 1990-2007

Actions to reduce emissions from vehicles, both in the U.S. and globally, historically have originated in California. In 2002, California passed Assembly Bill 1493 to establish regulations for reduced greenhouse gas emissions from vehicles, and in 2004 its Air Resources Board promulgated standards that require vehicle makers to reduce average new light duty vehicle GHG emissions (measured in CO_2-equivalent grams per mile) by 30% by model year 2016. Implementation is on hold as of mid-2007 as a result of legal challenges and a delayed federal approval of a waiver. Since California's 2004 adoption of the regulation, 14 other states have indicated intent to adopt the same rules (CCC, 2007). These 15 states represent 30% of total U.S. GHG emissions, 39% of U.S. motor gasoline usage, and 47% of U.S light duty vehicle sales.

California and other states have also adopted an assortment of renewable fuel initiatives that will impact light duty vehicle GHG emissions. At least 31 states now have mandates and incentives to blend biofuels into their transportation fuels (PCGCC, 2007). These 31 states with biofuel initiatives represent 72% of U.S. GHG emissions and 68% of U.S. motor gasoline usage. The most prominent state actions in this area are Minnesota's 20% ethanol fuel standard for gasoline by 2013 (State of Minnesota, 2005), Hawaii's alternative fuels standard for 20% renewable content in motor fuel by 2020 (State of Hawaii, 2006), and California's low carbon fuel standard to reduce the carbon fuel content of on-road vehicle fuels by 10% by 2020 (State of California, 2007).

In June 2006, the California Air Resources Board adopted its "low carbon fuel standard," aggressively championed by Governor Schwarzenegger, and began rulemaking. It is scheduled to take effect in January 2010. Other states are considering it, several leading candidates for the U.S. presidency endorsed it in 2007, the European Union was considering a similar rule, and several bills modeled on the California standard were submitted to the U.S. Congress. This standard is considered here for several reasons: (a) it is a GHG-specific mandate, (b) it could potentially have a large effect on GHG emissions, (c) it is a flexible performance target that is relatively attractive to industry because it allows alternative compliance (e.g., corn-based ethanol, cellulosic ethanol, plug-in hybrids), and (d) the California standards have historically been emulated elsewhere.

Estimation of the overall impacts of the state-level mitigation measures for transportation relies heavily on the U.S. Department of Energy's *Transportation Energy Data Book* (Davis and Diegel, 2006). Baseline gasoline and ethanol usage are based on federal motor gasoline receipts (U.S. FHWA, 2006), and baseline data on new light duty vehicle sales are derived from Polk data (from NADA, 2006).

Scenarios for adoption of California's vehicle and fuel GHG standards by other U.S. states are shown in Table 3. With adoption of the California vehicle regulation by just the 15 interested states, U.S light duty vehicle emissions in 2020 would be reduced by 4% from the baseline and 11% of the way toward the sector's 1990 level. If the 31 current biofuel-action states adopted the California low-carbon fuel standard, the effect would be about double that of the 15 vehicle GHG regulation-adopting states. If all of the U.S. states adopted both California's vehicle and fuel programs for GHG mitigation, the U.S. light duty vehicle sector would experience a 248 million metric tonne CO_2e reduction in emissions, or an 18% reduction, from the 2020 baseline.

Table 3. Impact of adoption of California vehicle and fuel GHG standards by U.S.

Scenario	2020 GHG emissions (MMT CO2e)	2020 GHG reduction (MMT CO2e)	Percent reduction from baseline	Percent of reductions to meet 1990 emissions level in 2020
U.S. light duty vehicle baseline (US EIA, 2007)	1,408	0	0%	0%
If 15 U.S. states implement California vehicle GHG standard [a]	1,357	51	4%	11%
If 31 U.S. states implement California low-carbon fuel standard [b]	1,311	97	7%	21%
If all U.S. states implement California vehicle GHG standard	1,294	114	8%	25%
If 15 U.S. states implement CA vehicle standards and 31 U.S. states implement CA fuel standard [a,b]	1,264	144	10%	32%
If all U.S. states implement California low-carbon fuel standard	1,262	146	10%	32%
If all U.S. states implement California vehicle and fuel standards	1,160	248	18%	55%
U.S. 1990 GHG emissions	955	453	32%	100%

[a] *the fifteen states that adopted or have expressed interest in adopting California's vehicle GHG regulation (PCGCC, 2007);*
[b] *the thirty-one states that have currently adopted biofuel mandates and incentives (PCGCC, 2007)*

Figure 3 shows the trend lines for U.S. light duty vehicle GHG emissions under varying levels of adoption of the California vehicle GHG regulation and California low carbon fuel standard. The impact of the vehicle regulation, phased into new vehicles through model year 2016, takes several years after that to impact emissions as older, higher-GHG vehicles gradually retire from the fleet. The low carbon fuel standard, phased in from 2010 to 2020, has approximately the same effect as the vehicle regulation when fully implemented, if adopted by the same states. Although adoption of the California vehicle standard by the 15 committed states and the fuel standard by the 31 biofuel incentive states have only modest impacts on total U.S. transportation GHG emissions, expanded adoption of these programs would yield sizable reductions. If all of the U.S. states adopted both California's vehicle and fuel programs for GHG mitigation, the U.S. light duty vehicle sector would be 55% of the way from the 2020 baseline to the 1990 level.

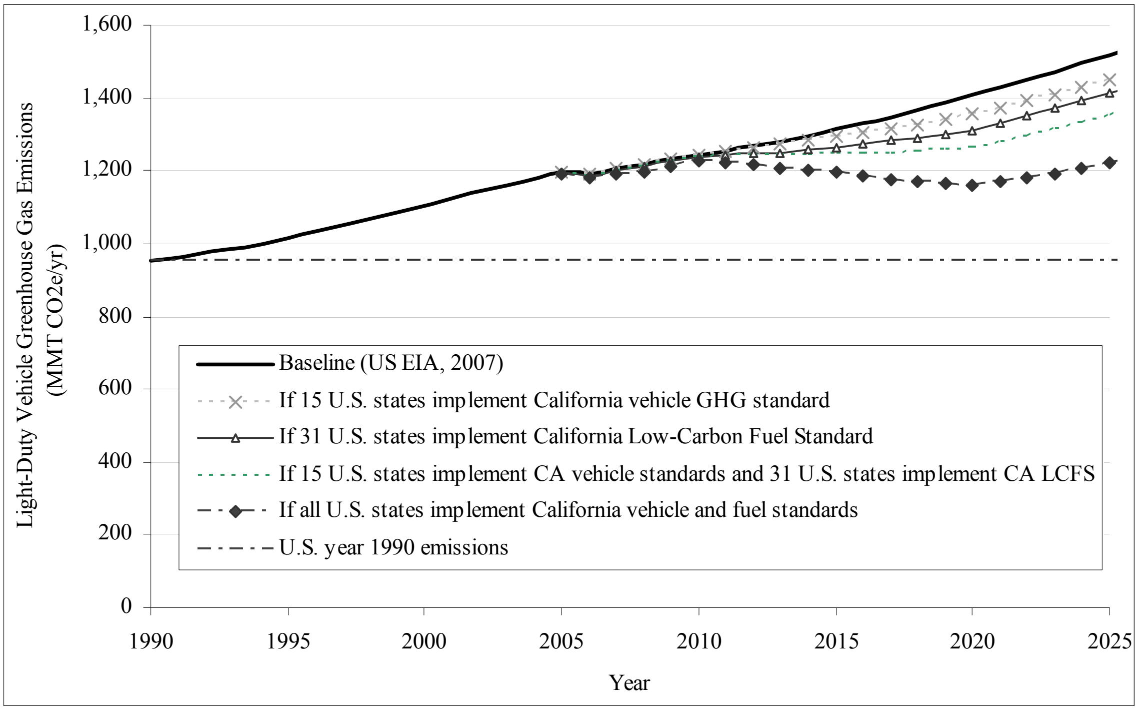


Figure 3. U.S. light duty vehicle greenhouse gas emissions with adoption of California vehicle and fuel standards by other U.S. states

A very different but potentially effective set of state-level strategies is being undertaken to reduce GHG emissions from the electricity sector. Several states have experimented with power plant regulations for GHG emissions. For example, Massachusetts and New Hampshire have introduced mandated reductions from older plants, while Oregon and Washington implemented regulations for levels of new power plant emissions (Ramseur, 2007). In addition, several states have adopted energy efficiency resource standards, which set targets for electricity and natural gas energy savings (Nadel, 2006). The most widespread power sector action is the adoption of renewable electricity portfolio standards (either as mandates or goals) that are now in place in 29 states (plus the District of Columbia). The state renewable electricity programs target increasing amounts of renewable energy to produce electricity.

The states renewable initiatives are diverse (Petersik, 2004). Some states include large conventional hydroelectric power, municipal solid waste, and geothermal electricity generation as acceptable, while others do not. Some mandate particular portions of the renewable electricity from particular sources like solar and wind. Some are voluntary commitments with particular utility companies while some are binding state mandates. Because of the current popularity of this particular mechanism, representing 52% of U.S. electric sector GHG emissions, 59% of total U.S. GHG emissions, and 59% of U.S. electric power generation, the impact of this measure is investigated for U.S. GHG impacts in this Chapter's analysis. The renewable percentage targets range from 2% up to 30% of the states' electricity, and generally have target years between 2015 and 2020. An electricity generation-weighted average of these measures is a 15% renewable portion of these states' electricity by 2017 (not including conventional large hydroelectric power in the percentage).

To quantify the emissions impacts of the state renewable initiatives, baseline state-by-state electricity characteristics were taken from the U.S. DOE (2006) data tables that quantify electricity by state and by source. Several assumptions are made to estimate the impact of the renewable electricity policies on U.S. electric sector emissions. The fossil fuel-related carbon intensity (GHG emissions per kWh electricity generation) of each state is assumed to improve at the same rate as the national average, based on the U.S. EIA (2007) forecast. New renewable electricity is assumed not to be from large conventional hydroelectricity (per general stipulation of state renewable electricity standards). A wide range of studies (e.g. Norton, 1999; Mann and Spath, 2002; Bergerson, 2005) suggest that renewable electricity from biomass, wind, solar, and hydro plants offer a 90% to greater than 100% reduction in GHG emission rates from baseline non-renewable (i.e. from present mix of fossil fuel and nuclear generation). A 95% GHG reduction from renewable electricity generation, as compared to average fossil fuel-based electricity generation, is assumed. After renewable percentages are entered for given target years for each state, the trends from 2006 to the target years are estimated as linear.

Figure 4 shows the resulting U.S. electric power sector emissions under the baseline, and for 29-state (plus D.C.) adoption of renewable electricity programs and full 50-state U.S. adoption. Here the general convention applied by states that large hydroelectric is not counted toward the renewable portfolio standards is followed. The combined impact of the state measures is equivalent to a 9% national renewable electricity target in 2020 assuming that large conventional hydroelectric power is not included (this equates to 17% total renewable if large hydroelectric is included in the calculation). The national emission trend is only modestly disrupted by the implementation of the 30 renewable electricity programs, with a 6% reduction in electric sector GHG emissions in 2020. Extending the renewable introduction beyond those 30 programs to the entire U.S. would more than double the emissions impact. If the average 17% renewable electricity standard was adopted across all 50 states (equivalent to 24% renewable electricity if large hydroelectric is included), the impact would reduce baseline 2020 emissions from the electricity sector by 18%. Extending renewable electricity goals to other states has a greater (i.e. non-linear) impact because the states in 2007 that do not have such programs have greater carbon intensities those states with renewable electricity standards.

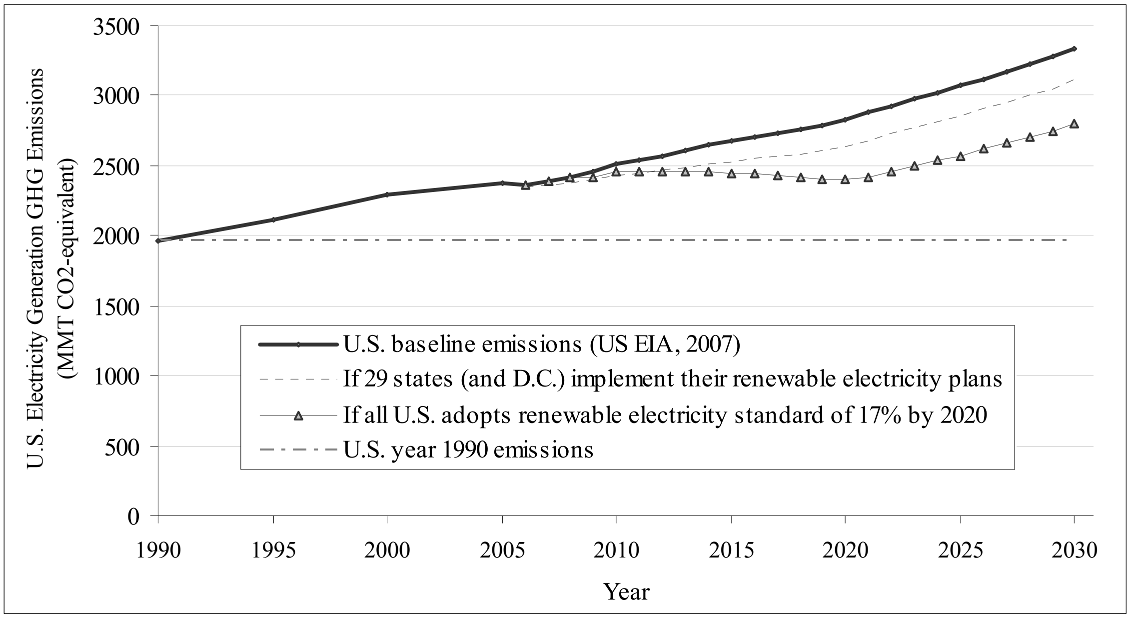


Figure 4. Impact of state renewable electricity plans on U.S. electricity GHG emissions

2.1.3. Trends in multi-government climate change coordination

Local and state governments in the U.S. are expanding their multi-government alliances to develop emission tracking systems and trading systems. As introduced in the literature review, state-level actions are often confounded by lack of policy expertise in these areas and their inability to deal with cross-boundary jurisdictional issues. To address these limitations, hundreds of dispersed city governments have joined together in information-sharing alliances, states are engaging in cross-sector cooperation and developing emissions trading mechanisms to connect and incentivize actions across state lines, and some states are even forging alliances with other countries. This subsection investigates these multi-government trends.

Table 4 summarizes the scale and coverage of major multi-government climate mitigation alliances in the U.S. These initiatives are listed chronologically in order of their particular statements or commitments that relate specifically to GHG mitigation. The alliances engage in standardization of emissions inventories and tracking, development of region-specific energy and emissions technologies, and development of emissions trading or cap-and-trade mechanisms to integrate the diverse mitigation programs of the participants. Two important features in these multi-government developments are (1) the mandatory aspect of the cap-and-trade system for participants of the Regional Greenhouse Gas Initiative, and (2) the setting of a specific time (i.e. August 2008) for establishment of a multi-sector market-based emissions trading system in the Western Climate Initiative.

Table 4. Multi-government climate change coordination involvement in the U.S.

Government partnership	U.S. participation (year of initiation)	Selected climate change coordinating actions	Percent U.S. population	Percent U.S. GHG emissions
New England Governors and Eastern Canadian Premiers [a] (NEG/ECP)	6 states: CT, MA, ME, NH, RI, VT (2001)	Standardize inventories, coordinate reduction plans, Create uniform regional registry to form basis for emissions banking and trading	5%	3%
West Coast Governors' Global Warming Initiative [b] (WCG GWI)	3 states: CA, OR, WA (2003)	Inventory update, protocol establishment, research collaboration, Establish a market-based carbon allowance system	16%	10%
U.S. Mayors' Climate Protection Agreement [c] (US MCPA)	684 cities (2004-2007)	Urge state and federal governments to enact climate policy and establish an emissions trading system	26%	23%
Regional Greenhouse Gas Initiative [d] (RGGI)	10 states : CT, DE, MA, ME, NH, NJ, NY, RI, VT, MD, also DC and PA observing (2005-2007)	Develop cap-and-trade program for GHG emissions, first for power plants. Accommodate diversity in participant states' programs, later expansion to other sources, states.	16%	10%
Western Governors' Association [e] (WGA)	19 states: AK, AZ, CA, CO, HI, ID, KS, MT, NE, NV, NM, ND, OK, OR, SD, TX, UT, WA, WY (2006)	Coordinate on development of renewable energy, energy efficiency, and carbon sequestration, and support market-based policy to reduce GHGs.	34%	35%
Powering the Plains [f] (PTP)	5 states: IA, MN, ND, SD, WI (2006)	Develop efficiency, renewable energy, and carbon sequestration technologies; develop renewable energy credit-tracking and trading system	5%	7%
Southwest Climate Change Initiative [g] (SWCI)	2 states: AZ, NM (2006)	Collaborate on GHG mitigation strategies, develop consistent forecasting, reporting, and crediting practices	3%	2%
Western Climate Initiative [h] (WCI)	5 states: AZ, CA, NM, OR, WA (2007)	Establish registry and tracking systems, regional emissions target, and by August 2008, multi-sector market-based system	19%	13%
The Climate Registry [l] (CR)	40 states (2007)	Collaboration to develop a common system for reporting greenhouse gas emissions	83%	73%
Total U.S. involvement in multi-government coordination initiatives (Through September 2007)			94%	89%

[a] NEG/ECP, 2001; [b] WCG EC, 2004; [c] U.S. MCPA, 2007; [d] RGGI, 2005; [e] WGA, 2006; [f] GPI, 2007, [g] New Mexico, 2006; [h] WCI, 2007; [i] CR, 2007

The time trend of the U.S. multi-government climate policy cooperation is shown in Figure 5. Most growth in multi-government coordination has occurred since 2002. Comparing these trends with the very similar trends in Figures 1 and 2 for state action plans, it would appear that states are becoming increasingly concerned about climate change and are recognizing the importance of allying with other states to coordinate, collaborate, and integrate their emission reduction initiatives. When including all of the states (and the cities not in those states) that are involved in the six major climate mitigation coordination efforts, approximately 90% of population and GHG emissions of the U.S. are involved in mid 2007 in actions to coordinate sub-national climate change mitigation.

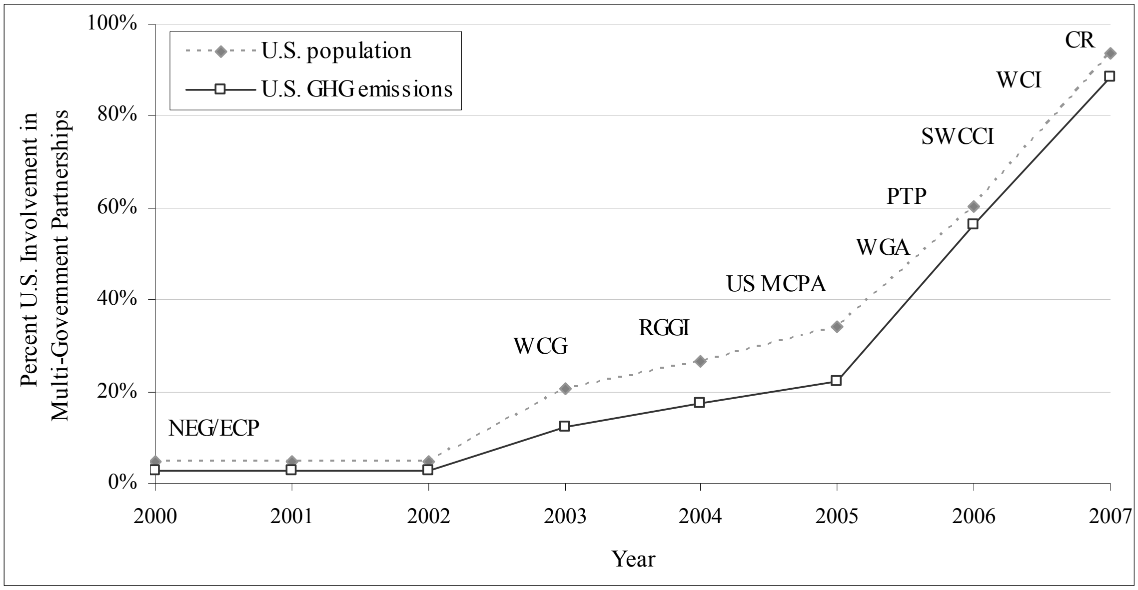


Figure 5. Trends in U.S. involvement in multi-government cooperation in climate change mitigation

2.3. Discussion

The benefits of decentralized sub-national government action can be substantial. There are many circumstances and cases where locally-led initiatives are quite compelling. For example, local governments can be more innovative and more responsive to local environmental preferences and economic circumstances. In the case of the U.S., where the federal government has been reluctant to lead efforts to reduce GHG emissions, efforts by lower level governments take on added weight. It may make sense for more resource-constrained or less innovative local and state governments to learn from, or emulate, others' actions in a cascading process.

In many cases, however, national initiatives are far more compelling than a patchwork of local initiatives. Vehicle emission standards are a good example, since standardization and mass production leads to lower technology costs. In the case of global pollutants, the case is even more compelling than with local pollutants, where the value and importance of reductions varies greatly depending upon the severity of the problem in any particular locale.

The critique that states do not have sufficient leverage on climate change – an example of the well known "commons" problem in environmental policy – is undermined by the expanding initiatives by lower level governments in the U.S. Victor et al. (2005) commented that state-level actions like emission target-setting, which at that time involved 10 states with 14% of U.S. electricity generation, lacked the necessary leverage for serious impacts. Earlier statements such as this did not anticipate the snowball effect now underway or the creative use of a variety of policy levers to effect change. The state renewable electricity standards cover more than half of U.S. electricity generation, and states representing about half of U.S. vehicle sales are poised to adopt the California GHG regulation for vehicles. A pivotal April 2007 U.S. Supreme Court (2007) ruling found that GHG emissions fit within the federal definition of "air pollutant" and that states have standing to further their GHG mitigation rulemaking efforts.

The overall U.S. GHG emissions effect of the state and city emission targets could, if realized, stabilize U.S. emissions at 2010 levels by 2020. The two major sector-specific mitigation efforts, those targeting vehicles and electricity, could put modest dents in national GHG emissions for their sectors with the current level of state involvement – and substantial reductions if extended to the entire U.S. Although these reductions are nowhere near the deeper longer-term reduction that would be required for climate stabilization, they are nonetheless substantial and significant relative to federal inaction.

Lower level U.S. governments are learning to avoid the problem of creating a patchwork of diverse regulations for industry. They are accomplishing this by following consistent sets of mitigation actions prescribed by state policy innovators and adopting approaches that do not dictate particular technologies. Government action on climate change mitigation is generally following the steps of establishing an emissions inventory, developing a mitigation action plan, setting an emission reduction target, enacting sector-specific policies, and partnering with other governments to integrate their efforts and leverage their reductions. To accommodate further adoption by other states, principles of flexibility and incentives are being widely adopted. The California vehicle GHG regulation, the California low carbon fuel standard, and renewable electricity standards are all performance standards that allow individual states (and industries in those states) the flexibility to choose the emission-reduction technologies that suit local circumstances.

The "commons" problem is falling away as more sub-national governments learn to work together. Early pioneering state actors saw themselves as models and leaders to be followed by others. For example, the first state-level emission target-setting, by Vermont, was advanced with a stated objective to demonstrate that "there are things individual Vermonters, the state and the nation can do" (Vermont, 1989). When California was developing its vehicle GHG regulations and later its low carbon fuel standard, state leaders very deliberately watched and coordinated their efforts with other governments, within and outside the U.S. The related vehicle regulatory report cites the importance of the combined impact of the adoption of similar mitigation measures for vehicles in other U.S. states and other countries (Canada, Japan, and in Europe) (CARB, 2005). In addition, the low carbon fuel standard was developed through continuing discussion with leaders in other U.S. states and the European Union, which proposed to adopt a standard nearly identical to California's just weeks after California's initial announcement (EU, 2007; State of California, 2007).

The tacit agreements between individual states are steadily giving way to formalized agreements between sub-national U.S. governments. The U.S. partnerships of western states, midwestern plains states, northeastern states, and cities across the map now represent about 90% of the U.S. population and GHG emissions. These partnerships bind their climate mitigation efforts with coordinated research into mitigation technologies, work toward consistent emissions inventory protocols, and seek to ultimately merge those emission-reduction submarkets. This trend toward committed partnerships, often involving emissions trading, offers the prospect of overcoming cross-boundary jurisdiction issues (e.g., electricity generated in one state is consumed in another), and also cross-sectoral issues (e.g. farm-grown ethanol blended in gasoline in other states).

Furthermore, U.S. multi-government initiatives are even creating bridges with countries *outside* the U.S. New Jersey and the Netherlands signed a letter of intent to develop joint mitigation initiatives and establish a framework for a crediting and trading system for GHG emissions (New Jersey, 1998). Some U.S. states and Canadian provinces are forming alliances to permit emissions trading between electricity plants and perhaps other sectors (WCI, 2007; RGGI, 2007; NEG/ECP, 2001). California and Canada policy-makers had numerous discussions on the stringency and consistency of their vehicle GHG programs as they both broke from federal U.S. vehicle emissions policy (NRCan 2005; CARB, 2004). The agreement between the governments of California and the United Kingdom to collaborate on climate change mitigation even aspires to work with other countries like China and India for further reductions outside their borders (State of California, 2006b). While these agreements and discussions may be hampered or even stopped by constitutionality questions, these pacts between U.S. state governments and foreign governments challenge the conventional wisdom that state-level action is incompatible with international involvement, and at a minimum likely will facilitate later agreements between the national governments.

In the end, though, the fact remains that about half the U.S. states have not yet meaningfully engaged in climate change mitigation. The implications of this uneven environmental performance are uncertain. In some cases, as with renewable electricity targets, national rules are not critical and may even be undesirable. For example, setting renewable electricity standards and their allowable criteria may very well depend on each state's particular available resources. In other cases, as with vehicle emissions, it is desirable to develop a single approach in dealing with automakers. Given that GHGs are a global concern and that the cost of mitigation can vary dramatically across regions and industries, it is important that local and state governments gain more experience and expertise. At some point they will likely be confronted with national initiatives. Some states, such as California, will be well prepared, as will some companies and industries (and may even resist being subsumed into national initiatives). Others will not be well prepared. The surge in local and state activity will play a crucial role in the formation of multi-government compacts to develop emissions trading systems across sectors and political jurisdictions.

2.4. The Promise and Limitations of Current U.S. Policy

A wide variety of sub-national initiatives to mitigate GHG emissions is underway. Many policy actions are leading to direct and significant emission reductions. Others are setting the stage for future incentives and enforceable policies and rules.

A consistent U.S. policy structure is emerging. States (and cities) inventory their emissions, investigate GHG mitigation action plans, and commit to future emission reductions. These governments then choose from a menu of available policy alternatives, such as vehicle GHG standards, fuel standards, appliance efficiency standards, and renewable electricity portfolio standards, and innovate with particular policy instruments that are tailored to each specific locale. State governments cooperate and coordinate their actions via multi-state regional initiatives, which appear to be on the way to eventually establishing emission trading markets. These actions are beginning to add up to a sizable portions of U.S. population and GHG emissions and substantial potential GHG emission reductions.

The commitments of lower governments on climate action are steadily amounting to substantial emissions reduction commitments. Sub-national U.S. mitigation efforts represent engagement by 43% to 89% of the affected populations and responsible parties – including 53% coverage of GHG emissions by state climate change mitigation action plans; 43% coverage of emission sources by state or city emission reduction targets; 58% coverage of U.S. electricity production by state renewable electricity standards; 47% coverage of U.S. vehicle sales by state vehicle GHG regulations; and 89% coverage of U.S. GHG emissions by multi-government partnerships supporting the establishment of GHG market mechanisms. If the 17 states that have set their own GHG emission reduction targets (generally to 1990 levels by the year 2020) in fact were to achieve those targets, nationwide U.S. GHG emissions would be stabilized at 2010 levels by 2020 – without any serious mitigation action taken by over half the states.

Governments are making progress toward overcoming the "commons" problem of climate change by putting in place a broad range of state and city-level policy mechanisms. They are gaining much experience about what works, how to leverage their efforts, and how to link across jurisdictions and sectors.

Of course, governments (and industry) are still at the bottom of the learning curve, though now perceptibly moving up that curve. Even so, these efforts should not be overstated. The adoption and pursuit of targets, goals, and potential reductions should not be confused with actual mitigation performance, and what has been accomplished still falls far short of the much deeper longer-term cuts that will be needed for global climate stabilization. Moreover, even the best intentions of multiple multi-government partnerships developing consistent emissions tracking systems do not ensure that a cross-jurisdiction and cross-sectoral emissions trading mechanism will come to fruition anytime soon, never mind function well.

What is clear, though, is that lower level government policy structure need not preclude, and can certainly advance, federal policy in the area of climate change. Broad efforts of states and cities are so pervasive at this point that future federal policy will benefit by adopting the most popular and best functioning GHG mitigation programs and by coordinating the many existing initiatives. Whether and how nationwide and worldwide emissions markets evolve remains highly uncertain. All this experimentation may well result in an assortment of diverse markets and policies, though founded on common metrics and protocols. That may turn out to be the best approach of all. Time will tell.

3. RESEARCH METHOD

The objectives of this chapter are to categorize states' climate change action plan methods for recommending climate change mitigation actions, highlight the strengths and weaknesses in the states' approaches, and extend methods from the environmental policy research literature into the state policy process. The methods that are employed by governments to mitigate climate change and utilized in the research literature will be critiqued. The goal of this chapter is to make improvements upon both government planning efforts and analytical research methods to develop a prioritization framework that assesses simultaneously, the cumulative impacts and cost-effectiveness of GHG mitigation alternatives.

The framework is employed here to assess federal-scale U.S. options, but the intention is to offer an evaluation tool that is equally applicable for more detailed state-specific prioritization assessments, as the motivation for this research is primarily driven from the state-level government climate change mitigation actions already underway.

3.1. Background on U.S. Climate Change Planning

This section reviews the processes and methods employed by governments in constructing their GHG mitigation plans, with a focus on how those processes differ, how they have evolved over the last two decades, and what are the particular strengths and weaknesses in the states' approaches. A brief review of the developments in U.S. GHG inventory and mitigation planning from the early 1990s to 2008 is provided here. "Best practices" from the state climate change action plan formation, as they relate to this dissertation research, are highlighted.

3.1.1. Evolution of state climate change planning

Most states have developed GHG inventories and mitigation plans, but all of these state efforts are not created equal. As chronicled in Chapter 2 (and Lutsey and Sperling, 2008), state inventorying of GHG emission began in the early 1990s, and the current level of state inventory completion is at 42 states, which is equivalent to 96% of the U.S. population and 93% of total U.S. GHG emissions. However, there is substantial variation in the level of detail and analytical effort that was applied to the inventories. Similarly, of the 28 states that have made the next step of creating GHG mitigation action plans, there is substantial variance in the plans' detail and rigor, and the intent of these states to follow these plans.

A closer inspection of the state inventories suggests that a four-category taxonomy to describe the spectrum and developmental stages of state climate planning is more useful. As of mid 2007, there are 8 "no action" states without inventory or mitigation plan, 14 states with an inventory but without mitigation plan, 17 states with an inventory with simple mitigation plan, and 11 "advanced mitigation planning" states with detailed strategies for mitigation with cost analyses. After the 8 remaining "no action" states, the 14 "inventory only" states have done bare-minimum mitigation first steps, generally under federal funding and without further state initiative to mitigate state GHG emissions. The features of the latter two categories are examined further.

The third category of states, having conducted relatively basic mitigation plans, show mixed signs of both inaction and cautious intent to mitigate. Many of these 17 states' action plans explicitly refrain from making specific recommended actions and emphasize the report as "preliminary," a "first step," or "a framework" toward a more detailed action planning report to come. Criteria to be used in determining climate strategies in these plans often mention the importance of "no regrets" policies (i.e. those that pay for themselves with energy savings) and cautiously emphasize political feasibility and institutional acceptability concerns. These more basic mitigation plans can be generalized as more qualitative in nature, with little or no quantitative evaluation of the cost-effectiveness of specific mitigation strategies. These states could be considered on the fence in terms of joining the more advanced mitigation planning stages – some have committed to establishing climate change advisory groups and commissioned more advanced not-yet-completed mitigation plan studies, while others have not.

In perusing these more basic state climate change plans, several shortcomings in current climate planning are apparent. These mitigation plans were generally conducted earlier and were funded under the 1990s Clinton Administrative U.S. EPA funding under the State and Local Outreach Program. In these plans, some states conduct target-driven "backcast" assessments, looking at future potential reductions and assembling policies that would get them there. Most states conducted their mitigation plans and offered recommendations without any cost-benefit or cost-effectiveness evaluation. Having stakeholders or advisory groups come to consensus, simply based on factors of perceived political feasibility and potential emission reductions may have precluded promising options, while including some that are cost-prohibitive.

Furthermore, some states have established formal executive orders for emission reduction targets without comprehensive detailed assessments of the mitigation measures and the cost-effectiveness of those measures' ability to deliver the state-wide reduction targets. This "putting the cart before the horse" could jeopardize a more rational consideration of which actions and how many actions are desirable, and the total potential costs involved. However, some states have put considerably more effort and state resources into the detail and accuracy of the emission reduction and cost impacts of their proposed actions. It is from examining these more advanced state plans that best practices in climate planning are observed.

3.1.2. Best practices in U.S. states' climate change mitigation planning

Several state action plans avoid the above simplicities and shortcomings and set clear examples of the "best practices" that can be followed to ensure inclusive input on various criteria and a detailed cost-effectiveness analysis are considered in mitigation action screening. Elements from the state climate plans that have exhibited a more comprehensive mitigation planning process are summarized here. Elements of particular interest for this dissertation are the formulation of screening criteria and the analytical methods used for the technical evaluation of policy options.

Eleven states have generally arrived at their recommended mitigation strategies through a system of establishing screening criteria for potential policy options, collecting diverse stakeholder input and consensus on options, and evaluating the cost and benefits of the options. Features of these states' mitigation plans are shown in Table 5. These states assemble advisory groups and/or stakeholder workgroups to screen mitigation options generally under the following criteria: (1) GHG emission reduction and timing of the emission reductions, (2) cost-effectiveness, (3) collateral impacts (ancillary benefits and costs, air quality, jobs, economic development), (4) equity or reductions across economic sectors, and (5) legislative or political feasibility. States either conduct their own technical evaluation of mitigation options with state government agencies and research experts in each economic sector (power generation, transportation, forestry, etc.) or contract the work to external research groups (e.g., Center for Climate Strategies, Raab Associates, Tellus Institute, Center for Clean Air Policy).

Table 5. Features of advanced state climate plans

State, climate action plan report	Conclusions	Criteria	Method elements
Arizona: Arizona Climate Change Advisory Group, 2006. *Climate Change Action Plan.*	49 policy actions recommended	Exec Order to develop GHG reduction recommendations which "may have multiple benefits including economic development, job creation, cost savings, and improved air quality" Recommendations, including "both quantified and non-quantified actions, with emphasis on numerical analysis of GHG reduction potential and cost effectiveness"	Sector-by sector analysis potential options, policy design, direct GHG impact, levelized cost-effectiveness; account for action interactions; quantify ancillary impacts if possible
California: California Climate Action Team, 2006. *Climate Action Team Report to Governor Schwarzenegger and the Legislature.*	45 strategies Cal/EPA will implement	(1) Emission reductions, based on own agency-by-agency analysis and other sources, (2) implementability: "Most of these strategies can be implemented with existing authority of the state agencies represented by the CAT," and (3) the net of all implementation is net positive on economy.	Economic assessment with computable general equilibrium (CGE) model (E-DRAM) of state economy to simulate sectoral and price interactions; no $/ton cost-effectiveness estimations
Connecticut: Governor's Steering Comm. on Climate Change, 2005. *Connecticut Climate Change Action Plan 2005*	38 policy actions recommended	Strong focus on metrics and accountability… employed advanced technical analysis methods to evaluate…GHG benefits/costs, additional benefits/costs, cumulative reductions	Some cost-effectiveness estimations and some discussion and attempt to capture associated co-benefits
Maine: Maine Dept of Environ. Protection. *A Climate Change Action Plan for Maine 2004.*	54 policy actions recommended	Recommendations reviewed for GHG reduction, cost effectiveness, and included on the basis of consensus among state advisory group members	-
New Jersey: New Jersey Dept of Environ. Protection, 1999. *Sustainability Greenhouse Gas Action Plan.*	Many proposed strategies	Stakeholder process (detailed description of screening process not give); estimate GHG reduction, and compare these to state-wide emission reduction goal (3.5% below 1990 by 2005). Impacts: GHG reduction, energy savings, economic impact, ancillary cost/benefit, key uncertainty	Plans for evaluation include integrated "bottom-up/top-down" framework to combine policy option analysis and economy-wide NJ impacts; No $/ton cost-effectiveness estimations
New Mexico: New Mexico Advisory Group, 2006. *Final Report.*	69 policy actions recommended	Achieve emission reduction targets established in the Executive Order; Recommendations determined by consensus of the Advisory Group, including "both quantified and non-quantified actions, with emphasis on numerical analysis of GHG reduction potential and cost effectiveness"	Sector-by sector analysis potential options, policy design, direct GHG impact, levelized cost-effectiveness; account for action interactions; quantify ancillary impacts if possible
New York: Center for Clean Air Policy, 2003. *Recommendations to Governor Pataki for Reducing Greenhouse New York State Greenhouse Gas Emissions.*	16 key actions recommended	Achieve the emission reduction target (5% below 1990 by 2010, 10% below 1990 by 2020). Consensus of tack force on criteria: (1) GHG reduction, (2) cost-effectiveness, (3) administrative/political feasibility, (4) impact on state economic competitiveness, (5) energy supply security, (6) ancillary societal benefits.	Bottom-up reductions, levelized CE of specific measures. Transportation CE $/ton values from from other sources Other sectors' sources are less clear.
Oregon: Governor's Advisory Group On Global Warming, 2004. *Oregon Strategy for Greenhouse Gas Reductions.*	46 policy actions recommended	"Oregon should first begin with the most cost-effective solutions." Criteria: (1) GHG reduction quantity, (2) timing of reductions (preference toward earlier), (3) technically feasibility and relative mitigation costs, (4) legislative-regulatory- political feasibility, (5) collateral issues: benefit/costs, impact equity, economic development, etc	Use "investment standard" for cost-effectiveness: "a preliminary estimate of whether a measure is projected to be cost-effective to the consumer over the lifetime of the measure"; simple yes/no answer on this question; no presentation of cost-per-ton.
Rhode Island: Rhode Island Dept of Envir. Management, 2002. *Rhode Island Greenhouse Gas Action Plan*	49 consensus options endorsed by all stakeholders	Mission to evaluate and prioritize… decision to include was based primarily on preliminary assessment of saved carbon and cost of saved carbon	Cost of saved carbon and net co-benefit cost ($/ton); cost-effectiveness methods not transparent; model net economic benefit of all options with LEAP 2000 software
Utah: Utah Department of Natural Resources, 2000. *Greenhouse Gas Reduction Strategies in Utah: An Economic and Policy Analysis*. For U.S. EPA.	37 strategies evaluated, but "no explicit recommendations"	General criteria: emission reduction, equitable participation across sectors, cost-efficiency, ancillary benefit/costs, political feasibility, and measurability (...may prove more valuable to policy makers and public at-large than those that are not measurable).	Cost-effectiveness, ranked by levelized cost per ton, supply curves, consideration of varying level of implementation; also assess overall strategies' impact with state-wide economic model
Vermont: Vermont Dept of Public Service, 1998. *Fueling Vermont's Future: Compr. Energy Plan and Greenhouse Gas Action Plan*	120 policy actions recommended	-	Computer modeling of composite policy case; no $/ton cost-effectiveness estimations

The chosen technical evaluation framework for comparing mitigation options for eight of these states' (Arizona, Connecticut, Maine, New Mexico, New York, Oregon, Rhode Island, and Utah[2]) climate plans is the "cost-effectiveness" of the policy options, whereby options' cost impacts are divided by the emission reduction (or sequestration or avoidance) potential. The evaluation yields a measure of the cost-per-ton, generally in the unit of dollars per metric tonne of carbon dioxide equivalent (\$/tonne CO_2e)[3]. In most cases, beyond the technology and implementation costs of the mitigation options, the direct cost implications of energy savings are included in the cost-effectiveness metric, to emphasize which options are "no regrets" options with net cost savings (regardless of climate impacts). States "levelize" mitigation costs by discounting future impacts and normalizing the costs to a standard year dollar value. Most plans discuss the additional, indirect implications of the mitigation options to the states. Such additional impacts, referred to as mutual or ancillary impacts, could result in terms of mutual benefits (or collateral trade-offs) in criteria pollutant emissions or state job development or economic impacts.

Several additional features, which are not employed by all of the advanced mitigation plan states, offer further quantitative rigor to the mitigation assessments. The Rhode Island plan offers additional quantitative results for the co-benefits for many the policy options. States plans of New Mexico and Arizona avoid the simple double-counting of measures which affect the same activities. Some states, like Utah and Rhode Island, also use a state-wide economic model to determine interactive affects of the measures and their impacts on activities, fuel prices, job development, etc. Also note that three of the ten advanced mitigation planning states – California, New Jersey, and Vermont – have not conducted cost-per-ton evaluations but have done state-wide economy impact modeling of their mitigation strategies. Several states, like Utah, Arizona, and New Mexico, use the individual action's cost-effectiveness measures to rank the measures. Utah simultaneously ranks mitigation options and plots the impacts on a cumulative GHG reduction "supply curve."

All of the state action plans, taken as a whole, are a fragmented, uneven group of climate change mitigation assessments; however, a process with consistent steps has emerged. To recommend climate mitigation actions to state legislatures and governors, a group of experts and stakeholders in each economic sector is assembled. These advisory groups' selection criteria from state-to-state differ somewhat. Almost uniformly these groups consider cost-effectiveness as the critical quantitative component of their prioritization. However, the states that have followed through with comprehensive analytical assessments of their recommended strategies are few. For example, only 8 of the 28 state mitigation plans attempt to quantify all of their recommendations with cost-per-ton evaluations.

To summarize this survey of state climate change plans, there are many commonalities in the desired quantifiable criteria by which the "action states" would like to base their climate

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[2] The Utah report declines to offer recommendations for climate mitigation policy action: "no explicit recommendations are formed regarding which measures or bundles of measures should logically be implemented"

[3] The Oregon plan uses the term "cost-effectiveness" differently than the typical cost-per-ton measure of comparing options; instead Oregon refers to "cost effective to the consumer over the effective lifetime of the measure," which is similar to the "no regrets" criteria and results in a discrete yes/no answer instead of the \$/ton metric.

change decision-making. For the states that have opted to mitigate their emissions, the stated quantifiable criteria for individual mitigation options include GHG emission reduction potential, implementation cost, direct variable and ancillary costs and benefits. In addition to the three criteria for individual mitigation options, a set of additional criteria also apply to the overall selection of options. To achieve the top-down overarching state GHG emission reductions for future years, a critical measure is the cumulative GHG emission reduction potential of bundles of mitigation options. And considering the economy-wide impacts, the cumulative costs, benefits, and net-benefits of bundle of mitigation options and multi-sector equity (ability to sum and compare, e.g., transportation and agricultural) should be factored in to the decision making.

Also, in quantifying and prioritizing GHG mitigation strategies, a larger issue must be addressed. The chosen environmental assessment method must be sufficiently flexible to allow for differing overarching goals, to account for not only the variance in cost-effectiveness estimations but also for the potentially larger variance in philosophical values of the deciders of the chosen emission-mitigation options. For example, some state plans opt to include only implementation costs in the their cost-effectiveness account; others include energy saving costs to determine “no regrets” options; and others aspire to more comprehensively capture ancillary or mutual benefits of the GHG policies.

The differences in these accounting frameworks could be far greater than other factors, such as varying of economic assumptions. Therefore, to address this “varying overarching values” issue for different decision-makers, the chosen analytical framework must be developed so as offer information based on the differing values. The following section draws upon the analytical environmental assessment tools in the research literature to address these issues of GHG mitigation prioritization.

3.2. Literature Review of Emissions Mitigation Assessment Methods

Using the evaluation criteria of current state climate change action plans as a starting point, this research draws on the environmental assessment literature to formulate a comprehensive cost-effectiveness framework for assessing GHG emission mitigation actions. A foremost question is whether there is a gap between the in-practice state climate planning and the theoretical environmental abatement prioritization literature. Furthermore, if any such gap exists, in what ways could analytical methods, not yet applied to state climate planning, be extended into the climate change mitigation prioritization process? In this section, a brief background is provided on emission abatement evaluation methods with a discussion of relative merits of variations on analyses of policy benefits and costs. A variant of the cost-effectiveness measure to evaluate emissions mitigation alternatives, whereby multiple benefits are accounted for, is introduced and applied to the “supply curve” method for comparing the cost-effectiveness of GHG mitigation alternatives. Also, limitations of the supply curve method as previously applied are highlighted.

3.2.1. Background on environmental assessment methods

Assessments of policy paths to mitigate potential future environmental impacts involve qualitative judgments and quantitative measurements. The use of qualitative assessment generally wins favor in decision-making processes if and when quantitative evaluations are difficult to establish, but where the will to act is nonetheless strong. Qualitative methods involve comparing (perhaps by ranking, rating, or voting) options by expected cost and emission-reduction outcomes, perceived technical feasibility, and political viability. As particular policy options and their impacts are better understood, the use of quantifiable metrics to weigh costs and benefits of options is likely to be more desirable to policy-makers in their selection criteria on mitigation options. Moreover, as resolve to mitigate solidifies, as in the case of numerous states' climate change planning, and there is a shift from "whether to act" to "how to act," some form of cost-effectiveness or benefit-cost analysis becomes critical to the selection of recommended actions.

Numerous variations in benefit-cost analysis methods have been used in researching and developing policy action plans in environmental areas. The simple premise of benefit-cost analysis is that if the summed benefits of a proposed measure outweigh the summed costs, the measure would increase public welfare and be said to be "economically efficient." There are many nuances and variations on the benefit-cost assessment techniques, depending on the data available on the costs and impacts of the problem of interest and potential solutions. The body of work using various benefit-cost techniques on emissions reduction and fuel saving technologies and policies is extensive. Examples of a common type of such research analysis is found in the economic-engineering relationships between the initial cost of fuel-saving technology on new vehicles and their associated fuel savings over the vehicle lifetime (Austin et al., 1999; DeCicco et al., 2001; EEA, 2001; NRC, 2002; Plotkin et al., 2002; Weiss et al., 2000). Similar types of studies are found for energy-and GHG-related technologies in all sectors.

The "cost-effectiveness" concept is generally a more limited form of economic analysis than benefit cost analysis, in that it often does not include the positive impacts of a course of action. Historically, cost-effectiveness values have been the conventional framework for evaluating government programs that are directed at reducing criteria pollutant emissions (e.g., particulate matter, oxides of nitrogen, hydrocarbons). In these criteria pollutant emission cases, the human health benefits (e.g., on cardiovascular and pulmonary diseases) of reducing the emissions could be far more uncertain – and more difficult to monetize – than the pollution control technology costs. As a result, the cost-effectiveness metric, generally measured as the cost-per-ton of emission reduction, has been widely used to more easily compare compliance alternatives for pollution standards. The cost-effectiveness of a course of action, is most simply evaluated as the initial technology cost divided by expected emission reductions ($/ton) for an emission abatement technology. If there are alternative actions to reduce emissions, the lowest cost option is deemed the most cost effective.

There are several reasons that the evaluation of the cost-effectiveness for criteria pollutant emission and for GHG emission abatement policies should differ. The original cost-effectiveness metric, initial costs divided by emission reduction, was appropriate and widely applied for criteria pollutant abatement evaluation because of the difficulty in establishing firm quantitative estimations of externality health and environmental benefits. In these situations, the initial technology cost of, for example, a pollutant trap to capture particulate matter and the resulting reduction in emissions to the atmosphere, made for a relatively straightforward calculation. However, in the case of GHG emissions, there are myriad other costs and benefits that could be accounted for in a more comprehensive cost-effectiveness evaluation. These factors could include the impacts of the GHG-reduction technologies on energy cost savings, ancillary impacts on criteria pollutant emissions.

To the extent that all the emissions and the cost, and benefit impacts are quantified in a cost-effectiveness value, the more comprehensive and useful the value can be in prioritizing mitigation options. Take for example the large scale deployment of energy-efficiency technology (e.g., an improved drivetrain) that reduces the vehicle fuel consumption rate by 10%. After the initial technology implementation cost of the technology, there are the direct fuel savings cost impacts for the vehicle user. If the technology also results in reduced criteria pollutants, the technology would have ancillary benefits. Reduced use of petroleum reduces the externality costs related to petroleum usage. In terms of the emission reduction, the measure would directly impact the GHG emission rate by 10% over the life of the vehicle. This in turn would also reduce the upstream energy inputs of supplying the fuel.

Cost-effectiveness and cost-benefit techniques both can involve costs (or benefits) of technologies that occur in future years. Future year impacts are handled with a discount rate which corresponds to the relative value of a dollar today versus one year in the future. If a person (or industry or government) chooses a discount rate of 7%, it is implied that he or she would be indifferent to the choice between getting \$100 today and getting \$93 one year later. The general concept for evaluating the summed, discounted costs and benefits (in various years) in present year dollars is refered to as “net present value,” and it is represented by the following formula:

$$NPV = \sum_{t=0}^{L} \frac{(B_t - C_t)}{(1+d)^t}$$

Where:

NPV = net present value of technology (in \$)

L = average lifetime of the technology being evaluated

t = time in years of the technology being evaluated

B_t = benefit impacts of technology in year t

C_t = cost impacts of technology in year t

d = discount rate

The cost effectiveness value of a technology, in turn, uses the net present value of the costs and benefits of the technology that is being evaluated as the numerator. The GHG emission reduction of the technology, as compared to the baseline or reference technology, is the denominator. The following formula shows this calculation for cost-effectiveness.

$$CE = \frac{NPV}{E_{GHG}}$$

Where:

CE = cost-effectiveness value of technology (in \$/tonne)

NPV = net present value of technology (in \$)

E_{GHG} = emission reduction over average technology lifetime (in tonne)

The clustering of all quantifiable impacts of emission reduction technologies can combine the strengths of benefit-cost analysis, to be inclusive of the full range of impacts, and of cost-effectiveness analysis to have a common metric of comparison for mitigation options. This clustering of multiple impacts for individual GHG mitigation options can meet the criteria for evaluating *individual* actions in governments' climate change plans (from the conclusion of Section 2.2). What remains is to analytically combine numerous individual technologies to determine the *cumulative* impact of a full portfolio of such actions. The combining of numerous individual measures is discussed in the following section.

3.2.2. Cost-effectiveness "supply curves"

The use of a "supply curve" approach offers the ability to combine the impacts and cost-effectiveness measurements of numerous GHG mitigation options at the same time. Borrowing from economics theory, the supply curve approach shows graphically the supply of a given resource (on the x-axis) that is available at a given price (on the y-axis). The use of supply curves to assess efficiency measures was introduced as a means of investigating technological alternatives in the electric sector in the early 1980s (Wright et al., 1981; Meier et al., 1982). Use of the supply curve approach for assessing electricity efficiency alternatives showed the incremental cost to the electricity supplier (e.g., in \$/kWh avoided) to adopt the energy avoidance measures represented by y-axis height. These measures are ranked and ordered by their relative cost and are indexed by the total magnitude of avoided, saved, or conserved energy (e.g. kWh) as a potential supply-side resource, which are shown as x-axis width. Many incremental independent energy-saving (or emission-reduction) measures can be ordered by increasing cost-per-energy unit (or cost-per-ton) and plotted to inform on their cumulative impact on avoided energy use.

Depending on the use and derivation of the costs and cumulative emission reduction data, the curves can more aptly be labeled as marginal abatement, incremental cost, cost of conserved carbon, or cost-effectiveness curves. The curves are sometimes shown as discrete step curves, to demonstrate the effect of additional "bottom-up" measures (to reflect discretely different initiatives enacted), or as continuous cost curves (reflecting theoretical free-market operation), which are more generally associated with macro-level economic models and referred to as "top-down" assessments.

A simple illustration of a cost-effectiveness supply curve is shown in Figure 6. From the application of the supply curve approach, several insights (and the resulting uses and strengths of the approach) are immediately apparent. The primary insight is one of cost-effectiveness prioritization; following the supply curve, from measure #1 in the lower left to measure #7 in the upper right, graphically presents the adoption of numerous GHG mitigation technologies, selecting the most cost-effective (i.e. lowest cost per CO_2-equivalent ton) measures first.

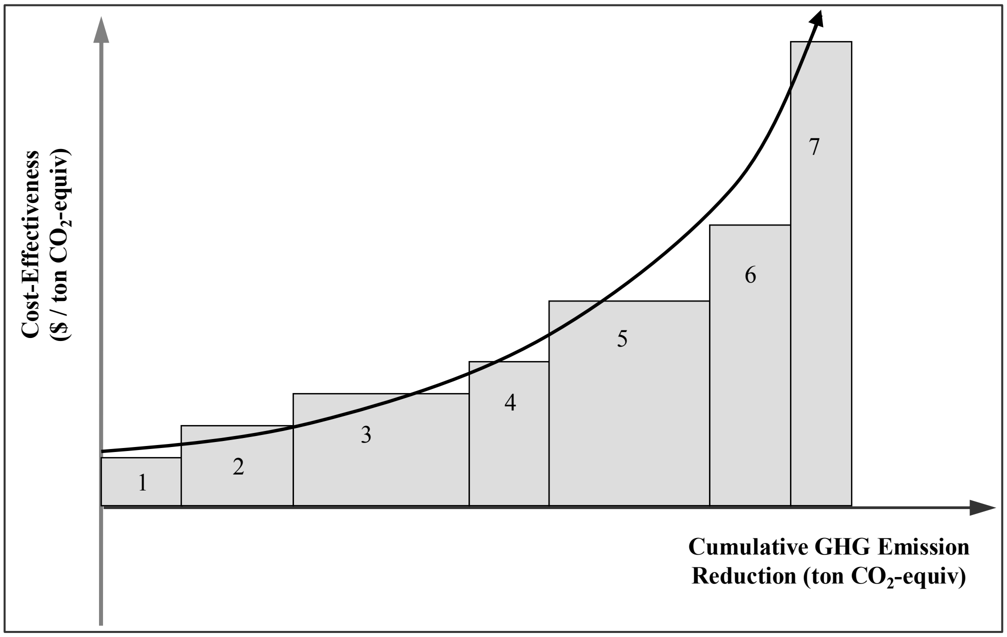


Figure 6. Illustration of cumulative CO_2 reduction cost-effectiveness curve

The integration of these cost-effectiveness data in the supply curve approach provides usefulness for many research and decision-making contexts. The method allows for the ability to compare and synthesize numerous mitigation actions, potentially from all economic sectors. With the ordered cost-effective options, their cumulative emissions reduction impact is shown, allowing for simple interpretability of the impact, in terms of both cost-effectiveness and the number of measures required to meet particular overall goals. For example, if the main desired attribute in setting policy is to achieve an economy-wide emission reduction target for 2020 to achieve the 1990 emission level, drawing a vertical line on the supply curve plot at the amount of total desired emission reduction would delineate the necessary actions that would be required to meet the overall goal. Furthermore, once mitigation options have been assembled, ranked, and graphed, the cost-effectiveness curve has implications for understanding which options have higher potential to be deployed in the circumstance where a emission trading system were introduced. For example, if the trading of GHG credits, as in the European Union, supported credits at $30 per metric tonne CO_2e, or some other level, the analysis estimates the level of total reduction and the measures that could be adopted up to that cost.

3.2.3. Use of cost-effectiveness curves in environmental assessment

This section gives an overview of the related literature in GHG emissions mitigation and the potential complications and limitations inherent to the use of supply curves. The use of supply curves to assess efficiency measures was introduced as a means of investigating technological alternatives in the electric sector in the early 1980s (Wright et al., 1981; Meier et al., 1982). Due to the mutual benefits of energy efficiency technologies yielding energy savings and carbon dioxide reductions, the supply curve method was adapted to energy sector greenhouse gas mitigation (Jackson, 1991) and expansively employed in various assessments of nationwide GHG mitigation options in multiple sectors (NAS, 1991; Rubin et al., 1992; IWG, 1997; Creyts et al., 2007).

Since the early usage of the supply curve method in the 1980s, the method has been much more thoroughly scrutinized. Early critique related to whether the supply curve approach, being employed up to that point by technologists, was and could be called or used as a "supply curve" according to the nomenclature and conventions of economics theory. Researchers classified the method as being closely related to true supply curves (Huntington, 1994; Blumstein and Stoft, 1995; Stoft, 1995). Stoft (1995) concludes that, "conservation supply curves" employed in the energy sector are not true supply curves because they differ theoretically in the way they are related to the production function from economic theory. Due to this point on the definition, in this research, the use of "supply curve" will be retained for general discussion of the method. More detailed discussion and construction of curves for this research will be more descriptive of what exactly is being constructed in each curve. Ultimately the term "marginal GHG emission abatement curve" or simply "cost effectiveness curve" are more commonly used in this dissertation research.

Besides arguing for the theoretical misnomer of "supply curve," Stoft (1995) makes several observations about potential pitfalls in the use of the method. First, there is the potential for interaction effects, or double-counting, when simultaneously assessing two or more measures that reduce the same emissions. For example, energy use reductions from the deployment of improved insulation and higher-efficiency air conditioning technology would not be strictly additive when applied to the same building. It the insulation was installed first, the energy savings from the air-conditioning would be reduced, because of the overall reduced requirement to cool the building.

In addition, several limitations result from the singular objective metric (cost per ton) and the resultant omission of other factors. Stoft (1995) points out difficulties in accounting for differences in utility that may result from the use of various technologies. Examples of this include more efficient light bulbs and appliances that could operate with compromised utility in other facets, such as turning on more slowly or operating more noisily. A more important example is what is referred to as the "rebound effect," whereby a household could, after installing energy saving devices, use their new energy savings to modify their behavior to consume more energy. Furthermore, incorporating this rebound, or "takeback," effect into the supply curve method is inconvenienced by the effect's dependence on the price of energy, which, in most studies, must be held at a constant base price.

Another concern with the single-metric aspect of the supply curve method, as traditionally applied, is its limited ability to demonstrate mutual, ancillary, or co- benefits that accompany the reduction of GHG emissions. Most of the GHG mitigation measures that are discussed herein have other, coincident objectives and associated benefits in areas such as resource conservation, economic efficiency, and human health. Displaying the GHG mitigation alternatives in single-objective, GHG-reduction conclusion figures loses sight of those other benefits that could differ substantially between GHG mitigation measures.

Confounding all mitigation cost assessments are data accuracy issues related to proper characterization of baseline technology in the future and cost and technology potential for non-baseline technologies in the future. Stoft (1995) refers to the “frozen baseline” issue as the problem of improperly holding constant baseline characteristics at current (i.e., time of the report) levels, when technologies in all fields can expect to result in some changes, likely improvements, even in “no-policy” or business-as-usual scenarios. Addressing data accuracy on the maximum potential technology adoption, Stoft (1995) points out that nearly all studies acknowledge they are offering optimistic upper “technical potential” boundaries for the technology adoption and some even suggest that their energy-saving impacts could be overestimated by about a factor of two.

In addition to limitations of the supply curve method raised by Stoft (1995), Verdonck and Verbruggen (1998) raise several other concerns regarding the use of the method. The supply curve method, as commonly applied is susceptible to incomplete estimation due to neglect of consideration for the “embodied energy” of particular technologies. Failing to consider the full embodied energy consequences of energy-reduction technologies can affect cost-effectiveness calculations in various ways. On one hand, the lack of consideration in the embodied energy in the manufacture of photovoltaic solar panels would overestimate their benefits. On the other hand, reduced gasoline usage via increased vehicle efficiency would also result in reductions in the upstream fuel cycle energy inputs to produce that gasoline; therefore, neglecting the upstream factors would underestimate the true impact of this measure.

Another concern is that the method, when considering both the reference case and the future potential technology characteristics, is based on assumptions of average single-point information (Verdonck and Verbruggen, 1998; Willeme, 2003). The reality is that the energy use activity of differing users of devices (e.g., vehicles) could be widely; therefore the estimation of the cost-effectiveness of an average improvement could distort the true distribution of costs and benefits of varied technology users.

Conveying time-related aspects is difficult with the supply curve approach because of the lack of any explicit time variable to the assessment. The time variable is implicitly acknowledged by the researcher in the selection and screening of GHG mitigation alternatives. In theory, policy-makers would, over time, incrementally work their way up the supply curve by choosing lowest cost measures first; however, possibilities for conveying chronological sequencing can be complicated by the fact that any given GHG mitigation options may be adopted before others, regardless of cost-effectiveness values. Additionally, some technologies have long timelines for delivering actual emission reductions due to slow stock turnover (e.g. of power plants), and depicting when these reductions occur is not straightforward.

Also, related to the “no explicit time factor” limitation, is the potential for the supply curve method to neglect key interactions and mutual exclusivity between GHG mitigation options. As mentioned above, care must be taken to properly account for the interaction or potential “double counting” of two technologies; moreover, though, interactions between technologies can impact and even restrict emission mitigation choices. Take the example of opting between the deployment of two vehicle technologies: incremental efficiency improvements in conventional gasoline technology versus vehicles and fueling infrastructure for a new fleet of hydrogen-fueled fuel cell vehicles. In this case, there is the issue of the available timing of the initiatives (i.e., widespread fuel cell initiatives being longer term than conventional gasoline improvements) and of the potential for the "locking up" of technology investment. By "lock-up," what is meant is that the large expenditure on one technology advancement could preclude investment in, or divert resources from, the alternative technology.

Less specific to the particular details of the supply curve method, general difficulties are encountered with the method. The supply curve method, with its sole use on cost-effectiveness measurements of new mitigation policies, is subject to a more serious limitation that it does not address the non-economic barriers, such as institutional implementability and political feasibility. Especially in the case of net-positive-benefit mitigation options, the questions about why such mitigation options are not already implemented are important in understanding the potential deployment of GHG mitigation technologies. Also, as with all future scenario assessments, the use of supply curve for future projections is highly dependent on various assumptions (on base case emissions characteristics, fuel prices, etc.).

3.3. Development of Multi-Benefit Cost-Effectiveness Assessment Approach

In this section, the prioritization criteria of state climate change planning and improvements to address the supply curve cost-effectiveness method limitations are combined to form a framework for improving the use of quantification methods in GHG mitigation decision-making. The first objective is to satisfy the needs identified in Section 3.1.2 regarding state climate change prioritization. The second objective of developing an analytical assessment framework is to address the methodological limitations in the research literature (summarized in Section 3.2.3) on the supply curve approach.

3.3.1. Satisfying U.S. state climate change planning criteria

The first objective is to determine the key attributes of a method to satisfy the needs for climate change prioritization planning in the U.S. To summarize, the states' quantifiable criteria for individual mitigation options include (1) GHG emission reduction potential, (2) implementation costs, (3) direct variable and ancillary costs and benefits, (4) cumulative GHG emission reduction potential of bundled mitigation options, (5) cumulative costs, benefits, and net-benefits of bundled mitigation options, and (6) multi-sector equity. The supply curve method can be tailored to satisfy these needs.

The use of a cost-effectiveness metric that accounts for all quantifiable impacts of measures makes a common cost-per-tonne of carbon dioxide reduction ($\$/tCO_2e$) measure to comparatively rank GHG mitigation options the obvious choice. The subsequent steps are to include all costs in the cost-per-tonne metric (implementation, direct cost impacts, and ancillary impacts) and to combine actions within sectors and across sectors. The proposed method to combine multiple impacts and mitigation actions is via the construction of multi-benefit multi-sector supply curves which charts policy actions' cost-effectiveness against their cumulative GHG emission reduction potential.

The supply curve approach is sufficiently flexible to allow for the multi-benefit cost-effectiveness accounting. As discussed in the above section, the cost-per-tonne measure can be defined by the net direct costs, including both initial implementation costs and direct energy saving benefits to the consumer and/or user of the GHG-reduction technologies. This is an important capability considering that many policy-makers view the "no regrets" criterion (i.e. where the lifetime benefits due to fuel savings or other benefits exceed the initial implementation costs) as critical in determining the first GHG mitigation measures to adopt.

Figure 7 gives a hypothetical plot of how the cost-effectiveness curve could be altered with the inclusion of the energy-reducing benefits of GHG mitigation measures. Using a net direct cost accounting framework can shift the curve down and can also require a re-ordering of the options, to add further importance to those measures with benefits (e.g. energy savings) that offset the initial cost increases of GHG reduction technologies. Perhaps most important for policy-makers that are more tentative on GHG mitigation, the curve unveils which options (in the plot, numbers 1-3) are "no regrets" options and their cumulative potential GHG mitigation impact. In addition, the further monetized ancillary benefits (e.g. from health benefits of reduced criteria pollutants, for policy-makers who sought to measure the net "public good" of GHG mitigation measures) could be incorporated in a third level of cost-effectiveness accounting that would be more akin to a benefit-cost analysis.

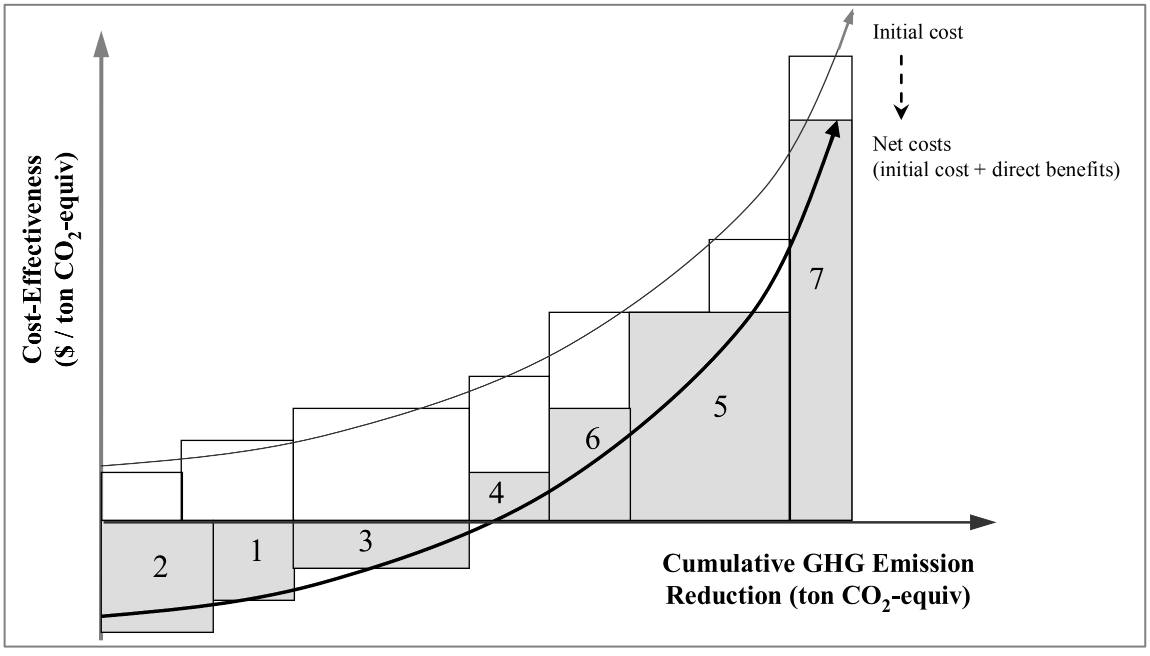


Figure 7. Illustration of cumulative CO$_2$ reduction cost-effectiveness curve, including direct lifetime technology benefits

After the development of the various sectors' GHG supply curves, the data from all sectors can be combined to compose a multi-sector GHG emission mitigation curve. Figure 8 illustrates the merging of the hypothetical sectors' GHG mitigation data into one multiple-sector figure. Examples of transportation alternatives include improved vehicle efficiency, alternative lower-carbon fuels, and the use an alternative air-conditioning refrigerant.

Considered electric sector options could include a combination of increased power plant efficiency, fuel substitution, increased renewable energy use, and carbon sequestration. Various industries, such as the cement industry, could be examined individually for GHG mitigation initiatives and incorporated into the analysis. Other economic sector or subsectors, like residential and commercial building applications, forestry and agricultural, and non-CO_2 GHGs (e.g., methane, and high-GWP) measures can similarly be incorporated in such a framework.

In Figure 8, the transportation sector options are highlighted in gray to draw attention to the usefulness of the overall approach in comparing and contrasting each sector's contributions toward overall economy-wide emission reductions. In this hypothetical construction, the gray-highlighted transportation options are interspersed through the multi-sector curve.

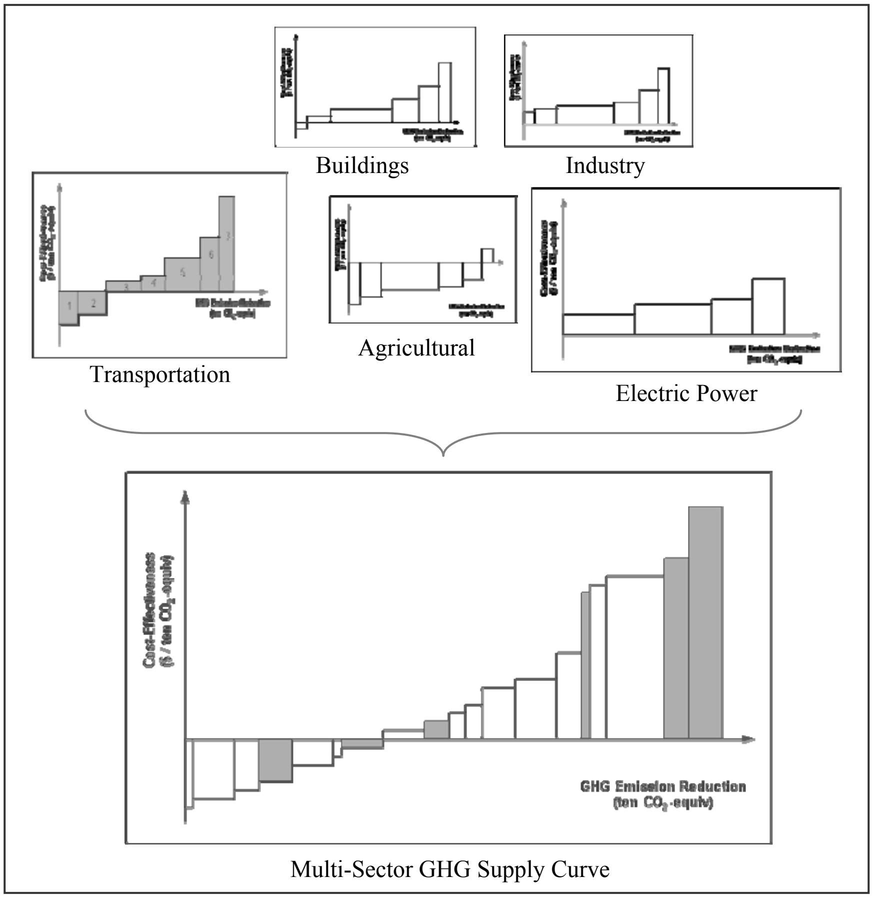


Figure 8. Integration of sectors' GHG cost-effectiveness curves to multi-sector curve

To address the "differing overarching values" issue raised above, whereby different policy-makers could differ fundamentally in their decisions on which cost and benefit impacts to include in their GHG mitigation choices, the supply curve analysis and presentation are to be conducted with two different accounting methods. The two cost-effectiveness accounting methods offer differing evaluations for the numerator, while leaving the denominator of the cost-effectiveness metric unchanged. The methods are (1) initial costs only, which are primarily initial technology costs, and (2) net cost impacts over the lifetime of the technology, which include initial costs plus discounted future energy cost reductions.

These two accounting methods reflect potentially very different results but equally real viewpoints of policy deciders or technology purchasers. The initial costs only method includes the most simple and conventional (i.e., for non-GHG, criteria pollutant emission reduction assessments) accounting of cost-effectiveness. Using an "upfront cost only" cost-effectiveness value resembles decision-making that is extremely change-averse and/or wholly excludes future energy savings from investment decisions.

By including net direct cost impacts, the most straightforward direct impacts of mitigation technologies that still accrue on the user/consumer of the mitigation technologies (e.g., the electric utility, vehicle consumer, electrical appliance consumer) are also included. This metric properly shows the advantages of using energy efficiency technologies over those that do not result in fuel savings (e.g. low-GWP air conditioning refrigerants). Using this "direct impacts" curve shows which mitigation options offer net benefits that are greater than their initial costs by having net cost-effectiveness values of $0-per-ton or less. Thus, this second accounting method yields the direct conclusion of which mitigation are "no-regrets" policies – those GHG mitigation efforts that are justifiable even for policy-makers with no interest in acting to mitigate climate change.

Presenting results for two different cost-effectiveness curves is important for expanding the usefulness of the work to particular viewpoints of decision makers and differing established criteria for policy development. This set of distinctions, based on cost-benefit accounting method, is potentially more important than the varying of assumptions in conventional sensitivity analysis for several reasons. Sensitivity analysis, as generally applied, varies potentially critical assumptions of the analysis (e.g. fuel prices, discount rate) to examine the resulting variance in the findings. However, variation in economic parameters are substantially more subtle than the more philosophical differences in which benefits should be accounted for according to the policy-makers at state and federal levels. For example, as already stated, some state plans opt to include only implementation costs in the their cost-effectiveness account; others include energy saving costs to determining "no regrets" options, and others attempt to more comprehensively capture ancillary or mutual benefits of the GHG policies.

3.3.2. Addressing supply curve approach limitations

A series of complications, difficulties, and potential pitfalls of the supply curve method were raised in the Section 3.2.3 literature review. This section address the ways in which this proposed use of the supply curve method can be used to offer a more useful GHG mitigation prioritization framework. In many cases, the complications can be overcome with analytical corrections. In other cases, the supply curve difficulties can be sidestepped with assumptions that do not compromise the analysis, while in a limited number of cases, the limitations of the supply curve can not be fully avoided.

The "interacting mitigation actions" complication can be avoided by (a) constructing supply curves with actions that are mutually exclusive in terms of their costs and impacts, or (b) analytically incorporating multiple interacting measures by adjusting the baseline emissions (and/or energy) characteristics before the addition of subsequent measures.

With the strengths of using a single-objective (cost-per-tonne) measure for priority assessment come the limitations of excluding other factors that cannot easily be bundled into the metric. To address this "other factors" issue, this proposed framework seeks to concurrently quantify, in the most inclusive way possible, all related direct and indirect impacts of GHG mitigation efforts. The primary way of dealing with this issue is to use data on technologies' costs and GHG reductions only for technologies that do not have other compromising factors (e.g. noisy or slow-starting light-bulbs, limited range vehicles). In this case, researching near-term technologies that are without compromises in other attributes, sidesteps this issue.

Other concerns with usage of the supply curve method relate to the initial assumptions of the technology assessment. As mentioned above, by holding any baseline characteristics stable in future years, the considered mitigation technology can easily be incorrectly credited with excess emissions-reduction impacts. This concern of a distorting "frozen baseline" is most easily accounted for by carefully constructing a baseline that incorporates business-as-usual trends and extrapolates on the known trends (e.g. gradual improvement in power plants gram CO_2/mWh over the past five years in a "no new GHG policy" case). In all cases for this dissertation, reference data for technologies and practices in each economic sector (e.g. in U.S. EIA, 2008) do already show such baseline technology improvements, and the remaining effort is simply to understand and articulate the chosen baseline.

Moreover, improving upon the accuracy of assessing the "technical potential" for future emission-mitigation technologies requires better up-to-date data sources. In some ways, the abundance of GHG mitigation research and budding GHG mitigation action in the U.S. has allowed for tighter such estimates. Noting the prevailing system of "states as experimental benches" for more widespread climate action, the utilization of the data resulting from the proliferation of sub-federal action and its related cost assessments could help shore up cost-effectiveness estimates for policy mitigation actions. Another critique of the supply curve method related to the general lack of accounting for differences in the "embodied energy" of various emission reduction technologies. This concern can be, and is in this dissertation, overcome with the use full energy cycle accounting of costs, energy, and emission impacts of mitigation technologies.

Related to the problem of using average single-point cost estimations (for multiple varied baseline users and use characteristics), Willeme (2003) suggests the use of continuous cost functions using an exponential algorithm for a logistical supply curve. This additional rigor, through theoretically justifiable, has the practical difficulties of obtaining distribution data for energy or emissions characteristics for all the technologies that are being assessed (e.g. lights, vehicles, washers, water heaters, power plants). This additional data collection to make continuous, instead of discrete step-function, supply curves is not justified in this research where sector-by-sector mitigation alternatives can vary by such wide margins in terms of cost-per-tonne values.

As noted above, there are potential consequences of the supply curve not explicitly conveying certain time-related aspects of the mitigation options, and therefore encountering sequencing complications. One such issue is technology “lock-up,” where a early investment in a particular technology could preclude investment in a competing technology (e.g. hybrid gasoline-electric vs. diesel vehicles). Dealing with this competitive technology issue can logically be dealt with by constructing alternative supply curve “paths” if two discrete, dominating technology scenarios appear equally likely. The flip-side of this issue is that some technologies could by synergistic (e.g., hybrid vs. grid-connection capable “plug-in” hybrid). Coping with the synergistic impacts can be analytically dealt with by subtracting out common component costs for subsequent steps. However, in this dissertation “winners” are chosen according to their cost-effectiveness values, and the level of deployments are justified and discussed in the text. This approach is justified to avoid mutually exclusive technologies to avoid the construction of myriad GHG abatement curves for each sector.

The choice of adopting the cost-effectiveness supply curve method, or almost any monetized environmental assessment approach for the matter, forces the omission of certain impacts that have not yet been well quantified. A variable of high importance to GHG mitigation assessments, the “environmental damage cost of GHG emissions,” falls into this category. Because it is not yet estimable with the exactitude of the costs of mitigation, its use is forgone. This is unavoidable, but to the extent that better, richer data on the full impacts are known, the less of an issue this limitation could mislead any decision-making. In any case, of course, the use of any strictly quantified assessment is seldom the final policy-making statement; it is more aptly a starting point for decision-maker judgments.

3.3.3. Establishing assumptions, constraints, and boundaries for this assessment

The two previous sections addressed the particular needs of current in-practice climate change planning and theoretical supply curve method assessment. In addition to these more particular needs, the use of any environmental assessment techniques that investigates future technologies is fraught with susceptibility to the chosen assumptions on which the assessed costs and benefits are based. This section discusses more generally the best practices to accompany the specific suggestions above in terms of the adopted parameters and assumptions for prioritizing GHG mitigation options for maximum potential usefulness in current policy discussions.

The use of the supply curve method, if it is to be useful in synthesizing multiple sectors' mitigation options, involves the collection of primary data from numerous sources. With the differences in the accounting methods and data employed by the various studies on the costs and benefits of climate change policy measures, the following assumptions are used for treatment of the primary data. The costs of the studied technology measures to be incorporated will include the private costs of initial incremental investment (e.g., of fuel-saving technology) and the variable private costs of using that technology (e.g., from fuel savings) throughout the lifetime of that technology.

Future costs and benefits are discounted at 7% (real) annually when including non-present year cost impacts. This assumption follows from (OMB, 1992), which recommends that for public investment and regulatory analyses, that “Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years." All cost evaluations are in year 2008 U.S. dollars, and where data came from other years, those cost numbers are adjusted to year 2008 based on the consumer price index. Future fuel prices, activity trends, and baseline greenhouse gas emissions are primarily based on the U.S. Department of Energy's *Annual Energy Outlook 2008* (U.S. EIA, 2008). Several other sources are applied and will be discussed in each Chapter. Note that data from U.S. EIA's "early release" is applied to this analysis – previous to the U.S. EIA's update for the provisions of the *Energy Independence and Security Act of 2007* federal energy legislation.

In the case of some of the GHG mitigation strategies, there is some ability to pick a level of GHG mitigation from a continuous GHG curve. Because the objective here is to inform policy on GHG mitigation actions from various sectors, each initiative is converted to a discrete unit that can be summed up in terms of a policy or voluntary industry initiative. For example, if a cost-reduction curve is given as a continuous fuel economy (in miles-per-gallon) versus cost relationship, the level of technology is distilled down to a discrete policy initiative (e.g. a 25% increase in light duty vehicle fuel economy standard).

Accounting for emissions of the various GHG emissions is done in carbon dioxide equivalent emissions (CO_2e). Therefore non-CO2 emissions (e.g., CH_4, N_2O, fluorinated gases) are converted into their equivalent CO_2 emission value according to their global warming potential (GWP), which is their equivalent impact on global warming as compared to carbon dioxide. Their GWPs are applied values from IPCC (2001a) for a 100-year time horizon. The unit most commonly used for GHG emissions in this analysis is million metric tonnes. One metric tonne (MT) is equivalent to 1000 kilograms (kg), and one kilogram is equivalent to 1000 grams (g).

Also several points must be made about what this research *does not attempt to do* and about justifications for sidestepping such aspects of the current climate change policy debate. This research on climate change mitigation does not investigate the more fundamental climate change science issues that motivate the current U.S. and international climate change mitigation actions. The bases for this omission of the science background is justified in that it would be well beyond the scope of this research on policy mitigation and is covered much more thoroughly elsewhere (e.g. IPCC, 2007).

Perhaps more importantly, this research sidesteps any further discussion of the climate change science motivation because one premise of this research is that there is, in 2008, such a critical mass of sub-federal climate change action in the U.S. to make federal policy all but inevitable. This is demonstrated in Chapter 2 (and in Lutsey and Sperling, 2008). The assertion of this research is that primarily what remains is a better prioritization of the available GHG mitigation technologies.

Several other parameters here regarding the objectives and constraints of this dissertation's assessment of GHG mitigation alternatives are noted. The focus of this research and the chosen primary data on GHG mitigation alternatives are chosen for their near-term practical viability. As such, the technologies evaluated are to be fully deployable with quantifiable

GHG benefits by the year 2020. In many cases, due to time lags in industry manufacturing and technology turnover (e.g., older vehicles retiring from the fleet), such initiatives often require that private company plans and/or regulation timelines are established well in advance of the actual emission reductions. The GHG reduction mechanisms for this study generally would require target-establishing actions within the next few years (i.e. by 2010).

Therefore, generally measures investigated in this dissertation are already being actively discussed in policy circles at various government levels and/or by industry leaders, are widely considered to be available for widespread deployment in the U.S. in the 2020 timeframe, have already emerged in the market place in limited numbers or are at a demonstration level of development, and are technology-focused.

The technological-only constraint of this assessment is driven by several considerations related to the dissertation's scope, timeframe, research method and known cost-effectiveness measurement reliability. Non-technology GHG mitigation measures that require behavioral change (e.g. changes in urban land growth, travel demand reduction) have costs and emission impacts that are not quantifiable with the exactitude of the technologies studied herein. The focus of this research on broader national-scale initiatives does not easily allow for behavior-changing GHG strategies that would have to be implemented at local, household, or individual levels.

These less-technology-based policies are nonetheless important, and could very well be vital for the magnitude of emission reductions required for climate stabilization of climate change. Considering that it is widely believed that, for climate change stabilization, emission reductions on the order of 60-80% from current levels by the year 2050 will be required, many diverse strategies will be needed. Finally, this research also avoids many questions about which overarching climate change policy frameworks – regulatory, cap-and-trade, or other – will be part of the ultimate system to drive GHG reductions in the U.S. economy. These issues are discussed further in Chapter 10.

3.4. Research Method Summary and Contribution

The cost-effectiveness method discussed here iss tailored specifically to answer the very questions that U.S. policy makers have sought in prioritizing their GHG mitigation actions. Because in some cases individual U.S. states have enacted substantial mitigation actions with rigorous cost-effectiveness assessments, a first question that is to be answered by this analytical framework is whether the GHG mitigation options that are already in progress are the "best" in terms of dollars-per-ton cost-effectiveness. That is, is the U.S. choosing the right, first GHG mitigation options?

The multiple-sector synthesis of GHG mitigation options is instructive on key questions about the differential impact of acting to mitigate GHG emission on each economic sector. If policy decisions were based strictly on cost-per-ton cost-effectiveness, what is each sector's role in bringing the U.S. into a Kyoto-like GHG emission reduction by 2020? Are some sectors (e.g. transportation) likely to contribute more to reductions? If each sector is required to "pull their weight," or reduce its emissions by a certain percent of its own reference emissions total, would it be far more costly for some sectors than others? What are the possible implications if multi-sector multi-emission GHG trading system was in place? The combination of results from all sectors' mitigation options offers findings on how many and which mitigation options would satisfy various goals (e.g. reducing below 1990 levels by 2030), as well as which options could be marketable under various cost-per-ton values in emissions trading schemes.

Presenting the cost-effectiveness results in the different decision-making viewpoints (initial cost only, initial cost plus direct impacts) offers an important set of findings. A particularly pressing question is how far overall emissions can be reduced solely with the enacting of "no regrets" policies that can be justified by their economic impacts, without considering the actual environmental impacts of climate change damages. The existence of net-benefit (i.e. less than zero cost-effectiveness) GHG mitigation options prompts numerous questions: What economic barriers might currently impede the deployment (e.g., market failure, imperfect information, implicit value of money, institutional barriers) of such GHG mitigation technologies? What other barriers (e.g., consumer acceptance, institutional, legal jurisdiction, valuation of future benefits) appear to stand in the way of net-public-benefit mitigation options? What role might government play in overcoming those barriers (e.g., information campaigns, education programs, consumer financial incentives, industry engineering costs through R&D grants)?

This chapter investigated the methods and needs of in-practice climate change policy in the U.S. and environmental assessment techniques in the research literature. The result was to marry the best practices from both bodies, address remaining methodological limitations, and develop an improved climate change mitigation prioritization framework.

One objective is to highlight the best practices in climate change mitigation planning in the U.S. Although different states have many similarities in their selection criteria and approach to mitigating GHG emission, their process and analytical rigor to go about prioritizing those actions varied greatly. It is the intention of this study to shine light on the more advanced state cost-effectiveness assessments to raise the bar for future state, regional, and federal climate change mitigation planning.

The foremost methodological contribution is to establish a multi-benefit cost-effectiveness framework that is inclusive of technology costs and lifetime energy cost impacts. This is a response to the climate change planning calls for quantification of the co-impacts of GHG mitigation options. Ultmately any number of ancillary costs and benefits could also be bundled in the cost-effectiveness framework. To contribute to the research literature, the analysis recognizes the chief limitation of the supply curve method – its singular variable ($/tonne) accounting of GHG mitigation options – and more broadly incorporates the impact of mitigation strategies' benefits and costs. The analysis is aimed toward conclusions and results on prioritizing the best (i.e. lowest cost-effectiveness value) GHG mitigation measures, on the amount and types of GHG mitigation measures that could be adopted to reach varying levels of emission reduction levels in the U.S. over the next two decades, and on how GHG emission reductions in various sectors compare with initiatives in other sectors.

Advancements from this study are in updating and synthesizing research that has not yet been combined. The use of the supply curve approach itself is advantageous, but not new.

Combining the various sectors' results into a multi-sector supply curve demonstrates multiple emissions mitigation options, the total amount of emission reduction potential of each measure individually and the cumulative total, and relative cost-effectiveness on the same plot – enabling straightforward and concise interpretation and visual illustration of technology alternatives. The method updates the research literature for current knowledge, more inclusively synthesizes the GHG emission reduction options in disparate fields that have not been considered together (e.g. studies of carbon dioxide reductions, of hydrofluorcarbon reductions, industrial processes, and of carbon sequestration).

4. TRANSPORTATION

As introduced in Chapter 2, policy-makers at sub-federal government levels are increasingly implementing sector-specific GHG mitigation actions to meet their overall emission-reduction targets. The transportation sector, representing about a third of U.S. GHG emissions (US EIA, 2008), is one area where numerous GHG mitigation initiatives have been researched and implemented. This chapter analyzes transportation-specific mitigation efforts that could deliver GHG emission reductions in the 2030 timeframe, using the methodological guidelines put forth in Chapter 3.

There are numerous GHG reduction technologies that are applicable near-term options for the transportation sector. The largest potential emission reductions in GHG mitigation assessments generally are associated with improving GHG reductions from the passenger vehicles, because they are such a large and growing portion of overall emissions. The general categories of measures addressing automobile emissions that are examined here include vehicle efficiency options, air-conditioning refrigerants, and fuels substitution (toward higher percentages of renewable or lower net-carbon fuels). In addition, this analysis investigates efficiency and fuel substitution options for commercial freight trucks. Other types of GHG reduction policies for road transportation that involve travel demand management and pricing policies (pricing based on fuel usage, vehicle-mile-traveled, congestion travel, parking, or insurance) are not analyzed due to this assessment's focus on nearer term technology-based GHG reductions.

Figure 9 shows the breakdown of greenhouse gas emissions by sub-sector in the transportation area with data from U.S. EIA (2008). Because passenger and freight truck operations represent approximately 61% and 21% of transportation energy use and GHG emissions, and are expected to doing so for decades to come, the majority of existing large-scale GHG reduction measures are in these two areas, and therefore these two areas are the major focus of this Chapter. Aircraft efficiency is also explored as a way to mitigate the approximately 13% of transportation sector GHG emissions that result from aviation. The "Other modes" category includes marine shipping, buses, military use, rail shipping, lubricants, and pipeline fuel sources of oil use.

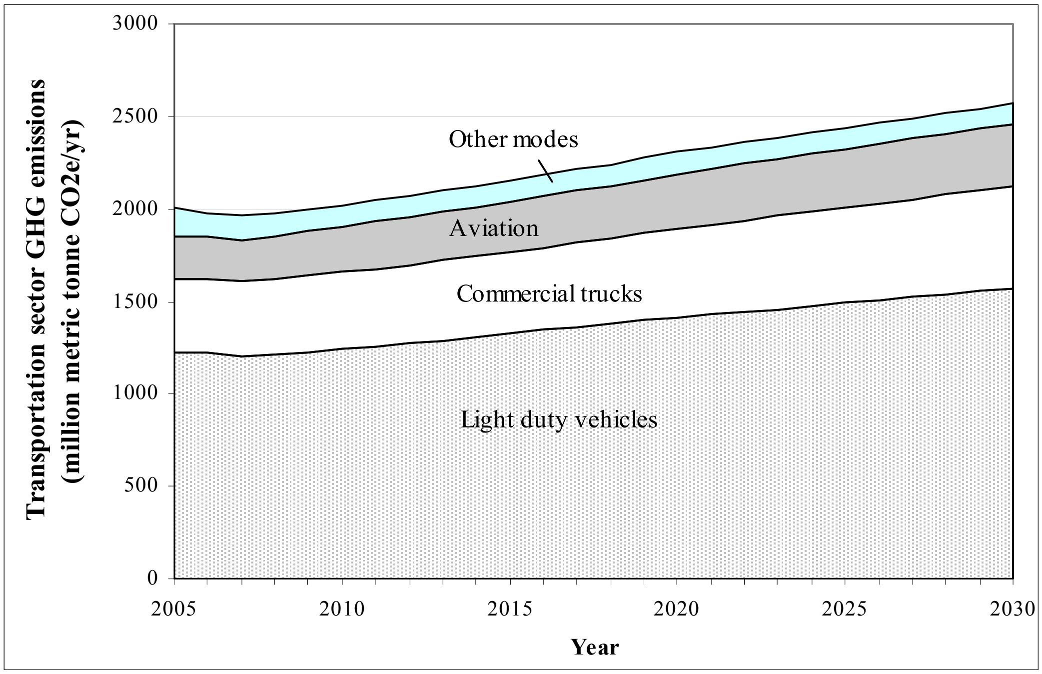


Figure 9. Transportation GHG emissions by mode

Related to this study's constraint of only considering mitigation options that can deliver near-term emission reductions, transportation sector-specific options are subject to the constraining factor of the linkage between fuels and vehicle technologies. Mitigation options in this chapter are confined to those fuel and vehicle technologies that cause relatively minor if any modifications in the other. For example, vehicle efficiency modifications that still use motor gasoline and ethanol-mixing in motor gasoline that requires little or no vehicle modification are considered. On the other hand, larger scale displacement of internal combustion engines by fuel cell or fully battery-electric drive systems are not included.

4.1. Passenger Vehicles

In the following sections, GHG mitigation actions in the U.S. transportation sector are analyzed. The starting point for analysis of transportation options is the baseline data on vehicle and energy use from the U.S. Department of Energy's 2008 *Annual Energy Outlook* (U.S. EIA, 2008) and other vehicle characteristics of *Transportation Energy Data Book* (Davis and Diegel, 2006). In each potential GHG mitigation action subsection, a brief statement on U.S. federal and state policy background in the area is provided, the available literature on cost and benefit impacts of each mitigation action is examined, an analysis of the cost-effectiveness of each mitigation action is conducted, and a deployment schedule for each GHG mitigation measure is offered. The general methodological steps outlined in Chapter 3 are followed, and various other details related to the specifics of the transportation sector are described.

In the following two sections, this study focuses on two different types of measures to improve light duty vehicle efficiency: (1) improvements in test-cycle fuel economy and (2) improvements to "on-road," or "in-use" fuel economy that may not be acknowledged by regulatory test cycles. This distinction is used because such measures are generally undertaken and measured independently. Test-cycle fuel efficiency improvements are driven by regulatory standards, namely by fuel economy or carbon dioxide standards, enacted for new vehicle sales. These efficiency improvements are easily validated by year-to-year emissions/fuel economy reporting by automakers. On the other hand, "in-use" efficiency improvements differ from regulatory test cycle standards in that they generally can affect vehicles, old or new, that are on the road, can be driven by driver education initiatives, and can be evaluated from surveys of vehicle use over time. "In-use" measures are considered in the following section.

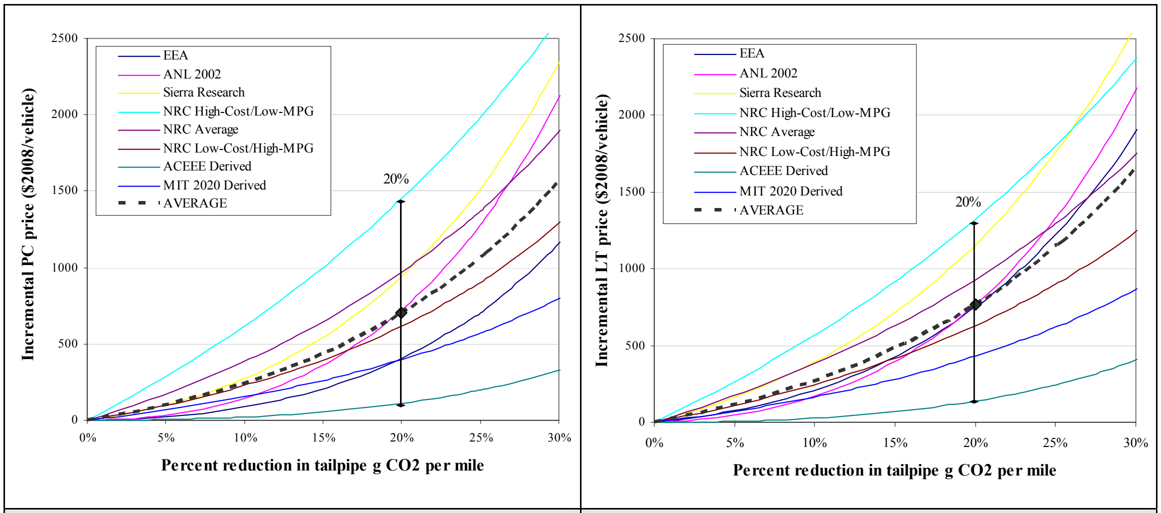
4.1.1. Test-cycle vehicle efficiency

New light duty vehicle efficiency is set to change according to the *Energy Independence and Security Act of 2007,* which was passed in December of 2007. This federal legislation mandates the first new car fuel economy standard change since 1984, and, for the first time, made a requirement that new cars and light trucks be averaged together for corporate average fuel economy (CAFE) standards. The passenger car CAFE standard had been set at 27.5 miles-per-gallon (mpg). National Highway Traffic and Safety Administration had set forth standards for modest improvements for passenger light trucks for model years 2005 through 2011, raising the standards from 20.7 to about 24 mpg (NHTSA, 2003; NHTSA, 2005). The *Energy Independence and Security Act of 2007* sets the combined car and truck CAFE standard of 35 mpg for new light duty vehicles in the year 2020. California's vehicle greenhouse gas regulation, as was discussed in Chapter 2, sets a somewhat more stringent standard on a more advanced timescale than the federal legislation.

Many studies have assessed technologies for light-duty vehicles to improve test-cycle vehicle efficiency to increase fuel economy and reduce greenhouse gas emissions, and many of these studies have also evaluated the increase in the vehicle cost that is associated with these efficiency technologies (e.g. Austin et al., 1999; DeCicco et al., 2001; EEA, 2001; NRC, 2002; Plotkin et al., 2002; Weiss et al., 2000). Engineering-economic studies of this nature generally apply emerging technologies to new vehicles in vehicle simulations on test cycles, such as the U.S. Federal Test Procedure "city" and "highway" cycles. These studies reveal smaller efficiency fuel efficiency gains for relatively low cost, but each additional incremental efficiency increase results in increasing marginal cost. Smaller magnitude changes in efficiency involve relatively minor vehicle changes, such as introducing emerging engine and transmission changes. Larger magnitude improvements in these studies involve more advanced technologies with various levels and architectures of hybridization of the vehicle.

Efficiency improvements from gasoline vehicles are treated here as two discretely different steps: one for incremental vehicle efficiency and one for more advanced hybrid gasoline-electric technology. This delineation was made due to clear differences in per-vehicle cost and efficiency improvements, overall uncertainty in the estimations, and the presumed difference in timing of mass production of the technologies – all of which are factors that impact the cost-effectiveness estimations for the two technologies in this study.

The relationship between change in test-cycle CO_2 emission rate and incremental vehicle cost for both passenger cars and light trucks were derived from various engineering-economic studies (Austin et al., 1999; DeCicco et al., 2001; EEA, 2001; NRC, 2002; Plotkin et al., 2002; Weiss et al., 2000), after converted to year 2008 dollars, and are shown in Figure 10. Curves in the figure are shown as the price to the vehicle consumer (after considering manufacturers' retail price mark-up on incremental technology costs). For this study, a 20% efficiency improvement (in L/100km of gram CO_2/mile) or 25% fuel economy (in miles/gallon) was assumed to be the limit for incremental efficiency technology. Common technologies from the various studies that yield up to 20% reduction in CO_2 emission rate include combinations of technologies for the engine (variable valve lift/timing, gasoline direct injection, cylinder deactivation), transmission (5- and 6-speed automatic, and automated manual transmissions), and overall vehicle (aerodynamics, light-weighting).



Passenger cars

Light trucks

Figure 10. Derived incremental price – GHG reduction relationships from various studies

The incremental price – CO_2 relationships are used to evaluate cost-effectiveness estimates for the improved incremental efficiency technology to reduce light duty vehicles' test-cycle CO_2 emission rate by 20%. As described in Chapter 3, cost-effectiveness is evaluated in initial and lifetime cost accounting forms. Initial cost-effectiveness accounting involves the initial technology cost divided by the total GHG reduction caused by that technology. The lifetime cost-effectiveness accounting includes the initial investment cost and the lifetime cost impacts (generally the resulting fuel savings) over the lifetime of the new technology investment, with any costs and benefits in future years discounted at a discount rate.

Several assumptions and adjustments are used to evaluate cost-effectiveness values. Applying the vehicle use assumptions from Davis and Diegel (2006), fuel prices from U.S. EIA (2008), and 7% discount rate on future fuel savings, the "lifetime" cost-effectiveness of incremental efficiency gains are calculated. After adjusting to 2008 dollars, the retail gasoline price from 2010-2020 is between $2.24 and $2.48 per gallon, with an average of $2.35 (U.S. EIA, 2008).

Cost-effectiveness estimates, based on the above discussed engineering-economic relationships and the discussed assumptions, are shown in Table 6. Results for passenger cars and light-duty trucks are weighted according to their respective emissions in future years to make for one light duty vehicle category. On average, the 20% improvement corresponds to a \$740 increase in light duty vehicles, though various studies' estimates range from about \$100 to \$1400 per vehicle for that level of efficiency gain. The initial vehicle costs divided by the lifetime per vehicle GHG reductions results in an average initial cost of \$46 per ton CO_2e reduced.

Although the per-vehicle range of initial costs is quite large, the cost-effectiveness – from initial and lifetime accounting approaches – have narrower ranges. Also, all studies' estimates for the cost of incremental fuel consumption improvements of 20% result in net benefits to consumer over the lifetime of the vehicles. The lifetime cost-effectiveness of incremental 20% fuel consumption improvements are an average of -\$110/tonne CO_2e. The negative value signifies a net benefit, with values from the various studies ranging from -\$148 to -\$69 per tCO_2e.

Table 6. Cost effectiveness of incremental efficiency for 20% CO_2-per-mile reduction for light duty vehicles

Study derived from	Incremental vehicle price increase (\$)	Initial cost-effectiveness (\$/tonne CO_2)	Lifetime cost-effectiveness (\$/tonne CO_2)
EEA (2001)	612	36.6	-120
ANL (Plotkin et al., 2002)	748	46.6	-109
Sierra Research (Austin et al., 1999)	1072	66.1	-90
NRC (2002) High-Cost/Low-mpg	1374	86.7	-69
NRC (2002) Average	945	59.4	-97
NRC (2002) Low-cost/High-mpg	623	39.0	-117
ACEEE (DeCicco et al., 2001)	127	7.8	-148
MIT 2020 (Weiss et al., 2000)	416	25.9	-130
AVERAGE	740	46.0	-110

Hybrid technology is treated as a separate discrete step from the above incremental efficiency measure in this cost effectiveness analysis. The studies on hybrid-electric vehicles (HEVs) that this report focuses on include varying degrees of hybridization, each with a range of different specific technology components. Hybrid types "mild," "moderate," "full," and "plug-in" are used to delineate hybrid scenarios. These hybrid types from the various hybrid vehicle studies (An et al., 2001; Graham et al., 2001; Lipman and Delucchi, 2003; Plotkin et al., 2001; Santini et al., 2001; Markel et al., 2006) are compared on a cost-per-ton-CO_2 cost effectiveness basis. The studies applied here each use weight reduction as an efficiency strategy to varying degrees within their HEV scenarios. For this reason, and because evaluating weight reduction strategies' impacts is optimally done simultaneously with integration of other efficiency technologies, vehicle weight reduction is not analyzed as a discrete and different step in this cost-effectiveness curve analysis. These HEV study estimates assume that some level of incremental efficiency technology has been deployed on their baseline vehicles by the time of hybrid deployment, and the average baseline fuel economy of those studies is 32 mpg.

Based on comparing the various HEV types' cost-effectiveness values (See Figure 11), the "full" HEV architecture was chosen. The same vehicle use and economic assumptions from the above incremental efficiency scenario are applied to the HEV technology estimates. As shown in Figure 11, the range of estimates for the lifetime cost-effectiveness of the full HEV technology is roughly the same as that of the moderate HEV technology; however, the full HEV offers an average 38% gram-per-mile GHG improvement compared to the moderate's 29% reduction. Also in the figure, the data indicate that the plug-in vehicle option offers only modest improvement (i.e., on average 43% vs. 38%, with similar ranges of GHG reduction percentages) over the full HEV but at considerably higher cost-effectiveness values (i.e. greater than three time higher). Note here that plug-in HEV data are based on U.S. data (i.e., not California-specific). Furthermore, of the plug-in HEV data points, it is only one data point that offers a GHG reduction benefit at a greater level than the range of full HEV technology estimates.

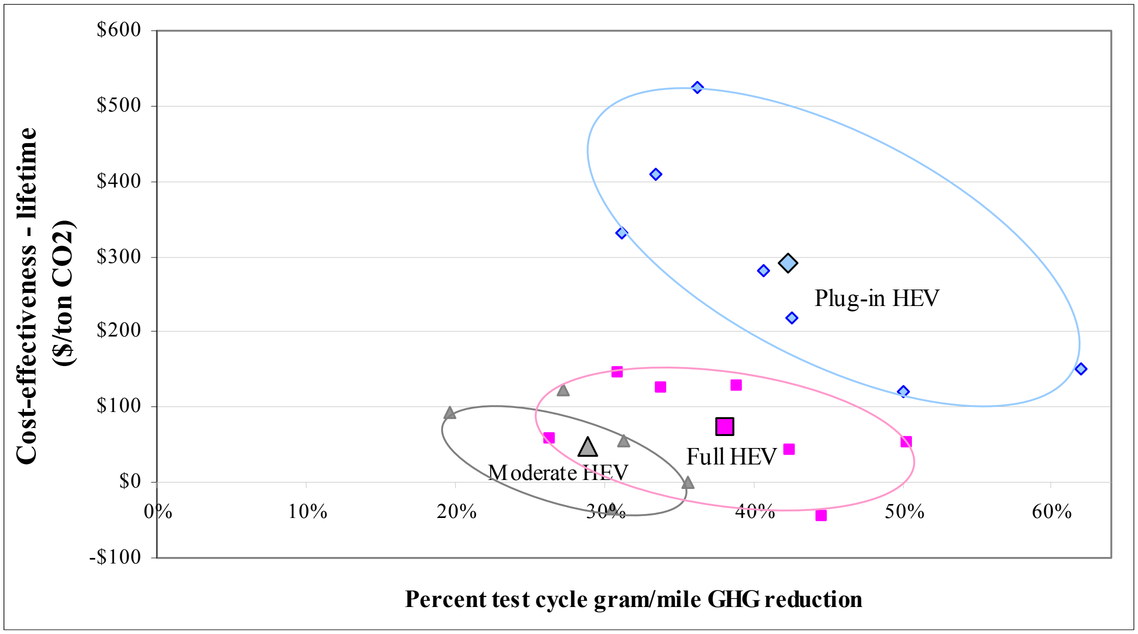


Figure 11. Cost-effectiveness of light duty vehicle GHG reduction from hybrid-electric technology

A summary of the cost effectiveness of the studies' full HEVs studies is shown in Table 7. The average full HEV technology, from the five studies' data, is to offer a 38% tailpipe CO_2 emission reduction for in incremental retail price increase of about $4000 per vehicle, with individual study findings ranging from $2000 to over $5000. The resulting cost-effectiveness values of the full HEV technology under the three accounting frameworks are $227 (initial) and $73 (with lifetime fuel savings) in units of 2008 dollars per tonne CO_2e reduced.

Table 7. Cost effectiveness of "full" hybrid electric vehicle technology for light duty vehicles

Study Derived From	Scenario	CO_2 Reduction	Incremental vehicle price increase [a] ($)	Initial cost-effectiveness ($/tonne CO_2)	Lifetime cost-effectiveness ($/tonne CO_2)
ANL 1 (Plotkin et al., 2001)	(12 s. 0-60 mph)	26.4%	$4,330	224	58
ANL 1 (Plotkin et al., 2001)	(10 s. 0-60 mph)	33.8%	$4,801	292	126
EF (An et al., 2001)	Full	38.9%	$5,729	294	127
EPRI (Graham et al., 2001)	Full (Base)	30.9%	$4,846	313	146
EPRI (Graham et al., 2001)	Full (Low)	44.6%	$2,728	122	-44
ANL 2 (Santini et al., 2001)	Full	42.4%	$5,577	209	43
ITS (Lipman and Delucchi, 2004)	Full (Mod. average)	50.3%	$5,175	137	53
Average		38.2%	$4,741	227	73

For the deployment timing of efficiency technology options into the light duty vehicle fleet, a logistical S-curve function is used to dictate the phasing in of the new technologies into new vehicle sales. The incremental efficiency step (with a 20% fuel consumption rate reduction) is phased in from now through 2020, with 10%-to-90% deployment taking place from 2011 though 2018 (previous to consideration of HEV deployment).

Due to the potential limitations of widespread HEV technology deployment in terms of all major manufacturers ramping up their mass-production of the technology and that HEV technology may not be able to fit every light duty vehicle application (from small sedans to large pick-ups), total HEV deployment is assumed to be limited to 50% for this analysis. Furthermore, imposing this 50% sales constraint on HEVs in this analysis assures the continuance of the recovery of investment in the first phase of GHG reduction technology, incremental efficiency, for automakers before retooling factories and switching over to another set of engine, transmission, and vehicle system technologies. The phase-in of a hybrid-electric new vehicle fleet has a 10%-to-50% deployment timeframe taking place from 2014 though 2025. The phase-in schedules of the two efficiency scenarios, with both considered together, is shown in Figure 12.

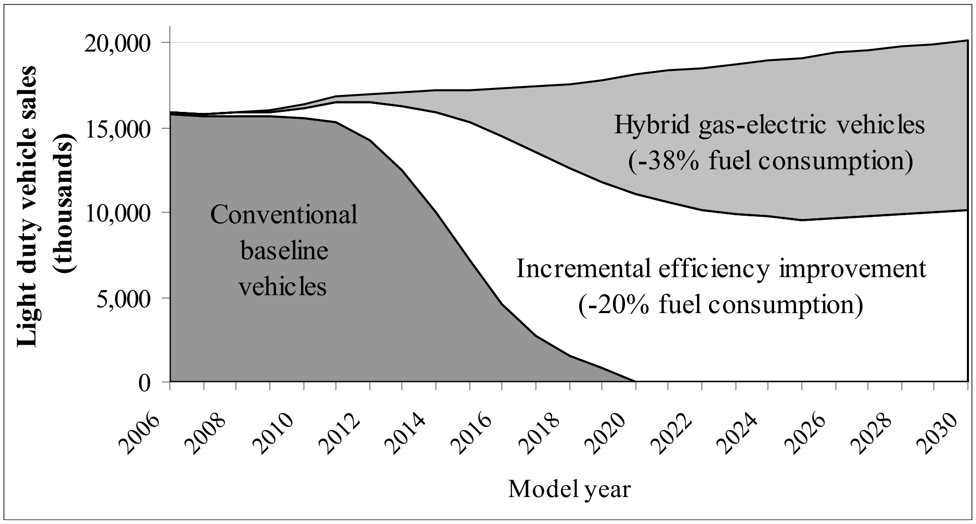


Figure 12. Light duty vehicle sales by vehicle efficiency type for this analysis

The impact of these two scheduled deployment phases on rated combined light-duty vehicles (cars plus light trucks) cycle fuel economy and tailpipe CO_2 emission rates are shown in Figure 13. From the 2005 fuel economy of about 25 mpg, the baseline from U.S. DOE's *Annual Energy Outlook* (U.S. EIA 2008) forecast a baseline improvement to 30 mpg by 2030, previous to being updated for new 2007-legislated fuel economy changes. The incremental efficiency scenario would increase combined test-cycle fuel economy to 33 mpg by model year 2020 (38 mpg for cars, 29 for light trucks). The implementation of the 50% HEV sales scenario, with the other 50% vehicle sales being of incremental efficiency technology, results in a combined new light duty vehicle fuel economy of 37 mpg by 2020 (42 mpg for cars, 33 mpg for light trucks). The same passenger car and light trucks mix from U.S. EIA (2008) for future years is assumed, whereby light trucks sales percentage gradually increases from just below 50% in 2006 to about 56% by model year 2026.

For context, this joint application of incremental and HEV efficiency measures is similar, but ultimately somewhat more stringent, than the federal *Energy Independence and Security Act of 2007*, which mandates a combined 35 mpg for new cars and light trucks by 2020. The new federal standards, to be implemented by the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA), are also shown in the figure.

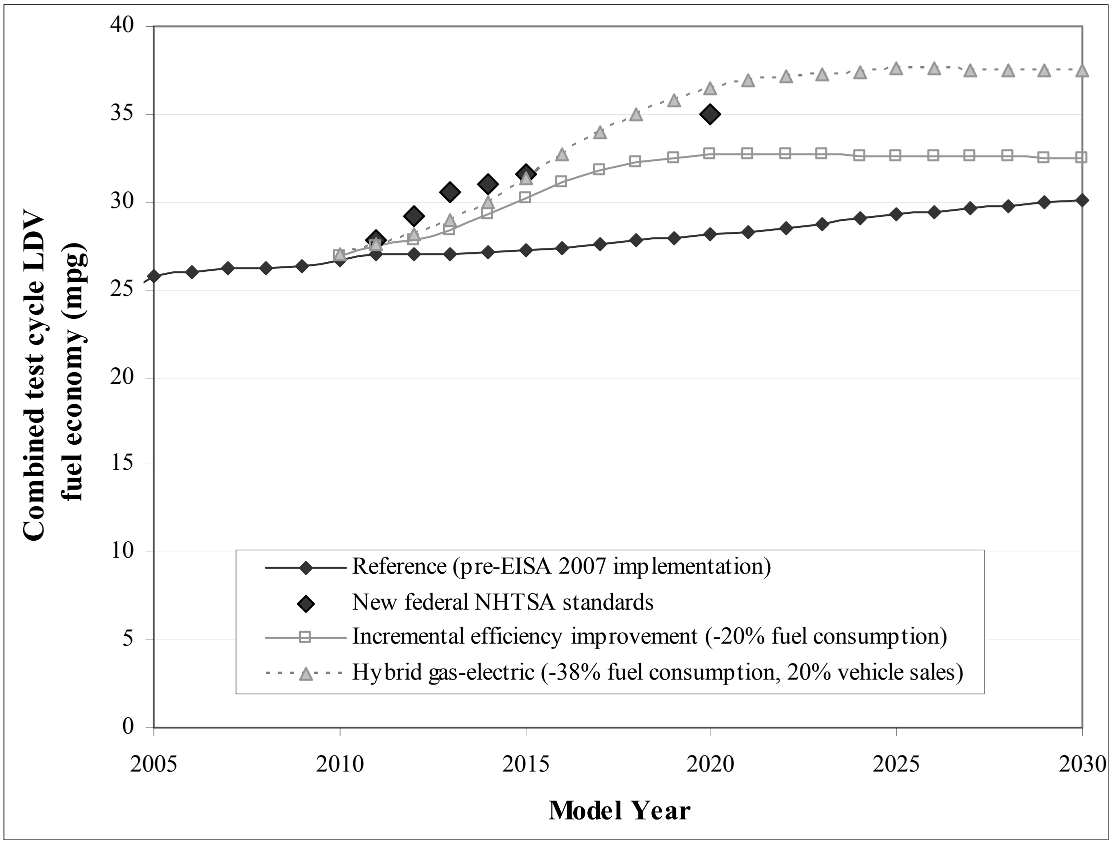


Figure 13. New light duty vehicle fuel economy with efficiency scenarios

4.1.2. "On-road" vehicle efficiency

Along with the investigation of test-cycle vehicle efficiency improvements, GHG and fuel use reductions that are not fully recognized by average new vehicle testing are assessed separately here. From very early in CAFE compliance testing, it was known that there was a gap between actual "in use" fuel economy and tested fuel economy (McNutt et al., 1982). Adjustments, or "correction factors," were put forward by U.S. EPA decrease tested "highway" fuel economy by 22% and tested "city" fuel economy by 10% (Hellman and Murrell, 1984). These corrections equate to an approximate 15%-increase in tested combined (city and highway) cycle fuel economy to establish more accurate measures for new vehicle fuel economy information for consumers and for use in public policy evaluations; however, these on-road corrections are not used in official regulatory testing for CAFE standards. The difference between test-cycle and actual on-road fuel economy is receiving considerably more attention lately because of the potential that the difference between the regulatory test and actual emissions/fuel use is widening. For data purposes, U.S. DOE estimations for on-road energy use in light-duty vehicles assume correction factors for both passenger cars and light trucks that increase fuel economy values by about 20% (U.S. EIA, 2008).

A combination of programs in driver and consumer education, vehicle technologies, and technologies that improve driver awareness of fuel use is explored here for CO_2 cost effectiveness. Driver education programs aim to influence driver behavior/practice driving habits toward more fuel efficient practices. This could involve making fuel efficient driving practices part of driver training curricula for both commercial and private licenses. The curricula could include dissemination of information to discourage unnecessary idling and peak-time congested travel, encourage shifting to higher gears more quickly, and inform on the use of overdrive and cruise control on highways. Consumer and maintenance education programs would train on recommended maintenance schedules, tires (on maintaining inflation levels and on low rolling resistance tire purchases), alignment, oil changes (frequency and low friction oil purchase), air filter replacement. Another alternative is for manufacturers to deploy technologies that aid in driver awareness of fuel economy, such as on-board indicator technologies like an instantaneous fuel economy meter, a tachometer with "efficiency rpm range," shift indicator lights (for manual transmissions), and a tire inflation monitor.

A recent study by ECMT and IEA (2005) has explored many of the above measures in terms of cost-effectiveness in reducing fuel consumption and CO_2 in various real-world conditions. This analysis adapts results from the ECMT/IEA study here to estimate the cost-effectiveness of CO_2 reduction from measures that increase "in-use" vehicle fuel use (but do not necessarily improve test-cycle fuel efficiency). The ECMT/IEA study assumptions are modified slightly to be consistent with our conventions used throughout the study. For example, the original study used a lower discount rate (3% compared with this analysis' 7%), and this study uses its own assumptions on fuel prices from U.S. EIA.

The most cost-effective in-use technologies include a shift indicator light for manual transmissions, dual cooling circuits, driver training, tire inflation monitor, and low rolling resistance tires. Other relatively cost effective in-use technologies include the use of low friction oil and improved accessories use. A study by CEC and CARB on vehicle maintenance (including tire inflation, oil change and air filter replacement) and consumer education (tire rolling resistance) programs also revealed highly cost effective in-use improvements (CEC and CARB, 2003). In addition, the proposed California GHG regulation for light duty vehicles incorporated improved efficiency accessory use, including high efficiency variable displacement air conditioning compressors, in its establishing its GHG standards (CARB, 2004).

The use of these "in-use" technologies and programs to improve the "on-road" fuel consumption could be considered somewhat more uncertain. For the use of any sort of education programs are less predictable (based on percent of drivers reached and percent affected by any programs), are more prone to confounding issues (whether improvements are actually caused by the measures), and are less easily validated (based on statistical data of vehicle use conditions and vehicle fuel consumption over time). Implementation of some in-use improvements could need a combination of support from government agencies, manufacturers, and dealerships to disseminate information as needed. However, the fact that there do appear to be numerous technology-based alternatives that offer net benefits to consumers over the technology lifetimes merits their consideration in this research.

Improving on-road efficiency to eliminate the shortfall between test cycle and in-use fuel economy appears feasible and highly cost effective. Most of the measures in Table 8, if independently installed on vehicles, would deliver net benefits to consumers due to their fuel saving benefits. To achieve this level of real-world fuel consumption reduction, measures involving in-dash indicators (for shifting in manual transmissions and for tire under-inflation), driver training, low rolling resistance tires, vehicle maintenance, and higher efficiency vehicle system accessories appear to be the most cost-effective. Due to this study's emphasis on technology-based measures, the vehicle operator maintenance measures that CEC and CARB (2003) finds to have low cost-effectiveness values, are not included here. In addition, the "driver training" element from the ECMT and IEA (2005) study is also excluded.

Furthermore, including a larger cluster of the in-use technologies – use of the nine technologies through the "efficient A/C system" measure in Table 8 – to approximately halve the 20% shortfall between rated test-cycle and on-road fuel economy also yields a net lifetime benefit to consumers for the chosen assumptions. These nine measures reduce independent energy uses and losses in the vehicle (e.g. rolling resistance, engine friction, parasitic loads, accessories), allowing for their packaging together. The on-road shortfall elimination technology package would increase initial vehicle cost by $670 and result in a roughly 12% fuel consumption rate decrease (equivalent to a 14% fuel economy increase).

Table 8. In-use technology GHG reduction and costs

In-use efficiency measure	CO_2 g/mi change	Cumulative CO_2 g/mi change [a]	Initial cost (2008$) [low / mid / high]			Cumulative initial cost of technology package [a] (2008$) [low / mid / high]		
Shift indicator light	-1.5%	-1.5%	29	34	40	29	34	40
Dual cooling circuits	-1.5%	-3.0%	34	46	57	63	80	98
Tire inflation monitor	-1.0%	3.9%	34	40	46	98	121	144
Low rolling resistance tires	-1.5%	5.4%	57	75	92	155	195	236
Efficient alternators	-1.1%	6.5%	46	57	69	201	253	305
0W-5W/20 oils	-1.0%	7.5%	46	57	69	247	310	374
Electric water pump	-2.2%	9.7%	115	144	172	362	454	546
Heat battery	-1.0%	10.7%	92	103	115	454	558	661
Efficient A/C system	-1.0%	11.7%	92	115	138	546	672	799
Idle stop/start (42V system)	-2.9%	14.6%	345	402	460	891	1,075	1,259
Heat pumps for A/C	-1.7%	16.3%	230	287	345	1,121	1,362	1,604
Adaptive cruise control	-6.1%	22.4%	1,150	1,437	1,724	2,270	2,799	3,328

[a] *Cumulative numbers include measures at and above that from the first column*

Applying the same vehicle use assumptions as for the above test-cycle efficiency GHG reduction options, the cost-effectiveness values of the in-use efficiency measures are shown in Table 9 and as marginal cost abatement curves in Figure 14. Table 9 shows the corresponding CO_2 emission rate impact, percentage point fuel economy shortfall, and initial and lifetime cost-effectiveness values of the technologies. For the adoption of in-use technologies to halve the test-cycle versus on-road gap, the package of all technologies through the "efficient A/C system" measures are included together. The cost-effectiveness values of this technology package are $95 (including only initial costs) and -$55 (including discounted energy savings over technology life) per CO_2e tonne.

Table 9. In-use technology GHG reduction and cost effectiveness values

In-use efficiency measure	Cumulative CO_2 g/mi change [a]	Percentage point change in test vs. in-use shortfall [a]	Initial cost effectiveness of in-technology package [a] (2008$/tonne CO_2) [low / mid / high]			Lifetime cost effectiveness of in-technology package [a] (2008$/tonne CO_2) [low / mid / high]		
Shift indicator light	-1.5%	0.8%	32.3	38.7	45.2	-117.8	-111.3	-104.9
Dual cooling circuits	-3.0%	2.1%	35.5	45.2	54.9	-114.6	-104.9	-95.2
Tire inflation monitor	3.9%	2.9%	41.1	50.8	60.4	-109.0	-99.3	-89.6
Low RR tires	5.4%	4.2%	47.5	59.8	72.1	-102.6	-90.3	-78.0
Efficient alternators	6.5%	5.6%	51.1	64.2	77.4	-99.0	-85.8	-72.7
0W-5W/20 oils	7.5%	6.5%	54.5	68.5	82.4	-95.6	-81.6	-67.7
Electric water pump	9.7%	8.4%	61.8	77.5	93.2	-88.3	-72.6	-56.9
Heat battery	10.7%	9.4%	70.3	86.4	102.4	-79.7	-63.7	-47.7
Efficient A/C system	11.7%	10.4%	77.4	95.4	113.3	-72.7	-54.7	-36.8
Idle stop/start (42V)	14.6%	13.6%	101.2	122.0	142.9	-48.9	-28.0	-7.2
Heat pumps for A/C	16.3%	15.2%	113.9	138.4	162.9	-36.2	-11.7	12.8
Adaptive cruise cont.	22.4%	22.6%	167.9	207.0	246.1	17.8	57.0	96.1

[a] *Cumulative numbers include measures at and above that from the first column*

The cost-effectiveness values, in the two accounting methods are shown graphically in Figure 14 to demonstrate the difference in cost-effectiveness from different accounting perspectives. Note that the ordering of the in-use measures, inserted into the figure from lower left to upper right, does not change due to the accounting of costs and benefits.

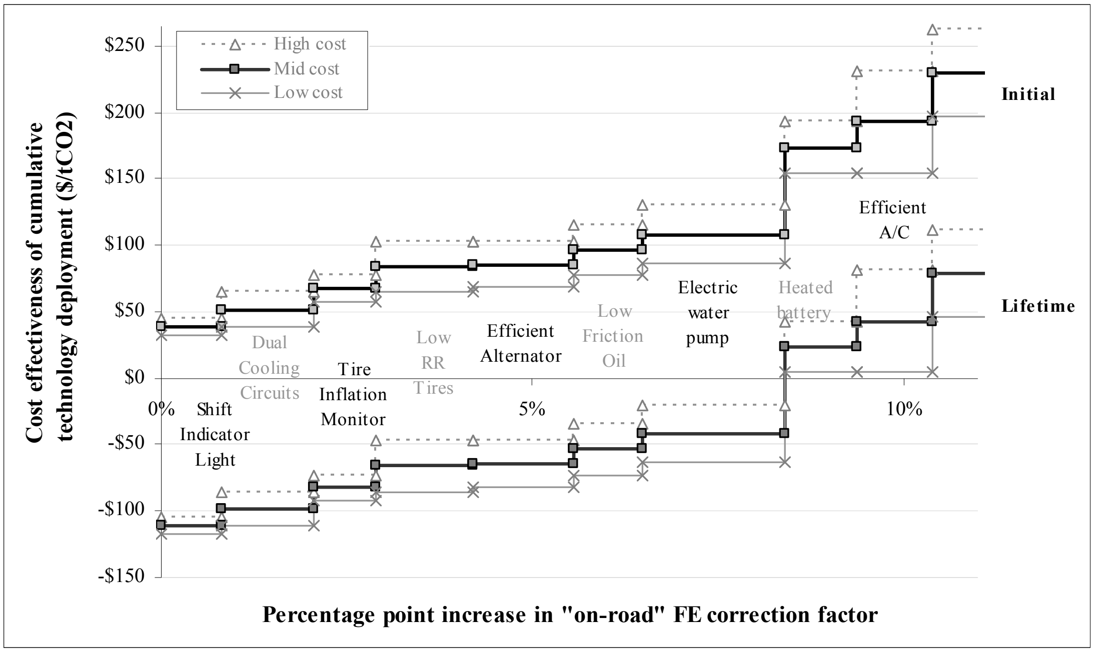


Figure 14. Cost-effectiveness curve for in-use vehicle fuel economy improvement measures

Figure 15 shows the assumed rate of deployment of technologies to halve the 20% shortfall between rated fuel economy and in-use fuel economy of vehicles in actual driving. As with the above technologies, a logistical curve is used to approximate manufacturers' gradual installment on in-use fuel efficiency improvements on new vehicles from model year 2010 through 2020.

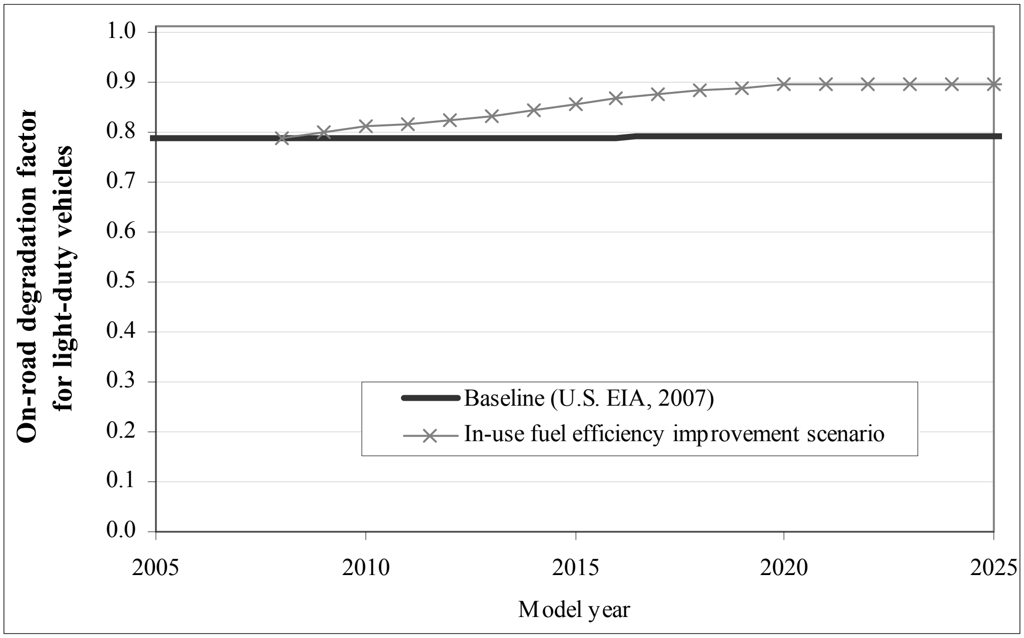


Figure 15. Phase-in of "in-use" fuel efficiency improvements

4.1.3. Air conditioning refrigerant replacement

The use of modified mobile alternative air conditioning systems to reduce light-duty vehicles greenhouse gases is considered by numerous regulatory agencies for adoption in new vehicles within the next decade. Reductions in refrigerant emissions can result from improvements in the recovery and recycling of the refrigerant from vehicles, reductions in leakage from vehicles, and by replacing the refrigerant with an alternative system. Because recycling of the conventional refrigerant HFC-134a from vehicles is already mandatory in the U.S., the focus here is on "on-vehicle" aspects of the air conditioning compressor system. Because the current refrigerant for new light vehicles, HFC-134a, has a relatively high global warming potential (GWP) of 1300, low-GWP replacements such as HFC-152a (GWP=120) and CO_2 (GWP=1) are alternative replacements. In addition, research on improving mobile air-conditioning systems' contribution to greenhouse gas emissions also involve tightening up the life-cycle leakage of refrigerant emissions.

There are ongoing regulatory initiatives directed at improving light duty vehicle HFC emissions, most prominently in Europe and California. In the European Union, in connection with regulatory agency-industry deliberations over reducing emissions to contribute to overall Kyoto Protocol reductions, ideas of incentivizing lower-GWP refrigerants and all-out bans on higher-GWP (>50) have been introduced. The changes are likely to be phased in on new cars over the 2010s, and if the high-GWP ban were enacted, the prevailing refrigerant would likely be CO_2 or a hydrocarbon.

In the proposed California climate change regulations for vehicles, the technology assessment assumes the use of a lower-leak system with the use of refrigerant HFC-152a, to be fully deployed across light-duty vehicles by the year 2016 (CARB, 2004). The CARB regulatory research, based primarily on a study by NESCCAF (2004), concludes that "low leak" technology (involving e.g., multiple O-rings at pipe and hose connections, ultra-low permeability barriers for hoses in contact with the refrigerant, and multiple-lip compressor shaft seals) can cut in-use leakage by 50%, equivalent to reducing vehicle greenhouse gas emissions by 3 grams CO_2-equivlent per mile. The same study reports that switching new vehicle systems from HFC-134a to HFC-152a offers a potential reduction of 8.5 grams CO_2 equivalent per mile (91% of direct MAC emissions); switching to CO_2 as a refrigerant resulted in 9 g/mi reduction (99% of direct MAC emissions).

This analysis applies cost estimates used in the California regulation determination assessment (based on NESCCAF, 2004; Meszler, 2004). The mass-produced equipment cost, after retail cost mark-up and conversion to 2008 dollars, for the HFC-134 system was determined to be \$106 and \$140 per vehicle. Under similar assumptions, these cost estimates are very similar to that of IPCC (2001b) estimates. The same vehicle use characteristics from above are assumed, and the change in vehicle operating costs from the refrigerant change is assumed to be negligible. The HFC-152a is estimated to reduce 1.1 to 2.5 tonne CO_2-eq. per vehicle lifetime. The CO_2-refrigerant is estimated to reduce 1.2 to 2.7 tonne CO_2-eq. per vehicle lifetime.

Based on the variation in estimated emission reductions, the cost effectiveness of the alternative MAC refrigerants are \$56 (range of \$43 to \$93) per ton CO_2e for the HFC-152a and \$67 (range of \$52 to \$112) per ton CO_2e for the CO_2-refrigerant system. These are the cost-effectiveness values for the initial technology cost and for the lifetime cost accounting, as these two technologies are assumed not to impact the lifetime fuel savings of vehicles, as compared to the current refrigerant HFC-134a. Note that these technology cost-effectiveness values are for each action taken independently. If, on the other hand, the CO_2-refrigerant technology were chosen sequentially after the HFC-152a technology were adopted, the cost-effectiveness of the CO_2-refrigerant system would be much more expensive because its marginal additional GHG reduction from the HFC-152a system would be relatively small. For this reason, and for the more obvious institutional reason that the auto industry is highly unlikely to make two discrete MAC refrigerant system changes within the timeframe of this analysis, one of these two MAC technologies must be chosen for this research.

As shown graphically in the cost-effectiveness curve of Figure 16, the expected cost-effectiveness values of the two alternative refrigerant technologies, HFC-152a and CO_2, are very similar, especially when their cost-effectiveness value error bars are considered. Because these two alternatives' ranges for cost-effectiveness values are so similar, the CO_2-refrigerant system is chosen because of its larger GHG reduction potential, i.e. 38 million versus 35 million tonne CO_2e in year 2030. The CO_2-refrigerant system is phased in with a logistic s-curve from vehicle model years 2010 through 2020.

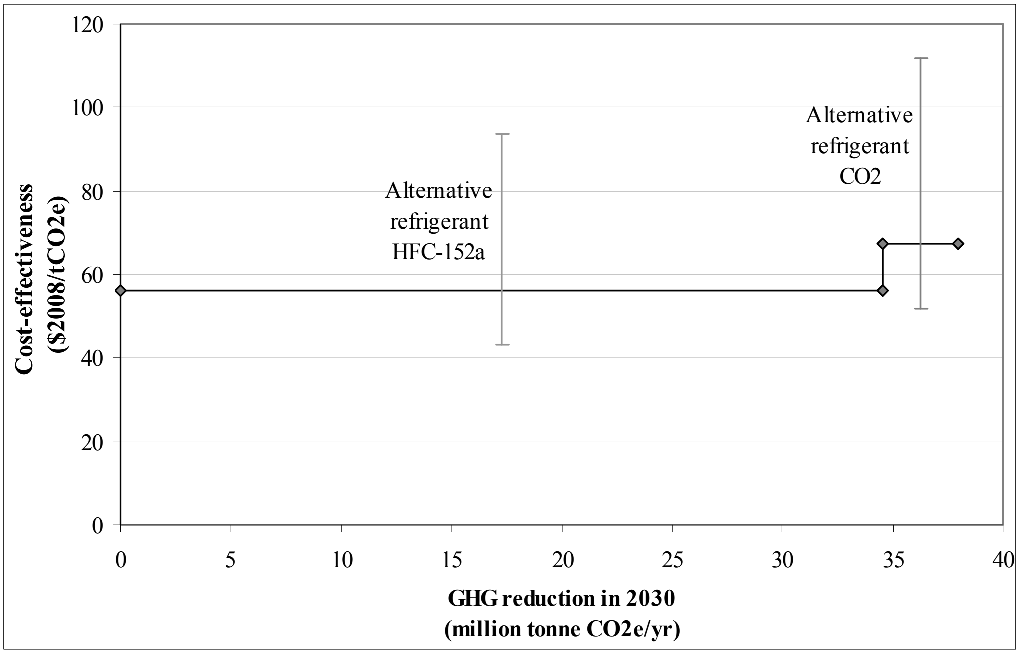


Figure 16. Greenhouse gas reduction cost-effectiveness of light duty vehicle refrigerant systems

4.1.4. Low carbon biofuel substitution

The use of ethanol is proposed often in discussions regarding fuel diversification, petroleum dependence, and climate change mitigation. Alternative fuels of various kinds generally initially face a combination of institutional, infrastructural, economic and feedstock barriers toward making significant headway in displacing petroleum use in vehicles. Ethanol has several serious advantages when compared with other lower-carbon fuels; foremost are its widespread availability from the U.S. agricultural sector and its ease of blending into gasoline fuel for use in conventional vehicles. Because of these substantial advantages, the use of ethanol mixing into motor gasoline is the only major alternative fuel for passenger vehicle considered in this near-term analysis. Other fuel systems (e.g., hydrogen fuel cells, electric vehicles, and compressed natural gas) are not considered to be of the same large-scale 2020 deployment potential of the expansion in use of ethanol as a motor fuel.

Ethanol derived from agricultural crops is a renewable fuel that harnesses CO_2 from the atmosphere in photosynthesis to produce energy in a chemical form that can be used to produce liquid fuels for vehicles. The net cycle of growing and harvesting the crops, transporting and chemically converting the crops to usable fuel for vehicles, and combusting the fuel for automobile propulsion can offer net GHG reductions, depending largely on crop feedstock and process characteristics. Although there is considerable uncertainty, conventional near-term ethanol from corn (or grain-based) is generally held to offer a modest life-cycle GHG improvement over conventional motor gasoline in transportation fuels (Hill et al., 2006; Farrell et al., 2006; Wang, 2005). Cellulose-based ethanol is associated with larger scale GHG benefits when displacing gasoline (Wang, 2005). Recent studies suggest that the land use shifts that result from expanded ethanol cultivation could far outweigh the

GHG benefit from displacing gasoline-related GHG emissions with many ethanol feedstocks (Delucchi, 2004; Searchinger et al., 2008; Fangione et al., 2008).

The studies that incorporate land use effects will spark further research that better clarifies GHG impacts of biofuels, based on the previous land on which is the feedstocks are cultivated (e.g., whether land was forest, unused marginal land, or another type of producing agricultural land); however, this analysis assumes the following benefits from the use of ethanol in transportation fuels. From conventional near-term ethanol from corn (or grain-based), levels of GHG benefit are in the range 12-20% when displacing gasoline in transportation fuels (Wang, 2005; Farrell et al., 2006; Hill et al., 2006). From those three studies, the average of 16% GHG reduction per gallon gasoline equivalent (gge) of corn-based ethanol that displaces gasoline is applied to this analysis. Using cellulose-based, instead of corn-based, ethanol is reported to have much greater GHG benefits – of up to and sometimes greater than 100% – when displacing motor gasoline. The updated GREET model impact of 85% reduction of GHG emissions per gge for cellulose-based ethanol that displaces gasoline (from Wang, 2005) is applied here. However, it is acknowledged here that the future inclusion of land use shifts due to expanded ethanol cultivation could potentially nullify some biofuel production methods as viable mitigation strategies.

Mixing ethanol into motor gasoline in blended proportions of up to 10% or 15% can be done without vehicle modifications. Blending at such levels would generally have a small effect on vehicle fuel economy and performance, due to ethanol's somewhat lower energy content per volume. Increasingly so-called "flex-fuel" E85 vehicles have been deployed by major automakers in the U.S. market. These vehicles have the capability to run on up to 85% ethanol (with the remaining 15% gasoline). Up to now, few of these E85-capable vehicles run on E85 fuel. However, the gradual increase in E85 vehicles on the road enables the eventuality of surpassing the 10% to 15% limitation that conventional non-E85 vehicles would otherwise face.

The reference case forecasts for the US include increases in ethanol mixing into motor gasoline over the next two decades. According to the U.S. DOE, about 6 billion gallons of ethanol in 2006 was blended with gasoline to represent approximately 4% by volume, or 3% by energy content, of motor gasoline (U.S. EIA, 2007). The "Renewable Fuel Standard Act" of 2005 would increase this amount to 12 billion gallons by the year 2010. After 2010, the U.S. EIA forecast for future ethanol use had relatively modest increases to lead to total ethanol consumption in fuel of 15 billion gallons by year 2025. However, the most recent federal energy legislation has greatly expanded these biofuel mandates.

The *Energy Independence and Security Act of 2007* has a provision to increase the minimum amount of renewable biofuels in transportation fuels to 36 billion gallons in 2022. Requirements starting in 2016 require that specific amounts of the total must be from "advanced" biofuels that are not based on cornstarch, with explicit mandates for cellulosic ethanol and biomass-based diesel. A stipulation for the new biofuel-producing refineries is that they are to reduce life-cycle GHG emissions by at least 20% relative to gasoline and diesel, and "advanced biofuels" are to have at least 50-60% GHG reductions.

In addition to this federal legislation, many states are furthering their own sets of mandates and incentives to increase the use of biofuels, as discussed in Chapter 2. At least 31 states now have mandates and incentives to blend biofuels into their transportation fuels (PCGCC, 2007). The most prominent state actions in this area are Minnesota's 20% ethanol fuel standard for gasoline by 2013 (State of Minnesota, 2004), Hawaii's alternative fuels standard for 20% renewable content in motor fuel by 2020 (State of Hawaii, 2006), and California's proposed low carbon fuel standard to reduce the GHG fuel content of passenger vehicle fuels by 10% by 2020 (State of California, 2007). In June 2006, the California Air Resources Board adopted its low carbon fuel standard and began rulemaking. It is scheduled to take effect in January 2010.

This analysis considers increased use of ethanol that is comparable to the 2007 federal energy policy legislation. This study's analysis was not tailored exactly to the mandated biofuel increases of *EISA of 2007.* Several recent studies of biofuel production have pointed out the importance of assessing the fully life-cycle effects of changing land uses (Delucchi, 2004, 2006; Searchinger et al., 2008; Fangione et al., 2008). To more comprehensively incorporate the land use changes due to expanded biofuel production and the soil carbon sequestration effects of the added biofuel production, this section's cellulosic ethanol expansion was matched up with the agricultural biofuel production as assessed for the agricultural sector, as will be discussed further in Chapters 8 and 9.

For this ethanol expansion scenario, ethanol usage in motor gasoline is increased to 32 billion gallons by 2022 and to just above 40 billion gallons by volume in 2030 (these numbers are equivalent to 21 and 27 billion gallons gasoline equivalent, respectively). Figure 17 shows this increase in cellulosic ethanol mixing in reference to the baseline ethanol consumption.

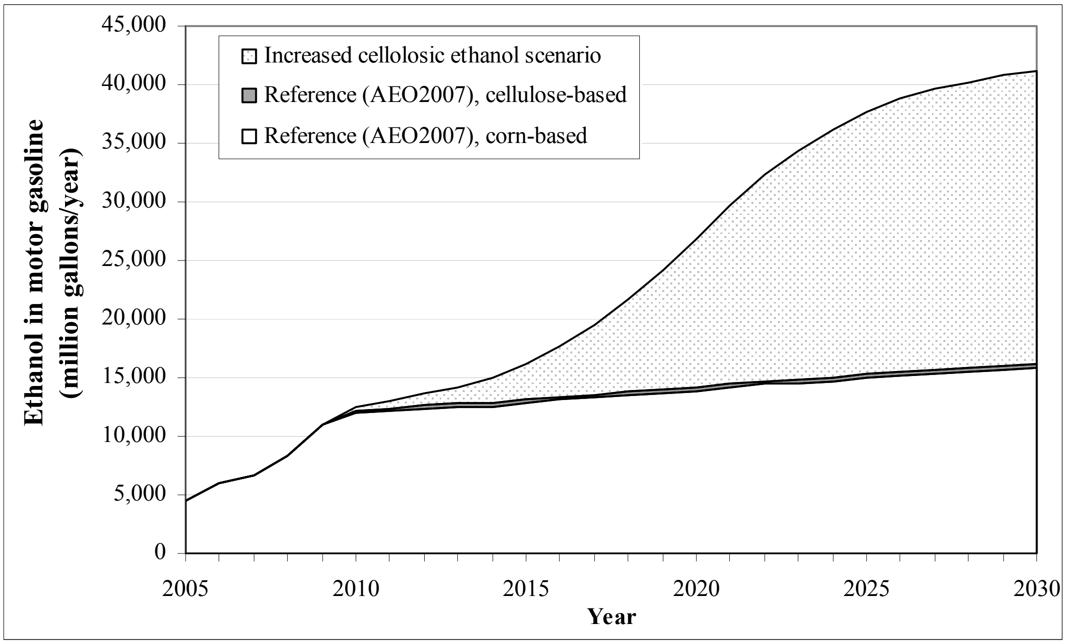


Figure 17. Ethanol production for transportation fuel – baseline and this study, 2005-2030

The increase in corn-based and cellulosic ethanol amounts, by fuel volume, to about 20% of total light-duty vehicle transportation fuel by 2020 and 31% in 2030. Converting the level of ethanol for transportation into gasoline gallon equivalence, the total amount of ethanol, by fuel energy content, in this increased cellulosic ethanol scenario is 13% by 2020 and 21% by 2030.

Applying the estimated 85% GHG benefit of cellulosic ethanol and the increased cellulosic ethanol mixing into transportation fuel, the resulting fuel GHG content is shown in Figure 19. From the 2010 baseline of about 8300 gram CO_2 per gallon, the increased cellulosic ethanol scenario results in reductions in fuel GHG emissions per gallon fuel of 11% in the year 2020 and 16% in 2030.

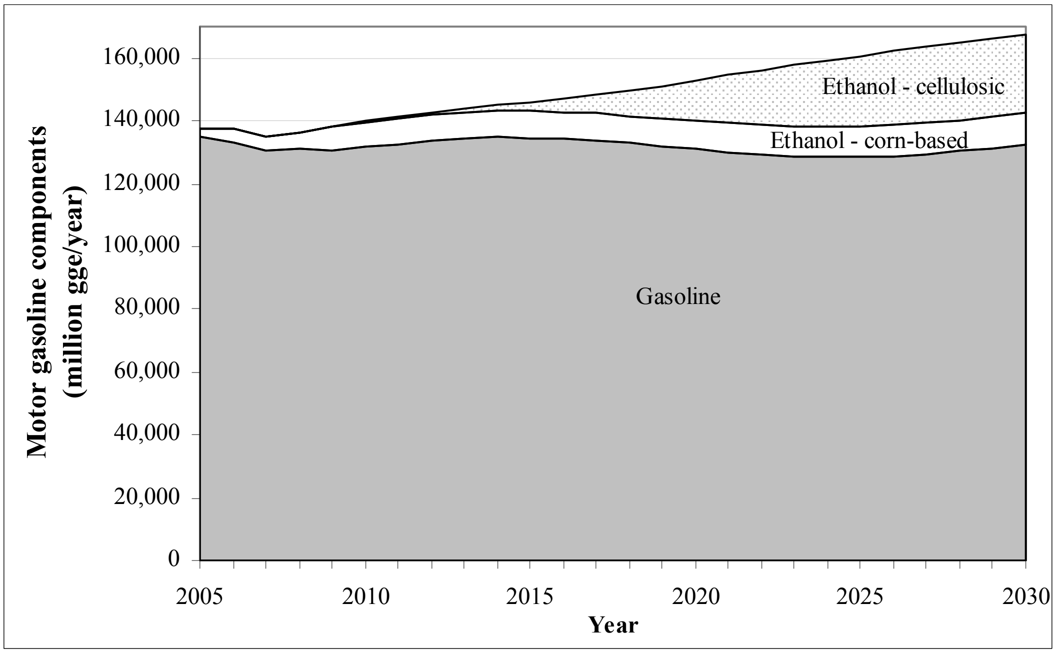


Figure 18. Motor gasoline content, with increased cellulosic ethanol

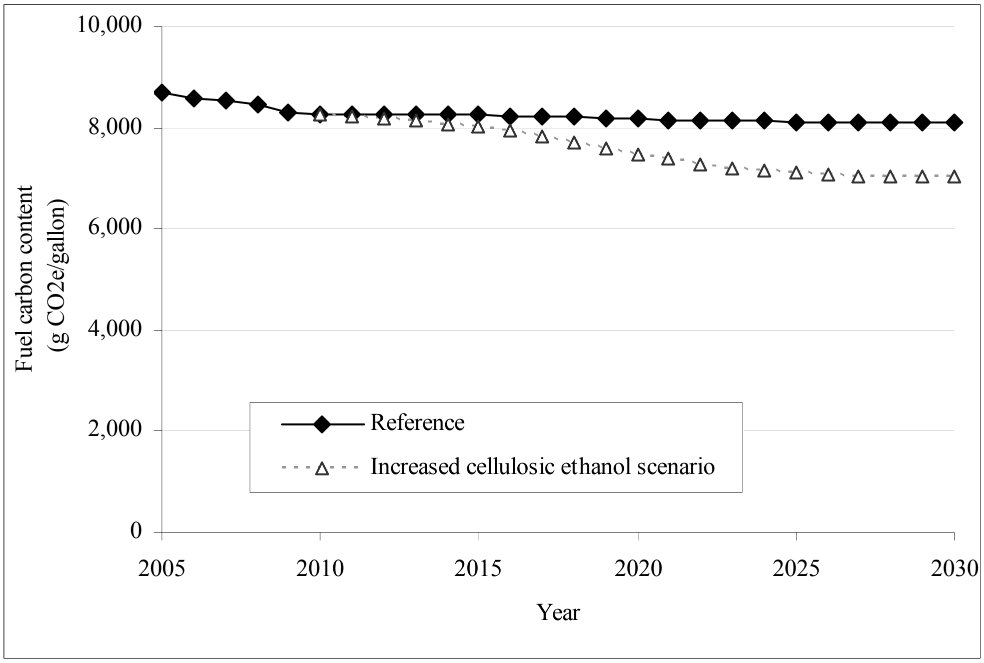


Figure 19. Change in motor gasoline carbon content with increased cellulosic ethanol scenario

The focus on ethanol for this study is on cellulosic-derived ethanol because of the substantial GHG benefit of its use and because there is potentially large available feedstocks in both residual waste (from agricultural, forest, consumer, and mill source) and dedicated energy crops in the U.S. The cost-effectiveness value estimation of the use of cellulosic ethanol as a feedstock is derived from several sources. It was of interest to tie this dissertation's analysis of GHG mitigation scenarios to primary data sources, which included the larger impacts of biofuel production on agriculture and natural carbon sinks. As a result, data from one particular study done by the U.S. EPA (2005), *Greenhouse Gas Mitigation Potential in the U.S. Forestry and Agriculture,* is applied here. That study, analyzing the integrated impacts of carbon mitigation policy on different types of agricultural lands, built on many of the noted limitations regarding interdependencies of GHG mitigation options with the agricultural and forestry sector.

Based on the U.S. EPA study (2005), agricultural production for biofuel offsets of up to 317 million tonnes of CO_2 can be generated from energy crops and waste residue at $37 per tonne of CO_2 reduced. Due to the competitiveness for that agricultural feedstock between transportation and electricity generation sectors under a GHG mitigation scenario, and without available research to determine a more likely apportionment, half of the agricultural feedstock apportioned to each sector. The result is that at that cost-effectiveness value of $37 per tonne, agriculture sector will generate 16 billion gge (from half of the overall expanded waste and energy crop production) after the shift is fully implemented in year 2030. Using the 85% life-cycle GHG reduction (per gge) gasoline displacement estimation, the resulting transportation sector GHG reduction in 2030 is approximately 124 million tonne CO_2 per year for the displacement of this amount of motor gasoline.

A forthcoming study contracted by a U.S. Department of Agriculture and U.S. Department of Energy (USDA and U.S. DOE, forthcoming) employs a supply curve analysis for biofuel production. The study is not yet finalized, but its findings offer similar results in terms of the cost-effectiveness of biofuels, as compared to the U.S. EPA (2005) study. The USDA and U.S. DOE study investigates biofuel feedstocks through western U.S. states (i.e. those states west of the Mississippi River. The study's preliminary findings suggest that from the western U.S. states' land, a quantity of 14 billion gallons gasoline equivalent can be produced at a marginal cost of $2.67 per gallon gasoline equivalent (gge) energy content. The average cost of this quantity of biofuel is $2.17 per gge. This level of biofuel production would supply approximately 15% of the western U.S. states' transportation fuel usage. The estimated cost-effectiveness, based on the difference in cost from the refined (untaxed) gasoline and ethanol is approximately $37 per ton CO_2 reduced.

4.1.5. Advanced fuel-vehicle technologies

More advanced longer-term vehicle technologies including alternative fuels such as compressed natural gas (CNG), fully electric vehicles, and fuel cell technologies, were also investigated for this study. These technologies are well researched (see e.g., Thomas et al., 1998; Santini et al., 2002; Jeong and Hoo, 2002; ADL, 2002; Weiss et al., 2000; and Ogden et al., 2004). However, these more advanced technologies are not at the same level of matuirity and commercial readiness of others presented in this dissertation. These technologies at present have various combinations of difficulties involving technological feasibility, infrastructural needs, criteria pollutant emissions, vehicle costs, and fuel costs (see e.g. Romm et al., 2004). These potential complications make the various alternative fuel vehicle-fuel technologies considerably more uncertain and, in all likelihood, more long-term than the technologies analyzed in this research for more recent large-scale deployment. A central tenet of this dissertation is to inform on the most viable, most near-term large-scale GHG-reduction mechanisms; therefore this research does not include such advanced fuel-vehicle technology packages for inclusion in the cost-effectiveness analysis. A more thorough, longer-term assessment of various climate planning alternatives for deeper emission cuts, of course, would have to speculate on one or more of these more advanced technologies that are under research and development phases.

4.1.6. Other options

There has been considerable study into options related to travel demand reduction, intelligent transportation systems, and congestion pricing – and how these measures could help to mitigate transportation GHG emissions (see e.g. Shaheen and Lipman, 2007; Ewing et al, 2007). There is also considerable policy action in this area. For example, recently, western states are engaged in a preliminary investigation of a tax on vehicle-miles-traveled, and New York City is actively considering a pricing scheme for vehicles entering the city like that of London. Other options in this category to reduce or modify travel behavior include parking management programs, provisions for alternative modes such as transit, and land use planning initiatives. However, this analysis does not include such options here for a variety of reasons, which are discussed in Chapter 10.

4.1.7. Summary of light-duty vehicle greenhouse gas reduction options

Table 10 summarizes the GHG-reduction measures have been analyzed for light duty vehicles. In characterizing transportation GHG mitigation options for passenger vehicles for this study, the focus is on the most probable near-term measures of vehicle technologies with capability for widespread or near universal adoption. Therefore focus here is on near-term gasoline efficiency measures (incremental efficiency and hybrid gas-electric) technologies, limited cellulosic ethanol substitution, and air conditioning refrigerant replacements.

Table 10. Summary of light duty vehicle GHG-reduction measures

Measure	Description	Phase-in scenario	Technologies involved	Primary studies referenced
Incremental Efficiency	20% reduction in rated new vehicle tailpipe CO_2 (g/mi)	Logistical S-curve for technology deployment from model year 2010 to 2020	Valve (timing and lift), Transmission (5-spd auto, AMT), Gasoline direct injection (GDI),	Austin et al., 1999; DeCicco et al., 2001; EEA, 2001 ; NRC, 2002; Plotkin et al., 2002; Weiss et al., 2000
"In-Use" Vehicle Efficiency	10% improvement in "on-road" fuel consumption	Cutting in half the gap between rated test-cycle and on-road fuel economy (from 20% to 10% correction factor from 2010 to 2020)	Tires (low rolling resistance and inflation), low friction oil, electric accessories, efficient air conditioning	ECMT and IEA, 2005; CEC/CARB, 2003
Alternative Refrigerant	Replacement of air-conditioning refrigerant HFC-134a with HFC-744a (CO_2)	Logistical S-curve for technology deployment from model year 2010 to 2020	Increased production of HFC-152a, slight modifications in A/C system (compressors, gaskets, etc.)	CARB, 2004; IPCC, 2001b
Ethanol Fuel Substitution	Increase mix of cellulosic ethanol to 13% (by volume) of gasoline by 2025	Logistical S-curve expansion of cellulosic ethanol to 13 billion gallons by 2020, 25 billion gallons by 2030	Agricultural industry production of cellulosic ethanol from both waste and dedicated energy crops	Wang, 2005; U.S. EPA, 2005
Advanced Hybrid-Electric Efficiency	38% reduction in new vehicle tailpipe CO_2 (g/mi) for half of new vehicle sales	Logistical S-curve for technology deployment – 10% by 2018, 50% by 2023, 90% by 2027	Full HEV (regenerative braking, battery-electric storage, propulsion from motor(s) and ICE engine)	An et al., 2001; Graham et al., 2001; Lipman and Delucchi, 2003; Plotkin et al., 2001; Santini et al., 2001

An important modification is made to account for "upstream" impacts of the measures before comparing their cost-effectiveness values and over emission reduction potential. In the scenarios under which petroleum usage is decreased, there are also additional life-cycle energy and GHG emission impacts that occur upstream (i.e., in the production, distribution, and refining of crude oil). Applying the upstream GHG multiplier of 1.21 (referring to the approximate 21% GHG contribution of overall gasoline usage that is previous to the combustion of the fuel in the vehicle), the options that reduce gasoline use are duly accounted for. This factor is taken from the Argonne National Laboratory GREET Model, Version 1.6 (ANL, 2007). Table 11 summarizes the resulting cost-effectiveness values of the light duty vehicles, after accounting for emission effects outside of the transportation sector.

Table 11. Summary of cost-effectiveness values for light duty vehicle GHG-reduction measures, independently implemented

GHG mitigation option	Initial cost -effectiveness (2008$/tonne CO_2e) [low / mid / high]			Lifetime c ost -effectiveness (2008$/tonne CO_2e) [low / mid / high]		
Incremental (20%) new vehicle rated fuel consumption improvement	5.4	32	60	-102	-75	-47
Improved "on-road" fuel economy (reduce by half the 20% shortfall between rated and "on-road" fuel economy)	55	66	78	-701	-59	-46
Hybrid-electric vehicles (50% of new vehicle sales by 2025)	80	153	206	-57	25	68
Cellulosic ethanol to reduce carbon-fuel content (13% of motor fuel by volume by 2025)	-21	37	94	-21	37	94
Air-conditioning refrigerant replacement (from HFC-134a to CO_2)	52	67	112	52	67	112

Note that this issue of the upstream multiplied brings up an important factor: that some emissions reductions that are considered in each economic sector actually occur in other sectors. For example, in this case, the shift in vehicle refrigerant would cause emission reductions in the chemical manufacturing industry, as well as from the vehicle operation. Efficiency measures in vehicles would result in GHG reductions in the petroleum industry. Increases in usage of cellulosic ethanol are likely to result in impacts in the agricultural sector. This research takes the stance the if GHG reductions result from changes in the end user (in this case, vehicle operators) then the reductions are credited to that end user and the sector under which their behavior is most aptly included (in this case, the transportation sector).

4.1.8. Combined impact of light-duty vehicle greenhouse gas reduction options

To examine the impact of introducing the chosen GHG-reduction technologies into the light duty vehicle fleet over the next several decades, a vehicle sales-stock-scrappage model was constructed to be consistent with on vehicle use characteristics from U.S. DOE's *Transportation Energy Data Book (*Davis and Diegel, 2003) and the fuel and greenhouse gas emissions characteristics of *Annual Energy Outlook 2008* (EIA, 2008). Applying the technologies and their phase-in scenarios as described in the text above and summarized in Table 10, the resulting light-duty greenhouse gas emissions impacts are shown in Figure 20. For context, the U.S. 1990 light duty vehicle GHG emissions level is shown on the plot as a benchmark.

Adjustments are made to determine the cumulative effects of the transportation GHG-reduction options, when implemented simultaneously. The results above showed the emission and cost impacts of the emission-reduction approaches as they were undertaken independently. When simultaneously considering the impact from two or more GHG-reduction technologies, several analytical adjustments are applied to avoid "double counting" of the emission-reduction effects. The use of a simple sum of emissions impacts would lead to an overestimation if two actions for example both increased the efficiency of vehicles. Correcting for this is straightforward: after installing each GHG-reduction mechanism, a new baseline is established before investigating the next (second, third, etc.) mechanism. The net results are that, when combining reduction mechanisms, the emission impact from each GHG-reduction mechanism decreases its independently implemented result and the cost-effectiveness value of each measure increases somewhat for later mechanisms.

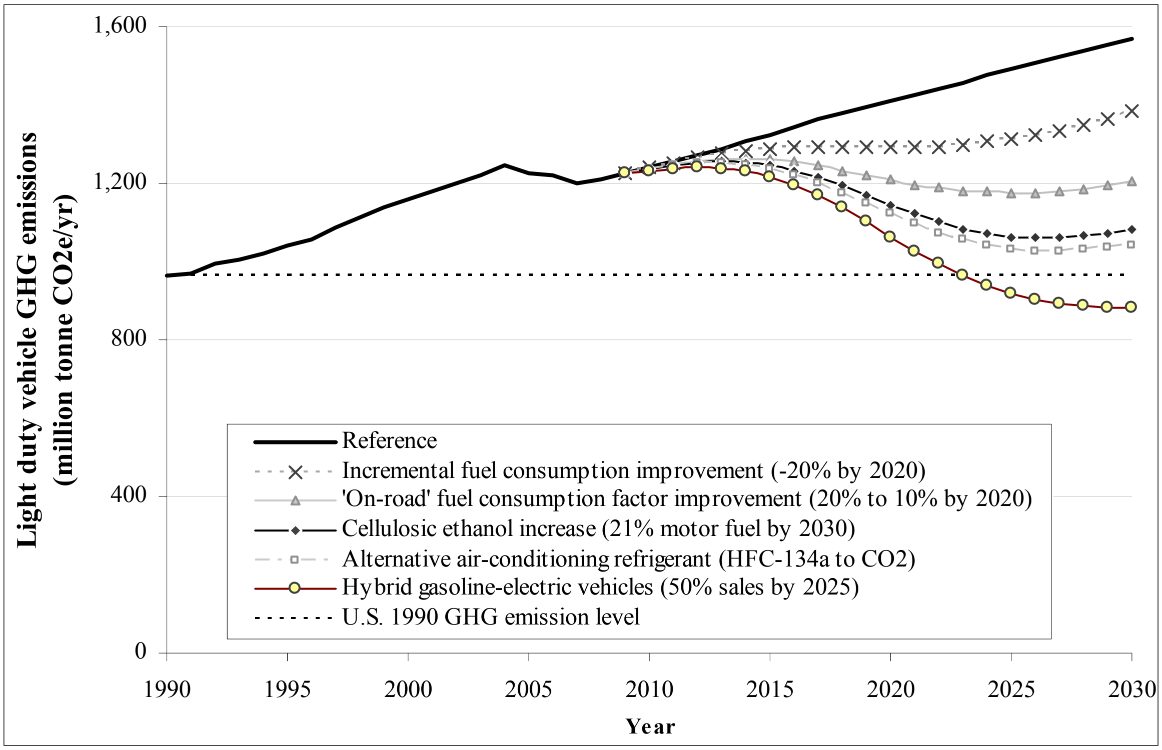


Figure 20. Light duty vehicle GHG emissions with emission-reduction measures through 2030

Applying the cost effectiveness values derived above and the reductions shown in Figure 20, the summary marginal cost effectiveness step curve of light duty vehicles is constructed in Figure 21. In the figure, the total reductions are taken from the year 2030 (which are equal to the vertical differences in curves of Figure 20). Error bars are shown to indicate the confidence in the technology and alternative fuel cost numbers discussed in the above text. Note that the curve shown is for the lifetime accounting system, which includes the initial technology costs and their lifetime impact on the vehicle operators. Presentation and discussion of the varying accounting frameworks (i.e. initial versus lifetime) will be addressed in the Chapter 9.

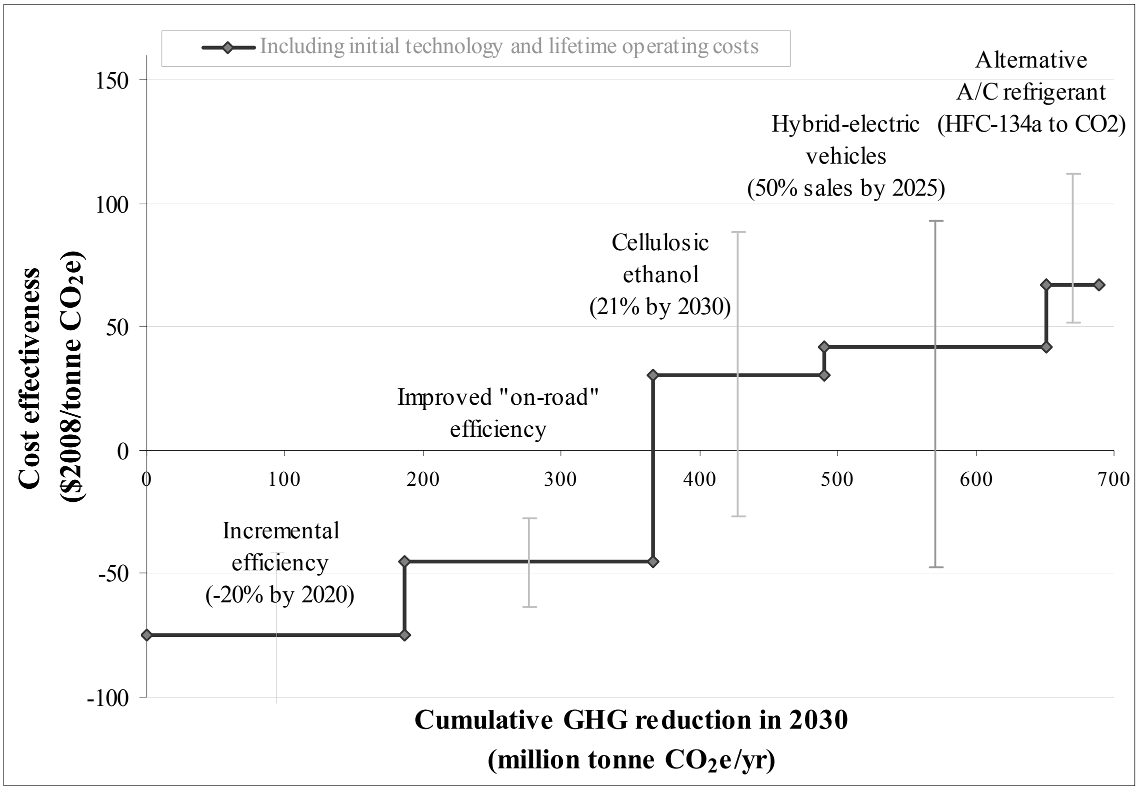


Figure 21. Light duty vehicle greenhouse gas emission reduction cost effectiveness in 2030

4.2. Commercial Trucks

Commercial trucks consume about one quarter of the energy of passenger vehicles, and 21% of the overall transportation energy use. Figure 22 shows the breakdown of commercial truck energy use by truck class groups. As is shown in the figure, the heaviest category of trucks, Class 7-8 (those with gross vehicle weight ratings of over 26,000 lbs), are the dominant road freight GHG contributor. In current years and for future year projections this category represents about 75% to 80% of commercial truck GHG emissions (based on U.S. EIA, 2008).

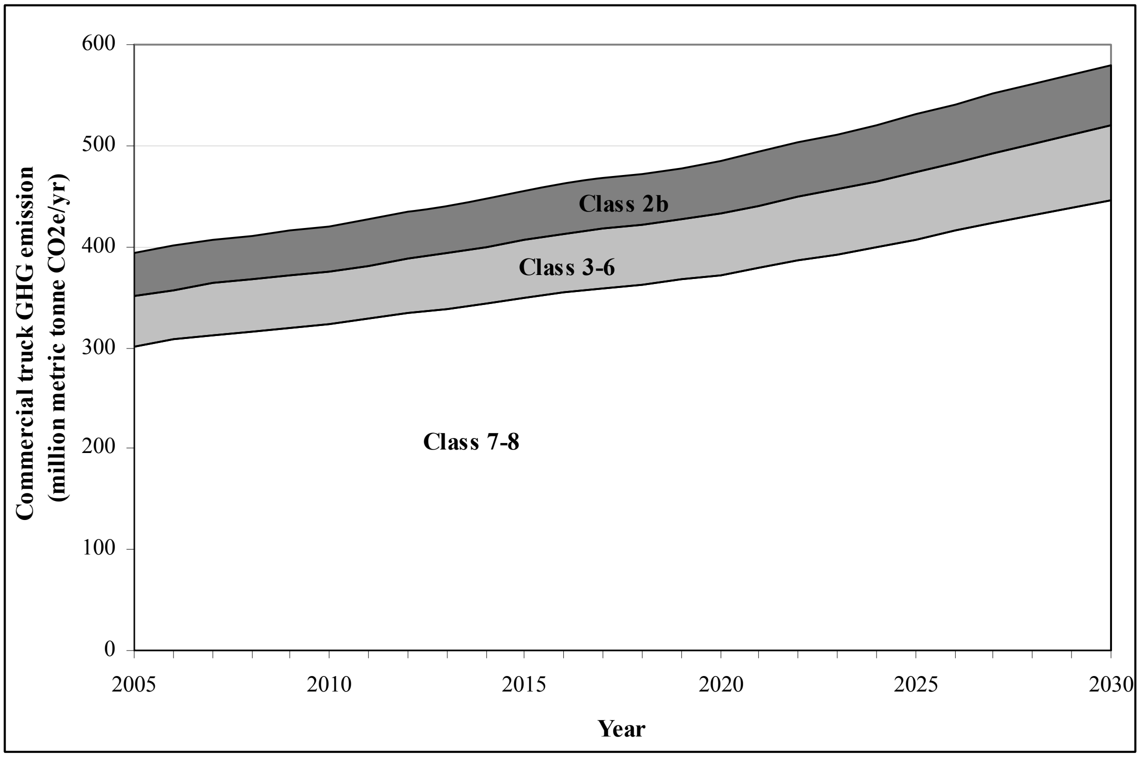


Figure 22. Commercial truck GHG emissions

A wide range of efficiency measures are available in commercial trucks to reduce their overall contribution to U.S. GHG emissions. Commercial trucks range from 40-ton heavy-duty long-haul Class 8 trucks getting approximately 6 miles-per-gallon (mpg) to 4-ton Class 2b trucks that achieve approximately 16 mpg and closely resemble light duty passenger pick-up trucks. Because these trucks' uses differ greatly depending on duty cycles (e.g. urban use or long-haul highway), there are different efficiency options that may be more applicable to different portions of the commercial truck fleet. For example, trucks that are extensively driven on highways are the best candidates for aerodynamic improvements; whereas trucks with predominantly urban duty cycles (i.e. higher idling frequency, frequent start/stop) are likely to be better suited for hybrid electric technology.

Compared with light-duty vehicles, the commercial truck sector has experienced few policy initiatives that have been directed at efficiency or alternative fuels. There is no comparable fuel efficiency regulation to light-duty vehicles' CAFE standards for commercial trucks with gross vehicle weight ratings of 8,500 lbs or greater. Commercial truck fleets are subject to the 1992 EPAct regulations, which mandate a percentage of alternative-fueled vehicles for fleet sizes of at least 20 vehicles that are centrally refueled (U.S. DOE, 2004). However, overall there is very little use of alternative fueled commercial trucks in the U.S.; the estimated use of Liquefied Petroleum Gas (LPG) is approximately 0.5% of total fuel usage for medium and heavy duty trucks, compared to 87.1% diesel and 12.4% gasoline (Davis and Diegel, 2004).

A principal U.S. DOE work outlining potential future emissions reduction technologies for trucks is the *21st Century Truck Program* (U.S. DOE, 2000). Several Argonne National

Laboratory studies have assessed various efficiency improvement and hybrid electric vehicle technologies for commercial trucks (e.g., An et al., 1999; Vyas et al., 2002). This analysis draws primarily on these studies to estimate the potential efficiency and GHG emissions benefits from commercial trucks in the following sections, which are separated into (a) Class 2b trucks, (b) Class 3-6 trucks, and (c) Class 7-8 trucks. Finally, the potential for GHG reduction opportunities from lower carbon content biofuel usage from the mixing of ethanol (into gasoline) and biodiesel (into conventional diesel) in these trucks is estimated.

4.2.1. Light duty (Class 2b) trucks

Class 2b trucks, or medium-duty personal vehicles, are similar to the "light-duty trucks," which include minivans, SUVs, and pick-ups that were investigated above in the passenger vehicle section above. Although these Class 2b trucks are classified differently, there is considerable overlap between the Class 2b and the passenger light truck (i.e., Class 2a) class in terms of the makes and models they encompass. Some larger light truck models (e.g. GMC 1500 pick-up, Ford Excursion) offer versions of the same model in each class, with various additional engine and drivetrain options adding enough weight to bring a model into the larger 2b truck class. For fuel economy regulations, light trucks that are considered passenger vehicles have a gross vehicle weight rating (GVWR) of up to 8500 lbs.

Class 2b truck GVWR ratings range from 8500 to 10,000 lbs and have been exempted from the CAFE standards for light duty vehicles on account of their more frequent commercial truck use and more demanding towing requirements (as compared to the similar light trucks, less than 8,500 lbs, that are more typically used for passenger vehicles). There was a reconsideration of this regulatory exemption status during the recent reforms in the light truck CAFE requirements for Class 1 and 2a light trucks of model years 2008 to 2011 (NHTSA, 2005), but ultimately no change was made. Estimates of the number of 2b trucks sold annually are at about 0.5 million, or about 6% of the total passenger Class 2a light truck market size (Davis and Truett, 2002).

Here Class 2b trucks are assessed as being similar to the "light-duty trucks" in terms of potential efficiency improvements and costs. Although Class 2b trucks currently have no governing fuel efficiency standards, their similarities in characteristics (e.g. truck type, body, size, engine, and drivetrain) with the passenger light duty trucks suggest that the same potential technologies are available for this class. When NHTSA (2005) considered new light truck fuel economy regulations, they suggested that it would be feasible to group these trucks with light truck CAFE requirements. For U.S. EPA criteria pollutant emission requirements, these Class 2b trucks are already subject to the same rules as light duty passenger vehicles that are less than 8,500 lbs. California's GHG regulations for light duty vehicles already will include trucks up to 10,000 lbs GVWR as light duty trucks in future years (CARB, 2004). The National Academies' (NRC, 2002) report on fuel economy for light duty vehicles recommends that these Class 2b trucks be rolled into the light truck category.

For Class 2b trucks, the same incremental price – fuel consumption improvement relationships as for light duty trucks (see right side of Figure 10) are used here. Baseline Class 2b trucks average approximately 15 mpg on-road fuel economy (U.S. EIA, 2007).

Based on economic-engineering relationships as above for light trucks, an estimated 33% fuel economy increase (i.e., a 25% CO_2 per mile emission rate reduction) can be obtained with an incremental price increase of $1150 per vehicle (after converting to $2008 dollars from Austin et al., 1999; DeCicco et al., 2001; EEA, 2001; NRC, 2002; Plotkin et al., 2002; Weiss et al., 2000). Truck use for this class is estimated to be about 189,000 miles over 15.5 years, with the annual mileage decreasing over the vehicle age (Davis and Diegel, 2005).

Using the same accounting assumptions as above, the cost-effectiveness values are computed. The average forecasted U.S. EIA (2008) fuel costs for 2010 through 2020 are $2.35 and $2.60 per gallon gasoline and diesel, respectively. Assumed upstream GHG multipliers of 1.21 for gasoline (referring to the approximate 21% GHG contribution of overall gasoline usage that is previous to the combustion of the fuel in the vehicle) and 1.17 for diesel are applied for petroleum reduction options. These factors are taken from the Argonne National Laboratory GREET Model, Version 1.6 (ANL, 2007). The cost effectiveness values for the 25% CO_2 emission reduction rate reduction technology are found to be $42 (initial cost only) and -$130 (initial plus fuel impacts) per tonne CO_2 reduced.

4.2.2. Medium duty (Class 3-6) trucks

Trucks classified as Classes 3 through 6 (i.e., those with gross vehicle weight ratings between 10,000 lbs and 26,000 lbs) are grouped together in this assessment. Generally these are "straight trucks" with the trailers permanently mounted on the chassis. Examples of these types of vehicles include beverage haulers, utility service trucks, and construction trucks. Because these vehicles have relatively different body types, uses, and duty cycles, it is difficult to make fleet-wide recommendations for efficiency and emissions-reduction improvements. For example, a vehicle that is much heavier and used entirely in urban delivery situations would have much different fuel savings potential with various technologies than would a lighter truck with frequent high-speed highway driving.

A series of studies quantifies the costs and benefits of improving efficiency of Class 3 to 6 commercial trucks with incremental technologies (e.g. engine, transmission, aerodynamics) as well as advanced parallel hybrid (gas or diesel) electric vehicle technology (Langer, 2004; Lovins et al., 2004; Vyas et al., 2002; An et al., 2000). The most detailed of those studies in terms of breakdown of non-hybrid electric vehicle technologies is Vyas et al. (2002), for which Table 12 shows the aggregate installment of the groups of technologies on gasoline and diesel baseline vehicles. Based on Vyas et al. (2002), efficiency improvements for this category of medium-duty trucks of over 33% from engine, drivetrain, and vehicle load reduction technologies can be achieved with an approximate incremental price increase of $7000 to $8000 for gasoline and diesel trucks. For gasoline trucks, the most cost-effective efficiency technologies are gasoline direct injection, lower rolling resistance tires, integrated starter-generator with idle-off ability, aerodynamics, and high-strength/lightweight technologies; for diesel trucks, the engine technology of turbocharging is also included.

Table 12. Medium duty truck efficiency technology impacts and costs (based on Vyas et al., 2002)

Fuel Type	Technology	Aggregate fuel economy increase	Aggregate CO_2 g/mi decrease	Cumulative technology cost per vehicle
Gasoline	Direct injection (GDI)	12%	11%	$1,000
	Low RR tires	15%	13%	$1,280
	Integrated starter/alternator with idle-off and limited regenerative braking	24%	19%	$2,480
	Closing/covering of cab-van gap, aerodyn. Bumper, underside baffles, wheel well covers	29%	22%	$3,280
	Cab top deflector, sloping hood, cab-side flares	32%	24%	$4,030
	High-strength, lightweight material	38%	27%	$6,030
	Van leading and trailing edge curvatures	39%	28%	$6,430
	Adv. transmission with lock-up, electronic controls, reduced friction	42%	30%	$7,330
Diesel	Low RR tires	3%	2%	$280
	Turbocharged, direct-injection	8%	7%	$1,280
	Closing/covering of cab-van gap, aerodyn. bumper, underside baffles, wheel well covers	12%	11%	$2,080
	Improved engine with lower friction, better injectors, and efficient combustion	21%	17%	$4,080
	Cab top deflector, sloping hood, cab-side flares	24%	19%	$4,830
	Van leading and trailing edge curvatures	25%	20%	$5,230
	High-strength, lightweight material	31%	24%	$7,230
	Adv. transmission with lock-up, electronic controls, reduced friction	33%	25%	$8,130

Using the estimations from all of the studies of Class 3-6 vehicle to bracket the error boundaries for this efficiency scenario, cost-effectiveness values were evaluated. These studies and their computed cost-effectiveness values are shown in Table 13. As above, Davis and Diegel (2006) vehicle use estimations are applied. These vehicles average 215,000 lifetime miles over 15 years with decreasing use per year. The cost-effectiveness values for Class 3 to 6 medium duty trucks are found to be $82 (initial cost only) and -$54 (initial plus lifetime fuel impacts per tonne CO_2 avoided.

Table 13. Medium duty truck GHG reduction potential and cost-effectiveness values, based on various studies

Source based upon	Truck class	Fuel	CO_2 per-mile emission rate change	Initial cost ($2008)	Initial cost-effectiveness ($2008/tonne CO_2e)	Lifetime cost-effectiveness ($2008/tonne CO_2e)
An et al., 2000	3-5	Diesel	-48%	$5,494	$40	-$95
An et al., 2000	6	Diesel	-42%	$6,598	$45	-$91
Langer, 2004	4-6	Diesel	-29%	$9,407	$96	-$40
Langer, 2004	4-6	Diesel	-41%	$9,407	$667	-$69
Lovins et al., 2004	3	Diesel	-44%	$10,921	$100	-$35
Lovins et al., 2004	4-6	Diesel	-46%	$14,208	$90	-$46
Lovins et al., 2004	3	Gasoline	-46%	$9,239	$91	-$49
Lovins et al., 2004	4-6	Gasoline	-49%	$13,087	$80	-$61
Vyas et al., 2002	4-6	Gasoline	-30%	$8,620	$101	-$39
Vyas et al., 2002	4-6	Diesel	-25%	$9,560	$116	-$20
Average			-40%	$9,654	$83	-$54

4.2.3. Heavy duty (Class 7-8) trucks

The largest and heaviest commercial trucks, Classes 7 and 8, consist of long-haul tractor trailers that used most commonly in highway driving situations. These 26,000-lb or greater trucks are driven the most annually, use the most fuel, and are responsible for the majority – about 75 percent – of the commercial truck CO_2 emissions. The lifetime of these trucks commonly involves initial use in long-haul highway situations for the first 4-6 years where the trucks are driven greater than 100,000 miles per year, after which the trucks are sold from long-haul freight companies to companies that utilize the trucks in lower-mileage more-urban situations.

Basing this analysis on Vyas et al. (2002), the various technologies for improvements in heavy duty vehicle rolling resistance, aerodynamics, engine efficiency, and transmission efficiency are ordered according to their initial cost-effectiveness in Table 14. The ordering (from lowest to highest $/tonne) of the GHG-reduction efficiency technologies are low rolling resistance tires, improved heat management, high-strength material use, super singles, improved fuel injectors, increased cylinder pressure, and improved engine friction. Other technologies include auxiliary power to reduce idling, aerodynamic improvements, pneumatic blowing, and advanced transmissions with lock-up. The total technology package – if all were simultaneously installed –for these heavy duty trucks resulted in a 40% CO_2 emission rate reduction for a $16,500 incremental price per new vehicle.

Table 14. Heavy duty truck efficiency technologies and initial costs (based on Vyas et al., 2002)

Technology	Aggregate CO_2 g/mi decrease	Cumulative technology cost per vehicle ($2008)
Low RR tires	3%	$550
Reduced waste heat and improved thermal management	12%	$2,550
High-strength, lightweight material	12%	$4,550
Super singles	22%	$5,250
Improved injectors and more efficient combustion	26%	$6,750
Increased peak cylinder pressure	29%	$7,750
Internal friction reduction through better lubricants, improved bearings	30%	$8,250
Fuel cell (with reformer)-operated auxiliaries (HVAC-included)	33%	$9,750
Cab top deflector, sloping hood, cab-side flares	34%	$10,500
Trailer leading and trailing edge curvatures	35%	$11,000
Pneumatic blowing (rolling resistance)	36%	$11,500
Pneumatic blowing (aerodynamic)	38%	$14,000
Adv. Transmission with lock-up, electronic controls, reduced friction	39%	$15,000
Closing/covering of cab-van gap, aerodynamic bumper, underside baffles, wheel well covers	40%	$16,500

Based on the DOE (Davis and Diegel, 2003) estimates for heavy vehicle, these trucks are approximated to be driven approximately 900,000 miles over 25 years, with almost an annual mileage of 60,000 in the first year of operation and decreasing about 7% per year. The cost-effectiveness of additional technologies for heavy duty trucks of the above figure are shown in the incremental cost-effectiveness curves for the two different accounting frameworks (i.e. initial and lifetime) in Figure 23. The cost-effectiveness values of the full technology impact from Vyas et al. (2002) that delivers a 40% GHG reduction per mile for heavy duty trucks are $28 (initial) and -$107 (lifetime) per tonne CO_2e reduction.

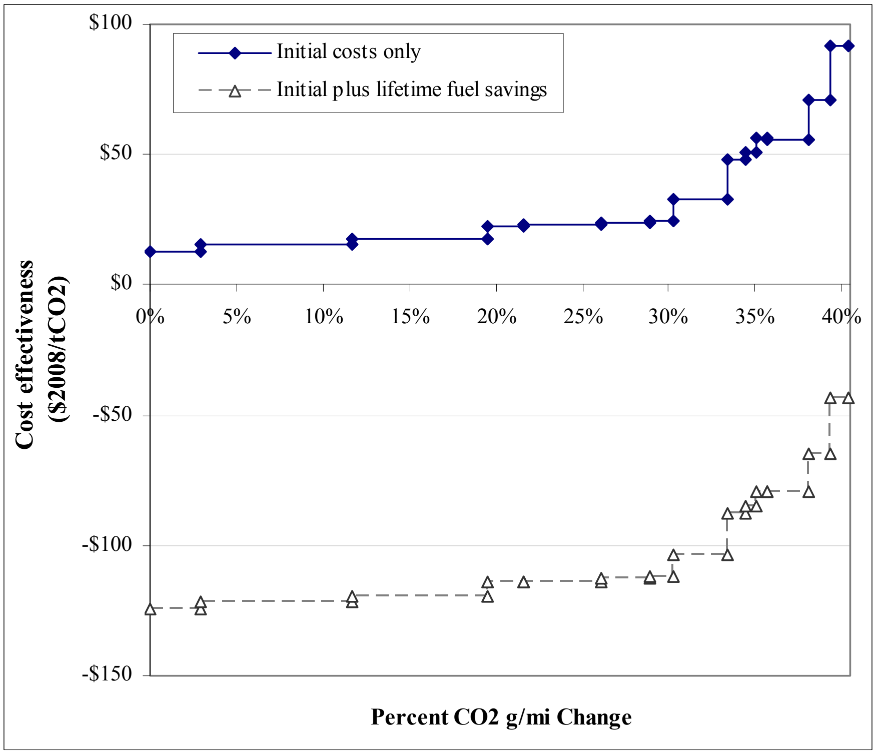


Figure 23. Average cost-effectiveness of aggregate efficiency technology package on heavy-duty trucks (Based on Vyas et al., 2002)

Several other studies, beyond Vyas et al. (2002), have investigated the cost and fuel savings impacts of new efficiency technology packages on heavy duty trucks. Based on five studies (Langer, 2004; Vyas et al., 2002; Schaefer and Jacoby, 2006; Muster, 2001; Lovins et al. 2004), the GHG-reduction potential and associated cost-effectiveness are shown in Table 15. The studies generally show a 24% to 40% GHG rate reduction potential with costs between $10,000 and $23,000 per truck. In calculating the cost-effectiveness for each case, the upstream diesel fuel energy use multiplier of 1.17 (for 17% upstream GHG emissions associated with transport, refining, etc of diesel fuel, from ANL, 2007) are applied. The heavy duty truck efficiency scenario is based on the average estimated cost-effectiveness values of these five studies are $32 (initial costs only) and -$88 (including lifetime technology impacts) per tonne CO_2e emission reduction.

Table 15. Heavy duty truck potential GHG reduction and cost effectiveness from various studies

Source based upon	CO_2 emission rate reduction	Initial cost ($2008)	Initial cost-effectiveness ($/tonne CO_2e)	Lifetime cost-effectiveness ($/tonne CO_2e)
Langer, 2004	-31%	$14,911	$28	-$92
Vyas et al. 2002	-40%	$19,403	$28	-$92
Schaefer and Jacoby, 2006	-36%	$18,390	$30	-$90
Muster, 2001	-24%	$23,821	$57	-$63
Lovins et al., 2004	-37%	$10,127	$16	-$104
Average	-34%	$17,330	$32	-$88

4.2.4. Low carbon fuel substitution

The above sections addressed the vehicle efficiency technologies that have potential to reduce the GHG emissions impacts of light, medium, and heavy duty commercial trucks. Modifications to the fuels that these trucks use for propulsion also have potential to reduce GHG emissions. The most realistic near-term options for alternative fuel use for commercial trucks are to increase the use of lower life cycle GHG content ethanol fuel (for gasoline-fueled trucks) and lower life cycle GHG content biomass-based diesel fuels (for diesel-fueled trucks). As mentioned above (in Section 4.1.4. on increased ethanol mixing into passenger vehicles' gasoline), increased ethanol blending has advantages over any other alternative fuels that face infrastructural, institutional, technology breakthrough hurdles in terms of large-scale use for gasoline vehicles. Similarly, for this relatively near-term assessment of GHG reduction actions, biodiesel is the only alternative fuel considered for diesel vehicles.

The same assumptions are applied to the increased mixing of ethanol in commercial trucks that are fueled by gasoline as above in the passenger vehicle section. Therefore the overall mixing percentage of ethanol in motor gasoline is increased from the U.S. EIA (2008) baseline of 8% in 2010 to 13% in 2020 and 21% (measured as percentage of fuel energy content) in 2030. This increase in ethanol usage by commercial trucks is at the same cost-effectiveness values as in the passenger vehicle section. The estimated cost-effectiveness values for initial cost and lifetime cost accounting, based on the difference in cost from the refined gasoline and ethanol are \$37 per ton CO_2 reduced, with a range of \$10 to \$85 per tonne CO_2 reduced.

For trucks, in addition to considering the ethanol substitution to the gasoline fuel usage, biodiesel mixing into diesel-fueled vehicles is considered for commercial trucks. From 2009 to 2020, forecasted average biodiesel usage is about 300 million gallons per year, or approximately 0.6% of all diesel usage by volume and energy content (U.S. EIA, 2007). Although the trend for forecasted biodiesel usage through 2020 reveals a relatively small biofuel content in future diesel trucks, there are policy and technology signs that this trend could change.

As of mid-2008 a scattering of initiatives encourage the increased use of biodiesel in diesel. An incentive of up to \$1.00 per gallon of virgin oil-based biodiesel (and \$0.50 per gallon for non-virgin "yellow grease" biodiesel) is provided to fuel blenders that mix biodiesel into diesel fuel; agricultural producers of biodiesel-capable oils have been further incentivized for expanded biodiesel production by about \$1.46 per gallon for soybean oil from the U.S. Department of Agriculture's Commodity Credit Corporation program. The Energy Policy Act (EPAct) mandates that truck fleets have alternative fueled vehicles, and the use of biodiesel blends (e.g. "B20" that is 20% biodiesel - 80% diesel blend) are included on a prorated basis in the regulation.

The U.S. EPA's Renewable Fuel Standard Program mandates that a certain portion of the national motor vehicle fuel supply is to be met with renewable fuels, and the dominant fuels that the Agency considers are ethanol and biodiesel; the federal energy legislation, *EISA of 2007,* mandates large increases in the volume of these biofuels in future years, as discussed above. The State of Minnesota mandates that 2% of diesel fuel sold in the state, equating to approximately 16 million gallons per year, must be biodiesel (State of Minnesota, 2007). Finally 2007 federal energy legislation mandates that at least 1 billion gallons of biodiesel will be blended into transportation fuels for year 2012 and later, and much more of that federal legislation's mandate for 21 billion gallons of "advanced biofuels" could also be biomass-based diesel fuel.

The National Biodiesel Board indicates that there will be a production capacity of 1.9 billion gallons of biodiesel, including planned new plant construction by the year 2009. This production would equate to approximately to a 4% displacement (by volume) of U.S. diesel demand in that year (NBB, 2007). Hill et al. (2006) point out that the total U.S. soybean output in the country (most of which is used for human and livestock caloric intake) is equivalent to 6% of the U.S. diesel demand. Therefore it is likely that large-scale biodiesel expansions would have to draw upon a broader feedstock base than soybean oil.

A study by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) considers the additional use of agricultural and food industry wastes. The NREL study concludes that a 3.5 billion gallon biodiesel capacity and national B5 standard are viable by 2015, and more aggressive land use changes make even 10 billion gallons biodiesel achievable by 2030 (Tyson et al., 2004). Tyson (2003) suggests that the progression in the expansion of biodiesel supplies from the current production (primarily from soybean and yellow grease) according to least-cost is to utilize olechemicals made from other vegetable oils, desaturated animal fats, decontaminated greases, saturated animal fats due to regulations regarding bovine spongiform encephalopathy, expanded corn oil recovery, and the development of new vegetable oil supplies.

The GHG mitigation potential of increased biodiesel blending in diesel is recognized by several studies. Sheehan et al. (1998) determined the GHG reduction benefit of pure biodiesel to be 78% over conventional diesel. U.S. EPA (2007), in its regulatory analysis for the Renewable Fuels Standard, finds that biodiesel GHG benefits of pure biodiesel are about 68%. Hill et al. (2006) find soybean-based biodiesel to be 41% lower GHG emissions when displacing diesel. University of California researchers, in their work for the California Low Carbon Fuel Standard, found soybean-based biodiesel to be 56% lower in GHG emissions than diesel per energy content basis (Farrell and Sperling, 2007). Note that these biodiesel benefit estimations, just as discussed above for ethanol, are subject to uncertain overall GHG impacts when considering the full life cycle and land use implications of expanded biodiesel production.

In order to compute cost-effectiveness values for the GHG emission reduction impacts of increased biodiesel blending, future estimated biodiesel prices are compared to the distributed refined (untaxed) diesel price. The U.S. EIA (2007) forecasted average prices from 2010 to 2020 of $2.60 per gallon retail, minus the average diesel federal and state taxes of $0.53 per gallon (from API, 2007), yields a price of $2.07 per gallon for comparison with biodiesel production. Biodiesel production costs from 2004 to 2007 for biodiesel are estimated to range between $1.50 and $2.50 per gallon (U.S. EPA, 2004; Radich, 2004; Tyson et al., 2004). The large range in finished biodiesel production cost reflects varying feedstock prices (e.g. from soybean or other vegetable oils, yellow grease, etc.) as well as the extent to which co-benefits from sale of co-products, such as glycerol, from biodiesel production process are included.

As technologies to produce biodiesel from varying agricultural feedstocks improve, per unit production costs will almost certainly decrease as the industry improves its production efficiency. However, as the desired biodiesel oil demand increases, the industry moves from the use of agricultural and food processing waste, to the use of products from marginal agricultural land, to the use of more valuable soybean and other oils that have competing value in the human food chain, there would be an increase per unit biodiesel feedstock costs. U.S. EPA (2007) uses a future value of \$2.13 per gallon in 2004 dollars – or \$2.39 per gallon in 2008 dollars – for biodiesel production cost after distribution in the year 2012. In the absence of better cost data, this analysis applies this value for the middle estimate, and plus/minus 20% for upper/lower estimates of future biodiesel costs.

The biodiesel future price estimates of \$1.91, \$2.39, and \$2.86 per gallon were compared with the pre-tax diesel price of \$2.07 per gallon. The average of the available GHG benefit estimates (from Sheehan, 1998; Hill et al., 2006; U.S. EPA, 2007c, Farrell and Sperling, 2007) or 61% improvement in life-cycle GHG emissions was applied to each future fuel displacement of diesel with biodiesel to determine the cost effectiveness. The cost-effectiveness of increasing the use of biodiesel to the equivalent of an average 5% (i.e. “B5”) national standard by 2020 is found to be \$51 per tonne CO_2e reduction (with low and high estimates of -\$26 and \$128 per tonne CO_2e).

4.2.5. Combined impact of commercial truck GHG reduction options

The GHG reduction measures of the previous sections for commercial truck efficiency and alternative fuel measures are summarized in Table 16. As for passenger vehicle technologies, the deployment phase-in period for each of the efficiency technologies was approximated as a logistical s-curve from 2010 to 2020.

Table 16. Summary of commercial truck GHG-reduction measures

Measure	Description	Phase-in scenario	Primary studies referenced
Class 2b Efficiency	25% CO_2 g/mi reduction	Logistical S-curve for new truck deployment from 2010 to 2020	Austin et al., 1999; DeCicco et al., 2001; EEA, 2001 ; NRC, 2002; Plotkin et al., 2002; Weiss et al., 2000
Class 3-6 Efficiency	40% CO_2 g/mi reduction	Logistical S-curve for new truck deployment from 2010 to 2020	Vyas et al., 2002; An et al., 2000; Lovins et al., 2004; Langer, 2004
Class 7-8 Efficiency	34% CO_2 g/mi reduction	Logistical S-curve for new truck deployment from 2010 to 2020	Vyas et al., 2002 ; Muster, 2001 ; Lovins et al., 2004 ; Schaefer and Jacoby, 2006 ; Langer, 2004
Ethanol Fuel Substitution	Increase mix of cellulosic ethanol to 13% (by volume) of gasoline by 2025	Logistical S-curve expansion of cellulosic ethanol to 13 billion gallons by 2020, 25 billion gallons by 2030	Wang, 2005; U.S. EPA, 2005
Biodiesel Fuel Substitution	Increase mix of biodiesel to 5% by volume of diesel by 2020	Phased in linearly from ~0% in 2010 to 5% in 2020	Sheehan et al. 1998; Hill et al., 2006; Farrell and Sperling, 2007; U.S. EPA, 2007c

The impacts of each of the efficiency packages on the new trucks that enter the fleet are shown in Figure 24. This figure shows the phasing in of new efficiency that include the levels of GHG reduction efficiency technologies discussed above. The baseline new vehicle fuel economy levels are based on two U.S. Department of Energy sources (U.S. EIA, 2007; Singh et al., 2003), and already include gradual fuel economy improvements. The baseline rate of fuel economy increase that is assumed to occur in the baseline is assumed to continue after the more rapid deployment of efficiency technology from model years 2010 to 2020.

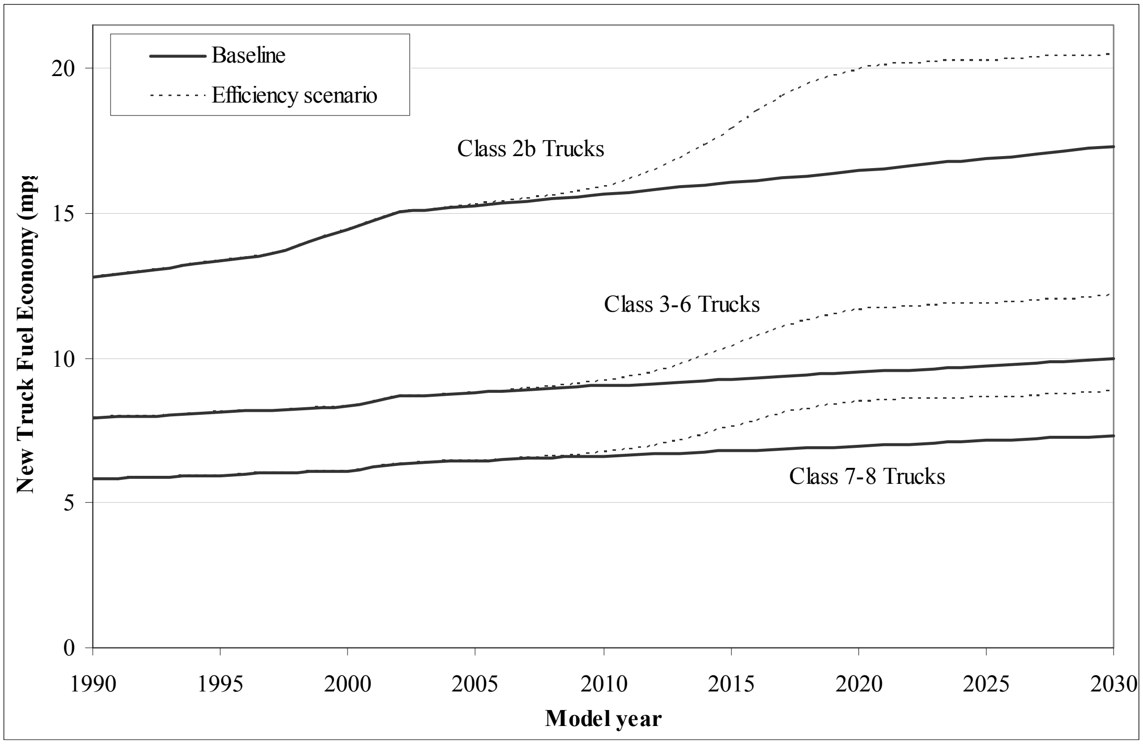


Figure 24. New commercial truck fuel economy

Figure 25 shows the impact of the new efficiency and alternative fuel measures on commercial truck sector GHG emissions. As is shown, the impact of all the measures, taken together, do not quite stabilize the sector's GHG emissions. After 2020, the GHG emission levels begin again to show annual increases due to the increase in commercial truck travel. Even with substantial GHG reduction measures for all light to heavy duty trucks, the GHG impacts do not sufficiently outweigh the growth in truck travel to reduce GHG emissions. The 2030 emissions after deploying the GHG mitigation measures result in a 18% reduction from the 2030 reference case.

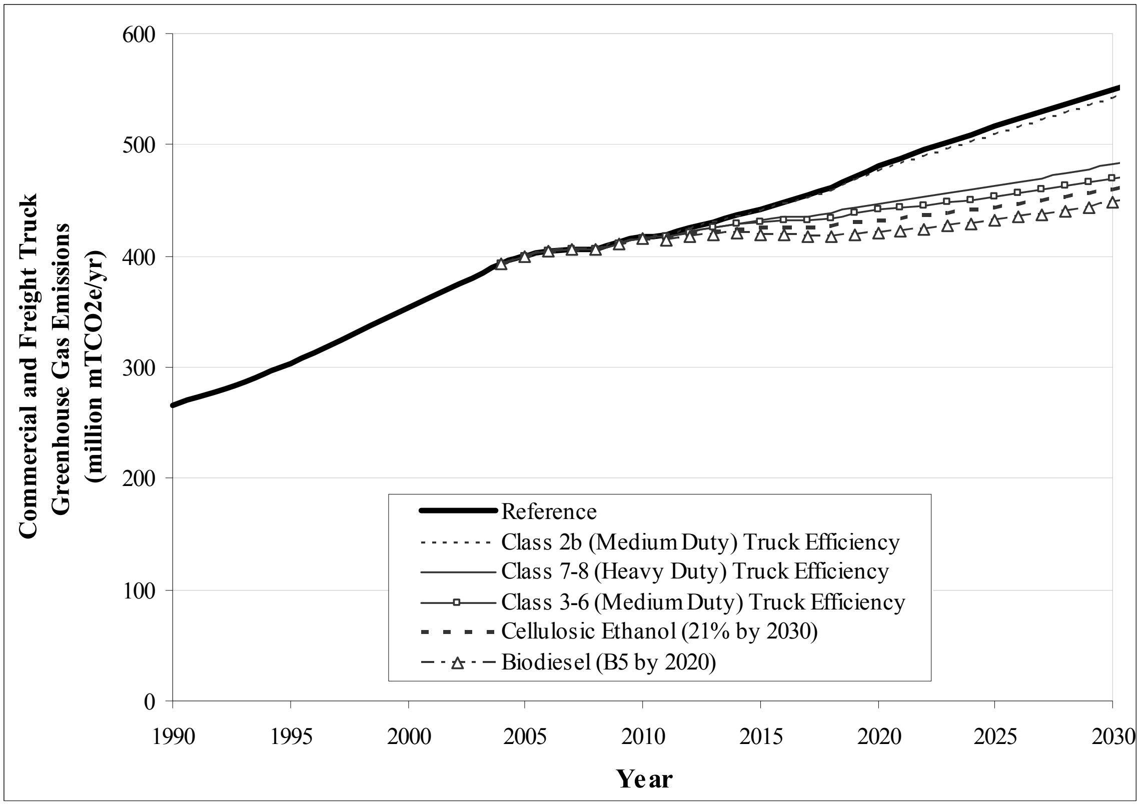


Figure 25. Commercial truck GHG emissions with emission-reduction measures through 2030

Applying the cost-effectiveness values derived above and the GHG emission reduction after the truck GHG reduction measures phase into the vehicle fleet, the cost effectiveness curve for this segment is presented as Figure 26.

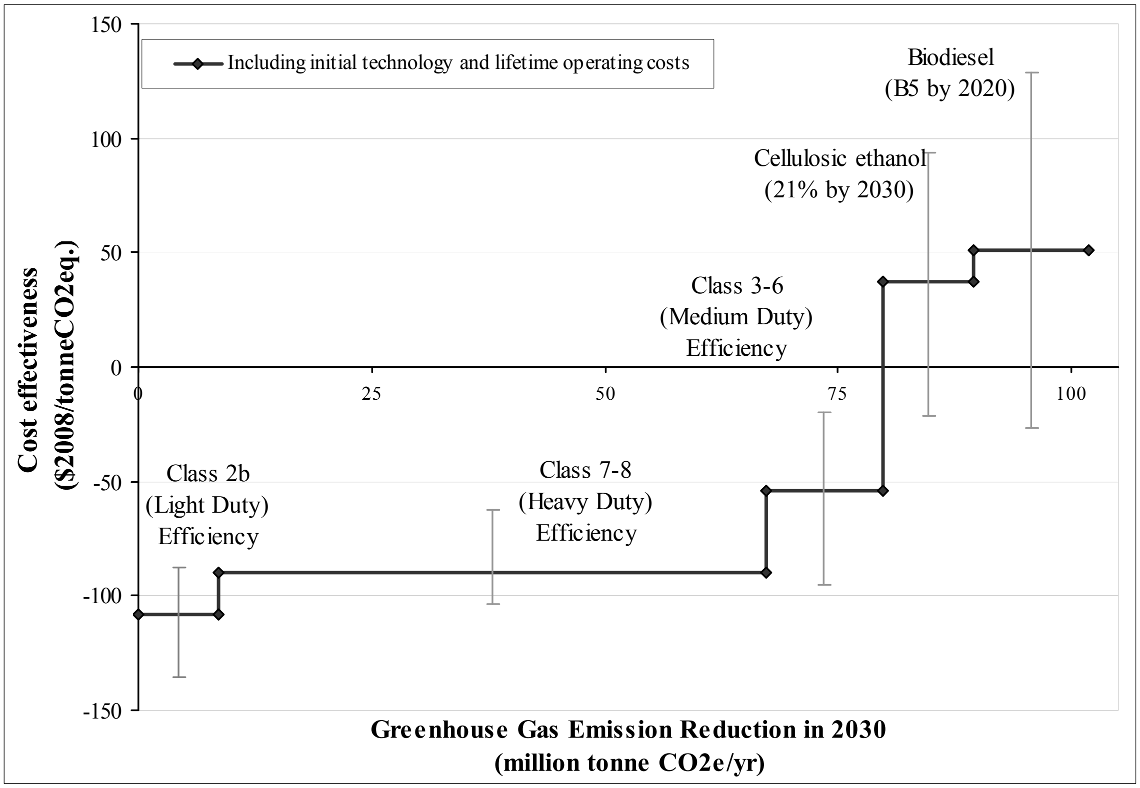


Figure 26. Cost effectiveness curve for truck GHG emission reduction measures

4.3. Other Modes

4.3.1. Aviation

As was shown in Figure 9, after passenger vehicle and commercial truck, the next most significant transportation sector greenhouse gas emission contributor is aviation, which results in about 13% of transportation GHG emissions in the U.S. Efficiency improvements in passenger, freight, and military aircraft are well researched by a number of government agencies, and the findings from these studies are used here to assess the potential GHG reductions in the aviation sector through the year 2030.

Many technology and operational factors contribute to the efficiency (and thus the fuel use and GHG emissions) of modern aircraft. The key technology factors affecting aircrafts' direct GHG emissions are engine efficiency, weight, aerodynamics, and structural efficiency; operational factors include the aircrafts load factor and capacity (Lee et al., 2001; Greene and Schafer, 2003). Each of these factors has seen marked improvements from 1970 to 2000, leading to overall energy (energy per passenger mile) improvements of about 60% (Lee et al., 2001). That improvement is attributed to engine efficiency (57% of the total improvement), aerodynamics (22%), seat occupancy rates (17%), and other factors like increased aircraft size (4%) (Lee et al., 2001).

The development of Boeing's 787 demonstrates the available emerging aircraft efficiency improvements. The early press on the development heralded the plane as the *7E7*, with the "E" being referred to as "efficiency" or "environmentally friendly." The 787 airliner, scheduled to enter commercial service in 2008, has marked innovations in engine efficiency, aerodynamics, and weight reductions from extensive use of composites (reducing use of heavier metals and fasteners). Press releases suggest the new airliner's technology innovations result in a 30% fuel efficiency improvement –787's 100 passenger-miles per gallon versus the 767's 76 passenger miles per gallon (Masters, 2007).

Prior to the information releases regarding the Boeing 787, many studies had assessed the potential for fuel efficiency improvements in future years. Taking into account the long technology lead times and slow aircraft stock turnover, several studies suggest that future improvement opportunities are available to improve aircraft efficiency by 25% to 45% by 2025 from the year 2000 base case technology (Greene, 1992; NRC, 1992; Lee et al., 2001).

A group of studies, analyzed by Lee (2000), looked specifically at the technology potential and the impacts on operating costs and initial capital costs of commercial aircrafts. Table 17 reproduces figures from Lee (2000) from seven sources (NRC, 1992; IPCC, 1999; ETSU, 1994; CAEP, 1995; DCAD, 1997; NASA, 1998; ADL, 2000). As shown in the table, the studies broadly show that substantial technical fuel economy improvements are available for introduction by the year 2015 (e.g. 26% to 162% increase in available seat-miles per gallon). Those efficiency improvements result in operating costs savings from 22% to 62%, but at considerable increases in initial aircraft costs (14% to 69% increases).

Table 17. Technology potential and cost impacts of aircraft efficiency

Aircraft	Year of introduction	Fuel economy (available seat miles per gallon)	Fuel economy percent change	Direct operating cost per revenue-passenger-mile	Operating cost percent change	Price/seat (thousand $1995)	Price percent change
Baseline	2000	67		3.37		286.8	
NRC, 1992	2010	105.4	57.3%	2.13	-37%	367.9	28.3%
IPCC, 1999	2015	83.7	24.9%	2.63	-22%	328.2	14.4%
ETSU, 1994 (low)	2015	129	92.5%	1.74	-48%	411.4	43.4%
ETSU, 1994 (high)	2015	175.6	162.1%	1.29	-62%	483.2	68.5%
CAEP, 1995	2015	89.1	33.0%	2.48	-26%	339	18.2%
DCAD, 1997	2015	84.3	25.8%	2.61	-23%	329.4	14.9%
NASA, 1998 (low)	2025	133.9	99.9%	1.64	-51%	424.4	48.0%
NASA, 1998 (high)	2025	176.2	163.0%	1.26	-63%	489.8	70.8%
ADL, 2000 (low)	2030	99.9	49.1%	2.15	-36%	366.4	27.8%
ADL, 2000 (high)	2030	113.5	69.4%	1.9	-44%	391.6	36.5%

From Lee, 2000

To estimate the cost effectiveness value for this assessment of aircraft efficiency, data from a selection of the scenarios from above were compared with average aircraft lifetime assumptions and U.S. EIA (2008) data. From Table 17, the data sources for airplane efficiency technologies that can be introduced by 2015 were utilized (i.e. NRC, 1992; IPCC, 1999; ETSU, 1994; CAEP, 1995; DCAD, 1997). This restriction was used to satisfy the constraint of this assessment whereby only relatively near-term technologies with substantial GHG reduction potential by the year 2025 are analyzed. Average aircraft assumptions or 171 seats per aircraft, 30 year aircraft lifetime, and 1.2 million miles per year are taken from the technical appendix of Lovins et al. (2004). A 7% discount rate and the U.S. EIA (2008) baseline jet fuel prices for future years are applied.

Table 18 shows the selected studies for aircraft efficiency improvements, their associated fuel consumption rates (in gallons of fuel per available seat mile) and their cost-effectiveness values under the three different accounting systems. First note that the average energy intensity of the efficiency scenarios from the five sources (0.0097 gal/seat-mile, or roughly 100 seat-mile/gal) is approximately equal to the reported figure for the Boeing 787, or "7E7", that is expected to first enter service in 2008. The average cost-effectiveness values from the studies are \$52 (initial cost increases only) and -\$9 (including lifetime reductions in operating costs) per tonne CO_2e reduction. The lowest and highest individual study's cost-effectiveness values are used to determine upper and lower boundaries.

Table 18. Cost effectiveness of aircraft efficiency improvement potential

Efficiency aircraft source	Energy intensity (gal fuel / available seat-mile)	Energy intensity change from baseline	Initial cost effectiveness (\$2008/tonne CO_2)	Lifetime cost effectiveness (\$2008/tonne CO_2)
NRC, 1992	0.0095	-36.4%	49.1	-10.7
IPCC, 1999	0.0119	-20.0%	45.8	-20.2
ETSU, 1994 (low)	0.0078	-48.1%	57.2	-0.4
ETSU, 1994 (high)	0.0057	-61.8%	70.0	16.6
CAEP, 1995	0.0112	-24.8%	46.4	-17.6
DCAD, 1997	0.0119	-20.5%	45.8	-19.9
Average	0.0097	-35.3%	52.4	-8.7

Figure 27 shows the impact of phasing in of the 35% fuel consumption aircraft technology (from Table 18) into the baseline aircraft fleet from the U.S. EIA (2008) forecast. As shown, a gradual efficiency improvement is already forecasted by U.S. EIA. The average forecasted improvement is 1.1% per year from 2005 to 2030. Also in the figure, the Boeing 787 is shown at the year of its expected 2008 commercial flight introduction for context.

The introduction of the new Boeing on the plot shows the feasibility of the efficiency scenario of this analysis, and it also demonstrates the relatively slow (as compared to automobiles) manufacturing, deployment, and stock turnover effects that are inherent to any large-scale technology change in the aviation industry. Based on standard successful aircraft production runs of 15-20 years and aircraft lifetimes of 25-35 years (IPCC, 2001b), the time from a new technology introduction to the full phase-in of the new technology fuel consumption characteristics in the fleet are more like 40+ years, or in this case, in the year 2050. Thus, the full GHG reduction impact of the aircraft efficiency technology discussed in this section are borne out later than the 2025-2030 timeframe used to report GHG reduction results in this dissertation.

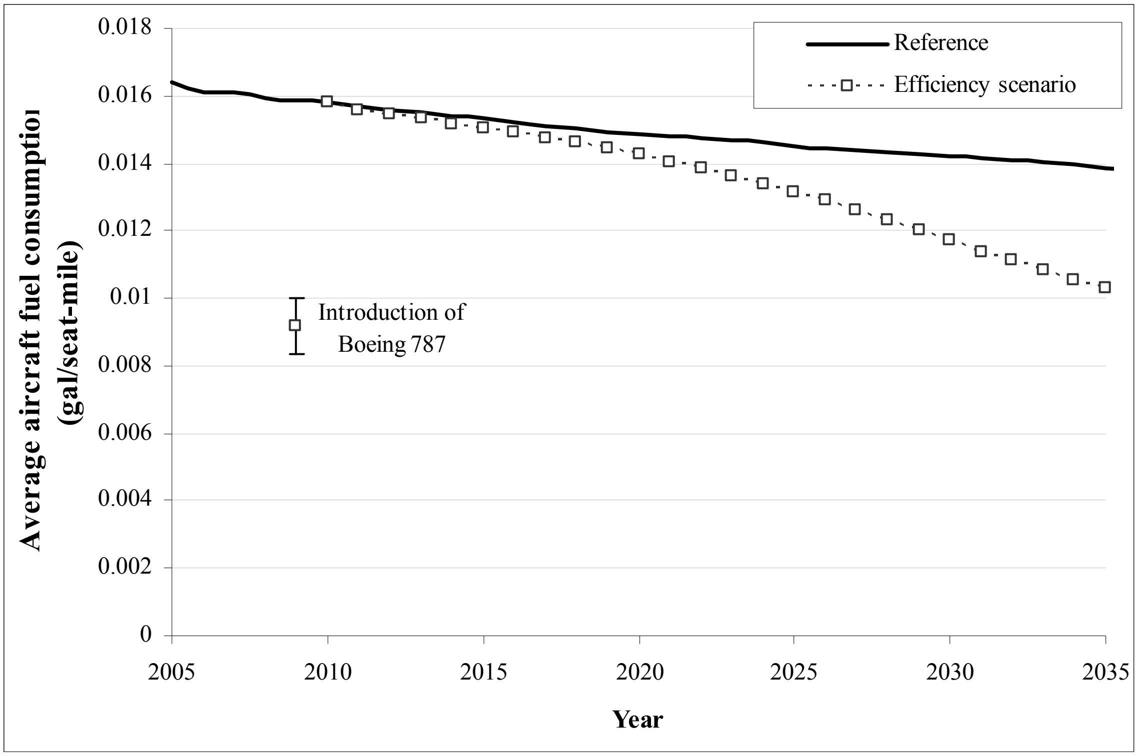


Figure 27. Aircraft fuel consumption baseline and with improved efficiency scenario

Figure 28 shows the impact of a 2010 to 2050 stock turnover in aircraft efficiency technology from the baseline U.S. EIA forecast technology to the 35% fuel consumption reduction technology discussed above. By 2025, the efficiency scenario results in a reduction of 22 million tonnes of CO_2 emissions, or 7% of that year's total GHG emission total. In 2030, the result is 59 million tonnes, or 18% of that year's emissions. As shown, this efficiency improvement is still not nearly sufficient to get aviation emissions by the year 2030 to their sector-specific 1990 emission level due to the large forecasted increases (of, on average, 2% per year) in aviation passenger travel demand over this time period.

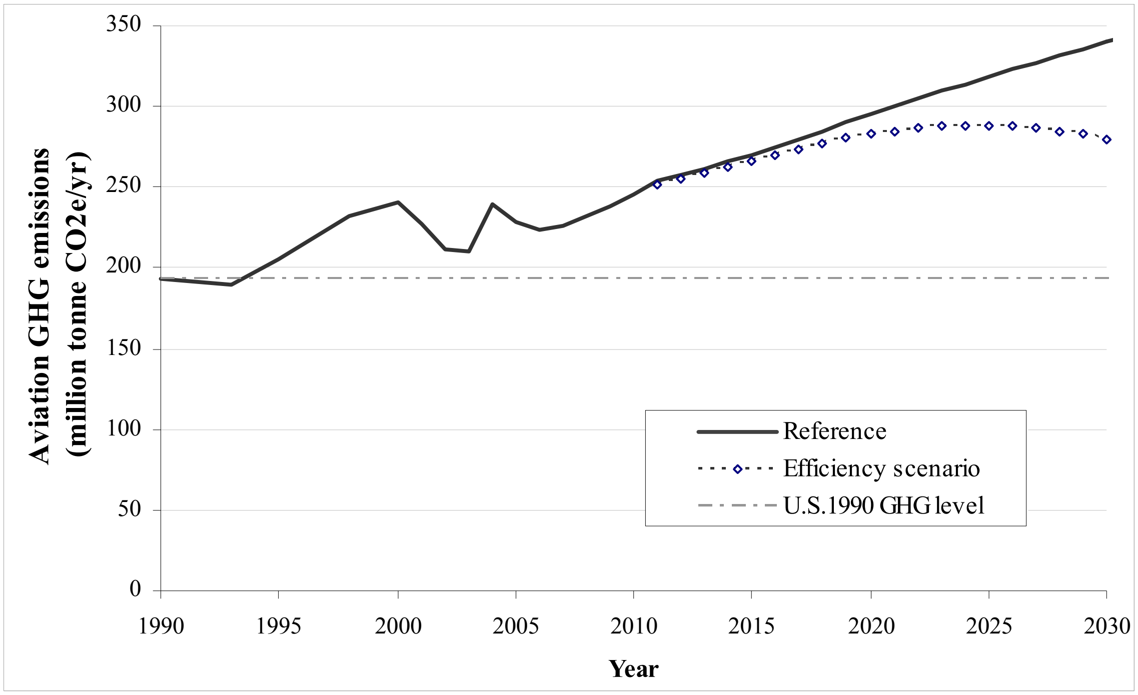


Figure 28. Greenhouse gas emission impact of increased aviation efficiency

5. RESIDENTIAL AND COMMERCIAL BUILDINGS

This Chapter examines the opportunities for GHG mitigation technologies in the residential and commercial building sectors. Buildings, and activities within, are responsible for substantial portions of U.S. energy use, and therefore GHG emissions. From U.S. EIA (2008) data, the contribution of residential and commercial sectors' GHG emissions equate to approximately 40% of U.S. energy-related GHG emissions from 2007 through 2030. Roughly half of these building sector emissions result from residential buildings and half are from commercial buildings.

Figure 29 shows the breakdown of residential and commercial sector GHG emissions according to their energy source (From U.S. EIA, 2008). Approximately 75% of the emissions result from the fuel combustion for the electricity generation to power the electricity demands of those buildings, while the remaining energy is directly from fossil fuels, mostly from direct natural gas-fueled (and some heavier petroleum-based oil) heating in furnaces and boilers. The overall growth is projected by U.S. EIA to be about 1.2% per year from 2007 through 2030.

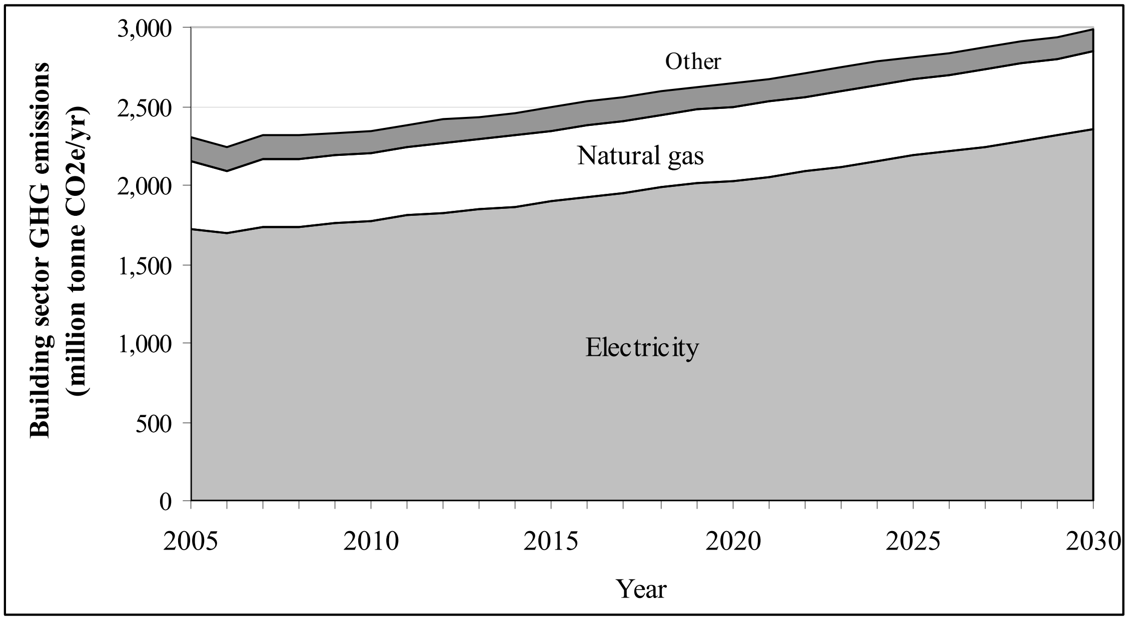


Figure 29. Baseline GHG emissions from residential and commercial buildings (from U.S. EIA, 2008)

Alternatively, the U.S. EIA data for overall building sector energy uses are broken down according to their end uses in Figure 30. The largest individual energy demands, in descending order, are for space heating, lighting, space cooling, water heating, computers (and other office equipment), and refrigeration.

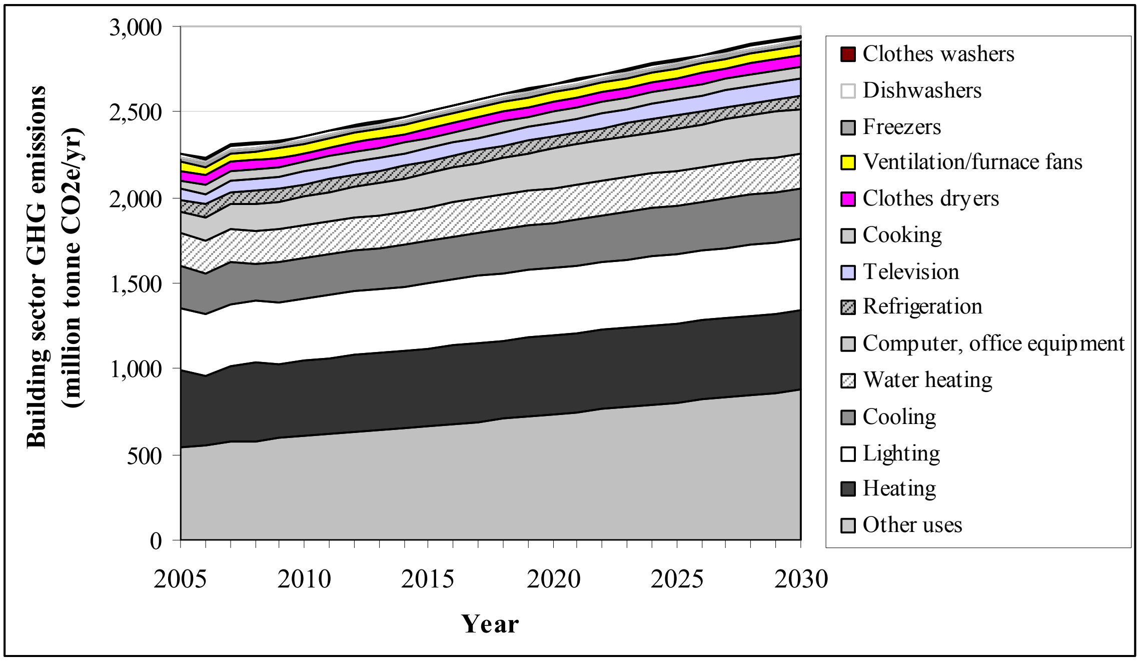


Figure 30. Breakdown of building sector GHG emissions by end use

There are numerous diverse ways in which existing and new buildings can be improved for GHG emissions. These improvements can broadly be categorized into five main areas: (a) improved appliance efficiency, (b) improved lighting efficiency, (c) improved heating, ventilation, and air-conditioning (HVAC) systems, (d) building shell technologies like improved insulation and windows, and (e) distributed power generation. Improvements to residential and commercial buildings in each of these areas generally include options of replacement of older equipment with new, more efficient equipment, as well as practices that reduce avoidable operation of current equipment. Technology alternatives with GHG mitigation potential are examined in the sections below for each of these areas.

For each section, the technologies are generally and briefly described, their costs and impacts are summarized, and their cost-effectiveness values are evaluated. Data on available and emerging technologies for improved efficiency in buildings are taken from many difference sources. A particularly important source is the Sachs et al. (2004) report, *Emerging Energy-Saving Technologies and Practices for the Building Sector as of 2004*, which offers a wealth of information on technologies that are emerging and are being developed for use in buildings.

The Sachs (2004) report has similar approach to the screening of its energy reduction measures as this dissertation's research of GHG mitigation measures. That report focused on technologies and practices that are expected to be widely commercially available to consumers by 2009 or are already available in relatively small numbers. The report's comprehensive and transparent reporting of technology costs, benefits, and reference sources makes the reference especially useful. Also, a host of U.S. Department of Energy and U.S. Environmental Protection Agency web sources (e.g., U.S. EPA and U.S. DOE, 2007; U.S. DOE, 2007) were investigated for available data on energy-efficiency technology data and their potential costs and energy savings. Other primary data sources that have been utilized are also referenced throughout.

The data from the Sachs et al. (2004) report and its primary sources that were utilized for this study required various adjustments to make them consistent with this dissertation's assumptions for GHG mitigation options in the other sectors. For example, energy price (for natural gas and electricity) from U.S. EIA (2008) were used, the 7% discount rate was applied, U.S. EIA greenhouse gas emissions characteristics for future years were applied, and all prices were adjusted to year 2008 dollars.

5.1. Appliance Efficiency

Energy efficiency standards for appliances in the U.S. were first established in various states, led by California, in the mid-1970s. To harmonize the state-standard-setting, the federal government regulated appliances under the National Appliance Energy Conservation Act of 1987. Further federal statutes were issued in the Energy Policy Acts of 1992 and 2005. Those statutes require the U.S. DOE to set appliance efficiency standards at levels that achieve the maximum improvement in energy efficiency that is technologically feasible and economically justified.

As of September 2007, there was pending rulemaking to be completed for 19 backlogged appliance standards and 10 new standards, and all of these are slated to be finalized by U.S. DOE by 2011 (U.S. DOE, 2007). In addition, several states have standards that apply to appliances for which there are not currently federal standards. At least eight different states have additional non-federal standards, and most of these standards, including the non-California ones, are based upon the standards established for California by the California Energy Commission (Nadel et al., 2005).

In addition, voluntary federal programs such as the ENERGY STAR have helped increase the purchase of the most energy-efficient appliance models for consumers, by providing information on annual average energy and cost savings to consumers. ENERGY STAR, run jointly by U.S. Department of Energy and U.S. Environmental Protection Agency program, puts forth standards for qualifying particular energy-efficient appliances and offers information resources about energy savings to aid consumers in their purchasing decisions. The program offers listings of ENERGY STAR-qualifying equipment and on-line calculators to compare that office equipment versus conventional (non-qualifying) equipment for many different office appliances, including computers, refrigerators, copiers, water coolers, and fax machines (See U.S. EPA and U.S. DOE, 2007). Many utilities, states, and localities incentivize the purchase of more efficient appliances by providing tax benefits/credits/deductions to consumers. Several U.S. states also use ENERGY STAR qualifying standards to set their own state regulations for appliances (Nadel et al., 2007).

Numerous studies have attempted to quantify the effects of appliance efficiency standards on improving energy use over time. A series of studies from the Lawrence Berkeley National Laboratory have quantified the cost-effectiveness of some previously phased-in appliance standards, as well as some currently-being-phased-in standards. Gillingham et al. (2004) studied the effects of previous energy efficiency measures, including appliance efficiency standards and voluntary measures like U.S. EPA's ENERGY STAR program, and determined that the measures had cost-effectiveness values of less than \$50/ton CO_2, before consideration of the consumer benefits. Several other studies, including the resulting energy savings from the more efficient appliances, have determined the efficiency standards to have much greater benefits than initial incremental costs (see, e.g., Koomey et al., 1998; Koomey et al., 1999; Meyers et al., 2003). Based on these analyses of the already enacted standards for appliances, estimations of the benefit-to-cost values are around 3-to-1, and these measures have had average cost-effectiveness values of between -\$100 /tonne CO_2 and -\$20/tonne CO_2.

Nadel et al. (2005) similarly shows net benefits for each of the 18 appliances (including commercial clothes washers, commercial refrigerators and freezers, commercial unit heaters, dehumidifiers, digital cable and satellite boxes, digital television adaptors, exit signs, large commercial air conditioners and heat pumps, transformers, lamp fixtures, and traffic signals) for which new efficiency standards were considered. Based on that analysis, the estimated average marginal cost-effectiveness of each appliance's standard was between -\$80 and -\$20 per ton CO_2, the cumulative effect of all those appliances is bring about approximately 50 million tonnes of CO_2 emissions reduced by the year 2020. Those analyzed standards now in large part make up standards from the Energy Policy Act of 2005 (EPAct 2005), which are, in 2007, in various stages of rulemaking and deployment (U.S. DOE, 2007). Because these EPAct 2005 measures are included in the official U.S. EIA reference case (U.S. EIA, 2008) and therefore this dissertation's baseline, these efficiency improvements are not included in this project's GHG abatement curves.

Appliances with GHG emission reduction potential are shown in Table 19. Consistent with this dissertation's calculation method, the cost-effectiveness values of the technologies are evaluated both based on technologies' initial costs and the lifetime costs, which include the cost savings to owners of the improved efficiency appliances. The data in the table is based upon Nadel et al. (2006), Sachs et al. (2004), and the primary data sources within the Sachs et al. (2004) report.

Among the appliance measures in the table are technologies for computers, water coolers, refrigerators, and water heaters. Computer management software programs can monitor energy usage for large office networks and control the computers' energy settings. Increased efficiency standards for refrigerators could bring all units up to the efficiency levels of ENERGY STAR units, bringing an approximate 15% electricity use reduction from federal standards for new appliances (Sunpower, 2003; LGE, 2003; Unger, 1999; Vineyard and Sand, 1997; Sachs et al., 2004). Bottle-type water coolers used in commercial buildings and households could similarly be set to match the increased efficiency of ENERGY STAR standards. Two water heater technologies are available with potential energy use and GHG emission reductions. The use of a heat pump water heater, with it use of a vapor compression refrigeration cycle, is more efficient than conventional tank water heater, and instantaneous (or "tankless" or "on-demand") water heaters avoid the water heater tank altogether by quickly heating water as needed.

The appliance efficiency measure with the largest GHG emission impact would be to establish a limit of 1 watt as the maximum stand-by energy requirement for all household appliances. Different aspects of this application and its impacts have been researched by a variety of sources (see Ross and Meier, 2000; Meier, 2002; Calwell and Reeder, 2002; Kubo et al., 2001; Sachs et al., 2004). This stand-by power reduction measure is estimated to cost \$2 per appliance, replace 15 appliances per household that consume stand-by power, and result in -\$82 per tonne CO_2 cost-effectiveness value. The measure would amount to about 36% of the total GHG reduction from the 18 measures of Table 19.

Table 19. Appliance efficiency GHG reduction measures

Measure	Initial cost effectiveness ($2008/tonne CO_2)	Lifetime cost effectiveness ($2008/tonne CO_2)	GHG reduction in 2030 (million tonne CO2e/yr)	Sources based upon
Advanced appliance and pump motors (for clothes washers, dishwashers, etc.)	2	-95	6	Sachs et al., 2004
Networked computer power management (e.g., EZConserve surveyor software)	27	-84	28	Degans 2003; LBNL 2002, Sachs et al., 2004
1-watt standby power limit for home appliances	29	-82	48	Ross and Meier, 2000; Meier, 2002; Calwell and Reeder, 2002; Kubo et al., 2001; Sachs et al., 2004
Pool heaters	64	-77	1	Nadel et al., 2006
Compact audio products	4	-74	1	Nadel et al., 2006
Bottle-type water dispensers	7	-69	0	Nadel et al., 2006
Residential heat pump water heaters	28	-69	15	Nadel 2002; Sachs et al., 2004
Walk-in refrigerators and freezers	11	-61	3	Nadel et al., 2006
Single-voltage external AC to DC power supplies	20	-60	4	Nadel et al., 2006
DVD players and recorders	21	-54	0	Nadel et al., 2006
Commercial hot food holding cabinets	19	-43	0	Nadel et al., 2006
Efficient refrigerator of ENERGY STAR energy usage level (~1 kWh/day)	44	-42	14	Sunpower, 2003; LGE, 2003; Unger, 1999; Vineyard and Sand, 1997; Sachs et al., 2004
Medium-voltage dry-type transformers	12	-31	0	Nadel et al., 2006
Liquid-immersed distribution transformers	16	-28	4	Nadel et al., 2006
Portable electric spas (hot tubs)	46	-27	0	Nadel et al., 2006
Residential pool pumps	61	-14	2	Nadel et al., 2006
Integrated home comfort systems (multi-function ventilation, heating, water heating)	136	41	4	Sachs et al., 2004
All measures	31	-69	136	

The above appliance efficiency measures are shown graphically in a cost-effectiveness curve in Figure 31. As shown all of the measures except for the final one have cost-effectiveness values below zero, and are therefore net beneficial on a lifetime cost accounting basis.

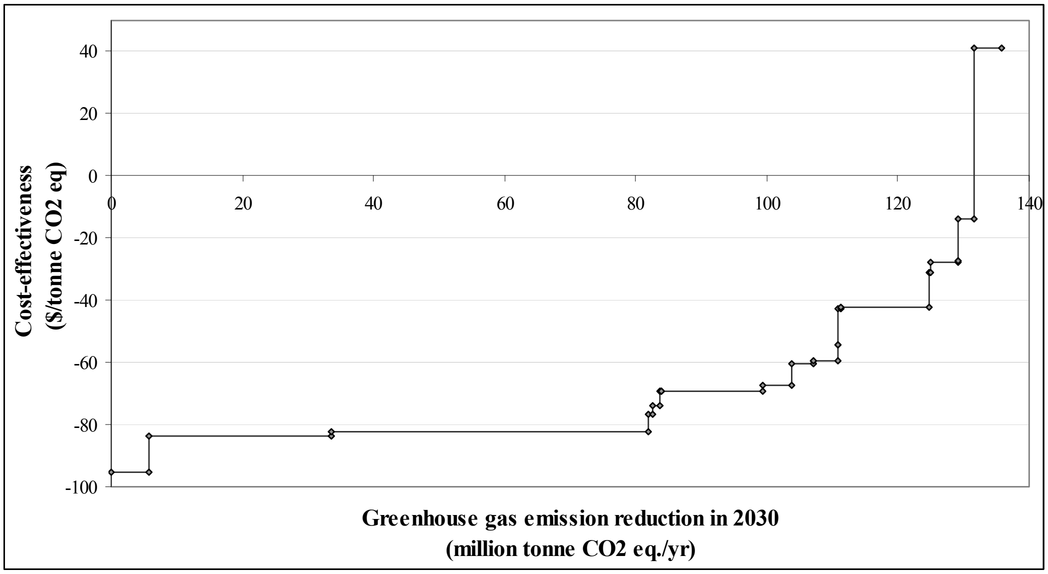


Figure 31. Cost-effectiveness curve for commercial and residential appliance efficiency GHG reduction technologies

5.2. Lighting Efficiency

Lighting is estimated to make up about 13% of all U.S. electricity demand (Mills, 2002). This electricity for lighting, in turn, represents about 5% of total U.S. GHG emissions (based on U.S. EIA, 2008). This lighting is predominantly in the residential and commercial sectors, with somewhat different demands and available technologies for lighting in each sector. Within the residential sector, household lighting is responsible for about 12% of electricity (and about 8% of residential GHG emissions). As percentages of the commercial sector totals, lighting needs are estimated to be relatively higher, representing approximately 25% of electricity and 19% of GHG emissions (Vorsatz et al., 1997; U.S. EIA, 2007).

The residential and commercial sectors have somewhat different lighting applications and technologies. Household lighting energy use is diversely spread through areas of the house. In decreasing order of energy use, the highest lighting requirements are the kitchen, living room, bathrooms, bedrooms, and outdoor applications; these represent about two-thirds of household lighting energy use (Vorsatz et al., 1997). The dominant lighting technology is the incandescent light bulb, trailed by tubular fluorescent lighting and compact fluorescent lightbulbs (CFLs) (Vorsatz et al., 1997). A variety of surveys from 2002 to 2004 suggest that households purchasing of CFLs was between 2-7% throughout the U.S., and that about 6-8% of the standard screwbase sockets had CFLs (Skumatz and Howlett, 2006).

In the commercial sector, office, retail, warehouse, and other building applications have somewhat different lighting technologies and potential for efficiency improvements than households. In commercial buildings, the lighting technology breakdown was 5% incandescent, 80% fluorescent (mostly 4- and 8-foot tubular style), and 15% high-intensity discharge (HID, including high pressure sodium, metal halide, and mercury vapor). All the non-incandescent technology options have higher efficiencies. General ranges for the efficiency, or luminous efficacy, of the technologies are incandescent, 10-20 lumens per watt (lum/W); CFL, 50-90 lum/W; tubular fluorescent, 55-90 lum/W; HID, 32-124 lum/W (Vorsatz et al., 1997).

Alternatives for lighting energy-reductions are summarized in Table 20. Technology replacement options are specific to the uses of current lighting in buildings. For example, different lighting efficiency options exist for the office use, hallways, warehouses, exit lights, and outdoor use. On average, in places where incandescent light bulbs are still in use, their replacement with ENERGY STAR-qualified compact fluorescent lights (CFLs) offers a 60-75% efficiency improvement. This has a breakeven as an energy investment within one year, and the bulbs also last ten times longer, thereby reducing the maintenance costs that would be required for replacing incandescent bulbs over their lifetime. As such, the national phase-out of incandescent bulbs has been set for the 2012 to 2014 time period according to the 2007 federal energy bill. The table lists two applications, portable (plug-in) lights and recessed downlighting, for which these CFL replacements will yield GHG reductions.

For office fluorescent tube-style lighting, shifting from the conventional T12 office fluorescent lighting to state-of-the-art T8 lighting offers an 81% efficiency improvement and with longer life (Sardinsky and Benya 2003; Sachs et al., 2004). At or near building exits and stairwells, the replacement of exit sign light bulbs can yield energy savings. Exit sign bulbs, which are generally 36-W incandescent bulbs, can be replaced with off-the-shelf ENERGY STAR-qualified light-emitting diodes (LEDs) that draw only 5 W per unit (U.S. EPA and U.S. DOE, 2008a). For outdoor, high ceiling, and parking garage lighting, there are two GHG-reducing alternative technologies: metal halide lamp fixtures with pulse-start technology which offer a 25% reduction (Nadel et al. 2006; PG&E, 2004b) and high intensity discharge (HID) lighting, which offers a 60% electricity reduction over metal halides (Gough, 2003; U.S. DOE, 2002; Sachs et al., 2004). All of these lighting technologies "break even" as an energy investment well within the technology lifetimes, as shown by their net negative cost-effectiveness values.

Installing occupancy and ambient light sensors allow for more optimally managing what lighting is needed at any given time in any given space – without relying on individuals to manually switch off or adjust lighting. Specifically for office lighting, there is the ability to decrease overall lighting requirement by simultaneously reducing the ambient overhead lighting while increasing the immediate workspace lighting (or "task lighting") with 5-W LED lights at each occupant's working area. This integrated approach both reduces overall energy needs (in watt per square foot of floor space) and improves each individual's lighting (foot candles or lumens per square foot of desk space). The use of more efficient LED task lighting and the installation of integrated office space lighting systems both are highly cost-effective, returning their initial cost well within the lifetimes (Ton et al., 2003; Kendall and Scholand, 2001; LumiLed, 2003, U.S. DOE, 2003; Sachs et al., 2004; Marbek, 2003; U.S. DOE, 2002).

Table 20. Lighting efficiency GHG reduction measures

Measure	Initial cost effectiveness ($2008/tonne CO_2)	Lifetime cost effectiveness ($2008/tonne CO_2)	GHG reduction in 2030 (million tonne CO2e/yr)	Sources based upon
Compact fluorescent lights - portable, plug-in fixtures	7	-177	42.1	Industry data, 2007; Sachs et al., 2004
Compact fluorescent lights - recessed downlighting	0	-113	38.3	LBNL, 2004; McCullough, 2003; DEG, 2003; Sachs et al., 2004
1-lamp fluorescent fixtures w/ high-perf. Lamps	10	-85	20.9	Thorne and Nadel, 2003; Sachs et al., 2004
High efficiency premium T8 lighting (100 lumen/W)	14	-84	33.9	Sardinsky and Benya, 2003; Sachs et al., 2004
Integrated skylight luminaire (ISL)	90	-70	24.8	Sachs et al., 2004
Commercial LED lighting	88	-64	17.1	Ton et al., 2003; Kendall and Scholand, 2001; LumlLed, 2003, U.S. DOE, 2003; Sachs et al., 2004
General service halogen IR reflecting lamp	123	-63	7.2	Vorsatz et al., 1997; U.S. DOE, 2002; Sachs et al., 2004
Advanced daylighting controls	26	-58	7.8	Marbek, 2003; U.S. DOE, 2002; Sachs et al., 2004
Metal halide lamp fixtures	6	-53	8.6	Nadel et al., 2006
Advanced HID lighting	80	-27	9.4	Gough, 2003; U.S. DOE, 2002; Sachs et al., 2004
All measures	32	-99	210	

The above lighting-related GHG reduction measures are shown as a cost-effectiveness – GHG reduction curve in Figure 32. As shown in that figure all of the measures are below zero and thus net-beneficial from a lifetime accounting perspective.

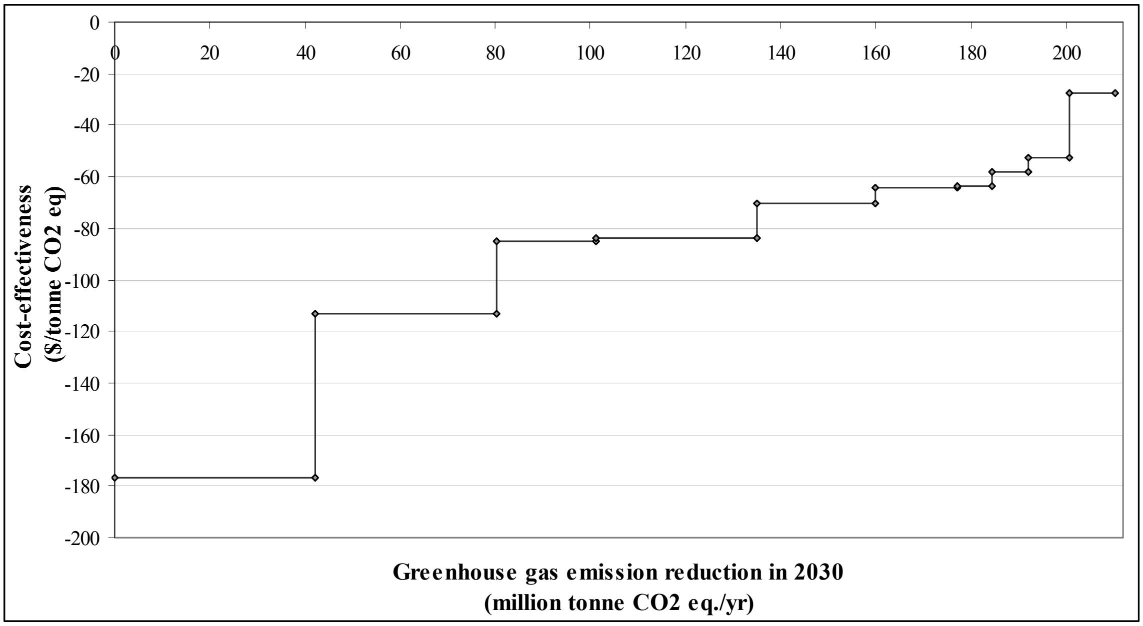


Figure 32. Cost-effectiveness curve for commercial and residential lighting efficiency GHG reduction technologies

5.3. Heating, Ventilation, and Air Conditioning Efficiency

A third major area in the residential and commercial building sector to investigate for potential GHG emission reduction potential is in heating, ventilation, and air conditioning (HVAC) systems. From the above Figure 29 in this building-related chapter's introduction, this HVAC category makes up substantial portions of GHG emissions from the major energy sources of electricity, natural gas, and "other" that are delivered to those buildings. Heating primarily results from direct natural gas-firing (and also heating oil-firing) in furnaces and boilers, and also from electricity. Residential and commercial air conditioning represents a substantial fraction of the electricity use within buildings. And the ventilation in buildings, including the handling of conditioned (i.e. heated or cooled) air, also requires electricity to drive circulation fans.

Heating is most commonly done from boilers for larger commercial buildings and furnaces in residential buildings. The efficiency of these devices is measured by their Annual Fuel Utilization Efficiency (AFUE). The standard in 1989 was an AFUE of 78% for hot-water boilers. Most boilers today are 80-84% AFUE, and available high-efficiency boilers and furnaces are 87-90% AFUE, depending on type and size. There are several improved efficiency heating technology options. In the market for a new boiler or furnace, the choice to get a state-of-the-art unit is beneficial, with paybacks of 6-8 years on units that last 20-25 years (Nadel et al., 2006). In some circumstances, because of the large potential energy savings for particularly old units, even some retrofitting of operational units for new efficiency can still be highly cost-effective (CEE, 2001; Sachs et al., 2004).

There are numerous air-conditioning-specific technologies with potential for GHG reductions. One low-cost measure is to replace the compressor (one component of the refrigeration cycle of the air conditioner) for the air conditioning systems with an advanced multiple-speed, or modulating, technology. Because conventional compressors are typically "on" at full load or "off" they are typically overpowered for all of the regular partial loads of air conditioning systems. Modulating compressors can cost $150 over conventional compressors and yield payback periods of around three years (U.S. EPA, 2003a; Sachs et al., 2004). Larger potential energy reductions can result from replacing air-conditioning units to best available technology. For packaged roof-top air-conditioning units, the conventional Energy Efficiency Ratio (EER) of 10.3 can be improved to EER 13.4 units at an incremental cost of about $1500 to $2000 per unit and with a 3-year payback period (Sachs et al., 2004).

The ventilation portion of the HVAC systems relates to how efficiently the conditioned air that has been either heated or cooled is transported throughout the buildings to maintain comfortable space temperatures. The most simple technology measure is to improve the efficiency of the ventilation motor to a modulating (i.e., not single-speed) motor that can be optimized for the amount of air flow that is required for given heating and cooling circumstances. Several different practices can help seal up the ducts that are used to transport conditioned air. The first duct-sealing option, with use of an aerosol-based sealing, can seal up duct holes and cracks up to 1/4-inch in diameter for existing building HVAC systems (Kallett et al., 2000; Bourne and Stein, 1999; Modera et al., 1996). Also, the use of mastic mechanical fastener systems can more drastically reduce air flow leakage when built into the original HVAC design in new building construction (Proctor, 2003). Another new building construction option for reduced ventilation system energy losses come from designing the new building HVAC system for lower parasitic losses and pressure drops (Westphalen and Loszalinski, 1999). Finally the use of sensors in space conditioned "zones" within buildings can be used to trigger ventilation controls to more optimally manage air flow requirements in buildings (Shaw, 2003; CEC, 2002).

There are several options that are more aptly considered as full system HVAC measures for GHG mitigation, and not exclusively as heating, cooling, or ventilation measures. One technology that can effectively provide heating and cooling is the heat pump. A heat pump can use either electricity or natural gas as an energy source, convert its energy source to useful work generally in a refrigeration cycle, and provide heating or cooling (thus avoiding the two separate systems of a boiler and chiller). Their costs and efficiencies (measured as coefficient of performance, or COP) have improved over the years, such that now a variety of heat pumps are now available with payback periods of less than half of their expected lifetimes of 18-20 years (RECS, 2003; U.S. DOE, 2001; Anderson, 2003; Ryan, 2002; Babyak, 2003; Groll, 2003). In new building construction, heat pump systems are further improved in "closed ground-loop" systems that utilize geothermal energy through underground piping; these systems tend to be more cost-effective in commercial applications than for residential (based on ASHRAE, 1998; DEG 1999a; DEG 1998; Sachs et al., 2004).

HVAC technologies, their cost-effectiveness values, their total potential GHG reduction in year 2030, and data sources are shown in Table 21. These data are shown in a GHG abatement curve in Figure 33.

Table 21. HVAC system efficiency GHG reduction measures

Measure	Initial cost effectiveness ($2008/tonne CO_2)	Lifetime cost effectiveness ($2008/tonne CO_2)	GHG reduction in 2030 (million tonne CO2e/yr)	Sources based upon
Efficient residential furnaces and boilers	0	-123	8.9	Nadel et al., 2006
Ground-coupled heat pumps – commercial	0	-88	7.3	ASHRAE 1998, Sachs et al., 2004
Integrated commercial designs for low parasitic (fan/pumping) losses	0	-84	9.2	Westphalen and Koszalinski 1999, Sachs et al., 2004
Advanced HVAC blower motors	19	-76	10.9	Sachs and Smith 2003, Sachs et al., 2004
Efficient microchannel heat exchangers	18	-70	12.9	Groll 2003, Sachs et al., 2004
"Robust" residential A/C and heat pumps	24	-65	27.1	RECS, 2003; U.S. DOE, 2001, Sachs et al., 2004
Advanced modulating A/C compressors	29	-60	19.5	U.S. EPA, 2003a, Sachs et al., 2004
Leakproof duct fittings	14	-53	31.7	Proctor, 2003; Sachs et al., 2004
Higher efficiency commercial roof-top AC units (13.4 EER, 10-ton)	44	-51	7.9	Modera et al., 1999; Sachs et al., 2004
Outdoor ventilation control (with CO2 IAQ sensors)	51	-44	15.9	Shaw, 2003; CEC, 2002; Sachs et al., 2004
Efficient commercial boilers	36	-44	0.2	Nadel et al., 2006
Aerosol-based duct sealing	101	26	34.5	Kallett et al., 2000; Bourne and Stein, 1999, Modera et al. 1996, Sachs et al., 2004
Ground-coupled heat pumps – residential	150	61	26.0	DEG, 1999a; DEG, 1998; Sachs et al. 2004
All measures	36	-49	186	

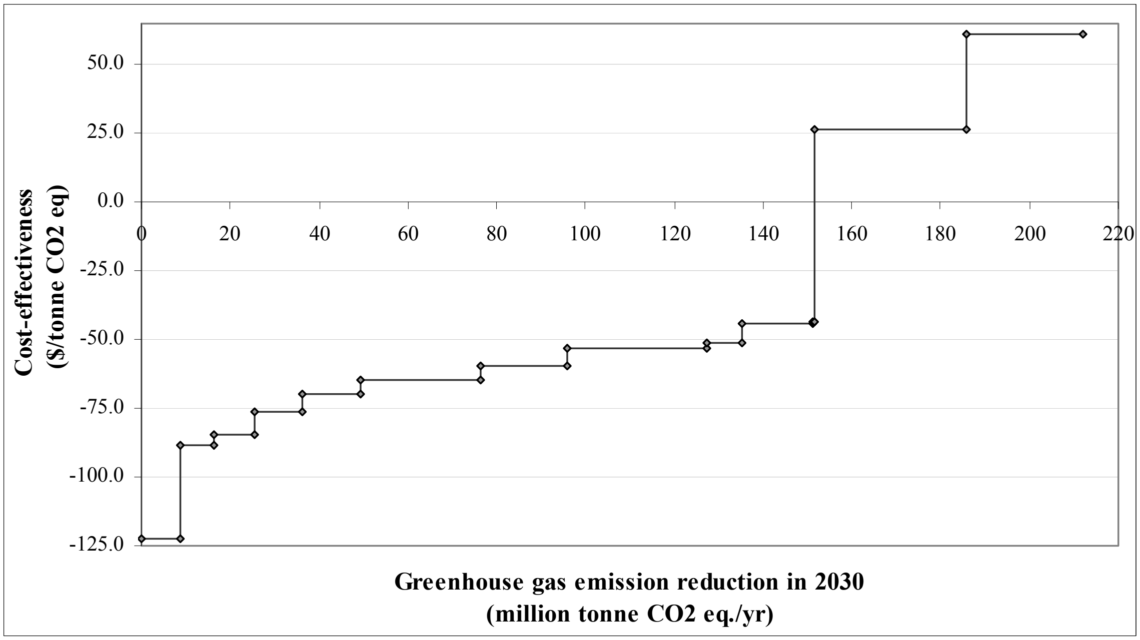


Figure 33. Cost effectiveness curve for HVAC system GHG reduction technologies

5.4. Building Shell and Operation Efficiency

The fourth area for this Chapter on building modifications for GHG reductions is for improvements in the "building shell." The building shell refers to the overall structure of the building, including its walls, insulation, windows, doors, etc. In addition to structural technologies that can be built (or retrofit) into buildings, there are technologies that monitor, troubleshoot, and optimize building operation that can help to ensure that buildings are operating as they were designed.

There are a number of overall building technology changes that greatly affect building energy use. Buildings without any computerized automation of their HVAC systems (with timing and temperature controls) could benefit from advanced building diagnostics systems. Even retrofit systems that cost $50,000 per building can break even from their resulting energy savings within three years of installation for larger commercial buildings (Krepchin, 2001; Sachs et al., 2004). Other retrofit ideas include the use of simple structures to better manage passive lighting and heat from windows. For example, the use of simple and inexpensive "light shelves" on the external wall of the building can help direct more natural light into the building, and the use of automated "smart" integrated Venetian-type blinds can better manage the natural daylighting and the passive solar heat as a resource in winter (and as an undesired load in summer (Lee and Selkowitz, 1998; CBECS, 1999).

Many building technologies are more readily applied to new building construction. Improved insulation with improved thermal characteristics can result in substantial cost-effective GHG reductions in either new building construction or through spray-applied insulation (DEG 2002, Lea 2003, Stover 2001, Sachs et al., 2004). For windows, high insulation technology, such as those with low-e fillings, multiple panes, inert gas fills, insulating spacers, or improved sealing window frames, are highly cost-effective (LBNL, 2003; Sachs et al. 2004). Also, there are available "cool roof" paints that have the ability to more effectively reflect solar heat in the summer to reduce building air conditioning loads that are externally applied to buildings (Desjarlais 2003, Reid 2003, Nixon 2003b, Sachs et al., 2004).

Additionally there are several technology options that provide heating and electricity to residential and commercial buildings. These options, which are sometimes known as distributed generation or micro-combined heat and power (CHP), could involve numerous types of technologies, including turbines, reciprocating engines, fuel cells, and micro-turbines. Residential micro-CHP systems are less than 10 kW as rated by their electricity generation, while smaller commercial systems are approximately rated 100-200 kW, and larger commercial systems can be several MWs. Having these systems on building sites allows for the waste heat to be utilized for heating or other on-site commercial purposes. Generally these systems are only viable where heating or cooling loads are prevalent and/or electricity rates are high. Included here are two systems: A 2-kW Stirling system is included for a 2000 sq. ft. residence (at a cost of $1500/kW) and a 200-kW natural-gas-fired micro-turbine is assessed for a 100,000 sq. ft. commercial building (at $1750/kW) (Based on Shipley, 2004; Reiss, Krepchin et al. 2002; Sachs et al., 2004).

Beyond direct changes by building operators, the use of outside building energy consultants can also help troubleshoot larger energy loses. The practice of "retro-commissioning" entails a thorough analysis of buildings' operations to pinpoint energy use reduction opportunities. A similar practice, called "bulls eye commissioning," does this troubleshooting in a more streamlined (but less comprehensive) manner that seeks out and finds the several largest building improvements more quickly. Both of these assessment techniques are generally highly cost-effective in delivering energy savings that offset the consulting and diagnostic fees within two years, and they are more effective in newer buildings with some level of computerized automation (Price and Hart, 2002; Thorne and Nadel, 2003; Gregerson, 1997; Sachs et al., 2004).

Larger building design changes can most easily be made to buildings during the construction phase. Using integrated building designs that incorporated energy-efficient design and technologies (e.g. the design principles of the U.S. Green Building Council's Leadership in Energy and Environmental Design [LEED] certification program) can reduce energy use intensity of buildings by 30% with estimated initial building cost increases of $1-$2 per square foot of construction, and payback periods of about two years (Brown and Koomey, 2002; Criscione 2002; IEA, 2002; NRCan, 2002).

A more stringent overall building design criterion is to mandate new buildings to have a "net-zero-energy" impact. The issue has been studied and can be relatively cost-effective, with a \$20/tonne CO_2 value on a lifetime basis (based Dakin, 2003; Sachs et al., 2003). The California Energy Commission has recommended that California's Title 24 energy standards for buildings be updated to include such a net-zero-energy requirement by 2030 (CEC, 2007). Other states with broad energy and climate change mitigation goals have mandated that all government building meet LEED or other criteria. Therefore it appears likely that some overall building performance goals will be promoted if not mandated in future years in states with ambitious energy and/or climate change mitigation goals.

Nonetheless, these overarching goals like LEED certification or zero-net-energy are not directly included in this dissertation’s listed, prioritized GHG mitigation technologies. These overall building designs are more difficult to quantify and are more prone to interaction effects, due to this area’s overlap with other areas like HVAC and lighting. Any such new building design that is to be LEED-certified or zero-net-energy would do so by incorporating many of the technologies investigated above for lighting, heating, cooling, window, insulation, etc. (as well as lower-GHG power generation technologies investigated below) to meet those overall building goals. Therefore, instead of choosing several overall building measures, all of the base technologies that would, in all likelihood, be required to achieve the targeted overall building performance are included in this analysis.

Building shell technologies, their cost-effectiveness values, their total potential GHG reduction in year 2030, and data sources are shown in Table 22. These data are shown in a GHG abatement curve in Figure 34.

Table 22. Overall building shell GHG reduction measures

Measure	Initial cost effectiveness ($2008/tonne CO_2)	Lifetime cost effectiveness ($2008/tonne CO_2)	GHG reduction in 2030 (million tonne CO2e/yr)	Sources based upon
Use proper (not over-) sizing HVAC furnace and A/C for smaller buildings	87	-437	11.0	Vieira et al. (undated), Sachs et al., 2004
High insulation technology with low-e fillings, double-paned, inert gas fills, insulating spacers, improved sealing window frames (U<0.25)	108	-243	8.0	LBNL, 2003; Sachs et al., 2004
Quicker form of retrocommisioning to spot largest energy issues efficiently on smaller (< 50000 sf) commercial buildings with automated meter reading (AMR) tests over 15-minute intervals	10	-101	4.6	Price and Hart, 2002; Sachs et al., 2004
Retrocommisioning - troublshoot problems in building operation and maintenance to restore building's designed operation	48	-94	43.1	Thone and Nadel 2003; Gregerson 1997, Sachs et al., 2004
An automated "smart" integrated window/lighting/cooling system of venetian-type blinds for retrofit or new building (25k sq ft building. with 2000 sq. ft. of window)	23	-72	9.1	Lee and Selkowitz, 1998; CBECS, 1999; Sachs et al., 2004
Optimize HVAC equipment through control, correction, and monitoring of overall building energy use (new large >50,000 sf buildings)	67	-69	68.6	Krepchin, 2001; Sachs et al., 2004
Residential micro-CHP using Stirling engines	40	-66	19.6	Krepchin, 2002; Sachs et al., 2004
Commercial micro-CHP using micro turbines (200 kW)	37	-46	67.4	Shipley, 2004; Sachs et al., 2004
Reflective surfacing of roofs (“cool roofs”) to reflect solar heat in summer	41	-43	14.0	Desjarlais, 2003; Reid, 2003; Nixon, 2003b; Sachs et al., 2004
Use of proper insulation through wall frames during construction, or spray-applied cellulose insulation to fill voids (effective R-value from R-8 to R-10)	133	-27	0.6	DEG, 2002; Lea, 2003; Stover, 2001; Sachs et al., 2004
All measures	51	-88	246	

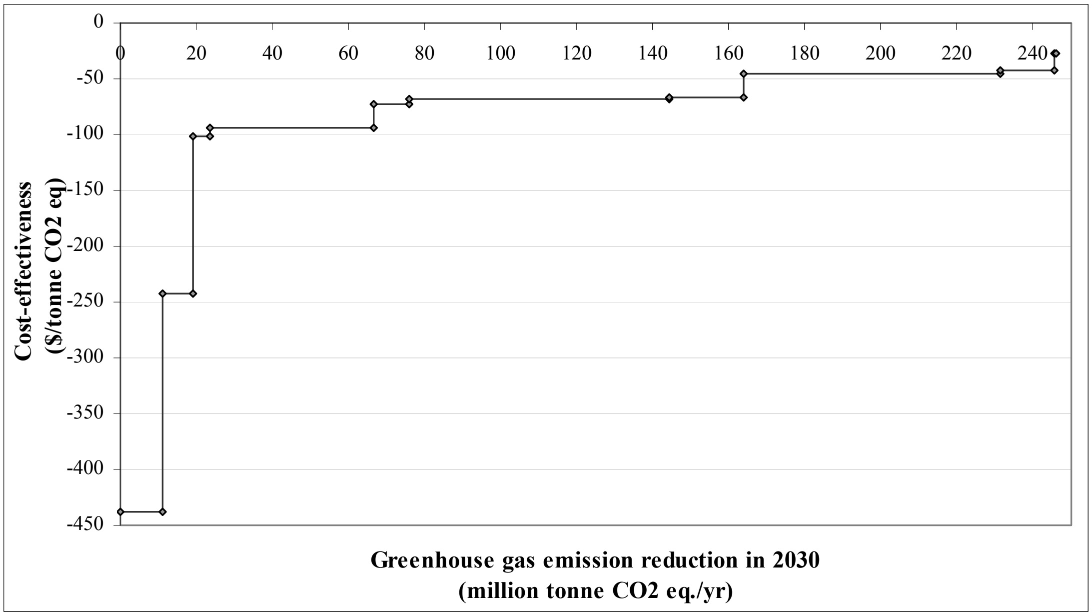


Figure 34. Cost effectiveness curve for building GHG reduction technologies

5.5. Summary of Building GHG Mitigation Technologies

The following figures summarize the GHG trends and the cost-effectiveness values of deploying the above building sector GHG mitigation technologies into residential and commercial buildings. Figure 35 shows the GHG trends of all of the building GHG mitigation technologies that have lifetime cost-effectiveness values at or below $50 per tonne CO_2. Figure 36 shows the combined cost effectiveness curve, after including all of the above measures from the appliance, building shell, lighting, HVAC, and distributed generation sections.

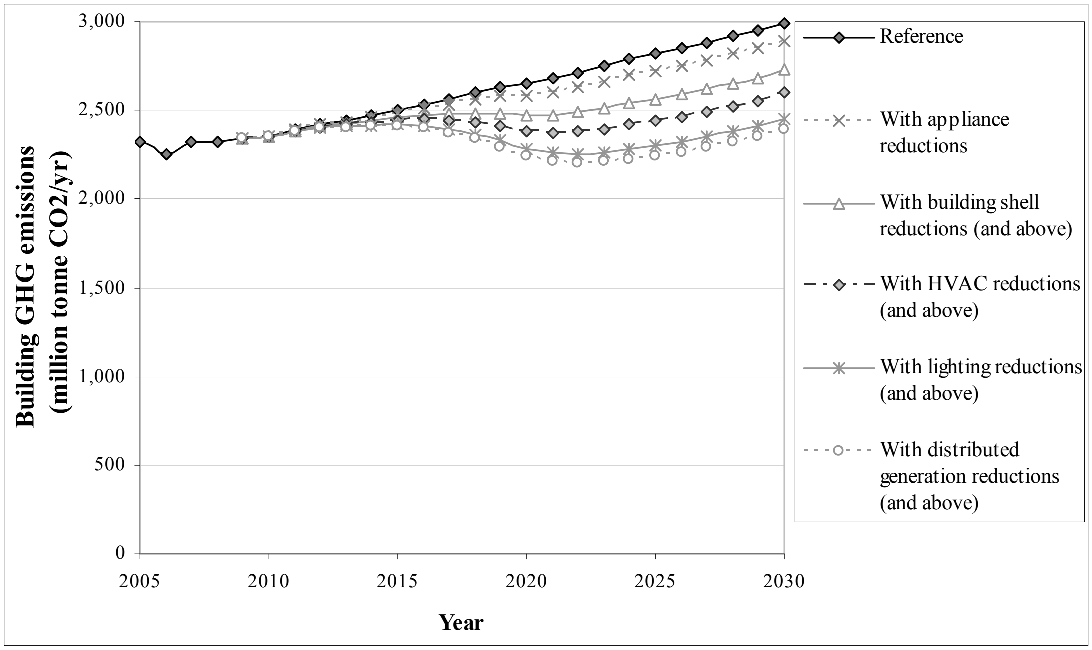


Figure 35. GHG emissions from building sector with GHG reduction technologies

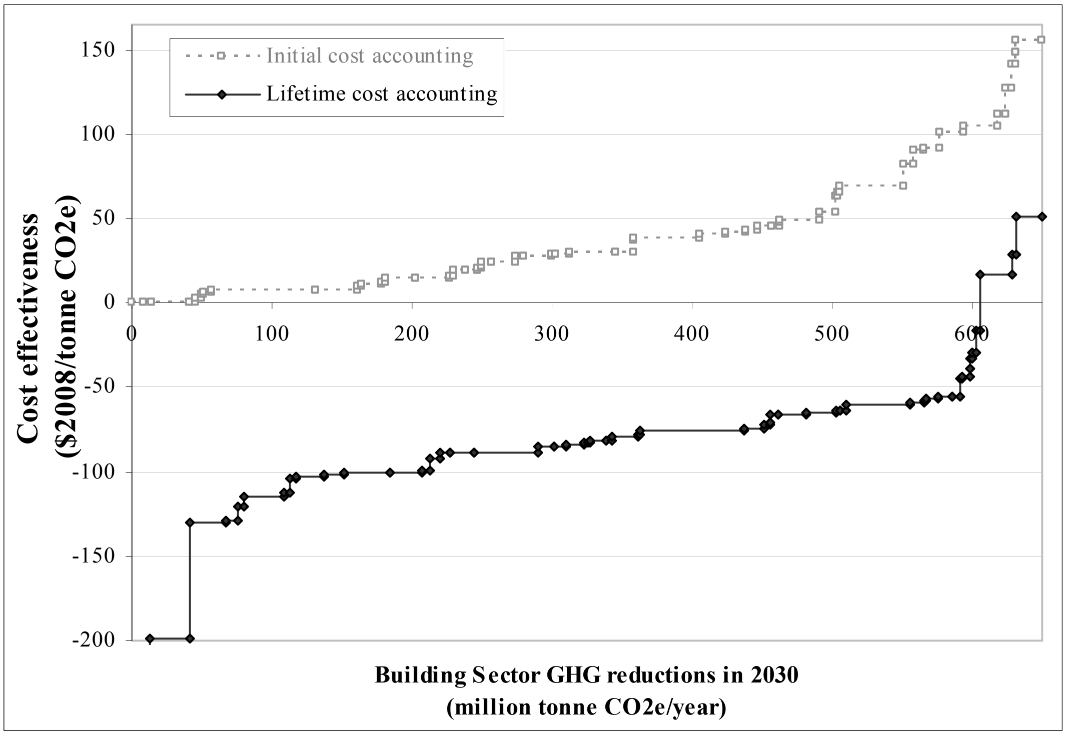


Figure 36. Cost effectiveness curve for GHG mitigation technologies for buildings

6. INDUSTRY

In addition to the energy-related greenhouse gas emission reduction alternatives assessed above, there are numerous options in various industrial processes, including manufacturing, waste treatment, metal production, and the energy to drive those processes. According to national agency estimates (U.S. EPA, 2007b; U.S. EIA, 2008), these factors equate to approximately one quarter of the overall U.S. GHG emission total for 2007. This chapter discusses potential GHG emission mitigation opportunities from industrial processes.

Figure 37 shows industry-related GHG emissions by broad categories. Whereas other chapters in this dissertation utilize mostly U.S. EIA's *AEO2008* (U.S. EIA, 2008), this figure and this chapter also utilizes numerous other sources to include the non-CO_2 and/or non-energy-use related reference GHG emissions (e.g., from U.S. EPA, 2006b, 2006c, 2007b).

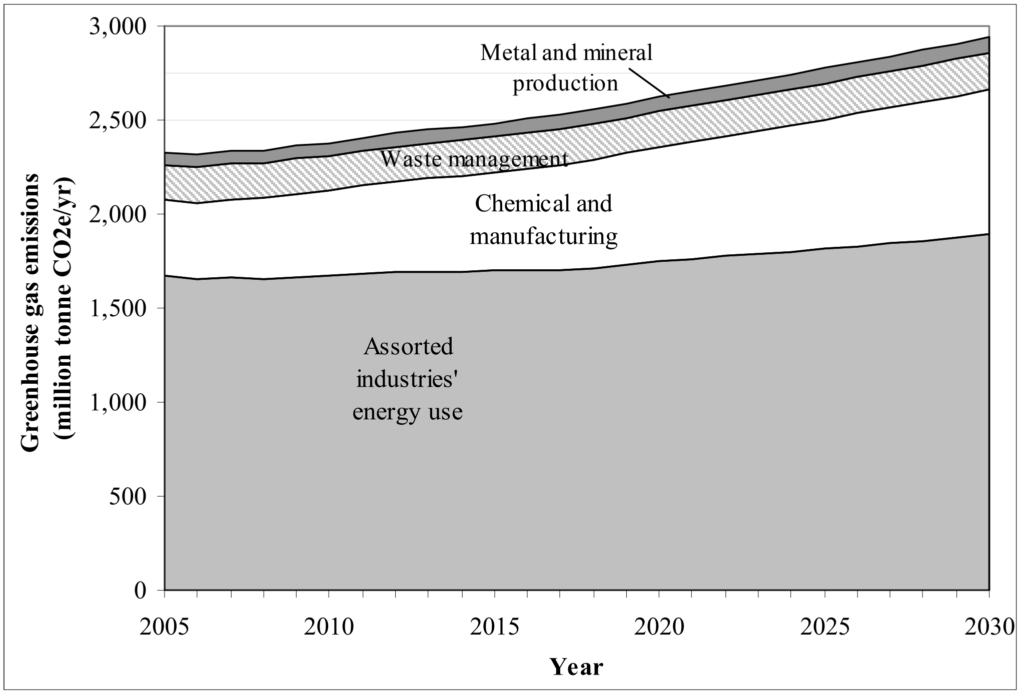


Figure 37. Greenhouse gas emissions from industrial processes

For 2007, the percentages of industry GHG emissions by category are industry energy use, 71%; chemical and manufacturing, 18%; waste management, 9%; and metal and mineral production, 3%. Note that within the largest category – industry energy – the breakdown is highly disaggregated among hundreds of subsectors, and a detailed breakdown of the category is not shown. This chapter discusses mitigation possibilities within these categories. Reference baseline data for this section were taken from several sources.

6.1. Chemical and Manufacturing

The industrial processes that account for GHG emissions from the chemical and manufacturing subsector are highly varied. In the context of this dissertation's broad context of comparing and prioritizing large-scale GHG mitigation opportunities, this sector focuses on the categories that (a) are the largest contributors to GHG emissions and (b) have available research data on cost and emission impacts of potential GHG mitigation technologies. For each manufacturing area, the processes involved are very briefly described, the GHG mitigation technologies are summarized, a cost-effectiveness curve is shown, and the impact on the processes emissions in future years is estimated.

6.1.1. Cement

Cement production is among the largest GHG sources in the industrial sector due to the facts that the industry is both highly energy-dependent and raw material-dependent. The manufacturing of cement involves the “calcination” of calcium carbonate into lime, which in turn is mixed with other minerals to eventually produce cement. CO_2 is produced and released to the atmosphere in the calcination process and through fuel combustion to drive the cement-making processes.

The primary energy use intensity for the cement production process has improved measurably in the past few decades. As measured by Martin et al. (1999), the energy intensity of the cement production has improved by about 30% since 1970. Continued improvements for GHG reductions have been investigated. At least four U.S. cement industry companies have voluntarily committed to reductions of their GHG emissions as part of the U.S. EPA’s Climate Leaders program. For example, the St. Lawrence Cement company pledged to reduce its GHG emissions by 20% per ton of cement from 2000 to 2012, and it has already achieved about 75% of its goal (US EPA, 2008d).

Van Oss and Padovani (2003) estimate that CO_2 reductions of 10% from technical upgrades at plants, 10-15% from noncarbonate calcium oxide in raw materials, and 30% from blending are achievable; however these changes would be slow due to the long-lived and high capital investment costs of cement plant. The California Air Resources Board, in it proposed “early action items” of its climate action plan for state-wide GHG emission reductions, has identified two cement-related GHG-mitigation technologies: (1) improved energy efficiency practices at cement manufacturing facilities and (2) increased blending of other materials such as fly ash and limestone in the production of hydraulic (most commonly “portland”) cement and mortars (CARB, 2007).

Martin et al. (1999) assess the costs and energy and GHG impact of various cement industry technologies. This analysis adapts data from that study on cost, energy, and GHG emissions for technologies in the cement. Applying consistent assumptions for this assessment (i.e., in year 2008 dollars, 7% discount rate), the resulting cost-effectiveness values of the technologies are listed in Table 23, shown as a cost effectiveness curve in Figure 38. The total impact of all of those emission reductions in context of the emissions baseline is depicted in Figure 39.

Table 23. Cement manufacturing GHG reduction measures

GHG reduction measure	Initial cost effectiveness ($2008/$tCO_2e$)	Lifetime cost effectiveness ($2008/$tCO_2e$)	GHG reduction in 2030 (million tonne CO_2e/yr)	Cumulative GHG reduction (million tCO_2e)
Preventative maintenance	0.4	-44.9	1.3	1.3
Kiln heat loss reduction (w)	4.6	-40.7	0.3	1.6
Kiln heat loss reduction (d)	4.6	-40.7	0.4	2.0
Use of waste fuels (w)	4.6	-40.7	0.6	2.6
Use of waste fuels (d)	4.6	-40.7	0.7	3.3
Conversion to semi-wet kiln	5.1	-40.2	0.6	3.9
Clinker cooler grate (w)	6.2	-39.1	0.4	4.3
Clinker cooler grate (d)	6.2	-39.1	1.0	5.3
Conversion to grate cooler (w)	7.0	-38.3	0.1	5.4
Conversion to grate cooler (d)	7.0	-38.3	0.3	5.7
High efficiency motors	10.7	-34.6	0.2	5.9
Kiln combustion system (w)	11.3	-34.0	0.1	5.9
Kiln combustion system (d)	15.8	-29.5	0.1	6.1
Process control system	21.3	-24.0	2.1	8.2
Variable speed drives	28.3	-17.0	0.2	8.4
Cogeneration (steam)	34.2	-11.2	0.0	8.5
Roller press/Horomill	37.0	-8.3	0.4	8.9
Precalciner on preheater kiln	43.1	-2.3	1.2	10.1
Conversion to preheater kiln	59.3	14.0	1.6	11.7
Conversion to precalciner kiln	61.2	15.9	2.0	13.7
Wet to precalciner kiln conversion	73.7	28.4	6.0	19.7
Pre-grinding- HP roller mill	78.1	32.8	0.1	19.8
Improved grinding media	95.0	49.7	0.0	19.8
High efficiency classifiers (d)	163.1	117.8	0.3	20.1
High efficiency roller mill	190.4	145.1	0.7	20.8
Low pressured drop cyclones	192.2	146.9	0.1	20.8
High efficiency classifiers (w)	208.3	163.0	0.1	20.9
Mechanical transport systems (d)	370.2	324.8	0.1	21.0
Mechanical transport systems (w)	370.2	324.8	0.1	21.0

Based on Martin et al., 1999

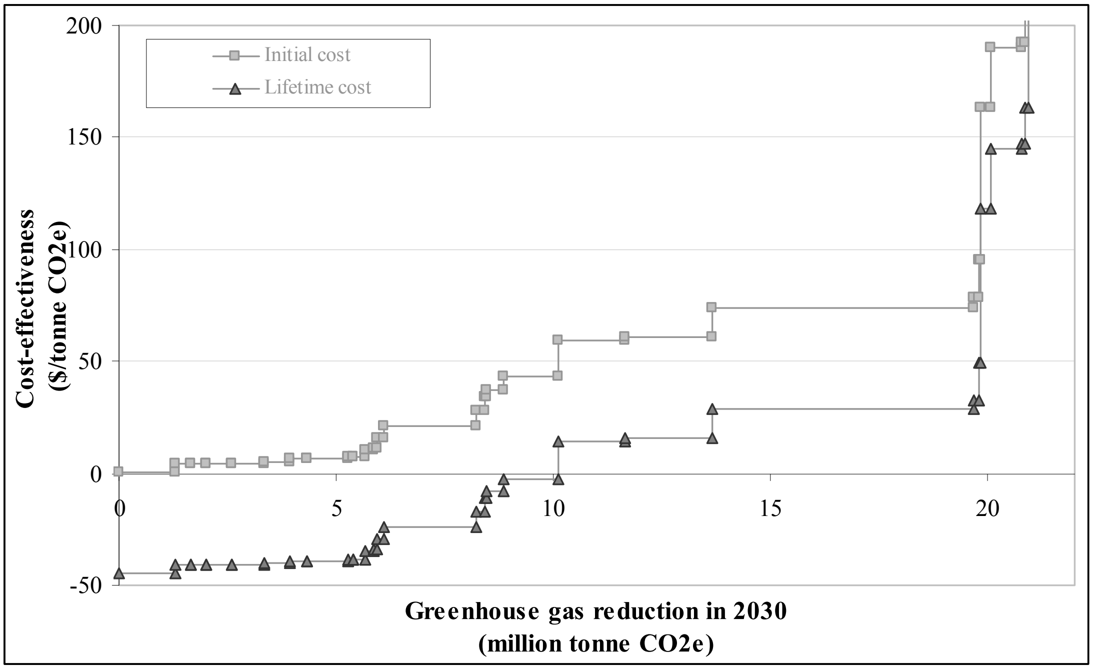


Figure 38. Cost effectiveness curve for cement manufacturing GHG reduction technologies

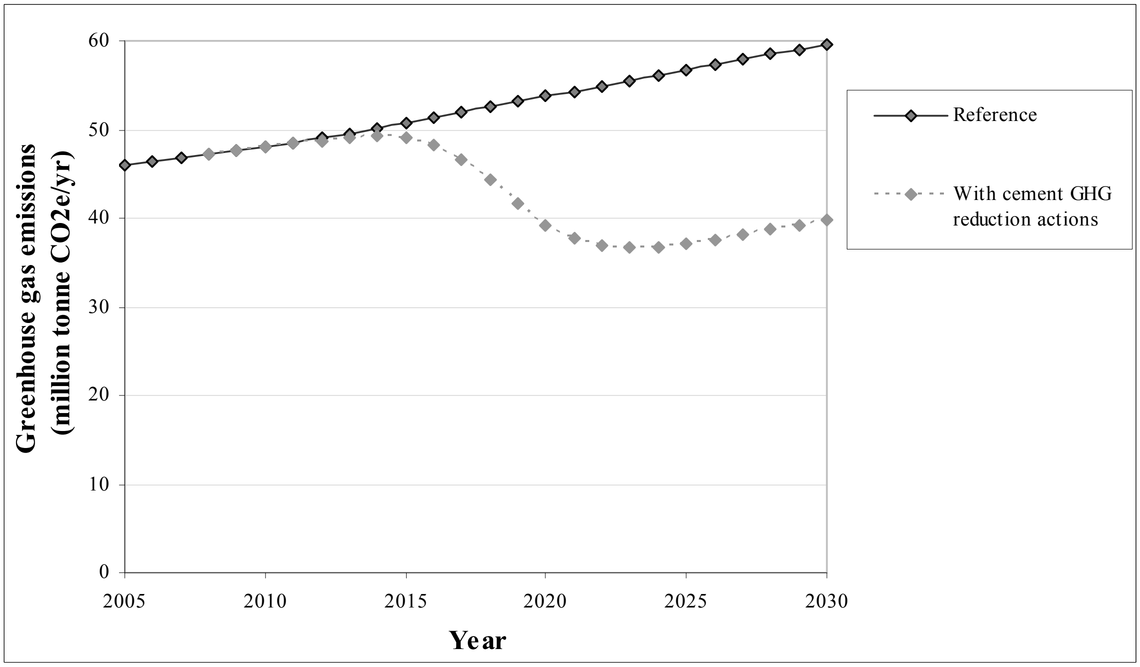


Figure 39. GHG emissions from cement manufacturing

6.1.2. Paper and pulp

The paper and pulp industry is one of the largest energy consumers in the manufacturing sector. Large amounts of energy are required to produce various types of pulp, paper, and paperboard from forest resources, and as such there has been considerable pressure to continually lower the energy intensity of the process. In past decades, the industry has shown an average 1% efficiency improvement per year (Martin et al., 2000).

There are several indications that potential opportunities exist to make the paper industry more efficient in the U.S. This industry has shown improved energy intensities for paper manufacturing in other countries (Farla et al., 1997). At least four major companies (Collins Companies, International Paper, Staples, and Xerox) in the wood pulp and paper industry have pledged GHG reductions of between 7% to 18% from 2000 levels by 2012 (U.S. EPA, 2008d). Note that, contrary to the above cement industry pledges, these company commitments are largely absolute reductions, and not GHG intensity (or per unit production) reductions.

Martin et al. (2000) assess the cost, energy, and GHG impacts of various paper industry technologies. This analysis adapts data from that study for paper industry technologies for consistency with this research. Applying consistent assumptions for this assessment (i.e., in year 2008 dollars, 7% discount rate), the resulting cost-effectiveness values of the technologies are listed in Table 24, shown as a cost effectiveness curve in Figure 40. The total impact of all of those emission reductions in context of the emissions baseline is depicted in Figure 41.

Table 24. Paper industry GHG reduction measures

Technology measure	CE initial ($2008/tCO$_2$e)	CE lifetime ($2008/tCO$_2$e)	GHG reduction in 2030 (million tonne CO$_2$e/yr)	Cumulative GHG reduction (million tCO$_2$e)
Bar-type chip screens	-13	-184	0.1	0.1
Screen out thick chips	-13	-184	0.1	0.3
Boiler maintenance	1	-169	0.8	1.0
Improved Process Control	1	-169	0.8	1.8
Condensate Return	5	-166	0.2	2.0
Automatic Steam Trap Monitoring	7	-164	1.4	3.3
Flue Gas Heat Recovery	10	-161	0.4	3.7
Continuous digester modifications	13	-157	0.9	4.6
Leak Repair	15	-155	0.2	4.8
Infrared profiling	16	-155	0.2	5.0
Batch digester modifications	19	-152	0.9	5.9
Blowdown Steam Recovery	28	-142	0.3	6.1
Pinch Analysis	33	-138	1.1	7.2
Steam trap maintenance	38	-133	2.7	9.9
Efficient motors	54	-117	6.6	16.5
Lime kiln modifications	56	-114	0.3	16.8
Reduced air requirements	90	-80	1.0	17.9
Refiner Improvements	105	-65	0.1	17.9
Recycled paper (31% to 37%)	111	-60	6.7	24.7
Heat recovery in pulping	113	-58	0.1	24.7
Energy-efficient lighting	119	-52	0.1	24.9
Condebelt drying	121	-50	2.8	27.7
Optimization of regular equipment	159	-12	0.3	28.0
Biopulping	178	8	0.3	28.3
Extended nip press (shoe press)	206	35	1.9	30.2
RTS	233	62	0.1	30.3
Continuous digesters	243	72	2.4	32.8
Washing presses	293	122	0.1	32.8
Hot Pressing	307	136	0.2	33.0
High consistency forming	310	139	1.0	34.1
Waste heat recovery	338	167	0.5	34.5

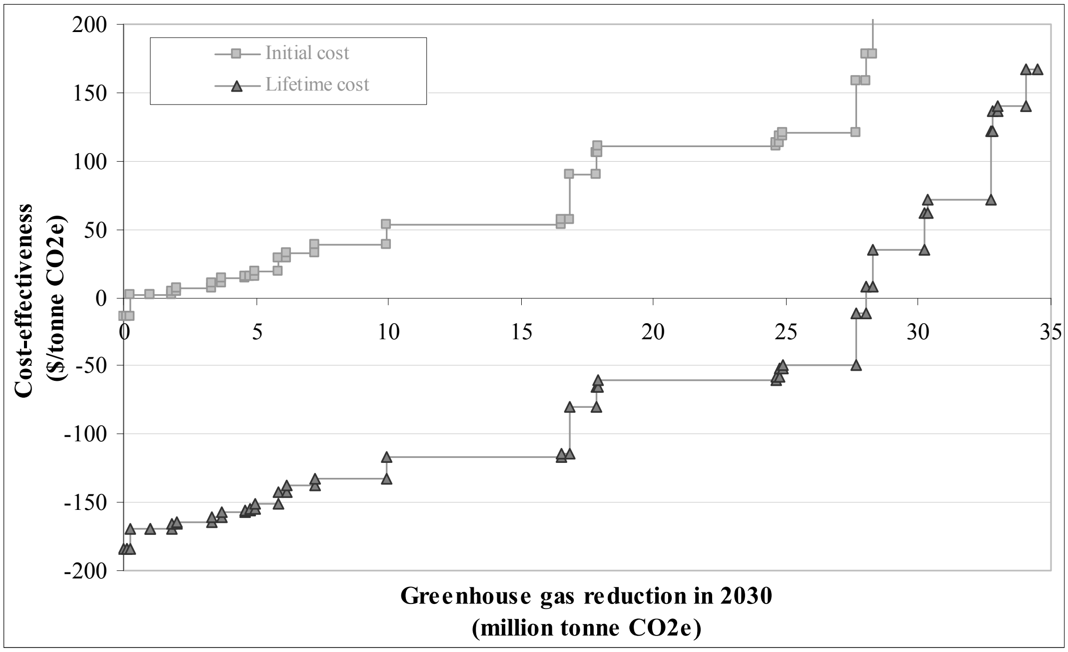


Figure 40. Cost effectiveness curve for paper industry GHG reduction technologies

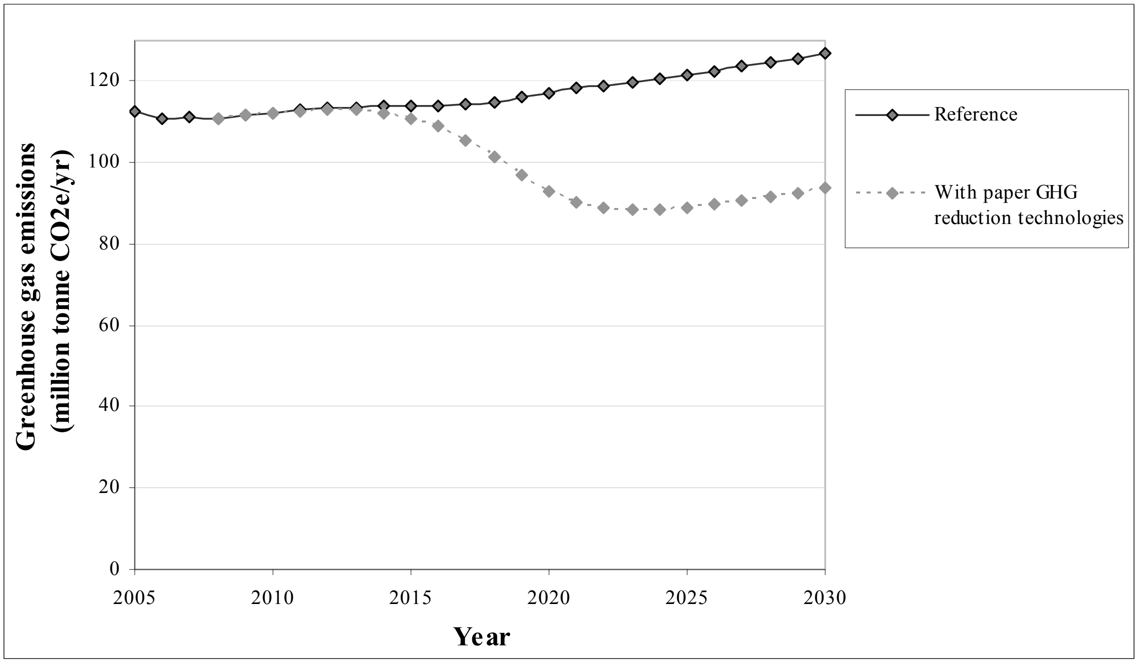


Figure 41. GHG emissions from the paper industry

6.1.3. High-GWP Gas Emissions

The category of emissions, together referred to as high global warming (GWP) gases, are responsible for about 2% of overall U.S. anthropogenic climate change emissions. These chemicals and their manufacturing processes generally involve chemical emissions that are released in relatively small amounts compared to the levels of CO_2 emissions discussed above. However, these molecules have very high global warming potential (GWP), often with a potencies that are greater than 1000 times the heat-trapping impact of a CO_2 molecule in the atmosphere.

This group of emissions is largely made up of fluorinated gases (or "f-gases"), and it includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). These compounds are dispersed throughout the U.S. economy in various industrial and consumer uses. The sources and applications of the fluorinated gas emissions are diverse, including electric power distribution, refrigeration and air-conditioning, aluminum smelting, HCFC-22 production, aerosols, solvents, foams, fire extinguishing, semiconductor manufacturing, and magnesium production.

The largest and fastest growing specific category within this chemical and manufacturing section is the class of chemicals called "substitution of ozone-depleting substances." These compounds are primarily HFCs that are used in refrigeration and air-conditioning systems, and they are the substitutes for the previously used compounds that were banned under the international Montreal Protocol and in the U.S. Clean Air Act Amendments of 1990 due to their deleterious effect on stratospheric ozone.

There are some policies, both voluntary and regulatory, that address fluorinated gas emissions. At the federal level, a series of voluntary initiatives are in place to encourage associated industries to reduce their GHG emissions of high GWP gases. For example, the aluminum industry has formed a partnership to reduce PFC emissions, and the semiconductor industry has set a goal to reduce its PFC emissions by 10% below 1995 levels by 2010, despite growth in the computer industry. In addition, the California Air Resources Board has identified several "early action items" in its effort to reduce state-wide GHG emissions. The targeted California fluorinated gas emission actions include mitigating emission leakage in consumer products (aerosols, electronic cleaning products), standards for PFC in the semiconductor industry, and enhanced refrigerant tracking and recovery.

Work in the U.S. and abroad suggest that there is considerable potential for cost-effective GHG mitigation in this category (de la Chesnaye et al., 2001). Research by U.S. EPA quantified and chronicled emission sources of fluorinated gas compounds. The U.S. EPA work resulted in a detailed breakdown of HFC, PFC, and SF_6 emissions, and the subsequently assessed the potential for GHG emission mitigation and the associated cost effectiveness (U.S. EPA, 1999). Data from that study by U.S. EPA are adapted here for this research. Note that a discount rate of 4%, was embedded in that study's data and could not be adjusted to be consistent with this dissertation's 7% discount rate assumption. The resulting cost-effectiveness values of the technologies are listed in Table 25, shown as a cost effectiveness curve in Figure 42. The total impact of all of those emission reductions in context of the emissions baseline is depicted in Figure 43.

Table 25. High GWP gases GHG reduction measures

Category	Technologies / replacement compounds	Lifetime cost effectiveness ($2008/tCO$_2$e)	GHG emission reduction in 2030 (million tonne CO$_2$e)
Aerosols	Use of hydrocarbon aerosol propellants; not-in-kind alternatives; switching to HFC-152a	-4.7	8.2
Magnesium Smelting	Good housekeeping; SF6 capture/recycling; SO2 replacement	-0.1	30.0
Refrigeration/AC	Replace DX with distributed system	0.0	8.2
HCFC-22 Production	Thermal oxidation	0.2	31.1
Solvents	Alternative solvents	0.3	4.4
Electric Utilities	Leak detection and repair; recycling equipment	0.6	8.2
Aluminum Smelting	Retrofits (VSS, SWPB, CWPB, HSS)	0.8	4.5
Refrigeration/AC	Leak reduction options	1.2	6.5
Solvents NIK	Not-in-kind aqueous and non-aqueous alternatives	5.4	0.3
Semiconductor Manufacturing	NF3 drop-in; NF3 remote cleaning; plasma abatement; capture and recycling; catalytic destruction; thermal destruction	14.1	92.8
Solvents	Retrofit options	14.7	0.2
Fire Extinguishing	Inert gas systems	16.4	1.8
Foams	PU spray foams - replace HFC-245fa/CO2 with CO2	16.7	5.6
Refrigeration/AC	HFC secondary loop systems	21.7	8.2
Refrigeration/AC	Ammonia secondary loop systems	34.1	3.3

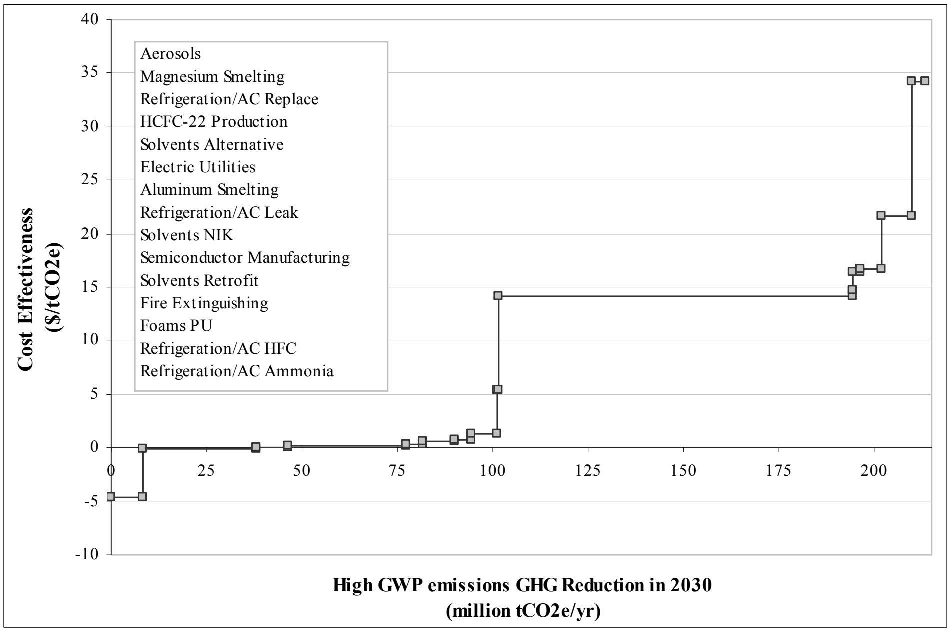


Figure 42. Cost effectiveness curve for high GWP gases

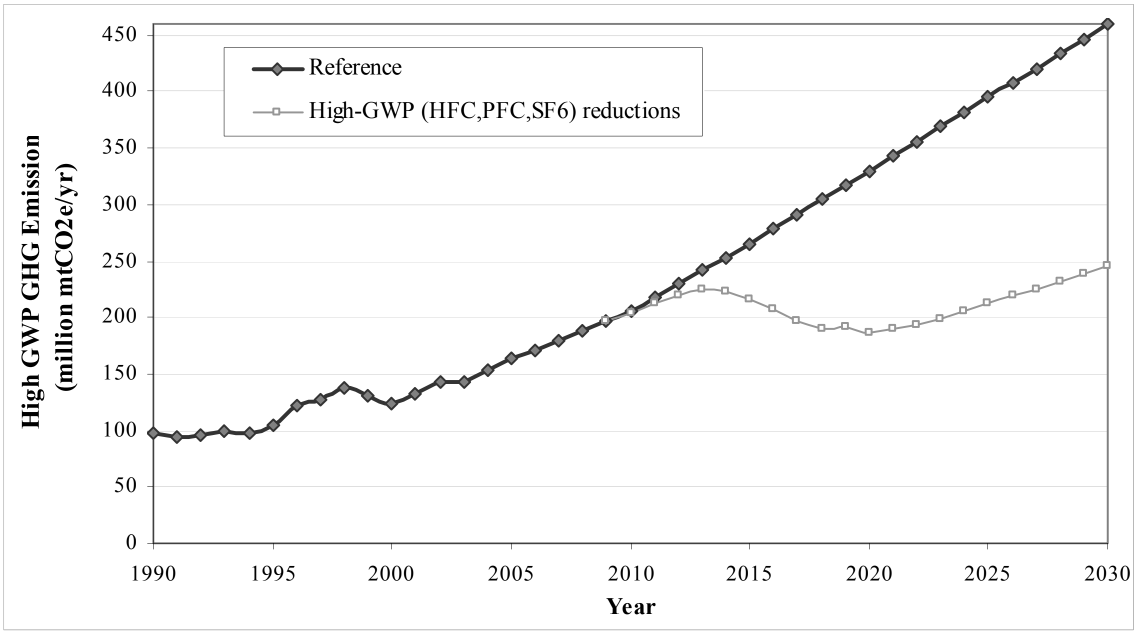


Figure 43. GHG emissions from GHG reduction technologies for high GWP gases

6.2. Waste Management

The handling and storage of waste is a substantial contributor to U.S. GHG emissions, equating to about 2% of national GHG emissions. The largest source of waste-related GHG emissions is the methane (CH_4) that is released from municipal solid waste landfill emissions, which make up about 80% of waste emissions and 24% of all U.S. CH_4 emissions (U.S. EPA, 2007b). This emission generation makes landfills the largest anthropogenic methane source in the U.S. Biological decomposition of organic matter in landfills releases methane, which slowly seeps out of landfills into the atmosphere. New standards for landfills require that new sources of landfill-emitted methane must now be either combusted (into carbon dioxide and water vapor) or utilized as an energy source (e.g., used directly for heating or converting to electricity via an engine or turbine).

The U.S. EPA work (U.S. EPA, 1999; U.S. EPA, 2003b) investigates utilizing methane from landfills for energy capture and emission reductions. The U.S. EPA work surveyed landfills and assessed the viability of various types of methane emission reduction technologies. Three landfill methane reduction technologies are summarized in Table 26. Converting landfills to utilize the landfill gas generally includes a gas collection system. Landfill gas from throughout landfills can be routed through lateral piping, and the collected gas can be (a) flared or simply combusted to convert CH_4 to CO_2, (b) used as a medium-heating-value fuel directly for heating or driving industrial processes or (c) fed to an engine, microturbine, or fuel cell to generate electricity.

Table 26. Landfill gas GHG reduction technologies

Technology	Initial cost-effectiveness ($2008/tCO$_2$e)	Lifetime cost-effectiveness ($2008/tCO$_2$e)	GHG reduction in 2030 (million tonne CO$_2$e)
Direct gas use - Gas recovered from landfills is used as a medium Btu fuel for boilers or industrial processes. Here, the gas is piped directly to a nearby customer and used as a replacement fuel.	39.3	2.0	30.5
Gas flaring - Recovered methane is flared to control odor and gas migration.	35.9	8.7	18.8
Electricity generation - Recovered methane is used for electricity generation	201.8	15.4	45.8

Based on U.S. EPA, 2003b; U.S. EPA, 1999.

The GHG reduction technologies for landfills from above are shown as a marginal cost-effectiveness curve in Figure 44. The estimated impact of all three measures on future waste-related GHG emissions is shown in Figure 45.

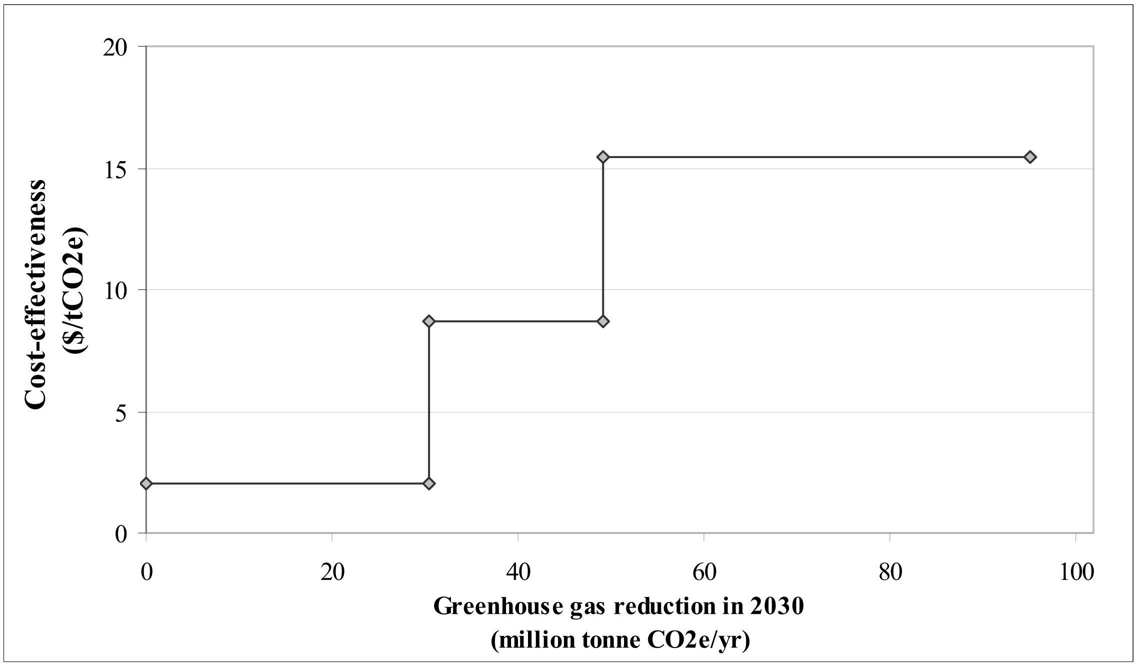


Figure 44. Cost-effectiveness curve for waste-related GHG reduction technologies

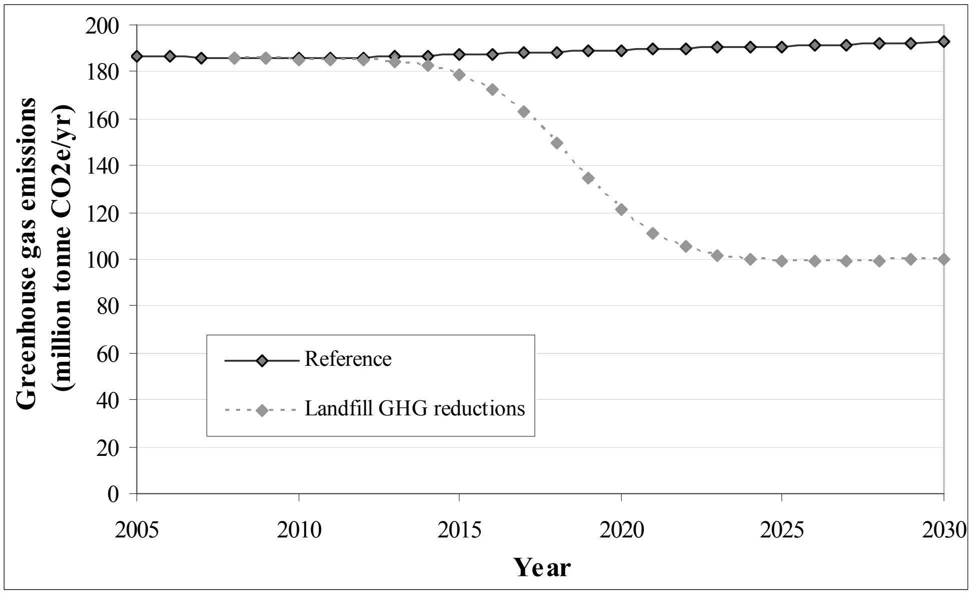


Figure 45. GHG emissions from waste through 2030

6.3. Metal and Mineral Production

The extraction, production, and processing of metals and minerals result in both process-related and energy-use-related GHG emissions. Iron, steel, and aluminum industries are all significant contributors to U.S. GHG emissions. The production of iron and steel (which is predominantly iron) are responsible for process-related CO_2 and CH_4 emissions, as well as considerable energy use-related CO_2 emissions. The iron and steel production process is among the four highest GHG-generating industrial processes (along with cement, paper and pulp, fluorinated gases) in the U.S. The iron and steel industry is the only area in which publicly available data on GHG mitigation strategies were found for incorporation in this section.

The iron-making process has seen considerable energy intensity improvements over the past several decades. From the 1960s to the 1990s, the energy intensity (energy per tonne steel production) improved by 27% and GHG intensity (in CO_2 per tonne steel production) reduced by 39% (Worrell et al.., 1999). In addition, there appears to be considerable potential for GHG reductions within the industry. Several steel and steel-intensive companies, including Baltimore Aircoil, Steelcase, and U.S. Steel, have voluntarily pledged to reduce their GHG emissions impacts.

Worrell et al. (1999) assess fifty-seven available technologies in the iron production process and those technologies' associated energy, GHG, and cost implications. Data from that study are adapted for use here, and these data are shown as a cost effectiveness curve in Figure 46 and are reductions from the reference trend line in Figure 47.

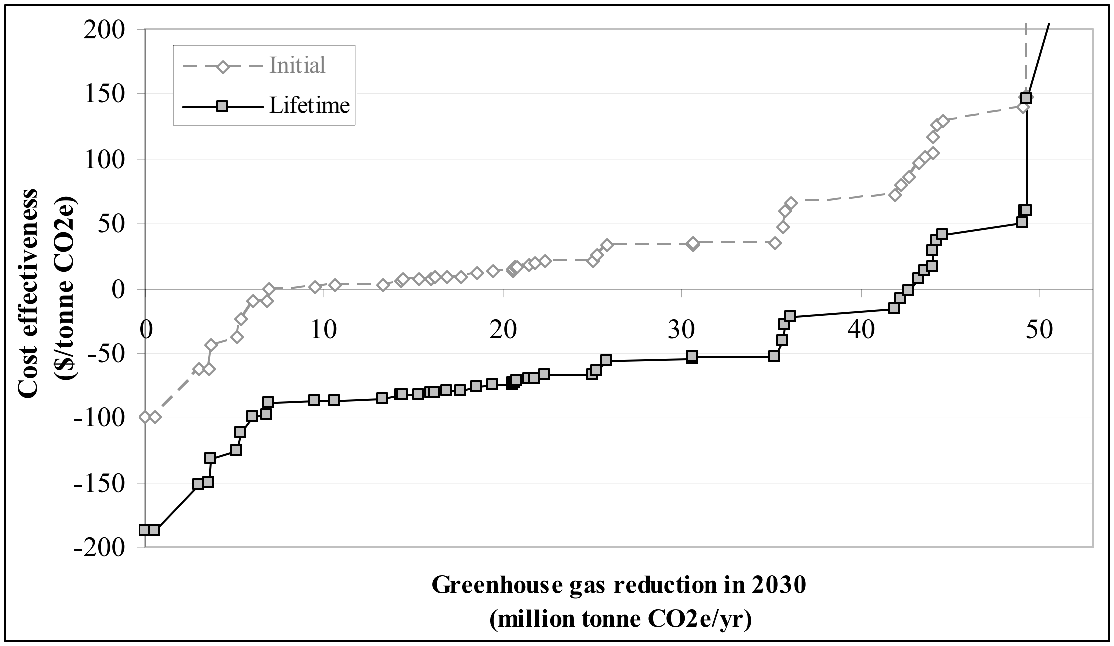


Figure 46. Cost effectiveness curve for iron and steel production

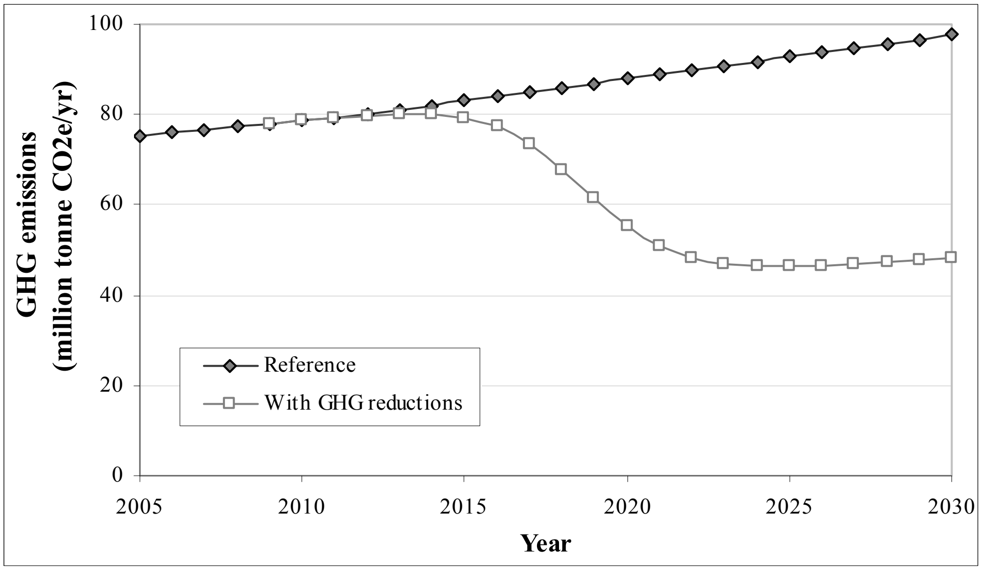


Figure 47. GHG emissions and GHG reduction technologies for iron and steel production

6.4. Combined Heat and Power

The use of combined heat and power (CHP), or cogeneration, can offer a more efficient use of the fuel that is used to produce electricity by using unutilized thermal energy to perform work near an electricity-generating unit. The thermal energy can be used for heating and cooling, thereby reducing or eliminating the need to have separate boilers and chillers. CHP is most common in industries that have relatively high heating, cooling, or steam needs at the same facility. The most common use of CHP is in the manufacturing industries for pulp and paper, chemicals, and petroleum refining. Other CHP applications include use of heating and cooling lines from power units to provide space heating, water heating, and/or air conditioning in nearby commercial and industrial buildings and various institutions with groups of buildings (e.g. universities, hospitals).

The U.S. is experiencing little growth in CHP, despite considerable growth in other countries. Use of CHP grew from the 1970s to the 1990s in the U.S., but has since stagnated. Current U.S. CHP capacity in the power sector is at approximately 41 GW, roughly 4% of total electricity-generating capacity, and no growth is projected in CHP within the electric sector through 2030 (U.S. EIA, 2008). In addition, CHP capacity in the industrial and commercial sectors in the 1990s was about 40-50 GW (Khrushch,et al., 1999). Many institutional barriers to the wider use of CHP have been cited (Kaarsberg and Elliot, 2001), and several states are attempting to ease these barriers with various initiatives in deregulation, incentives, and statutes (Brown and Elliot, 2003).

There are several signs of potential growth in CHP in upcoming years. The U.S. DOE "CHP Challenge," U.S. EPA "CHP Partnership," and the private U.S. CHP Association are each working to increase the use of CHP in the U.S. economy. The U.S. DOE CHP Challenge target is aimed at doubling the installed CHP capacity from 46 GW in 1998 to 92 GW in 2010. European nations routinely target CHP growth as a key contributor in GHG reduction plans. The EU-25 nations' have set a target of 18% of total electricity production from CHP, which would double their 2000 percentage of 9% (CEC, 2000).

Several groups have estimated the available capacity for, and the potential energy and emissions saving from, the increased use of CHP technology. One study that examined the potential for smaller (<50 MW) CHP systems in the U.S. found that there is potential for at least 22 GW of increased installed CHP capacity with a 6-year or less payback period, and the strongest candidate industries are chemicals, metals, paper, food (RDC, 2003). Another study found that at least 25 GW of CHP capacity was cost-effective in the chemicals industry alone, and another 13 GW in the pulp and paper industry. There are additional CHP expansion opportunities in the commercial sector (e.g., hotels, hospitals, large office buildings).

A portion of the U.S. DOE *Scenarios for a Clean Energy Future* study assessed the technical potential for CHP for industrial uses in its "advanced" scenario to be 76 GW, respectively by the year 2020 (Lemar, 2001). Another study had similar findings whereby industrial CHP could cost-effectively utilize 62 GW of CHP capacity by 2020 (Elliot and Spurr, 1999). Data from those two studies' costs and impacts are adapted here and the key characteristics are summarized in Table 27. Based on those results, the addition of 69 GW of CHP capacity would reduce GHG emissions by 138 million CO_2e per year, or an 8% decrease in annual industrial GHG emissions by 2020 (shown in Figure 48). With initial cost accounting, this GHG mitigation action would have a cost-effectiveness value of $20 per tonne CO_2 reduced; using lifetime accounting the cost-effectiveness value would be -$26 per tonne.

Table 27. Potential GHG mitigation from CHP expansion

Study based on	Addition. CHP capacity (GW)	Initial cost ($/kW)	Electricity displaced (TWh/yr)	Nat. gas net reduction (tBtu/yr)	GHG reduction (million tonne CO$_2$e/yr)	Initial cost-effect. ($2008/tonne CO$_2$e)	Lifetime cost-effect. ($2008/tonne CO$_2$e)
Lemar, 2001	76,200	600	501	2,337	157	18	-34
Elliot and Spurr, 1999	62,000	650	396	1,931	120	21	-18
Average	69,100				138	20	-26

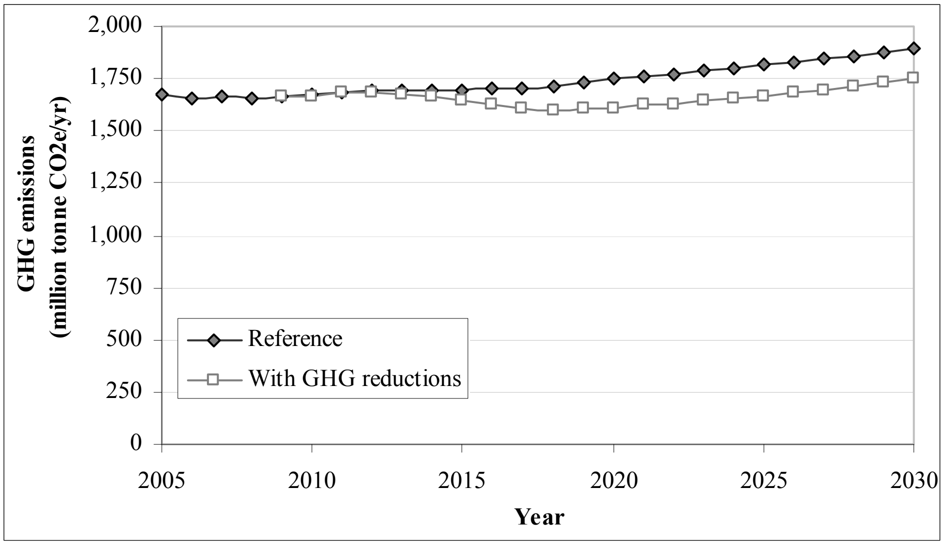


Figure 48. GHG emissions from industry energy use and with GHG emission reductions from CHP technology

6.5. Summary of Industry Sector GHG Mitigation Technologies

The following figures summarize the GHG trends and the cost-effectiveness values of deploying the above industry sector GHG mitigation technologies into residential and commercial buildings. Figure 49 shows the GHG trends of all of the building GHG mitigation technologies that have lifetime cost-effectiveness values at or below $50 per tonne CO$_2$. Figure 50 shows the combined cost effectiveness curve, after including the technology measures from the cement, paper and pulp, high-GWP, landfill, steel and iron, and CHP sections.

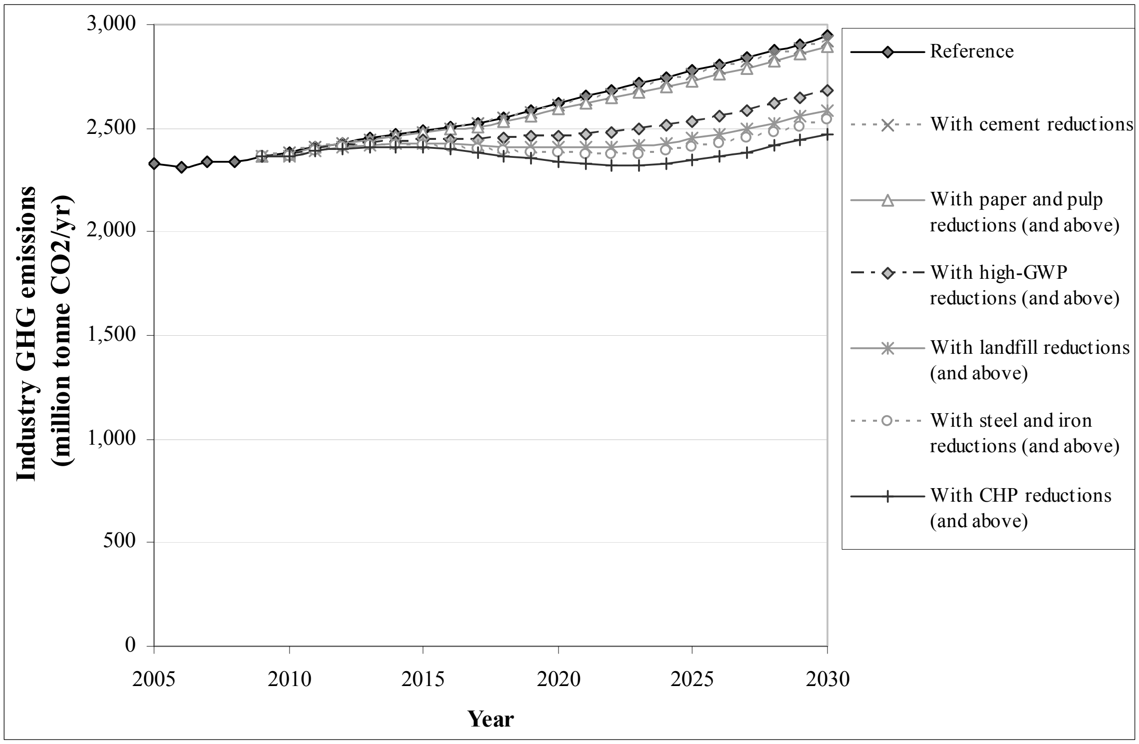


Figure 49. GHG emissions from industry sector with GHG reduction technologies

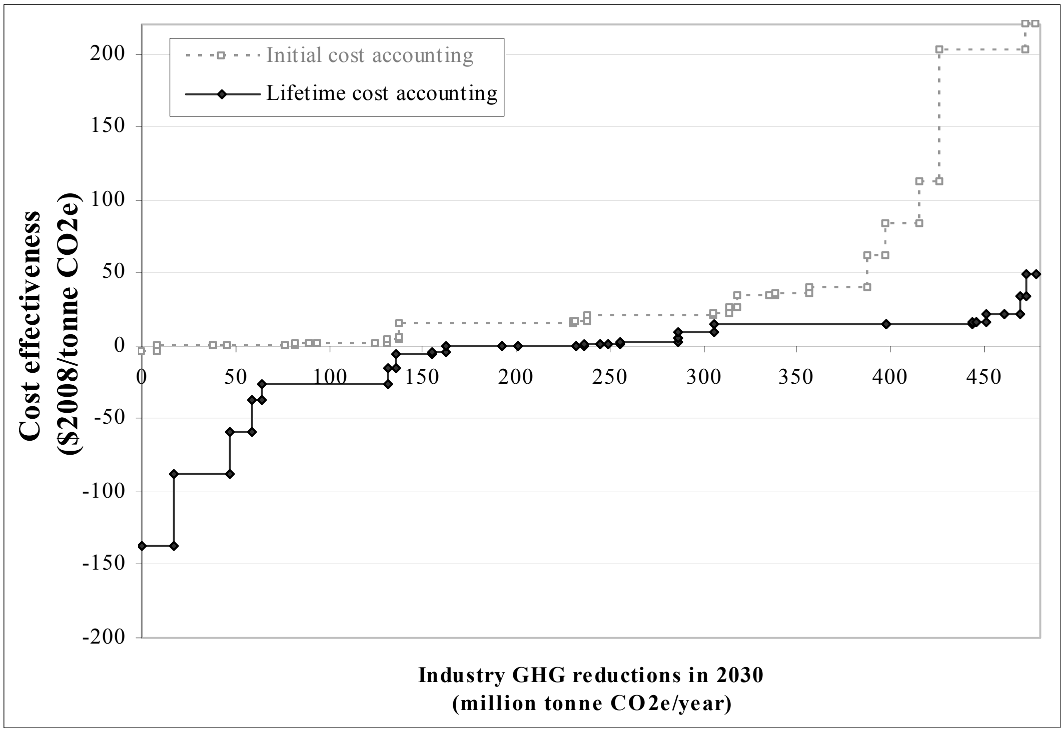


Figure 50. Cost effectiveness curve for GHG mitigation technologies for industry

7. ENERGY PRODUCTION

The vast majority of anthropogenic GHG emissions are associated with energy use, via the extraction, processing, refining, transport, and distribution of fossil fuels into useful energy products such as natural gas, petroleum, heating, and electricity. In this section, potential GHG reduction measures in energy production processes are assessed. The section is split into two parts: (1) fuel feedstock-related emission mitigation actions associated with natural gas wells, petroleum, and coalbeds, (2) technologies that mitigate carbon dioxide emissions from electricity generation.

7.1. Fuel Feedstock

Emissions of methane result from the mining and retrieval of fossil fuels. Due to biological and geological forces surrounding fossil fuel deposits, methane can be deposited in and around coal mines and petroleum wells. The extraction of coal and petroleum, without precautions to manage the release of such emissions, results in a release of methane to the atmosphere. Likewise with natural gas mining and transport, there is potential leakage of methane (the dominant gas within natural gas) at all parts of the gas delivery system.

There are two voluntary U.S. EPA programs that aim at brining about methane emission reductions from fossil fuel feedstocks: (1) the Coalbed Methane Outreach Program, which works with coal and natural gas industries to collect and use methane that is released during mining, and (2) Natural Gas STAR Program, which works with the companies that produce, transmit, and distribute natural gas to reduce leaks and losses of methane.

Nonetheless, the escape of methane through fossil fuel delivery systems is projected to continue increasing along with fossil fuel usage. There is considerable research conducted by and for the U.S. EPA to assess these emissions and potential technologies to mitigate them (U.S. EPA, 2006b; U.S. EPA, 1999). This study adapts data from the ongoing U.S. EPA research on GHG mitigation from coal, petroleum, and coal processes (see U.S. EPA, 2003b).

Technologies for GHG reduction in fossil fuel feedstock systems are shown in Table 28. The majority of the measures relate the to natural gas delivery system, where shoring up the amount of gas leakage keeps more of the salable gas in the system. As a result, many of these GHG mitigation reductions are net beneficial due to the additional recovered methane outweighing the additional capital cost of the technologies. These mitigation measures are shown as a marginal cost effectiveness curve in Figure 51. The result of all the emission reduction technologies that are at or below \$50 per tonne CO_2 reduction (lifetime cost accounting) on overall fossil fuel feedstock system GHG emissions is shown in Figure 52.

Table 28. Fuel feedstock GHG reduction measures

Category	Technology	Initial cost effectiveness ($2008/tCO$_2$e)	Lifetime cost effectiveness ($2008/tCO$_2$e)	GHG emission reduction in 2030 (million tonne CO$_2$e)
Natural gas	Dry Seals on Centrifugal Compressors (P&T)	118.77	-32.1	3.72
Natural gas	Fuel Gas Retrofit for Blowdown Valve	2.38	-24.1	2.57
Natural gas	Reducing the Glycol Circulation Rates in Dehydrators (P&T)	0.00	-22.8	0.16
Natural gas	Reducing the Glycol Circulation Rates in Dehydrators (Production)	0.00	-18.7	0.55
Natural gas	P&T-D I&M (Compressor Stations)	0.70	-18.7	0.52
Natural gas	P&T-D I&M (Compressor Stations: Enhanced)	0.50	-16.7	0.57
Natural gas	P&T - Compressors-Altering Start-Up Procedure during Maintenance	0.00	-13.6	0.15
Natural gas	Replace high-bleed pneumatic devices with low-bleed pneumatic devices (Production)	17.21	-12.5	8.48
Natural gas	Replace high-bleed pneumatic devices with low-bleed pneumatic devices (P&T)	17.21	-12.5	1.82
Natural gas	D-D I&M (Distribution)	5.99	-9.0	2.76
Coal	Degasification and Pipeline Injection	6.94	-2.4	36.11
Coal	Enhanced Degasification, Gas Enrichment, and Pipeline Injection	26.44	3.1	12.67
Natural gas	Installation of Flash Tank Separators (P&T)	40.04	3.2	0.22
Natural gas	Electronic Monitoring at Large Surface Facilities (D)	34.48	7.6	6.22
Oil	Associated Gas (vented) Mix with Other Options	68.19	12.9	2.06
Coal	Catalytic Oxidation (US)	55.92	13.4	14.28
Oil	Flaring instead of Venting (Onshore)	40.91	17.1	0.45
Oil	Associated Gas (flared) Mix with Other Options	81.83	21.5	1.30
Natural gas	Static-Pacs on reciprocating compressors (P&T)	17.91	33.3	0.47
Natural gas	D-D I&M (Enhanced: Distribution)	25.97	61.7	5.14
Natural gas	Installation of Flash Tank Separators (Production)	124.05	65.4	3.76
Natural gas	Catalytic Converter (P&T)	112.35	65.6	3.77
Natural gas	Prod-D I&M (Offshore)	56.28	72.0	0.37
Natural gas	P&T - Use gas turbines instead of reciprocating engines	204.56	88.5	7.11

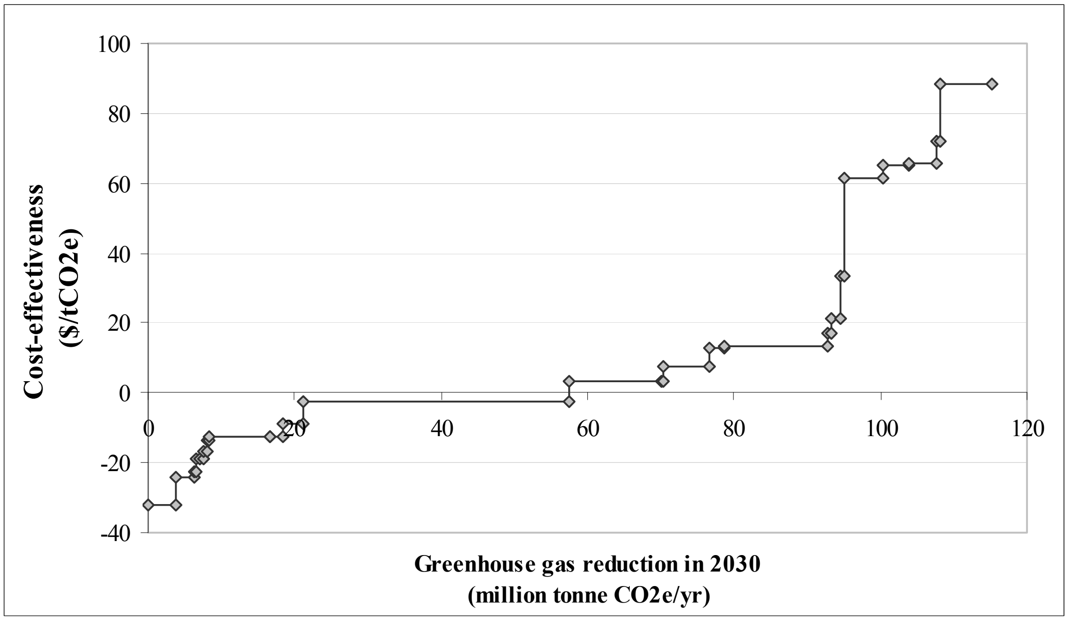


Figure 51. Cost effectiveness curve for fuel feedstock GHG reduction technologies

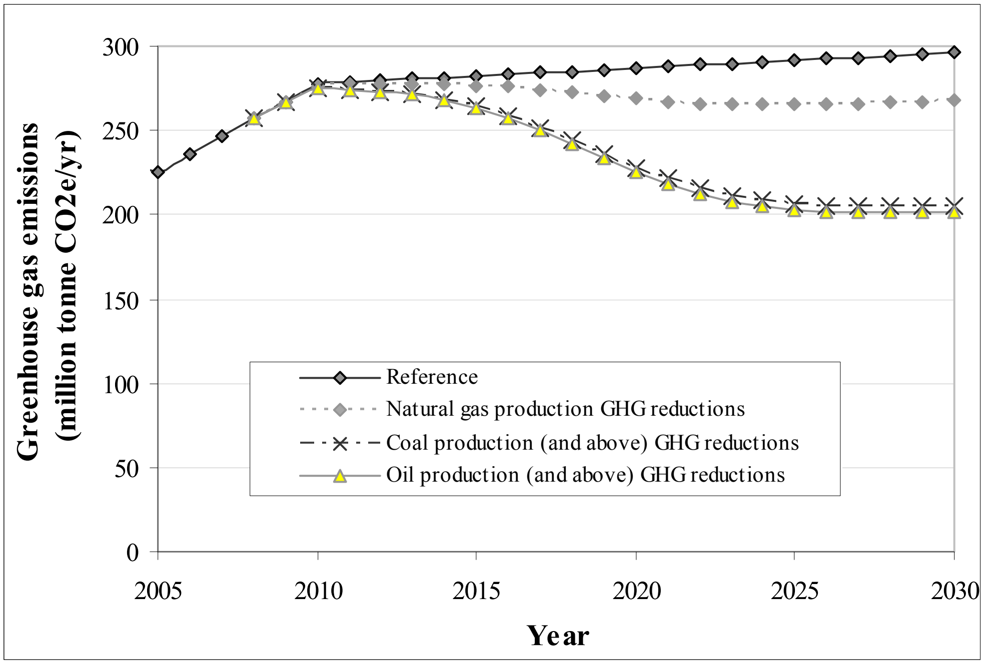


Figure 52. GHG emissions for fuel feedstock systems

7.2. Electricity Generation

Electricity generation accounts for a large amount – approximately 40% – of total U.S. GHG emissions. There are numerous potential technologies and regulatory initiatives that are targeted at reducing these electricity generation emissions by reducing the average GHG intensity (CO_2-per-kWh of generation) of electricity and capturing and sequestering power plant GHG emissions.

The actions of U.S. states give some indication of the electricity-related GHG mitigation technologies that are likely to be implemented over the next few decades. As highlighted in Chapter 2, the state climate change mitigation-related initiatives that affect the electricity-generation business are pervasive and diverse. Two prominent power sector GHG mitigation actions that are directed at electricity generation are establishing (1) greater percentages of electric power from renewable sources, often through renewable portfolio standards, and (2) performance standards that establish a maximum allowable level of GHG emissions per unit of generated electricity. More generally, regional GHG cap-and-trade schemes for utilities that are being explored in northeastern and western states could effectively encourage both of these GHG mitigation actions.

More than half of the states (comprising greater than half of U.S. electricity generation) have targets or mandates for portions of their electricity generation that are to come from renewable electricity sources. The state renewable percentage targets range from 2% up to 30% of the states' electricity, and generally have target years between 2015 and 2020. An electricity generation-weighted average of these measures is a 15% renewable portion of these states' electricity by 2017 (not including conventional large hydroelectric power). The combined national impact of the state measures is equivalent to a 9% national renewable electricity target in 2020 assuming that large conventional hydroelectric power is not included (this equates to 17% total renewable if large hydroelectric is included in the calculation). However, as noted above, many of these are non-binding goals.

Some Northeast states have mandated reductions form older power plants. For example, Massachusetts, as part of its "4-Pollutant" rule in 2001, established a CO_2 emission cap of 818 g CO_2/kWh for fossil fuel power plants to target the state's six highest-emitting plants (with off-site GHG offsets permitted). Some western states, like California and Oregon, have adopted performance standards to make all new baseload generation have GHG emissions-per-unit-generation at or below that of natural gas-powered combined cycle power plants. The most recent federal energy legislation, the *Energy Independence and Security Act of 2007*, did not establish standards for electricity generation GHG emission rates or national level renewable electricity portfolio percentages.

Federal government efforts toward climate change mitigation in the electric power sector have been dominated by voluntary industry efforts and public-private partnerships to share research and development costs on advanced technology. Partnerships involve technology assessment and monitoring, research and development cost-sharing, and collaboration projects ran or administered by the U.S. DOE (e.g., Climate Challenge Program, Power Partners) or the U.S. EPA (e.g., EPA Climate Leaders, Green Power Partnership, CHP

Partnership). These research programs cover technologies such as integrated gasification combined cycle (IGCC) coal plants, carbon capture and sequestration (CCS), and various forms of renewable energy (e.g., solar, geothermal, wind, biomass).

Electricity utility providers are reacting in different ways to the regulatory uncertainty regarding future GHG emission constraints. At least ten major generating companies have committed to some form of voluntary GHG reduction in the 2010 timeframe for their own companies' emissions. Many companies are, assuming some cap-and-trade or regulatory mechanism, including a cost of carbon emissions in their long-term planning goals. A group of major utilities (including Calpine Corp., Consolidated Edison of New York, Entergy, Exelon, PG&E, PSE&G, Sempra Energy, and Northeast Utilities) has formed the Clean Energy Group, which has argued for regulatory certainty and advocated legislation that would mandate a reductions of CO_2 emissions from power plants to 1990 levels by 2008 with further reduction by 2012.

The vast majority of GHG emissions from electric power plants result from the combustion of fossil fuels. U.S. DOE estimates for current through year 2025 electric power generation GHG emissions are roughly 82-87% from coal and 12-19% from natural gas (U.S. EIA, 2008). As such, the two basic strategies in this sector are to minimize the GHG emission per fossil fuel usage and further diversify electricity generation with the increased use of non-fossil fuels, such as nuclear and renewable energy sources.

The electric sector options to reduce GHG emissions have been analyzed for potential mitigation measures by many groups (Tellus, 1997; OTA, 1991; NRC 92; IPCC, 2001; Palmer and Burtaw, 2004; U.S. EIA, 2000; U.S. EIA, 2004; IPCC, 2001). Generally, these assessments of GHG reductions in the electricity sector involve power plant efficiency improvements, shift to lower-carbon fossil fuels, increased renewable fuels, increased nuclear power, and carbon capture and sequestration. These low-GHG electricity technologies, their costs, and their potential GHG reductions are investigated in this section.

This study uses the U.S. Department of Energy's *Annual Energy Outlook 2008* (U.S. EIA, 2008) study as a baseline for current and future electricity generation and emissions. The forecasted U.S. electricity production is shown in Figure 53. Current electricity generation is approximately 50% from coal, 20% from natural gas, 20% from nuclear, 9% from renewable sources. The U.S. EIA data do not explicitly include all of the numerous state-level renewable electricity portfolio initiatives in the national electricity forecast. The total generation is expected to increase at roughly 1.1% per year through 2030, with most new electricity generation additions forecasted by U.S. EIA to be from coal feedstocks. A main assumption for this chapter is that there is no change in end-use electricity demand (e.g., those in Chapter 5) over time from the reference, except those that are built into the U.S. EIA forecast. Note, however, that the end use efficiency mitigation actions from the industry and building chapters are considered concurrently with electricity sector changes in the multi-sector synthesis chapter, Chapter 9.

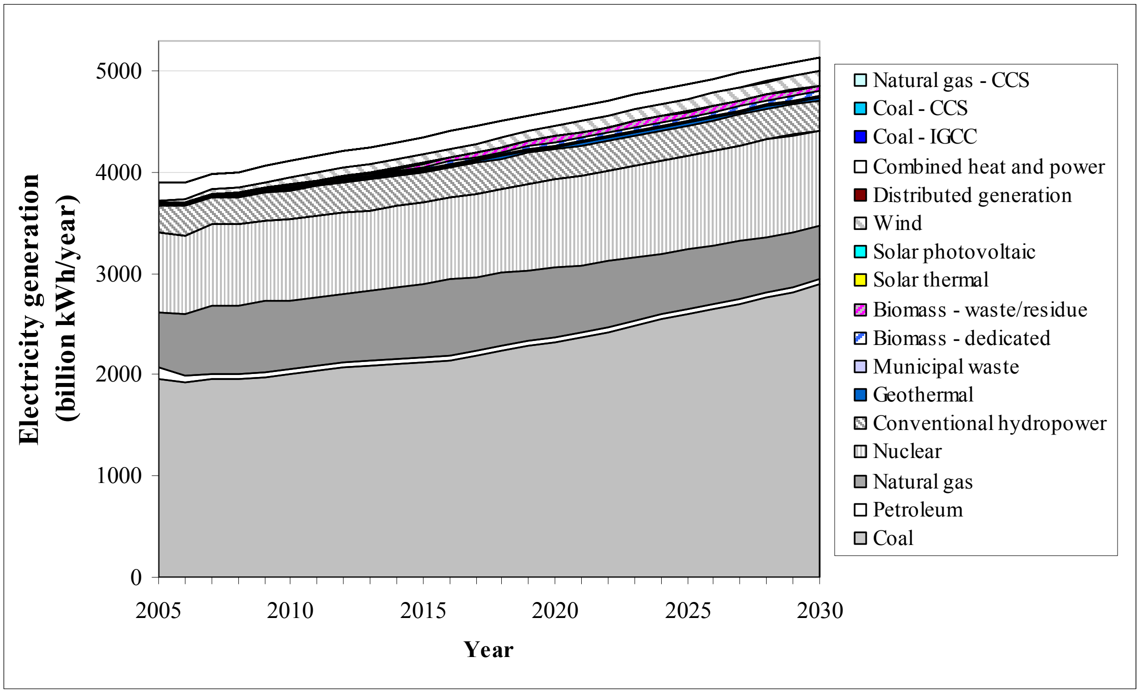


Figure 53. Reference electricity generation by energy source through 2030 (U.S. EIA, 2008)

The abundance and low cost of fossil fuels all but ensure that coal and natural gas will be key feedstocks for decades to come; the U.S. EIA forecast (shown in Figure 53) reflects this in its reference forecast. The three main GHG emission reduction measures available within fossil fuel electricity generation are (1) to shift future projected coal generation increases to natural gas-generating plant, (2) to increase use of advanced coal and natural gas technologies that are more efficient than their older counterparts, and (3) to capture and sequester carbon emissions from coal and natural gas plants.

There is a general incremental decrease in fossil fuel plants' specific GHG emissions (emission per kWh output) due to efficiency improvements in the business-as-usual reference baseline of the U.S. EIA's *AEO 2008*. The technologies considered for GHG mitigation for power plants offer substantially larger GHG reductions than these gradual incremental changes. The advanced fossil fuel-based GHG-reduction efficiency strategies considered here are to expand the use of integrated gasification combined cycle (IGCC) technology for coal and increased use of combined cycle gas turbines (CCGT) technology for natural gas. Both of these technologies offer improvements in efficiency to baseline generation specific GHG emission rates at increased overall electricity generation cost. CCGT has now become the baseline technology used for new plants and applied to state standard-setting as maximum allowable specific GHG emission rate (CO_2-per-kWh) (e.g., State of California, 2006). In 2008, there are two U.S. power plants that employ IGCC technology (and ten total world-wide) and several others are planning stages. IGCC technology, along with reducing the specific GHG emission rate, lowers the cost of sequestering the CO_2 emissions.

In 2008, capture and sequestration of CO_2 emissions from plants is at a pilot project level of development, with at least four industrial-scale projects in operation world-wide and many other proposed projects in the works. With the inevitability of low-cost fossil fuels like coal in future decades, carbon sequestration offers the possibility of extending the use of natural gas and coal for power generation even in a carbon-constrained world. Possible subterranean options for geologic storage of CO_2 are in depleted oil and gas reservoirs, deep saline aquifers, un-mineable coal seams, or deep within oceans. Although there are still a number of concerns over the long-term value of sequestration as a way of mitigating GHG emissions, there is some growing consensus from climate scientists that substantial, reliable GHG reductions should be considered for low-cost carbon reduction opportunities. A CCS plant generally requires about 10-40% greater energy use to capture and compress the CO_2 emissions, and the storage of the emissions results in an overall 80-90% reduction in specific GHG emission rate (IPCC, 2007).

In addition to lower GHG intensity electricity generation, included here are several near-zero GHG emissions technologies, including the use of nuclear and renewable energy sources such as geothermal, solar, and wind. Each of these is sometimes referred to as having no GHG emissions because of their lack of direct point-source CO_2 emissions at those plants. However, each of these technologies does have some GHG footprint due to the energy associated with technologies' plant construction and the production and processing of uranium and other materials. These emissions generally equate to greater than a 95% reduction in CO_2-per-kWh generation as compared to fossil fuel-generated electricity that does not have carbon capture and sequestration. Table 29 shows a summary of this analysis' cost effectiveness evaluations for low-GHG electricity generation technologies. There has been a lot of work by many different researchers in this area of GHG emission reduction options within the power sector. Key summarized findings on specific GHG rate and average cost-per-kWh of generation of that technology and data sources on which the data are based are shown in the table. The last row shows the average future GHG emission rate of coal and natural gas-generated electricity according to U.S. EIA (2008) and the average associated electricity production cost of new coal and natural gas plants from various sources. The cost-effectiveness values are calculated as the incremental cost-per-kWh of the low-GHG technology (as compared to the reference), divided by the CO_2 reduction-per-kWh (as compared to the reference). As applied throughout this dissertation, a 7% real discount rate is applied to the future energy costs and savings). The range in cost-effectiveness estimates reflects the different forecasted costs of the lower-GHG generation technologies.

Table 29. GHG mitigation technologies for electricity generation

Generation technology	GHG intensity (gram CO_2/kWh)	Cost ($2008/ kWh)	Cost effectiveness ($2008/tonne CO_2) [low / mid / high]			Reference technology used as baseline	Data sources based upon
New CC natural gas plant	403	0.047	-23	3.8	47	New coal plant	Rubin et al., 2007; Sims et al., 2003; Meier et al., 2005; IEA/NEA, 2005; Williams, 2001
Nuclear	14	0.050	-12	5.2	21	Average new plant	Williams, 2001; Meier et al., 2005; Weissner 2007; IEA/NEA, 2005
Geothermal	21	0.050	-9.1	5.7	21	Average new plant	Meier et al., 2005; IEA/NEA, 2005; Beurskens et al., 2005; Awerbuch et al., 2005
Wind	20	0.053	-2.6	9.0	21	Average new plant	Norton, 1999; Bergerson, 2005; Meier et al., 2005; Weissner, 2007; IEA/NEA, 2005
Coal IGCC	756	0.046	-77	14	81	New coal plant	Rubin et al., 2007; Sims et al., 2003; IEA/NEA, 2005; Williams, 2001; Sekar et al., 2007
Biomass	52	0.072	17	32	41	Average new plant	Norton, 1999; Mann and Spath, 2002; Meier et al., 2005; Weissner, 2007; IEA/NEA, 2005
Coal CCS	132	0.075	-9.9	42	78	New coal plant	Rubin et al., 2007; Sims et al., 2003; IEA/NEA, 2005; Williams, 2001; Sekar et al., 2007
Natural gas CCS	50	0.066	26	53	112	New natural gas plant	Rubin et al., 2007; Sims et al., 2003; IEA/NEA, 2005; Williams, 2001
Solar thermal	23	0.115	40	81	226	Average new plant	Norton, 1999; Bergerson, 2005; Meier et al., 2005; IEA/NEA, 2005
Solar photovoltaic	62	0.147	85	125	183	Average new plant	Norton, 1999; Meier et al., 2005; Weissner, 2007; IEA/NEA, 2005
Average new plant (fossil, 2030)	875	0.046					US EIA, 2008; Rubin et al., 2007; Sims et al., 2003; IEA/NEA, 2005; Williams, 2001

The GHG intensity and cost of generation from new fossil fuel plants are used as reference baselines for the calculation of the cost-effectiveness values of the GHG mitigation technology shifts. For the expanded use of combined-cycle natural gas generation, the reference of pulverized coal generation is applied, thus making the scenario a "coal-to-gas shift." Coal IGCC and CCS technologies are also compared specifically to their own reference fuel (coal or natural gas) technology (and not the general coal-plus-natural gas mix reference). This assumption follows the logic that the technology decision (IGCC or CCS) comes after the energy source decision (coal or gas), or that governmental planners could permit the construction of coal plant, contingent upon its use of a low-GHG technology (like IGCC or CCS). The other GHG mitigation technologies use a generic weighted coal-and-gas mix as the reference, for it is assumed to be equally likely that these technologies will displace the new construction of either of these types of plants in future years.

Many technologies in Table 29 are nearly cost-competitive with new fossil fuel coal and gas plants. The range of cost-effectiveness values (on the "low" side) reaches below zero for combined cycle gas plants, nuclear, geothermal, wind, coal IGCC, and coal CCS, is an indication that these technologies have some justification for construction independent of any carbon constraints. This assessment makes no effort to show regional cost differences that would promote various power plant types differentially across the U.S. Other technologies with higher, less attractive cost-effectiveness values, such as solar technologies, have much larger error boundaries on account of their more uncertain future costs.

Expanded electricity generation from GHG mitigation technologies is considered here based on literature forecasts and potential growth rates of low-GHG technologies for electricity generation. Somewhat different assumptions are applied to determine varying amounts of capacity expansions by the different technologies. Due to the long lifetimes of existing power plants (30-40 years), the transition to lower-GHG technologies for this sector is slower than for other sectors. As existing (and already planned-for-construction) power plants retire, the U.S. EIA *Annual Energy Outlook* forecasts small expansions in nuclear and renewable sources, with the vast majority of new generation coming from coal and natural gas. The analysis presented here apportions the new demanded generation differently to accommodate more low-GHG technologies than otherwise forecasted.

Figure 54 shows the expanded use of lower GHG technologies in the U.S. electricity generation portfolio for this analysis, as compared with the U.S. EIA (2008) reference forecast. The expansion of the renewable electricity sources through 2030 is set to be greater than the reference baseline, but far lower than the 2003-2007 trends (where 20-40% annual growth rates have been common). Annual wind expansion is set at about 10%, resulting in 78 GW of capacity expansion above the EIA baseline for 2030. Geothermal electricity generation capacity is assumed to increase to about 7 GW over the U.S. EIA reference by 2030, and this expansion equated to an approximate 8% annual growth rate. Annual growth in solar electricity generation technologies were set to about 21% for thermal solar and about 30% for photovoltaic solar, adding an additional 19 GW and 11 GW of capacity, respectively. Nuclear generation is assumed to increase by 20% (or 20 GW of capacity) over the 2030 reference.

These rates of expansion for renewable sources of electricity are supported by existing trends and future regulatory initiatives. The U.S. state-level initiatives (discussed in Chapter 2), generally involve 10-20% annual growth rates in renewable electricity generation. Actual technology growth trends have surpassed these policy targets, with 30-40% annual growth for solar photovoltaic power (Jager-Waldau, 2004) and 26% annual growth for wind turbine power (Junginger et al., 2005).

The impact of the expansion of biomass for electricity generation in this section is tied directly to the impacts on GHG emissions due to land use and agricultural carbon sequestration. The expanded use of biomass here was set to be consistent with the level of biomass production that occurs with given carbon constraints and their overall impact on land use from the next chapter, "Agriculture and Forestry." The expanded biomass production for electricity biofuels for this analysis equates to an additional 13 GW of capacity, a 17% annual growth rate in biomass-related generation through 2030. The biomass includes primarily dedicated energy crops that are used in biomass-specific power plants and in co-firing with coal in coal plants. This amount of generation was fueled by half of the agriculture biofuels production produced for under \$50/tonne CO_2, as will be discussed in the Agriculture chapter below; the other half of the biomass is diverted to transportation fuels.

After factoring in those growth rates for renewable and nuclear power sources, the remainder of reference electricity demand was met by coal and natural gas technologies. Existing fossil fuel plants are phased out using a logistical function from 2008 through 2040. All new coal generation was to be with one of the discussed lower-GHG technologies. The apportionment of new coal generation was two-thirds to IGCC (without sequestration) and one-third to CCS technology. Half of the new natural gas generation was apportioned each to new combined cycle plant and CCS technology. This apportionment of electricity generation is clearly speculative; however, detailed cost curves for supply of each of the discussed technologies are not available, and dynamic dispatch modeling of the technologies in a competitive market is outside the scope of this analysis.

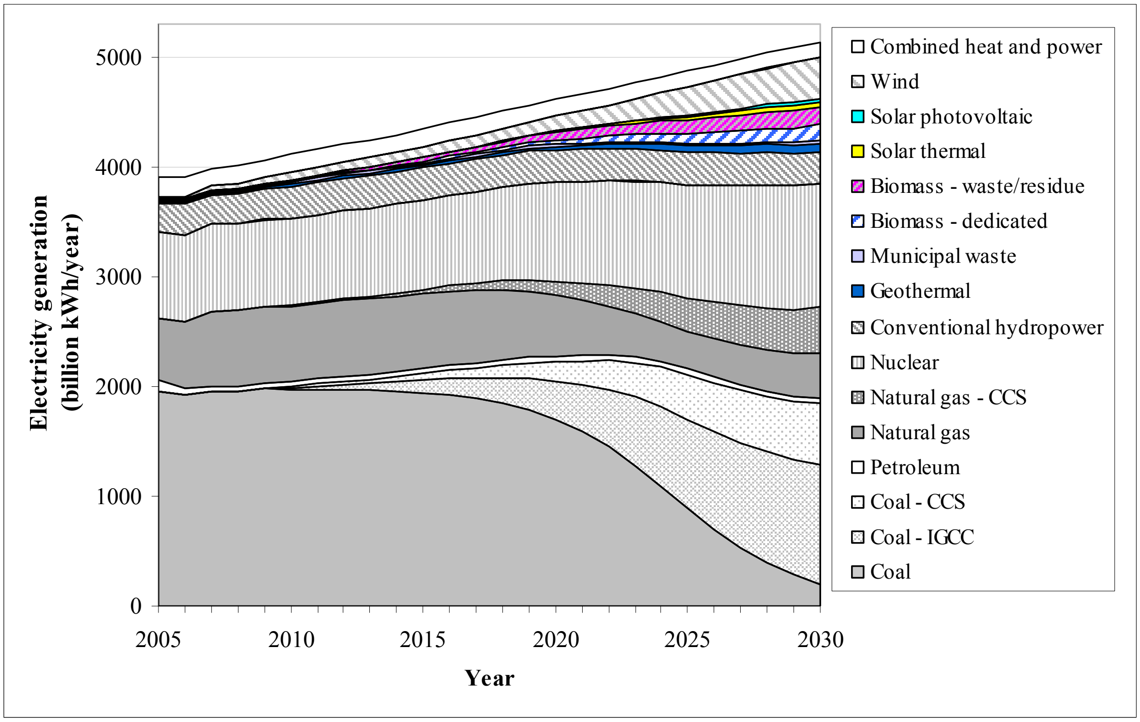


Figure 54. Electricity generation by energy source with expanded use of lower GHG emission technologies

The specified penetration of lower GHG generation technologies in this research analysis results in significant overall shifts in technologies. The reference percentage of generation that comes from renewable energy sources (hydroelectric, solar, geothermal, biomass, waste, and wind) in 2010 is about 9%. The U.S. EIA forecast for year 2030 is 11% renewable. This scenario in this analysis results in 23% of U.S. generation from these renewable sources by 2030. The expanded nuclear generation results in an increase from the reference 18% in 2030 to 22% in this scenario. The level of generation that has CCS technology (including from coal and natural gas) for this analysis represents 19% of all generation and 35% of fossil fuel generation by 2030.

Figure 55 shows the impact of the expansion of the low-GHG technologies for electricity generation's specific GHG rate (in g CO_2/kWh, equivalent to kg CO_2/MWh). The top line shows the U.S. EIA reference GHG emission rate, based on its forecasted mix of electricity generation technologies. Each successive line going down in the figure applies the expansion in the use of one GHG-reduction technology, in increasing order of their average estimated cost-effectiveness values from Table 29. This GHG emission rate, with the full deployment of the ten GHG-reduction technologies, approximately halves the average U.S. specific GHG rate in 2030 from the reference 611 to 324 gram CO_2 per kWh.

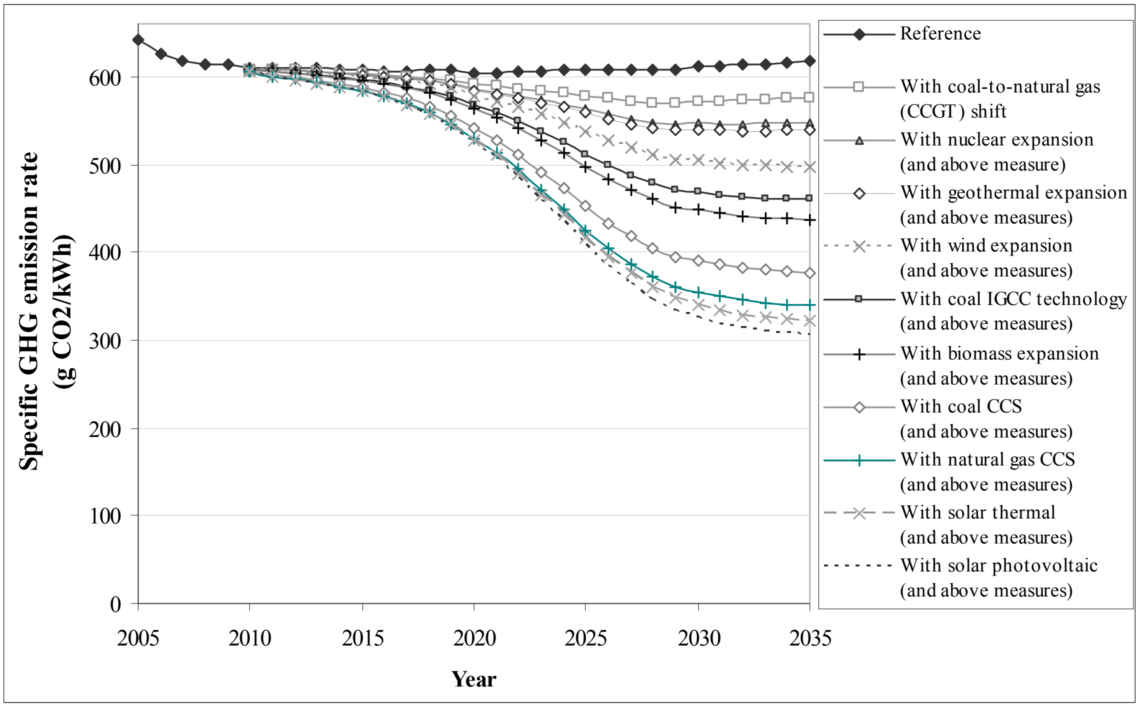


Figure 55. Specific GHG emission rate of electricity generation with expanded use of lower GHG emission technologies

The result of the deployment of lower-GHG electricity generation into the generation grid to meet the forecasted electricity demand is shown in Figure 56. The result of the full deployment GHG-reduction technologies cuts overall GHG emissions approximately in half for 2030 and beyond. The 2030 level of GHG emissions from electricity generation is approximately 32% below the 2008 level and 17% below the 1990 level (assuming no change in the electricity demand from the U.S. EIA forecasted levels). After combining the results from the cost-effectiveness value from Table 29 and the total 2030 GHG reductions of Figure 56, the resulting marginal cost-effectiveness curve is shown in Figure 57.

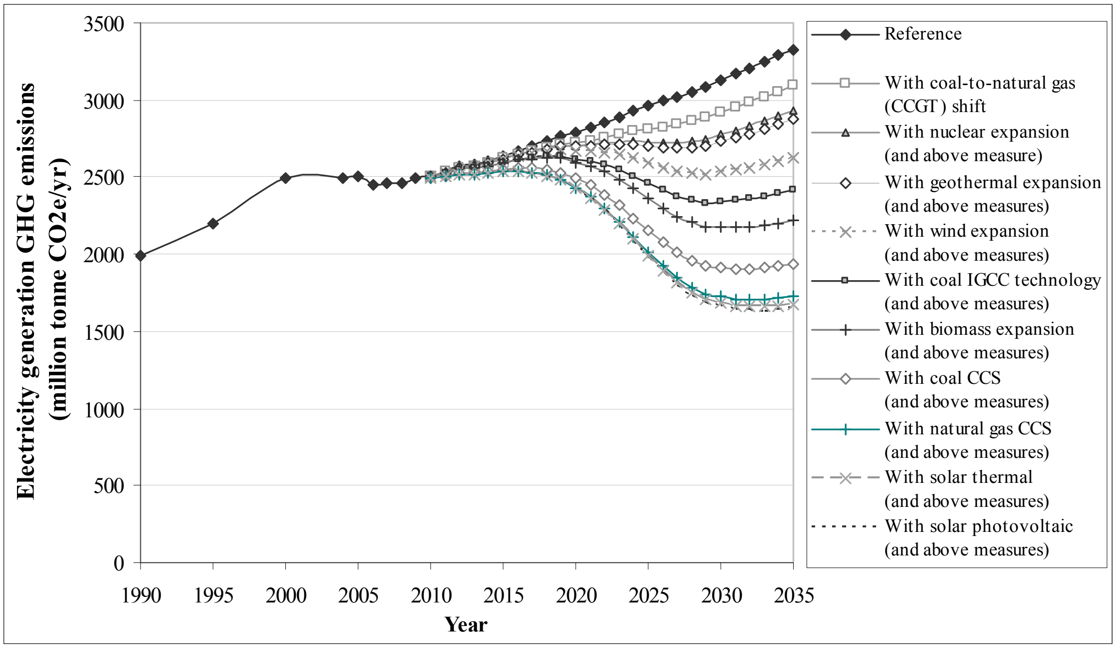


Figure 56. GHG emissions from electricity generation with expanded use of GHG mitigation technologies

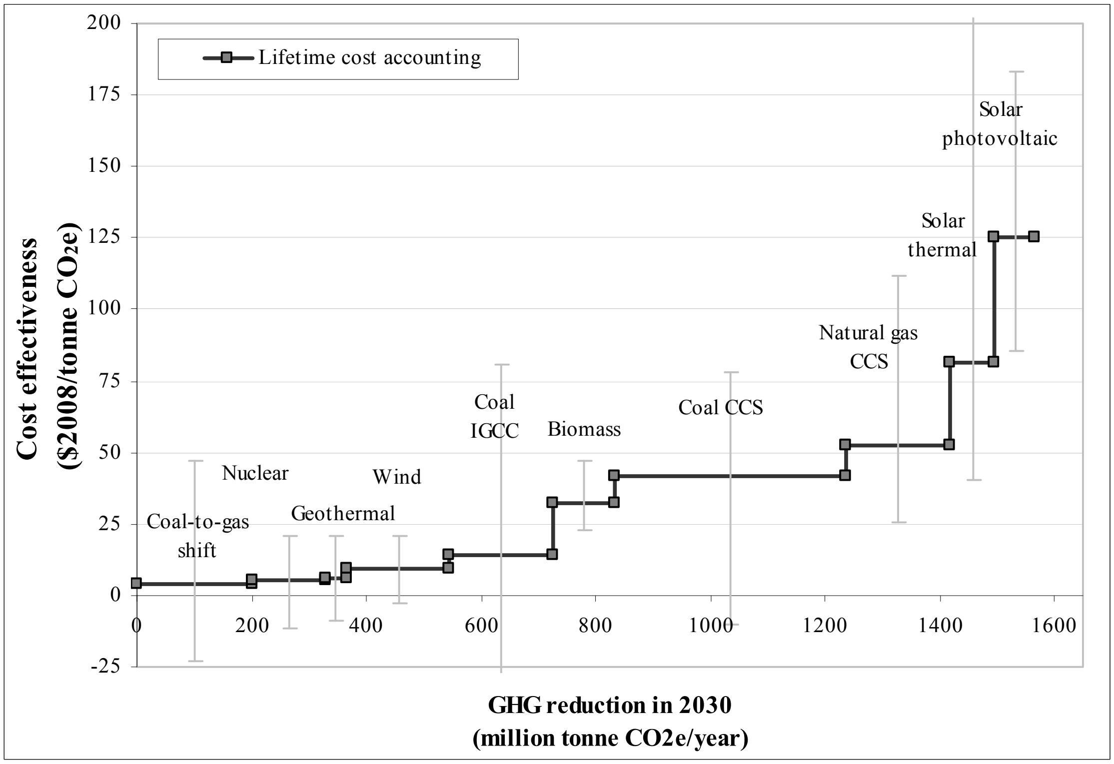


Figure 57. Cost effectiveness curve for GHG mitigation technologies in electricity generation

8. AGRICULTURE AND FORESTRY

The agriculture sector in the U.S. impacts GHG emissions in numerous ways. The growth of biofuel feedstocks has the potential to displace fossil fuel feedstock for transportation fuels and electricity primary energy, as is shown in Chapters 4 and 7 above. Agricultural practices more directly impact GHG emissions in several other ways, including, for example, impacts on the amount of carbon that is sequestered in soils and biomass, methane emissions from livestock systems, and nitrogen emissions related to fertilizer practices.

This Chapter investigates agricultural GHG impacts and potential GHG mitigation measures, including shifts in crop and livestock management practices that impact nitrous oxide and methane emissions, the sequestration of carbon in soil, and forestry-based carbon sequestration. According to U.S. EPA’s 2007 inventory, crop and livestock practices that are responsible for CH_4 and N_2O emissions result in about 8% of U.S. GHG emissions; in addition, the overall carbon sequestration due to land use, land use change, and forestry equate to about 11-16% of the U.S. GHG emissions total (U.S. EPA, 2007b; U.S. DOS, 2007). Due to these factors – and the ability to also influence fuel use in other sectors – the agricultural sector is a potentially important factor in U.S. GHG emissions mitigation policy.

The total effects of efforts to address the different GHG mitigation categories within the agricultural sector are often highly interdependent upon each other. Interdependent factors can be either competitive or complementary. Land use types that impact GHG emissions like farming (for food or biofuel feedstocks) and forestry are in competition for land; therefore the evaluation of carbon sequestration in either land type for GHG mitigation purposes would optimally be done together. On the other hand, agricultural GHG mitigation practices can be complimentary in that soil carbon sequestration practices can reduce fossil fuel and nitrogenous fertilizer inputs while also enhancing agricultural activity. Due to such interdependencies, an aggregated approach is warranted if not necessary to reduce potential uncertainty and double-counting in the assessment of the multiple agriculture sector measures (McCarl and Schneider, 2001). Therefore, care is taken in this analysis to exclusively apply aggregated mitigation measures.

Research that investigates multiple agriculture-based changes for GHG mitigation simultaneously, or in an aggregated fashion, is complicated by many factors regarding the heterogeneity and interdependencies in agricultural systems (McCarl and Schneider, 2001). The heterogeneity between soils, climate conditions, land management history each make for different GHG mitigation potential for different fields. Estimating the GHG mitigation potential is reliant upon an accounting for interdependencies between crop choices, tillage practices, livestock and manure management practices, fertilizer use, irrigation, and varying land use types (e.g. forest, crops, energy crops). As a result, this analysis primarily relies on one particular study done by the U.S. EPA (2005), *Greenhouse Gas Mitigation Potential in the U.S. Forestry and Agriculture,* which reviews and builds upon the previous analytical work, and thus minimizes the potential limitations regarding interdependencies of GHG mitigation options within the agricultural and forestry sector.

8.1. Livestock and Soil Management

This section looks at agricultural practices that impact non-carbon GHG emissions of N_2O and CH_4. Figure 58 shows the breakdown of all of these non-carbon emissions from agriculture (based on U.S. EPA, 2007b, U.S. DOS, 2007). The vast majority (i.e., 93%) of these emissions results from three activities: agricultural soil management N_2O emissions (66%), enteric fermentation emissions of CH_4 (20%), and manure management that results in CH_4 emissions (7%). This section focuses on the GHG mitigation potential in these three areas.

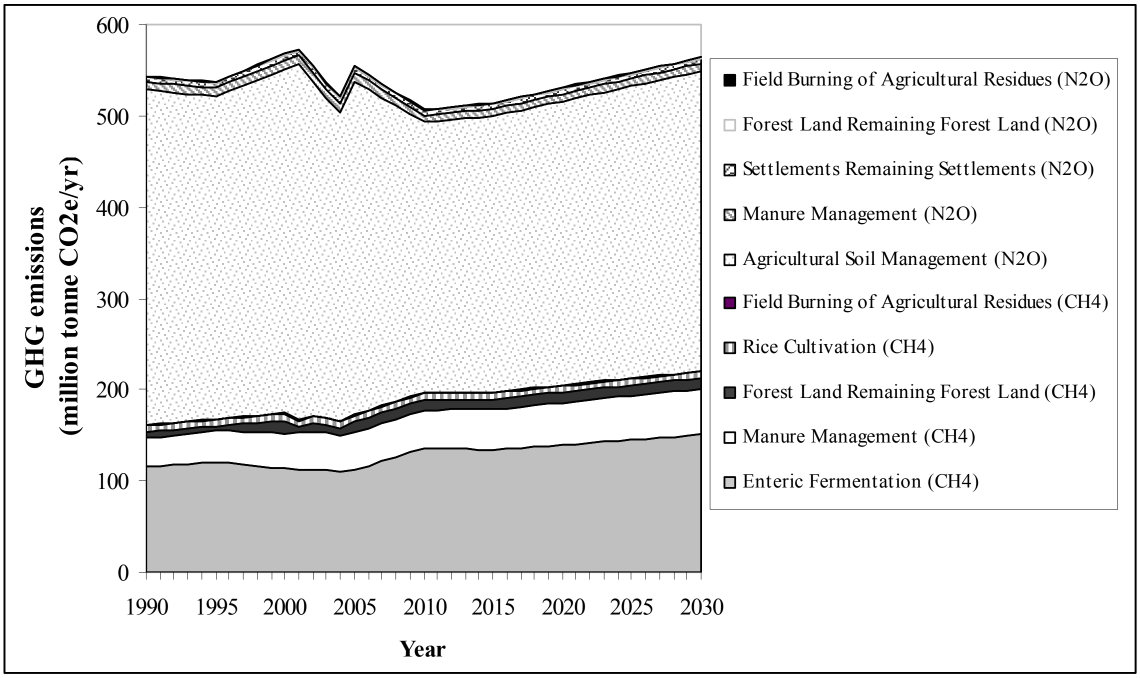


Figure 58. Agricultural non-carbon GHG emissions

Anthropogenic methane emissions are predominantly a result of decomposition of biomass from agricultural livestock systems. Livestock systems result in methane emission in two ways: enteric fermentation and anaerobic digestion of manure. Enteric fermentation is the microbial breakdown of feed within the digestion system of ruminant livestock, predominantly bovines such as cows. Methane is a byproduct of fermentation in the livestock digestion process and is expelled from cattle via belching. The second cause of methane emissions from livestock is from the management of the livestock manure. Cattle, swine, and poultry manure, when it decomposes under anaerobic (i.e., without oxygen) conditions, results in methane emissions.

Two prominent U.S. EPA programs in the agricultural sector target methane emissions from animal waste and livestock feed. The Ruminant Livestock Efficiency Program (RLEP) seeks to reduce methane emission reductions via improved grazing management, additions of soil amendments, supplementation of cattle diets with nutrients, and improved genetics (U.S. EPA, 2008b). The second program, called AgSTAR, works with livestock producers to help in the digestion of manure and the recovery of methane from animal waste for possible use in producing heat and/or electricity (U.S. EPA, 2008c). In addition, private industry outside the agricultural sector has identified manure management for its GHG reduction benefits. For example, the California utility Pacific Gas & Electric has utilized manure management for it ClimateSmart program to offset its customers' GHG emissions (PG&E, 2008)

Using several U.S. EPA sources (U.S. EPA 1999, 2003, 2005) and data from McCarl and Schneider (2003), marginal cost-effectiveness GHG abatement curves are constructed in Figure 59. Although the studies' methods differ, the results are reasonably consistent with one another. As mentioned above use the U.S. EPA (2005) results are used for this agriculture chapter due to that analysis' updated treatment of available research data and its inclusion of aggregated effects of GHG policy on multiple portions of agricultural sector. Also note that, in the figure, individual measures are not shown on the plot because multiple measures (e.g., crop tillage, manure management changes) exist at each cost-effectiveness value. The strategies of most importance in this area are reduced nitrogen fertilization and manure and grazing management changes, including the digestion of cattle and swine manure for energy recovery.

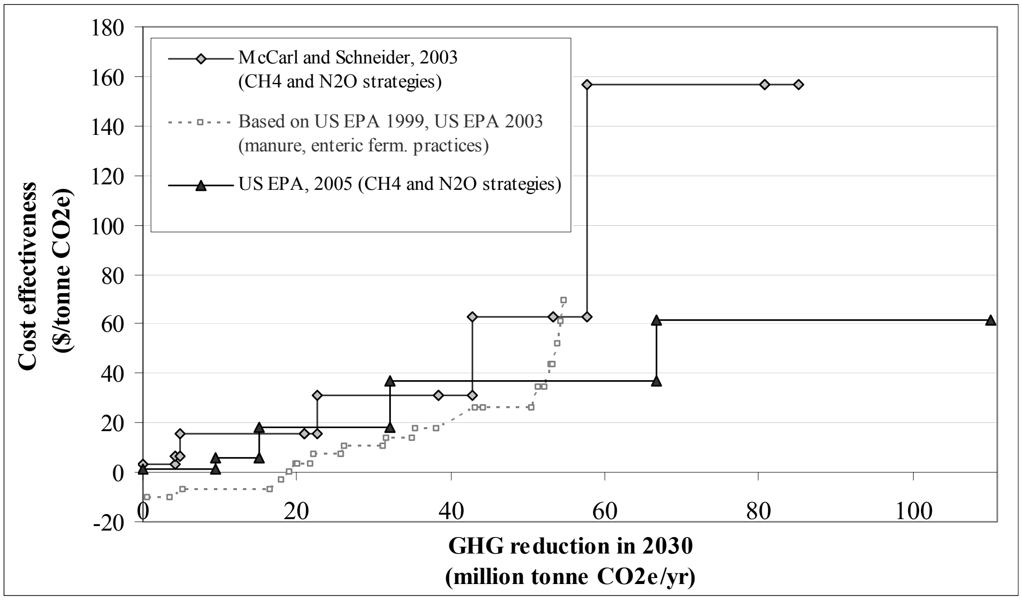


Figure 59. Cost effectiveness curve for non-carbon agricultural measures

Applying the CH_4 and N_2O reduction measures from U.S. EPA (2005) that are below $50 per tonne CO_2e and phased into agriculture sector from year 2010 on, the resulting trendlines are shown in Figure 60. The reductions - of about 66 million tonne CO_2e per year from 2020 on – result in an approximate 12% reduction in non-carbon GHG emissions from this part of the agricultural sector.

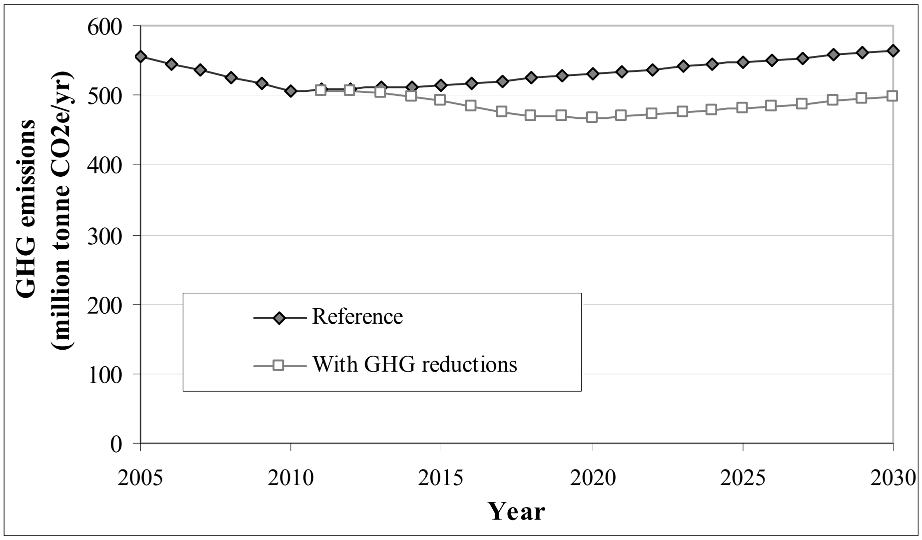


Figure 60. Agricultural non-carbon GHG emissions

8.2. Land Use Changes

Forests and agricultural soils are responsible for the sequestration of large amounts of CO_2 from the atmosphere on an annual basis. Organic matter fixes atmospheric CO_2 into carbon at different carbon flux rates depending on type of land (i.e. cropland, grassland, forest), the type of vegetation, soil properties, the maturity of the land in that form, and the management of that land (whether vegetation growth is harvested, tillage practices for agricultural soils). Official sources estimated that U.S. land use "sinks" were responsible for sequestering approximately 780-824 million tonne CO_2 per year – or about 11-16% of the net annually emitting U.S. GHG emissions in 2004 (U.S. EPA, 2007b; U.S. DOS, 2007).

Potential land use change for GHG mitigation fall into four main areas: soil carbon sequestration, biomass harvesting, forest management, and afforestation. Soil carbon sequestration can be impacted to reduce GHG emissions by switching from conventional to no-till crop management, changing fields' crop mixes to ones with higher carbon fixing rates, fertilization changes that prevent carbon from being leached from the soil, and conversion of agricultural land to grassland. Biofuel production of ethanol as a fuel for vehicles or biomass for power plants can sequester atmospheric carbon and offset the release of carbon from fossil fuel burning in the transportation and electricity generation sectors.

Forest management practices that can lead to GHG reductions include increasing forest management intensity, forest preservation, and avoided deforestation. Finally, afforestation refers to converting agricultural lands to forest. Each of these areas has a large amount of research and data on their potential impacts and costs. These land use practices (and their literatures) are summarized and analyzed in U.S. EPA (2005).

As noted above, changes in agriculture and forestry are highly interdependent, as increases in one land use type can cause increases or decreases elsewhere, and all land use changes are tied to some extent to food and commodity prices. Several recent studies of biofuel production pointed out the importance of such issues in assessing the fully life-cycle effects of changing land uses (Delucchi, 2004, 2006; Searchinger et al., 2008; Fangione et al., 2008). In addition, many land-based carbon sequestration practices for soils (though, e.g., no-till practices) and forests have characteristic saturation points where by their carbon-fixing flux, after a certain amount of years, diminishes. As such, the GHG cycle of land-based GHG measures must account for full cycle of forests over decades and report results on average annualized levels of GHG mitigation.

Several studies, e.g. McCarl and Schneider, 2001, have accounted for such factors. For this analysis and cost-effectiveness curve estimation, the data of U.S. EPA, 2005 are used. This was a more recent study that accounts for the issues in the literature and compares its own findings for consistency with results in the literature. The U.S. EPA study results for potential mitigation are shown in Table 30, with its data converted into 2008 dollars.

Table 30. GHG reduction for given price of CO_2 reduction for agricultural land use changes

	GHG reduction (million tonne CO_2e/year) for a given cost-effectiveness (\$2008/tCO_2) [a]				
	1.2	6.1	18.4	36.9	61.4
Afforestation	0	2.3	137	435	823
Forest management	24.8	105.1	219	314	385
Agricultural soil carbon sequestration	62	122.7	168	162	131
Biofuel offsets	0	0.1	57	375	561
All	87	230	582	1,286	1,900

[a] *Based on US EPA (2005)*

The results are shown as a marginal cost-effectiveness curve in Figure 61. Note, as above, that the U.S. EPA (2005) data is applied for this dissertation's analysis because the dataset was the most inclusive of all measures and state-of-the-art in addressing the known complexities in assessing GHG mitigation potential in agriculture and forestry systems. Also note that, in the figure, individual measures are not shown on the plot because multiple measures (e.g., crop tillage, manure management changes) exist at each cost-effectiveness value.

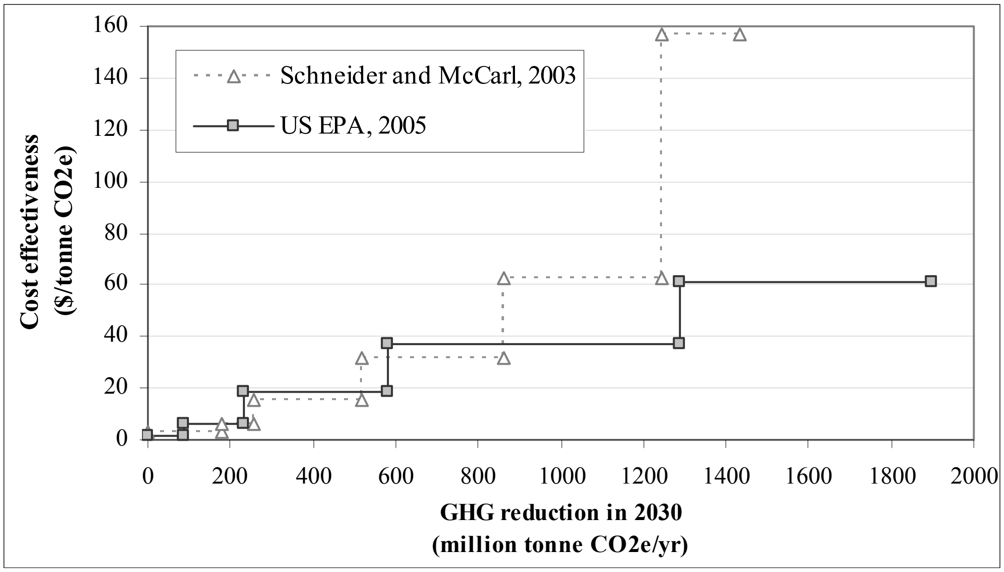


Figure 61. Cost effectiveness curve for agricultural land use changes

8.3. Summary of Agriculture and Forestry Sector GHG Mitigation Technologies

The following figures summarize the GHG trends and the cost-effectiveness values of the above agriculture sector GHG mitigation strategies. Figure 62 shows the reference data for the net greenhouse gas impacts agricultural practices in the U.S. (including livestock and soil management and carbon sequestration that occur due to land, land use changes, and forestry). As shown, the values in the figure are negative, due to the agriculture and forestry sector's fixing of carbon from the atmosphere having a net sequestration impact. The timing and scale of the implementation of the GHG mitigation practices are based upon the partial equilibrium modeling of U.S. EPA 2005, the same research on which the GHG migration potentials are based. Also shown in the figure is the impact of all of the measures from U.S. EPA (2005) that are below $50 per tonne CO_2, eventually resulting in an annual average reduction of GHG emissions by approximately 1300 million tonne CO_2e.

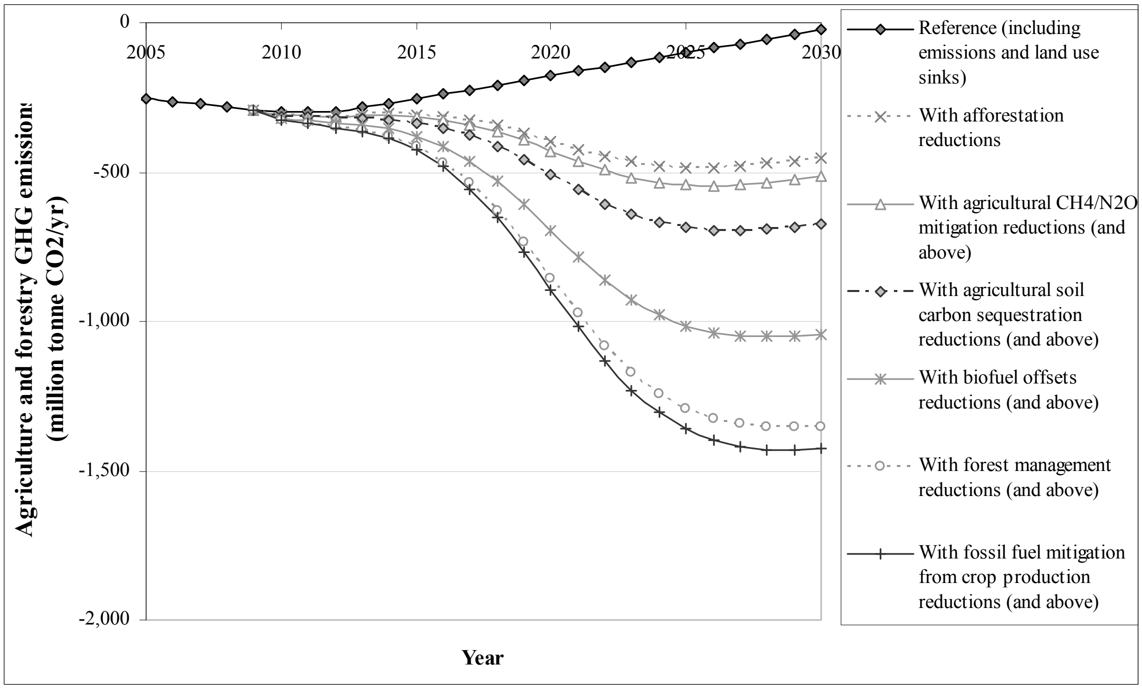


Figure 62. Greenhouse gas emissions for land, land use changes, and forestry

9. MULTI-SECTOR COST EFFECTIVENESS CURVES

This chapter combines the results of Chapters 4 through 8 on GHG mitigation strategies in the different economic sectors. The following sections compare and combine the various sectors' GHG mitigation curves in order to highlight different aspects of the cumulative multi-sector GHG mitigation scenarios.

Note that several adjustments are made in this Chapter to combine the different sectors' marginal abatement curves to avoid "interaction effects," or double counting, of GHG mitigation actions that impact multiple sectors' emissions. These changes make the individual supply curves in some cases in this multi-sector chapter different from the previous individual sectors' chapters. One such modification is in cumulatively including end use electricity efficiency technologies (e.g., in building sector) and electricity generation technologies. The cumulative emission reduction of these GHG mitigation technologies is less than the sum of their parts because each sector action changes the baseline characteristics of the other sector, thus reducing the total emission reduction potential. Another such modification is required for the impact of biomass production in the agriculture sector that produced GHG offsets when utilized in electricity generation and transportation fuels. The GHG reductions from the agriculture sector are allocated to those sectors and excluded from the agriculture sector's abatement curve.

9.1. Comparing Sector-by-Sector Cost-Effectiveness Results

The following two figures compare the marginal GHG abatement curves from the previous chapters. The first figure, Figure 63, compares the sectors' GHG cost effectiveness curves using an "initial-technology-cost only" accounting framework, while the second figure, Figure 64, does the same but for the lifetime "net-cost" accounting that includes energy savings. As shown in both figures, there are substantial GHG reduction opportunities from technologies in each sector with cost effectiveness values at or below \$50/tonne CO_2e. For a given cost-effectiveness value, very different amounts of GHG mitigation are available from each of the sectors. For example, at an initial cost-effectiveness value of \$50 per tonne CO_2e, there are about 400 million tonnes of CO_2e reduction available each in the industry, building, and transportation sectors; however, at that same initial cost-per-tonne of \$50, approximately 1000 million tonne CO_2e are available in the electric sector - and over 1400 million tonnes in the agriculture sector.

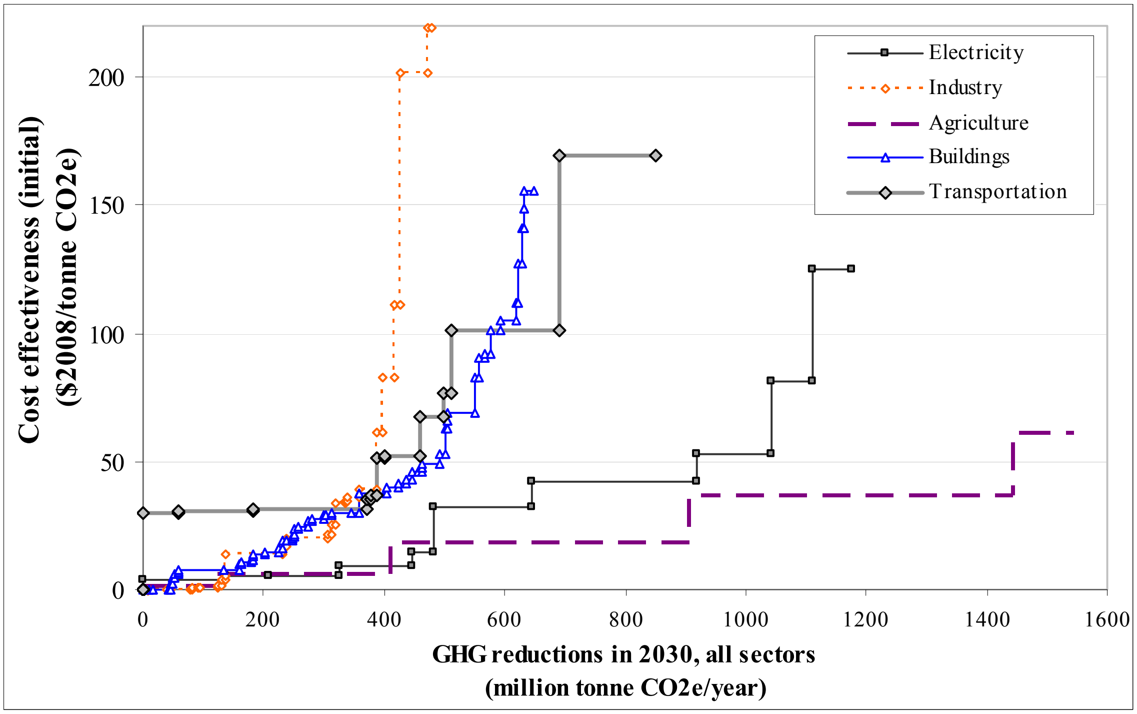


Figure 63. Cost effectiveness curves for different economic sectors, initial cost accounting

Figure 64, shown as lifetime cost-effectiveness instead of initial cost accounting, tells a different story from Figure 63. Just as for initial cost accounting, for a given cost-effectiveness value, very different amounts of GHG mitigation are available from each of the sectors. However, when accounting for lifetime costs, the answer to which sectors offer greater potential for reductions at lower cost-effectiveness values (e.g., below $0/tonne CO_2e) switches. Below $0/tonne lifetime cost-effectiveness value, GHG reduction potential for each sector are transportation (500 million tonnes per year), buildings (600), industry (200), electricity (0), and agriculture (0). At larger lifetime cost-effectiveness values, such as $50/tonne, electricity and agriculture sectors still offer much greater total GHG reduction potential than the other sectors.

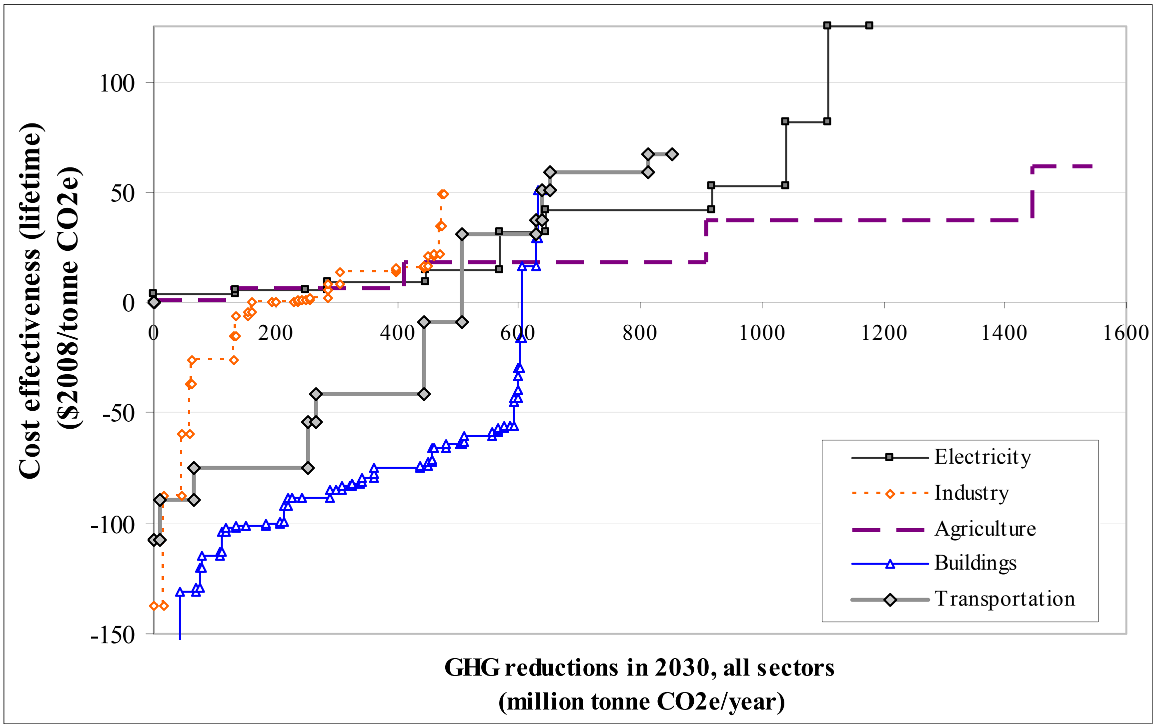


Figure 64. Cost effectiveness curves for different economic sectors, lifetime cost accounting

The following two figures compare the marginal GHG abatement curves from the previous chapters; however these figures show the curves as they relate to each sector's own GHG emissions. These curves simply convert the x-axis from the previous two figures into percentages of each sector's (i.e., electricity, industry, etc.) reference 2030 emissions. The first figure, Figure 65, compares the sectors' GHG cost effectiveness curves using an "initial-technology-cost" only accounting framework, while the second figure, Figure 66, does the same but for the lifetime "net cost" accounting.

Showing GHG reductions as a percent of each sector's own reference emissions provides context for the extent to which each sector's GHG emissions can be reduced for a given cost-effectiveness value – based on the sector's own baseline emissions. From Figure 65, all sectors have substantial GHG reduction opportunities from technologies that have cost effectiveness values at or below \$50/tonne CO_2e. At or below an initial cost effectiveness value of \$50/tonne CO_2e, the industrial sector reduces its GHG emissions by 13%, transportation by 15%, buildings by 16%, and electricity by 29%.

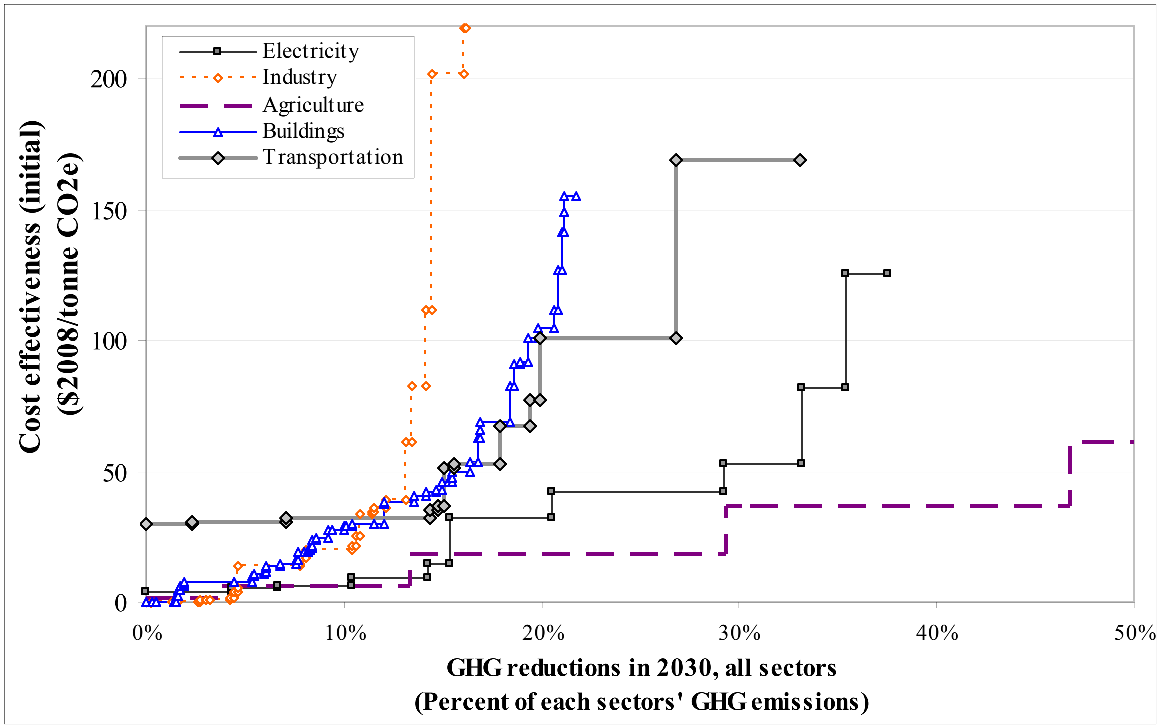


Figure 65. Cost effectiveness curves, as percent of sectoral emissions, initial cost accounting

As shown in Figure 66, at or below a lifetime cost effectiveness value of $0/tonne CO_2e, the transportation sector reduces its GHG emissions by 20%, buildings by 20%, and industry by 6%. Note that the agriculture sector, due to its negative value carbon sequestration potential, can not be easily converted to this metric of the percent of sectoral GHG emissions. As a result, for these plots, 50% was arbitrarily chosen for the maximum x-axis value for the agriculture sector so it could be shown on the same plots.

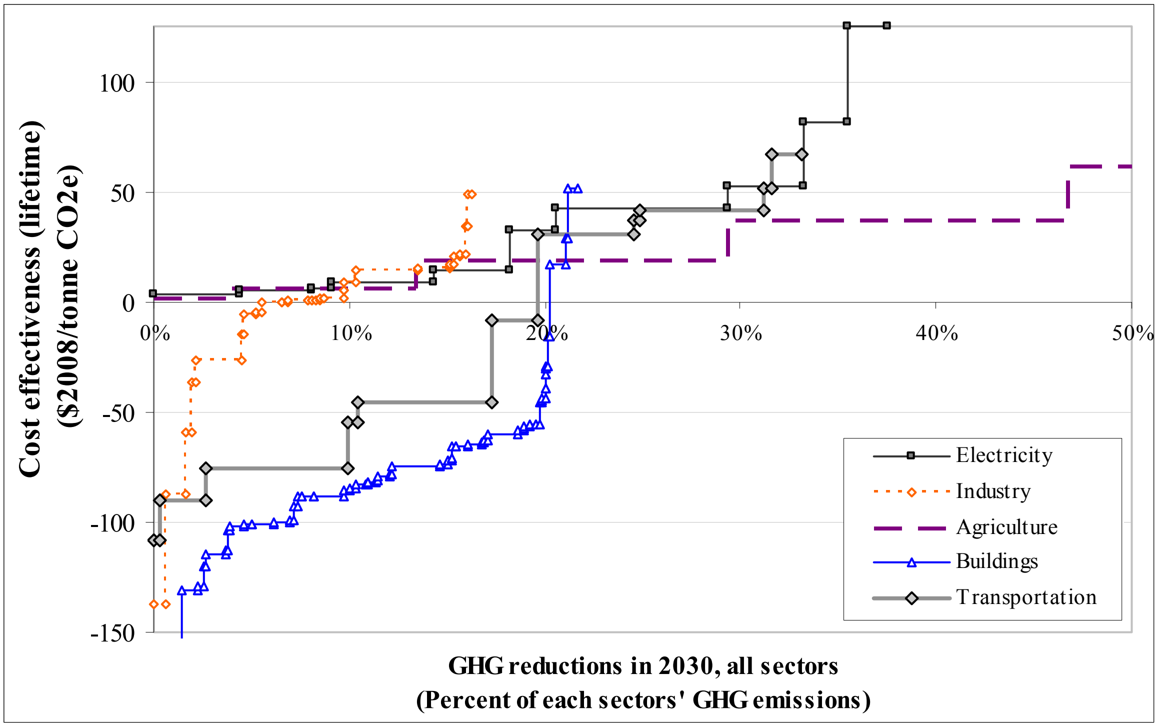


Figure 66. Cost effectiveness curves, as percent of sectoral emissions, lifetime cost accounting

9.2. Combined Multi-Sector Cost-Effectiveness Curve Results

This section merges the marginal cost-effectiveness GHG reduction curves from each sector to construct multi-sector GHG curves. Figure 67 shows the multi-sector cost effectiveness curves for both initial and lifetime cost accounting frameworks. Also shown on the figure for context is the amount of GHG reduction from the 2030 reference that would be required to bring U.S. economy-wide GHG emissions to their 1990 level. Prioritizing the GHG reduction measures by their initial cost-effectiveness, the reductions to achieve 1990 GHG emission level – approximately 2800 million tonnes CO_2e reduction per year – could be met with GHG-reduction technologies with initial costs no greater than $40/tonne. If instead prioritizing the GHG reduction measures by their lifetime cost-effectiveness, the reductions to achieve 1990 GHG emission level could be met with GHG-reduction technologies with net costs no greater than $30/tonne. Also note, from the lifetime cost accounting curve, that approximately half of the 1990 GHG emission target by 2030 could be achieved with GHG mitigation technologies that are below $0/tonne CO_2e.

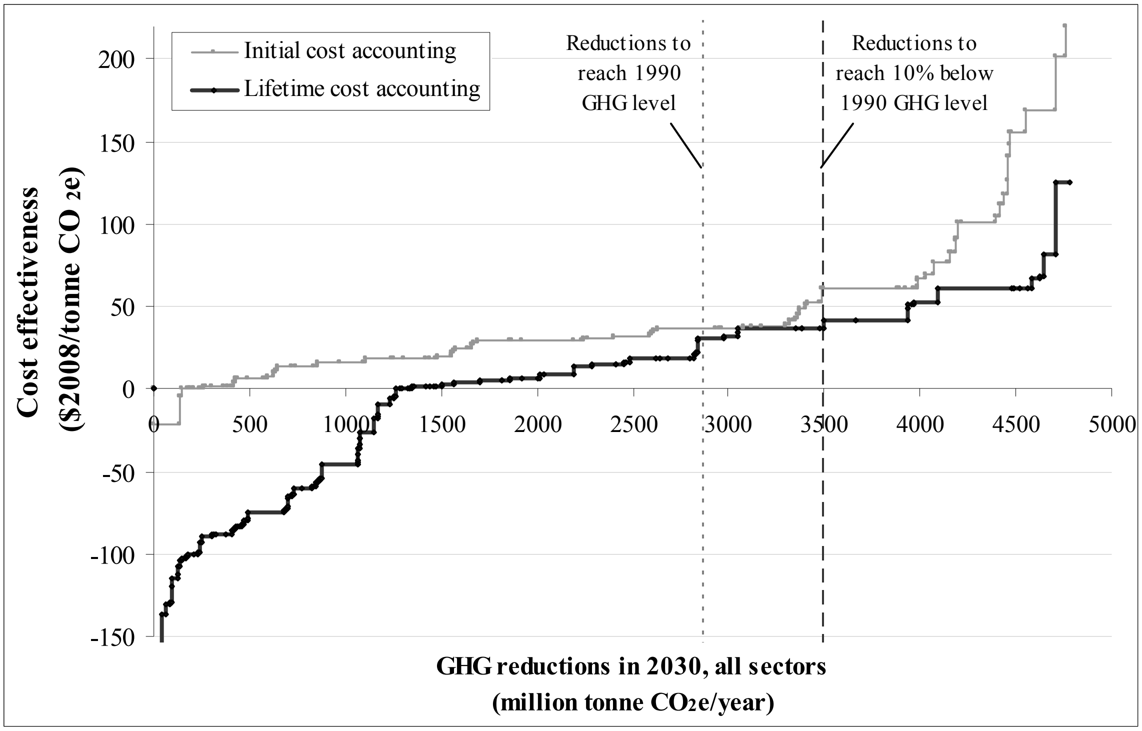


Figure 67. Multi-sector cost-effectiveness curves for GHG reduction technologies, using initial and lifetime cost accounting

The following figure, Figure 68, shows the impact on overall U.S. GHG emissions through 2030 of the deployment of all GHG technologies from this report that have lifetime cost-effectiveness values at or below \$50 per tonne CO_2e reduced. The cumulative result of all measures at or below \$50 per tonne CO_2e reduced from all sectors is an approximate 4000 million tonne CO_2e reduction in 2030 from the reference baseline. The resulting reduced level of GHG emissions with these GHG-reduction technologies amounts to a 43% reduction from the 2030 baseline and a 17% reduction from the 1990 level.

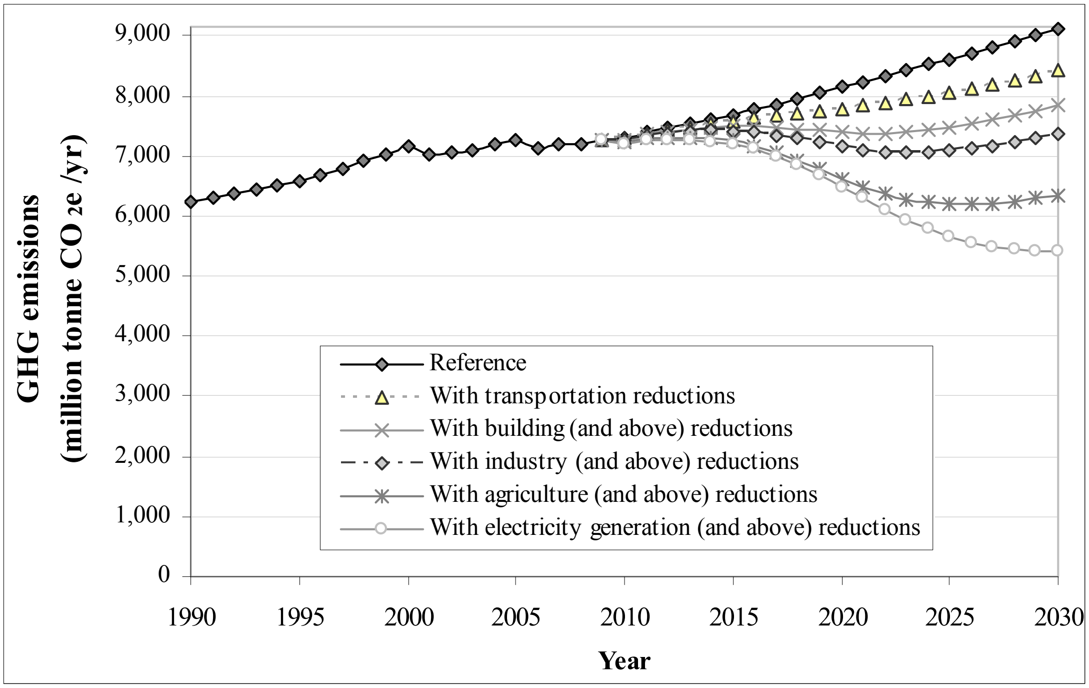


Figure 68. GHG emission impacts of technologies with net cost of less than \$50/tonne CO_2e

If only the GHG reduction technologies with less-than-zero lifetime cost effectiveness values are implemented, the resulting overall GHG reductions are considerably smaller but still substantial. Figure 69 shows a scenario with the deployment of all such "no regrets" technologies. In this case all of the GHG reductions are from the transportation, building, and industry sectors, and the overall impact is to reduce the reference 2030 GHG emissions by about 14%. This scenario roughly stabilizes GHG emissions at 2005 levels through 2022.

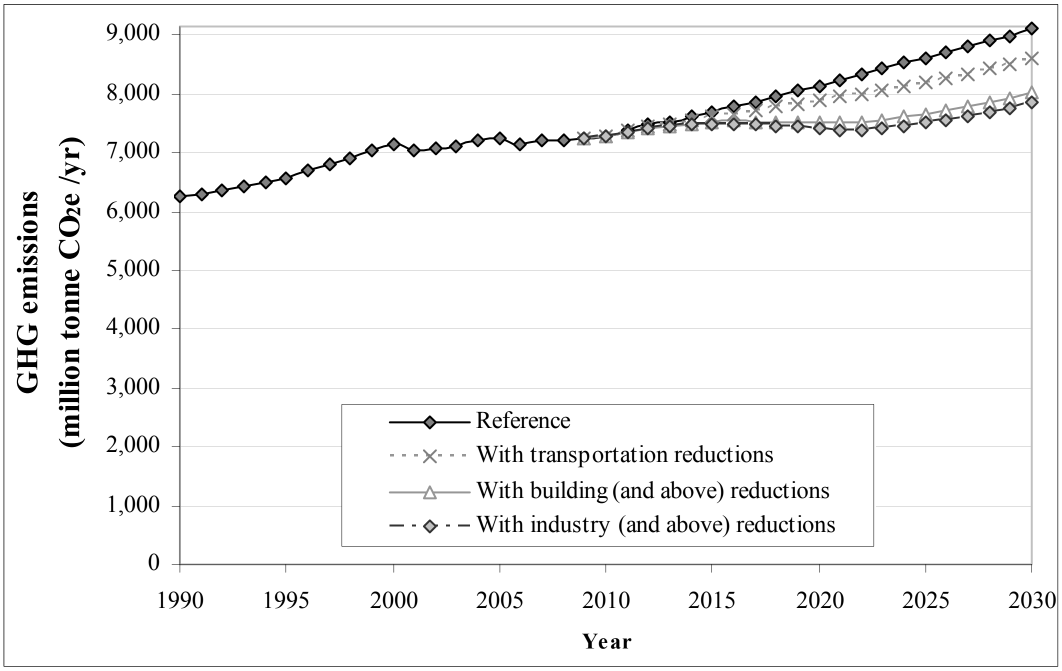


Figure 69. GHG emission impacts of "no regrets" technologies (with lifetime cost effectiveness values at or below $0/tonne)

Table 31 summarizes the impact of deploying all technologies that are at or below a given cost-effectiveness value (from $0 to $50 per tonne CO_2e, lifetime accounting). The GHG reductions from each sector, and from all sectors combined, are shown. At lower lifetime cost-effectiveness values, the total potential reductions are dominated by the transportation and building sectors. At higher cost effectiveness values, agriculture and electricity sector GHG mitigation technologies make up the largest portions of the overall GHG emission reductions. Also shown in the table are the total multi-sector reductions, as percentages of the total reference 2030 emission level, and the corresponding GHG level relative to year 1990 emissions. The deployment of all technologies with lifetime cost-effectiveness values below $30/tonne results in the achievement of the benchmark 1990 GHG level in the U.S. by year 2030.

Table 31. GHG reductions at various cost-effectiveness values

Sector	GHG reductions (million tonnes CO_2e/yr) in 2030 for a given lifetime cost effectiveness (\$/tonne CO_2e)					
	0	10	20	30	40	50
Transportation	505	505	505	505	639	801
Buildings	570	570	594	597	597	597
Industry	193	305	451	469	473	478
Agriculture	0	277	610	610	1,056	1,056
Electricity	21	540	664	664	738	1,015
Total GHG reduction	1,289	2,198	2,824	2,845	3,503	3,946
Percent reduction from reference 2030 GHG emission level (all sector actions)	14%	24%	31%	31%	38%	43%
Percent below 1990 GHG level (all sector actions)	-	-	-	0%	-10%	-17%

9.3. Impact of Cost Accounting Framework on Prioritizing Mitigation Actions

This section examines the impact of the cost accounting framework by calculating the total impacts of prioritizing GHG mitigation actions based on two different scenarios: one that prioritizes GHG mitigation actions by initial costs only, and one that prioritizes based on net discounted lifetime costs. Table 32 shows the impact of the chosen cost-effectiveness accounting framework – initial or lifetime – that is used for prioritization of mitigation actions on sectoral GHG emission reductions. For an overarching GHG reduction goal of reducing 2030 economy-wide GHG emissions in the U.S. to 10% below 1990 levels, the percent of GHG reductions that would come from each sector is quite different if the scenario is based on lowest initial cost-effectiveness versus lowest lifetime cost-effectiveness. Prioritization based on initial cost-effectiveness makes larger percentages of GHG reductions from agriculture and electricity sectors. Basing the ordering of adopted GHG reduction technologies on lifetime cost effectiveness more evenly distributes the amount of GHG reductions for which each sector is responsible.

Table 32. Impact of two cost accounting frameworks on prioritization of mitigation actions

		Scenario with mitigation options prioritized according to *initial* cost accounting	Scenario with mitigation options prioritized according to *lifetime* cost accounting
Percent of GHG reductions from each sector to achieve 10% below 1990 GHG level by 2030	Transportation	13%	18%
	Buildings	13%	17%
	Industry	11%	14%
	Agriculture	41%	30%
	Electricity	29%	21%
Total GHG reductions 2030 (million tonne CO2e/yr)		3,500	3,500
Average cost-effectiveness [a] ($/tonne)	Initial	23	31
	Lifetime	-4	-16
Total annualized impacts [a] ($billion/year)	Initial technology cost	80	109
	Lifetime technology cost impacts	-94	-164
	Net costs	-14	-56

[a] *positive values are costs, negative values are benefits*

Moving from initial to lifetime cost accounting shifts more of the GHG mitigation actions to the "end use" sectors of transportation, buildings, and industry, where there are more energy savings to counteract the upfront initial costs of the mitigation technology. The result of this shift from initial to net lifetime cost accounting is to increase the average initial cost-effectiveness (from $23 to $31 per tonne) -- but to reduce the net lifetime cost effectiveness (from -$4 to -$16 per tonne).

Also shown in Table 32 is the total technology cost impacts of the two GHG mitigation scenarios, based on the different prioritization of GHG mitigation actions, and their overall costs and benefits. Ordering GHG mitigation actions according to lowest initial cost-effectiveness yields an annual average initial cost of $80 billion dollars, annual average benefits of those technologies' energy use reductions of $94 billion, and a net benefit of $14 billion. If GHG mitigation options are ordered instead by their lifetime cost-effectiveness, the total initial cost is increased by about 40% to $109 billion, but the energy saving benefits are almost doubled to $164 billion, and the net benefits are multiplied by four to $56 billion.

9.4. Examining Transportation Mitigation Technologies

Highlighting transportation sector GHG mitigation actions in particular on marginal abatement curves demonstrates the shift that occur in GHG mitigation priorities when moving from a initial cost only framework to a technology lifetime cost accounting framework. The following two figures, Figure 70 and Figure 71, highlight transportation measures on the multi-sector initial cost and lifetime cost marginal GHG abatement curves. In the initial cost Figure 70, several transportation GHG mitigation options are in the middle of the marginal abatement curve and several are near the end. However, the following lifetime cost Figure 71, several transportation GHG mitigation measures shift to the left toward the lowest (i.e., more cost-effective) quartile of cost-effective mitigation technologies.

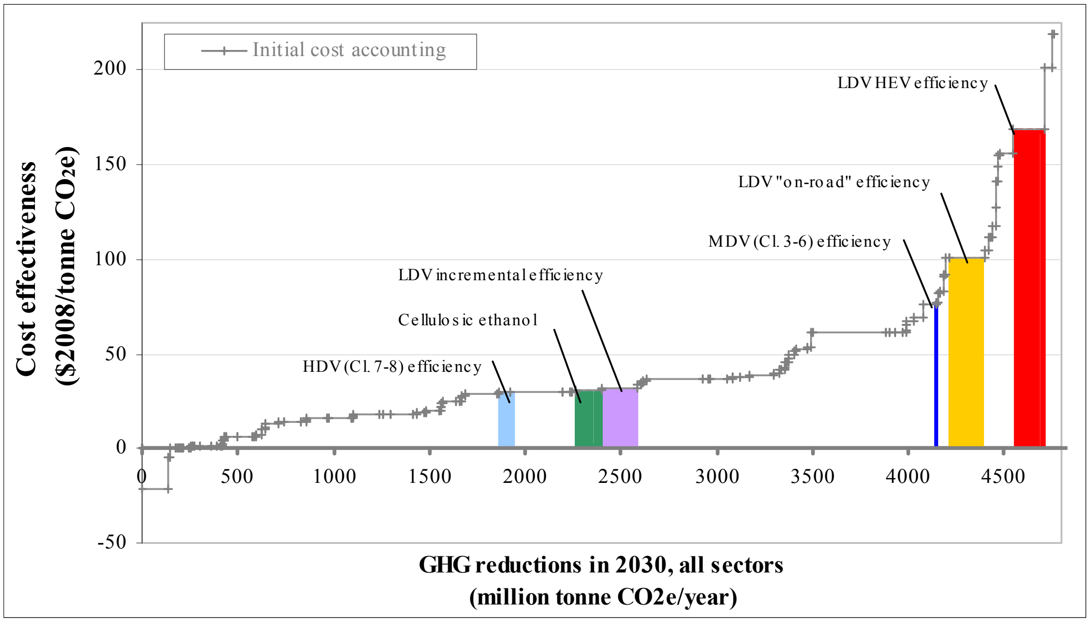


Figure 70. Cost effectiveness curve for GHG emission reductions, with transportation options highlighted, initial cost accounting

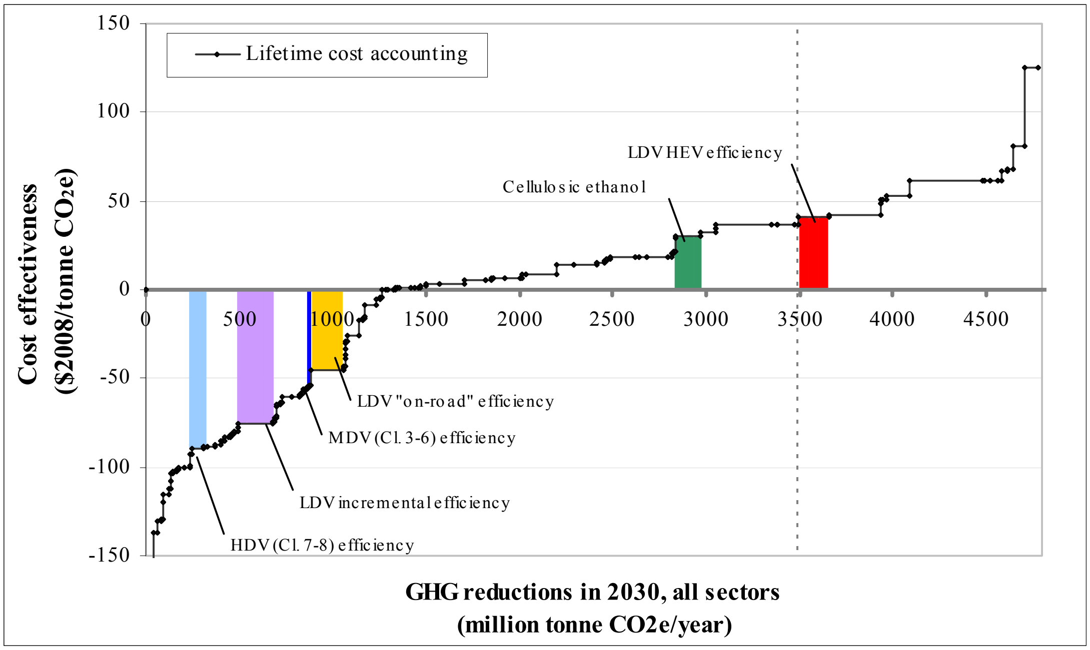


Figure 71. Cost effectiveness curve for GHG emission reductions, with transportation options highlighted, lifetime cost accounting

10. DISCUSSION

In this research and analysis to aid in the prioritization of GHG mitigation actions, many technologies have been highlighted and quantified as to the extent to which they could contribute to larger GHG reduction goals in the U.S. In the process of this research, a number of issues and topics have either arisen or been alluded to that have not been directly addressed. This chapter discusses several such issues in order to reflect on the findings' implications and point toward future research directions left unexplored. In particular, this Chapter discusses issues related to comparable GHG mitigation research, non-technology GHG mitigation strategies, ancillary impacts of GHG mitigation strategies, and potential GHG mitigation policy instruments in light of this dissertation's results.

10.1. Comparison to Similar Research

Comparable analytical work to the marginal abatement curve research in this dissertation has been done elsewhere. There are many studies that are similar but not directly comparable for a variety of reasons. The somewhat older studies (e.g. NAS, 1991; NRC, 1992; Rubin et al., 1992; IWG, 2007) have different baseline technology characteristics as well as different alternative low-GHG technologies and different timeframes for GHG mitigation. Other studies extensively research GHG across sectors mitigation potential but do not include cost-effectiveness evaluation. Other studies that do incorporate cost-effectiveness evaluations do so without the level of detail into each sector's technology options. However, the only study that is directly comparable to this one in terms of the studies' timing, methodological approach, and level of detail is the McKinsey & Company's *Reducing Greenhouse Gas Emissions: How Much at What Cost?* (Creyts et al., 2007). This section briefly discusses similarities and differences between the McKinsey study and this dissertation.

The established baselines from this study and the McKinsey report are both predominantly based upon reference data from U.S. Energy Information Administration's *Annual Energy Outlook* for energy and activity trends though 2030. The McKinsey study uses the U.S. EIA's year 2006 reference, and this study applies year 2007 reference data. The 2007 data from U.S. EIA's "early release" that is applied to this analysis is still previous to the update for *Energy Independence and Security Act of 2007* federal energy legislation, and is very similar to the 2006 reference data. Also both studies use U.S. EPA studies for historical data and for non-CO_2 emissions (U.S. EPA, 2006b; U.S. EPA, 2007b). The McKinsey report evaluates GHG mitigation possibilities independently for five regions of the U.S., whereas this dissertation reports only on aggregated national impacts.

The two studies cost accounting frameworks are very similar. Both studies include the costs related to the initial capital costs and lifetime operating cost savings in the cost-effectiveness evaluations. Predominantly these operating cost differences between baseline and low-GHG technologies are the energy savings, for which both studies apply a real 7% discount rate to benefits and costs in future years. Both studies use U.S. EIA reference energy costs through the year 2030. Neither study includes various other costs (e.g., administrative, taxes, subsidies, information campaigns) related to deploying the GHG-reduction technologies.

Neither study incorporates any form of a carbon price or any dynamic market affects that could result from the energy use implications for the assumed technology adoption. The primary methodological difference between the two studies' costs is that this dissertation separately evaluates "initial" and net "lifetime" cost-effectiveness values for the GHG mitigation technologies, to highlight the implementation barriers in many of the technologies. The McKinsey study includes only a lifetime cost accounting evaluation.

The McKinsey study provides three cases for different levels of adoption of the GHG-reducing technologies, whereas this dissertation research does not. The three McKinsey cases, low-, mid-, and high-range cases correspond to the overall U.S. response toward climate change mitigation of incremental change, concerted effort, and urgent national mobilization, respectively. This dissertation research does not attempt to provide fractional deployment of the technologies evaluated; doing so could most simply be accomplished by dividing the GHG reduction (i.e. the curves' horizontal x-axis) by an estimated maximum penetration factor. For example, to adjust this dissertation's findings to half of the chosen rates of deployment, the GHG reduction potential of each of the technologies could be divided by two.

Looking at the two studies' evaluated GHG-reduction technologies, there appears to be many similarities. The guidelines for technologies to be included for the McKinsey study includes "high-potential emerging technologies" that must be at least in the pilot stage of development, be generally supported among experts as technologically and commercially feasible, and have quantifiable values so as to allow their evaluation. These screening criteria are in line with those of this study (as outlined in Chapter 3). Both studies make an effort to assure that the technologies studied result is no compromise in the utility of the adopters of the technology. For example, adopters of building technologies are not to suffer from a loss in comfort due to space restrictions of temperature differences; vehicle users are not to suffer from reduced acceleration, space, driving range, etc. The primary method employed in this research to be able to make this "constant utility" assumption is the inclusion of only primary technology data from studies that, in turn, avoid any compromised utility factors.

To compare results from the two studies, data are drawn from the conclusion figures of the McKinsey report for comparison with this dissertation's findings in Figure 72 and Table 33. The results of this dissertation's lifetime cost-effectiveness accounting most closely resemble the GHG abatement curve of McKinsey's "high-range case." McKinsey's high-range case suggests that there is a 8% greater GHG reduction potential in 2030 at a cost-effectiveness below \$50/tonne CO_2e than the findings from this dissertation (McKinsey's mid-case value is 24% below this dissertation's). The McKinsey report indicates higher potential GHG emission reductions from electricity production, industry, and buildings sectors; conversely, this dissertation shows higher total reduction potential in the transportation and agricultural sectors.

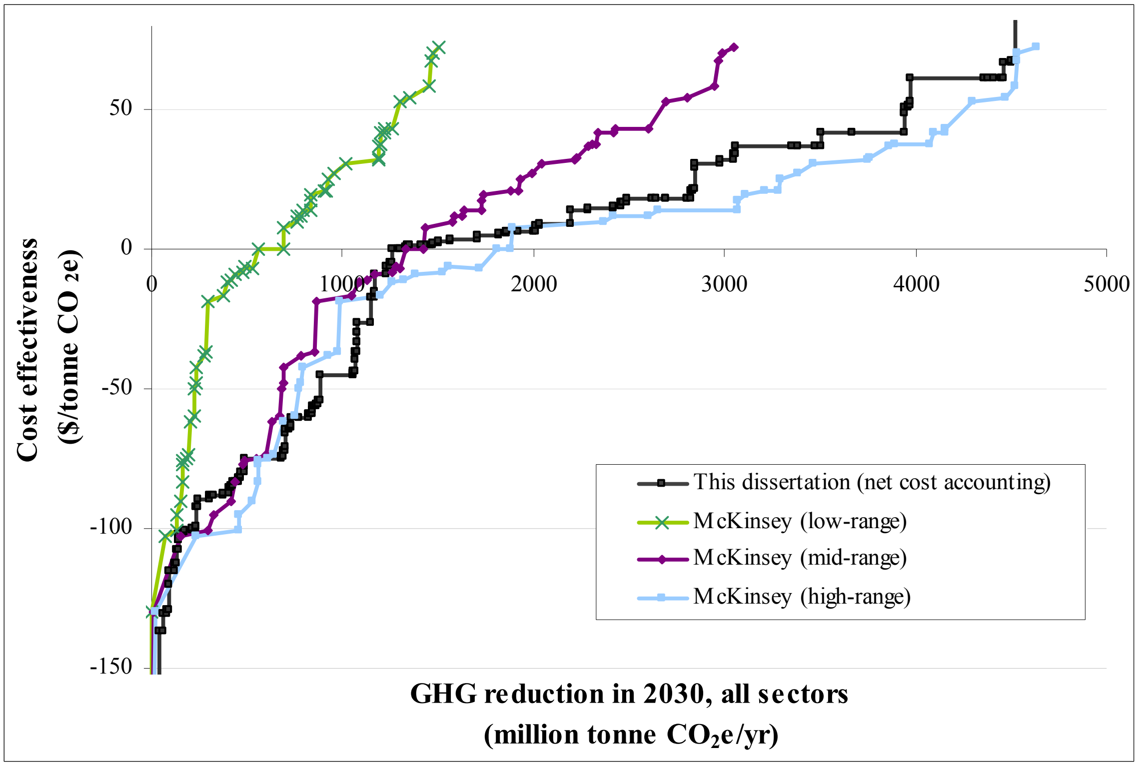


Figure 72. Comparison with McKinsey study for marginal abatement GHG curves

Table 33. Comparison with McKinsey study for the potential GHG emission reduction below $50 per tonne CO_2e in 2030

		McKinsey report[a] "High-range"	This research - Lifetime cost accounting
Sectoral GHG reduction (million tonne CO_2e/yr) (and percent)	Transportation	638 (15%)	800 (20%)
	Buildings	808 (19%)	600 (15%)
	Industry	723 (17%)	480 (12%)
	Energy production	1488 (35%)	1010 (26%)
	Agriculture	695 (14%)	1060 (27%)
Total U.S. GHG emission reduction below $50/tonne CO_2e in 2030 (million tonne CO_2e/yr)		4250	3950

[a] *approximated from Creyts et al., 2007. Values are from the "high-range" case, which most closely resembles the technology deployment assumptions of this dissertation*

[b] *from this dissertation's lifetime cost accounting prioritization framework*

More specific, detailed comparisons between the two studies are complicated by the overall complexity of the analyses. Both studies evaluate dozens of technologies across different sectors with many nuanced details regarding the embedded reference data and the handling of different assumptions, thus making side-by-side comparisons tedious and difficult. In addition, the methods and data sources of the McKinsey study are not fully publicly available. The McKinsey study utilizes unreferenced data and a team of expert reviewers. This dissertation utilizes publicly available data and attempts to transparently describe how the available data are applied.

10.2. On Top-Down Studies and the Existence of Net-Private-Benefit Options

The very existence of values on a "supply curve" that offer GHG reductions at below-zero-net-costs merits further discussion and research. From a strict economist's perspective, technology options with net private benefits should not exist in an efficient market; therefore, the "net economic benefits" findings, such as those in this dissertation, more simply indicate that the analysis is excluding other implementation costs or implicit costs in these types of investment. This section discusses such theoretical issues as they relate with economics theory and the interpretation of this research's findings.

Economics theory generally suggests that markets already efficiently allocate resources, and that therefore bottom-up technology studies such as this, where net-benefits can outweigh costs, should not exist. The more traditional economists' approach applies a "top-down" computable general equilibrium (CGE) models which assumes that investment in capital goods has (or will at least in the long-run equilibrium) allocate net-private-benefit technologies to those that demand them. Therefore CGE models would generally model the mitigation of GHG emissions as a new constraint that would generate a new economic equilibrium, and the economic growth that was forgone to meet the GHG constraint would be the cost of compliance. Such an approach precludes "no regrets," net-beneficial options.

Two of the major discrepancies between the economist top-down and technology bottom-up analyses are accounted for by (a) top-down studies' assumption that energy markets are efficient and (b) bottom-up studies' use of social discount rates, which can be much lower than private discount rates that are applied implicitly or explicitly in private energy investments (see, e.g., Ayres, 1994; Jaffe and Stavins, 1994; Krause et al., 1995). The net result of these differences is to have energy conservation (or GHG abatement) cost curves from top-down and bottom-up studies that have the same increasing cost relationship. However the top-down studies generally begin at or near zero (i.e., \$0/kWh, \$0/tonne, etc) on the y-axis like the "initial cost" curve from this dissertation, whereas the bottom-up curves generally begin well below zero like the "net lifetime cost" curve from this dissertation.

Top-down studies are conducted in very different ways with different methods and assumptions. However, for illustration purposes, this dissertation's results are charted alongside two top-down studies by Massachusetts Institute of Technology (MIT) researchers in Figure 73. A study by Hyman et al. (2002) modeled GHG abatement including both CO_2 and non-CO_2 emissions. A study by Persatz et al. (2007) modeled the range of prominent federal climate change policy proposals (e.g. the Lieberman-McCain and Kerry-Snowe proposals in the U.S. Senate) for their impacts on GHG reductions and costs to the economy. Findings are drawn from the two studies for the overall costs of economy-wide compliance with GHG emission reduction goals by 2030. As shown in the figure, the MIT top-down modeling studies' results for climate change mitigation costs resemble the initial cost accounting GHG abatement curve from this dissertation.

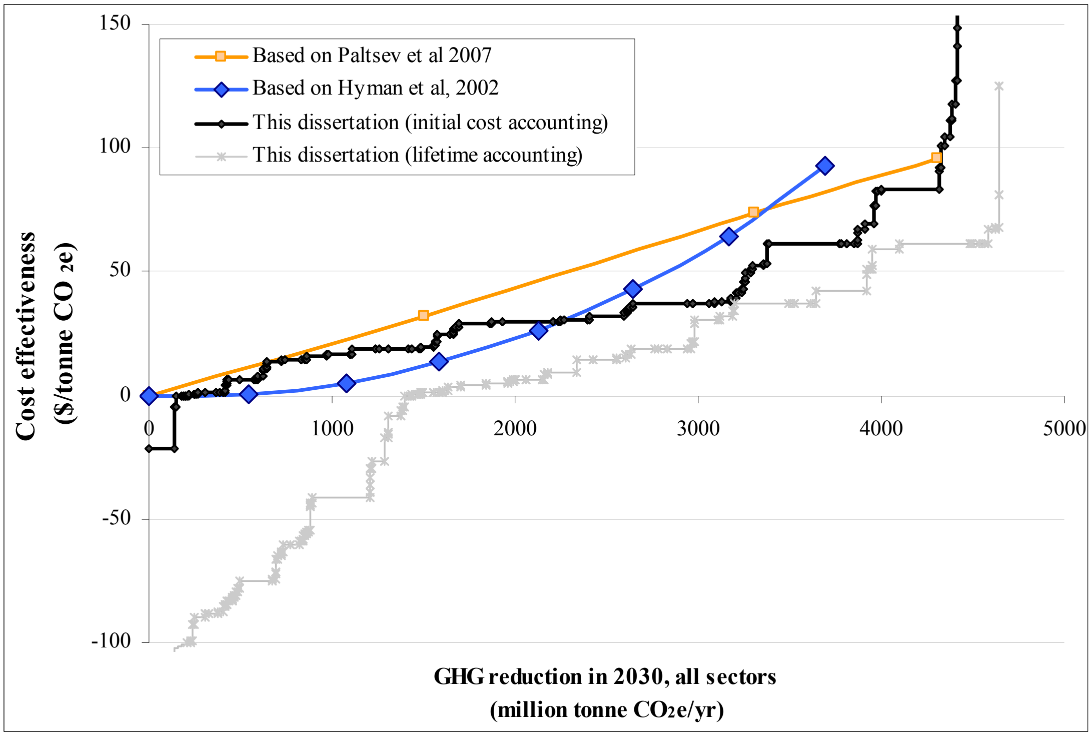


Figure 73. Comparison of findings to top-down GHG reduction studies

Between the two curves is an "efficiency gap" that can potentially be explained by a host of factors, such as a failure in the market for efficiency technologies, unevaluated costs or trade-offs that are left out of analses, institutional barriers, or simply the slow diffusion of technologies into the market or the heterogeneity of the many energy users that is reported as simple average values. One prominent market failure explanation is the limitation in the availability of information to technology purchasers and users about the energy-reducing technologies, the technologies' impact on energy use over time, and the future costs of energy. One market failure that has been relatively poorly quantified is the principal-agent problem in energy-related decisions, whereby the purchaser of the energy-related investment is not the same as the recipient of the energy saving (or costs).

There are several prominent areas in this dissertation where net-benefit technologies exist – and where some explanations have been put forth in the literature on reasons for the existing impediments and market failures that prevent their wider adoption. In the case of automotive efficiency for passenger and commercial vehicles, numerous technology packages were found whereby the initial technology cost is outweighed by the future discounted energy saving benefits. Assymetric information for both consumers and industry could both be issues in this sector. Turrentine and Kurani (2007) find that consumers lack in basic knowledge to estimate the energy impacts of their vehicle purchases, make large errors when estimating their energy savings over time, and can ascribe considerable symbolic value to car purchases (in excess of economically rational value). As such the marketing of incrementally more efficient vehicles could be benefited greatly by better consumer understanding of their vehicles' energy use repercussions. The early success in the deployment of hybrid gas-electric vehicle technology, which generally is not net-beneficial from a private cost perspective – and by only some automakers – suggests that the auto industry, too, could benefit from better information about their consumers' symbolic valuation of various efficiency packages.

Similarly there has been some study of the limitations in energy efficiency investments in the building and industry sectors. This dissertation research finds many net-private-benefit technology opportunities in many appliance and lighting applications in residential and commercial building applications. Meier and Eide (2007) found that about a quarter of residential energy use could be subject to the principal-agent disconnect, because energy appliance investments in the residential sector are often made by property owners who are not the energy-using residents (e.g. of space heating, water heating, refrigerators); in such cases, the idea of an energy-related "price signal" is unlikely to have much direct effect. For some commercial and industrial settings, combined heating and power (CHP) appears to be a similarly underutilized net-benefit technology option. In this technology area, institutional barriers related to the interconnection and tariff policies on utilities, as well as other environmental and taxation barriers that have impeded market penetration (Elliot et al., 2003).

So in interpreting this dissertation's findings in light of these musings on economics theory, several points can be made. First, the summary findings of this dissertation – where net benefits of the deployment of GHG mitigation technologies could be in excess of $10 billion annually – should not be construed as suggesting that these options are easy, available with little effort, or inevitable even without policy action. There are diverse and pervasive impediments that stand in the way of the broader adoption of these low-GHG mitigation technologies. In these cases, it would appear that the more typical issue of reducing industry engineering costs through research and development grants is less important. Investigating and breaking down these institutional and informational barriers could ultimately be much more valuable in bringing about GHG emission mitigation. Supportive actions by consumer groups, government agencies, and corporations could include further advancements in research about consumer preferences, the dissemination of information on energy-use characteristics of various technology purchases, and consumer financial incentives.

10.3. Non-Technology Mitigation Strategies

The central question of this dissertation relates to which GHG mitigation technologies are most promising and cost-effective in delivering future potential GHG emission reduction targets at a minimized cost for 2020 and later years. This approach, focusing on technological emission-reduction options, is not fully inclusive of all possible mitigation alternatives. This study, aside from excluding all technology options for which cost-effectiveness values could not be found or estimated, also does not include non-technology GHG mitigation strategies.

This dissertation's emphasis on technology-based mitigation options is intentional. The GHG-mitigation options throughout this dissertation are well-studied and quantified because they are emerging technologies that are thought to be ready for widespread deployment within the next couple decades. The studied technologies are, according to conventional wisdom in the various economic sectors, the potential technology "winners" in a near-term

GHG-constrained world. The dissertation prioritizes how these technology options rank against one another. Technology-based options are the most popular, and by definition the least behavior-changing, of the known GHG-reduction options from which society can choose.

Historical and current environmental policy-making in the U.S. have demonstrated a strong proclivity for technological approaches over any types of behavior-changing policies. For example, the chosen U.S. automobile and power generation policies routinely opt for technology-mandating standards or regulations (e.g., vehicle fuel economy regulations, power plant emission caps, renewable electricity standards, etc.) over increased user fees or demand-reduction programs. With this technology bent in environmental decision-making, the choice of this dissertation's focus on technology-based GHG mitigation strategies is an easily justified one to prioritize feasible first steps for GHG mitigation.

However, it was not the intent of this research to downplay the importance of behavioral shifts that individuals (or companies, households, etc.) can undertake to reduce GHG emissions. The case has been made, for example by Goodall (2007), that, instead of relying on the large-scale actions of governments and industry, reducing GHG emissions is a duty incumbent upon all individuals. The great magnitude of GHG reductions that would be required for worldwide climate change stabilization will almost surely require behavioral, or actor-based, modifications of some sort by individuals – beyond simply withstanding incremental cost increases in their vehicles, electricity bills, appliances, and fuels due to the deployment of new technologies.

For context, consider the further reductions that would be required to reduce GHG emissions to achieve the deeper cuts required for climate stabilization in 2050 in one particular economic sector. Figure 74 shows the reference light duty vehicle GHG emissions, with technology (vehicle and fuel) GHG strategies' impacts on GHG emissions, as they were evaluated above. For this figure, trends through the year 2050 are extrapolated, and a hypothetical GHG reduction trend line is presented for the additional reductions that would be required to bring transportation sector GHG reduction to 80% below its 1990 level. This is the approximate level for GHG emissions required for climate stabilization, and it is the long-term reduction goal that has been established by the state of California.

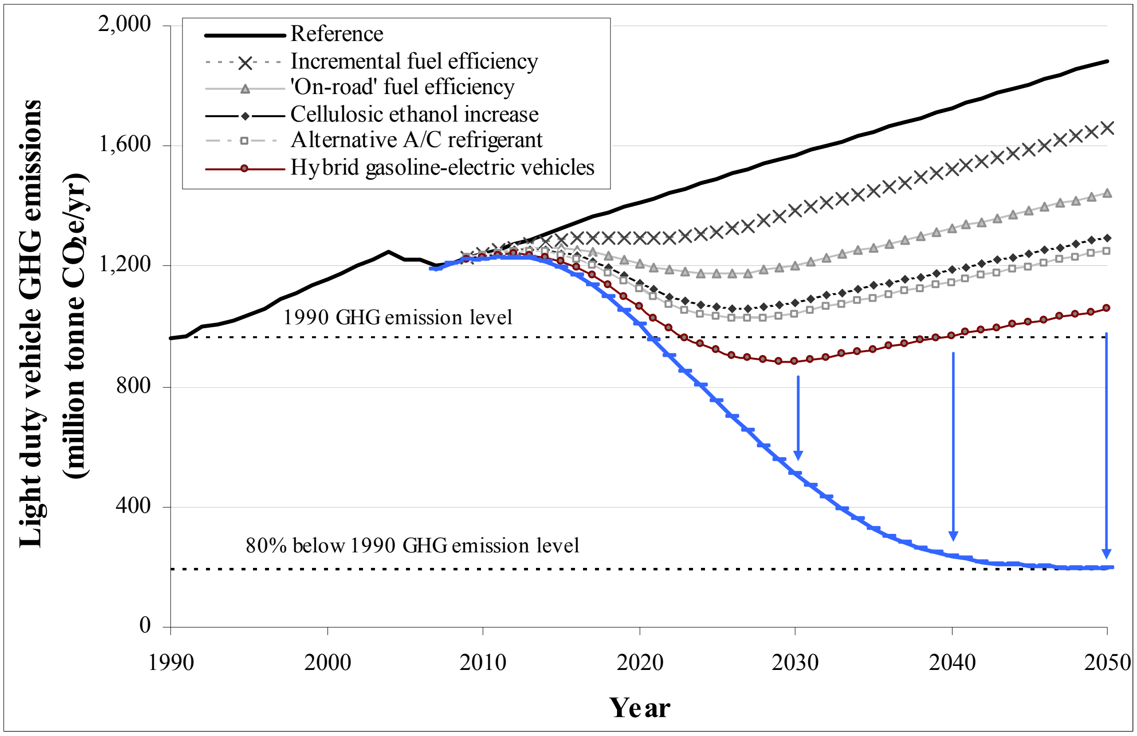


Figure 74. Light duty vehicle GHG emissions after technology GHG mitigation options, and reductions remaining to achieve 2050 target

Although it may be safe to assume a new round of technologies will emerge to help bridge this long-term GHG reduction gap by 2050, the magnitude of the required reduction to achieve the "80%-by-2050" target for the transportation sector would still require sizable GHG reductions. After deploying the level of GHG reduction technology for vehicles and fuels as described in this study (and no further advances), the travel demand reduction to achieve the 2050 target would be quite severe. For this amount of GHG reductions to come from travel reductions, national light-duty vehicle travel would have to be reduced annually by approximately 4%, instead of the forecasted increase of about 1.8% annually from 2010 on. Even after a new crop of vehicle and fuel technologies (e.g. plug-in hybrid-electric vehicles) emerges, it appears safe to speculate that some significant amount reduction in vehicle-miles-traveled will be needed to augment technology shifts to achieve deeper, longer-term GHG reductions.

This point – that technology and alternative fuels alone will not achieve the deeper long-term 2050 GHG reduction targets for transportation – has been made elsewhere (Ewing et al., 2007). Just as there is a whole portfolio of technology-based options to mitigate transportation GHG emissions, there too is a portfolio of available actor-based options. The location where one chooses to reside, and its distance from the residents' workplaces, is a very important behavioral decision for transportation GHG emissions. Therefore, urban development planning that promotes denser land use would also be a valuable GHG mitigation strategy. Road and congestion pricing could also be cost-effective GHG mitigation strategies by moderating traffic and encouraging lower-GHG-intense travel modes. Consumers who elect to compromise vehicle attributes like size and acceleration bring about GHG reductions without more costly technology changes. Less aggressive driving styles with lower speeds and accelerations also reduce fuel use and GHG emissions.

Such non-technology GHG mitigation options exist across all the sectors studied in this dissertation. Turning off unused appliances and lighting in household, offices, and warehouses is more cost-effective than purchasing more efficient technologies. Changing or automating residential and commercial building thermostat setting costs nearly nothing and brings forth energy and GHG reductions. Various other activities including recycling and choosing locally grown food could also have significant GHG implications. However, this area of evaluating the cost-effectiveness of these types of measures for GHG mitigation is relatively unexplored and therefore currently not compared in large-scale GHG mitigation assessments.

Incorporating non-technology GHG mitigation actions would be a difficult but important addition to the GHG analyses such as this. The explicit cost of many behavioral changes is near zero; however, evaluating actions based on elasticity functions or individuals' implicit willingness to pay for various services (e.g., to drive) yields a very different cost result. That discrepancy in cost is the primary difficulty in including such measures in analyses like these. Future analyses that simultaneously incorporate and evaluate the cost-effectiveness of combined technology and non-technology GHG strategies would be doing a service to the GHG mitigation decision-making process by ensuring that all mitigation options – technology-based or not – are considered equally.

10.4. Other Associated Impacts of Mitigation Strategies

This dissertation's findings reveal that the inclusion of the net lifetime cost impacts in an analysis of GHG reduction alternatives shifts our technology priorities and allows for greater abatement potential at lower net societal costs. There are, however, many other economically quantifiable impacts of the GHG mitigation technologies studied in this dissertation, and many such ancillary impacts would also result in additional benefits to society. Such ancillary benefits associated with the GHG mitigation technologies include the concurrent reductions in petroleum dependence, peak electricity demand, and criteria pollutant emissions. On the other hand, it is also possible that some secondary impacts (e.g., on land use, water use, or food prices) could have ancillary costs that tip the cost-effectiveness values in the other direction.

Another benefit that could be included in a more comprehensive cost-effectiveness analysis would be the reduction in the environmental damage costs associated with climate change itself. A GHG damage impact charge would not be an ancillary (or co- or mutual) benefit of GHG mitigation technologies, for the prime motivating objective of GHG emission reduction activities is of course to mitigate the environmental damage that results from GHG emissions. However, this environmental damage cost for climate change emissions is valued in the literature at widely varying cost-per-tonne values. For example, the review of published studies by Tol (2005) indicates \$14/tonne CO_2 as an upper bound on GHG damage costs, while Stern (2006) suggests that the social cost of GHG emissions could be \$85/tonne CO_2. Noting this uncertainty, a GHG damage cost is not applied to this analysis.

On the whole, just as including energy savings in the cost-effectiveness analysis shifts the "supply curve" lower, it is likely that the inclusion of the other ancillary benefits of GHG mitigation technologies would further shift the overall curve lower. The shift to a lower supply curve with inclusion of ancillary benefits offers the advantages of further refining the true value of GHG technologies' cost-effectiveness and highlighting more net-beneficial "no regrets" policies. Such an all-inclusive cost-effectiveness metric could begin to approach a unifying sustainability metric that bundles all quantifiable environmental and cost impacts, thus becoming a more powerful prioritization tool.

Figure 75 shows the hypothetical marginal cost-effectiveness curve with the simple modification of an additional \$25/tonne CO_2e benefit attached to all of the GHG mitigation technologies. Such a benefit could be associated with the mitigated damage cost of GHG emissions or the ancillary benefits of emission control devices. Although the constant benefit charge is overly simplistic when flatly applied to all measures, it shows the hypothetical, illustrative impact of such a modest ancillary benefit making a substantial impact by doubling the number of GHG reduction measures that can be net-beneficial (i.e. less \$0/tonne).

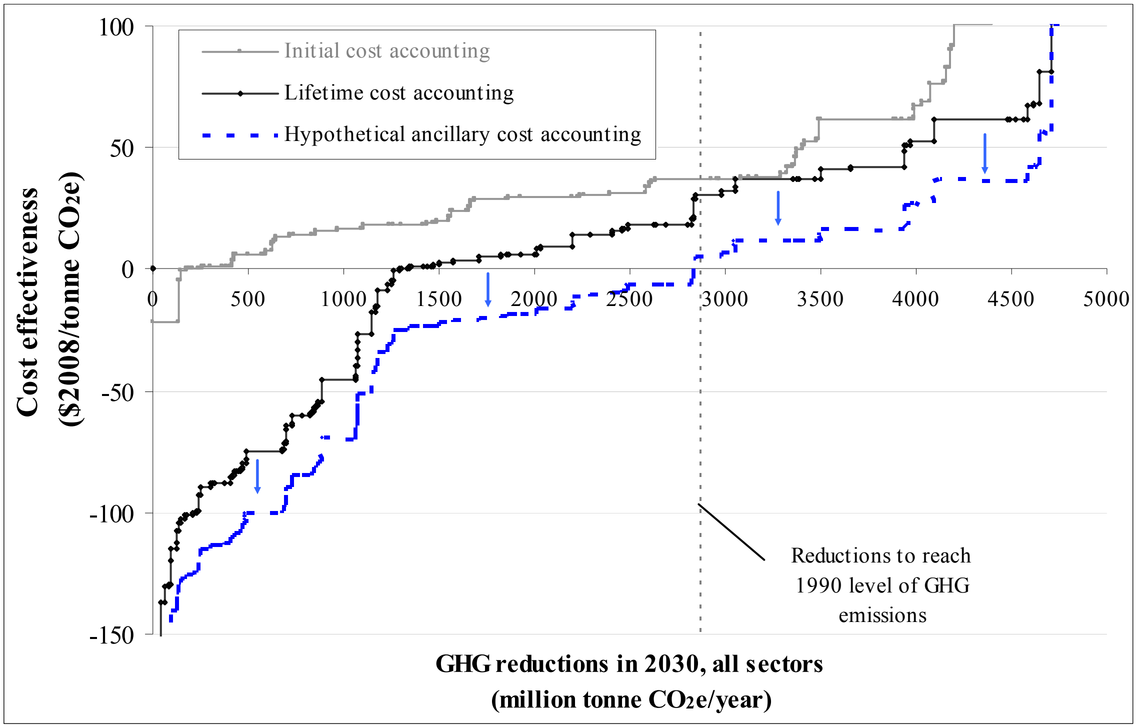


Figure 75. Cost effectiveness curves, with hypothetical ancillary cost accounting curve

10.5. Policy Approaches

By choosing a technology-based approach, this dissertation reports on mitigation opportunities irrespective of any policy instruments that can advance the deployment of the GHG technologies. As such, this research has been intentionally agnostic on the questions of which mechanisms would best be applied to bring about the GHG reductions. However, the findings of this research do offer several implications that are relevant to the choice of policy instruments.

This study avoids the larger question of comparing market-based vs. regulatory mechanisms for GHG emission reductions. However, imposing the value of carbon credits from the European Union Emission Trading Scheme (ETS), offers some illustration of the level of potential GHG emission reductions available if a comprehensive GHG policy with some form of carbon-constraints were developed in the U.S. Carbon credits on the ETS from 2005 to April 2006, when the scheme was functioning, generally ranged in value from 20-25 € per tonne CO_2e. At an exchange rate of $1 per 0.65 €, these GHG credits are roughly equivalent in value to $30-40 per tonne CO_2e.

Figure 76 shows the cost-effectiveness curves in comparison with that value of GHG emission reduction. If an emissions scheme with that value per tonne of emission resulted, the supply curves indicate that emission reductions of deployed technologies could range from 2000 to 3500 million tonne CO_2e reductions per year. The lower part of that emission reduction range corresponds to the deployment of GHG technologies in closer accord to the initial cost accounting, and the higher part corresponds to a lifetime cost accounting where discounted energy impacts of the GHG mitigation technologies are incorporated into the decision-making.

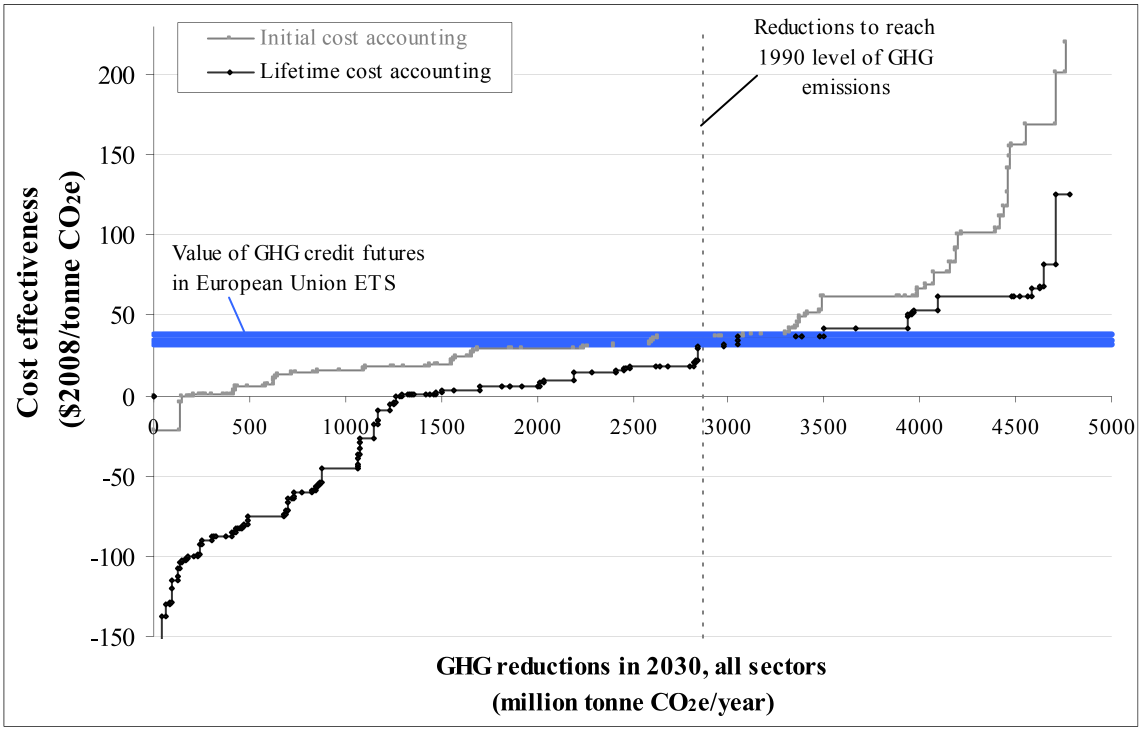


Figure 76. Cost effectiveness curves for GHG reduction technologies, compared with value of GHG credits in European Union

The technologies assessed herein could feasibly be brought into the market via business-as-usual market demand (in the case of increasing fuel prices), voluntary industry initiatives, regulatory performance standards, or by the introduction of an emissions trading exchange for greenhouse gas emissions. The mechanism, however, would clearly influence the timing of the introduction and the relative deployment of the technologies. Historically the range of fuel prices in the U.S. has not been high enough to encourage large-scale GHG mitigation from widely available low-GHG technologies. Likewise, the prevailing system of voluntary initiatives in the U.S. has not brought forth large-scale GHG mitigation. Therefore, it would appear that more forceful policy instruments, such as performance standards for technologies and/or some form of emissions pricing, will be required to encourage the deployment of GHG mitigation technologies on the scales discussed in this analysis.

There are more policy alternatives to promote and/or mandate GHG mitigation technologies than there are GHG mitigation technologies. The most important question in light of this research is about which policy instruments can better promote adoption of the technologies with net economic benefits from the various economic sectors. For broad national climate change mitigation, there are three general policy approaches: (1) GHG emissions caps with a trading scheme, (2) prices or fees that are tied to GHG emissions (and/or energy use), and (3) performance or regulatory standards that mandate lower GHG technologies. These policies to promote deployment of lower GHG technologies are not mutually exclusive. Different approaches for different sectors could even be advantageous, considering the characteristics, relative cost-effectiveness, and available technologies for each economic sector.

A comprehensive GHG emissions cap-and-trade system is likely to promote deployment of many of the GHG mitigation technologies in accord with how these technologies are ranked on the initial cost-effectiveness curve. Such a system is likely to provide clear GHG price signals to institutional and industrial actors, e.g. in the electric power. Such emissions schemes have had success for the power sector in cost-effectively reducing criteria pollutant emissions in the U.S. EPA's acid rain program to reduce sulfur dioxide and oxides of nitrogen emissions. On the other hand, a cap-and-trade system would have a more difficult time reaching and promoting GHG-reduction actions among millions of dispersed and diverse end users (e.g. vehicle, appliance, and building users/purchasers) of GHG-generating technologies.

Of the broad policy approaches, the GHG-fee-based system is most likely to promote technology adoption that resembles the lifetime cost accounting supply curve from this analysis. A fee-based GHG mitigation policy internalizes GHG emissions – and, for the efficiency technologies, energy use – in the decisions of the purchasers and users of the GHG-generating technologies. Such a policy approach is more likely to efficiently direct GHG mitigation actions toward those that are net beneficial – those below \$0/tonne CO_2e in lifetime costs. As a result this form of policy is likely to be more effective in capturing the potential GHG emission reductions in the transportation and building sectors, where technology users are less likely to otherwise consider the energy cost impacts of their purchases

Performance or regulatory standards to mandate lower-GHG emissions characteristics of various products and processes could also be applied to push the GHG mitigation technologies evaluated in this research. Standards become more attractive in sectors and subsectors that are practically or politically not as easily compatible with cap-and-trade or fee-based systems. One example of such a GHG mitigation area would be a regulation on the global warming potential of refrigerants. Such refrigerants result in higher-potency non-CO_2 GHG emissions, but they could be outside the purview of a CO_2 emissions trading scheme, and an energy-based fee would not impact these GHG emissions.

Other policy instruments could offer further promotion of more cost-effective GHG mitigation. With carbon constraints in the economy, the cost-effective deployment of any GHG technologies – and especially those with associated energy savings – would benefit from better education and dissemination of information regarding the uses of various technologies and their associated energy and GHG consequences. There are a number of technologies with great GHG reduction potential that were evaluated to have considerably higher cost-effectiveness values (e.g., advanced electric drivetrain vehicles and solar electricity generation) largely on account of their less mature state of research development. Technologies at this stage could more readily benefit from cost-sharing research and development and pilot studies until initial costs come down and their cost effectiveness is sufficiently low to justify more widespread industry or policy action.

11. CONCLUSIONS

This research identifies and quantifies many aspects of available, near-term GHG mitigation technologies, their potential impacts, and their relative and cumulative cost-effectiveness. Scores of near-term and emerging GHG mitigation technologies in all sectors of the U.S. economy are analyzed. A framework is developed to evaluate the technologies' cost-effectiveness according to their initial costs, lifetime discounted cost impacts, and emission reduction impacts. By applying the evaluation framework to the portfolio of mitigation technologies on an equal footing, the available GHG mitigation options are compared, contrasted, combined, and studied more deeply. The results of the analysis bring forth a number of research contributions and policy implications.

All major economic sectors (i.e. transportation, residential and commercial buildings, industry, agriculture, and electricity generation) have technology options that offer substantial GHG reductions at low cost-effectiveness values. At an initial technology cost-effectiveness value of $50 per tonne CO_2e, each major sector can reduce its own sector's emissions by 13%-29% from baseline 2030 emissions with near-term technologies identified in this research. When considering the beneficial energy impacts of these known GHG-reduction technologies, greater emission reductions are feasible and cost-effective.

Considering actions from the multiple sectors together and including the energy savings of the GHG reduction technologies, reductions to achieve the benchmark of the U.S. 1990 GHG emission level – a 31% reduction from reference 2030 emissions – could be met with GHG-reduction technologies that each have lifetime technology costs no greater than $30 per tonne CO_2e. Deploying all technologies with lifetime cost-effectiveness values at or below $0 per tonne CO_2e (i.e., the so-called "no regrets" options) would achieve approximately half of the reductions that would be needed to reduce U.S. GHG emissions to their 1990 levels by 2030.

Different economic sectors have very different "supply curve" characteristics for the amount of GHG mitigation that is available at for a given cost. That is, for a given cost-effectiveness value, very different amounts of GHG mitigation are available from technologies in each of the sectors. These different cost-effectiveness curve characteristics could impact whether future climate change mitigation policy would seek to make each sector "pull its weight," or contribute consistently to overarching GHG reduction targets. Agriculture and electricity generation sectors offer the largest potential amount of GHG reductions; however, the transportation, residential and commercial building, and industrial sectors all offer greater reductions when looking specifically at lower cost-effectiveness values, largely on account of technologies in those sectors having greater energy savings associated with the efficiency-related GHG mitigation technologies.

A contribution of this research is that by separately evaluating GHG mitigation curves by initial cost-effectiveness and lifetime cost-effectiveness, two distinct supply curves are created. The initial-cost-only mitigation curve more closely resembles how society operates, on account of, among other things, there being no carbon constraint and that people heavily discount or exclude future energy savings when purchasing technology. The construction of mitigation curves that bundle the lifetime economic impacts of the energy use-reducing equipment into the cost-effectiveness evaluation allows for a more comprehensive evaluation and prioritization of available GHG mitigation technologies.

Whether GHG mitigation policy prioritizes GHG mitigation actions according to their initial or lifetime cost-effectiveness evaluations would have a number of effects. As shown in this research, the chosen cost accounting framework used for prioritizing mitigation technologies impacts the ordering of technologies deployed, the average cost-effectiveness, the amount of GHG reductions that come from each sector, and the overall economic impacts. Lifetime cost effectiveness accounting on the whole reveals GHG mitigation opportunities with lower overall costs. Shifting from initial cost accounting to lifetime cost accounting distributes the GHG mitigation actions across the sectors more evenly among electric utilities, vehicle users, farms, industries, and households. Prioritizing GHG mitigation actions by lifetime cost effectiveness, although it would increase the initial technology deployment costs (by about 40%), would greatly increase the lifetime energy savings (by almost a factor of two) and increase the net benefits of a GHG mitigation scenario (by a factor of four).

Because there is an abundance of GHG technologies with net economic benefits that are currently available but not widely adopted, this is an apt area for policy to lend some guidance. Broad GHG mitigation policy approaches, such as cap-and-trading schemes, price- or fee- based incentives for GHG-generating practices or products, or regulatory standards, to promote deployment of lower GHG technologies are not mutually exclusive. In fact different approaches for different sectors could even be advantageous, considering how different attributes of the general policy approaches align more closely with the available GHG mitigation technologies in each economic sector. In any case policies that do not recognize the diversity of GHG reduction opportunities available throughout the economy could easily miss out on golden opportunities that simultaneously yield emission reductions and net economic benefits.

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