Carnegie Mellon University

Energy Efficiency in the U.S. Residential Sector:

An Engineering and Economic Assessment of Opportunities for Large Energy Savings and Greenhouse Gas Emissions Reductions

A dissertation submitted in partial fulfillment of the requirement of the degree of

Doctor of Philosophy in Engineering and Public Policy

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List of Abbreviations

AEC	Annual Energy Consumption
AEO	Annual Energy Outlook
ARRA	American Recovery and Reinvestment Act
CEC	California Energy Commission
CCS	Carbon Capture and Storage
CCT	Color Correlated Temperature
CFI	Carbon Financial Instrument
CFL	Compact Fluorescent Lamp
CRI	Color Rendering Index
CPUC	California Public Utilities Commission
DEER	Database on Energy Efficient Resources
DOE	Department of Energy
ECX	European Climate Exchange
EE	Energy Efficiency
EERE	Energy Efficiency and Renewable Energy

EIA	Energy Information Agency
ER	Earning Rate
ERAM	Energy Rate Adjustment Mechanism
ESCOs	Energy Service Companies
EPACT	Energy Policy and Conservation Act
EPRI	Electric Power Research Institute
EISA	Energy Independence and Security Act of 2007
EU	European Union
EU-ETS	European Emissions Trading Scheme
EU15	European Union with 15 member countries
EU25	European Union with 25 member countries
FERC	Federal Energy Regulatory Commission
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emission
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IOU	Independently Owned Utility
LAC	Levelized Annual Cost (2007$/year per unit of equipment)
LED	Light Emitting Diodes
LPG	Liquefied petroleum gas
NAEPA	National Appliance Energy Conservation Act

NEMS	National Energy Modeling System
NGCC	Natural Gas Combined Cycle
NPV	Net Present Value
NRDC	Natural Resources Defense Council
NYSERA	New York State Energy Research and Development Authority
OLED	Organic Light Emitting Diodes
OTA	Office of Technology Assessment
PC	Pulverized Coal Power Plant
PEB	Performance Earnings Basis
PPP	Purchasing power parities
PURPA	Public Utility Regulatory Policy Act
PV	Photovoltaic
RGGI	Regional Greenhouse Gas Initiative
RREEM	Regional Residential Energy Efficiency Model
RFF	Resources for the Future
SEER	Seasonal Energy Efficiency Ratio
SSL	Solid State Lighting
UEC	Unit Energy Consumption
US	United States of America
ΔLAC	Incremental Levelized Annual Costa Samaras
ΔNPV	Incremental Net Present Value

Units

BTU	British thermal units
GWh	Giga-watt hour
kWh	Kilowatt hour
lm	Lumen
MMBTU	Million metric British thermal units
MWh	Mega-watt hour
ton CO_2	Metric ton of carbon dioxide
TWh	Tera-watt hour

Abstract

Addressing the issue of climate change mitigation will be one of the most daunting tasks of our generation. A large set of strategies for carbon mitigation are needed on a global scale to reduce greenhouse gas (GHG) emissions by 80% below 1990 levels by 2050, in order to avoid global irreversible consequences of climate change. In light of possible near-term GHG regulations, the US Government is now paying more attention to various options for carbon mitigation. Energy efficiency and conservation is a very promising part of a portfolio of strategies.

Today, US residential buildings sector account for nearly 17% of US GHG emissions and several new technologies and energy efficiency measures offer potential for large energy savings. While energy efficiency options are currently being deployed or considered as a means of reducing carbon emissions, there is still large uncertainty about the effect of such measures on overall carbon savings.

The first part of this thesis provides an assessment, at the national level, of the energy efficiency potential in the residential sector. I estimate the 2009 energy efficiency potential for the residential sector and its costs under several different scenarios. These include assuming that consumers bear the costs of new technologies, assuming that utilities are incentivized to promote energy efficiency, and estimating the societal costs and benefits of energy efficiency.

Throughout this work, I build the argument that energy efficiency policies cannot consider efficiency gains in energy, electricity or carbon dioxide alone. Instead, the effects of each of these three indicators should be considered in energy efficiency assessments.

I conclude that there is a large potential for energy efficiency in the U.S. residential sector, but large investments are needed realize this potential, since consumers are unlikely to voluntary adopt the most efficient end-use devices.

The second part of this thesis deals with a detailed assessment of the potential for white-light LEDs for energy and carbon dioxide savings in the U.S. commercial and residential sectors. Lighting constitutes more than 20% of total U.S. electricity consumption, a similar fraction in the E.U., and an even a larger fraction in many developing countries. Because many current lighting technologies are highly inefficient, improved technologies for lighting hold great potential for energy savings and for reducing associated greenhouse gas emissions. Solid-state lighting shows great promise as a source of efficient, affordable, color-balanced white light.

Indeed, assuming market discount rates, engineering-economic analysis demonstrates that white solid-state lighting already has a lower levelized annual cost (LAC) than incandescent bulbs. The LAC for white solid-state lighting will be lower than that of the most efficient fluorescent bulbs by the end of this decade. However, a large literature indicates that households do not make their decisions in terms of simple expected economic value.

After a review of the technology, I compare the electricity consumption, carbon emissions and cost-effectiveness of current lighting technologies, accounting for expected performance evolution through 2015. I then simulate the lighting electricity consumption and implicit greenhouse gases emissions for the U.S. residential and commercial sectors through 2015 under different policy scenarios: voluntary solid-state lighting adoption, implementation of lighting standards in new construction and rebate programs or equivalent subsidies. Finally, I provide a measure of cost-effectiveness for solid-state lighting in the context of other climate change abatement policies.

Acknowledgements

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There are many good mentors in Academia, but I feel it would be difficult to outpace Granger Morgan. Working with him during these last three and a half years (and hopefully for many more years to come in future joint work), made me grow immensely as a researcher. Granger provided me the independence I needed to develop my own projects, but also wonderful guidance whenever needed. The experience at the Engineering and Public Policy Department wouldn't be the same without him. Managing to work in such a diverse set of interesting environmental and energy related issues and at the same time being able to have such a great interaction with students, those are two things I learned from Granger and aim to achieve myself as a researcher.

I also feel extremely lucky with my committee members. Lester Lave and Jay Apt provided continuous support of my work and constructive critiques. These interactions helped me refine my research goals and made me consistently try to improve the quality of my work. This is something that will accompany me for the rest of my professional life. Karen Palmer, from Resources for the Future, provided much more of her time than could possibly be expected from an external committee member. Our bi-weekly meetings to discuss the status of my research during the last year were extremely important to the energy efficiency part of this dissertation. Karen was also a wonderful and dedicated advisor during the two internships I have pursued at Resources for the Future. Finally, Paulo Cadete Ferrão, from IST, always supported my work: since my time as an undergraduate at IST, as a master student working under his supervision, and finally during my PhD work at Carnegie Mellon University. He was the faculty member who most encouraged me to apply to the EPP PhD program Carnegie Mellon University, encouragement for which I am very thankful.

During my PhD I was fortunate to be able to spend two summers collaborating with researchers at Resources for the Future. Besides Karen Palmer, I would like to also thank Dallas Burtraw, Shalini Vajjhala, and Anthony Paul for the great environment provided during my internships. I would like to offer a special acknowledgment to Erica Myers for her work on transforming the input tables from NEMS to a useful database. Also, the first part of this dissertation would not have been possible without the tables of input and output data and explanations of how those are used in NEMS provided by John Cymbalsky from the Department of Energy. The work on solid-state lighting was much improved with the suggestions of Fritz Morgan and Kevin Dowling from Color Kinetics, and from Scott Mathews at CMU.

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Part 1. Using Regional Residential Efficiency Supply Curves for Decision-Making

Chapter 1. Introduction

1.1 Background

Climate policy in the US is gaining momentum and a framework for greenhouse gas emissions trading is likely to emerge over the next several years. The likely future cap-and-trade program will encourage a transition to a low-carbon economy. Yet, if the program has low allowance prices, it is unlikely that the large investments necessary in the power sector to reduce the carbon intensity of electricity generation will occur. This has been the case in the EU-ETS, with the European Climate Exchange CFI Futures contracts now being traded at around €10/tonCO_2 (\$13/tonCO_2)[1]. Similarly, in the Regional Greenhouse Gas Initiative (RGGI) allowances are currently traded at roughly \$3 per ton of CO_2[2]. Such a low allowance price is likely to only marginally affect consumer behavior in the residential sector due to the small share of electricity expenses in the overall household bundle of goods.

In order to come close to the large emissions reductions needed, additional measures beyond cap and trade will be necessary [1]. While an enormous amount of effort has been devoted to understanding potential mitigation strategies on the supply side, at least in the US, energy efficiency and conservation is only now receiving increased attention.

I define energy efficiency as the set of measures that can be used to provide the same energy service (lighting, heating, cooling, etc) using less energy. Therefore, "energy efficiency" does not account for efforts made by consumers to decrease energy consumption via behavioral changes, such as lowering thermostats or switching off light bulbs. Such efforts are defined as conservation measures. While the understanding of behavioral pattern changes may be an important part of solving the climate change problem, the primary scope of this work is to assess the energy efficiency potential in the residential sector, excluding conservation measures.

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[1] See the European Climate Exchange (ECX) for further details. Prices for futures in 2008, depending on the settlement date, ranged from €14 to €38 per tonCO_2. Source: http://www.europeanclimateexchange.com

[2] See the Regional Greenhouse Gas Initiative for further details. Source: http://www.rggi.org/home

The large contribution of the residential sector to energy consumption and carbon emissions makes it a very important component in achieving a more sustainable energy system. In fact, the residential sector accounts for 37%[3] of national electricity consumption, 17%[4] of greenhouse gas emissions and 22%[5] of primary energy consumption. For electricity-powered end-uses, the conversion losses from primary energy to the plug are approximately 60%, Figure 1.

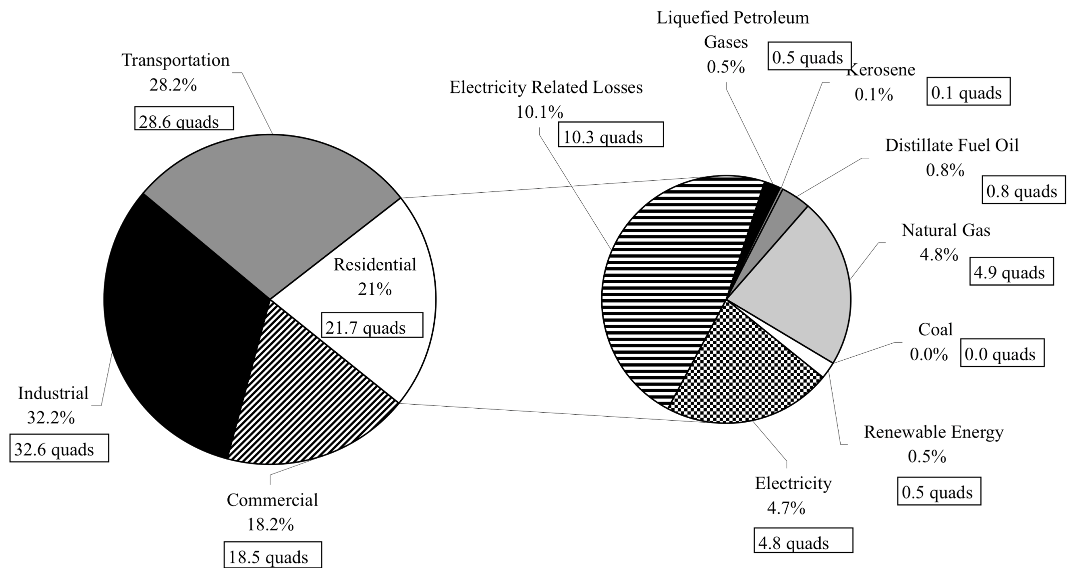

Figure 1 – Share of primary energy consumption by sector (in quadrillion BTU). Detail on residential primary energy consumption by fuel and electricity related losses. Constructed using data from EIA, AEO 2008 data for 2007 [2].

[3] Using 2008 AEO detailed tables, Table 10 – Energy Consumption .by Sector and Source, United States.
[4] Using EIA GHG flow from 2006. EIA reports that the residential sector is responsible for 1,234 million metric ton of carbon dioxide equivalent, and that total greenhouse gases emissions in the United States are 7,076 million metric ton of carbon dioxide equivalent.
[5] Using AEO 2008 detailed tables, Table 10 – Energy Consumption by Sector and Source, United States. In 2008, the residential sector accounted for 22 quads of primary energy consumption. The national primary energy consumption was 102 quads.

Despite wide acknowledgment that the residential sector provides an opportunity for large energy and greenhouse gas savings, harvesting such potential is rather challenging. Supply-side options targeting the power sector can be confined to roughly 17,000 generators, but demand-side options in the residential sector are likely to need to consider end-use appliances and devices distributed in more than 128,000 million homes[6]. Therefore the distributed nature of end-use devices and appliances, as well as heating and water heating systems, requires rather different policy approaches from those applied to the electric sector.

Efforts to increase the efficiency of residential end-uses should couple the goals of both energy and climate policy. This in turn raises the question of whether to prioritize efficiency measures in terms of primary energy, delivered energy, electricity, greenhouse gas reduction, or some other metric. The policy design is very likely to change depending on the goals pursued. For example, while the largest contributors of primary energy consumption and carbon dioxide emissions in the residential sector are heating, hot water, lighting and cooling, in decreasing order, as shown in Figure 2 and Figure 3, the largest contributors in terms of electricity consumption are, in decreasing order, lighting, cooling, refrigerators and heating. There are also substantial regional differences across end-uses and across their impacts. Therefore, a large part of this work deals with how different criteria for comparing outcomes of energy efficiency for different end-uses affect decision-making and policy recommendations.

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[6] http://www.census.gov/Press-Release/www/releases/archives/housing/012760.html

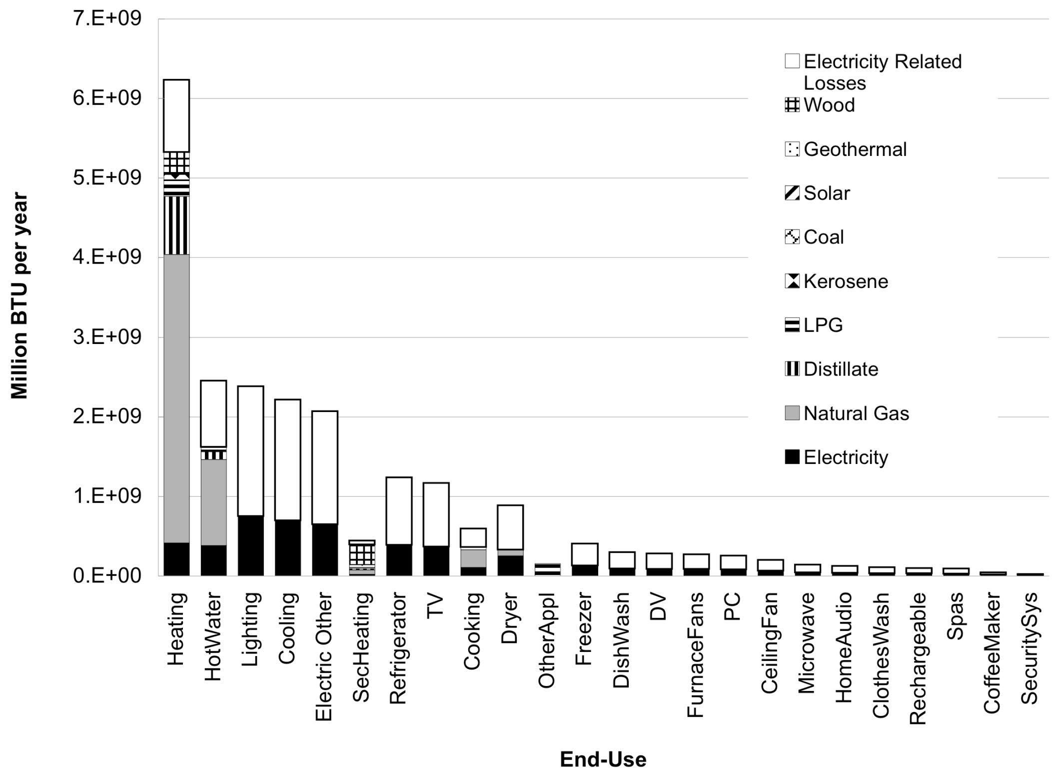

Figure 2 – Contribution of different residential end-uses to primary energy consumption (million BTU). Source: constructed using data from DOE [3] [4].

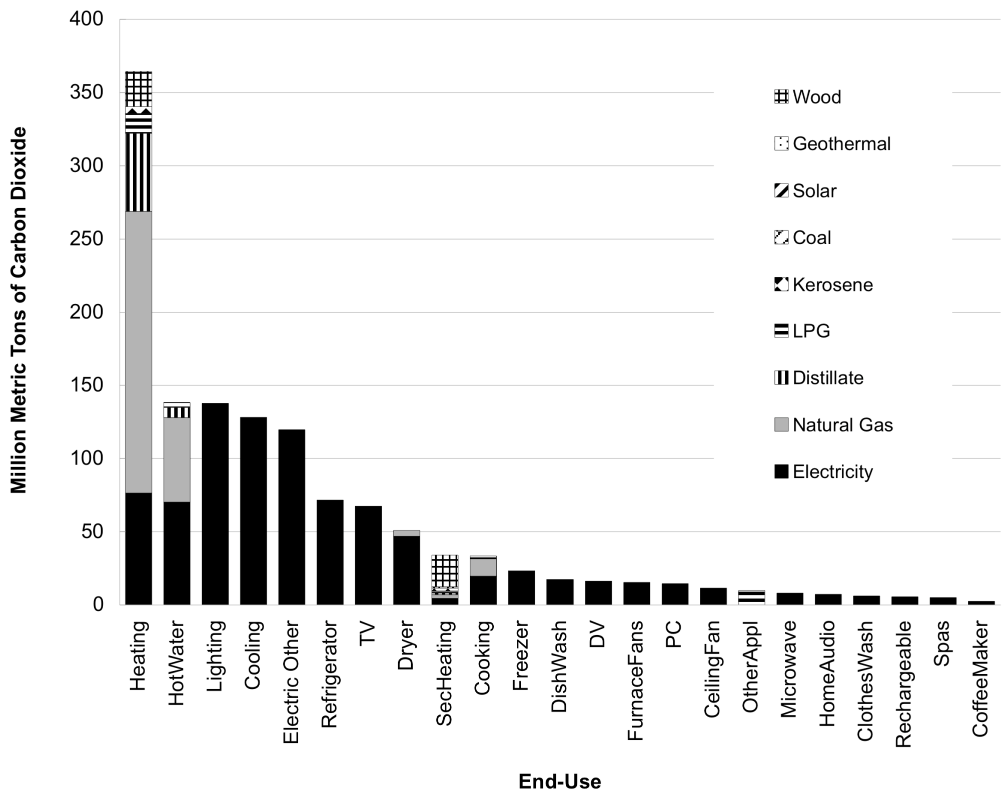

Figure 3 - Contribution of different residential end-uses to greenhouse gas emissions (million metric ton of CO_2). Data from [2] [3].

1.2 Grounds for Policy Intervention

An ongoing debate regarding the use of policies to promote the adoption of more efficient end use devices concerns whether the inclusion of minimum efficiency standards or similar policies might be seen as restricting consumer choice with implications of a reduction of social welfare. According to the perspective of standard neoclassical economics, this might be the case in a decentralized market under idealized conditions [5]. Such idealized conditions include the assumption that that consumers behave rationally and that no externalities exist. A violation of one or more of these idealized conditions constitutes a market failure or market imperfection, and the efficient outcome will not occur in the absence of policy intervention [5]. Market barriers include all the "feature(s) of the energy services market that are believed to inhibit investment in energy efficiency" [6]. Some of the main barriers (which might or might not be due to market failures) identified in engineering-economic approaches include:

- Misplaced incentives [7] [8]
- Imperfect information [7] [5]
- Decisions influenced by habit [7]
- Non-perfect substitutability [7]

- Externalities [5] [7].
- Electricity price [5] [7].
- Bounded rationality [5]
- Uncertainty[7] [7]
- Transaction costs [5] [7].
- Lack of access to financing [6] [7].

While technologists, through engineering-economic analysis, argue that the market failures and barriers listed above provide grounds for policy intervention, Sutherland [5], [9] and other economists argue that there is no evidence that consumers would be better off if regulatory policies, such as standards, were in place. Sutherland claims that if such large net benefits could be gained, then consumers would already be taking advantage of them. These opposing schools of thought on the nature and existence of the "energy efficiency gap" are still engaged in an ongoing debate. This work assesses the energy efficiency potential assuming an engineering-economic perspective. Furthermore, some simulations that are not included in the present work were run to explain the energy efficiency gap with the use of high implicit discount rates used by consumers when making decisions[8]. It is assumed, throughout this work, that policies are in fact needed to

[7] Lovins [7] includes both irreversibility and uncertainty as barriers to the adoption of energy efficient technologies. However, I would argue from the description of the "irreversibility" barrier that the irreversibility is already accounted for in the "uncertainty" barrier.

[8] The key findings from those simulations is described in Chapter 8.

harvest the energy efficiency potential. Whether or not consumers are behaving rationally, as defended by Sutherland, grounds for policy implementation still hold given environmental externalities and issues of security of supply.

1.3 Energy Efficiency Policies

1. 3. 1. Efficiency Standards

Efficiency standards are defined as regulations that require end-use technologies to meet minimum efficiency requirements [10]. No restrictions are placed on the way manufactures design products, as long as they meet the specified efficiency levels [10]. Historically, appliance standards have proven to be an effective mean of harvesting energy efficiency potential in a number of cases.

The particular context of the 1970s, with the OPEC oil embargo of 1973, the Iranian hostage crisis of 1979 and the Iran-Iraq war in 1980, led to sharp increases in petroleum prices [11],[12]. Energy became an important part of the public debate as increases in energy costs occurred. At the same time, the construction of new power plants became decreasingly profitable to utilities [8]. High-energy prices and growing environmental concerns led regulators and industries to turn to energy efficiency and conservation as means to help meet the US energy demand. During that period, California was a pioneer in developing and implementing standards. The 1974 Warren-Alquist Act established the

California Energy Commission (CEC) [10], which was provided with the authority to set appliance efficiency standards[9] [13]. Standards were also enacted in New York State in the same year[10].

Interest in expanding standards nationally followed after the pioneer effort of states like California. The Energy Policy and Conservation Act of 1975 (EPACT 1975) during the Ford Administration called for voluntary standards targeting on average a 20% reduction in new appliance energy use relative to the current levels [10]. In 1978, during the Carter Administration, Congress passed the National Energy Conservation and Policy Act, which called for mandatory standards. Due to the time it took to develop such standards during the Carter Administration and the setbacks suffered during the Reagan Administration, the standards were only implements a decade latter [10].

Only in 1987, through a joint effort of industry and energy efficiency advocates, were standards finally included in the National Appliance Energy Conservation Act (NAEPA), which established national standards for 15 categories of household

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[9] The first mandatory standards taking effect in 1976. Today, CEC is also the State's primary energy policy and planning agency. Its mission is to forecast future energy needs, administer various sources of support for renewable energy, license thermal power plants 50 MW or larger, support energy related research, development, and demonstration programs, and promote energy efficiency by setting and enforcing the State's appliance and building efficiency standards.

Meanwhile, the California Public Utility Commission’s (CPUC) mission is to oversee the regulation of privately owned electric and natural gas, and require companies to ensure that consumers have safe and reliable utility service at reasonable rates.

For more detail, see: http://www.energy.ca.gov/commission/index.html

[10] For more detail, see: http://www.energy.ca.gov/commission/index.html

appliances[11] [14] [10]. These standards were updated and expanded to other products in 1988 and in 1992. DOE periodically updates standards through a rulemaking process [10]. The revisions of 1992, under the Energy Policy Act (EPACT), extended standards to induction motors and lamps.

California, New York, Florida, and Massachusetts had already adopted minimum efficiency standards by 1986. Today, these States are also in the forefront of policy making regarding greenhouse gases regulation.

In 2005, the new Energy Policy Act updated or added energy standards for several products[12]. [15]. Recently, under the 2007 Energy Independence and Security Act (EISA 2007), several appliance standards were implemented or updated, allowing DOE to expedite rulemakings in response to broad consensus agreements on recommended new standards [16], [17][13].

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[11] Those were refrigerators, freezers, clothes washers, clothes driers, dishwashers, kitchen ranges, kitchen ovens, room air conditioners, direct heating equipments, water heaters, pool heaters, central airs conditioners, central heat pumps, furnaces, and boilers.

[12] Updates or new standards for residential end-uses included lighting fixtures, compact fluorescent lamps, dehumidifiers, mercury vapor lamp ballasts, fluorescent lamp ballasts, and ceiling fan light kits.

In addition, it calls for the DOE to set efficiency standards via a rulemaking on external power supplies and battery chargers. Other relevant provisions of 2005's EPACT included: a public awareness campaign and an update of the *Energy Guide* appliance labeling by the Federal Trade Commission; a call for a study on State and regional policies to promote energy efficiency; the expansion of an existing technical assistance program to States to include a component on code implementation; authorization for continued and new R&D programs; and, a program to co-fund appliance rebate programs established by states

[13] The updated or new residential appliance and equipment efficiency standards included dishwashers and dehumidifiers, residential boilers, incandescent lamps, external power supplies, and metal halide lamp fixtures.

It has been claimed that efficiency standards might increase the production costs to manufacturers, resulting in higher retail prices to consumers. There are mixed findings concerning this effect. In fact, there is evidence that in some cases the retail prices of devices or appliances have decreased after the implementation of standards. For example, Greening et al. [18] found that the average real retail price of refrigerators remained unchanged following the 1990 standards, and that the price of refrigerators decreased following the 1993 standards [10]. Standards for refrigerators were implemented in California in 1977, Figure 4. From then on, refrigerators became larger, cheaper and by 2002 consumed one third of the energy they did in the 1970s. However, there is also evidence that the price of products like air conditioners, refrigerators and clothes washers increased after standards were enacted, though such increases were smaller than what DOE assessments predicted [19].

Table 1 summarizes a timeline of federal standards for different types of end-uses and appliances.

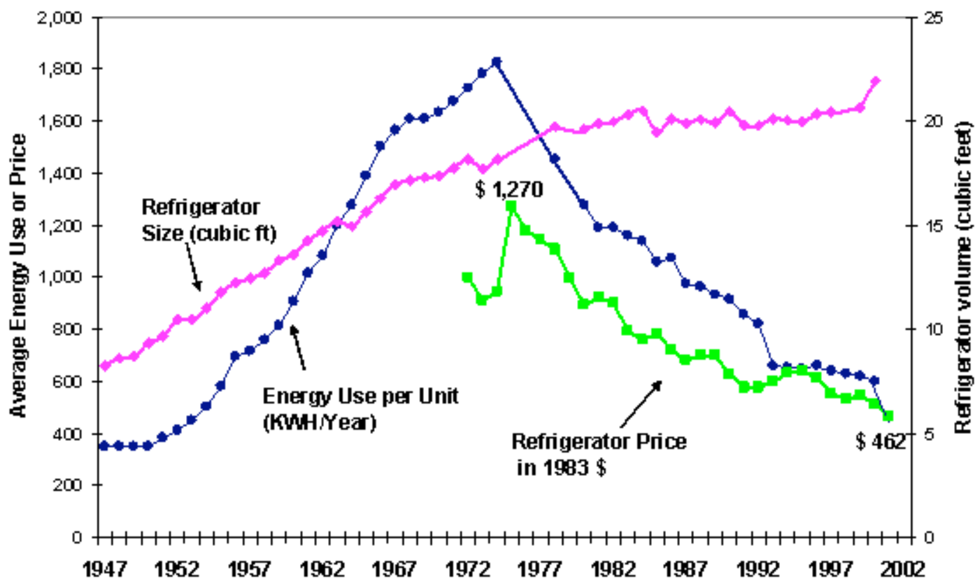

Figure 4 – Average energy use (kWh/year), price (in $1983) and size (cubic feet) of refrigerators in the United States. Source: CLASP and APEC ESIS.

Table 1 – U.S. Equipment efficiency standards by product and initial effective date. Adapted from [10] and [20]

Product/ Year	1988	89	90	91	92	93	94	~	2000	01	02	03	04	05	06	07	08	09
Refrigerators Freezers			x			x				x								
Clothes Washers	x						x						x			x		
Clothes Dryers	x						x											
Dishwashers	x						x											
Room Air Conditioners			x						x									
Residential Central A/C, Heat Pumps, Furnaces					x										x			
Direct Heating Equipment			x															
Residential Water Heater			x										x					
Boilers					X													
Kitchen Ranges and Ovens			x															
Pool Heaters			X															
Lighting			X										X	x				

1. 3. 2. Informing the Consumers and Labeling Products

Information and consumer awareness campaigns, including product labeling, have been part of U.S. energy efficiency policies since the 1980s. The success of these programs varies widely. While the "Energy Guide" label has very little impact on consumers' product choices, the "Energy Star" labeling program run by the U.S. Environmental Protection Agency (EPA) has had a very big impact for some products [10]. Gillingham et al. [14] found that voluntary programs achieved approximately the same amounts of energy savings as mandatory programs, while costing substantially less money. However, the savings from voluntary programs is more difficult to quantify than from mandatory programs since typically no audit or verification process occurs.

1. 3. 3. Utility Sponsored Energy Efficiency Programs

Despite the decline in demand growth during the 1970s, which led to an excess of generating capacity, the 1980s demand growth raised fears of electricity shortages, which led to the adoption of the Public Utility Regulatory Policy Act (PURPA). PURPA directed the states to consider alternatives to traditional ratemaking approaches with the intention of encouraging energy efficiency and conservation, and sending clear price signals to consumers [8].

An integrated resource planning perspective was adopted by some states, aiming to minimize costs to society of meeting demand for electric energy services [21].

This issue led several states to implement or consider "decoupling". Under decoupling, utilities are ensured of recovering their fixed-costs of delivering electricity, independent of future electricity sales. Under a system of decoupling of electricity sales, utilities are not necessarily encouraged to pursue energy efficiency programs. Without a further incentive or regulation, utilities do not realize any benefits in doing so. Therefore, decoupling may address utility concerns about lost revenues, but it is not a sufficient condition for encouraging investments in energy efficiency.

With restructuring of the electricity sector, risk-aversion towards energy efficiency programs increased [21]. Utilities were uncertain on how the future mechanisms would allow them to recover the costs in such programs. As Gellings [21] describes it:

> "Before the restructuring of the electricity sector, regulators could mandate the utilities to include programs costs in the utility rates, but when utilities moved from vertically integrated monopolies to competitive generation, there was a concern that including program costs in the rates would create a competitive disadvantage for the incumbent utilities."

In order to guarantee that utilities or ESCOs recover the investment costs in energy efficiency, independently of whether or not decoupling is in place, "non by-passable" surcharges are applied. Two general designs exist for such charges. One design is to impose a "system benefit charge" on a per kWh basis, which is included in customers' bills from the distribution utility. This is the case in California, where the fund raises $228 million annually, for energy efficiency programs and measures, by charging consumers roughly 0.0054$/kWh[14]. The IOUs[15] use these funds for program implementation, with the oversight of the CPUC. Using information from [23], I conclude that Connecticut, Illinois, Maine, Massachusetts, New Hampshire, New Mexico, New York and Oregon, have similar designs to California for fund allocation, where a specific system benefit charge and respective fund are aimed to pursue energy efficiency measures. However, in Delaware, D.C., Michigan, Montana, New Jersey, Ohio, Pennsylvania, Rhode Island, Vermont and Wisconsin the funds are used both for energy efficiency and renewable technology programs. While investments in energy efficiency are likely to reduce electricity sales, investments in renewable energy will help to maintain electricity sales levels. Therefore, in the areas where decoupling does not exist, a lack of specific allocation of funds to energy efficiency might induce utilities to invest in renewable energy instead of energy efficiency measures. I suggest that in such cases, the state PUCs should guarantee that at least part of the funds should be directed to energy efficiency programs. The amount of the funding directed to efficiency will depend on the specific priorities of each region.

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[14] Note: The rates vary by utility and customer class. Source: http://www.dsireusa.org/library/includes/seeallincentivetype.cfm?type=PBF&currentpageid=7&back=RegEETab&TType=2&EE=1&RE=1

[15] Pacific Gas & Electric (PG&E), Southern California Edison, Southern California Gas Company, and San Diego Gas & Electric.

The other funding mechanism is to include the charges as a flat monthly fee, rather than on a per kWh basis. Different approaches are also used for the administration of the revenue collected. While some states rely on administration by utilities of those funds' allocated to different energy efficiency programs (as is the case in California), other states rely on government agencies or non-profit organizations. An example of the latter is the non-profit organization Efficiency Vermont.

In recent years, some states have again shifted towards a decoupling approach. Figure 5 presents a map showing those states, which currently have decoupling, or aim to move towards decoupling mechanisms in the near future.

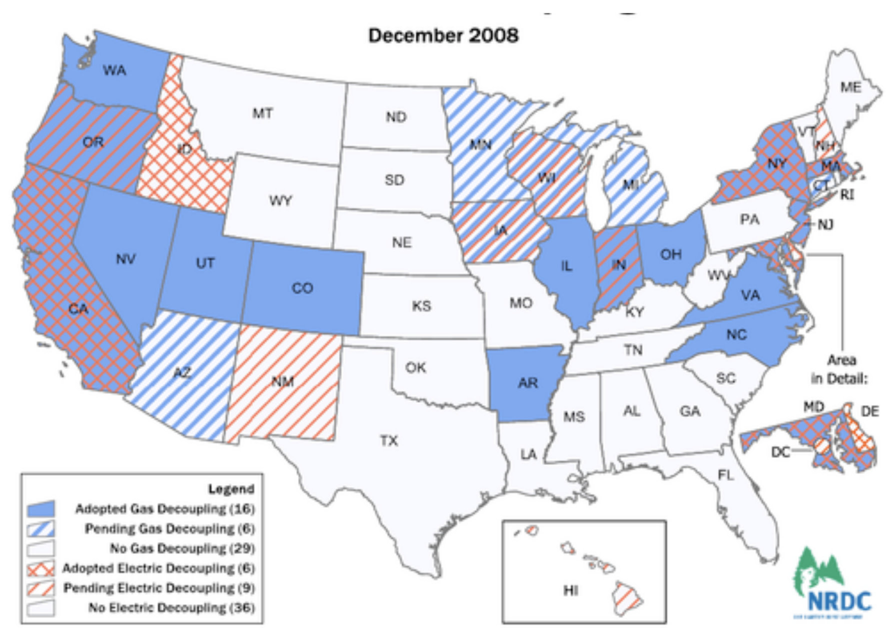

Figure 5 – States where decoupling of natural gas or electricity is adopted or pending. Source: NRDC, December 2008[16].

[16] Available at: http://switchboard.nrdc.org/blogs/bcolander/decoupling_and_energy_efficien.html, Last accessed: March 8, 2009.

The language of the recent American Recovery and Reinvestment Act also seems to indicate a push towards decoupling by stating that the State regulatory authority should, to the extent of its authority, implement regulatory policies that ensure the recovery of the fixed costs of service that are independent from its retail sales. There is still an ongoing debate about whether state regulators will have the authority to do so under the restructured electricity market.

The revenue decoupling, while necessary, is not a sufficient condition to foster investment in energy efficiency [24]. In California, the regulatory environment promoted energy efficiency through three strategies, which Cicchetti [27] specifies as being key to the success of energy efficiency in the State: (i) specify efficiency goals for utilities; (ii) decouple revenue from energy savings; (iii) pay for energy efficiency and reward shareholders. Figure 6 illustrates the savings from energy efficiency program from utilities, building standards and appliance standards in California. However, it is interesting to notice that even before the decoupling of electricity revenues and electricity sales in 1982, the utility-sponsored energy efficiency programs are estimated to be responsible for most of the savings.

The system of shareholder incentives is a commonly used approach for states with a regulatory commitment to utility-based energy efficiency programs [22]. One particular design of shareholder incentives receiving a lot of attention is the shared-savings incentive mechanism. Different versions of such incentives are now used in six states, including California [25]. The current system of penalties and incentives in California is as follows. The CPUC establishes the target reductions in terms of electricity, peak load and therms for electricity and natural gas utilities. The shareholder reward is then calculated by multiplying the earnings rate (ER) by the performance earnings basis (PEB). The performance earnings basis corresponds to the dollar value from the efficiency saving of the avoided costs of supply-side generation, transmission, distribution and environmental costs as established by the CPUC, minus the costs of energy-efficiency program implementation. The earning rate only accrues when the portfolio is cost-effective, so that the resources' benefits are greater than the costs. In Figure 7, I show a representation of the system of penalties and incentives currently proposed by the CEC.

Today, some of the conditions that occurred during the 1970s again obtain. Oil prices have risen sharply in recent years, averaging roughly $100 per barrel in 2008 and peaking at $137 per barrel in July of that year. While the prices have recently fallen (hitting roughly $40 per barrel in February 2009), there is no doubt they will climb again. Capital constraints, sitting difficulties and uncertainties about the future regulatory environment for power plants have led to delays in the construction of new generating capacity. At the same time, public environmental concerns about the likely future consequences of climate change direct attention to the dramatic changes that will be needed in energy infrastructure in order to effectively tackle the climate problem. These factors direct attention to energy efficiency and conservation.

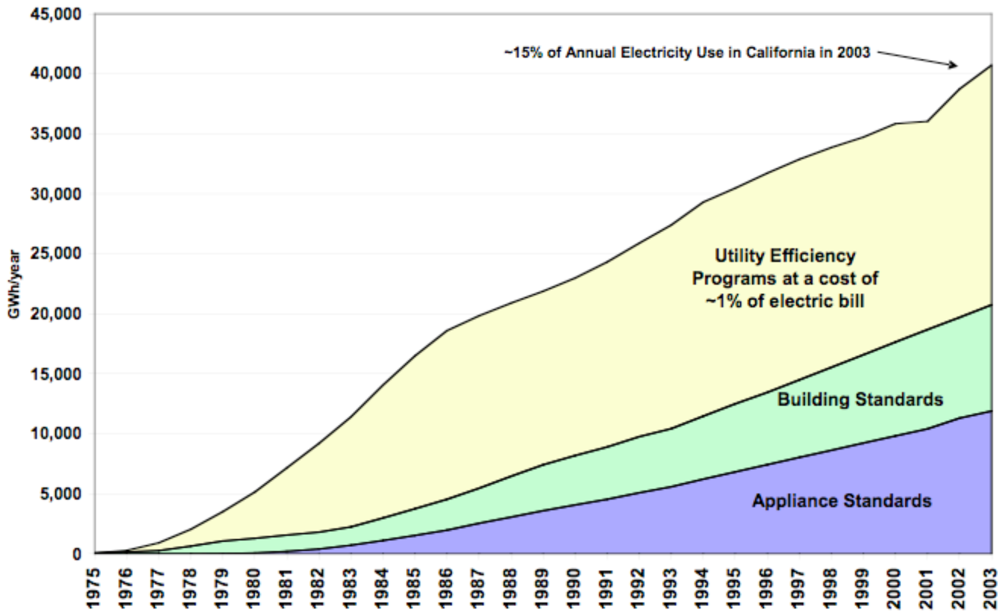

Figure 6 – Annual energy savings from efficiency programs and standards. Source: [28]

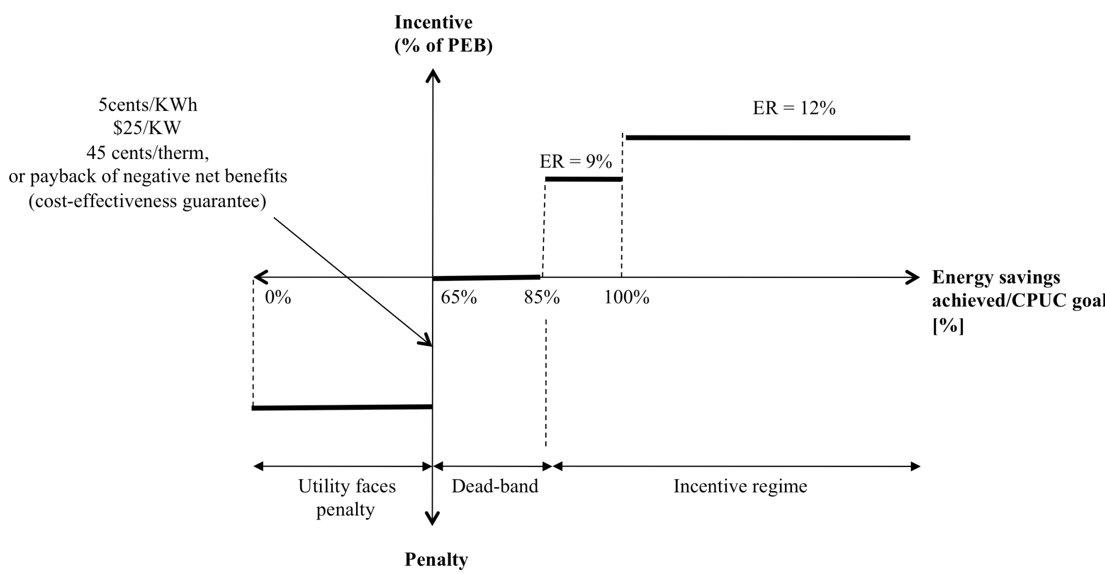

Figure 7 – California shared-savings incentive mechanism. Adapted from [26]. ER = Earnings Rate; PEB = Performance Earning Basis.

1.4 Existing Approaches to Assess Energy Efficiency Savings and Economic Costs in a Climate Policy Context

Efforts to address the economic, societal and environmental impacts of carbon mitigation measures fall in two broad categories, generally called *top-down* and *bottom-up* approaches. Both these models generally include energy efficiency amongst the possible mitigation options. *Top-down* approaches use macroeconomic models, thus predicting economy wide impacts based on price elasticity, resource intensity, growth parameters and fuel prices [29]. *Bottom-up* or engineering-economic models use data on technological costs to construct economic estimates on a technology-by-technology basis [30]. Similarly to what is done in the energy efficiency literature, the outcomes of bottom-up models are generally presented in terms of incremental costs of specific measures or interventions. Jackson [29] reports that despite the large variability of results across top-down and bottom-up approaches, the main difference between the two approaches has been that:

> "Macroeconomic models have predicted considerable economic costs associated with reducing emissions of greenhouse gases, whereas microeconomic models have identified considerable potential for the introduction of technological measures, which are cost-effective even now and would lead to substantial economic benefits for the implementing party".

The same conclusions hold when assessing the costs and benefits from energy or electricity efficiency measures instead of carbon mitigation measures.

Assessments of energy and monetary savings from energy efficiency are particularly difficult, not only due to the assessment of the direct effects of efficiency measures, but also due to the indirect effects. If efficiency measures save money for consumers, they may then spend the money saved on other goods and services. Some economists' therefore claim that energy efficiency improvements reduce the effective cost of energy services, thereby increasing demand and inducing less-than-proportional reductions in energy use [31].

A review of this direct "take-back" or "rebound effect" by Greening et al. [32] suggest that the size of the rebound effect for residential consumers ranges from 0% to 50%, expressed as "a percentage increase in consumption estimated to result from a 100% increase in efficiency". Greening et al. also show that the size of the rebound effect depends heavily on the type of end-use and economic agent. However, the authors also state that more studies are needed to better pinpoint the size of this effect.

The concept of rebound effect has been expanded to include wider economy effects. This broader definition is based on the claim that cost-effective energy efficiency improvements may improve productivity, promote capital investments, enhance economic growth, and ultimately increase energy demand [33].

Furthermore, it has been claimed that a combination of such growth coupled with rebounding can overwhelm the demand-reducing effect of efficiency under realistic conditions, which can namely hold in the U.S. economy [14]. However, an overview from Nadel [35] and Grubb [34][36] found little or no evidence of rebound effect in a review of 42 studies. Despite this finding, Greening et al. [32] claim that the rebound effect can either be insignificant or important for policy design depending on the interpretation and definition of the rebound effect itself.

In the next sections, I explore in detail the bottom-up approaches to estimate the impact of energy efficiency, and described the bottom-up model I constructed to assess national and regional energy efficiency technical, economic and achievable potential.

1.5 Energy Efficiency Supply Curves

1. 5. 1. Definitions

The concepts of cost of conserved energy and of conservation supply curves (also called energy efficiency supply curves or energy reduction supply curves) were first introduced by Rosenfeld and Meier [37]-[40], stimulated by a suggestion of Roger Sant [38]. According to Rosenfeld, before the representation of energy efficiency through supply curves, "one of the drawbacks of seeing energy efficiency as an alternative to additional electricity generation was [is] the inability of easily comparing both the economics and the scale of conservation with the new energy supplies" [40]. The solution he and his students provided was a new investment metric, the *cost of conserved energy*, and a graphical display of the potential energy savings as conservation supply curve [40]. Rosenfeld and Meier estimate the cost of conserved energy as the annualized payment divided by the annual energy savings. Thus, according to this approach, the cost of conserved energy (CCE) is given by:

CCE = [annualized investment cost]/[annual energy savings]

The annualized investment cost is given by the initial investment multiplied by the capital recovery rate (CCR), with $CCR = d/(1-(1+d)^{-n})$, where d is the discount rate and n the number of years over which the measure is set in place.

The assumption that a certain level of energy service is kept constant remains at the heart of this approach. As Meier [37] describes it:

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

Energy efficiency supply curves (or carbon marginal abatement cost curves) provide the optimal path for energy efficiency (or carbon mitigation) investments, under particular sets of assumptions. Since Rosenfeld and Meier first developed this approach, several studies have assessed the potential energy efficiency savings and related costs [21],[29],[30],[37],[39]-[56]. Some of these studies account avoided fuel costs. In addition, while some studies include only electricity or target a specific sector, others include several economic sectors or several fuel types.

A generalized supply curve for energy savings or GHG emissions reductions is provided in Figure 8. The potential for energy/carbon efficiency and respective cost per unit of energy saved or unit of pollutant avoided will depend on the particular year, region, and economic agent being considered. The shape of the efficiency supply curve will also depend on the discount rate assumed and on whether the fuel costs to run the technologies are incorporated in the estimate of the costs per unit saved or not.

The energy efficiency or carbon mitigation supply curves can be used to prioritize measures and as a guiding tool for policy recommendations. They should be seen as providing an indication of which steps can be undertaken to achieve reductions of energy consumption or GHG emissions at a certain cost. The curves may not provide the cheapest cost options. This will depend on the quality of the technology characterization used in the models, the types of fuels considered and the sectors being included. These supply curves do not aim to provide a positive or descriptive tool that forecasts how much energy savings will be achieved. Instead, they should be viewed as a normative tool that indicates how much could be saved if the least costly path shown in the curve is undertaken in order to achieve a particular level of energy savings or GHG mitigation.

Further, the efficiency supply curves are by definition a static approach and should not be used over long time frames. Efficiency supply curves do not account easily for abrupt changes in fuel prices. The annualized cost of energy efficiency investments is generally compared to an average fuel price over the lifetime of the efficiency measure.

Alternatively, the economic potential is defined as the energy or emissions savings that can be achieved at a cost lower than retail energy or electricity prices. Also, the supply curves do not easily incorporate the availability of new technologies over time. The process of adoption of new technologies is generally embedded in the baseline assumptions of capital turnover.

There are several other limitations to consider when using the supply curves approach. For example, Soft [59], details the conceptual challenges of assessing the cost of conserved energy as follows:

> "The crucial step in the construction [of a conservation supply curve] is the calculation of the marginal cost of conserved energy (*CCE*), which is computed by dividing the total cost of conservation (*TCC*) by the total energy savings (*E*). The difficulty with the concept of the cost of conserved energy is in knowing to what it applies. Clearly, to compute *E*, we must consider two production technologies, one before and one after the conservation measure. But, conservation measures are usually defined in such a way that one does not know either the starting or ending technology, but only the change in technology. For example, a measure might specify an increase in ceiling insulation from four inches to eight inches, without specifying the efficiency of the building's furnace[17]".

Figure 8 provides the generalized shape of an efficiency or carbon abatement supply curve.

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[17] This was one of the limitations of an earlier model I developed to assess energy efficiency supply curves at the national level, using available databases provided by ACEEE and publicly available form the California Energy Commission. The limitation was overcome by using the underlying data used in NEMS for the AEO 2008 residential energy use and technology characterization, provided by DOE.

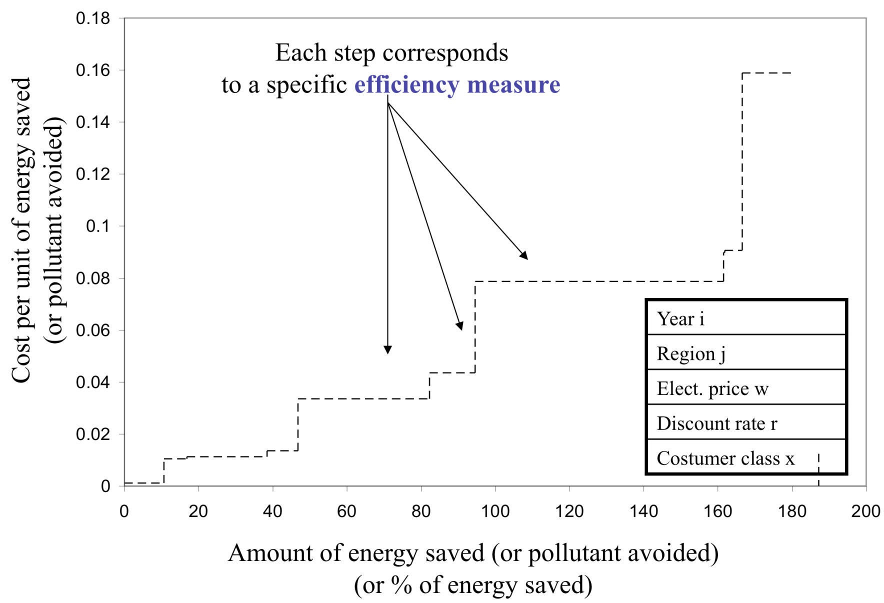

Figure 8 – A generalized energy or GHG mitigation efficiency supply curve. The potential for energy/carbon efficiency and respective cost per unit of energy saved or unit of pollutant avoided will depend on the particular year, region, and customer class being considered. The shape of the efficiency supply curve will also depend on the discount rate assumed and on whether the fuel costs to run the technologies are incorporated in the estimates of the costs per unit saved or not.

Some energy efficiency assessments provide three distinct measures of the energy efficiency potential: the *technological potential*, the *economic potential* and the *realistic or feasible potential*. The technological potential generally accounts for how much energy can be saved, while disregarding the investments costs and the implementation barriers.

The economic potential is a subset of the technological potential that only includes the measures that are cost-effective at a specific energy price. For example, concerning the electricity savings potential, the economic potential will increase as electricity price increases.

Finally, the feasible potential accounts for the rate of turnover of the capital stock and the impact of market failures and market barriers to the implementation of energy efficiency measures, under a specific set of policies.

To account for different efficiency metrics in more detail, Figure 10 provides a graphical illustration of the technological potential, economic potential, and feasible potential. The figure also includes the general effects of the indirect costs and the rebound-effect when assessing the real costs of energy efficiency.

In the present work, I estimate the technological and economic potential, but I do not provide an assessment of the feasible potential.

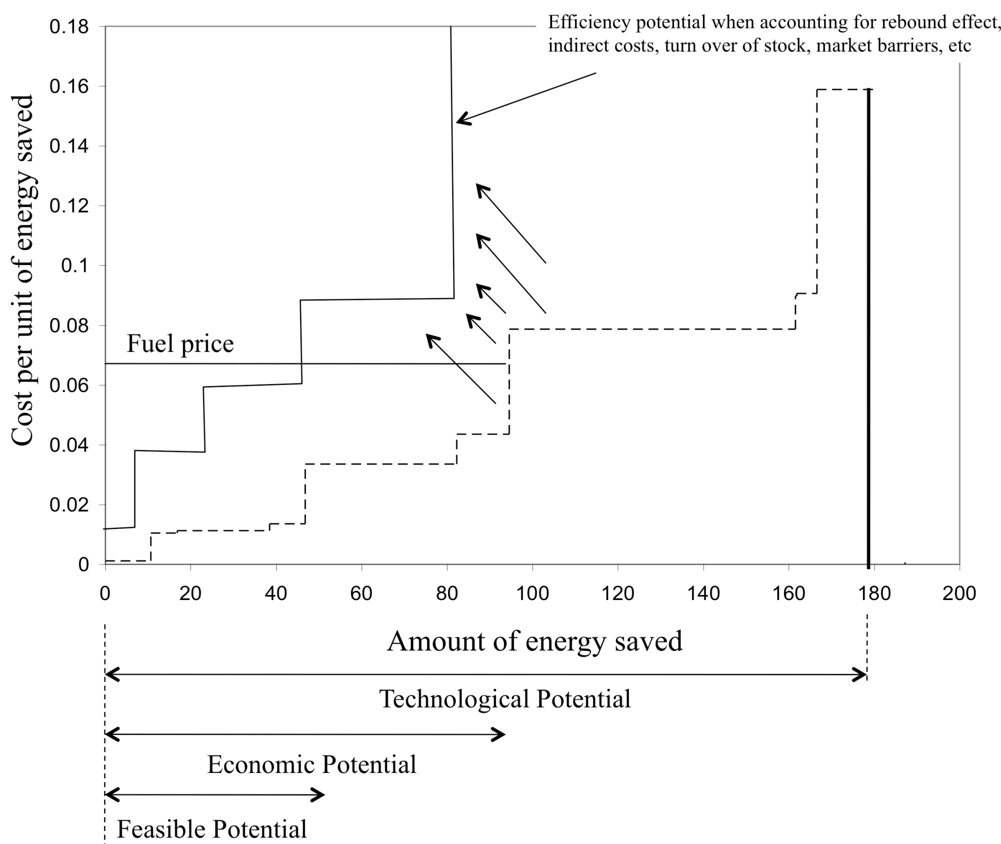

Figure 9 – A generalized energy efficiency supply curve highlighting the technological, economic and feasible potentials. The technological potential is the maximum value achieved in the x-axis. The economic potential corresponds to the level of efficiency investments up to the point where those reach the retail fuel price. The feasible supply curve accounts for indirect costs, the effect of market failures and barriers, and the rebound effect. The feasible potential corresponds to the level of feasible efficiency curve that reaches the retail fuel price.

1. 5. 2. Previous Studies: Electricity Savings through Energy Efficiency

Several studies in the past specifically assessed electricity supply curves at the national level [21], [43]-[37], [55]. Even when accounting only for the electricity savings potential, the studies differ in the approach they employ for estimating the cost of energy efficiency measures and the respective savings. For example, while both the Five-Lab study [47] (Figure 10) and Gellings et. al. [21] (Figure 12) estimate the electricity savings potential at the national level for 2010, the former accounts for incremental costs and the latter accounts for the full cost of the new technologies. Gellings et al. [21] suggest that up to 100 TWh could be saved in the three sectors by 2010 at a cost of less than 0.10$/kWh (in $2005).

Figure 10 provides the results from the 1997 Five-Lab study [47] for the electricity supply curve by end-use for buildings in 2010, under a high-efficiency and low carbon scenario. The efficiency potential is estimated assuming 65% of the techno-economic potential is captured[18]. The study suggests that under that scenario, up to 16% of the baseline electricity consumption (assumed to be 2,453 TWh for all sectors) could be saved at a cost lower than the retail electricity price (assumed to be 7.4 cents/kWh).

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[18] Furthermore, the savings from reflective roofing are contained in the residential and commercial space conditioning end-use categories.

Koomey et al.[45], in a similar approach to the one I developed, estimated the energy efficiency potential for the residential sector, but only accounted for electricity related end-uses and only assumed incremental costs, Figure 11. His findings suggest that 40% of the baseline residential electricity usage (projected to be 1,019 TWh) could have been saved by 2010 at cost below the residential electricity price (7.8 cents/KWh, in 1990$).

In 1993, the work Rubin et al. [55] was published in *Science* with considerable exposure for the mitigation panel of the National Academy of Sciences on the policy implications of greenhouse warming. This work takes illustrative examples of energy efficiency mitigation options and assesses both electricity savings and GHG avoided. The findings for the electricity savings are displayed in Figure 13.

I have adjusted the cost of energy savings to 2008 dollars, and find that these studies suggest that between 100 TWh and 734 TWh could be saved in 2010 (for all studies except Rubin et al. [55], which pertains to 1989) at a cost between 0.06 and 0.11 $2008/kWh, Table 2.

Table 2 – Summary of findings from studies on electricity supply curves.

Study	**Electricity Saving Potential (TWh)**	**Marginal Cost of Electricity Assumed ($/kWh)**	**Marginal Cost of Electricity Assumed (2008$/kWh)**	**Notes**
Gellings et al., 2000	100	0.1 ($2005)	0.11	All sectors
Koomey et al., 1993	400	0.078 ($1990)	0.13	Residential
5-Lab, 1996	400	0.045 ($1997)	0.06	All sectors
Rubin et al., 1993	734	0.064 ($1993)	0.09	Buildings

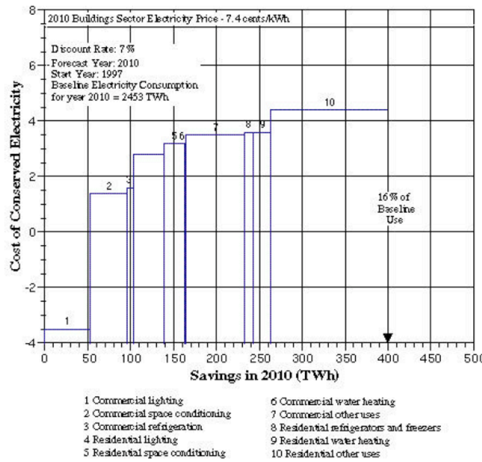

Figure 10 – Five-Lab electricity supply curve by end-use for buildings in 2010 for the high-efficiency and low carbon case. Source: [47].

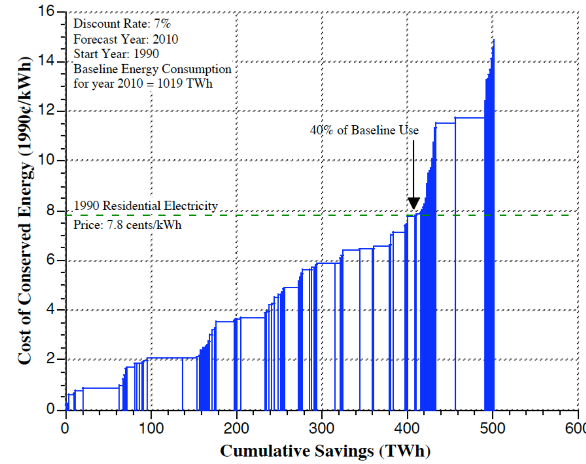

Figure 11 – Koomey et al. residential electricity efficiency supply curve in 2010. Source: [45].

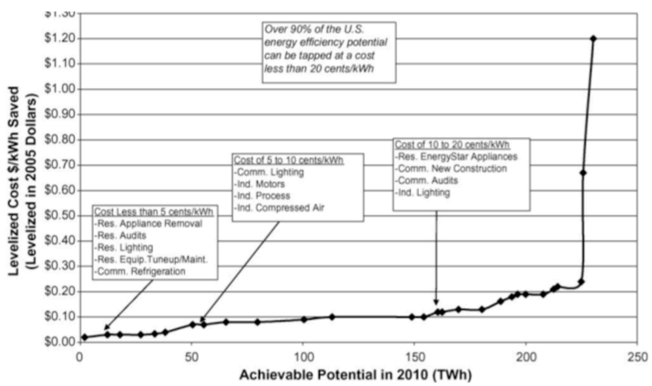

Figure 12 – Gellings et al. electricity supply curve by end-use for all sectors 2010. Source: [21]

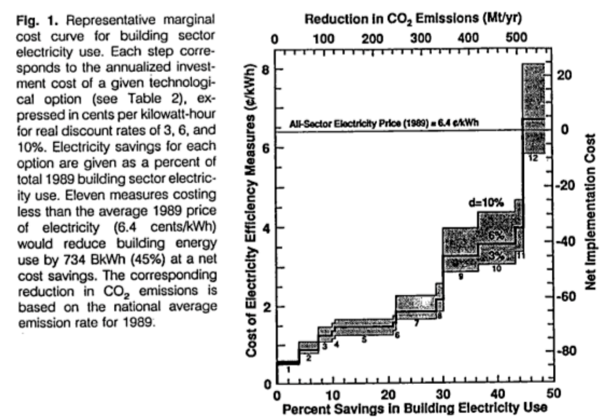

Figure 13 – NAS electricity supply curve by end-use for buildings in 1989. Source: [55]

1. 5. 3. Previous Studies: GHG Mitigation Through Energy Efficiency

Several studies assess the costs of GHG mitigation when pursuing energy efficiency measures instead of focusing on an energy perspective. Providing estimates in terms of carbon emissions avoided requires the assumption of specific carbon intensities for electricity generation and assumes specific baseline emissions that the efficiency option is compared to. For example, when buying a more efficient refrigerator, it can be assumed that the avoided emissions from the reduction in energy use correspond to the national average emissions factor, regional or state specific emissions factor, or the marginal power plant being displaced. Figure 14 to Figure 17, taken from Brown et al. [49], provide the estimates of the buildings' efficiency potential for several studies. The studies generally included an optimistic and pessimistic scenario for energy efficiency. Emissions avoided through the deployment of energy efficiency measures range from 172 to 891 million metric tons of CO_2 annually by 2010. Converting all costs to \$2008, the implementation of such measures entails marginal costs that range from -\$146 to -\$47 per ton of CO_2 avoided, therefore always offering net benefits, Table 3.

A note concerning the McKinsey projections of the GHG emissions potential is in order. The McKinsey study [43] lacks transparency in the assumptions made that led to their estimates of GHG savings. It is not clear from their methodological appendix whether incremental or total costs were considered or what expression was used to estimate cost-effectiveness, Figure 18.

In this work, I estimate both energy reduction supply curves and carbon reduction supply curves, and several cost metrics are included. I further explore the potential for electricity savings alone. Through this analysis, consumer, producer and social welfare perspectives are provided. The details of the constructed model, the Regional Residential Energy Efficiency Model or RREEM are described in the next Chapter.

Table 3 – Summary of findings from carbon dioxide mitigation supply curves.

Study	**Scenario**	**Potential for GHG Avoided (million metric ton CO_2 avoided)**	**Marginal Abatement Cost ($/ton CO_2 avoided)**	**Marginal Cost ($2008/ton CO_2 avoided)**
OTA [55]	Optimistic	315	-79 ($1990)	-77
	Pessimistic	315	-47 ($1990)	-129
5-Lab [47]	Optimistic	216	-89 ($1995)	-125
	Pessimistic	172	-71 ($1995)	-71
NAS [55]	Optimistic	891	-78 ($1987)	-146
	Pessimistic	224	-47 ($1987)	-88
Tellus [54]	-	257	-68 ($1987)	-90

Note: Negative values correspond to net benefits.

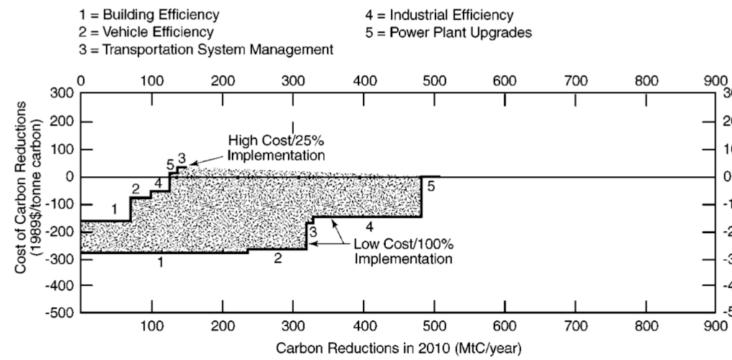

Figure 14 – OTA GHG mitigation supply curve for all sectors in 2010. Source: [55]. Image from [49].

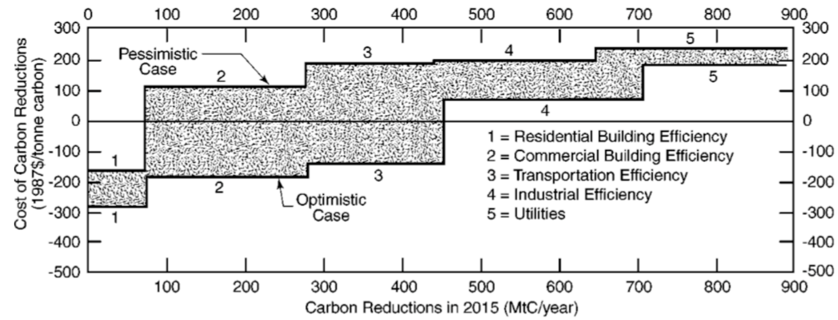

Figure 15 – NAS GHG mitigation supply curve by end-use for all sectors 2010. Source: [55]. Image from [49].

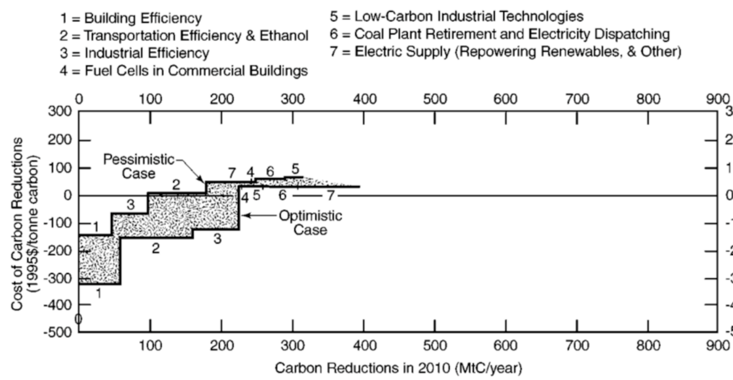

Figure 16 – Five-Lab GHG mitigation supply curve for all sectors in 1989. Source: [47]. Image from [49].

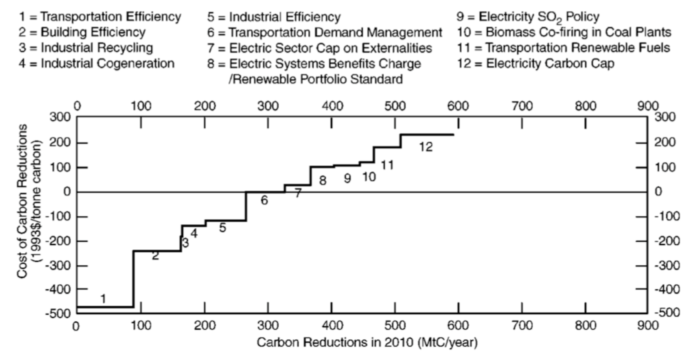

Figure 17 – Tellus GHG mitigation supply curve for all sectors in 2010. Source: [54]. Image from [49].

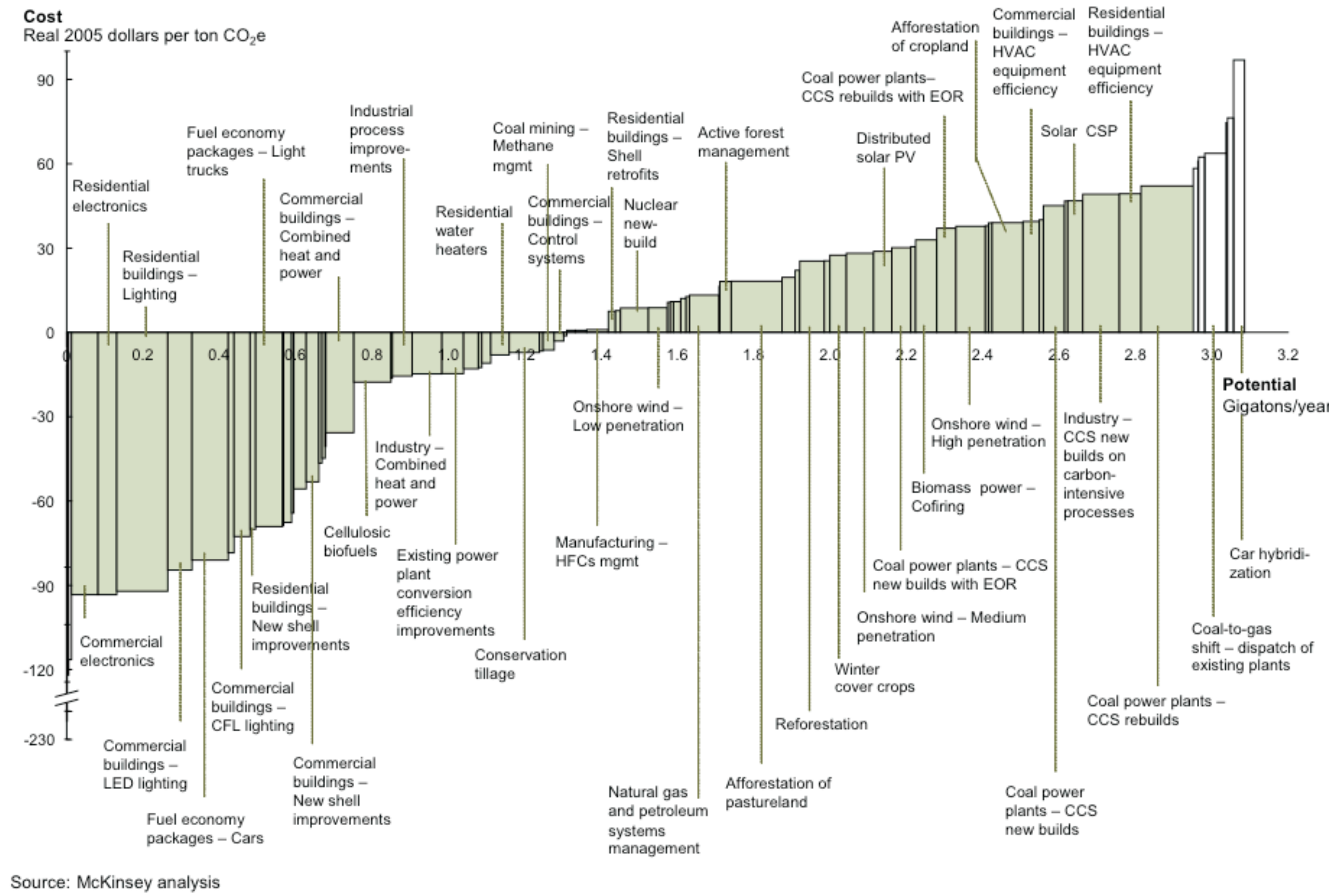

Figure 18 – McKinsey GHG mitigation supply curve for all sectors in 2030. Source: [43].

Chapter 2. The Regional Residential Energy Efficiency Model (RREEM)

2.1 Purpose and General Structure of RREEM

The Regional Residential Energy Efficiency Model (RREEM) estimates the optimal path of reductions of primary or final energy consumption (in millions of BTU), electricity consumption (in MWh) or carbon dioxide emissions (in million metric tons of CO_2) for the U.S. residential sector and respective levelized annual costs. RREEM maximizes the variable of interest using data and simulation projections from the EIA National Energy Modeling System (NEMS) model at census division level for any year between 2006 and 2030. The results are displayed as efficiency supply curves for the variable of interest. All the results presented in this thesis are for the year 2009.

The model performs the maximization: :

$$\underset{UEC}{Max} \sum_{region=1}^{m} \sum_{end\_use=1}^{n} A \qquad \text{Equation 1}$$

Where *A*, is either reductions in primary energy, delivered energy, electricity or carbon dioxide in a given region. This is done among a list of discrete technology choices, while maintaining a constant level of energy services. The *regions* can be any number of the following: New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain and Pacific, as presented in Figure 19.

The *end_use* can be any number of the following list of residential end-uses: heating, cooling, clothes washer, dishwashers, hot water, cooking, clothes dryer, refrigerator, freezers and lighting.

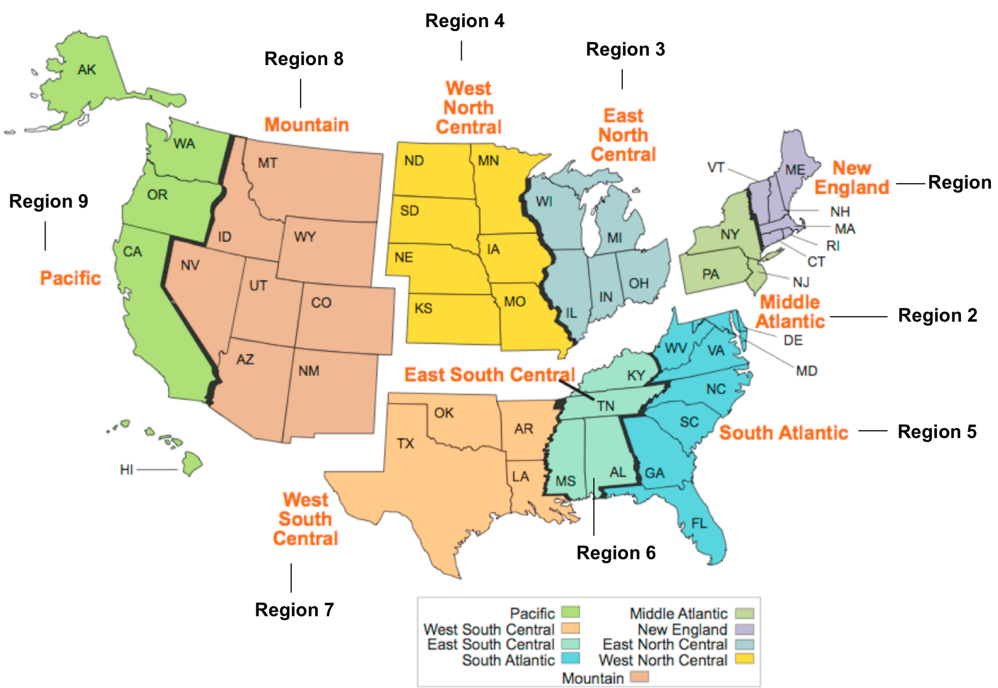

Figure 19 – Census division level regions. Source: adapted from EIA, 2008.

The variable of interest, *A*, corresponds the energy or carbon savings expressed as:

$$A = Stock_{year,region,end\_use,tech\_type} \times (UEC_{year,region,end\_use,baseline\_tech\_type} - UEC_{year,region,end\_use,tech\_type})$$

Equation 2

The variable *stock* is the number of units of end-use equipment in a specific year, region and for a particular technology type. The equipment types considered in RREEM are assigned a fuel or fuel carrier use for each technology type. The fuel types included in the database are natural gas, electricity, kerosene, wood, geothermal, coal, solar, distillate and LPG.

UEC represents the annual average energy consumption, electricity consumption or carbon emissions for equipment of a certain technology type, in a specific year and region (in either million BTU/unit per year, or kWh/unit per year or tonCO_2/unit per year depending on the objective function selected).

There are a discrete number of technologies available in RREEM for each end use, each having a specific UEC value that varies by end-use, technology type, technology class, region and year. The data provided by EIA are reported in delivered BTU/unit per year. These data were then converted to estimates of primary BTU/unit per year, kWh/unit per year and tonCO_2/unit per year. The assumptions used in making these conversions are provided below.

As illustrated by equation 1, the optimization process is based on variable *UEC*. This implies that the number of units of equipment in the stock for a particular end-use and for a particular technology type is the same as under the baseline scenario, and only the *UEC* changes to one of the discrete values available in the dataset. The data used in the construction of RREEM come from output tables from the National Energy Modeling System (NEMS) Annual Energy Outlook 2008 provided by the Energy Information Administration (EIA).

Figures for capital and retail costs and technology lifetimes were used directly from the tables provided by EIA. Furthermore, based on such tables, RFF provided an inferred set of annual estimates and projections for unit energy consumption, capital stocks, new purchases and replacements by end-use, region, technology type and technology class. See Appendix 1 for further detail on the work performed by RFF.

Joint work with RFF yielded a database in a format appropriate to support the construction of efficiency supply curves. See Appendix 2 for the full resulting database for year 2009. The full database include years 2006 to 2030.

The user interface developed for RREEM is displayed in Figure 20.

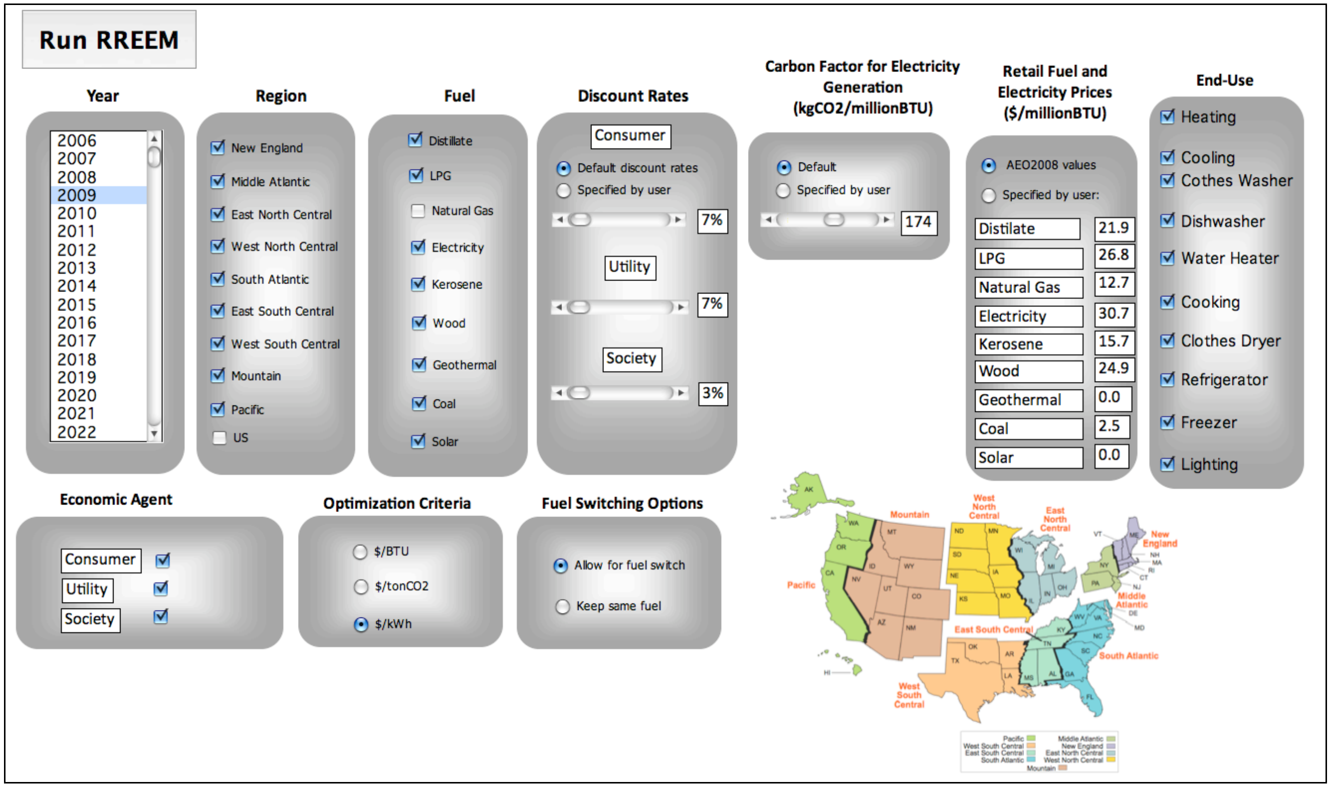

Figure 20 – User interface for RREEM model.

On the left, the first choice bar provides the range of years to select (2006 to 2030). The second choice bar corresponds to the census division regions and the third corresponds to which fuels will be included in the simulation. If only one fuel is chosen only the stock of appliances that is projected to use natural gas in the baseline case will be considered in the simulation. The model considers three different actors (consumers, utilities and regulatory agencies), and the user can specify a discount rate for each. For "consumers" there is also the option to choose the implicit discount rates the literature has shown consumers employ when making choices concerning efficient end-use appliances. The user can select the "default carbon factor" for electricity generation or select a value of her choice. The default carbon factor corresponds to my estimates based on AEO 2008 annual forecasts of the carbon factors at census division level. The user can choose to run the model using the default fuel prices from AEO 2008 or can specify other values. The bar on the right corresponds to the end-uses considered in the simulation. There are three-optimization criteria to build the efficiency supply curves ($/million BTU avoided, $/tonCO$_2$ avoided, $/kWh avoided). There are two fuel options for the economic agents' choice: keep the same fuel as in the baseline or allow for fuel changes when that is less costly.

2.2 Data

2. 2. 1. List of Technologies Included in the Data Set

The raw data used by the model consist of the number of units of stock for each technology type, average delivered unit energy consumption, capital investment and retail costs, minimum, average and maximum theoretical lifetimes of equipments of a specific technology type by census division regions and year. The technology types for each end-use and respective efficiency considered in REEM are provided in Tables 4 to 7. The estimates of the equipment stock and unit energy consumption for each of these technology types depend on the specific year and region considered.

Table 4 – List of lighting devices considered in RREEM. These are the same technologies used in NEMS residential end-use characterization. The same technology can have different unit energy consumption, reflecting different average usages across regions and years of analysis.

End-Use: Lighting			
Efficiency Measure	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
watts		General Service - Incandescent	67.1 watts
watts		General Service - CFL	13 watts
watts		General Service - LED	10 watts
watts		Linear Fluorescent #1	32 watts
watts		Linear Fluorescent #2	28 watts
watts		Torchiere #1	190 watts
watts		Torchiere CFL	70 watts

Table 5 – List of heating technologies considered in RREEM. These are the same technologies used in NEMS residential end-use characterization. The same technology can have different unit energy consumption, reflecting different average usages across regions and years of analysis.

End Use: Heating					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	COP	1	Electric Furnace	
2	1	HSPF/3.412	2.26	Air-Source Heat Pum #1	
2	2	HSPF/3.413	2.4	Air-Source Heat Pum #2	
2	3	HSPF/3.414	2.75	Air-Source Heat Pum #3	
2	4	HSPF/3.415	3.11	Air-Source Heat Pum #4	
3	1	AFUE	0.78	Natural Gas Furnace #1	
3	2	AFUE	0.8	Natural Gas Furnace #2	
3	3	AFUE	0.83	Natural Gas Furnace #3	
3	4	AFUE	0.9	Natural Gas Furnace #4	Condensing
3	50	AFUE	0.96	Natural Gas Furnace #5	Condensing
4	1	AFUE	0.81	Natural Gas Boiler #1	
4	2	AFUE	0.85	Natural Gas Boiler #2	
4	3	AFUE	0.95	Natural Gas Boiler #3	
5	1	AFUE	0.81	Kerosene Furnace #1	
5	2	AFUE	0.83	Kerosene Furnace #2	
5	3	AFUE	0.95	Kerosene Furnace #3	
6	1	AFUE	0.78	LPG Furnace #1	
6	2	AFUE	0.8	LPG Furnace #2	
6	3	AFUE	0.83	LPG Furnace #3	
6	4	AFUE	0.9	LPG Furnace #4	Condensing
6	5	AFUE	0.96	LPG Furnace #5	Condensing
7	1	AFUE	0.81	Fuel Oil Furnace #1	
7	2	AFUE	0.83	Fuel Oil Furnace #2	
7	3	AFUE	0.95	Fuel Oil Furnace #3	
8	1	AFUE	0.81	Fuel Oil Boiler #1	
8	2	AFUE	0.85	Fuel Oil Boiler #2	
8	3	AFUE	0.95	Fuel Oil Boiler #3	
9	28	COP	1	Wood Stove	9
10	1	COP	5	Ground-Source Heat Pump #1	
10	2	COP	5	Ground-Source Heat Pump #2	
11	1	COP	1.3	Natural Gas Heat Pump	

Table 6 – List of cooling, clothes washers, dishwashers, clothes dryers considered in RREEM. These are the same technologies used in NEMS residential end-use characterization. The same technology can have different unit energy consumption, reflecting different average usages across regions and years of analysis.

End Use: Cooling					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	SEER/3.412	2.87	Room AC #1	
1	2	SEER/3.413	3.17	Room AC #2	
1	3	SEER/3.414	3.52	Room AC #3	
2	1	SEER/3.415	3.81	Central AC #1	
2	2	SEER/3.416	4.1	Central AC #2	
2	3	SEER/3.417	4.4	Central AC #3	
2	4	SEER/3.418	6.15	Central AC #4	
3	1	SEER/3.419	3.81	Air-Source Heat Pump #1	
3	2	SEER/3.420	4.1	Air-Source Heat Pump #2	
3	3	SEER/3.421	4.54	Air-Source Heat Pump #3	
3	4	SEER/3.422	4.98	Air-Source Heat Pump #4	
4	1	EER	14.1	Ground-Source Heat Pump #1	
4	2	EER	30	Ground-Source Heat Pump #2	
5	1	EER	0.67	Natural Gas Heat Pump	
End Use: Clothes Washers					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	kWh/Cycle (motor)	0.242	Clothes Washer #1	Also gives value for MEF
1	2	kWh/Cycle (motor)	0.133	Clothes Washer #2	Also gives value for MEF
1	3	kWh/Cycle (motor)	0.114	Clothes Washer #3	Also gives value for MEF
End-Use: Dishwasher					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	EF	0.46	Dishwasher #1	
1	2	EF	0.65	Dishwasher #2	
1	3	EF	1.1	Dishwasher #3	
End-Use: Clothes Dryer					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	EF	0.86	Natural Gas Clothes Dryer #1	
1	2	EF	0.88	Natural Gas Clothes Dryer #2	
2	1	EF	3.02	Electric Clothes Dryer #1	
2	2	EF	3.22	Electric Clothes Dryer #2	

Table 7 – List of water heaters, cooking, refrigerators and freezers considered in RREEM. The same technologies are used in NEMS.

End-Use: Water Heating					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	EF	0.59	Natural Gas Water Heater #1	Instantaneous
1	2	EF	0.61	Natural Gas Water Heater #2	
1	3	EF	0.64	Natural Gas Water Heater #3	
1	4	EF	0.8	Natural Gas Water Heater #4	
2	1	EF	0.9	Electricity Water Heater #1	Heat Pump
2	2	EF	0.91	Electricity Water Heater #2	Heat Pump
2	3	EF	0.95	Electricity Water Heater #3	
2	4	EF	2.3	Electricity Water Heater #4	
2	5	EF	2.4	Electricity Water Heater #5	
3	1	EF	0.55	Fuel Oil Water Heater #1	
3	2	EF	0.62	Fuel Oil Water Heater #2	
3	3	EF	0.68	Fuel Oil Water Heater #3	
4	1	EF	0.59	LPG Water Heater #1	
4	2	EF	0.61	LPG Water Heater #2	
4	3	EF	0.64	LPG Water Heater #3	
4	4	EF	0.8	LPG Water Heater #4	Instantaneous
5	1	EF	1	Solar Water Heater	Assume 1/2 Electric
End-Use: Cooking					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	Btu Out/Btu In	0.399	Natural Gas Cooking #1	
1	2	Btu Out/Btu In	0.42	Natural Gas Cooking #2	
2	1	Btu Out/Btu In	0.399	LPG Cooking #1	
2	2	Btu Out/Btu In	0.42	LPG Cooking #2	
3	1	kWh/yr	601	Electric Cooking #1	
3	2	kWh/yr	601	Electric Cooking #2	
End-Use: Refrigerator					
Class	**Type**	**Efficiency Measure**	**Efficiency**	**Name in RTEKTY.txt File**	**Notes**
1	1	kWh/yr	510	Refrigerator #1	
1	2	kWh/yr	475	Refrigerator #2	
1	3	kWh/yr	434	Refrigerator #3	
1	4	kWh/yr	417	Refrigerator #4	
1	5	kWh/yr	659	Side-by-side Refrigerator	
End-Use: Freezer					
1	1	kWh/yr	394	Chest Freezer #1	
1	2	kWh/yr	350	Chest Freezer #2	
1	3	kWh/yr	302	Chest Freezer #3	
1	4	kWh/yr	520	Upright Freezer	

2. 2. 2. Raw Database and Variables Based on DOE Detailed Tables

The database used in the optimization is organized by year, region, end-use, and technology class and technology type. Table 8 shows the first and last lines of the database. All the technologies within the same class use the same fuel, but differ in terms of efficiency, cost or lifetime.

Table 8 – Illustration of the raw technology database used in RREEM.
Categories and ranges are explained in the text.

Year	Region	End use	Tech Class	Tech Type	Stock	UEC (1000BTU)	Max life (year)	Min life (year)	Avg life (year)	Capital cost ($/unit)	Retail cost ($/unit)	Fuel type	Base stock	Base UEC (1000 BTU)	Shipments	Retirements
1	1	1	1	1	14431	25	25	10	17.5	1900	1200	4	271186	29	14431	15136
1	1	1	2	1	2238	19	21	7	14	3162	2700	4	0	21	2238	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
25	9	9	11	12	500	89	25	10	17.5	4650	4150	5	4060	116	500	304

Details on the variables shown in Table 5 are as follows:

- ***Year*** represents the year of analysis and can assume values from 1 to 25, where 1 corresponds to the year 2006 and 25 to the year 2030.
- ***Region*** represents the geographical region of analysis and can assume values from 1 to 9, corresponding to New England, Middle Atlantic, East North Central,

West North Central, South Atlantic, East South Central, West South Central, Mountain or Pacific, respectively.

- ***End-Use*** represents the residential end-use considered and ranges from 1 to 10 representing heating, cooling, clothes washer, dishwashers, hot water, cooking, clothes dryer, refrigerator, freezers and lighting, respectively.
- ***Tech Class*** and ***Tech Type*** correspond to the different but similar technologies that can be used to provide the same end-use service, as shown previously in Tables 4 to 7. Technology classes correspond to different technologies using the same fuel that are used to provide the same energy service. The technology type is a sub-category of technology class, which lists equipments using the same fuel but with different efficiencies. For example, the first three rows in Table 6 correspond to room AC technologies. All the technologies pertain to the same class (1) because they are powered by electricity, but have different technology types, since the efficiencies vary.
- ***Stock*** corresponds to the number of units of equipment in each year and region for a specific technology type.
- ***UEC*** is the average unit energy consumption in millions of BTU per unit and year.
- ***Max life***, ***Min life*** and ***Avg life*** are the maximum, minimum and average theoretical lifetime of new equipments of a certain class and type, in years.
- ***Retail cost is*** the retail cost of a new piece of equipment, in $/unit ($2006)

- ***Capital cost*** is the sum of the retail cost and the installation cost of a new piece of equipment, in $/unit ($2006).
- ***Fuel type*** represents the fuel used by the technology represented in the row of the database. It can assume values from 1 to 9, corresponding to distillate, LPG, natural gas, electricity, kerosene, wood, geothermal, coal and solar, respectively.
- ***Base stock*** and ***base UEC***: for each end-use in a specific year and region, there is a base-stock prior to the year of analysis that does not correspond to any of the technology available for selection in the mix of new choices for that year. For example, if a specific type of refrigerator was bought in 1990, but is not available for purchase in any of the years of analysis, it will not fit in any of the categories of technology class in the database. To cope with these cases, I use the same approach as NEMS and create a separate category that corresponds to the "base stock" and "base unit energy consumption". The base stock therefore corresponds to a mix of vintages and is not available as a replacing technology.

Obviously, the results provided by RREEM will only be as good as the underlying data from the EIA. The EIA raw tables provide a level of precision and a degree of detail that does not reflect the uncertainty in the actual stock and unit energy consumption for different technology types, regions and years. Furthermore, the data do not account for the distribution of usage patterns for each technology type. Instead, EIA (and therefore RREEM) uses a representative value for the average annual delivered energy consumption by a certain share of the stock in a particular year and region (denoted United Energy Consumption, or UEC).

The EIA uses the residential energy consumption survey (RECS) for historical estimates of stocks of equipment and to estimate the unit energy consumption for different technology types. The EIA also uses studies prepared by Navigant Consulting to project the cost and performance of new technologies. The EIA then uses the National Energy Modeling System model to estimate and project the share of units each technology type within each class and the unit energy consumption of different technologies types and classes for different end uses in the residential sector at regional level and over time. These NEMS projections are used as a baseline from which savings are calculated in RREEM. The data used in RREEM are therefore a combination of EIA's input data in NEMS (for the capital and retail costs, lifetime, efficiency) and outputs from NEMS (for stock shares of different technologies over time, and unit energy consumption).

Table 6 provides descriptive statistics on the key variables of the RREEM database for each of the end-uses considered in RREEM, for year 2009, and aggregated to the national level. Table 4 shows the number of pieces of equipment (stock) for each end use in 2009 assumed in RREEM. It is from this baseline that energy savings potential and energy savings supply curves are derived. RREEM does not account for uncertainty in these baseline figures, since these are data directly drawn from NEMS data and projections, which also do not account for uncertainty. However, RREEM allows the user to test the impact of uncertainty on the stock share through sensitivity analysis. The

UEC values in Table 4 are the minimum, average and maximum value that are used in RREEM (as drawn by EIA) for the average annual delivered energy consumption for different equipment types. While Table 4 provides the national UEC figures for 2009, note that the UEC values vary by region in RREEM.

The values for *Cost* presented in Table 4 correspond to the sum of the capital and installation costs for equipment for each end use. These costs do not include opportunity costs of time lost to install new equipment before the end of life of the current equipment, nor do they include the cost of the infrastructure to deliver a particular fuel or energy carrier to the households that might be required in order to switch to other fuels. The *Lifetime* figures represent the theoretical useful lifetime of new equipment. In the simulations provided in the next Chapters, the average values for the unit energy consumption and theoretical lifetimes are used.

Table 9 – Summary of 2009 projections of delivered energy consumption used in RREEM by end-use. Based on EIA and RFF figures.

		UEC (MMBTU/unit)			Cost ($/unit)			Lifetime (year)		
	Stock (units)	Min	Average	Max	Min	Average	Max	Min	Average	Max
Heating	1.2E+08	6	37	103	1,700	2,424	10,000	7	17	30
Cooling	1.3E+08	2	6	17	310	1,868	6,000	7	13	30
Clothes Washer	9.5E+07	0	0	0	700	747	950	11	15	18
Dishwasher	6.8E+07	1	1	2	745	750	1,200	11	15	18
Water Heating	1.1E+08	3	16	25	390	1,000	3,811	4	10	30
Cooking	1.1E+08	2	3	5	350	356	450	19	406	16
Clothes Dryer	9.0E+07	3	3	4	375	432	500	11	16	20
Refrigerator	1.4E+08	2	2	3	550	813	1,400	7	17	26
Freezer	3.9E+07	1	2	3	400	1,099	1,400	7	18	31

Note: UEC is in delivered MMBTU/unit.

2. 2. 3. Assumptions for Default Electricity and Carbon Estimates for UEC

As mentioned earlier, RREEM estimates potential savings and costs in terms of primary and delivered energy, electricity and CO_2 emissions. Estimates for the electricity consumption of end-use devices are based on EIA's unit energy consumption data presented previously, by only selecting the end-uses using electricity, and converting from delivered energy in million BTU to kWh. Table 7 shows a summary of the stock figures, and descriptive statistics for the unit energy consumption (now in kWh/unit.year), retail costs and lifetime.

Table 10 – Summary of 2009 projections of electricity consumption, used in RREEM by end-use. Based on EIA and RFF figures.

		UEC (KWh/unit.year)			Retail Cost ($/unit)			Lifetime (year)		
	Stock (units)	Min	Average	Max	Min	Average	Max	Min	Average	Max
Heating	3.9E+07	0	3821	4085	1,900	2,401	4,574	7	15	25
Cooling	1.3E+08	0	1683	2338	310	1,862	6,000	7	13	21
Clothes Washer	9.5E+07	60	69	70	700	747	950	11	15	18
Dishwasher	6.8E+07	198	350	474	745	750	1,200	11	15	18
Water Heating	-	-	-	0	-	-	-	-	-	-
Cooking	6.9E+07	0	443	443	350	350	350	19	400	16
Clothes Dryer	3.3E+07	0	911	960	375	426	450	11	16	20
Refrigerator	1.4E+08	520	680	822	550	813	1,400	7	17	26
Freezer	3.9E+07	400	721	822	400	1,099	1,400	7	18	31

The default values used as estimates for electricity carbon emission factors at the Census Division level are based on the electricity generation mix for each region as projected by AEO 2008. Electricity imports or exports between census division regions have 2008's average national carbon intensity (184 metric ton CO_2/MMBTU). According to AEO 2008, the electricity generation portfolio will change over time and so will carbon intensity of electricity. EIA projects the electricity generation mix at the census division level between 2006 and 2030 in terms of quadrillion BTU of delivered energy. It also reports an estimate of electricity generation losses. EIA includes the following fuels for electricity generation: natural gas, steam coal, nuclear power, renewable energy, distillate fuel oil, residual fuel oil and electricity imports.

The AEO 2008 estimates for electricity generation by census division over time used in RREEM are presented in Tables 11 to 16 [19].

[19] Tables available at: http://www.eia.doe.gov/oiaf/archive/aeo08/supplement/supref.html , Table 1 to 10.

Table 11 – AEO 2008 projections of electricity generation by fuel type between 2006 and 2015 for each census division. These projections were used to estimate carbon factors for electricity used in RREEM (in quadrillion BTU).

		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
New England	Distillate Fuel Oil	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Residual Fuel Oil	0.04	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
	Natural Gas	0.38	0.51	0.49	0.48	0.46	0.46	0.47	0.47	0.48	0.46
	Steam Coal	0.20	0.18	0.18	0.18	0.18	0.18	0.19	0.19	0.19	0.19
	Nuclear Power	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
	Renewable Energy	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.13	0.13	0.13
	Electricity Imports	0.03	0.04	0.04	0.03	0.02	0.02	0.03	0.03	0.03	0.02
	Total	1.17	1.27	1.25	1.24	1.21	1.21	1.23	1.24	1.24	1.23
Middle Atlantic	Distillate Fuel Oil	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.03	0.03
	Residual Fuel Oil	0.08	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Natural Gas	0.65	0.64	0.69	0.69	0.63	0.65	0.65	0.60	0.58	0.63
	Steam Coal	1.57	1.49	1.48	1.49	1.44	1.47	1.45	1.45	1.46	1.48
	Nuclear Power	1.54	1.55	1.55	1.54	1.56	1.56	1.56	1.56	1.56	1.56
	Renewable Energy	0.36	0.34	0.34	0.35	0.42	0.41	0.44	0.46	0.47	0.47
	Electricity Imports	0.03	0.05	0.05	0.04	0.03	0.03	0.03	0.04	0.03	0.02
	Total	4.27	4.22	4.27	4.27	4.23	4.27	4.29	4.27	4.26	4.31
East North Central	Distillate Fuel Oil	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03
	Residual Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.26	0.41	0.51	0.59	0.53	0.51	0.51	0.46	0.46	0.46
	Steam Coal	4.72	4.73	4.69	4.76	4.85	4.95	5.04	5.10	5.15	5.10
	Nuclear Power	1.57	1.59	1.58	1.57	1.57	1.58	1.58	1.58	1.58	1.58
	Renewable Energy	0.10	0.10	0.12	0.14	0.22	0.27	0.29	0.31	0.33	0.36
	Electricity Imports	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00
	Total	6.68	6.87	6.94	7.10	7.22	7.36	7.46	7.51	7.57	7.55
West North Central	Distillate Fuel Oil	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
	Residual Fuel Oil	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.11	0.04	0.05	0.07	0.08	0.08	0.08	0.08	0.08	0.08
	Steam Coal	2.45	2.50	2.50	2.52	2.52	2.54	2.55	2.57	2.59	2.62
	Nuclear Power	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
	Renewable Energy	0.18	0.21	0.24	0.25	0.26	0.26	0.26	0.27	0.27	0.27
	Electricity Imports	0.03	0.04	0.04	0.04	0.02	0.02	0.03	0.03	0.03	0.02
	Total	3.26	3.31	3.33	3.38	3.38	3.40	3.42	3.44	3.47	3.48

Table 12 – AEO 2008 projections of electricity generation by fuel type between 2006 and 2015 for each census division. These projections were used to estimate carbon factors for electricity used in RREEM (in quadrillion BTU).

		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
South Atlantic	Distillate Fuel Oil	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05
	Residual Fuel Oil	0.23	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
	Natural Gas	1.04	0.82	0.86	0.81	0.86	0.86	0.91	0.89	0.87	0.86
	Steam Coal	4.22	4.35	4.34	4.41	4.43	4.45	4.45	4.48	4.58	4.69
	Nuclear Power	2.03	2.05	2.04	2.02	2.03	2.03	2.03	2.03	2.03	2.04
	Renewable Energy	0.21	0.20	0.21	0.21	0.35	0.35	0.36	0.37	0.39	0.41
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	7.80	7.66	7.69	7.70	7.90	7.93	7.99	8.01	8.11	8.24
West North Central	Distillate Fuel Oil	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Residual Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.31	0.57	0.56	0.47	0.50	0.48	0.49	0.46	0.46	0.47
	Steam Coal	2.55	2.58	2.55	2.57	2.61	2.65	2.69	2.71	2.75	2.79
	Nuclear Power	0.72	0.79	0.81	0.80	0.80	0.82	0.84	0.86	0.87	0.87
	Renewable Energy	0.25	0.23	0.23	0.24	0.24	0.24	0.24	0.25	0.26	0.26
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	3.88	4.18	4.17	4.10	4.17	4.21	4.29	4.30	4.36	4.41
West South Central	Distillate Fuel Oil	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Residual Fuel Oil	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01
	Natural Gas	2.11	2.18	2.15	2.17	2.19	2.18	2.13	2.06	2.05	2.10
	Steam Coal	2.42	2.39	2.37	2.37	2.42	2.51	2.62	2.63	2.64	2.64
	Nuclear Power	0.72	0.73	0.73	0.72	0.72	0.72	0.73	0.73	0.74	0.74
	Renewable Energy	0.17	0.20	0.23	0.24	0.24	0.24	0.24	0.26	0.26	0.28
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	5.46	5.52	5.49	5.52	5.59	5.67	5.73	5.70	5.72	5.79

Table 13 – AEO 2008 projections of electricity generation by fuel type between 2006 and 2015 for each census division. These projections were used to estimate carbon factors for electricity used in RREEM (in quadrillion BTU).

		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mountain	Distillate Fuel Oil	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Residual Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.57	0.71	0.79	0.74	0.74	0.70	0.73	0.71	0.71	0.71
	Steam Coal	2.21	2.30	2.30	2.33	2.39	2.50	2.50	2.51	2.51	2.49
	Nuclear Power	0.32	0.33	0.32	0.32	0.32	0.33	0.33	0.33	0.33	0.33
	Renewable Energy	0.39	0.39	0.43	0.45	0.48	0.51	0.54	0.55	0.56	0.59
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	3.50	3.74	3.85	3.85	3.94	4.04	4.10	4.10	4.11	4.13
Pacific	Distillate Fuel Oil	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Residual Fuel Oil	0.10	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	Natural Gas	0.99	1.08	0.92	0.94	0.90	0.90	0.90	0.87	0.90	0.97
	Steam Coal	0.14	0.16	0.16	0.17	0.17	0.17	0.17	0.18	0.18	0.18
	Nuclear Power	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	Renewable Energy	1.97	1.87	1.98	2.12	2.20	2.27	2.28	2.28	2.28	2.28
	Electricity Imports	-0.02	-0.03	-0.03	-0.03	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01
	Total	3.65	3.64	3.59	3.76	3.81	3.89	3.90	3.87	3.91	3.99
US	Distillate Fuel Oil	0.18	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.18
	Residual Fuel Oil	0.46	0.38	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.39
	Natural Gas	6.42	6.97	7.02	6.96	6.89	6.82	6.86	6.60	6.59	6.75
	Steam Coal	20.48	20.68	20.58	20.80	21.01	21.42	21.67	21.82	22.04	22.18
	Nuclear Power	8.21	8.34	8.34	8.29	8.31	8.34	8.36	8.38	8.40	8.41
	Renewable Energy	3.74	3.65	3.89	4.12	4.53	4.68	4.78	4.88	4.96	5.05
	Electricity Imports	0.06	0.09	0.09	0.08	0.05	0.05	0.06	0.07	0.06	0.04
	Total	39.68	40.40	40.58	40.91	41.46	41.98	42.42	42.43	42.75	43.12

Table 14 – Estimates based on AEO 2008 projections of electricity generation by fuel type between 2016 and 2030 for each census division. These projections were used to estimate carbon factors for electricity used in RREEM (in quadrillion BTU).

		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
New England	Distillate Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Residual Fuel Oil	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Natural Gas	0.46	0.46	0.47	0.47	0.48	0.49	0.50	0.50	0.50	0.49	0.49	0.49	0.49	0.49	0.47
	Steam Coal	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	Nuclear Power	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
	Renewable Energy	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
	Electricity Imports	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.03	0.04
	Total	1.23	1.24	1.25	1.25	1.27	1.27	1.28	1.28	1.29	1.28	1.28	1.28	1.28	1.28	1.27
Middle Atlantic	Distillate Fuel Oil	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
	Residual Fuel Oil	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Natural Gas	0.64	0.64	0.61	0.59	0.58	0.57	0.57	0.56	0.56	0.55	0.54	0.52	0.51	0.50	0.49
	Steam Coal	1.49	1.52	1.56	1.60	1.61	1.62	1.63	1.64	1.65	1.67	1.71	1.78	1.83	1.91	2.03
	Nuclear Power	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.54	1.41
	Renewable Energy	0.47	0.48	0.49	0.47	0.48	0.47	0.48	0.48	0.49	0.49	0.49	0.49	0.49	0.50	0.50
	Electricity Imports	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04
	Total	4.35	4.39	4.41	4.42	4.41	4.42	4.42	4.43	4.45	4.47	4.50	4.54	4.59	4.65	4.63
East North Central	Distillate Fuel Oil	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	Residual Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.46	0.44	0.45	0.40	0.40	0.41	0.42	0.41	0.42	0.42	0.43	0.44	0.45	0.46	0.49
	Steam Coal	5.13	5.15	5.11	5.12	5.09	5.09	5.12	5.12	5.13	5.14	5.13	5.12	5.14	5.13	5.22
	Nuclear Power	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.51
	Renewable Energy	0.39	0.41	0.45	0.48	0.50	0.51	0.51	0.54	0.56	0.59	0.59	0.59	0.59	0.59	0.58
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01
	Total	7.60	7.62	7.63	7.62	7.61	7.63	7.67	7.68	7.74	7.76	7.77	7.77	7.80	7.80	7.84

Table 15 – Estimates based on AEO 2008 projections of electricity generation by fuel type between 2016 and 2030 for each census division. These projections were used to estimate carbon factors for electricity used in RREEM (in quadrillion BTU).

		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
West North Central	Distillate Fuel Oil	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Residual Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.08	0.08	0.08	0.07	0.08	0.09	0.08	0.08	0.08	0.07	0.07	0.07	0.09	0.07	0.07
	Steam Coal	2.63	2.66	2.71	2.76	2.81	2.85	2.89	2.92	2.96	3.00	3.03	3.06	3.08	3.08	3.10
	Nuclear Power	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
	Renewable Energy	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
	Electricity Imports	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.04	0.04
	Total	3.51	3.54	3.59	3.64	3.70	3.75	3.77	3.81	3.85	3.88	3.91	3.94	3.98	3.97	3.99
South Atlantic	Distillate Fuel Oil	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06
	Residual Fuel Oil	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
	Natural Gas	0.85	0.82	0.79	0.76	0.71	0.69	0.67	0.65	0.64	0.63	0.64	0.65	0.66	0.64	0.64
	Steam Coal	4.77	4.88	4.99	5.09	5.18	5.25	5.23	5.23	5.24	5.25	5.25	5.26	5.31	5.35	5.36
	Nuclear Power	2.06	2.08	2.08	2.08	2.08	2.08	2.16	2.25	2.34	2.45	2.54	2.60	2.61	2.64	2.74
	Renewable Energy	0.45	0.46	0.49	0.53	0.54	0.54	0.55	0.55	0.55	0.55	0.56	0.56	0.57	0.56	0.57
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	8.38	8.49	8.60	8.70	8.77	8.81	8.86	8.93	9.01	9.13	9.24	9.33	9.40	9.46	9.56
West North Central	Distillate Fuel Oil	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Residual Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.48	0.48	0.47	0.44	0.39	0.32	0.31	0.32	0.32	0.32	0.33	0.32	0.34	0.33	0.32
	Steam Coal	2.82	2.83	2.83	2.86	2.87	3.03	3.17	3.32	3.43	3.54	3.62	3.74	3.82	3.89	3.96
	Nuclear Power	0.87	0.92	1.05	1.23	1.45	1.52	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
	Renewable Energy	0.27	0.28	0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	4.46	4.52	4.65	4.84	5.03	5.19	5.34	5.48	5.60	5.70	5.80	5.92	6.02	6.08	6.15
West South Central	Distillate Fuel Oil	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	Residual Fuel Oil	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Natural Gas	2.14	2.13	1.99	1.94	1.85	1.78	1.75	1.71	1.66	1.65	1.65	1.63	1.60	1.55	1.52
	Steam Coal	2.64	2.67	2.82	2.83	2.90	2.90	2.91	2.98	3.06	3.12	3.18	3.23	3.27	3.37	3.48
	Nuclear Power	0.74	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	Renewable Energy	0.28	0.29	0.30	0.31	0.39	0.39	0.41	0.43	0.44	0.46	0.48	0.50	0.51	0.50	0.52
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	5.83	5.87	5.90	5.86	5.92	5.85	5.86	5.90	5.95	6.02	6.09	6.15	6.17	6.21	6.30

Table 16 – Estimates based on AEO 2008 projections of electricity generation by fuel type between 2016 and 2030 for each census division. These projections were used to estimate carbon factors for electricity used in RREEM (in quadrillion BTU).

		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Mountain	Distillate Fuel Oil	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
	Residual Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Natural Gas	0.68	0.64	0.60	0.57	0.56	0.58	0.53	0.46	0.42	0.36	0.31	0.29	0.25	0.24	0.23
	Steam Coal	2.50	2.57	2.65	2.73	2.81	2.91	3.03	3.15	3.25	3.36	3.48	3.61	3.73	3.84	3.94
	Nuclear Power	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
	Renewable Energy	0.61	0.63	0.65	0.68	0.73	0.74	0.76	0.79	0.81	0.84	0.85	0.87	0.93	0.94	0.96
	Electricity Imports	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	4.13	4.17	4.24	4.32	4.44	4.57	4.66	4.74	4.82	4.90	5.00	5.11	5.25	5.37	5.49
Pacific	Distillate Fuel Oil	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Residual Fuel Oil	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11
	Natural Gas	1.05	1.08	1.09	1.10	1.02	1.00	0.99	0.99	0.97	0.95	0.95	0.94	0.93	0.90	0.89
	Steam Coal	0.18	0.19	0.19	0.19	0.19	0.19	0.20	0.21	0.24	0.24	0.25	0.25	0.25	0.25	0.25
	Nuclear Power	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	Renewable Energy	2.28	2.28	2.28	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
	Electricity Imports	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.03	-0.03
	Total	4.06	4.10	4.12	4.12	4.06	4.04	4.03	4.05	4.05	4.04	4.04	4.04	4.03	4.00	3.99
US	Distillate Fuel Oil	0.18	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.21	0.21	0.22	0.22	0.22	0.23	0.23
	Residual Fuel Oil	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.40
	Natural Gas	6.85	6.77	6.55	6.33	6.09	5.93	5.83	5.68	5.56	5.45	5.40	5.36	5.31	5.18	5.13
	Steam Coal	22.36	22.66	23.07	23.39	23.67	24.06	24.38	24.76	25.17	25.51	25.86	26.25	26.63	27.02	27.55
	Nuclear Power	8.44	8.51	8.64	8.83	9.05	9.11	9.21	9.30	9.39	9.50	9.59	9.65	9.66	9.68	9.57
	Renewable Energy	5.16	5.24	5.37	5.48	5.64	5.67	5.71	5.79	5.86	5.94	5.98	6.01	6.10	6.12	6.13
	Electricity Imports	0.04	0.05	0.05	0.06	0.04	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.05	0.07	0.08
	Total	43.55	43.94	44.38	44.79	45.21	45.53	45.90	46.31	46.77	47.19	47.62	48.07	48.51	48.82	49.21

The carbon factors used for each fuel type are presented in Table 17. Again, the values are those presented by EIA[20].

Table 17 – Carbon emission factors in $kgCO_2$ per million BTU of delivered energy.

FUEL TYPE	CARBON FACTOR (kgCO2/MMBTU)
Distillate	73
LPG	63
Natural Gas	53
Electricity Imports/Exports	184
Kerosene	72
Wood	88
Geothermal	0
Coal	93
Solar	0

The carbon emission factors are estimated for each census region and for each year between 2006 and 2030 by constructing a weighted average using the information presented in Tables 11 to 17 as:

$$Carbon\ Factor_{region,year} = \frac{\sum_{fuel=1}^{x}\left[Electricity\ Generation_{fuel}[MMBTU] \times Carbon\ Intensity_{fuel}[kgCO_2/MMBTU]\right]}{\sum_{fuel=1}^{x}\left[Electricity\ Generation_{fuel}[MMBTU]\right]}$$

Equation 3

Electricity Generation $_{fuel}$ is the electricity generated (or projected to be generated) by each fuel listed in Tables 11 to 16 in million BTU of delivered energy and the *Carbon Intensity* $_{fuel}$ is the CO_2 emitted to produce that electricity as illustrated in Table 17.

[20] See table on "Carbon Emissions Factors" in quadrillion BTU available at: http://www.eia.doe.gov/environment.html. The value for electricity assumed the national average.

Table 18 provides the default values used in RREEM for regional projections of electricity carbon intensity factors for the different census division regions and between 2006 and 2030. For the sake of illustration, the last row provides the carbon factors in $kgCO_2/kWh$ for the year 2008.

Table 18 – Estimates of regional projections of electricity carbon intensity between 2006 and 2030 (in $kgCO_2$ per MMBTU delivered).

	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
2006	112	153	230	247	177	231	197	272	57	187
2007	116	148	228	245	171	235	193	279	59	186
2008	113	148	228	242	168	235	190	279	53	184
2009	112	149	230	248	167	233	189	280	52	183
2010	107	141	230	243	165	234	188	280	51	182
2011	106	142	232	242	163	232	188	283	51	181
2012	107	141	234	242	161	233	190	280	50	181
2013	108	139	236	245	160	233	188	279	49	181
2014	108	138	237	245	161	234	186	275	50	181
2015	105	140	233	245	161	236	185	269	53	180
2016	104	142	232	244	161	236	185	264	55	180
2017	105	143	231	245	161	235	184	264	56	180
2018	106	144	229	247	161	232	185	266	56	180
2019	106	145	227	250	161	232	182	268	56	180
2020	107	145	224	254	161	229	182	272	53	179
2021	107	145	224	257	161	237	178	278	52	180
2022	107	144	224	258	158	245	176	282	51	180
2023	106	144	223	260	155	254	176	284	51	180
2024	106	144	222	261	152	260	176	287	52	180
2025	105	145	221	262	151	265	176	289	51	180
2026	104	146	220	263	148	269	177	293	51	180
2027	103	149	218	264	147	275	176	297	50	180
2028	103	151	218	265	146	279	175	300	49	181
2029	103	155	217	262	145	282	176	304	48	181
2030	101	162	220	263	143	284	178	307	47	182
kgCO2/kWh (2008)	**0.38**	**0.51**	**0.78**	**0.83**	**0.57**	**0.80**	**0.65**	**0.95**	**0.18**	**0.63**

2.3 Scenarios Considered in RREEM

The optimization described in Section 2.1 is performed for several descriptive scenarios. The scenarios account for either instantaneously changing the entire stock of end-use appliances to the most efficient appliance in the market or only replacing those appliances that are forecast to be purchased in a given year with the most efficient technology available in that year. The first case therefore represents overnight replacement of the stock, without accounting for the turn-over of the equipment. The second case corresponds to the impact of the implementation of stringent efficiency standards, or voluntary adoption of the most efficient technology. There are two other classes of scenarios, which consider whether or not switching between fuels is allowed when adopting the new technology. The 16 different scenarios that result are illustrated in Figure 21.

Furthermore, the perspectives of three different set of economic agents are considered, when estimating the efficiency supply curves. The first economic agent perspective builds upon recent studies, which suggest that there is a large untapped potential for energy efficiency options with net benefits for consumers. The studies reach these conclusions by comparing the costs of energy efficiency investments to fuel costs (or in most cases to electricity retail prices), and often by only considering incremental costs (i.e., the difference in cost between efficient technologies and baseline technologies).

Accordingly, this study includes a scenario for the potential changes that would arise from voluntary adoption of the most efficient available technologies. This family of scenarios provides an indication of how much consumer surplus would increase if consumers were to adopt all options with negative incremental engineering costs.

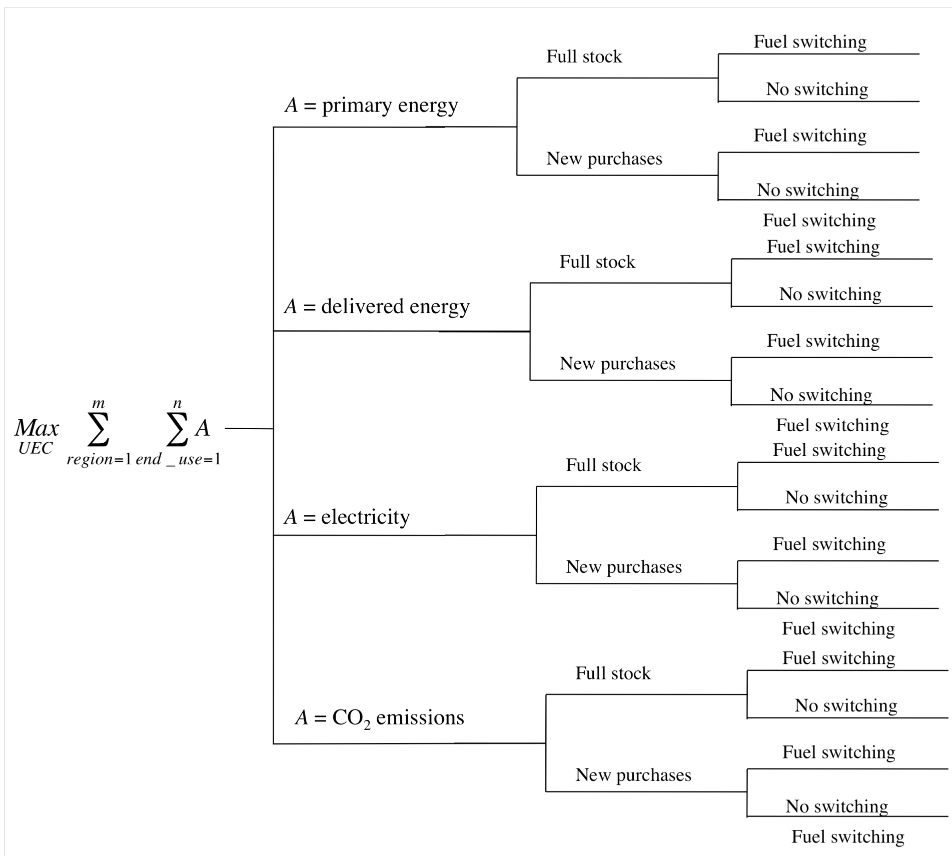

Figure 21 – Set of scenarios represented in RREEM.

As in past studies, there are strong assumptions underlying such estimates. It is assumed throughout this modeling approach that the quality of the energy services provided by the different technologies is virtually the same. However, problems of substitutability have occurred in the past with several technologies. The difference in performance of CFLs when compared with incandescent bulbs is a commonly cited example.

Also, the scenario assumes that consumers behave as fully rational decision-makers and that there are no prevailing market barriers for energy efficiency investments. RREEM allows for simulations where consumers place no value on the current stock of technologies, therefore only considering incremental costs. It also supports a scenario under which consumers do place a value on the existing stock, and where, therefore, the full cost of the more efficient technology is included in the cost metrics. The simulations addressing the consumer perspective also provide an indirect insight into how much consumers would need to be paid to adopt energy efficient technologies that involve positive incremental costs.

As mentioned above, RREEM assumes a normative approach when assessing the energy efficiency (or electricity or carbon savings) potential. The savings represent the potential energy or carbon dioxide savings that would arise if consumers were to use a market discount rate when choosing among options that maximize reductions in energy use. To allow for a more behaviorally realistic and descriptive model of consumer behavior, RREEM also allows for simulations using the findings from the literature on high implicit discount rates, and using different implicit discount rates within the ranges provided in the literature for each end-use.

For a long time, utilities have invested in demand-side programs to promote energy efficiency and conservation. Utility sponsored programs can take many forms, from rebate programs to information campaigns. The second economic agent perspective considered represents how much a utility would need to spend on new end use technologies to save different levels of energy or reduce GHG emissions. The costs incurred by utilities are estimated in two ways. First, it is assumed that the cost of the conservation program is simply the incremental cost between the end use technology the consumers choose if there is no program in place and the cost of the most efficient technology. This cost mechanism is similar to considering the implementation of a rebate program. The second set of simulations assumes that utilities pay the full cost of the new efficient technologies. All these simulations assume that there is a system of regulatory incentives for utilities to invest in energy efficiency. While RREEM is built as a technology oriented model, it is reasonable to assume that utilities entail substantial administrative costs to implement energy efficiency measures. That has proven to be the case with demand-side management programs. Exogenous to RREEM but as part of the dissertation work, estimates of the changes in the supply curves due to program costs for the particular case of electricity efficiency supply curves are provided. In the future development of RREEM, such costs will be directly embodied in the supply curves.

Finally, the last set of scenarios adopts a societal perspective. This set of scenarios aims to guide regulatory agencies on the best level of implementation of specific policies, namely product standards or other incentives to achieve specified levels of energy or carbon dioxide reductions.

In Figure 22 the several dimensions of RREEM are illustrated.

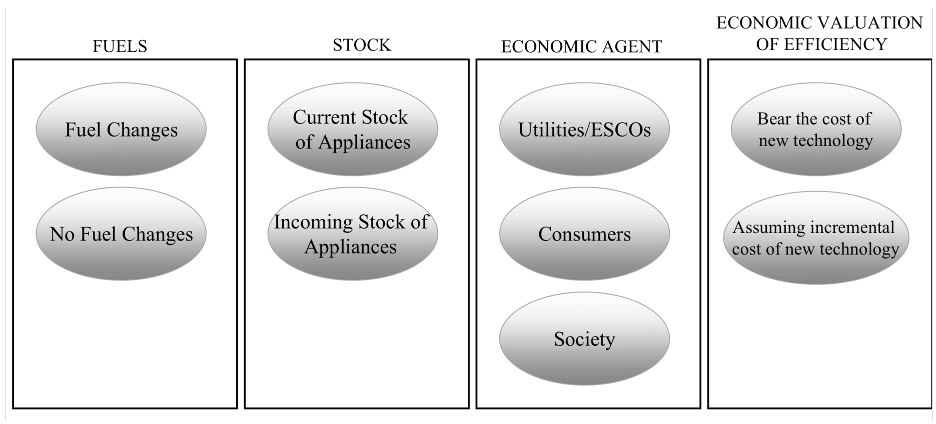

Figure 22 – Illustration of the various dimensions of the explored scenarios for energy efficiency. See the text above for a detailed discussion on the scenarios assumed.

2.4 RREEM Algorithm

RREEM is a Visual Basic program, which uses an Excel user-interface. The model's algorithm operates as follows. First, the relevant data for a simulation are extracted based on the RREEM model user's selection. The user selects the efficiency criteria for the optimization process. RREEM tests to determine for each technology in the baseline stock what is the best available alternative technology (e.g. the one that that provides the largest savings) under a criterion of optimization (energy or GHG). For example, the user might be interested in understanding the potential for reducing delivered energy consumption from efficient heating systems in New England in 2009, as illustrated below in Table 19. As explained in the variables description in section 2.2, this corresponds to "Year" = 4, "Region" = 1 and "End-Use" = 1, which are the three first columns provided in Table 19. In this case, the row of data for stock (in number of equipment units), unit energy consumption (in million BTU), average lifetime (in years) and the capital and retail costs (in US2006 dollar per unit) corresponding to each heating technology (as presented previously in Table 5) will be selected.

The baseline consumption (in terms of primary or delivered energy, electricity or CO_2) is estimated by multiplying the stock size by the average unit energy consumption (express either in MMBTU of primary or final energy, or KWh or ton of CO_2), as:

$$AEC = Stock_{year,region,end\_use,tech\_type} \times UEC_{year,region,end\_use,baseline\_tech\_type} \quad \text{Equation 4}$$

AEC is the annual energy consumption, electricity consumption or carbon dioxide emissions (depending on which criterion of optimization is selected) from the stock of a particular technology type and class, in a specific year and region.

Then, if fuel switching is allowed, the unit with lowest energy consumption (or electricity consumption or carbon dioxide emissions) from that set is selected as the best available technology. In Table 19, for example, this corresponds to Tech Class = 10 and Tech Type = 2, which has an average unit energy consumption of 12 MMBTU per unit of equipment and per year. From Table 5 it can be determined that this corresponds to a ground-source heat pump with COP = 5. The average energy consumption of this best available technology is then reported in the column "Min UEC (MMBTU)" shown in Table 19. The fuel used by that device, the retail and capital costs, and the average lifetime are also reported in other columns, which, for sake of simplicity, are not shown in Table 19.

Table 19 – Detail of RREEM database for 2009, for heating systems in New England.

Year	Re.	End use	Tech Class	Tech Type	Stock	UEC (MMBTU)	Avg life (year)	Capital cost ($/unit)	Retail cost ($/unit)	Fuel type	AEC (MMBTU)	Fuel of Min UEC	Min UEC (MMBTU)
4	1	1	1	1	60451	28	18	1900	1200	4	8.10E+06	7	12
4	1	1	2	1	8875	21	14	3162	2700	4	1.82E+05	7	12
4	1	1	2	2	3748	19	14	3495	3500	4	7.26E+04	7	12
4	1	1	2	3	615	17	14	4660	4250	4	1.04E+04	7	12
4	1	1	2	4	355	15	14	5825	5000	4	5.30E+03	7	12
4	1	1	3	1	0	67	18	10000	750	3	0.00E+00	7	12
4	1	1	3	2	109083	66	18	1900	1200	3	1.91E+07	7	12
4	1	1	3	3	45941	63	18	2000	1300	3	1.64E+07	7	12
4	1	1	3	4	50489	58	18	2400	1400	3	1.58E+07	7	12
4	1	1	3	5	23369	55	18	3200	2200	3	8.08E+06	7	12
4	1	1	4	1	168123	68	25	3000	1500	3	6.79E+07	7	12
4	1	1	4	2	82819	65	25	3600	1600	3	3.30E+07	7	12
4	1	1	4	3	20137	58	25	5000	3000	3	8.20E+06	7	12
4	1	1	5	1	12997	115	18	2350	1850	5	4.23E+06	7	12
4	1	1	5	2	6132	112	18	2650	2150	5	2.92E+06	7	12
4	1	1	5	3	2074	98	18	4800	4300	5	5.79E+05	7	12
4	1	1	6	1	0	72	18	10000	750	2	0.00E+00	7	12
4	1	1	6	2	21038	70	18	1900	1200	2	2.25E+06	7	12
4	1	1	6	3	2566	68	18	2000	1300	2	1.45E+06	7	12
4	1	1	6	4	9806	62	18	2400	1400	2	3.20E+06	7	12
4	1	1	6	5	8034	59	18	3200	2200	2	2.77E+06	7	12
4	1	1	7	1	100547	96	18	2350	1850	1	4.12E+07	7	12
4	1	1	7	2	83821	93	18	2650	2150	1	3.55E+07	7	12
4	1	1	7	3	31952	82	18	4800	4300	1	8.79E+06	7	12
4	1	1	8	1	73010	115	25	3000	1500	1	6.94E+07	7	12
4	1	1	8	2	53659	109	25	3600	1600	1	5.73E+07	7	12
4	1	1	8	3	65131	98	25	5000	3000	1	4.67E+07	7	12
4	1	1	9	1	15315	97	25	1700	1000	6	1.49E+07	7	12
4	1	1	10	1	1279	19	20	6657	4000	7	3.04E+04	7	12
4	1	1	10	2	12	12	20	11233	6000	7	1.47E+02	7	12
4	1	1	11	1	0	48	14	3328	3000	3	0.00E+00	7	12

The next step is to compute several energy, CO_2 and cost related estimates. The annual energy savings (or electricity or CO_2 savings if those are the indicators of interest) for each stock share (i.e, the number of equipment units in a specific year and region that correspond to a specific technology type and technology class as listed in Tables 4 to 7) is computed as:

$$AES_{tech\_type} = Stock_{year,region,end\_use,tech\_type=i} \times (UEC_{year,region,end\_use,tech\_type=i} - UEC_{year,region,end\_use,tech\_type=j})$$

Equation 5

AES_{tech_type} is the annual energy or CO_2 saved for each stock share (in MMBTU of delivered energy in the case of the example provided in Table 19), *Stock* is the number of units of a certain type in a specific year, region and specified end use, and *UEC* is the corresponding unit energy consumption (or carbon dioxide emissions). The technology type "i" is the technology considered under the baseline, and the technology "j" is the best available technology for the considered indicator (12 MMBTU in the example provided in Table 19). The total energy saved or carbon dioxide avoided for each end-use "e", or AES_{end_use} is computed as:

$$AES_{end\_use=e} = \sum_{tech\_type=1}^{i} \left[Stock_{year,region,end\_use,tech\_type} \times \left(UEC_{year,region,end\_use,tech\_type} - UEC_{year,region,end\_use,tech\_type=j} \right) \right]$$

Equation 6

The total energy saved or carbon dioxide avoided in a specific year and region, or AES_{total} is then computed as:

$$AES_{total} = \sum_{end\_use=1}^{x} \left[AES_{end\_use} \right] \qquad \text{Equation 7}$$

For each pair of baseline-efficient technologies "i" and "j", the levelized annual cost to consumers, utilities and regulators is then estimated using the general expression:

$$CCE_{tech\_type} = \frac{I_j \dfrac{d}{\left(1-(1+d)^{-n}\right)} + (Fuel\_Price_j \times E_j) - I_i \dfrac{d}{\left(1-(1+d)^{-n}\right)} - (Fuel\_Price_i \times E_i)}{E_i - E_j}$$

Equation 8

CCE_{tech_type} is the annualized cost of conserved energy (or electricity or CO_2 emissions depending on the quantity being optimized) in 2006 \$/millionBTU (or \$/kWh or \$/tonCO_2 avoided), *I* is the investment or retail cost (in 2006 \$/unit), *Fuel_Price* is the price of the fuel used by the technology (in \$/MMBTU, \$/kWh or \$/tonCO_2), *d* is the discount rate and *E* is the annual energy (or electricity or carbon dioxide emissions) consumed by the technology in one year. Again, "i" corresponds to each of the baseline technologies (the list of technologies and respective stock shares presented in Table 19) and "j" represents the efficient technology (the ground source heat pump in the example above).

Depending on the scenario considered, some changes to Equation 8 are needed. The expression in Equation 8 is appropriate when estimating the costs of new equipment that would be purchased in a certain year under the baseline. Referring back to the heating systems example, this corresponds to the choice between buying a more efficient heating system or the one that the consumer would be expected to buy under the baseline.

For the scenario on the assessment of the monetary costs and energy savings from retrofitting the full stock of existing equipment, the decision is whether to keep current appliances or invest in new one. In that case, the opportunity cost is to do nothing. Therefore, in that case, the cost of conserved energy (or electricity or carbon dioxide emissions) becomes:

$$CCE_{tech\_type} = \frac{I_j \frac{d}{\left(1-(1+d)^{-n}\right)} + (Fuel\_Price_j \times E_j) - (Fuel\_Price_i \times E_i)}{E_i - E_j}$$

Equation 9

Furthermore, for scenarios that represent the utility or ESCO decision-making, the energy (or electricity or carbon) savings should not be included in the cost of conserved energy. In this case the correct expression to estimate the cost of retrofitting existing equipment becomes:

$$CCE_{tech\_type} = \frac{I_j \frac{d}{\left(1-(1+d)^{-n}\right)}}{E_i - E_j}$$

Equation 10

After the appropriate cost metrics are estimated, the efficiency options are then ranked accordingly by cost and plotted as the supply curve.

In the efficiency supply curve representation, efficiency options are ranked from the most cost-effective to the least cost-effective along the y-axis of the curve. Thus, the decision criterion for cost-effectiveness determines how the available energy efficiency options will be ranked. In RREEM, such a ranking can be made in terms of $/MMBTU, $/ton CO_2 or $/kWh. If the user chooses $/MMBTU, that energy efficiency supply curve will be constructed by ranking available technologies based on this criterion. However, two other plots based on $/ton$CO_2$ and $/kWh are also created so that the user can see how different cost-effectiveness criterion lead to different optimal choices of technologies. All monetary values for the cost-effectiveness criteria are expressed in 2006 real USD.

The default fuel prices assumed in RREEM (which are used in Equations 8 and 9) correspond to the AOE 2008 projections from the EIA for retail fuel prices between 2006 and 2030, at the census division level, and are presented in Appendix 3

2.5 Advantages and Drawbacks in RREEM

A criticism of the efficiency supply curves and marginal abatement curves found in previous studies is that they lack transparency regarding the assumptions in how they were constructed. As a consequence, many knowledgeable economists and engineers outside of the energy efficiency advocacy community view efficiency supply curves as an elegant approach with limited real world applications. Despite that, policy-makers often make policy recommendations on the basis of such studies without being aware of their limitations and assumptions.

Due to the uncertainties regarding several aspects of technology characterization, market shares of technologies, behavioral patterns, regional mix of technologies, fuels used to generate electricity and carbon factors, no single supply curve can comprehensively describe the state of the world with respect to how much energy can be saved and at what cost.

This study incorporates some of the assumptions taken from the literature but devotes special attention to making explicit the assumptions underlying these different scenarios, the policies and the key sources of uncertainty. With RREEM, a transparent tool is provided for decision-making purposes.

The key assumptions made in RREEM are provided above in Sections 2.1 to 2.4. RREEM has the flexibility to test some of the assumptions by easily running the model with different values for fuel prices, carbon intensity factors and discount rates. With some more work, it is not difficult to test the assumptions of unit energy consumption and stock share of different equipment types.

Still, there are several important uncertainties and limitations to RREEM that need to be made clear. An important uncertain aspect that arises under any attempt of estimated the energy efficiency potential regards the projections of the baseline. Determining energy efficiency potential requires that plausible projections of future residential energy consumption are used as a baseline. In RREEM, I assumed the projections from the Annual Energy Outlook (AEO) 2008 reference case, which accounts for the effect of ongoing policies. However, the AEO projections provided annually by EIA exhibit substantial changes from year to year. Therefore, while RREEM includes the functionality to simulate the annual energy consumption and annual energy savings between 2009 and 2030 under different types of assumptions, looking further than five or ten years into the future will yield very uncertain results given the large uncertainty on the future energy consumption of the US residential sector. The mix of end-use technologies, their lifetime, efficiency and usage will be very dependent on the policies implemented between now and then.

More precisely, there are at least four effects which could account for dramatic changes in future residential energy consumption: (i) the impact of future policies; (ii) unanticipated structural changes in the economy or dramatic and unanticipated price fluctuations; (iii) changes in weather patterns or climate; (iv) new technologies and products that rapidly gain market share.

An example of the impact of policies on short-term projections of residential energy consumption is depicted in Figure 23, which shows the effect of the EISA on the estimates of total final residential energy delivered in quadrillion BTU. The implementation of EISA alone is estimated to have a projected reduction of 2.5% in total final residential energy delivered by 2015 and 3.4% by 2030.

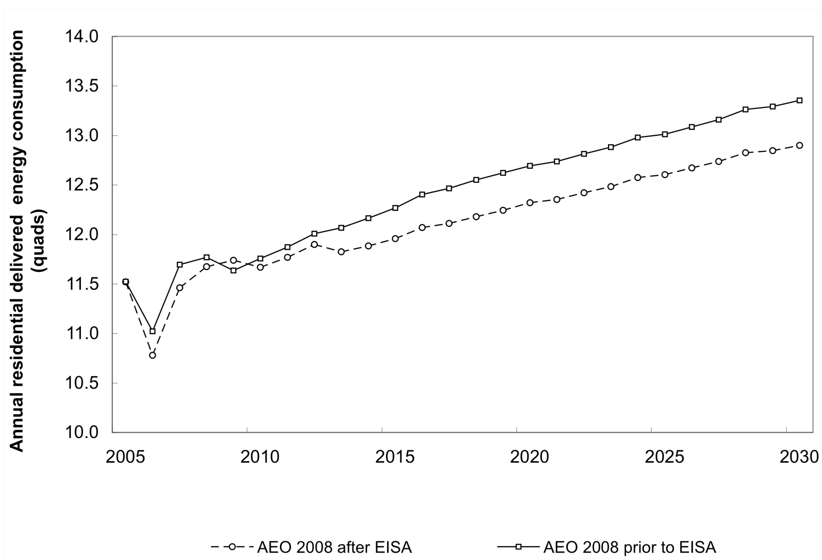

Figure 23 – Historical values (between 2005 and 2007) and projections (between 2009 and 2030) of annual delivered energy consumption, for the U.S. residential sector, based on the early version of the Annual Energy Outlook (prior to incorporating the effect of the Energy Independence and Security Act, EISA) and the final version (after incorporating EISA). Constructed based on data from the AEO 2008 early and final releases, EIA, 2008.

Efficiency supply curves are by definition static. Yet, energy efficiency measures implemented today will have impact over several years, with the lasting effect of efficiency being dependent on the types of efficiency measures implemented. For example, replacing current incandescent light bulbs with fluorescent lamps might have an impact over the next 3-5 years after which additional investments will be needed. Investing in a new heat-pump system using an air-source heat pump will have an impact that persists between 7 and 21 years. Furthermore, assessing the effect of energy efficiency policies in the future requires taking into account energy and climate policies that might be implemented between now and then. In contrast to previous models, RREEM partially addresses that issue by providing simulations for any year between 2006 and 2030. However, whatever the year is selected for the analysis, the AEO 2008 projections are assumed to be in place up until that year.

Chapter 3. Estimating the Technological Potential for Efficient End-Use Technologies in the Residential Sector

National and regional energy efficiency assessments often include the technological potential for energy efficiency. The technological potential corresponds to the magnitude of the energy savings that can be achieved through energy efficiency measures while maintaining the level of the energy service provided. The technological potential disregards any type economic assessment and generally corresponds to scenario where all less efficient technologies are being replaced overnight. All these simplifications lead to the provision of very unrealistic scenarios, yet the results are useful as an upper bound to what technology alone could deliver if economic measures and barriers to energy efficiency were ignored.

Several considerations will alter the estimates of a technological potential. Among other factors, the geographical delimitations, the period of analysis, the end-uses considered and respective technological characterizations, and the patterns of usage all lead to different estimates of the technological potential. Despite the underlying uncertainty, assessing the technological potential for energy, electricity and carbon savings provides a benchmark for what policy could ultimately aim to achieve. Furthermore, it provides an insight on whether or not policy objectives in energy and climate strategies align. For example, when assessing the technological potential for the delivered energy consumption from residential end-uses[21], the losses that arise in electricity generation, transportation and delivery are disregarded.

Using RREEM, I estimate the technological potential for four important aspects of energy and climate policy design: primary energy; delivered energy; electricity; carbon dioxide emissions. In addition, I provide the estimates for each of the above criteria under four scenarios:

1. Assuming an overnight replacement of all stock with the most efficient available technology and allowing for fuel switching from the business-as-usual scenario;
2. Same as in 1, but with no changes in fuel.
3. Assuming that new stock (purchases of equipment in 2009) corresponds to the most efficient available technologies and allowing for fuel switching from the business-as-usual scenario;
4. Same as 3, but with no changes in fuel.

The estimates of the reduction in energy, electricity and carbon emissions that can be achieved under these scenarios are presented in the sections that follow.

[21] Assuming that the same level of energy services is provided.

3.1 Primary Energy Consumption

Figure 24 and Figure 25 provide the results of RREEM simulations for the nationwide energy consumption and energy efficiency technological potential in terms of primary energy in 2009. The simulations from RREEM suggest that 2009’s residential delivered energy consumption for the largest end uses are roughly 15.7 quads. In AEO 2008 it is reported that all residential end-uses in 2009 account for 22 quads of delivered energy. Therefore, the end-uses covered in RREEM are accounting for 74% of delivered energy consumption, which suggest most of the potentially available major efficiency gains are captured in RREEM.

The simulations in Figure 25 and 26 account for four energy efficiency scenarios: (i) assuming that the purchases of equipment in 2009 correspond to the most efficient available technology using the same fuel as the business-as-usual scenario; (ii) as in (i) but efficient technologies can use a different fuel from the business-as-usual scenario; (iii) assuming an overnight replacement of all stock with the most efficient available technology using the same fuel as the business-as-usual scenario; (iv) as in (iii) but assuming that efficient technologies can use a different fuel from the business-as-usual scenario.

Simulations from RREEM result in a residential energy efficiency technological potential (the amount of primary energy reduction that could be saved regardless of the costs and by allowing fuel switching) on the order of 10.8 quads (see Figure 24 for detailed savings by end-use), with the largest contributions in terms of absolute reductions coming from improving heating systems (-4.9 quads), cooling (-2 quads), lighting (-1.6 quads) and water heating (-1.3 quads).

This estimate assumes that there could be switching from electricity to natural gas (or changes from or to other fuels). If I add the constraint of keeping the same fuels as in the baseline (therefore assuming that due to infrastructure limitations the fuel source needs to remain the same), the technological potential drops to 4.9 quads of saved energy. In that case, the largest contributors to the delivered energy savings are, in decreasing order, lighting, cooling, heating, and water heating.

Replacing the full stock of appliances overnight is a very unrealistic scenario. If instead only the new stock of devices and appliances added in 2009 were improved to the most efficient available technology, then primary energy reductions of the order of 1.2 quads would be achieved if one allows for fuel switching between end-use options and 0.8 quads if the fuels would need to remain the same as in the business as usual case.

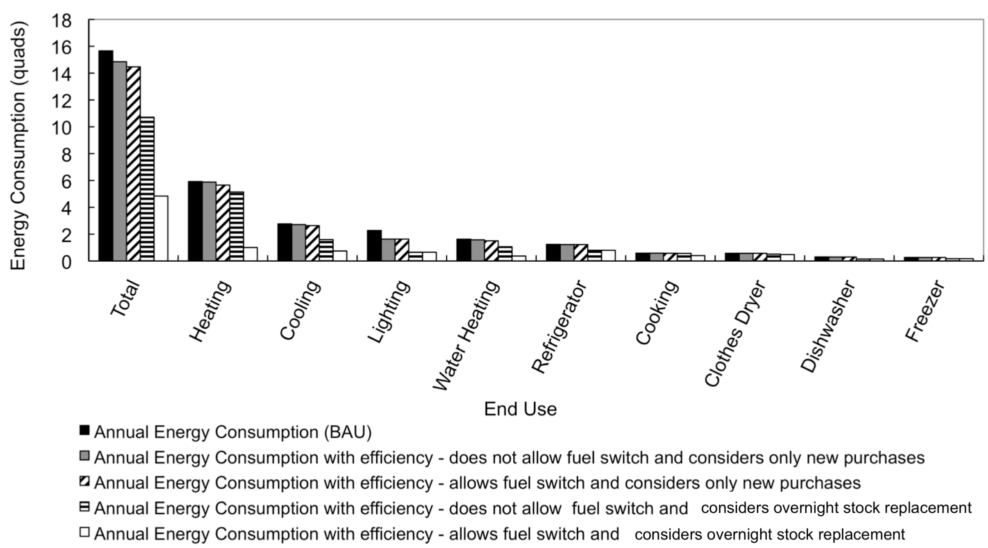

Figure 24 –2009's annual primary energy consumption (in quadrillion BTU) for the largest energy end-uses under several energy efficiency scenarios.

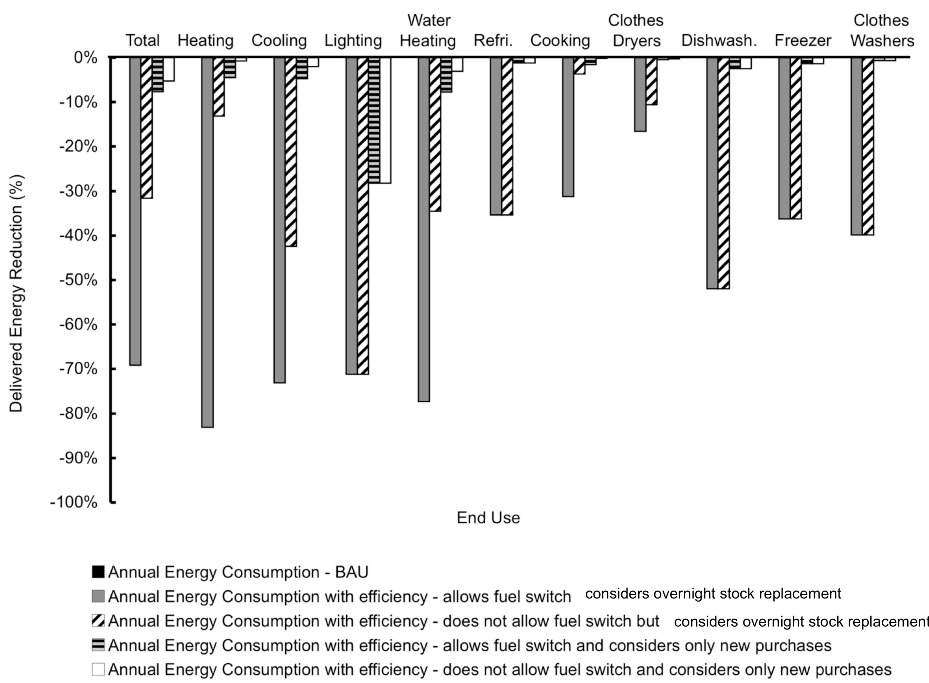

Figure 25 – Reductions in 2009's annual primary energy consumption from the AEO 2008 reference case for several energy efficiency scenarios.

3.2 Delivered Energy

Figure 26 and Figure 27 provide the results of RREEM simulations for the nationwide energy consumption and energy efficiency technological potential in terms of delivered energy in 2009. The simulations from RREEM suggest that 2009's residential delivered energy consumption for the largest end uses would be roughly 9.7 quads. In AEO 2008 it is reported that all residential end-uses account for 11.7 quads of delivered energy. Therefore, the end-uses covered in RREEM are accounting for 94% of delivered energy consumption, which suggest that the major efficiency gains will be captured in RREEM.

As in the case of the primary energy scenario, the simulations in Figure 26 and 27 account for four energy efficiency scenarios: (i) assuming that the purchases of equipment in 2009 correspond to the most efficient available technology using the same fuel as the business-as-usual scenario; (ii) as in (i) but efficient technologies can use a different fuel from the business-as-usual scenario; (iii) assuming an overnight replacement of all stock with the most efficient available technology using the same fuel as the business-as-usual scenario; (iv) as in (iii) but assuming that efficient technologies can use a different fuel from the business-as-usual scenario

The residential energy efficiency potential (the amount of reduction in delivered energy consumption that could be achieved regardless of the costs and by allowing fuel switching) is estimated to be on the order of 7.4 quads (see Figure 26 for detailed savings by end-use), with the largest contributions in terms of absolute reductions coming from improving heating systems (-4.5 quads), water heating (-1.2 quads), cooling (-0.6 quads) and lighting (-0.5 quads). As in the previous section, this estimate assumes that there could be switching from electricity to natural gas (or changes from or to other fuels). If instead it is assumed that due to infrastructure limitations, fuel sources must remain unchanged, the technological potential drops to 2.4 quads of saved energy. In that case, the largest contributors to the delivered energy savings are still heating, water heating, cooling and lighting, each contributing about the same amount. Undertaking energy conservation by changing the incoming stock of new devices and appliances in 2009 would only lead to delivered energy reductions in the order of 0.6 quads if one allows for fuel switching between end-use options and 0.3 quads if the fuels would need to remain the same as in the business as usual case. If a policy is designed to target only incoming stock instead of dealing with retrofits, it will take more than 12 years to achieve the savings that could arise from retrofitting the entire stock overnight.

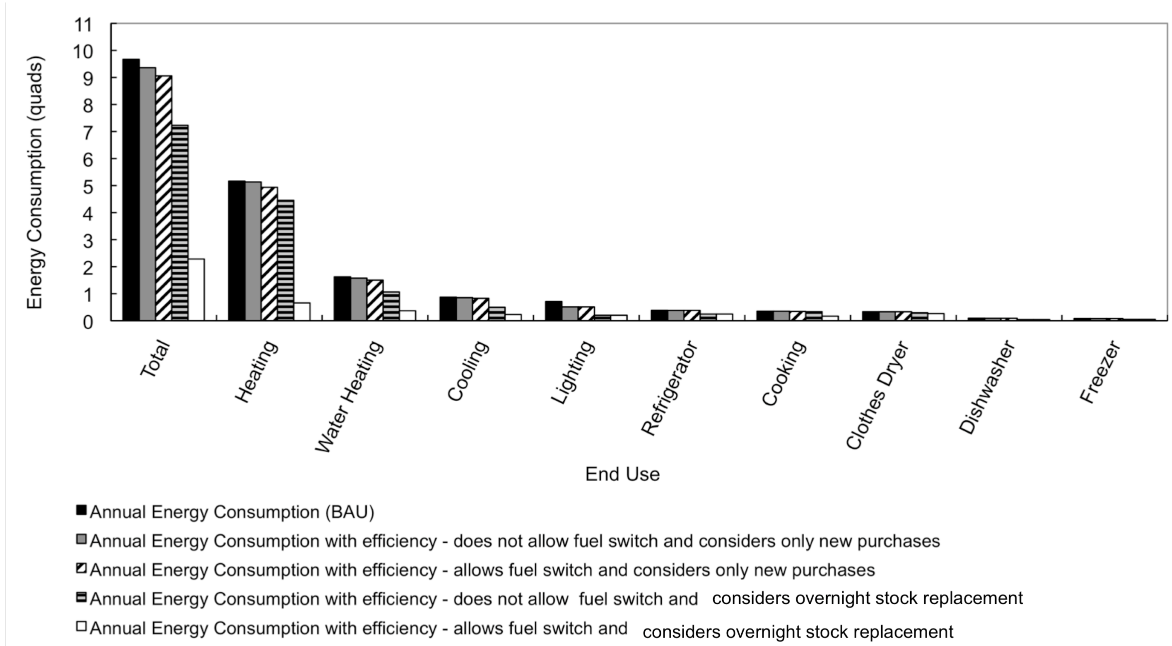

Figure 26 –2009's annual delivered energy consumption (in quadrillion BTU) for the largest energy end-uses under several energy efficiency scenarios.

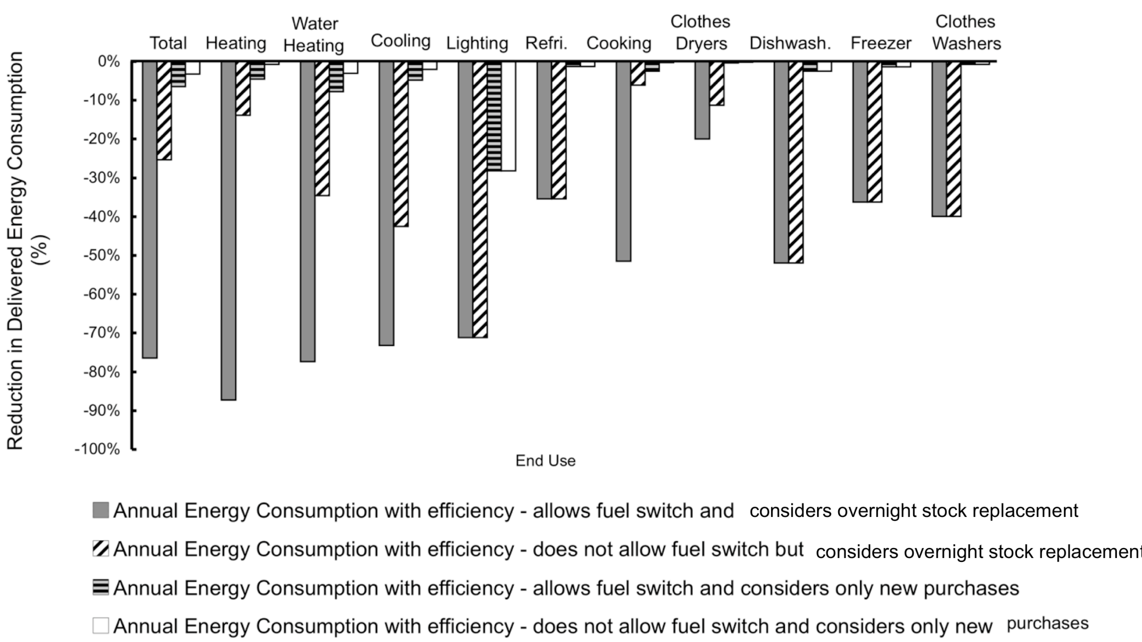

Figure 27 – Reductions in 2009's annual delivered energy consumption from the AEO 2008 reference case for several energy efficiency scenarios.

3.3 Electricity

Figure 28 and Figure 29 provide the results of RREEM simulations for the nationwide electricity consumption and energy efficiency technological potential in terms of delivered electricity in 2009. The simulations from RREEM suggest that 2009's residential delivered electricity consumption for the largest end uses would be roughly 800 TWh. In AEO 2008 it is reported that all residential end-uses account for roughly 1,400 TWh of delivered electricity. Therefore, the end-uses covered in RREEM are accounting for 57% of delivered electricity consumption.

Again, the simulations in Figure 28 and 29 account for four energy efficiency scenarios: (i) assuming that the purchases of equipment in 2009 correspond to the most efficient available technology using the same fuel as the business-as-usual scenario; (ii) as in (i) but efficient technologies can use a different fuel from the business-as-usual scenario; (iii) assuming an overnight replacement of all stock with the most efficient available technology using the same fuel as the business-as-usual scenario; (iv) as in (iii) but assuming that efficient technologies can use a different fuel from the business-as-usual scenario.

The simulations from RREEM suggest that 2009's residential electricity efficiency technological potential in the order of 430 TWh (see Figure 28 for detailed savings by end-use), with the largest contributions in terms of absolute reductions coming from improving cooling (-186 TWh), lighting (-148 TWh), refrigerators (-40 TWh) and heating systems (-25 TWh).

These estimates assume it is possible to switch fuels. If instead, due to infrastructure limitations or resources availability, it is assumed that fuel must remain the same, potential savings drop to 335 TWh. In that case, the largest contributors to the delivered energy savings by decreasing order are lighting, cooling, heating systems and refrigerators.

Reducing energy consumption by changing the incoming stock of devices and appliances in 2009 would only lead to delivered energy reductions in the order of 75TWh if one allows for fuel switching by end-use options and 67 TWh if the fuels remain unchanged as in the business as usual case.

The results suggest that it would take close to six years for the energy saving arising from changing in new purchases to equal the saving that can be achieve with one single year if retrofits are made to current stock.

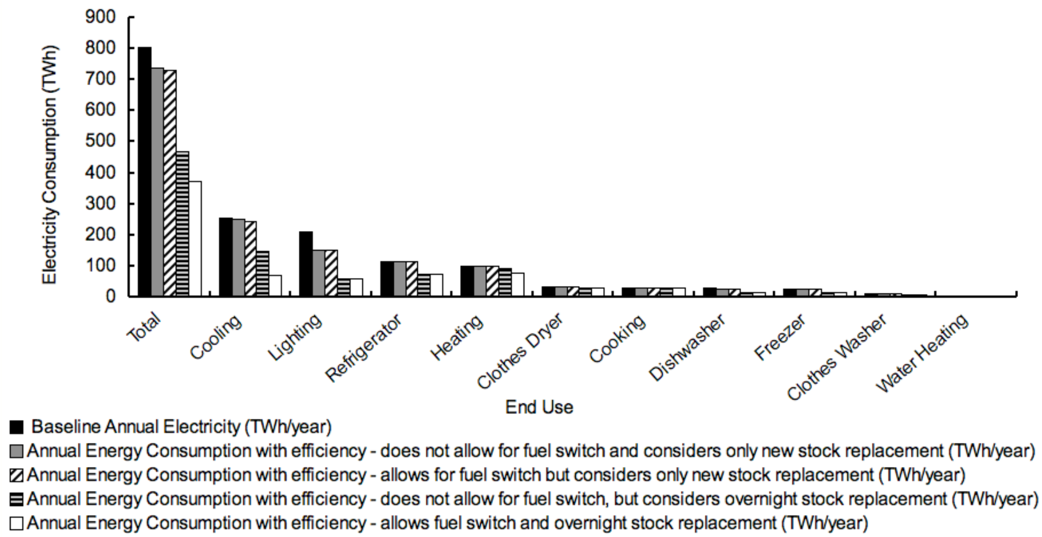

Figure 28 –2009's annual electricity consumption (in TWh) for the largest energy end-uses under several energy efficiency scenarios.

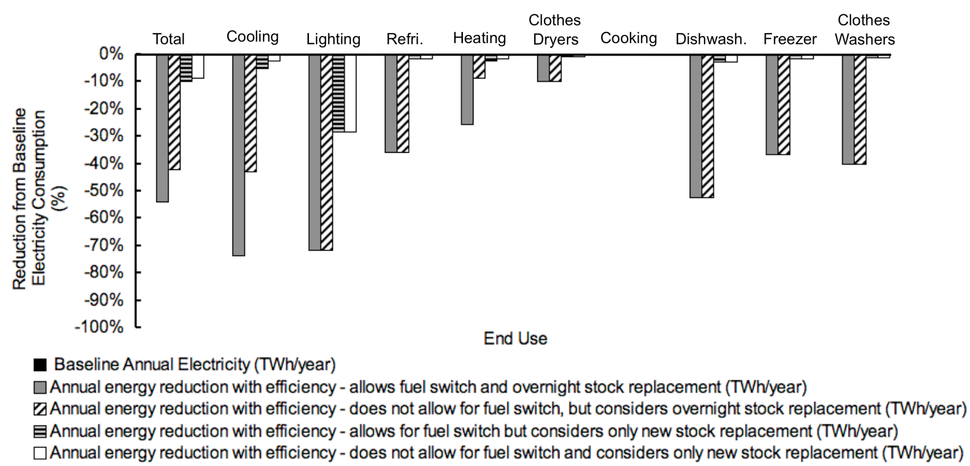

Figure 29 – Reductions in 2009's electricity consumption from the AEO 2008 reference case for several energy efficiency scenarios.

3.4 Carbon Dioxide

In Figure 30, I provide the results of RREEM simulations for potential in residential nationwide carbon dioxide emissions. Again this provides an estimate of the upper bound on how much technology can deliver, disregarding issues of implementation and cost. The simulations from RREEM suggest that the largest end-uses in the residential sector contribute roughly 900 million metric tons of CO_2. The end-uses covered in RREEM account for 71% of residential emissions[22], which again suggests that the major efficiency gains will be captured in RREEM.

The simulations in Figure 29 account for four energy efficiency scenarios: (i) assuming that the purchases of equipment in 2009 correspond to the most efficient available technology using the same fuel as the business-as-usual scenario; (ii) as in (i) but efficient technologies can use a different fuel from the business-as-usual scenario; (iii) assuming an overnight replacement of all stock with the most efficient available technology using the same fuel as the business-as-usual scenario; (iv) as in (iii) but assuming that efficient technologies can use a different fuel from the business-as-usual scenario.

[22] In AEO 2008 it is reported that all residential end-uses account for 1,260 million metric tons of CO_2.

Simulations from RREEM result in an ultimate carbon dioxide reduction potential of 787 million metric tons of CO_2 (see Figure 30 for detailed savings by end-use), with the largest contributions in terms of absolute reductions coming from improving heating systems, cooling, lighting and water heating.

If the fuel powering the end-use technology must remain the same as in the baseline projections, potential savings drop to 314 million metric tons of CO_2 avoided. In that case, the largest contributors to the delivered energy savings by decreasing order are lighting, cooling, heating, and water heating. Reducing energy consumption by changing the incoming stock of devices and appliances in 2009 would only lead to delivered energy reductions in the order of 91 million metric tons of CO_2 if one allows for fuel switching by end-use options and 59 million metric tons of CO_2 if the fuels remain unchanged as in the business as usual case.

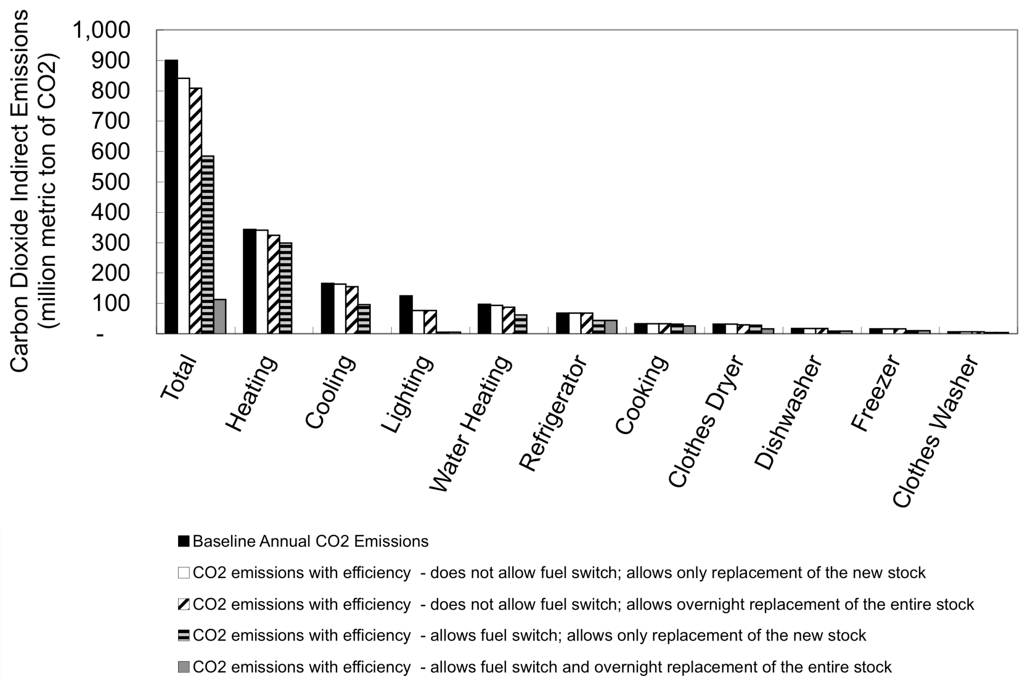

Figure 30 –2009's Carbon dioxide emissions in the residential sector under several energy efficiency scenarios.

3.5 Policy Implications

This Chapter has provided an overview of technological potential assessments using different energy and climate policy related criteria. I estimate that the ultimate technological potential for the largest uses in the residential sector is on the order of a 70% reduction from the baseline[23] for primary energy, 87% for CO_2 emissions, 76% reduction for delivered energy and more than 50% reduction for electricity, Table 20. Considering a technology perspective alone, and disregarding economic costs, this suggest that a policy goal of reducing primary energy consumption or GHG emissions should prioritize heating, cooling, water heating and lighting, and foster a move to different types of fuels from the ones used today.

Table 20 – Summary of reductions from baseline consumption that can be achieved for primary energy, delivered energy, electricity and CO_2 emissions.

	Primary Energy	Delivered Energy	Electricity	CO_2 emissions
Assumed baseline for the largest energy end-uses	15.7 quads	9.7 quads	800 TWh	900 $MMtonCO_2$
Allow fuel switching and overnight stock replacement	69%	76%	54%	87%
Not allow fuel switching but allow overnight stock replacement	32%	25%	42%	35%
Allow fuel switching and considering only new purchases	8%	6%	9%	10%
Not allowing fuel switching and considering only new purchases	5%	3%	8%	7%

[23] The assumed baseline here is the energy, electricity or GHG emissions from the largest end-uses, in 2009.

In the short term, policies targeting new purchases would lead to reductions of less than 10% from the baseline energy, electricity or carbon dioxide emissions. To get serious about energy efficiency also requires policies that tackle the existing stock of appliances.

In the present work, the technological potential was estimated for different important aspects of policy implementation, namely in terms of energy, electricity and carbon savings. This exercise provides an indication of how the prioritization of different end-uses arises when using such different criteria.

Instead of accounting for market turn over of the stock of existing technologies, the approach in this Chapter was to estimate the order of magnitude of the savings that could be achieved if one were to pursue a total replacement of the existing stock or just targeted new purchases. These engineering-based approaches do not include an assessment of how much it would costs to achieve such savings or which types of policies are required to make sure the efficiency potential is achieved. To address this issue, the next chapters provide an insight to the costs involved in adopting more efficient appliances in new purchases and the costs of retrofitting current equipment. Namely, I explore how such costs differ when adopting the perspective of consumers, electric utilities, an ESCO or society as a whole.

Chapter 4. Utilities or ESCOs Investments in Energy Efficiency

4.1 Focus on Electricity: Comparing RREEM Simulations with Previous Assessments

In Chapter 1, I described some of the mechanisms used by electric utilities to promote energy efficiency. The DSM programs implemented by electric utilities as a means of reducing electricity consumption and the energy efficiency programs developed by ESCOs often include two cost components: a technology related cost and an indirect cost. The former might represent either a system of rebates over more efficient end-use technologies or the full cost of those efficient technologies. The latter might correspond to administrative costs, management costs, education and information costs, or other.

In this chapter, I estimate the direct and indirect costs supported by electric utilities or ESCOs when different levels of energy efficiency investments are pursued.

A mechanism similar to a rebate program is simulated by assuming that the electric utilities or ESCOs incur the incremental costs between a baseline and an efficient technology. I also explore a scenario where electric utilities/ESCOs are responsible for the full cost of the efficient technology.

Efficiency supply curves can be used to estimate the potential energy savings, electricity savings or carbon avoided at a certain cost. Ranking technological options in terms of each of these criteria leads to different optimal path of technology adoption. Currently, electric utilities and ESCOs efficiency programs tackle only electricity reduction and peak capacity management. Some electricity utilities are even mandated to only include electricity-related energy efficiency programs by regulation. For example, the New York State Energy Research and Development Authority (NYSERDA), must spend the resources raised through a system of benefits charges in electricity-related DSM. Conversely, NYSERDA is likely to be responsible for the funds allocated for the RGGI, where the aim will be to reduce carbon emissions in the most cost-effective way. The RGGI programs are still in the early proposal stage, so the final design might have other considerations. I argue that the allocation of funds to efficiency programs should simultaneously include a consideration of both the electricity and energy saved and greenhouse gas avoided.

I start by presenting in Figure 31 to 32 several scenarios for electricity supply curves. Figure 31 corresponds to the set of scenarios where the full stock of residential equipment is retrofitted by utilities or ESCOs in 2009. Variants of this main scenario in the figure correspond to either allowing or not allowing fuel-switching options, and whether utilities pay the full cost or the incremental cost of the efficient technology.

From now on, through Chapter 4 to 8, unless stated otherwise, each steps represented in a supply curve corresponds to an energy efficiency measure in a specific census division level, for a specific end-use, and for the stock (or alternatively just new purchases) corresponding to a certain technology type. For sake of illustration, in Figure 33 I provide a detail of Figure 31. Figure 33 shows the end-uses and regions corresponding to the first steps of the curve simulating a retrofit of the full stock of appliance, assuming utilities pay the full cost of the new technology and that fuel switching can occur (blue line in Figure 31). In order to extract these results, a routine was built in Mat Lab, indicating the region and end-use that each step in the efficiency curve corresponds to.

I estimate that electric utilities or ESCOs could promote electric energy efficiency programs that would save between roughly 142 TWh and 345 TWh for a direct cost of less than 0.10$/kWh ($2006), depending on whether or not fuel switching is allowed[24]. Between 56 TWh and 68 TWh could be saved by targeting new equipment purchases.

A 5% reduction in residential electricity consumption would require annualized costs from zero to $8 billion ($2006), Table 21. The costs accrue as more ambitious energy efficiency goals are pursued. For example, technology investments that would range

[24] The estimates also depend on whether electric utilities or ESCOs only need to provide a rebate to foster the change or need to pay fully for the new technology. The figures assume that the current stock of appliances is targeted.

from zero for the cheapest energy efficiency options to $13 billion ($2006) for the most expensive ones would be required to achieve a reduction of 10% from the baseline, Table 21.

These costs do not include the indirect costs for program implementation, management, etc. In the "no fuel switching scenario", the costs of achieving a 5% reduction in the baseline range from $2 to $8 billion ($2006), Table 21 and Table 22.

In the case where the equipment is retrofitted and utilities only provide a rebate (thus paying incremental costs between the baseline and the efficient technology), some other economic agent (the consumer or the regulatory agency) would need to bear the remaining of the cost, which corresponds to the value of the existing stock. Throughout the present work, I study the scenario of retrofitting the full stock of equipment as the upper bound on the energy efficiency potential. However, what I just stated in terms of a scheme where utilities only pay the rebate value will always be true when only parts of the stock are retrofitted. Such costs are not presented in Table 21 since the table aims to represent just the net costs or benefits to utilities.

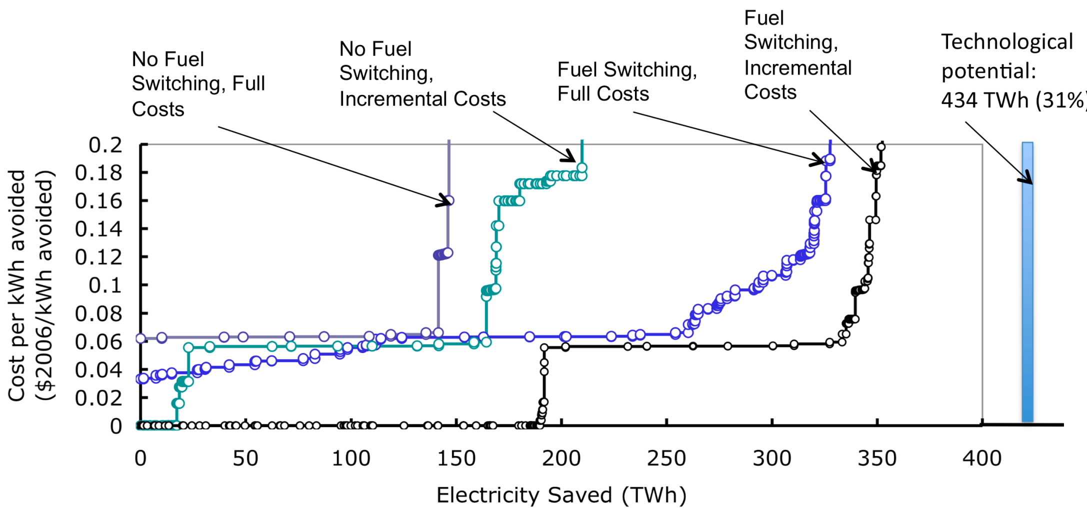

Figure 31 – Electricity supply curves for energy efficiency measures promoted by utilities or ESCOs for the stock of goods in 2009, using a 7% real discount rate and technology data from AEO 2008.

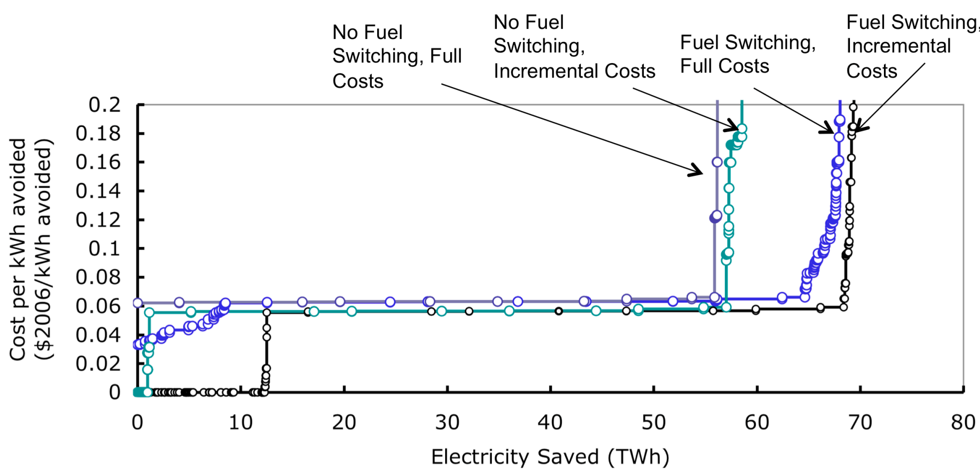

Figure 32 – Electricity supply curves for energy efficiency measures concerning new purchases in 2009 promoted by utilities or ESCOs, using a 7% real discount rate and technology data from AEO 2008.

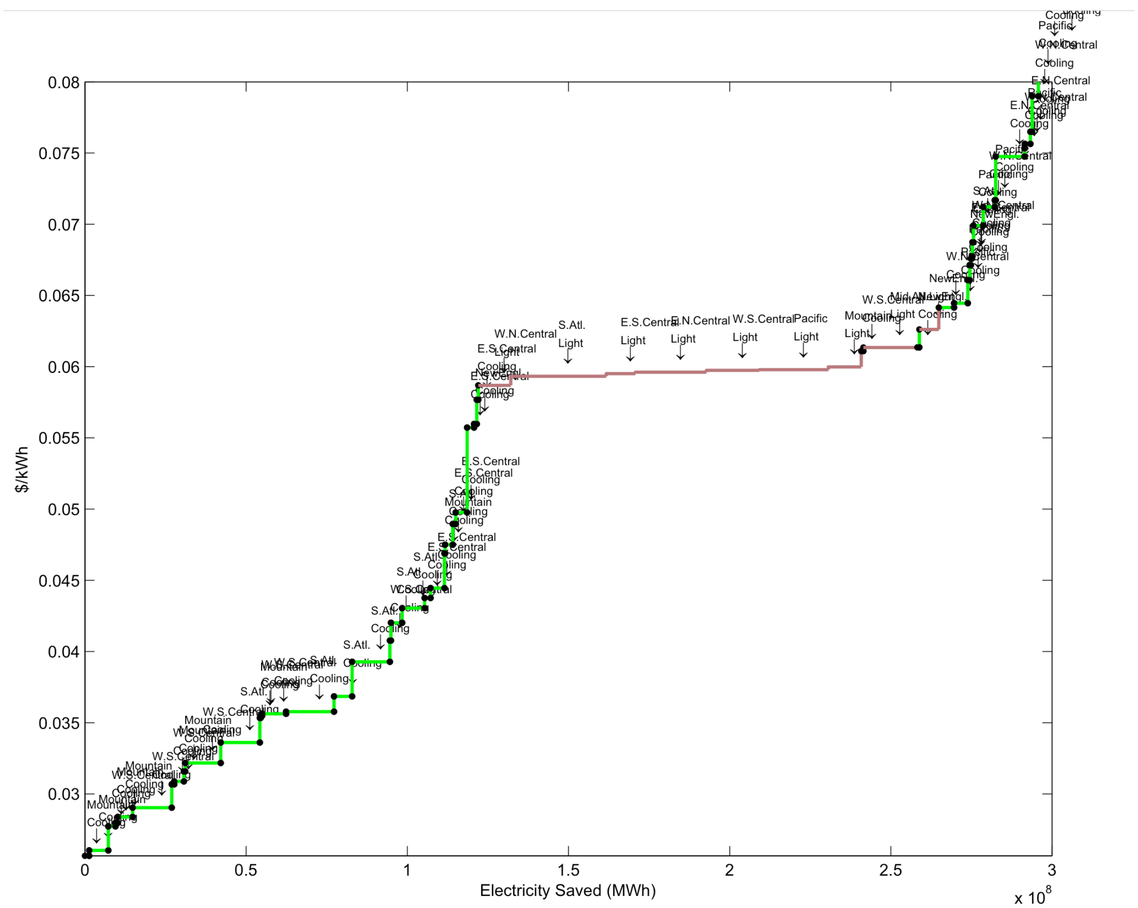

Figure 33 – Detail on firsts steps of electricity supply curve shown in Figure 31 by region and end-use. The simulation corresponds to the scenario where utilities retrofit the full stock, pay for the efficient technology and fuel switching is allowed.

Table 21 – Net annual costs for utilities/ESCOs from energy efficiency investments to achieve different levels of reductions from the baseline (1,400 TWh in 2009), using a 7% discount rate. The utilities/ESCOs can either pay for the incremental cost of the technology or pay fully for the technology replacements, and either targets the purchases in 2009 or retrofit existing stock. Figures account for technology related costs only. Indirect costs of program management and other costs are not included.

	UTILITIES							
ANNUAL COST (billion $2006)	utilities pay for incremental cost of technology		utilities fully pay for technology replacement		only targeting new stock and pay for incremental cost of technology		only targeting new stock and pay fully for cost of technology	
Reduction from baseline	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes
<5%	0	2	5	5	2	7	5	8
<10%	0	8	13	13	-	-	-	-
<20%	0	37	22	39	-	-	-	-
<30%	12	-	98		-	-	-	-
<40%	-	-	-		-	-	-	-

Table 22 – Summary of the achieved electricity reductions from the baseline (1,400 TWh) due to investments in energy efficiency by utilities or ESCOs, using a 7% discount rate.

% reduction from the baseline that corresponds to:	Utilities/ESCOs pay for incremental cost of technology		Utilities/ESCOs fully pay for technology replacement		Only targeting new stock and pay for incremental cost of technology		Only targeting new stock and pay fully for cost of technology	
	Allow fuel switching	No fuel switching	Allow fuel switching	No fuel switching	Allow fuel switching	No fuel switching	Allow fuel switching	No fuel switching
Net savings (<0$/kWh):	14%	1%	0%	0%	<1%	<1%	0%	0%
Investment costs below 0.10$/kWh:	25%	12%	21%	10%	5%	4%	5%	4%
Maximum achievable:	31%	24%	31%	24%	5%	5%	5%	5%

I benchmark the results from the present study with past studies [21], [43]-[37], [55]. In Chapter 1, I detail the differences in the cost metrics considered by each study. The past studies generally compared the electricity savings with the residential retail electricity price. I find that the present study is in agreement with the past estimates, Table 23. Table 24 provides a comparison between my estimates when using only investments costs in new technologies and Gellings's results, providing similar findings.

Table 23 – Summary of findings from electricity supply curves and comparison with the present study.

Study	**Electricity Saving Potential (TWh)**	**Retail Electricity Price ($/kWh)**	**Retail Electricity Price ($2008/kWh)**	**Notes**
Present study	142 - 345	0.10 ($2006)	0.11	Residential, considers both full costs and no fuel switch (low end estimate) and incremental costs and fuel switching (high end estimate)
Gellings et al., 2000	100	0.10 ($2005)	0.11	All sectors, Full cost
Koomey et al. , 1993	400	0.078 ($1990)	0.13	Residential, Incremental costs
5-Lab, 1996	400	0.045 ($1997)	0.06	All sectors, Incremental costs
Rubin et al., 1993	734	0.064 ($1993)	0.09	Buildings, incremental costs

Table 24 – Comparison between the present study and Gellings et al. [21] estimates for the potential of energy efficiency using electricity measures.

Costs assume the full cost of the most efficient technology.

Cost of efficiency measures of less than:	**RREEM Simulations for 2009 (TWh of saved electricity)**	**Gellings et al., 2006 (TWh of saved electricity)**
0.05 $/kWh avoided	~ 94 (fuel switching; replacing full stock) ~ 7 (fuel switching; only new stock)	~50 TWh
0.10 $/kWh avoided	~ 295 (fuel switching; replacing full stock) ~ 142 (no fuel switching; replacing full stock) ~ 66 (fuel switching; only new stock) ~ 55 (no fuel switching; only new stock)	150 TWh
0.20 $/kWh avoided	~327 (fuel switching; replacing full stock) ~ 147 (no fuel switching; replacing full stock) ~ 68 (fuel switching; only new stock) ~ 56 (no fuel switching; only new stock)	~ 230 TWh

4.2 A Resource Planning Approach: Comparison between Investments in Energy Efficiency and in New Generation Capacity

An ongoing policy debate in many states focuses on whether energy efficiency can displace or delay the addition of new generation capacity. The extent to which utilities will choose to invest in energy efficiency over supply side options will depend on two issues. First, the choice will depend on the costs of investing in energy efficiency versus the costs of investing in supply side options. Secondly, it will depend on whether or not utilities lose profit by investing in energy efficiency. If electricity sales are not decoupled from revenues, that will be the case. The level investment in energy efficiency will depend on the design of the incentives provided by regulators. Without a system of incentives and penalties, unless mandated by regulation, utilities will not invest in energy efficiency.

While the design of a proper system of incentives will be fundamental to the widespread adoption of energy efficiency programs by electric utilities, here I address only the question of how much it will cost to utilities to invest in energy efficiency. Any system of incentives would need to guarantee that the utilities can at least recover such costs, and provide an additional carrot for them to foster investments in energy efficiency.

In Figure 35, I show the cost for utilities to invest in efficiency in the residential sector through devices that are more efficient, estimated using RREEM, and compare such estimates with the costs of adding new generation capacity. Different types of utility investments in energy efficiency are provided in the figure, namely the cases where utilities bear the full cost of the devices and where utilities would only pay the incremental cost between the current devices and the more efficient ones (corresponding to a rebate scheme or a similar policy mechanism). A scenario where electric utilities or ESCOs are mandated to only invest in electricity efficiency measures is included.

The costs of new generation capacity are seldom uncertain. Key factors driving the costs of future generation include the efficiency of the power plants, the plant size, the fuel quality, the fuel costs, the number of hours of operation, the operating life of the plant, and costs of capital [64]. The generation-side options accounted for in Figure 35 include the conventional power generation technologies, such as pulverized coal power plans (PC), super critical coal power plants (SCPC), integrated gasification combined cycle (IGCC), natural gas combined cycle and gas peakers, as well as alternative generation technologies, namely geothermal, wind, landfill gas, biomass with direct combustion, solar thermal, and solar PV (thin film and crystalline technologies).

Table 25 shows the range of values for capital costs, capacity factors and heat rates used to estimate the cost of electricity generation from the different plant types. The capital costs, the heat rates ranges, the fuel costs and the capacity factors are adapted from the ranges provided in [61]-[63]. An operational lifetime of 40 years was considered for all conventional power plants.

For geothermal, wind and solar technologies, a 25-year operational lifetime was considered. Fuel costs were assumed to range from \$4 to \$18 per million BTU for natural gas, and a value of \$2.5 per million BTU was considered for coal. For landfill gas, I assumed fuel costs ranges from \$1.5 to \$3 per million BTU [61]. Other important assumptions for the generation costs of Figure 35 include a 7% real discount rate and a maintenance cost of all generating technologies of 2% of the annualized capital costs. The generation costs provided in Figure 35 also include intermittency costs of \$0.01/kWh for solar PV and wind.

In terms of future resource planning, considerations for avoided transmission and distribution costs can also be included when providing comparisons with investments in energy efficiency. Consumers face retail electricity prices that differ from the wholesale price based on the economic dispatch of power plants. Newcomer et al. [68] estimate that the markup from wholesale prices for residential consumers was 7.1 cents/kWh (\$2005) in PJM, 5.4 cents/kWh (\$2005) in ERCOT and 4.4 cents/kWh (\$2005) in the MISO area.

As representative values, I assumed transmission and distribution costs ranging from 4 to 8 cents/kWh ($2006). In Figure 34, I provide estimates of the ranges of levelized annual costs for new capacity generation for three cases: i) including only for the annualized capital costs; ii) including the annualized capital costs as well as maintenance, fuel and intermittency costs; iii) the same as in ii) plus annual transmissions and distribution costs.

Table 25 – Ranges for capital costs, capacity factors and heat rates used to estimate the cost of electricity generation from the different plant types. The average values between the low and high estimates where used in the analysis below.

		Capital Cost ($/kWh)		Capacity Factor	Heat Rate (BTU/kWh)	
		Low	**High**		**Min**	**Max**
Conventional Technologies	PC	2550	3500	0.7	8870	11900
	SCPC	2550	3500	0.7	8870	11900
	IGCC	3750	4300	0.7	8800	10520
	GCC	900	1100	0.4	6800	7200
	Nuclear	5750	7550	0.9	10450	10450
	Gas Peaking	650	1500	0.1	10880	10200
Alternative Technologies	Geothermal	3000	4000	0.8		
	Wind	1900	2500	0.3		
	Landfill Gas	1500	2000	0.4	13500	13500
	Biomass Direct	2750	3500	0.4	14500	14500
	Solar Thermal	4500	6300	0.3		
	Solar PV - Thin Film	3500	4000	0.2		
	Solar PV- Crystalline	5500	6000	0.2		

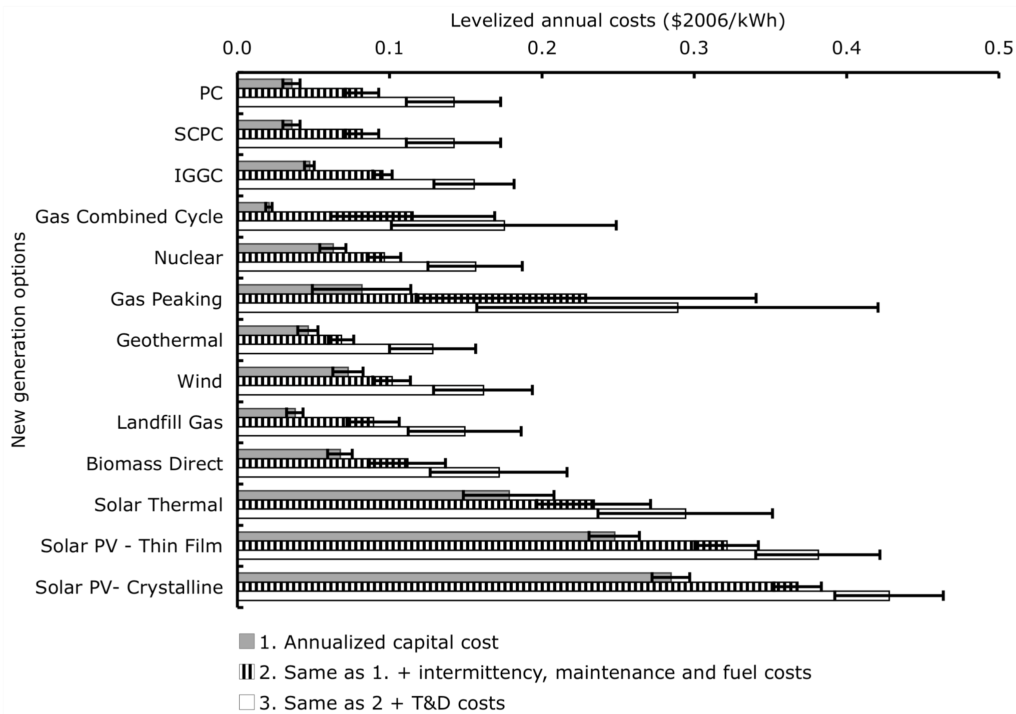

Figure 34 – Annualized costs of new generating capacity. The estimates include annualized costs for new capacity generation for three cases: i) including only for the annualized capital costs; ii) same as i) plus maintenance, fuel and intermittency costs; iii) the same as in ii) plus annual transmissions and distribution costs. Table 25 provides the assumption for capital costs, capacity factors and heat rates. See text below for assumptions concerning maintenance costs, intermittency costs and T&D costs.

In the left-hand side of Figure 35, I provide the electricity energy efficiency supply curve that assumes that electric utilities or ESCOs either pay the incremental or total cost of new technologies. In the right-hand side of the figure, I provide the ranges of costs for supply side options. In Figure 36 the same information is provided, only now considering the new purchases, which are forecasted to occur in 2009. Both figures exclude the indirect costs of energy efficiency. The supply side options account for capital, fuel, intermittency, and maintenance costs. Transmission and distribution costs are excluded.

Figure 35 suggests that in 2009, 200 TWh (or 14% of residential electricity demand) could be saved at virtually no cost if utilities were willing to just pay the incremental cost of efficiency measures. This assumes however that consumers do not value the current stock of appliances. If utilities promote efficiency measures using the same fuel as the baseline, then this potential for electricity savings drops to 10 TWh.

Utilities could choose to pay fully for the new technology investments and be rewarded to do so. In that case, close to 207 TWh could be saved at a cost of less than $0.07 per KWh, which is comparable with the ranges of the least expensive conventional and of alternative energy generation.

Instead of retrofitting existing equipment, policies can foster energy efficiency through the adoption of more efficient purchases of new residential equipment. In that case, the potential savings at a cost of less than $0.07 per KWh ranges from 50 to 70 TWh, depending on the simulation considered, Figure 36.

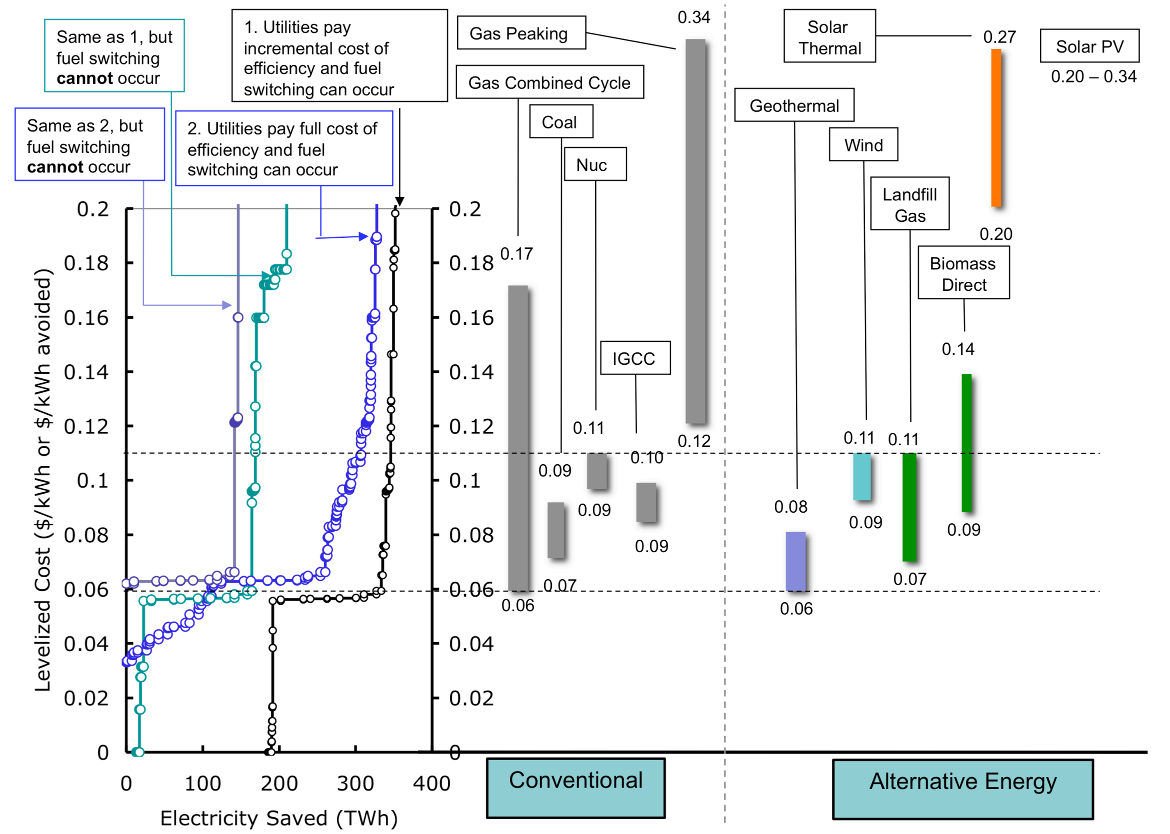

Figure 35 – Simulations for electricity efficiency supply curves for utilities or ESCOs and cost of supply side alternatives. The simulations correspond to scenarios for “utilities, full stock, full cost, fuel switching”; “utilities, full stock, incremental cost, fuel switching”; “utilities, full stock, incremental cost, no fuel switching” and “utilities, full stock, full cost, no fuel switching”. Assumptions: 7% real discount rate; technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009. The levelized annual cost of efficiency measures is compared with the cost of electricity generating technologies. The cost on the supply-side options includes capital, fuel costs, O&M and intermittency costs. Transmission and distribution costs are not included. Data on generating technologies is from [61] and [64].

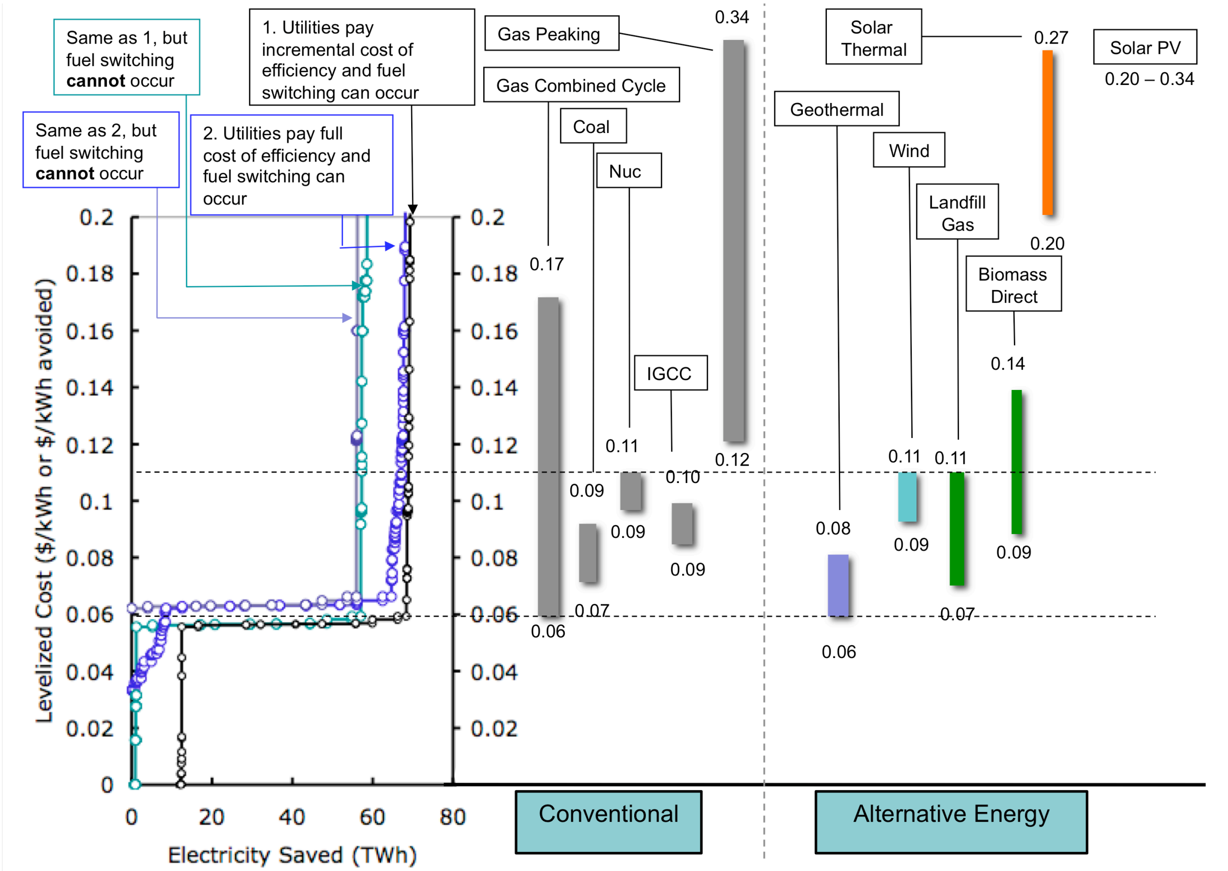

Figure 36 – Simulations for electricity efficiency supply curves for utilities or ESCOs. The simulations corresponds to scenarios for “utilities, full stock, full cost, fuel switching”; “utilities, full stock, incremental cost, fuel switching”; “utilities, full stock, incremental cost, no fuel switching” and “utilities, full stock, full cost, no fuel switching”, respectively. Assumptions: 7% real discount rate; technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009. The cost on the supply-side options includes capital, fuel costs, O&M and intermittency costs. Transmission and distribution costs are not included. Data on generating technologies is from [61] and [64].

To compare the costs of new electricity generation with energy efficiency measures in an equal way, the indirect costs incurred when energy efficiency measures are set in place by utilities or other entities also need to be accounted for. In practice, energy efficiency programs costs differ from the technological costs assessed in the previous sections, namely due to the indirect costs. Often, the indirect costs include administrative, marketing, and monitoring and evaluation costs. There is a large uncertainty and poor data on how to account for such indirect costs. Furthermore, the existing literature only accounts for indirect costs for electricity, and no such data is available for delivered or primary energy, or carbon emissions avoided.

In a study from 2003, ACEEE assumed that for most measures administrative costs ranged from 20% to 50% of incremental measure costs regarding electricity using energy efficiency measures. A recent study from the Center for Integrative Environmental Research estimates that the administrative program costs in New York, Vermont and Maine range from 35% to 66% of total program costs for an unweighted average of about 50% for the residential programs. The typical cost-effectiveness for such programs was 1.7 to 3.1 cents for utilities, with overall cost-effectiveness including customer costs of between 3.7 and 5.8 cents per kWh [88].

In order to have a recent estimate of the administrative costs of energy efficiency programs, I used the EIA database on utility data from the 2006 EIA-861 form. The EIA-861 database provides, among other electric utility related data, information on

Demand Side Management (DSM) energy savings and monetary spending[25] for 2,974 entities. Of those, 281 indicated having energy savings from energy efficiency-related activities in the residential, commercial or industrial sector.

The electric utilities are also asked to report the direct annual costs from energy efficiency, the incentives provided and the indirect costs[26]. The latter are defined in the EIA-861 form as "costs that may not be meaningfully included in any program category, but could be identified with an accounting cost category (e.g., Administrative, Marketing, Monitoring & Evaluation, Company-Earned Incentives, Other)", and include both the indirect costs from energy efficiency activities and load management activities. The various cost metrics from the EIA-861 database are not provided by sector.

To estimate the indirect costs per unit of electricity saved, I used the indirect costs and the total incremental energy saved by energy efficiency activities for the 217 entities with largest incremental energy savings from energy efficiency, which reported energy efficiency activities to estimate the indirect costs per KWh[27].

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[25] Source: Energy Information Administration. Available at: http://www.eia.doe.gov/cneaf/electricity/epa/epat9p6.html

[26] The entities also need to report the direct and indirect costs for load management. Here, we account only for what utilities reported as "energy efficiency" spending.

[27] While there were 281 entities reporting energy savings from energy efficiency activities, I decided to choose only the entities reporting more than 96 MWh of incremental annual savings. This is because the indirect costs account for both energy efficiency and load management costs, and using the indirect costs. Using the indirect costs as a proxy when the activities are mainly targeting load management provides a biased estimate of indirect costs.

If one considers just the first year indirect costs that are reported by the entities in the EIA-861 form, these range from 0$/kWh saved to 4.4$/kWh saved. Several distributions have been fit to the estimated data. The key statistics for different distribution used to fit the data are described below. The median of the first-year indirect costs range from $0.06 to $2.22 per kWh saved in that year. The exponential distribution provides the best fit, with a chi-square of 1,065 and a corresponding median of $0.06 per kWh saved.

Table 26 – Fitting distributions to indirect costs per KWh saved from energy efficiency activities reported in EIA-861 form.

Fit	**Mean ($/kWh)**	**Median ($/kWh)**	**Std. DEv.**	**95% Interval ($/kWh)**	**Chi-Sq**
Exponential	0.09	0.06	0.09	0 – 0.26	1065
Rayleigh	0.37	0.35	0.20	0.09 – 0.73	493
Triangular	1.48	1.30	1.05	0.11 – 3.44	2637
Uniform	2.22	2.22	1.28	0.22 – 4.22	2899

However, one of the features not accounted for in the previous table is that the energy efficiency investment in a certain year prevails for a certain time period. A key uncertainty is how many years these energy efficiency measures will prevail, and unfortunately the EIA-861 form does not provide any information on that. The National Action Plan for Energy Efficiency assumes that efficiency programs last for more than 10 years for some of the estimates provided in their document [25] However, the prevalence of the effect of energy efficiency program will depend on the types of programs, customer and funding deployed. For example, investing in fluorescent bulbs or better cooling systems will have completely different lasting effects due to the different technology lifetimes.

I chose to parametrically estimate the impact of assuming that the measures prevail over a different number of years on the average indirect costs of efficiency programs, Figure 37. The average indirect costs range from less than 1 cent/kWh ($2006) to 8 cents/kWh ($2006) depending on the number of years that the efficiency measures are assumed to prevail (a time range from 1 to 20 years is considered). To account for the indirect costs of efficiency, I assume a value of 2 cents/kWh ($2006), which corresponds to assuming that the measures prevail for 5 years.

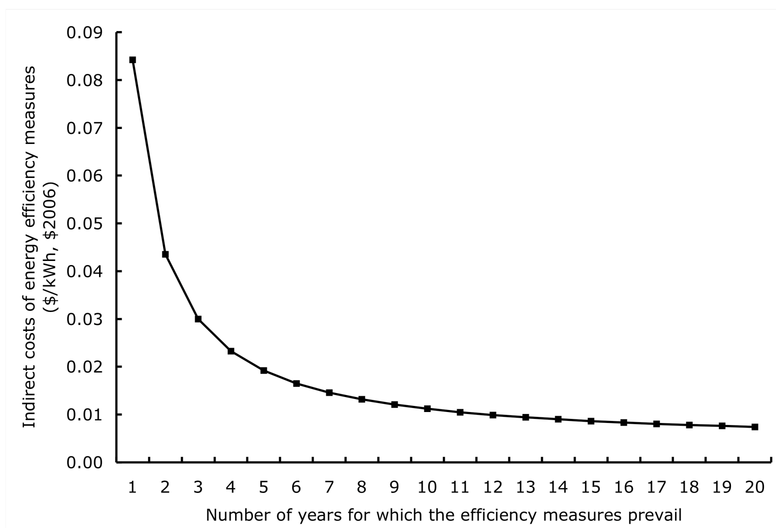

Figure 37 – Average indirect costs of energy efficiency measures. Estimated using the 117 entities which reported the largest annual energy savings in the 2006 EIA-861 form, as function of the number of years for which the energy efficiency measures prevail.

In Figure 38, I compare the marginal costs of energy efficiency (including the technology-related costs, the program implementation and other indirect costs) with supply side options when reductions in demand of 5%, 10%, 20% or 30% are pursued. I incorporate the indirect costs of energy efficiency measures in the figure. Furthermore, the transmission and distribution costs are included for supply side options. The cost of deploying energy efficiency measures increases as more ambitious targets of energy efficiency savings are pursued. When accounting for all these costs and sources of uncertainty, the best investment opportunities become less clear.

The results are as follows. If the utility only need to pay the incremental cost between the baseline an new the technology, and fuel switching is allowed, then energy efficiency is the least cost option up to a 30% reduction from the baseline. However, in this case, someone other than the utilities would need to bear the rest of the cost to make the efficiency investments happen. Without fuel switching it is not possible to reach energy savings of 30% or more from the baseline.

Generally, the results in Figure 38 indicate that investing up to 10% in reducing electricity consumption using energy efficiency measures would be less costly than investing in most types of new power plants.

Pursuing efficiency efforts targeting a 20% reduction of electricity are expected to be more costly than investments in new generation when fuel switching is not allowed. However, if fuel switching is allowed, energy efficiency efforts to up to a 20% reduction from the baseline are competitive with generation side opportunities, even if utilities decide to pay for the full cost of energy efficiency investments.

If the distribution and transmission costs are disregarded in the analysis, then energy savings up to 10% of the baseline residential electricity consumption can be achieved at a lower cost then most supply side options (expect geothermal, where available). Note that this roughly corresponds to 70 power plants of 500 MW[28].

There is generally the idea that investing in energy efficiency is a cheap way to achieve large reductions in energy consumption. What Figure 38 shows is that in the perspective of the utilities there is no free lunch. There is a large uncertainty in the figures provided that suggests that perhaps a fairer conclusion is that energy efficiency investments and supply side investments cost roughly the same. This is true for all supply-side options except solar and gas peaking.

[28] Assuming that the plant as a capacity facto of 70% and runs 5000h per year.

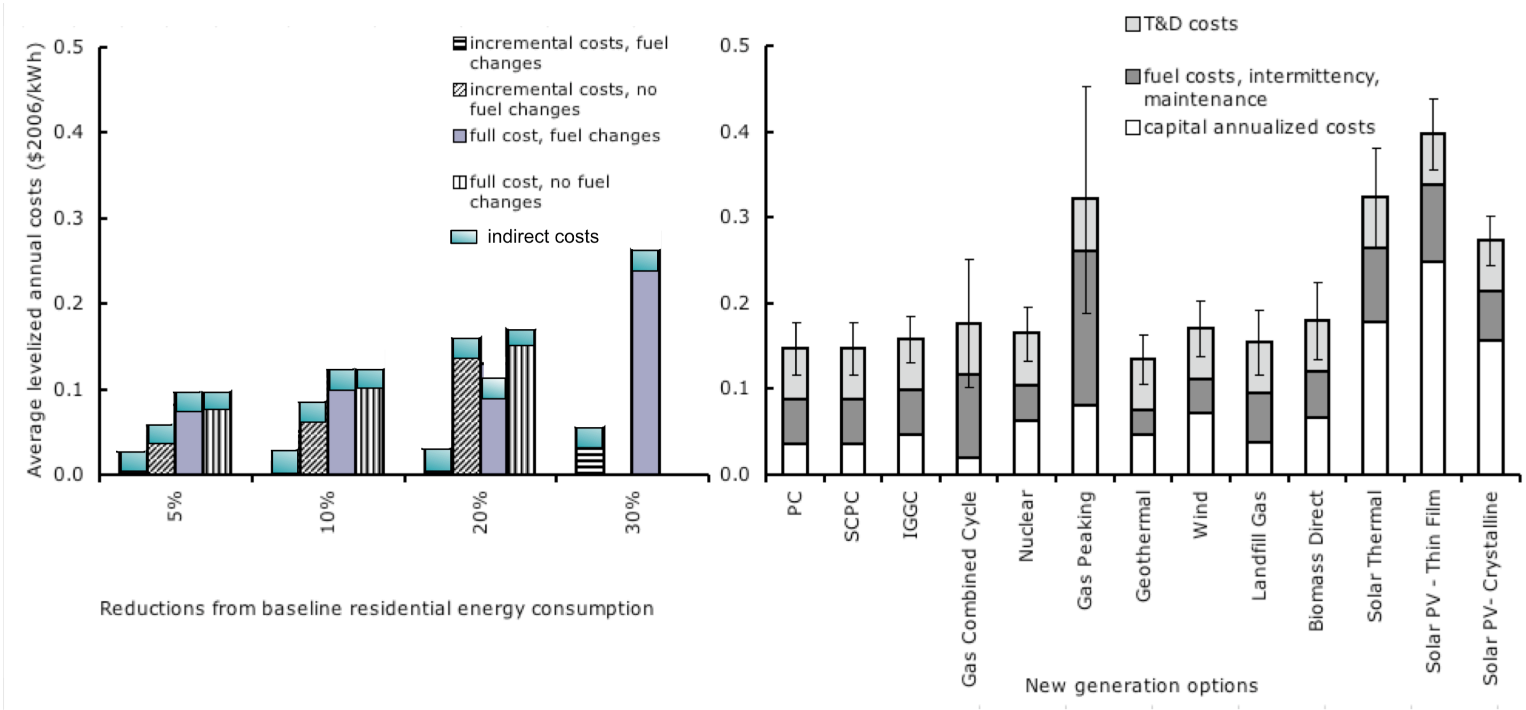

Figure 38 – Comparing energy efficiency and new generation investments. Four types of energy efficiency investments are considered. Either utilities provide the incremental cost of new technologies to consumers, and there fuel switching is either allowed for not, or utilities fully pay for the new technologies and again fuel switching is allowed or not. For estimates of the levelized annual cost of new generation capacity, the capital costs, fuel costs, intermittency costs, maintenance and transmission and distribution costs were considered. A 7% discount rate is assumed for all cases.

4.3 Comparing Electricity Supply Curves with DSM

Well-designed DSM programs have been considered a successful way to harvest energy efficiency potential, Table 27. DOE estimates that DSM saved just over 64 TWh in 2006 (63 TWh from energy efficiency programs and slightly less than 1 TWh from load management)[29], due to programs implemented in 2006 or previously[30]. The energy saved in the residential sector was 21 TWh, or 33% of DSM savings.

Table 27 – Leading states in DSM energy efficiency programs.
Adapted from [21]

State	Year	Annual incremental Electricity savings (GWh)	Electricity Sales (GWh)	Savings/Year (%)
California	2001	4,760	239,654	2.0
Connecticut	2001	314	30,000	1.0
	2002	246	31,000	0.8
Massachusetts	2001	273	51,773	0.5
	2002	309	52,092	0.6
Rhode island	2001	61	7,341	0.8
	2002	51	7,516	0.7
Vermont	2001	37	5,051	0.7
	2002	4	5,077	0.8
	2003	54	5,127	1.1

[29] Source: Energy Information Administration. Available at: http://www.eia.doe.gov/cneaf/electricity/epa/epat9p6.html

[30] Source: Ibid. According to the instructions from the EIA-861 form, programs started after 1992 can be accounted for in the reporting.

York and Kushler [65] report that the cumulative energy savings achieved by electric energy efficiency programs were 1.9% of total national energy sales in 2003. Some states have achieved a larger share of savings, with California achieving 6% electricity savings in 2001 [66].

Accounting only for the incremental effects, DSM energy efficiency programs resulted in 5.3 TWh of saved energy in 2006, of which 2.1 TWh corresponded to the residential sector. Fifteen utilities alone accounted for more than 68% of the savings[31]. Those utilities had savings of at least 90 GWh, with Southern California Edison and Pacific Gas & Electricity accounting for nearly 780 GWh each[32].

In 2006, the direct costs[33] of DSM efficiency programs were roughly \$620 million, and the energy efficiency incentives were roughly \$650 million (with total DSM costs of \$2

[31] Source: Ibid. Those are: (1) Southern California Edison Co; (2)Pacific Gas & Electric Co; (3) Connecticut Light & Power Co.; (4) Massachusetts Electric Co; (5) Northern States Power Co; (6) Florida Power & Light Co; (7) PacifiCorp; (8) Puget Sound Energy Inc; (9) TXU Electric Delivery Company; (10) MidAmerican Energy Co; (11) Nevada Power Company; (12) Interstate Power and Light Co; (13) City of Pasadena; (14) Narragansett Electric Co, (15) Long Island Power Authority. Except for the City of Pasadena and Long Island Power Authority, these are all investor owned utilities.

[32] Southern California Edison accounted for 787 GWh electricity saved from energy efficiency DSM programs in 2006, and Pacific Gas & Electricity accounted for 779 GWh. Source: ibid.

[33] The EIA-861 instruction form defined the "direct costs" as the costs that are directly attributable to a particular DSM program (e.g., energy efficiency or load management), "indirect costs" as the costs that may not be meaningfully included in any program category, but could be identified with an accounting cost category (e.g., administrative, marketing, monitoring & evaluation, company-earned incentives, or other). Incentive costs are not defined, with in the instructions for the "Supplemental Information" (Schedule 6, Part C), "incentive-based demand response programs" are defined as "direct load control, interruptible programs, demand bidding/buyback, emergency demand response, capacity market programs, and ancillary service market program". Source: ibid.

billion when accounting for direct load management costs, indirect costs, and financial incentives for efficiency and for load management)[34].

Figure 39 shows my estimate of the incremental electricity saved through energy efficiency DSM programs for the 50-largest energy savings utilities[35]. The y-axis on the left reports the energy saved for residential, commercial, and industrial programs. The y-axis on the right reports the direct cost of those programs and the incentives provided to utilities to pursue efficiency efforts[36] The x-axis identifies the 50-largest energy savings utilities in terms of electricity saved through energy efficiency DSM programs in 2006.

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[34] Source: ibid.

[35] Figure constructed based on the EIA's EIA-861 database, available at: http://www.eia.doe.gov/cneaf/electricity/page/eia861.html

[36] The cost figures are for the three sectors (residential, commercial and, industrial). The database does not include costs separated by sector.

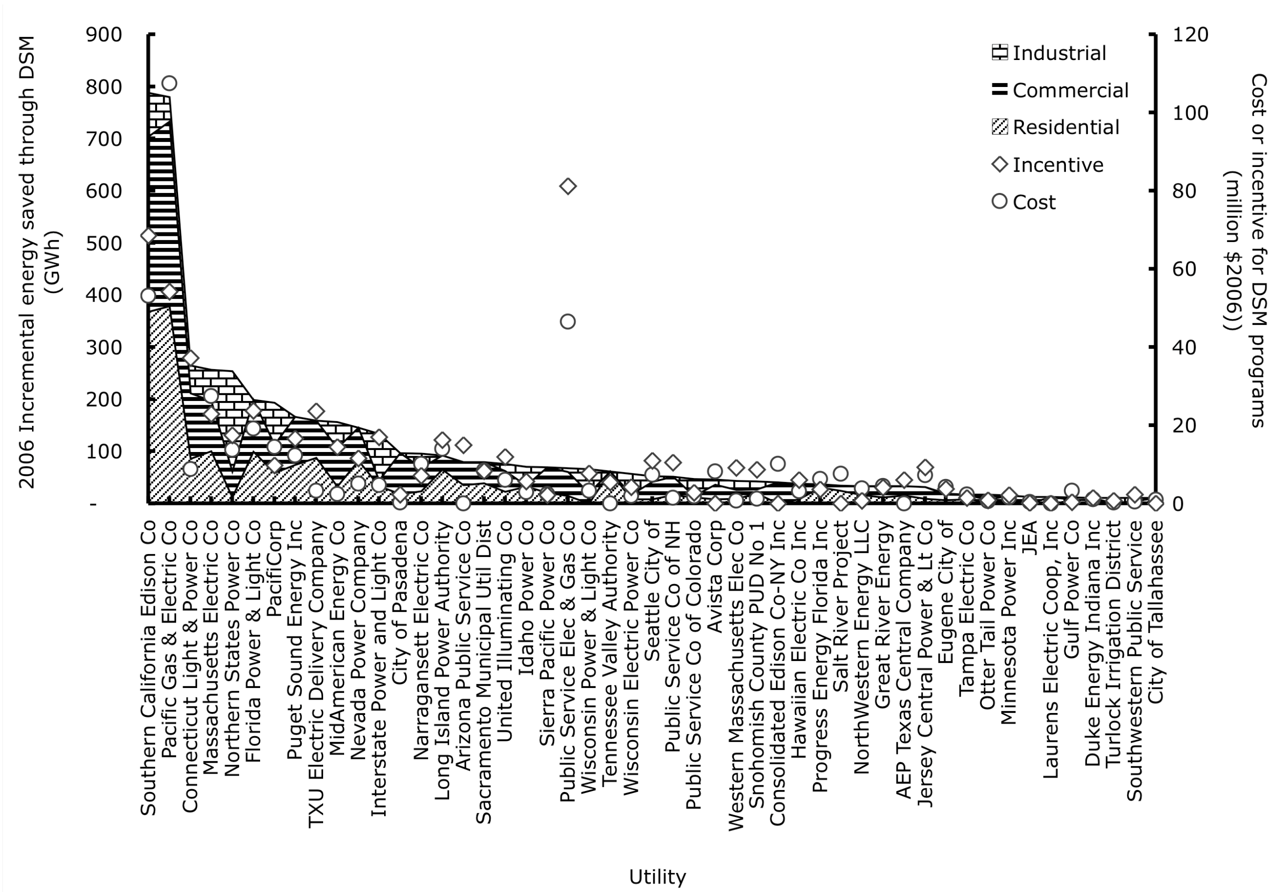

Figure 39 – 2006's electricity saved through energy efficiency DSM programs for the 50 utilities with the largest savings (x-axis). The left-hand y-axis provides the electricity saved in each sector. The right-hand y-axis provides the direct costs and incentives of DSM energy efficiency related programs. Figure constructed with data from [67].

RREEM provides a first order approximation of whether the DSM amount in energy efficiency is spent in a cost-effective manner. RREEM results suggest that if the least-cost path was chosen[37] (see Figure 31), the same annual amount of DMS direct spending in energy efficiency programs ($650 million) could have saved 33 TWh (six times more than what was achieved through DSM in all sectors). This result considers that consumers would be willing to accept that utilities pay the difference between the baseline and efficient technologies, and consumers would bear the rest of the cost. Assuming instead that utilities fully pay for the new technologies, 6.7 TWh could have been saved, which is still more than what was achieved through DSM in 2006. In addition, the energy efficiency-related savings from DSM result from not only direct spending but also from financial incentives. This indicates that it should be possible to make significant improvements in the design of utility efficiency programs so as to provide more energy savings while maintaining the same level of spending.

[37] The most cost-effective choices in $/kWh avoided, assuming a 7% discount rate, and assuming that utilities would be rewarded through a incentive mechanism. The simulation does not allow for fuel switching.

4.4 Accounting for Delivered Energy Consumption

Utilities would be able to provide larger energy savings at a lower cost if the investments in energy efficiency accounted for investments that use other fuels instead of using electricity as a carrier. As society moves towards a paradigm of sustainable energy systems, the inclusion of an integrated portfolio of efficiency measures where primary and final energy, electricity and greenhouse gas emissions are all considered becomes relevant. In the present work I do not provide a framework to integrate all these criteria into one single decision-making criteria, since this could be misleading for decision-making purposes.

I do include in RREEM the feature of maximizing the energy or the electricity saved, or the GHG avoided at the least-path cost. I do also include the feature of estimating how much is lost in terms of energy and economic savings in the remaining criteria by not choosing the least cost path and best available technology. Thus, if decisions are optimized in an energy basis, it is unlikely that the optimal savings of GHG will be achieved. There is a penalty for pursuing the optimal decisions under only one singly criteria.

The previous sections looked at how much electricity utilities could save when pursuing investments in energy efficiency to retrofit the existing electricity end-use equipment (or by fostering the adoption of more efficient technologies in the new purchases). Here, I simulate how much energy utilities could save at what cost if instead they are able to invest in any end-use in the residential sector, independently of the fuel that that technology is currently using. This would provide more flexibility for the utility to choose the least cost investments. Note that is was already mentioned above that in some areas of the country, as is the case New York State, the system of benefits charges can only be spend in electricity-related DSM. As the country moves towards strategies that aim to include GHG savings from energy efficiency, as is likely to be the case with RGGI, the allocation of funds to efficiency programs should include considerations on the electricity and (primary and delivered) energy saved and greenhouse gas avoided simultaneously.

For sake of illustration, I provide the case of the least cost path to maximize the delivered energy savings while maintaining the same level of the energy service. Under a system of rebates or a similar policy, utilities or ESCOs would be able to achieve savings in the order of 8% of the current baseline energy consumption without incurring any direct costs, as shown in Figure 40. They would still incur indirect costs. The indirect costs for energy efficiency measures other than electric are not well studied in the literature. Figure 41 shows the results when accounting only for the new purchases. Table 28 and Table 29 provide a summary of the costs and energy savings for all cases.

As I will detail in Chapter 5, when the consumers' decision-making process is considered, the optimal amount of energy efficiency generally corresponds to the point where the marginal costs of energy efficiency reach the energy retail price. In the utility case, the optimal amount of energy efficiency depends on the particular scheme of incentives and penalties the utility will face. For example, if the utilities could be rewarded for energy efficiency measures at the residential electricity price (0.10 $/kWh or 29$/millionBTU), up to 6.16 quads of delivered energy would be saved. This assumes utilities would be responsible for the full costs of the new technologies, as shown in Figure 40.

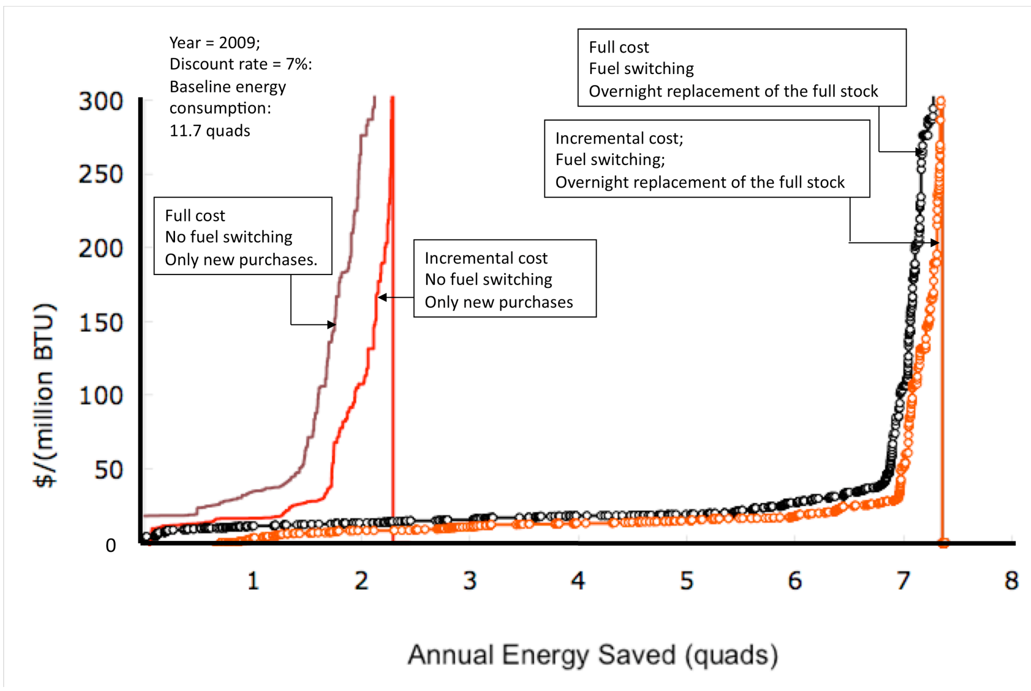

Figure 40 – Utilities or ESCOs least cost path to save the maximum amount of delivered energy, using a 7% discount rate. The simulations correspond to the scenarios for “utilities, full stock, full cost, fuel switching”; “utilities, full stock, incremental cost, fuel switching”; “utilities, full stock, incremental cost, no fuel switching” and “utilities, full stock, full cost, no fuel switching”

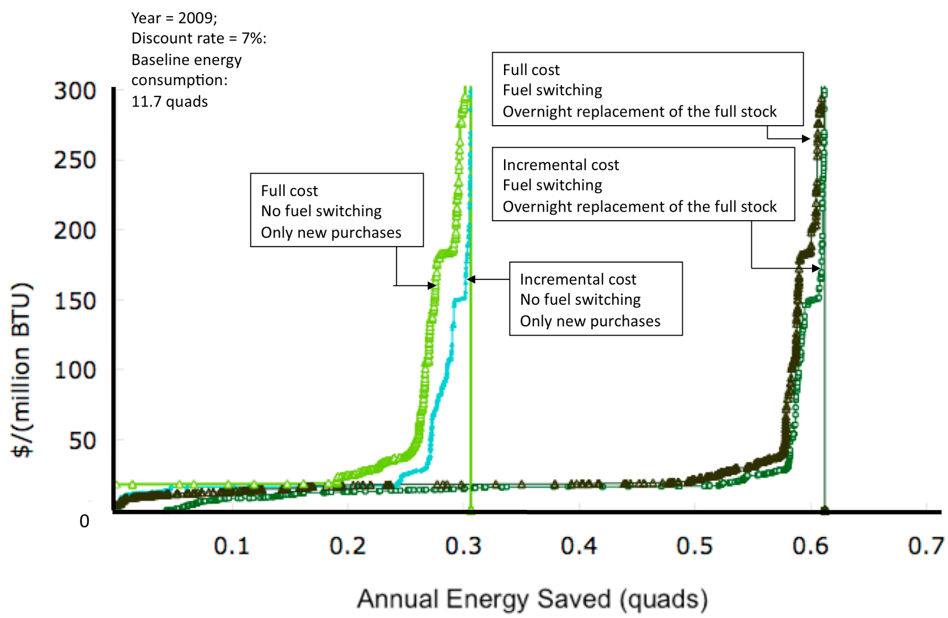

Figure 41 – Utilities or ESCOs least cost path to save the maximum amount of delivered energy, using a 7% discount rate. The measures only include new purchases in 2009. The simulations corresponds to scenarios for “utilities, full stock, full cost, fuel switching”; “utilities, full stock, incremental cost, fuel switching”; “ “utilities, full stock, incremental cost, no fuel switching” and “utilities, full stock, full cost, no fuel switching”.

Table 28 - Net costs for utilities or ESCOs investments in energy efficiency for different reduction levels, using a 7% real discount rate. The measures are optimized to maximize delivered energy savings. The entities can either pay the full cost of new technologies or just incremental costs, select energy efficiency measures using different fuels from the baseline or not, and target the full stock of end-use appliances and devices or just the new purchases in 2009.

ANNUAL COST (billion $2006)	utilities pay for incremental cost of technology		utilities fully pay for technology replacement		only targeting new stock and pay for incremental cost of technology		only targeting new stock and pay fully for cost of technology	
Reduction from baseline	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes
5%	0	4	5	16	6	5	8	10
10%	0	18	9	-	-	-	-	-
20%	10	32	26	-	-	-	-	-
30%	23	-	42	-	-	-	-	-
40%	35	-	65	-	-	-	-	-
50%	53		85					
60%	85		131					
70%	115		191					

Table 29 – Reductions from the baseline energy consumption (1.7 quads of delivered energy by 2009) which can be achieved when utilities perform different types of energy efficiency investments.

	Utilities pay for incremental cost of technology and retrofits are considered		Utilities fully pay for technology replacement		Only targeting new stock and pay for incremental cost of technology		Only targeting new stock and pay fully for cost of technology	
Reduction from baseline that corresponds to:	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes
Net savings (<0$/kWh):	8%	0%	0%	0%	<1%	<1%	0%	0%
Maximum achievable reduction from baseline:	63%	21%	63%	21%	5%	3%	5%	3%

Chapter 5. Consumers' Investments in Energy Efficiency

5.1 Consumers as Rational Economic Decision-Makers

As mentioned in Chapter 1, the decision-making models generally used to describe the consumers' choice of energy efficient appliances compare the costs of energy efficiency investments to fuel costs faced by consumers (or, in most cases, to electricity retail prices). Also, in Chapter 1, I elaborated on the fact that some studies only include incremental investment costs between a baseline and an efficient technology, even when simulating the effect of retrofitting equipment. This implies that consumers are assumed to place no value on the current stock of technologies. As I did in Chapter 4 for the utilities and ESCOs perspective, here I develop a set of simulations to describe the decision process from consumers under several scenarios.

I start by considering a scenario where consumers are facing the decision of whether to keep their current appliances[38] or to buy the most efficient appliances available in the market, Figure 42. This means that investment costs for new technologies are included in the analysis, instead of incremental values between the baseline and the efficient technology. I am considering several fuel types, with different residential retail prices. Therefore, there is no easy way to compare directly the energy savings with the fuel prices in the supply curve. Instead, to address this issue, the reduction in energy bills that arises form the use of a more efficient technology is included in the levelized annual cost. This makes it possible to compare the cost per unit of energy saved across several fuel types. The scenario accounts for the whole stock of appliances and devices that are responsible for the largest end uses of energy consumption.

In section 3.2, it was estimated that 2009's ultimate residential energy efficiency technological potential (the amount of delivered energy consumption reduction that could be saved regardless of the costs and by allowing fuel switching) is 7.4 quads[39]. This potential was estimated under the assumptions that the residential delivered energy consumption in 2009 for the largest end uses is roughly 9.7 quads and that all residential end uses account for 11.7 quads. In Figure 42,

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[38] This simulation corresponds to the situation where appliances and devices are retrofitted. In the case of the purchases of equipment that occur during 2009, I assume that the decision is whether to buy the baseline equipment or the most efficient one available in the market.
[39] This corresponds to the maximum value shown in the x-axis Figure 42.

I show that consumers could reduce 30% of the total residential delivered energy consumption with net annual savings[40] of ~ \$43 billion (\$2006). If more stringent energy savings goals are pursued, reductions up to 60% of the baseline could be achieved until the net benefits would overcome the costs of the more expensive energy efficiency measures.

Under the strong assumptions that standards implementation would provide energy services with the same quality as the technologies in place in the current stock [41], the previous results suggest that consumers' surplus could increase by ~ \$43 billion (\$2006) with the implementation of proper standards[42]. Furthermore, standards could be designed to save up to 60% of the baseline energy consumption while leaving the consumers' surplus unchanged.

Gillingham et al. [14] reviewed the literature on energy efficiency programs. They concluded that taken together, there are up to four quads of energy savings annually from these programs, at least half of which is attributable to appliance standards and utility-based demand-side management. My optimistic scenario suggests that, in addition

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[40] E.g., choosing efficiency measure which have a cost-effectiveness of less than 0 \$/million BTU.

[41] Some authors argue that minimum efficiency standards for residential products reduce the product choice, therefore reducing consumers' marginal utility. See the discussion on product standards and respective costs in Chapter 2 for further detail.

[42] This is similar to the arguments provided by Brown [45] for the case of standards implementation in the residential sector. Brown only considers residential electricity end-uses.

to such ongoing savings, stringent efficiency standards could save between 0.5 quads to 3.4 quads – depending on fuel availability – with no net cost to consumers.

The simulation in Figure 42 assumes no constraints in terms of fuel switching. For example, the consumer can switch from an electric furnace to a natural gas furnace or to a ground source heat pump. Similarly, the consumer can switch from a gas water heater to a solar water heater. Therefore, this scenario does not account for the lack of fuel resources or infrastructure availability in a specific region. To address this issue, Figure 43 provides a simulation where the technological choices are constrained to the same fuel.

As mentioned in Section 3.2, the technological potential for energy efficient measures decreases from 7.4 quads to 2.4 quads when the fuel availability is constrained. Fuel constraint leads to energy efficiency measures with net benefits of 4% of the baseline energy consumption, with $22 billion ($2006) of net annual savings to consumers. Again, this suggests that under a more realistic scenario where fuel constraints are considered, well-designed standards would lead to an increase in $22 billion dollars to consumers. More aggressive standards could save up to 14% of residential electricity consumption while leaving the consumer surplus unchanged.

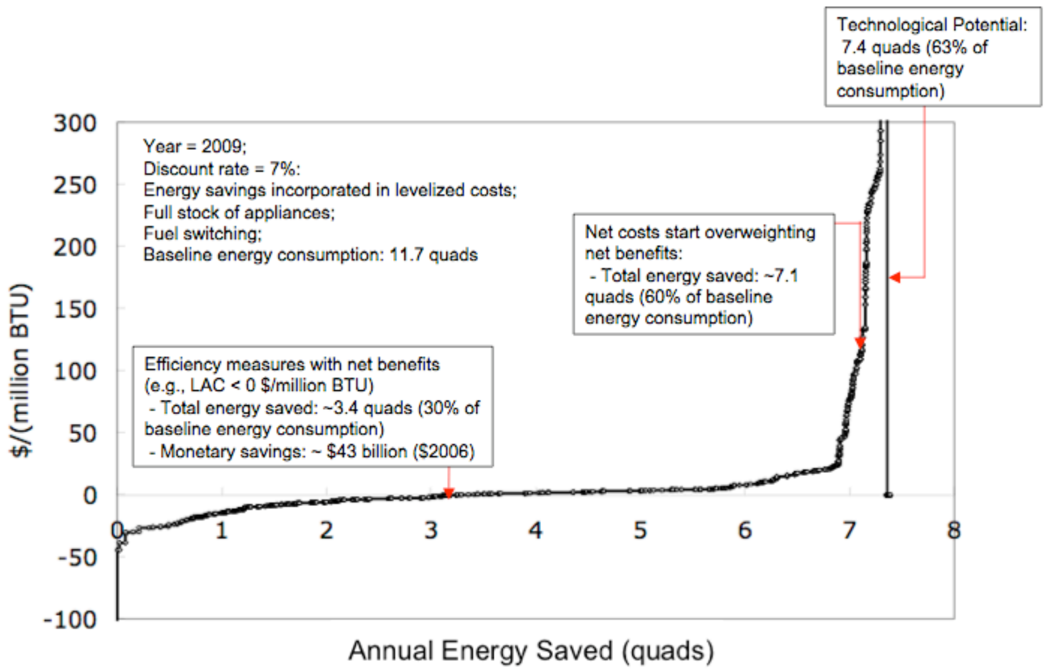

Figure 42 – Optimizing delivered energy efficiency supply curves for U.S. households. This simulation corresponds to the scenario for "consumer, full stock, valuing existing stock, fuel switching". The simulation accounts for a consumer perspective, therefore reduction in energy bills to more efficient end use technologies/efficiency measures is included in the levelized annual cost. The simulation assumes that consumers are facing the decision of whether to keep the appliance/device they already have or the most efficient one available in the market. This explains why some costs are negative, suggesting actual monetary benefits to consumers. Assumptions: 7% real discount rate; technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009.

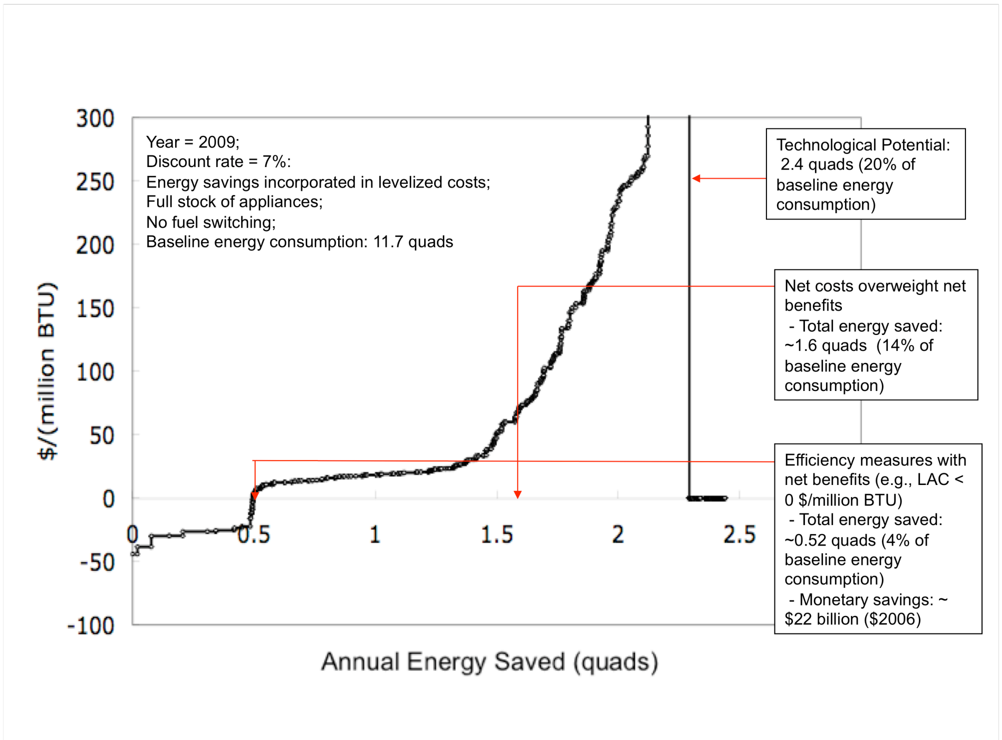

Figure 43 – Optimizing delivered energy efficiency supply curves for U.S. households. This simulation corresponds to a scenario for "consumers, full stock, valuing existing stock, no fuel switching". The simulation accounts for a consumer perspective, therefore reduction in electricity bills to more efficient end use technologies/efficiency measures is included in the levelized annual cost. The simulation assumes that consumers are facing the decision of whether to buy an appliance identical to the one they already have or the most efficient one available in the market. This explains why some costs are negative, suggesting actual monetary benefits to consumers. Assumptions: 7% real discount rate; technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009.

Some studies [43] assume the incremental costs between new technologies, as well as the monetary savings from reductions in energy consumption as decision-making criteria to invest in energy efficiency. In practice, means that the stock of appliances and devices would be replaced overnight, and that the consumers wouldn't place any value on the existence of the current stock. Other studies, such has ACEEE (2007), treat early retirements assuming that:

> "By interrupting the natural replacement cycle, early retirement permanently postpones the future replacement cycle. The economic potential analysis of energy-efficiency resources explicitly accounts for both the baseline shift and the equipment replacement deferral credit associated with early-retirement efficiency retrofits."

Figure 44 provides a simulation under the assumption that no value is placed on the current stock. Under this optimistic simulation, energy consumption could be reduced by 63% while still providing a net annual benefit of ~60 billion dollars ($2006) to consumers. Relaxing the assumption of placing a value on the existing stock therefore increases the net benefits to consumers by threefold. Results for a similar simulation with fuel constraints is presented in Figure 44. Fuel constraints limit the energy reduction to 21% of the baseline (corresponding to the technological potential). This potential could be achieved with net annual savings to consumers in the order of ~ $22 billion ($2006).

I strongly argue that such optimistic figures are not appropriate for policy decision-making given their lack of realistic implementation. While most studies account for more complex modeling and include rates of stock retirement, these assumptions need to be made very clear, especially if such studies are used as grounds for specific policy-making advocacy. The scenarios where no value is placed in the current stock will be maintained throughout the dissertation for the electricity and carbon cases for sake of comparison with previous literature and to illustrate the calibration of RREEM to previous models. However, only the results for the scenario where current stock valuation is included are relevant for real application in energy and carbon policy design.

In order to move towards a more realistic energy efficiency implementation assessment, in Figure 45, I consider a scenario that would affect only the purchase of new products. This, in fact, represents the potential of implementing efficiency standards at the level of the most energy efficient technology in the market. In this case, the maximum potential that can be achieved is a 5% reduction from the baseline with annual net savings of $9 billion ($2006) if the constraint on fuel switching is relaxed and a 3% reduction from the baseline with annual net savings of $6 billion ($2006) if the fuel is constrained to be the same as under the AEO 2008 projections for new purchases.

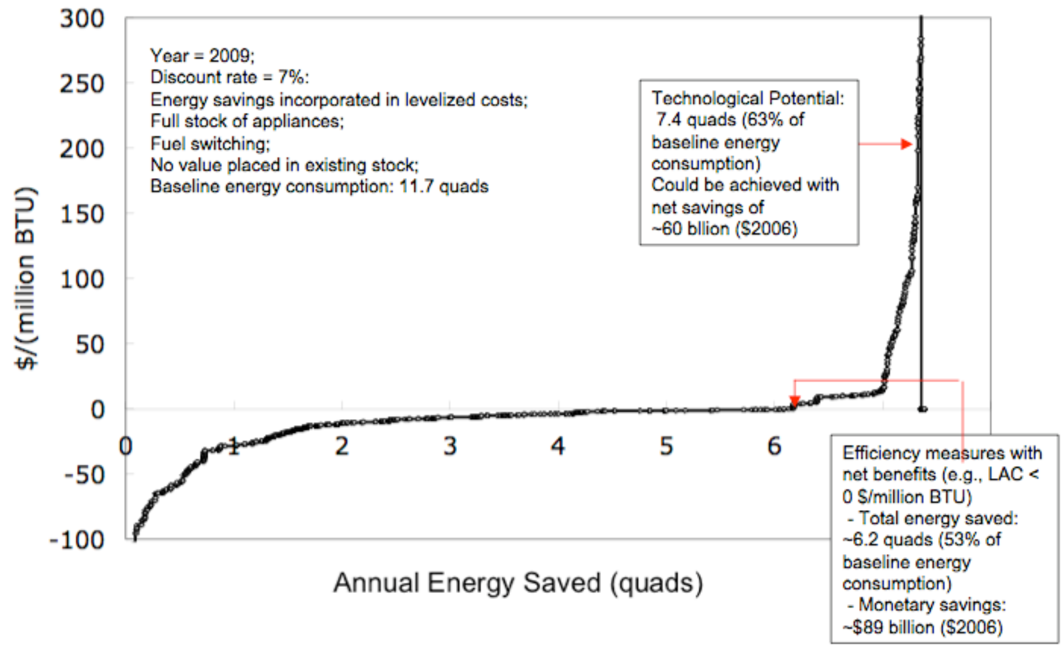

Figure 44 – Optimizing delivered energy efficiency supply curves for U.S. households. This simulation corresponds to a scenario for "consumer, full stock, no value placed on existing stock, fuel switching". The simulation accounts for a consumer perspective, therefore reduction in electricity bills to more efficient end use technologies/efficiency measures is included in the levelized annual cost. The simulation assumes that consumers are facing the decision of whether to buy an appliance identical to the one they already have or the most efficient one available in the market. This explains why some costs are negative, suggesting actual monetary benefits to consumers. Assumptions: 7% real discount rate; technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009.

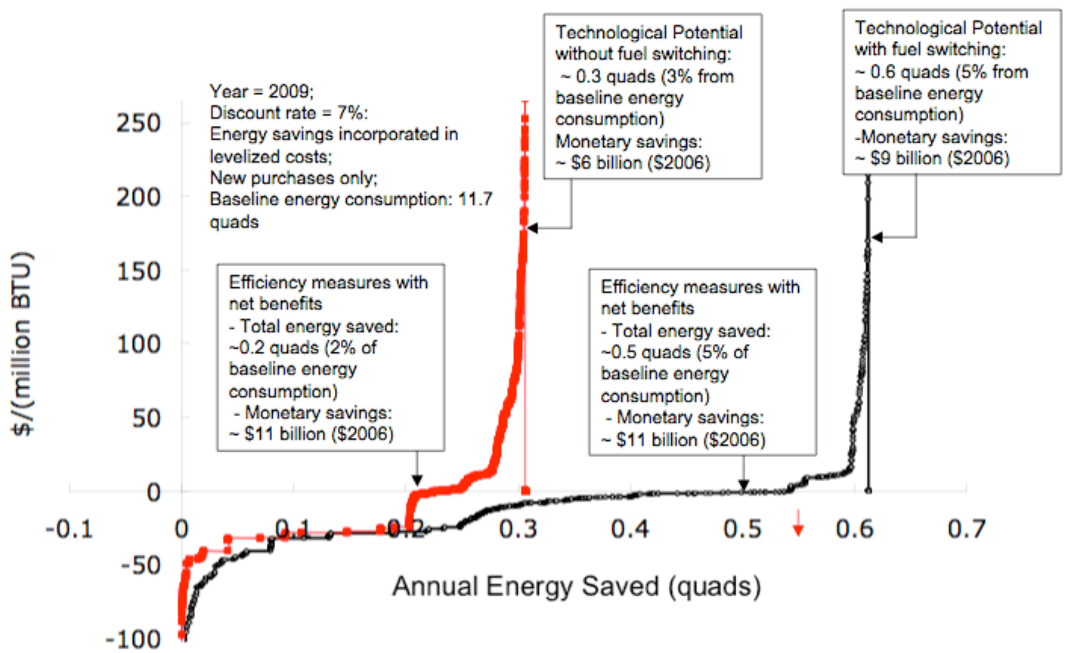

Figure 45 – Optimizing delivered energy efficiency supply curves for new purchases by U.S. households. The simulations corresponds to a scenario for "consumer, new purchases, fuel switching" and "consumer, new purchases, no fuel switching", respectively. The simulation accounts for a consumer perspective, therefore reduction in energy bills to more efficient end use technologies/efficiency measures is included in the levelized annual cost. The simulation assumes that consumers are facing the decision of whether to buy the appliance projected under AEO 2008 or the most efficient one available in the market. This explains why some costs are negative, suggesting actual monetary benefits to consumers. Assumptions: 7% real discount rate; technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009.

5.2 Consumers Choices in Electricity Using Equipments

Electricity consumption in the residential sector corresponds roughly to 21% of residential primary energy use[43]. Improvements in the efficiency of electricity consumption deserve major attention, since investing in energy efficiency may delay or reduce investments in additional generation capacity, thus contributing to the security of energy supply and reducing impacts on climate change and air pollution. Simulations accounting for only electricity investments were performed using RREEM. Figure 46 and 47 provide the summary of the results for all the scenarios simulated. Furthermore, Table 32 and 33 summarize some of the key results for all the simulations.

If it is assumed that consumers do not value the existing stock, which corresponds to the most optimistic scenario for energy efficiency potential since only incremental technology costs are considered, then up to 25% (350 TWh) of current residential electricity consumption could be saved with net benefits to consumers. This value, however, is impractical and only stated for purposes of comparison with previous studies. For example, using similar assumptions, Koomey and his colleagues [45] estimated that roughly 400 TWh could be saved by 2010 at a cost of below the electricity price, therefore having very similar findings to mine.

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[43] Using AEO 2008 detailed tables, Table 10 – Energy Consumption Sy Sector and Source, United States .

Despite the fact that the previous figure might be considered optimistic, even when accounting for the value of the current stock of end-use appliances, there is still 21% of the current electricity consumption, which could be saved with net benefits to consumers. This value drops to 10% when considering that fuel switching is not allowed. Furthermore, I estimate that if consumers' buy the most efficient and cost-effective appliance in 2009 purchases, still electricity consumption could still be reduced 4 to 5% from the projected baseline.

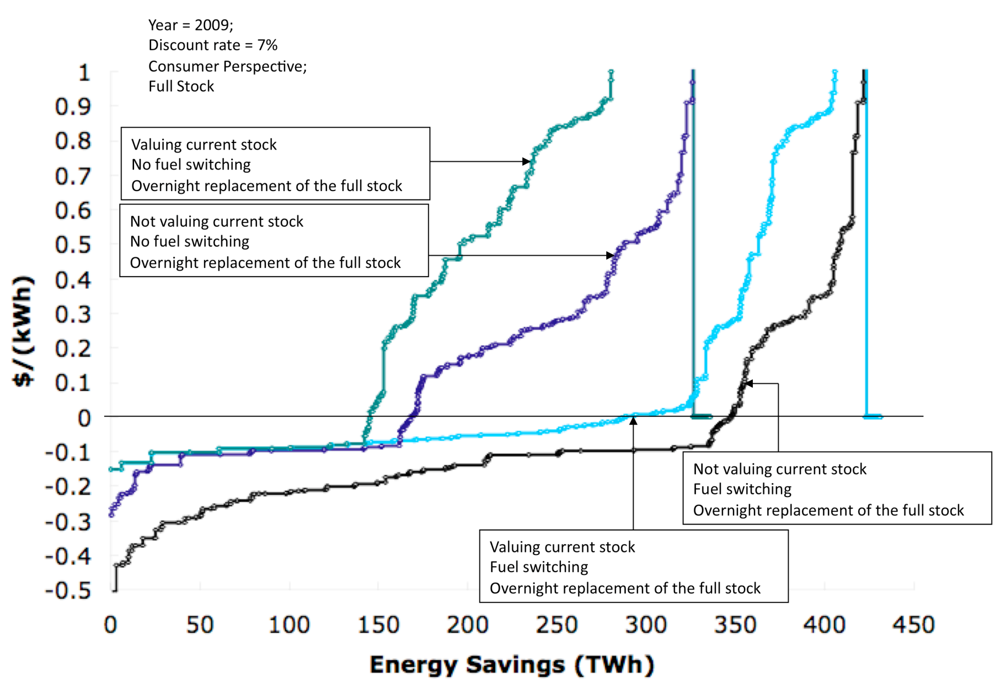

Figure 46 – Simulations for electricity efficiency supply curves for households. All the curves assume a 7% real discount rate technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009.

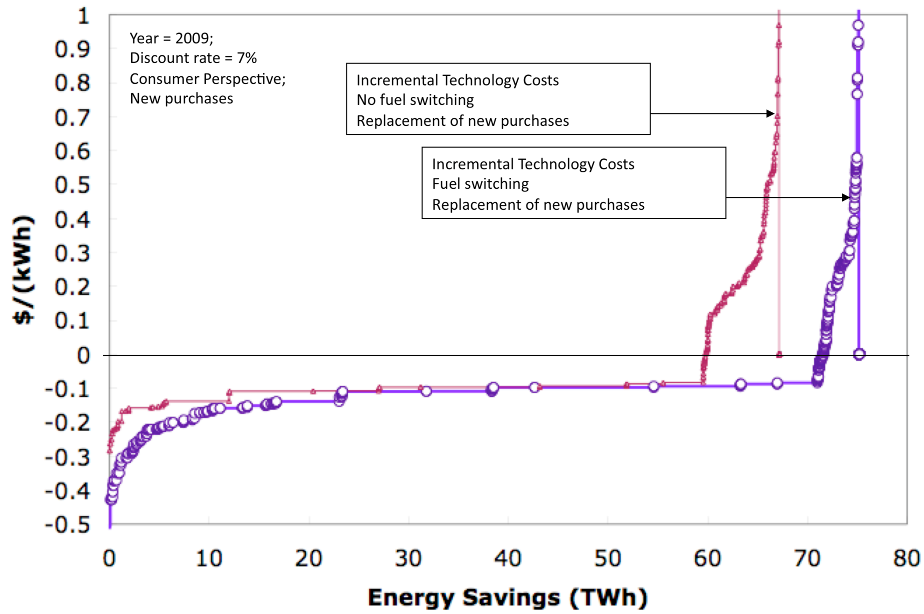

Figure 47 – Simulations for electricity efficiency supply curves for new stock only. All the curves assume a 7% real discount rate technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009.

Table 30 – Net savings (negative values) or costs (positive values) for consumers due to energy efficiency investments in electricity end uses (7% real discount rate). The results consider different reduction levels from the baseline energy consumption (1400 TWh in 2009). The scenarios considered are: (i) consumers value the existing stock; (ii) no value placed in the existing stock; (iii) only targeting new stock.

ANNUAL VALUE (billion $2006)	valuing existing stock		no value placed on existing stock		only targeting new stock	
Reduction from baseline	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes
5%	(11)	(11)	(15)	(12)	(9)	(4)
10%	(21)	(21)	(27)	(21)	-	-
20%	(18)	23	(48)	(13)	-	-
30%	19	-	(46)	-	-	-
40%	-	-	-	-	-	-

Table 31 – Summary reductions from baseline with net savings.

	valuing existing stock		no value placed on existing stock		only targeting new stock	
% reductions from baseline when:	Fuel switching	No fuel switching	Fuel switching	No fuel switching	Fuel switching	No fuel swiching
There are net savings (<0$/kWh) (equivalent to marginal efficiency costs being equal to retail energy prices)	21%	10%	25%	12%	5%	4%
Net measure benefits to overcome the measure costs	27%	16%	31%	24%	5%	5%
Maximum achievable reduction from baseline:	31%	24%	31%	24%	5%	5%

Chapter 6. Carbon Abatement Supply Curves

6.1 Comparing RREEM GHG Abatement Potential with Previous Studies?

Several studies [21]**Error! Reference source not found.**,[30],[42]-[56], show that energy efficiency can yield substantial reductions in U.S. emissions and/or electricity demand. EPRI suggests that sustained energy efficiency strategies nationwide could account for a reduction of 400 million metric ton of CO_2 per year by 2030 [42], Figure 48.

A recent study from McKinsey [43] suggests savings of roughly 1,000 million metric ton of CO_2 per year could be achieved by 2030 through energy efficiency measures across all sectors at a cost below zero (in real 2005$). According to that same study, buildings and appliances could account for 700 to 900 million metric tons of CO_2 reductions annually by 2030, at a cost less than 50$/ton$CO_2$.

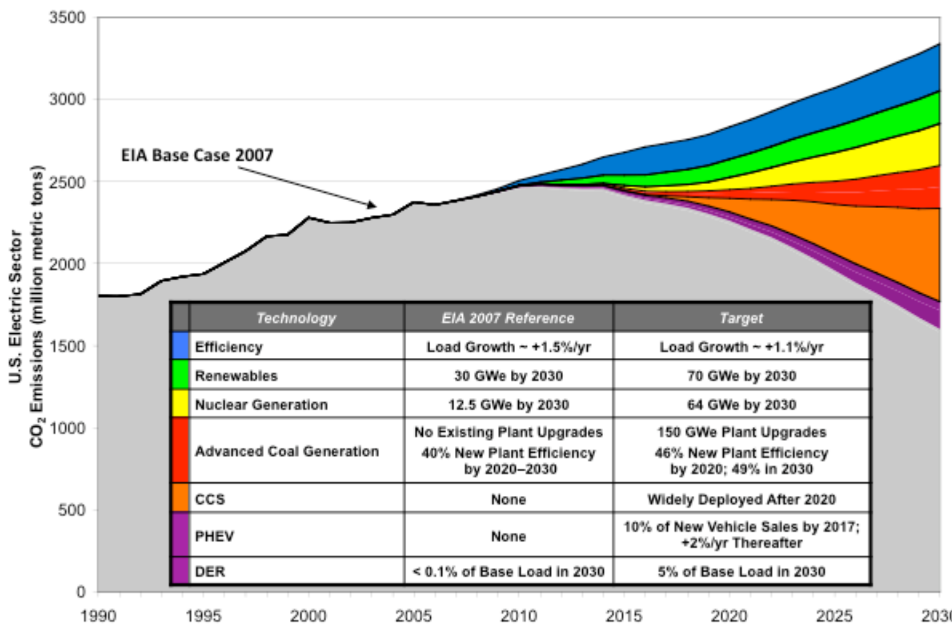

Figure 48 – Electric Power Institute (EPRI) suggested portfolio strategy for greenhouse gas emissions reductions. Deploying all strategies would achieve 1990 emissions levels by 3030. Scenario based on EIA AEO reference case from 2007. Source: [42].

The findings from past studies on the residential sector's energy efficiency potential vary widely but substantiate the finding that energy efficiency measures in buildings provide net benefits and are among the cheapest carbon mitigation measures. For example, the 1991 study from OTA [53] assumes two scenarios: a high cost, low efficiency implementation scenario; and a low cost, high efficiency implementation scenario. The authors estimated that by 2010, 86 million metric tons of carbon could be saved in the residential sector at a marginal cost of -291 to -174 $/ton of carbon (in $1990).

OTA estimates are optimistic when compared to other studies performed during the same period. For example, six year latter the Five-lab study [47] estimated that the efficiency of buildings could save the nation between 47 and 59 million metric tons of carbon at a cost between -$327 and -$187 per ton of carbon (in 1995$) depending on whether a pessimistic or optimistic case

was considered. The Five-lab study includes only incremental costs between the baseline and improved technologies.

Similarly, a study from NAS [52] concludes that by 2010, buildings could save between 61 to 243 million metric tons of carbon at marginal costs ranging from -$286 to -$172 per ton of carbon avoided (in $1987). Also for the reference year of 2010, the Tellus Study estimates that 70 million metric tons of carbon could be saved in buildings at a cost of -$248 per ton of carbon.

In Figure 49, RREEM1 and RREEM2 correspond engineering-economic most estimates from RREEM for the full stock GHG abatement potential. RREEM1 and RREEM2 both account for the full stock of end-use equipment, assume overnight turnover and allow fuel switching amongst the mitigation options. The difference between the two scenarios is that RREEM1 includes the reductions in energy bills in the cost-effectiveness measure, while RREEM2 does not. The figure also includes the most optimistic RREEM simulation, which corresponds to substituting the stock overnight, allowing for fuel switching, no value is placed on existing stock and the cost figures include the monetary savings from reductions in energy bills. The "pessimistic" RREEM simulation assumes the full cost of new technologies, that the stock is replaced overnight and that no fuel switching occurs.

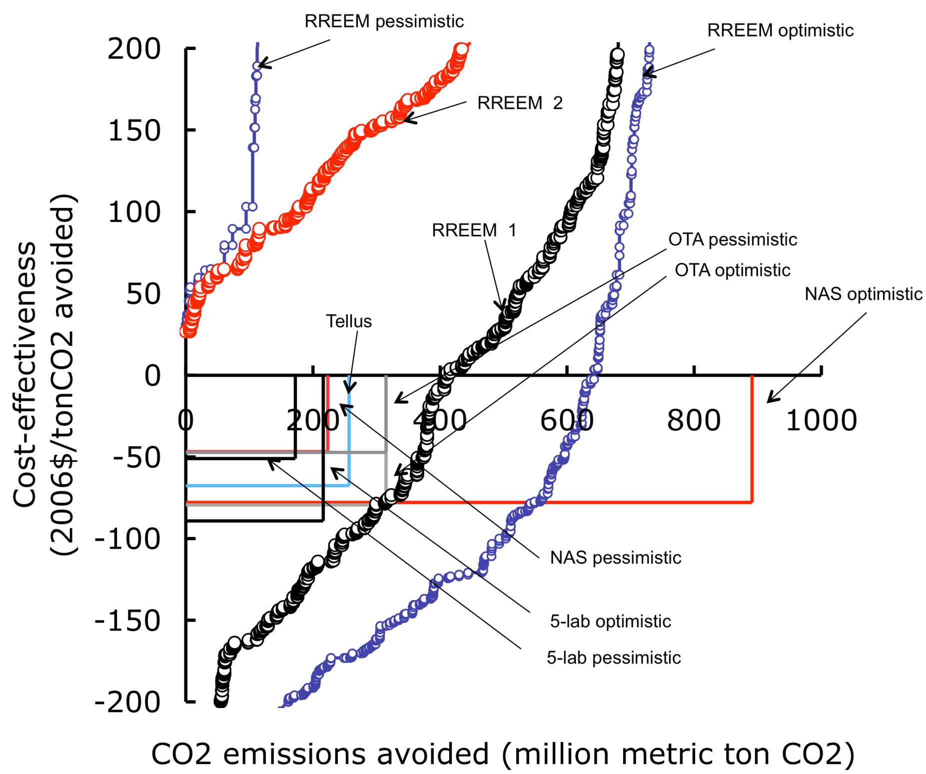

Figure 49 – Comparison of carbon supply curves. The figure includes the most optimistic (consumer approach, full stock, fuel switch, no value on existing stock) and pessimistic (utility pays full cost, full stock, no fuel switch) RREEM simulations for full stock. RREEM 1 and RREEM2 correspond to that I consider to be the most reasonable estimates from RREEM for the full stock GHG abatement potential. RREEM1 and RREEM2 both account for the full stock of end-use equipment and allow fuel switching amongst the mitigation options. The difference is that RREEM1 include the reductions in energy bills in the cost-effectiveness measure, while RREEM2 does not. All the curves assume a 7% real discount rate technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009.

Part 1 – Chapter 6: Carbon Abatement Supply Curves

6.2 Which End-Uses should be Targeted to Maximize Carbon Savings?

The previous sections detailed the potential for carbon mitigation in the residential sector at the national level under various sets of assumptions. In order to implement specific programs and policies, further detail is needed on which types of end-uses should be targeted.

Carbon performance standards corresponding to adopting the largest carbon reducing technologies for the full stock of existing appliance could save 400 million metric tons of CO_2 per year with net benefits to consumers. In Figure 50, I illustrate the savings that could be achieved by different end-uses. Improving heating and cooling systems and changing light bulbs would provide the largest net benefits to consumers. Note that negative values correspond to options where the annualized investment in efficiency measures is less than the fuel price.

In Figure 51, I present the direct costs for utilities or ESCOs of investing energy efficiency programs targeting different end-uses. The y-axis represents the cost-effectiveness of the options in dollar per ton of CO_2 avoided. In this simulation, it is assumed that utilities or ESCOs would fully bear the cost of implementing new technologies in the residential sector. The bars on the right represent the cost-effectiveness ranges for supply-side mitigation options (current photovoltaic (PV), nuclear, future photovoltaics, wind, new natural gas combined cycle power plant with carbon capture and sequestration (NGCC with CCS), new pulverized coal power plant with carbon capture and sequestration (PC with CCS), and new integrated gasification combined cycle with capture and new gasification (IGCC with CCS)). These supply side figures assume the national carbon emissions' factor as the baseline being displaced. The investment costs for supply side are the annualized costs of a new power plant[44], which include the capital cost, the O&M costs, fuel costs and intermittency costs.

Investments in energy efficiency program that retrofit lighting, heating and cooling systems will prove large CO_2 savings at a lower or similar cost then supply side mitigation alternatives.

[44] So the costs do not represent incremental costs between a new power plant and a PC power plant or other.

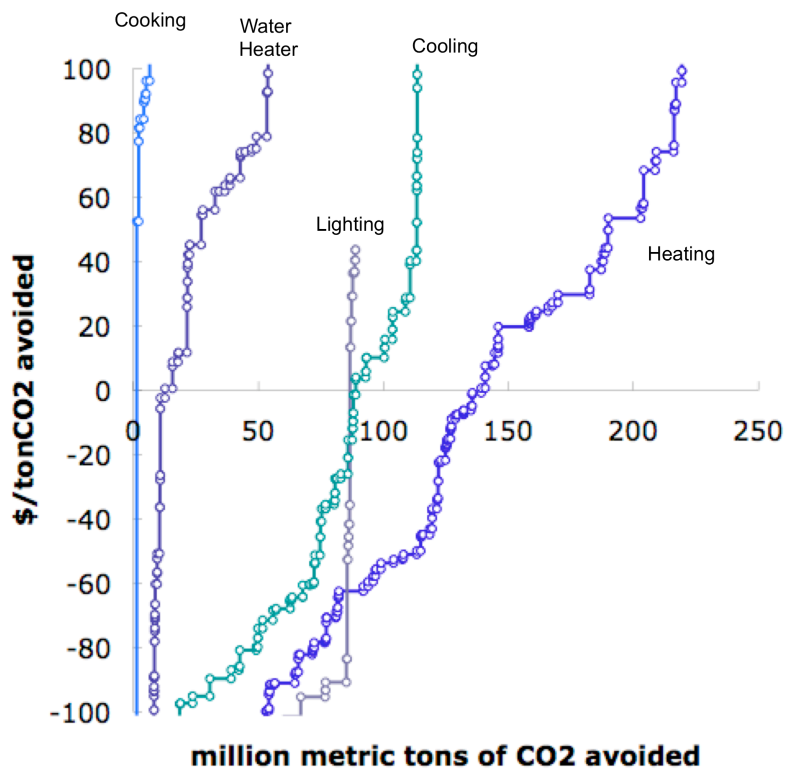

Figure 50 - Simulations for carbon efficiency supply curves for some of the largest energy end uses in the residential sector. The y-axis represents the cost-effectiveness of the options in \$/ton CO_2 avoided. In this simulation, it is assumed that consumers value the current stock. Therefore, the levelized annual cost only accounts for the investment cost in the new technology. All the curves assume a 7% real discount rate technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009. The bars on the right represent the cost-effectiveness ranges for supply-side mitigation options (current photovoltaics (PV), nuclear, future photovoltaics, wind, new natural gas combined cycle power plant with carbon capture and sequestration (NGCC with CCS), new pulverized coal power plant with carbon capture and sequestration (PC with CCS), and new integrated gasification combined cycle with capture and new gasification (IGCC with CCS)).

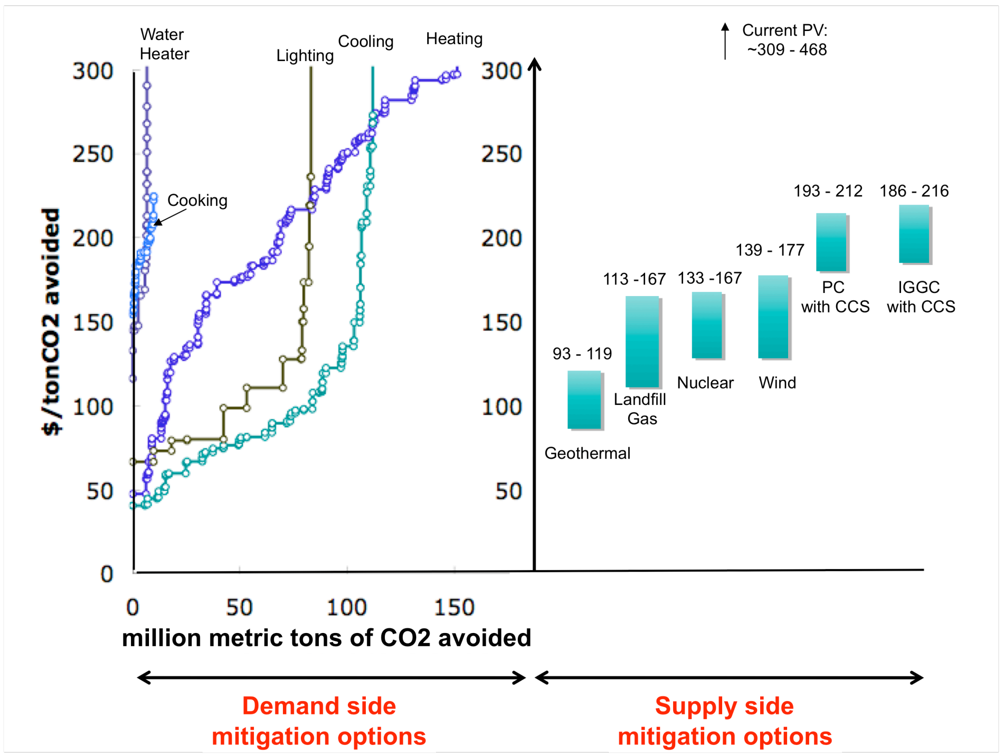

Figure 51 – Simulations for carbon efficiency supply curves for some of the largest energy end uses in the residential sector.

The y-axis represents the cost-effectiveness of the options in $ per ton of CO_2 avoided. In this simulation, it is assumed that utilities or ESCOs would fully bear the cost of implementing new technologies in the residential sector. All the curves assume a 7% real discount rate technology data from AEO 2008 underlying data provided by DOE; retail electricity prices as in AEO 2008 forecasts for 2009. The bars on the right represent the cost-effectiveness ranges for supply-side mitigation options when investing in new power plants (current photovoltaics (PV), nuclear, future photovoltaics, wind, new natural gas combined cycle power plant with carbon capture and sequestration (NGCC with CCS), new pulverized coal power plant with carbon capture and sequestration (PC with CCS), and new integrated gasification combined cycle with capture and new gasification (IGCC with CCS)).

Chapter 7. How Much Should Society Invest in Energy Efficiency?

Investments in energy efficiency are generally seen as socially desirable because they implicitly reduce environmental and health related externalities from greenhouse gases and criteria pollutant emissions for electricity generation. Energy efficiency investments also avoid O&M, fuel and intermittency and reliability costs to utilities. Additionally, in the long-term, energy efficiency measures might delay the construction of additional electricity generation capacity and possibly avoid transmission and distribution costs. The costs avoided from supply side options are therefore the key benefits of energy efficiency. In Chapter 4, I provide a comparison of the costs of investments in energy efficiency and in new generation capacity, based on a total resource cost approach. This chapter differs from Chapter 4 by adopting a societal perspective.

Undertaking a societal analysis to estimate the costs and the benefits of energy efficiency investments is a complex task, and several strong assumptions must be made. I assume a

3% social discount rate[45] for all investments. I explicitly distinguish societal costs in the short term and in the long-term.

In the short-term, the available energy system is locked in the present infrastructure, and energy efficiency investments will not delay or displace capital investments in additional generation capacity. Therefore, in the short-term, the avoided costs from energy efficiency correspond to reductions in fuel, O&M, intermittency and reliability costs.

In the long term, in addition to the previously stated avoided costs, avoided costs also include the additions of new generation capacity and avoided transmission and distribution costs.

It is worth pointing out whether or not to include the cost of additional generation, and transmission and distribution capacity investments in the avoided costs might be debatable even when adopting a long-term perspective. Even under a scenario where energy efficiency efforts are large and successful at reducing demand, it is very unlikely that they could avoid the need for new transmission and distribution lines, as the existing system is aging and is in need of being upgraded. Furthermore, other regional and demographic factors should be taken into account to determine whether such costs should be included. In regions where population is growing, additional infrastructure is likely to be required. Despite this uncertainty regarding when and where the additional generation capacity and the transmissions and distribution lines will be needed, their avoided costs will be included in the long-term analysis.

[45] As opposed to the 7% real discount rate used in the utitlities/ESCOs analysis.

For all the supply side options, I assume the same ranges of values for capital costs, fuel prices, maintenance costs, intermittency and reliability costs, and transmission and distribution costs as in Chapter 4[46].

Emissions of carbon dioxide, NO_x SO_2 and fine particulate matter constitute negative externalities for fossil power plants, which society can choose to internalize. The environmental externalities caused by each of those pollutants are substantially different in terms of their environmental and health related impacts and also vary geographically and for how long environmental impacts will last.

If not removed from the stack (using electrostatic precipitators), particulate matter, particularly for particles with diameters smaller then 10 μm, leads to respiratory and cardiovascular diseases [70].

Sulfur dioxide (SO_2) reacts with the water vapor, leading to sulfuric acid. Nitrogen oxide emissions (NO_x) out of the stack will gradually oxidize to NO_2 in the atmosphere. As with SO_2, a reaction with water vapor in the atmosphere might lead to the formation of nitric acid. The sulfuric and nitric acid content in precipitation will decreases its pH, which in turn potentially acidifies surface waters and land, leaches nutrients from the soil and changes soil chemistry [93]. SO_2 and NO_x have also the adverse effect of reacting chemically in the atmosphere, to form fine nitrate particles that contribute to an increase in particulate matter (< 2.5 μm) [70]. Further, in the presence of sunlight, NO_x emissions are precursors for tropospheric ozone formation, which causes serious

[46] With the difference that the capital costs discounted at a 3% real discount rate.

respiratory and other heath related problems [93]. The SO_2 emissions can be reduced by using different types of scrubber technologies, or by switching from high sulfur to low sulfur coal.

There is much uncertainty when valuing environmental externalities, and many different approaches can be considered. Matthews and Lave [89] review the literature on environmental externalities valuation for these pollutants and found the ranges of values provided in Table 32. I use the median values from Matthews and Lave in the analysis provided below.

There is also a large uncertainty regarding the amount of emissions per unit of electricity produced of from these pollutants for different generator types. Table 33 reports the representative values I assumed for each generating technology, based on the ranges provided in [62], [64], [91], [92]. The four studies from are based on the Integrated Environmental Control Model (IECM) model from Carnegie Mellon University.

The emissions factors for biomass power plants are from Mann and Spath [90]. For gas combined cycle power plants and gas peaking plants, I assume the emissions factors for the usage phase of natural gas combustion as in [91]. Further work on societal cost analysis should include a more detailed assessment of regional emissions factors for each generating technology using E-Grid and other sources, and a careful uncertainty analysis, which is not included here.

Table 32 – Review from Matthews and Lave on costs of internalizing environmental externalities (CO_2, NO_x, SO_2 and PM_{10}). Source: [89]. The values in Matthews and Lave were adjusted from $1992 to $2006.

$2008	**Low**	**Median**	**Mean**	**High**
$/ton CO_2	3	21	20	35
$/ton NO_x	336	1,621	4,281	14,526
$/ton SO_2	1,177	2,752	3,058	7,187
$/ton PM_{10}	1,453	4,281	6,575	24,771

Table 33 – Representative values for emissions per unit of electricity generated for different supply side options. Adapted from [61] - [63].

		Kg of CO_2 per MWh	**Kg of NO_x per MWh**	**Kg of SO_2 per MWh**	**Kg of PM_{10} per MWh**
Conventional Technologies	PC	900	2.60	22.00	34.47
	SCPC	816	0.05	0.54	0.13
	IGGC	860	0.09	0.28	0.00
	Gas Combined Cycle	500	1.20	0.30	0.01
	Nuclear	0	0	0.00	0
	Gas Peaking	500	1.20	0.30	0.01
Conventional Technologies with CCS	PC with CCS	115	0.06	0.00	0.08
	SCPC with CCS	115	0.06	0.00	0.08
	IGCC with CCS	115	0.06	0.07	0.01
Alternative Technologies	Geothermal	0	0	0	0
	Wind	0	0	0	0
	Landfill Gas	0	0	0	0
	Biomass Direct	0	0.48	0.25	0.00
	Solar Thermal	0	0	0	0
	Solar PV - Thin Film	0	0	0	0
	Solar PV- Crystalline	0	0	0	0

To evaluate the demand-side potential, the baseline considered is the projected electricity using appliances and devices in the residential sector in 2009 (~1400TWh). The costs of energy efficiency investments are computed using RREEM. I provide the estimates of average and marginal costs for energy efficiency investments to achieve a 5%, 10% and 20% level of electricity consumption reduction from the baseline in Table 34.

Generally, efficiency assessments include incremental costs of energy efficiency investments. This represents only the incremental investment between the considered baseline technology and the efficient technology. This is a measure that makes perfect sense when the opportunity cost corresponds to buying the less efficient appliance. Thus, when modeling the new purchases of equipment, the consumer is deciding whether to buy a more or less efficient appliance.

Energy savings from new purchases can provide at most a reduction in 5% from the baseline energy consumption in a given year. Policies aiming to target energy savings of more than 5% of the baseline through the adoption of more efficient technologies, the decision becomes whether to keep the baseline appliance or to throw it away and buy a new, more efficient appliance. In that case, the opportunity cost is zero, since it corresponds to doing nothing. Thus, the full cost of new technologies should be used when assessing the marginal costs of energy efficiency investments.

Another source of differences in the assessment of the costs of energy efficiency measures arises from the use of marginal or average costs. In Table 34 I show the marginal and average costs to achieve a 5%, 10%, 20% or 30% reduction in the baseline electricity consumption. The average costs are generally an order of magnitude lower than the marginal costs. The marginal and average costs of the investments in energy efficiency increases as the levels of energy savings pursued increases. In the analysis provided below, I used the marginal costs from investing in new efficient technologies while allowing for fuel switching (corresponding to the fourth column in Table 34).

Table 34 – Energy efficiency average and marginal cost estimates from RREEM for a 5%, 10%, 20% and 30% reduction from the baseline electricity consumption (1400TWh, 2009). I assume a 3% discount rate. Costs include the cases for incremental and full technological costs, with and without fuel switching.

	Marginal Costs ($/kWh avoided)				**Average Costs ($/kavoided)**			
	Incremental cost of technology		**Fully cost of technology replacement**		**Incremental cost of technology**		**Fully cost of technology replacement**	
Reduction from Baseline	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes	allowing fuel changes	not allowing fuel changes
5%	0	0.05	0.04	0.06	0	<0.01	<0.01	<0.01
10%	0	0.05	0.06	0.06	0	<0.01	<0.01	<0.01
20%	0.05	0.08	0.07	0.77	<0.01	0.04	<0.01	0.04
30%	0.49	-	1	-	0.02	-	0.063	-

In Figure 52, I provide the results for the short-term benefit-cost analysis from a societal perspective. The left-hand side of the picture shows the direct (e.g., the marginal annualized capital cost of the efficient technologies) and indirect costs (e.g., program implementation, administrative or marketing costs) of investing in energy efficiency.

The right-hand side of the picture provides the avoided costs from the supply side power plants when investments in energy efficiency are pursued. Since in Figure 52 I am focusing on the short-term impacts of energy efficiency investment, the capital costs of new generation capacity are not included.

The analysis suggests that in the short-term, there are net social benefits in retrofitting the existing equipment up to a reduction of 5% of the baseline residential electricity consumption when such investments are compared with the provision of electricity through pulverized coal power plants, gas combined cycle or gas peaking power plants. If one considers only the direct costs in energy efficiency (the red bars in Figure 52), the option of reducing electricity consumption by 5% through energy efficiency is also competitive with IGCC and landfill gas.

Reaching more ambitious reduction on the residential electricity consumption (e.g., 10%) would be a competitive alternative to the natural gas powered supply side options[47], under a scenario of reasonably high natural gas prices.

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[47] The natural gas price is assumed to be $9 per million BTU.

The costs of efficiency investments appear to be, in the short-term, more expensive than most of the renewable opportunities. However, we are comparing the cost of reducing energy consumption by 5% with the cost of providing the energy service through renewables. Yet, only less than 2.5% of the electricity generation is provided through renewables (excluding conventional hydroelectric power plants).

While for simplification I have used typical generation side technologies, the electricity consumption avoided due to investments in energy efficiency would displace a portfolio of generation side technologies, as opposed to a typical power plants. The actual costs avoided will also depend on the usage patterns of the end-uses being replaced.

In Figure 52 I am assuming a reasonable low externality cost for carbon dioxide emissions ($21 per ton of CO_2 emitted). Under the RRGGI the carbon prices have been much lower than the assumed price, but it might be expected that as the number of allowances decreases, the price of CO_2 will increase. As the price of CO_2 emissions allowances increases, the energy efficiency measures become more attractive. Yet, if reductions in the baseline residential electricity consumption of more than 20% are pursued, the carbon dioxide emissions price would need to reach $60 per ton of CO_2 for the investments in energy efficient to be comparable with the avoided costs from the most of the traditional supply side options.

The conclusions are substantially different if the average costs of energy efficiency are used instead of the marginal costs that will be required to achieve 5%, 10%, 20% or 30% of the baseline electricity consumption. Average costs for energy efficiency investments are estimated to be always less than $0.01 per kWh for up to a 10% reduction in electricity consumption from the baseline. Furthermore, I assumed indirect costs of $0.02 per kWh for program implementation, which I estimated in Chapter 4. However, other sources from the literature assume that energy efficiency measures and programs prevail for longer, which decreases the annualized indirect costs.

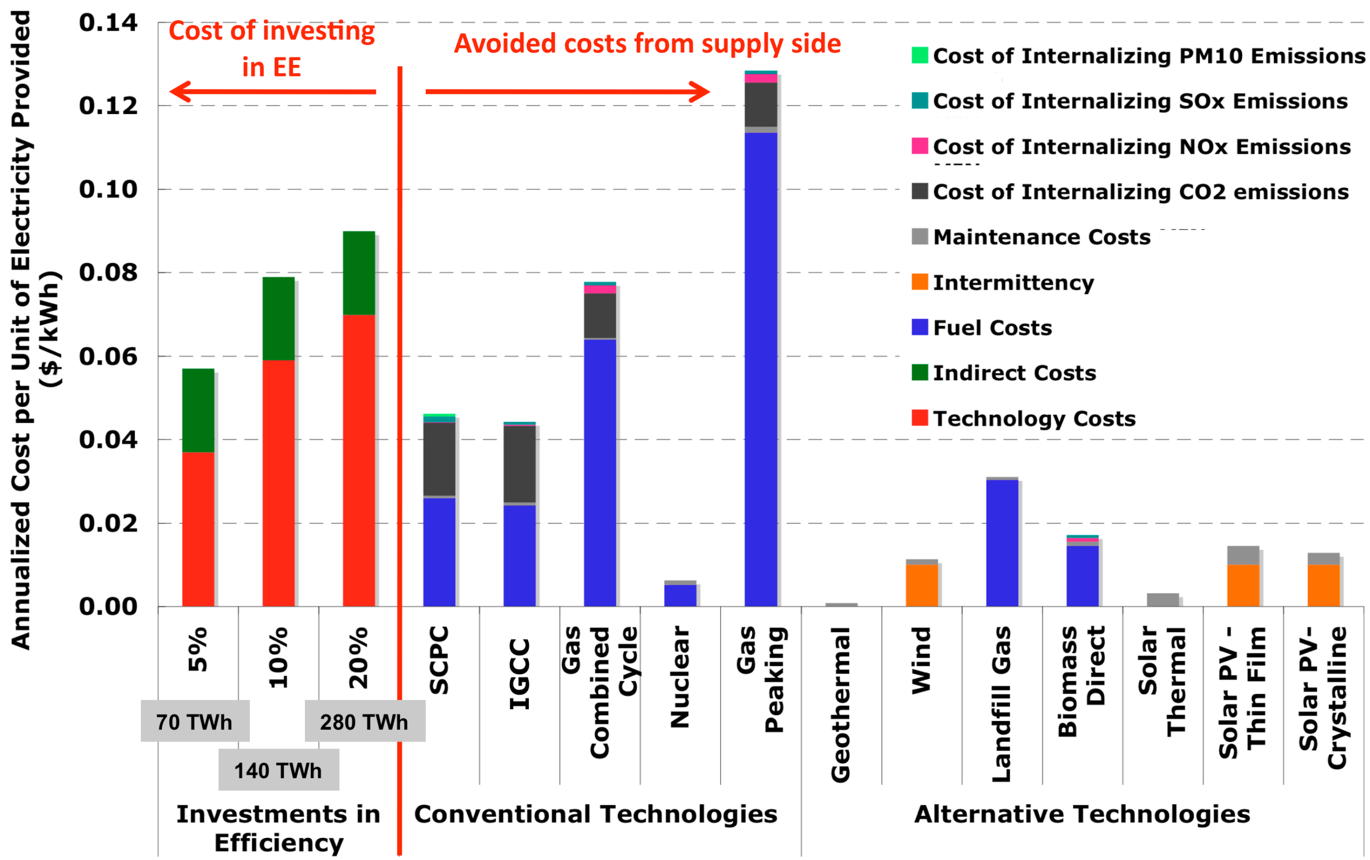

Figure 52 – Comparison of short-term societal costs of energy efficiency and supply side options, using a social discount rate of 3% for all options.

Figure 53 provides a societal benefit-cost analysis in the long term. The left-hand side of the picture corresponds, once again, to the annualized investment costs in energy efficiency, as in Figure 52. In addition to the power plants provided previously in Figure 52, The supply-side options include, power plants with carbon capture and sequestration (CCS). The assumptions for the costs of such plants are the same as in Chapter 4. Choosing the option of CCS will require also building the pipelines to transport the carbon dioxide to the sequestration site, and the costs storage.

Rubin [64] uses IPCC estimates [94] adjusted for 2007 and reports that transportation costs range from \$1 to \$10 per ton of CO_2 transported and storage costs in deep geological formations range from \$0.5 to \$10 per ton of CO_2 transported. Using the carbon emissions from Table 35, this corresponds to an added cost for supply side options with CCS that ranges from \$0.001 per kWh generated to \$0.015 per kWh depending on the power plant considered. The average of those values is used in Figure 53.

The long-term societal analysis of the costs and benefits (or avoided costs from supply side) shows that investments energy efficiency to achieve a 5% reduction from the baseline provide net benefits when compared to most supply side alternatives, the exceptions being nuclear power and geothermal. The same is true for reductions from the baseline to up to 20%, when accounting only for the direct costs of energy efficiency.

When the indirect and direct costs of energy efficiency are considered, reductions in electricity consumption by 10% from the baseline entails small net societal costs when compared with nuclear, geothermal, wind, and landfill gas. The reduction by 10% is still less expensive than the remaining supply side options, and would become even more attractive as the price of CO_2 emissions allowances increase[48].

[48] Here I am assuming a price for carbon emissions of $21 per ton of CO_2.

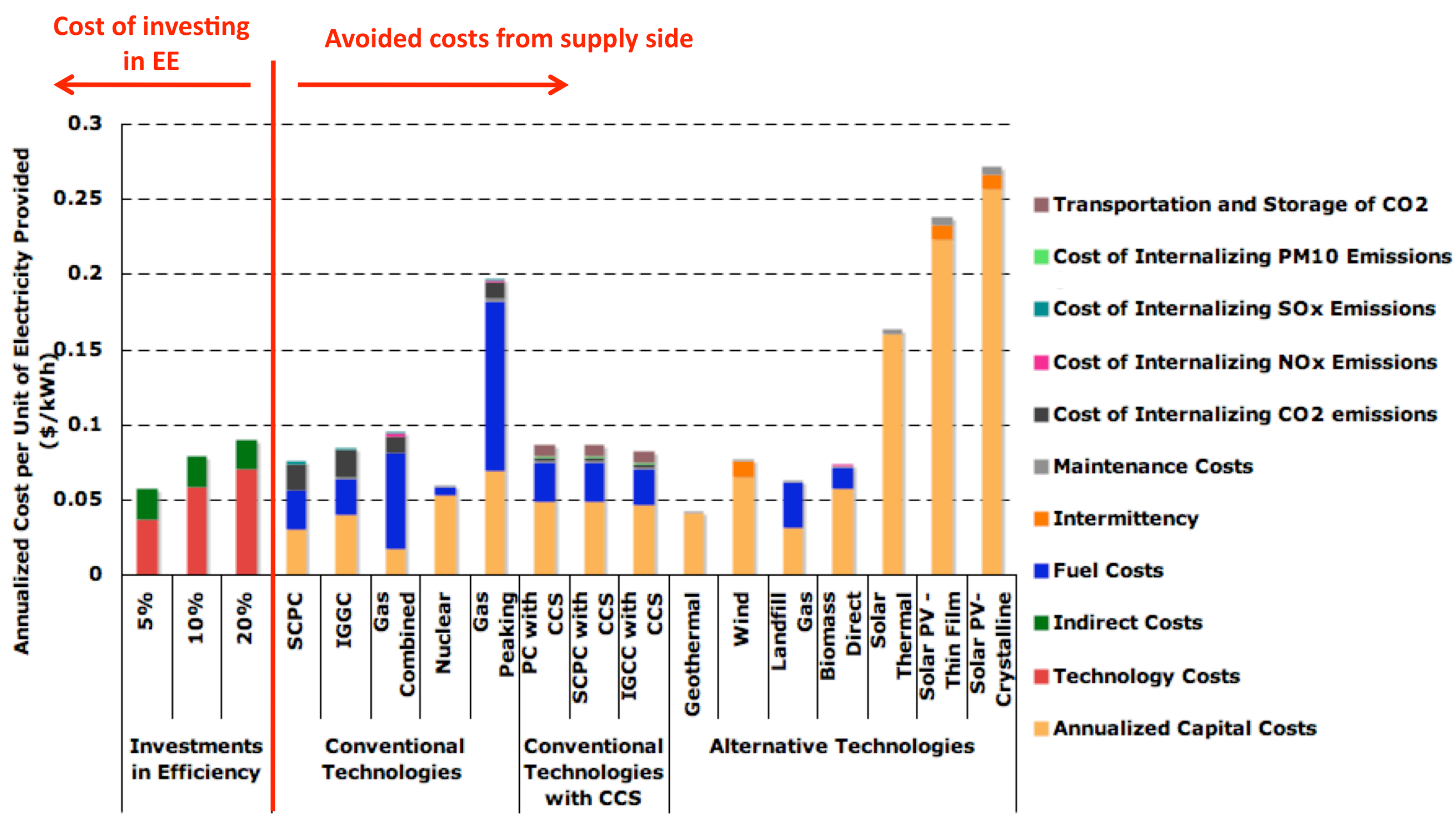

Figure 53 – Comparison of long-term societal costs of energy efficiency and supply side options, using a social discount rate of 3% for all options.

Several important considerations that were left out of this benefit-cost analysis are worth mentioning. The approach does not detail who harvests the benefits and who faces the costs of energy efficiency investments. The approach lumps together the costs and the benefits for all the economic agents. Therefore, important issues such as equity, fairness, and distributional effects are left out of the analysis.

Also, the analysis does not include other important avoided external costs from energy efficiency investments. Those avoided costs that arise from land use, waste disposal, and cooling of supply side option were not considered [93]. Land use impacts include the environmental impact of resources extraction (namely surface coal mining) and in generation and transmission sitting (e.g. decrease of property value near high-voltage transmission lines due to households concerns of health effects of magnetic fields). Environmental impacts related with land use for supply side options can also include the visual impact in landscape. Avoided costs from disposal of nuclear waste, or ashes and sludge from coal power plants were not included in the analysis. The environmental externalities associated with the large amounts of high temperature water released into the environment due to the cooling processes in nuclear and fossil-fueled generation power plants were also not included. All these aspect would make energy efficiency investments look more attractive than what was shown in Figures 52 and 53.

There is considerably uncertainty arising from the engineering and economic assumption for both the supply side and demand side characterization. There is also a large uncertainty in the environmental and health externality valuations. Also, the outcomes of the societal analysis are highly sensitive to the social discount rate considered.

The societal analysis only considers the electricity end-uses from the residential sector. A broader analysis using RREEM could include the energy efficiency potential for non-electricity end-uses. Further, there are regional considerations that were not tacked in this analysis and will be left for further work. The U.S. regions vary widely in their baseline energy consumption, electricity consumption, GHG emissions and share of different types of end-use equipment and usage patterns. For example, I estimated from RREEM the primary and final energy consumption, electricity consumption and carbon emissions at Census Division level, which I provide in Figure 54. In the present work, the focus is on a national assessment of energy efficiency. Therefore, a regional societal analysis at a census division level is not presented here.

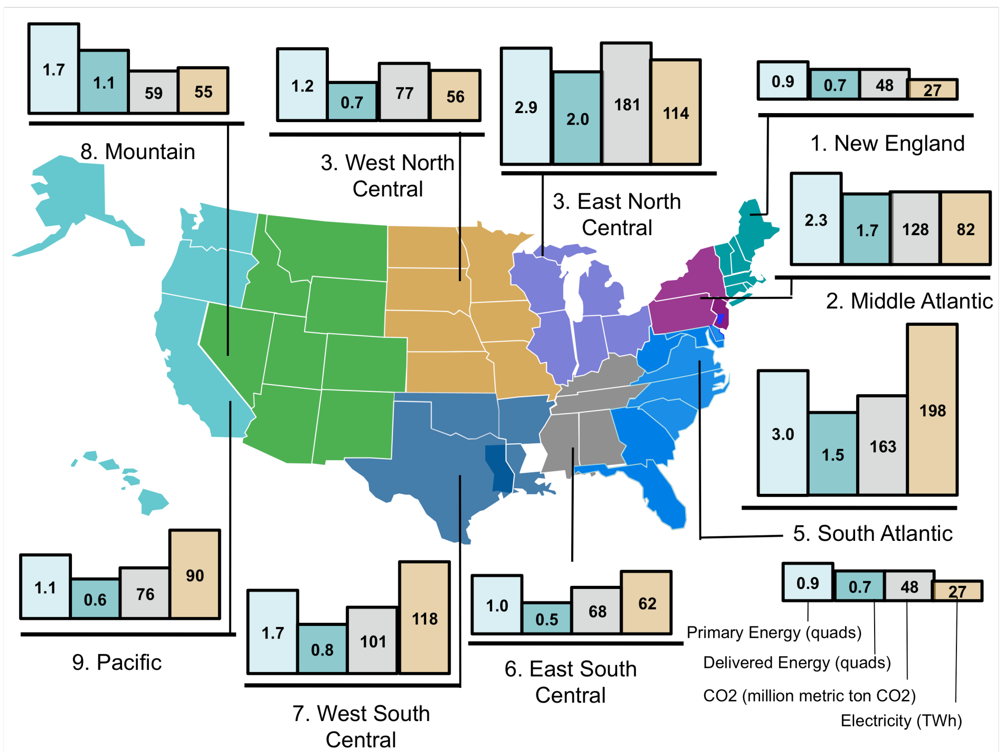

Figure 54 – Estimates of primary energy (quads), delivered energy (quads), carbon dioxide emissions (million metric ton of CO_2) and electricity (TWh) consumption at Census Division level extracted from RREEM for the U.S. largest energy consuming end-uses.

Chapter 8. Conclusions, Policy Recommendations and Further Work

8.1 Conclusions and Policy Recommendations

In the last couple of years, energy efficiency policies have assumed an increasingly important role in the discussions of U.S. energy policy. This is due to high oil prices and to concerns about climate change and other environmental impacts that results from the consumption of fossil fuels. In the context of the recent American recession, issues of affordability are also becoming more relevant. American households want to maintain the quality of life they now enjoy through the use of energy services. In addition, concerns of security of supply also call for alternative ways to design more sustainable energy systems.

Energy efficiency has long been viewed by its proponents as the cheapest form of providing energy services, reducing costs to consumers and addressing climate change issues. This work shows that there are some interesting energy efficiency opportunities in the residential sector. However, the amount of the energy savings, GHG avoided and the costs to the different economic agents depend on the design of energy efficiency policies and on the and on the structure of the energy market.

The technologies and regions that efficiency policy should target change depending on whether one aims at reducing primary energy, delivered energy consumption, electricity or carbon dioxide emissions. Any national policy should account for the effects of specific energy efficiency measures on these different indicators.

Looking at technology alone, I estimate that energy consumption could be reduced by more than 50% in any of these key indicators. Targeting only new purchases yields only a reduction of 5% from the baseline. The baseline considered here is the consumption of the largest energy end-uses.

However, technological potentials do not provide a realistic approach for estimating how much energy can be saved or for how carbon dioxide can be avoided. Relevant measures for policy making need to account for economic costs, benefits and who bears them. For example, a recent study from McKinsey [43] provides figures for GHG abatement costs from different mitigation options, including energy efficiency. However, their assumptions are unclear, and they do not discuss who pays for what.

I argue that there needs to be a shift in the standard practice of displaying energy efficiency costs and savings. Costs and savings are meaningless if one does not clearly state which economic agent and policy is being simulated. In the present work I tackled this issue by building a flexible model for energy efficiency assessment in the residential sector that accounts for the perspectives of different agents. This model, the Regional

Residential Energy Efficiency Model, or RREEM, accounts also for different types of end-uses, fuels, and regions. The model provides additional flexibility for constructing energy efficiency potentials based on different energy and pollutant criteria.

A key finding from exploring this model is that consumer surplus could be increased or maintained when retrofitting a large part of the existing stock of appliances. Following the least-cost path provided in the efficiency supply curves, consumers could save up to 30% of delivered energy consumption, 20% of electricity consumption and 32% of carbon emissions from the total residential consumption, at a cost lower than retail fuel prices. While there is uncertainty in these figures, RREEM provides a first order estimate of the magnitude of the available savings. Further, for new purchases, consumers could save 5% of electricity, delivered energy or GHG emissions with energy efficiency measures for which the annualized cost is less than the energy price.

However, literature shows that consumers do not perform decisions using a market discount rate. Consumers use higher discount rates, which, together with other barriers to energy efficiency, delay the adoption of efficient technologies. Thus, several efforts should be pursued to harvest the energy efficiency potential of new purchases and existing equipment. For new equipment, I suggest that minimum efficiency standards should be defined in terms of primary and delivered energy. These standards should represent the most efficient and yet cost-effective option for consumers.

Since consumers are unlikely to voluntarily adopt efficient technologies, even when that makes economic sense, policies are needed to retrofit the existing stock in the cases where that is cost-effective. One way to pursue such a goal is to have utilities or ESCOs invest and install the efficient equipment. For the least capital-intensive efficiency options, utilities or ESCOs could bear such costs directly and recover them through a system of public benefit funds. Note that utilities will only feel compelled to make such investments if the spending is either mandatory or if the utilities are operating in a market where decoupling occurs and a system of incentives is provided. In any other case, investing in energy efficiency would result in losses of revenue due to a decrease in sales.

The low cost options for investments in energy efficiency can only provide a portion of total possible savings. For the high upfront-cost energy efficiency measures, that are still cost-effective because they promote large energy or carbon savings, one of the market-based mechanisms that should be explored is to have the utility or an ESCO install and manage the equipment. This scheme might make sense for long lasting equipments, as heating systems white LEDs.

My simulations suggest that electric utilities could foster energy efficiency measures that save up to 20% of the residential electricity consumption. Pursuing this strategy wouldn't be cheap. An annualized cost between \$22 and \$39 billion would be necessary to make such retrofits. Between 10% and 20% of those savings would be done at a cost below the actual retail residential electricity price.

My findings also suggest that on a \$/kWh basis, for up to a 10% reduction from the residential electricity consumption, it would be cheaper to invest in energy efficiency than investing in most types of new power plants. Pursuing efficiency efforts targeting 20% of electricity reduction are expected to be more costly than investments in new generation when fuel switching is not allowed. However, if fuel switching is allowed, energy efficiency efforts to up to a 20% reduction from the baseline are competitive with generation side opportunities, even if utilities decide to pay for the full cost of energy efficiency investments.

I performed a societal benefit-cost analysis on energy efficiency investments. I conclude that, in the short-term, there are net social benefits in retrofitting the existing equipment up to a reduction of 5% of the baseline residential electricity consumption when such investments are compared with the provision of electricity through pulverized coal power plants, gas combined cycle or gas peaking power plants. If one considers only the direct costs in energy efficiency the option of reducing electricity consumption by 5% through energy efficiency is also competitive with IGCC and landfill gas. Achieving more ambitious reductions in the residential electricity consumption (e.g., 10%) would be a competitive alternative to the natural gas powered supply side options, under a scenario of reasonably high natural gas prices. Reductions in the baseline residential electricity consumption of more than 20% would only be competitive with the avoided costs from the most of the traditional supply side options if the carbon dioxide price reaches \$60 per ton of CO_2.

The long-term societal analysis of the costs and benefits (or avoided costs from the supply side) shows that investments in energy efficiency to achieve a 5% reduction from the baseline provide net benefits when compared to supply side alternatives, the exceptions being nuclear power and geothermal. The same is true for reductions from the baseline to up to 20%, when accounting only for the direct costs of energy efficiency. When the indirect and direct costs of energy efficiency are considered, reductions electricity consumption by 10% from the baseline entails small net societal costs when compared with nuclear, geothermal, wind, and landfill gas.

The American Recovery and Reinvestment Act (ARRA) has several provisions related to energy efficiency. Of particular interest for the purpose of this work are the provisions relative to the state energy programs ($3.1 billion), the energy efficiency and conservation block program ($3.2 billion), and the energy star program ($0.3 billion). There is still large uncertainty concerning the magnitude of the impact that energy efficiency investment can achieve. For example, if state energy programs funds are used according to the least-cost path in RREEM, a direct investment of the magnitude of the energy efficiency and conservation block program ($3.2 billion) could save the nation close to 5% of the current residential energy consumption.

Detailed regional assessments are needed to determine which existing equipment can be retrofitted cost-effectively. The RREEM provides a unique tool to determine such priorities. Poor information on the current stock hampers identifying cost-effective opportunities. The underlying data used in NEMS, which was used to build RREEM, provides the best source of data in the US. Data are also lacking in what regards usage patterns. In NEMS, the "average unit energy consumption" is used to characterize annual energy consumption for different end-uses. Historical values for the average unit energy consumptions are estimated by DOE using the Residential Energy Consumption Survey and other sources, and then projected into the future. DOE should gather better estimates of the distributions of equipments and usage patterns, so that policies priorities are designed accordingly.

Part 1 – Chapter 8: Conclusions, Policy Recommendations and Further Work

8.2 Other Analysis Not Reported

All of the results I have reported assume that consumers behave as rational economic actors. In additional analysis, not reported in this thesis, I have explored the implications of using more realistic behavioral models. If consumers do not choose to make economically efficient decisions we can use the results from RREEM to work backwards to estimate an implicit discount rate. These rates are estimated to range from 7% to 27% for heating, 33% to 85% for cooling, from 9% to 41% for water heaters, from 13% to 32% for cooking, from 8% to 15% for refrigerators and freezers, and from 9% to 408% for lighting. For clothes washers, dishwashers, and clothes dryers, all the efficient technological options were more expensive than the baseline technology, and therefore the implicit discount rates could not be assessed. This method provides similar ranges for implicit discount rates to what has been found in the econometric literature.

Other analysis not reported in the thesis has explores issues of natural gas availability. A key finding from such analysis is that there does not appear to be serious pipeline capacity constraints at the Canadian or Mexican borders.

8.3 Future Work

My RREEM simulations accounted for retrofitting either a full stock by the most efficient options or only new purchases. However, it is easy to use RREEM to simulate scenarios in between. For example, I could use expert elicitation to determine the share of stock that would be affected by different types of policies. Another extension of the model for purposes of policy analysis would be to include the effect of a carbon price on the least-cost path provided by the model.

The regional features of RREEM have not been explored in this work but RREEM provides a strong tool to compare the regional energy efficiency potential and test which regions would be winners and losers if specific programs are implemented. For example, I can study which census division regions would benefit more from a system of white certificates (or similarly, what would happen if under RRGGI or another CO_2 market-trading scheme).

A broader perspective on energy efficiency should include other sectors besides the residential sector. Work was already been initiated with colleagues at Carnegie Mellon to study, at a household perspective, what would be the least-cost path for carbon mitigation measures that includes efficiency from residential equipment as well as transportation options.

In the future, detailed regional assessments should also include a consideration on a regional context, or issues such as fairness, equity, transparency and ease of implementation of the different energy efficiency policy designs.

Chapter 9. References

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Part 2. The Transition to Solid State Lighting

Chapter 1. Introduction

Lighting consumes more than 20% of all electricity generated in the United States (U.S.)[49]. This corresponds to just below 800 TWh per year. The fraction is similar in the European Union (E.U.), and even higher in some developing countries, since lighting is one of the largest uses of electric power [3]. The International Energy Agency (IEA) [3] has estimated that worldwide lighting is responsible for emissions of approximately 1 900 Mt CO_2 per year "equivalent to 70% of the emissions from the world's light passenger vehicles." Eighty percent of these emissions from lighting are associated with electricity generation, but the IEA estimates that about 20% come from the 1% of global lighting that is produced by the direct combustion of paraffin and oil lamps used by the

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[49] Estimated using [1] and [2].

1.6-billion people who have no access to electricity [3]. Hence, dramatically improved lighting system efficiency together with electrification that replaces oil lamps with electric lamps, could make a big contribution to controlling global CO_2 emissions. In Chapter 3, an overview of the literature [4]-[13] and the estimates produced using RREEM, illustrate the cost-effectiveness of greenhouse gas mitigation through the use of energy efficient technologies such as improved lighting.

Climate change is not the only concern moving lighting on to policy agendas. While oil plays a relatively minor role in U.S. electricity generation, natural gas, imported from increasingly unreliable parts of the world, fuels slightly over 20% of U.S. generation [14] and 39% of generation in the EU25 [15]. While great progress has been made in reducing emissions of SO_2 and NO_x from power generation, local and regional air pollution, including emissions of heavy metals such as lead, are ongoing concerns. Again, improved end use efficiency can help to reduce those emissions.

Conventional incandescent bulbs, which convert only between 1% and 5% the electricity they consume into usable light (when compared with the maximum efficacy of 408 lm/W for a near white light source), have been the initial focus of policy attention. This attention is clearly justified, since households and the commercial sector are responsible for 37% and 35% of the U.S. total electricity consumption[50]. Smil [16] argues that the provision of illumination is one of the most promising areas for future improvement in energy efficiency, suggesting that by the middle of the 21st century the average lighting

[50] Estimated using [1] and [2].

efficacy in rich countries could be 50% above today's level. The role of lighting technologies is also emphasized in recent California policy initiatives, as Title 24 [17], and at the Federal level in the 2005 Energy Policy Act [18], which creates a Next Generation Lighting Initiative that will support R&D to accelerate the rate of improvement in white solid-state lighting, and the 2007 Energy Independence and Security Act [19]. As a result of concerns about CO_2 emissions, energy security, and conventional air pollution, legislatures and regulators in Australia, Brazil, Canada, Ireland, Italy, New Zealand, the United States and Venezuela have all recently moved to implement a mandatory phase-out of most standard incandescent bulbs over the coming decade. Most of the remaining countries in the E.U. are likely to adopt similar policies. However, currently available replacement technologies will not meet all consumers' needs. Scientists, engineers and policy makers are increasingly looking to solid-state lighting for better solutions.

Part 2 begins with a brief account of the evolution of electric lighting technologies over the past century, Chapter 2. It then discusses key lighting systems characteristics, before going on in Chapter 4 to discuss the likely future evolution of the performance of light emitting diodes (LEDs) that produce white light - either by combining monochromatic LEDs or by using a down-converting phosphor layer. Many consumers do not choose long-lived technologies on the basis of standard market discount rates. I discuss consumer choice and the literature on implicit discount rates in Chapter 5.

Then, in Chapter 6, I present engineering-economic estimates of the future cost of light from the perspective of both commercial and residential customers. Other factors, such as total energy use and greenhouse gases emissions are also important from a social perspective. Thus, Chapter 7 explores the social cost-effectiveness of white LEDs. Then, in Chapter 8 I estimate the potential energy savings and greenhouse gas reductions that could be achieved under different types of policies. I conclude Part 2 with recommendations on policy implementation for a rapid and widespread adoption of more efficient lighting in the near future.

Chapter 2. Brief History of Lighting Technologies

2.1 Incandescent Lamps

While Edison is credited with the development of the first commercially practical incandescent lamp in 1879, many others had worked on the idea over the preceding century [21]. Early bulbs used carbon filaments, which had limited lifetime and could not be operated at a high enough temperature to produce fully satisfactory light. General Electric patented the first tungsten filament for commercial use in 1906. Further improvements followed, including the use of inert gas in the bulb and the use of coiled tungsten filaments. While manufacturing costs continued to fall, the efficacy (the ratio of light output to the input electric power) with which incandescent bulbs convert electricity in to light has reached an asymptote at just under 18 lumens per Watt (Figure 55).

2.2 Fluorescent Lamps

General Electric developed low voltage fluorescent lamps in the 1930s. These were first marketed as “tint lighting” for decorative purposes. However, it soon became apparent that fluorescent lamps also held great potential for general lighting. The electric power industry became seriously concerned that the rapid proliferation of more efficient fluorescent lighting might reduce demand and thus negatively impact power sales. They were also concerned that the need for reactive power imposed by ballasts would increase current flows on their lines without resulting in marketable real power. As historian Wiebe Bijker [22] has detailed, a series of negotiations followed between the power industry and GE and the GE licensees (the Mazada companies) in which it was agreed not to market fluorescents aggressively until much brighter “high intensity” lights, that required more power, could be developed. Today, with power companies and lighting firms experiencing much reduced market power, with much stricter anti-trust law and enforcement, and with power companies struggling to meet load, such collusion between lamp manufactures and power companies is not a serious issue. Indeed, given the challenge of building new power plants, and growing concerns about CO2 emissions, many U.S. power companies are actively promoting more efficient lighting. However, while fluorescents, and especially compact fluorescents, are now being actively promoted, their conversion efficacy is unlikely to grow much above 100 lm/W (see Figure 55).

2.3 Solid-state Lighting

While H. J. Round [23] reported observing “cold light” emission from a cat-whisker point contact SiC crystal detector diode as early as 1907, the invention of the light emitting diode is now attributed to O. V. Losev, a largely forgotten Russian scientist [24]. Losev [24] correctly postulated that the luminescence wasn’t the result of incandescence, but was due to another process “very similar to cold electronic discharge”. Loebener [25] notes “There is little doubt that Losev […] was consciously pursuing work on light emitting diodes for communications applications. Between 1927 and his death [from starvation during the siege of Leningrad] in 1942, he published sixteen papers and obtained four patents on LED's photodiodes and optical recorders for high frequency signals.” This early work was largely forgotten, and until recently credit for the discovery and development of the LEDs went to a number Western investigators including K. Lehovec and co-workers [26], R. Braunstein [27] and N. Holonyak [28].

In 1962, Holonyak, while at General Electric's Solid-State Device Research Laboratory, made a red emitting GaAsP inorganic LED [28]. The output was very low (about 0.1 lm/W), corresponding to an efficiency of 0.05% [28]. Changing materials (to AlGaAs/GaAs) and incorporating quantum wells, by 1980, the efficacy of his red LED had grown to 2 lm/W, about the same as the first filament light bulb invented by Thomas

Edison in 1879. An output of 10 lm/W was achieved in 1990 and a red emitting light AllnGaP/GaP based LEDs reached an output of 100 lm/W in 2000 [28]. In 1993, Shuji Nakamura demonstrated InGaN blue LEDs [29]. By adding additional indium he then produced green LEDs and finally, by adding a layer of yellow phosphor on top of the blue LED he was able to produce the first white LED. By 1996, Nichia developed the first white LED based on a blue monochromatic light and a YAG down-converter. Figure 55 illustrates the evolution in the conversion efficacy of different lighting technologies since the mid 19th century. Today, red and green LED efficacies are as good or better than fluorescent and high intensity discharge technologies. Commercialized white solid-state lighting is expected to reach those levels in just the next few years, and still is far from reaching theoretical limits that have already constrained future improvements in incandescent and fluorescent lamps.

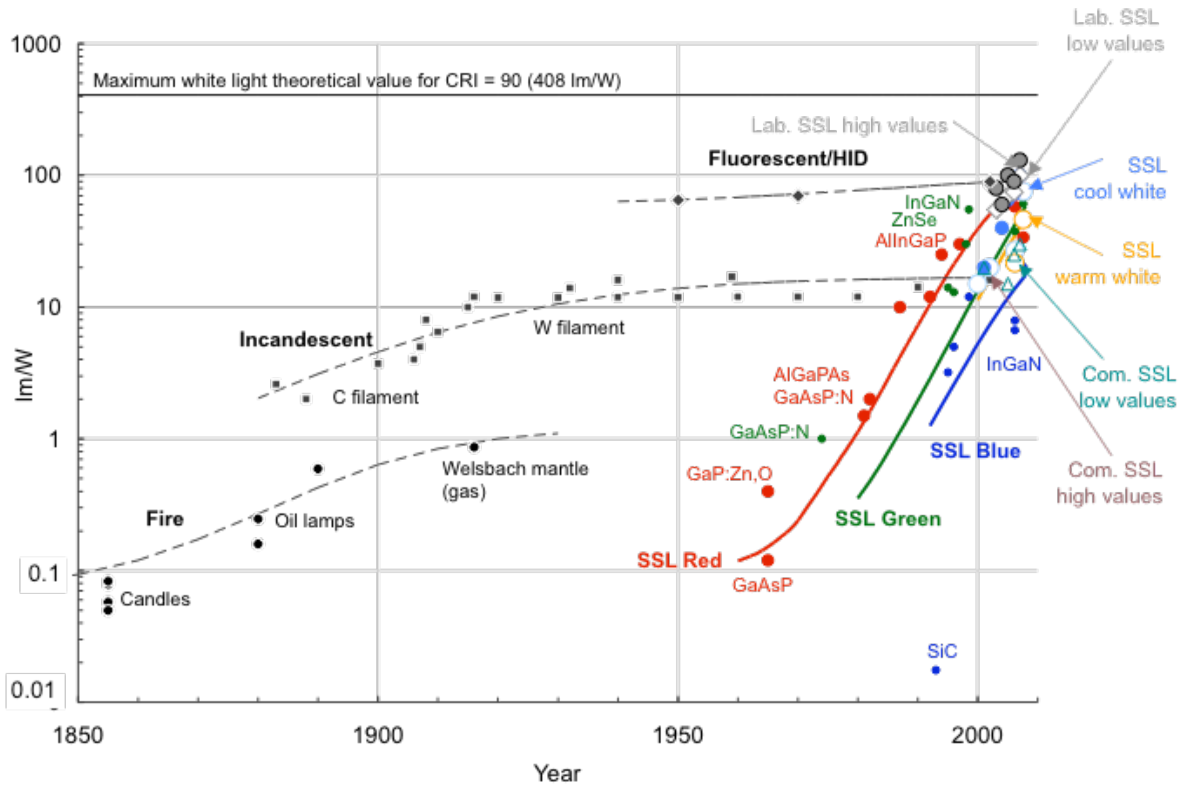


Figure 55 – Efficacies of selected lighting technologies between 1850 and 2006. Values for fire, incandescence, fluorescence, high intensity discharge (HID) and red, blue and green solid-state lighting (SSL) provided by Jeffery Y. Tsao of Sandia National Laboratory. White LED values adapted from [30], [31]. Lab. = Laboratory; Com = Commercial. Efficacies are a function of the wattage, which is not shown in this figure. The theoretical limit for white light for a CRI of< 90 is defined as in [35].

Chapter 3. Lighting Systems Characteristics

3.1 Efficiency and Lifetime

The efficiency with which a system converts useful energy into a desired service such as transportation, heating, cooling or light, can be a useful metric. However, efficiency in its own right is not the primary concern of most individual consumers or of society as a whole. Consumers and policy makers care about cost, about non-market externalities such as environmental pollution and energy security, and about a variety of service attributes. In the case of illumination, one of the services attributes of great interest is the quality of the light.

For much of the past century the price of electricity was continuously declining. There were also relatively low levels of concern about the local and global environmental consequences of generating electricity and most fuel came from domestic sources. In such circumstances, highly inefficient incandescent lamps were a perfectly acceptable source of light. Today, none of those conditions still obtain.

As a result, improving the efficiency with which electricity can be converted into light in a cost-effective way, and with acceptable color balance, has become an important issue for public policy.

In discussions of efficiency, it is important to be careful to compare systems on an equal footing. Too often, the efficiency of an entire lighting system (which includes electronics, source and fixture) gets compared with that of just a source.

Luminous flux, measured in lumen (lm), represents the light power of a source as perceived by the human eye. A monochromatic light source that emits optical power of 1/683 W at 555 nm has a luminous flux of 1 lm [36]. I define device efficacy as the ratio between the luminous flux (in lumens) of light output to the input electric power (in Watts). The device efficacy does not account for losses due to the fixtures. Similarly, I define system efficacy as the overall ratio between luminous flux and input of electric power, but accounting for the losses in the fixture. The distinction between lamp and system efficacy is clearly important, since a high source efficacy is not always an indication of the overall system efficacy. Figure 56 reports the range of efficacies for incandescent, fluorescent and LED sources. The numbers in the central columns report the range of the efficacies of commercial devices. The numbers in the column on the right report overall system efficacy, that is, the amount of light output from the system per watt of 60 Hz AC input power. The numbers on the first and third column represent ballast and fixture efficiencies.

Because lamps produce glare and are esthetically unpleasing, most devices are not used alone. Rather, they are placed in a variety of fixtures. In experimental studies commissioned by Color Kinetics, Inc., ITL Boulder evaluated a number of common fixtures and found that the associated light losses ranged from about 10% to over 60%. The right most columns in Figure 56 degrades the values for incandescent and fluorescent systems, reported in the center column, by those amounts. If LEDs are placed in similar fixture to those in use today, one can anticipate a similar range of fixture losses. However, given that LED systems are only now coming into widespread use, designers have the freedom to develop new fixtures for LED systems with much lower fixture losses. In Figure 56, I have used a minimum fixture loss value of 5%, consistent with the recently released DOE target [31] and a maximum value of 60%, consistent with replacing conventional sources with LED sources in the least efficient existing fixtures.

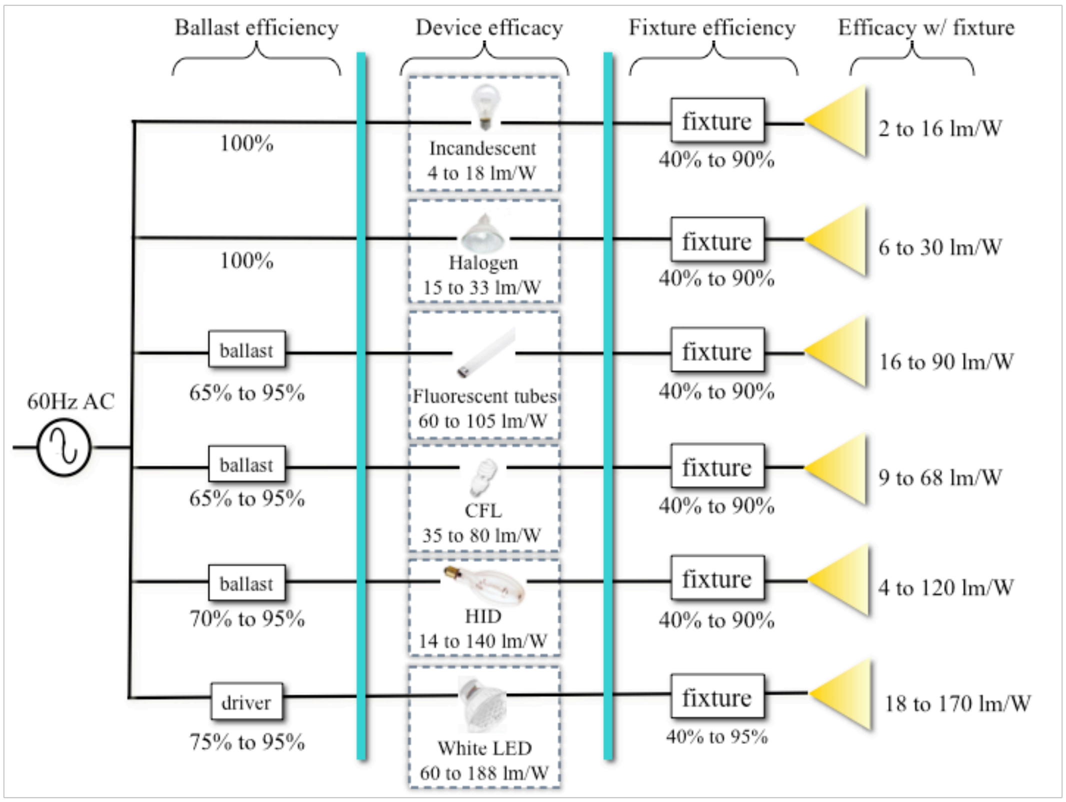


Figure 56 – Efficacy of lighting devices and fixtures. Values in the left-most column report the range of efficiencies for ballasts and electronic drivers. Values in the central column report efficacies for different lighting devices. The values on the third column report ranges of fixture efficiencies. The values on the right-most column report the overall system efficacies of lighting systems. The 188 lumen/W for the LED device efficacy corresponds to the target for white LEDs for 2015 from [30], [31].

The light output of most sources decreases over the course of their lifetime. This decrease in lumen output, or lumen depreciation, varies with technology and results from different factors for each. In the case of incandescent lamps, the lumen depreciation ranges from 10% to 15% of the initial output over the course of the ~1,000 hour lifetime. This mainly results from depletion of the tungsten filament over time and the accumulation of evaporated tungsten particles on the interior surface of the bulb. Fluorescent lamps usually experience less than 20% depreciation over their 10,000-hour lifetime. However, depreciation is generally less than 10% for the case of high quality fluorescent tubes using rare earth phosphors [32]. The lumen depreciation in fluorescent lamps arises from photochemical degradation of the phosphor coating and the glass tube, as well as the accumulation of light-absorbing deposits within the lamp. In the case of LEDs, lumen depreciation is generally due to a poor removal the heat generated at the LED junction, leading to an increase in the lamp temperature, which results in a lower light output. Because of their long lifetimes, the lumen depreciation for white LEDs is still being studied. The DOE Solid-State Lighting CALiPER Program is currently testing several products. Interim results report that seven out of the thirteen products tested were producing over 96% of their initial output after more than 5,000 hours of operation [33]. Of course the overall output from a lighting fixture also depends on how much light is absorbed by the fixture. This fraction can increase over time as glass or plastic covers become dirty and as reflecting surfaces degrade [34].

If fixtures are not regularly cleaned and maintained, this contribution to overall degradation can exceed that of the source.

The efficacy of incandescent lamps has been stable for decades, ranging from 4 to 18 lm/watt depending largely on the wattage of the bulb. Considering the 683 lm/W theoretical maximum efficacy, this translates to only about 0.2% to 2.6% of the electric energy consumed being converted into useful light. These lamps work by heating a metal resistive filament in a glass envelope containing a low-pressure inert gas. The only way to significantly increase efficiency would be to run the filament hotter. Most filaments are made of tungsten, which at 3,695 K, has the highest melting point and lowest evaporation rate of metals. Of course, the filament cannot be run quite that hot. Most bulbs operate at temperatures between 2,000 K and 3,300 K. By replacing the inert gas with a halogen, which limits evaporative loss and deposits tungsten on the filament, the operating temperature can be increased to about 3,450K. So far, no one has developed a practical way to further increase filament operating temperature and efficiency in incandescent bulbs.

Incandescent bulbs fail either as a result of mechanical vibration, which breaks the filament, or as a result of evaporation of tungsten from the filament. Evaporation can be dramatically increased at hot-spots if the filament is not uniform.

Lifetimes for conventional incandescent bulbs are typically between a few hundred and several thousand hours [3]. Because the halogen gas reduces evaporative losses from the filament, tungsten halogen bulbs can achieve somewhat longer lifetimes.

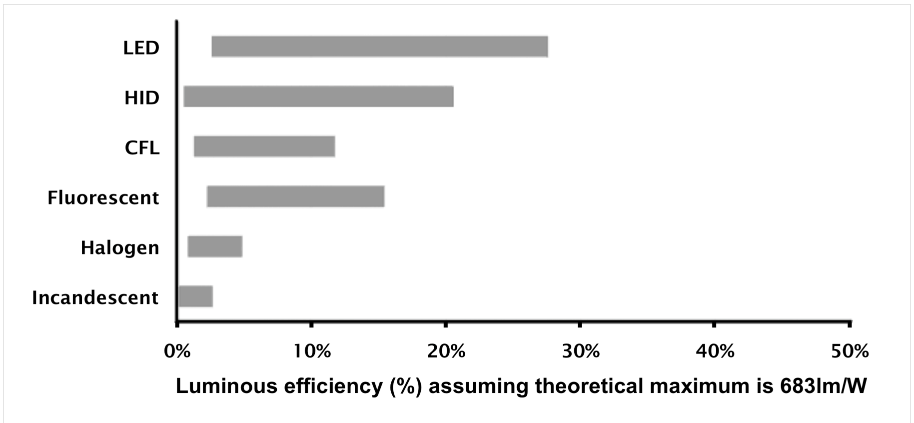
Fluorescent lamps use a stabilized low-pressure gas discharge in a tube of a noble gas and mercury vapor. Electrons ionize mercury atoms, which upon relaxation to their base state emit a photon in the ultraviolet at a wavelength of $253.7x10^{-9}$ m. The interior of the discharge tube is coated with a phosphor that, when irradiated with UV, emits visible light. The current in the discharge must be limited since the resistance of the discharge column drops as the current increases. Typically current is limited through the use of an inductive "ballast" that also often involves an autotransformer to increase the operating voltage. Modern compact fluorescents achieve the same function with solid-state electronics.

Early fluorescent lamps used phosphors that emitted a broad spectrum in the blue, producing "cool" light. Today, the use of mixed phosphors has lead to the creation of fluorescent lamps that produce a "warmer" light (i.e., more emission in the red). Under optimal conditions, accounting for losses both in the conversion of input electrical energy into UV radiation and the conversion of UV into visible light, fluorescent lamps operate with an efficiency of roughly 13% (if one considers the theoretical maximum of 683 lm/W), approximately 5 times higher than the conversion efficiency of incandescent lamps (see Figure 57).

The efficacy of a fluorescent bulb depends heavily on the power: it ranges from 35 lm/W to 40 lm/W for low power units (from 4 W to 5 W), from 75 lm/W to 100 lm/W in bulbs with larger power (from 70 W to 125 W) or electronically ballasts (form 10 W to 60 W). Lifetimes of fluorescent lamps range from 3,000 to 30,000 hours [3].

Failure, or dramatically reduced performance typically results from deterioration of the cathode or its emitting surface. Mercury loss to walls and other internal components, decay in the conversion efficiency of phosphor, and infrequently, failures in electronic components, can also limit lifetime.

(a)



(b)

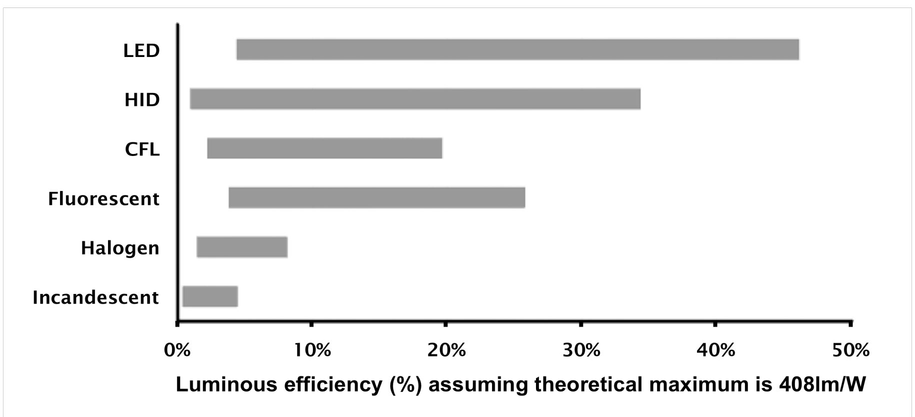


Figure 57 – Overall efficiencies of lighting systems (lower bounds) and devices (upper bounds) when assuming that the theoretical maximum efficacy is either (a) 683 lm/W or (b) 408 lm/W.

Note: LED = light emitting diodes; HID = high intensity discharge lamps; CFL = compact fluorescent lamps.

White LEDs have undergone dramatic improvements in efficacy since they were first developed in 1996 (Figure 55). Today the efficacy of a cool white LED is around 80 lm/W [31]. By 2015 the U.S. Department of Energy is projecting cool white LEDs to be at 174 lm/W [31].

These advancements will come from improvements in internal quantum efficiency (the ratio of injected electrons to emitted photons in the active region), extraction efficiency (the efficiency of extracting generated photons from the active regions out of the packaged part), phosphor advancements and improvements in scattering efficiency (the efficiency of extracting photons from the phosphor vs. all the photons coming from the chip).

Figure 58 outlines the way in which DOE anticipates that a number of these improvements will be achieved. In addition to improvements in efficiency, improvements in packaging are increasing the lifetime of LEDs to 30,000 h to 50,000 hour.

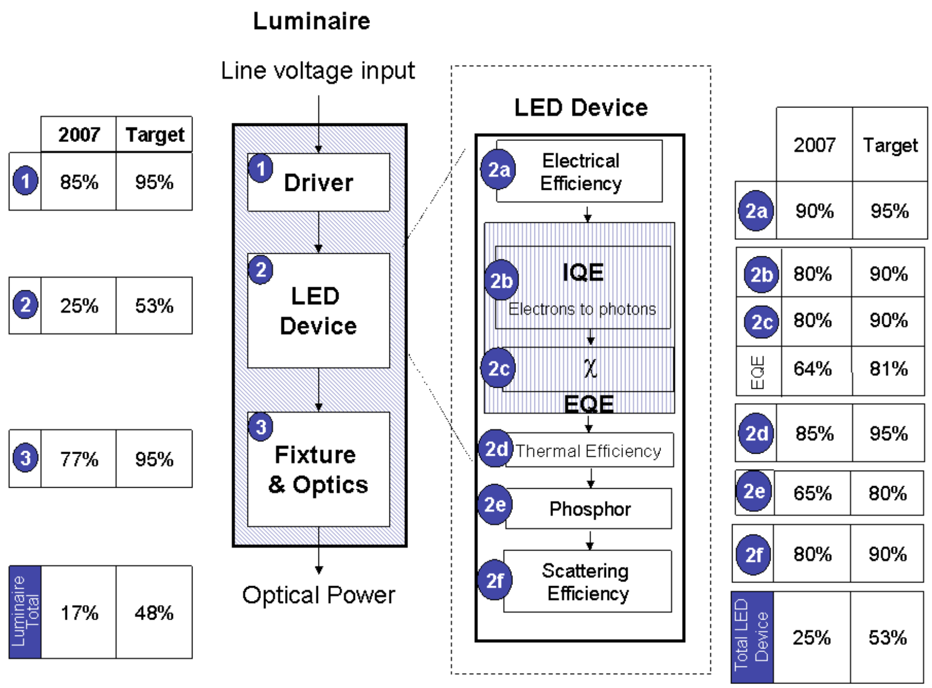


Figure 58 –Phosphor converting LED luminaire efficiencies for 2007 and DOE's 2015 targets for steady state operation. The targets assume a CCT of 4 100 K and CRI of 80. Currently, CCT ranges from 4 100 K to 6 500 K and CRI sands at 75. Figure from [31].

3.2 Color

Efficiency, lifetime and cost are not the only factors that determine adoption of lighting sources. The perceived color of light and the way in which illuminated colored surfaces appear are also important. Indeed, for years this was the principle obstacle to the widespread adoption of compact fluorescents. Solar radiation at the top of the atmosphere has a spectrum that is close to that of a black body with a temperature of 5,500 K. Absorption lines in the ultraviolet resulting from ozone and in the infrared resulting from water vapor, carbon dioxide and other "greenhouse gases" limit much of the radiation that reaches the earth's surface to the "visible spectrum." The curves in Figure 59 compare the spectrum of incident solar radiation and radiation that reaches the surface. Of course, it is no accident that we call much of this spectral range the "visible spectrum" since the human eye evolved in the context of the earth's natural illumination. Photoreceptors in the human eye include three types of cone cells (termed S, M, and L for short, medium, and long wavelength receptors), which produce peak responses when illuminated respectively by light that is violet ($\lambda \approx 420$ - 440×10^{-9} m), yellow-green ($\lambda \approx 534 - 545 \times 10^{-9}$ m) and yellow-amber ($\lambda \approx 564 - 580 \times 10^{-9}$ m). The curve in Figure 60 displays the sensitivity of the human eye, commonly termed $V(\lambda)$, which corresponds to the response of the cone cell M. Maximum sensitivity occurs at $\lambda = 555 \times$

10^{-9} m, in the yellow-green. Note that just as the intensity of surface sunlight falls off dramatically in the violet, so too the sensitivity of the eye falls off rapidly in the violet.

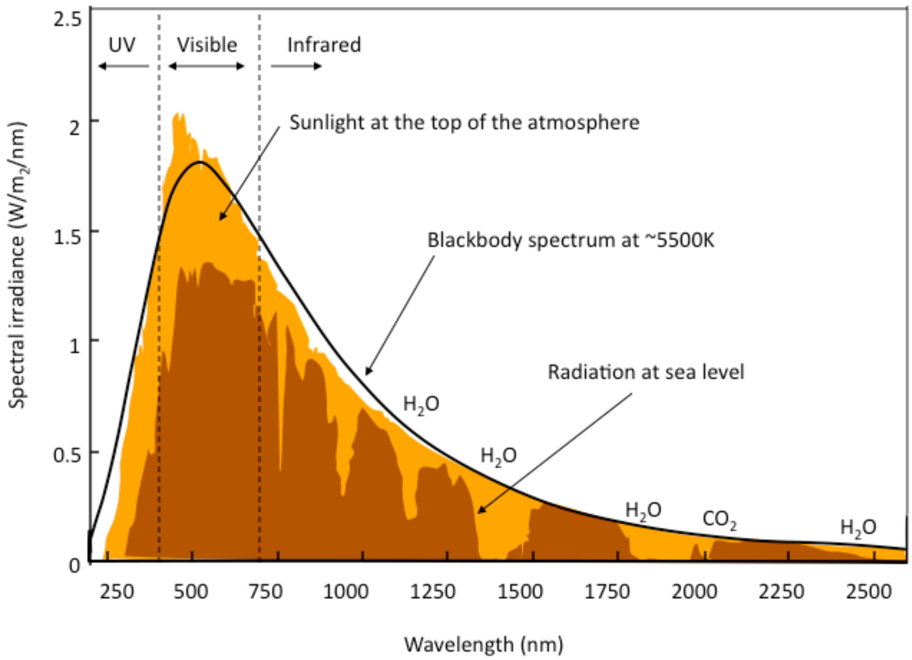


Figure 59 – Solar radiation t the top of the atmosphere (orange) and at the surface (red) as compared with a black body at 5,500 K. Absorption in the UV is by O_3 and in the IR primarily by H_2O and CO_2.

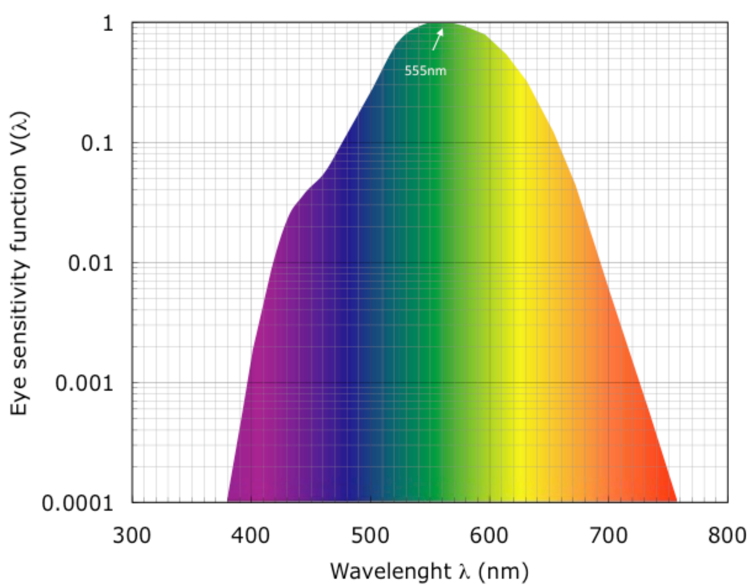


Figure 60 – Sensitivity of the human eye (*V(λ)*) as a function of wavelength (*λ*) across the visible spectrum. Adapted from [37].

LED's that directly produce colored light have narrow spectral outputs ($\approx 20 \times 10^{-9}$ m). By mixing the light from monochromatic blue, green and red LEDs, and adjusting the intensities appropriately, the eye will see what appears to be white light (Figure 61). However, because these sources produce almost no illumination over intervening portions of the visible spectrum, they will not yield properly perceived color if the resulting "white" light is reflected from a surface whose color lies in one of the gaps in the combined spectrum.

A variety of strategies have been devised to describe how well a particular light source renders colors. None does a perfect job of addressing all issues. Perhaps the most common is the color chromaticity space developed by the Commission Internationale de L'Éclairage (CIE) [39]. This two dimensional space (Figure 62) is based on a set of three non-dimensional "color matching functions" that collectively sum to unity. One, termed "y" corresponds to $V(\lambda)$ and the other two correspond more loosely to the response of the S and L cones.

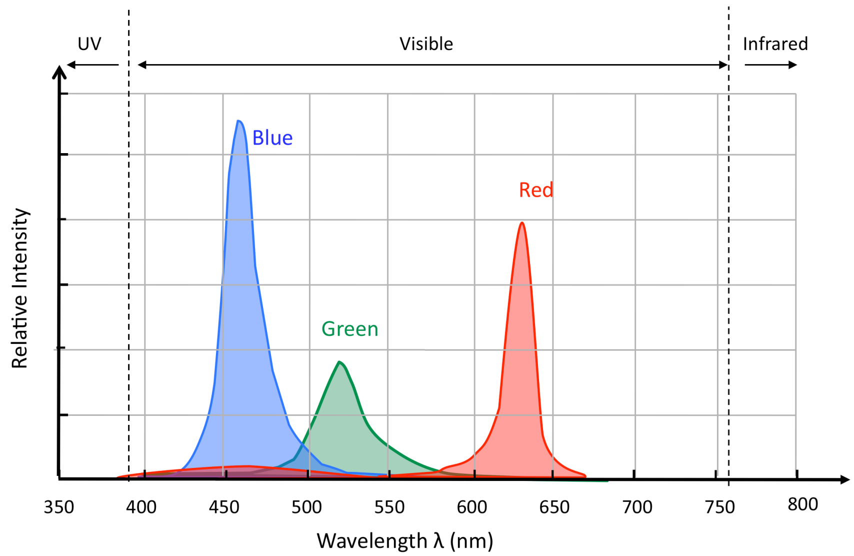


Figure 61 – Typical spectrum of “white” light created by mixing the output of red, green and blue monochromatic LEDs. Adapted from [38]. Relative intensity is represented in arbitrary units.

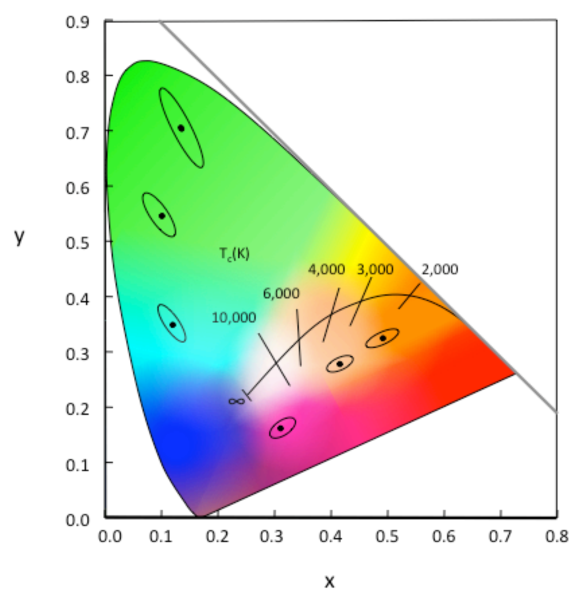


Figure 62 - CIE color chromaticity space. Definitions of the x-y axis are provided in the text. Saturated colors are arrayed along the outside of the arc. Black body emission (Wein’s law) falls along the curved line. The lines crossing the Wein’s law curved line correspond to different “color correlated temperatures”. Ovals are examples of McAdam’s ellipses, enlarged by a factor of 10. Within these ovals the eye does not distinguish color variations. Adapted from [39].

Points around the outside of the CIE space correspond to pure monochromatic colors. White light falls in the center of the space. It is also common to plot the locus of the maximum intensity of radiation from a black body radiator (Wein's law) as a curve through this space. Similar trajectories can be plotted in other spaces commonly used to describe color perception.

Incandescent bulbs produce emission spectra that are close to that of a black body radiator. Thus, it is common to refer to the emissions from such bulbs in terms of a "color temperature." Sources of white light whose spectra are not close to that of a black body are characterized by a "correlated color temperature," according to where they fall on the lines crossing the Wein's law black body emission curve in Figure 62.

The color rendering properties of the light sources of interest in this chapter (i.e. sources with color temperatures ≤ 5 000 K) are measured by illuminating a number of standard color chips with a reference black body source that has the same color temperature as the light source of interest. This is then compared with the result obtained by illuminating an identical color chip with the light source of interest. The distance between the two chips is then observed for a set of standard reference chips. While there are a total of 14 standard chips, historically only eight (or sometimes nine) of the more pastel colors (i.e., colors that lie toward the interior of the CIE color chromaticity space) have been used.

A general color rendering index (CRI) is often computed as:

$$CRI = 100 - 4.6\Delta\overline{CD},$$

where CRI is the general color rendering index and, $\Delta\overline{CD}$ is the average of the distance between the location of the observations in the CIE space (or in various other transformations of that space). The result is normalized so that a source that has a black body spectrum that is the same as that of the reference has a CRI of 100. Other sources then have CRI's that are less than 100. Because the way these other sources render colors may be different for sources with different spectral compositions, two sources with the same CRI may render some colors in notably different ways. This may also mean that in some applications consumers may prefer light from a source with a lower CRI to that from a source with a higher CRI. Using CRI as a measure of light quality means that any deviations of object color appearance from how it appears under a light source with a blackbody spectrum (or any other source used as reference) is considered bad. In practical applications, however, increases in chromatic saturation, may yield better visual clarity and enhance perceived brightness [40].

Recently there has been a move to include the full set of 14 standard chips and include more saturated colors (i.e., that lie toward the exterior of the CIE color chromaticity space) to better include the narrow band properties of some LED sources. Furthermore, the National Institute of Standards and Technology (NIST), is currently working closely with the lighting industry and CIE to develop a new light quality indicator, the Color

Quality Scale (CQS). This scale will include several aspects of color quality, namely color rendering, chromatic discrimination, and observer preferences [40].

To make white light with reasonable color rending properties using LEDs, one of the current strategies is to add one or more phosphors that absorb photons from a monochromatic LED and then reradiate photons of lower energy across the visible spectrum. Figure 63 and Figure 64 illustrate two device geometries. The latter displays a design from Philips Lumileds that uses a conformal coating process that eliminates the blue-ring effect (blue light from the LED driver that makes it through, largely around the outside).

The simplest strategy to produce the appearance of white light is to use a blue or violet LED and design the phosphor layer so that some of the light energy from the LED passes through the phosphor. By adjusting the relative amount of direct radiation from the LED that passes through the phosphor, it is possible to shift the output through the white region of the CIE color chromaticity space. By adding additional types of phosphors somewhat flatter spectra can be produced across the visible range, with improved color rendering characteristics.

A region within the CIE color chromaticity space across which the eye is not able to distinguish a difference in color are termed a MacAdam ellipse, where the examples of ellipses shown in Figure 62 have been enlarged by a factor of 10). The size of this region is relatively large in the green upper portion of the space, but becomes quite small in the lower portions of the space, including in the white light regions, where the long axis lies roughly tangent to the curve of black body spectra. This means that human observers can readily detect even small vertical variations in the light, either upwards toward the green or downwards toward the red in this space.

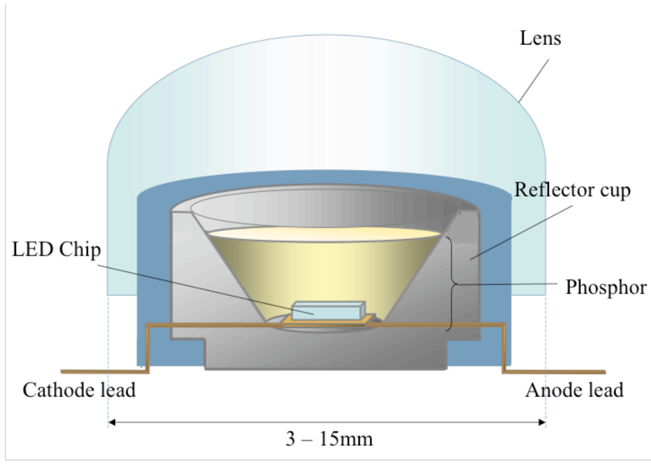


Figure 63 - UV-phosphor based white light emitting diode.

A phosphor or a mixture of phosphors fills the reflector cut. To produce the appearance of white light, phosphors absorb the UV-Purple light and reradiate photons of lower energy across the visible spectrum.

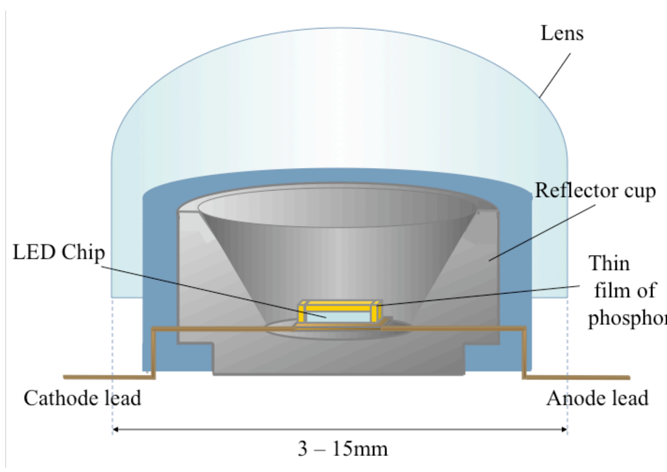


Figure 64 – UV-phosphor based white light emitting diode.

To eliminate a blue-ring effect, a conformal coating process is used (thin film of phosphor). To produce the appearance of white light, phosphors absorb the UV-Purple light and reradiate photons of lower energy across the visible spectrum.

This high human sensitivity complicates the problem faced by LED manufactures. Today blue LEDs are made of indium gallium nitride (InGaN) containing quantum wells that facilitate the recombination of electrons and holes, resulting in the release of photons of blue or green light.[51] The color of the photons emitted depends upon the amount of indium (or other materials) that has been added.

Current fabrication methods do not allow perfect control of the composition or distribution of these materials across the 2-4 inch wafer on which large numbers of LEDs are simultaneously grown. Hence, once they have been completed and cut (diced) into separate devices, each LED must be individually tested, their emission measured, and sorted into bins. This, of course, adds considerably to the cost of the device.

To make a white LED one or a mixture of several types of phosphor are deposited onto the LED during the packaging process. The composition of these phosphors, and their deposition, is also not perfectly uniform. Hence, after the devices are packaged, a second round of binning is done to sort by spectral output[52].

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[51] These materials develop a significant number of dislocations, and there is ongoing uncertainty about why GaN-based LEDs are able to emit brilliant light with dislocations densities as high as 10^9 cm^{-2}. For details see [28].

[52] For examples of binning of white LEDs see pp. 5 of [41] and pp. 22 of [42].

Figure 65 compares typical spectra from a white LED with an incandescent lamp, and a fluorescent lamp. In an incandescent lamp, the heated filament radiates with approximately the Planck black body spectral distribution (slightly blue-shifted). Because of the limit on the temperature at which the filament can be operated, the peak output is in the infrared, at a wavelength of about 10^{-6} m, and the spectrum across the visible range is steeply sloped toward the red.

In contrast, early fluorescent lamps with just one phosphor tended to produce color that was bluer. Warmer fluorescent lamps use phosphors that yield an emission spectrum that produce relatively more light in the red, resulting in a “warmer" light.”

Many people prefer warmer light (i.e. light with more red), especially for illuminating pale skin [43]. Thus, morning and evening outdoor light, which is more red due to the filtering effect of the longer path through the atmosphere and the associated scattering by fine aerosols, is typically preferred by many to the flatter spectrum of mid-day sun. In the U.S. and Europe, where many people have pale skin, the temperature of white light from TV monitors is set at 6,500 K. In contrast, in Japan the temperature is moved to 9,300 K. This may also be one reason why illumination by incandescent light, which is peaked toward the red, remains more popular in North America than in Japan.

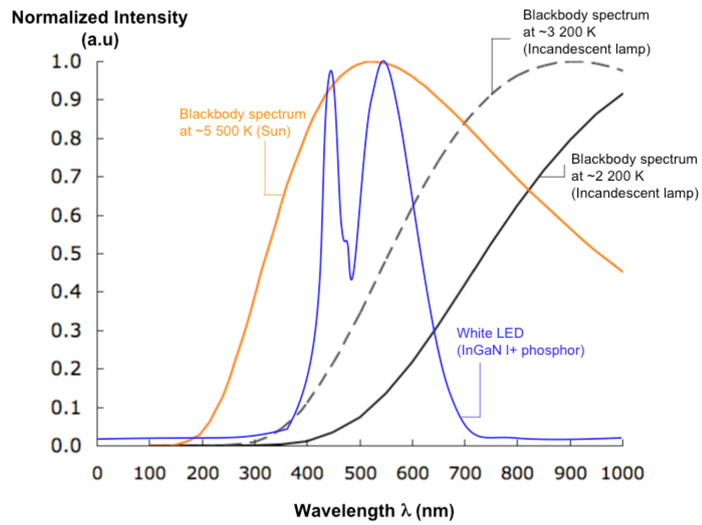

Figure 65 – Normalized intensity in arbitrary units (a.u.) for a blackbody radiator at 5 500 K (Sun), for a blackbody radiator at 3 200 K (warm white incandescent lamp), for a blackbody radiator at 2 200 K (cooler white incandescent lamps) and for a white LED, where the perceptions of white light is achieved using a blue LED + phosphor.

3.3 Comparison of the Key Characteristics of Lighting Technologies

Table 35 provides comparison of the principle characteristics of commercially available lamps, including the technologies discussed above.

Table 35 – Main characteristics of lamps.

Lamp	**Type**	**Power (W)**	**Efficacy (lumen/W)**	**Lifetime (thousand h)**	**CCT (K)**	**CRI**
INC	-	3 - 150	4 - 18	1	2 400 – 3 100	98 - 100
Halogen	-		15 - 33	2 - 6	3 000 – 3 100	98 - 100
HID	-	40 - 400	14 - 140	6 - 28	2 900 – 5 700	15 - 62
LID	LPNa	26 - 180	70 - 200	7.5 - 30	1 700 - 7 500	75 - 95
	T12	14 - 90	60 - 105	7 - 20	3 000 – 6 500	62 - 75
	T8				3 000 – 6 500	75 - 98
	T5				3 000 – 6 500	75
CFL	*ballasts integrated*	4 – 120	35 - 80	5 – 15	3 000 – 6 500	75 - 90
CFL	*external ballasts*	40 - 95	60 - 80	10 – 20	2 700 – 6 500	80 - 85
White SSL	LED	1 - 20	160 (lab), 20 - 55	20 - 40	5 000 – 6 000	70 - 80
	OLED	1 - 20	<18	<4	3 000 – 6 000	~80

Notes: INC = Incandescent; HID = High Intensity Discharge; LID = Low Intensity Discharge; LP Na = Low Pressure Sodium; CFL = Compact Fluorescent Lamps; SSL = Solid-state Lighting; LED = Light Emitting Diodes; OLED = Organic Light Emitting Diodes; CRI = Color Rendering Index; CCT = Correlated Color Temperature. Sources: [3], [30], [31], [44] and, [45].

3.4 RF Noise and Flicker

The switched-mode power supplies used for LED lights, the electronics used in compact fluorescents, and the dimmer switches used with incandescent bulbs all emit high frequency electromagnetic radiation and impose high frequency waveforms on power lines. While these RF emissions are typically not a problem, in some situations they can be problematic, and the growing use of such electronics means that the issue warrants continued attention.

The Federal Communications Commission (FCC) and other national regulatory bodies are concerned about interference due to radiated emissions in the communication bands between approximately 3 MHz and 1 GHz for radiated emissions and conducted emissions for those between approximately 150 kHz to 30 MHz. Manufactures are required to test the emissions from their lamp systems to ensure that they do not produce radiated or conducted emissions as defined by internationally harmonized standard EN55022 [46].

Because the filament in an incandescent bulb has considerable thermal inertia, dimmers that use a chopped waveform typically do not produce noticeable flicker. Flicker is sometimes visible (especially to younger eyes) from fluorescent bulbs, and can be a greater problem with 50 Hz power (100 Hz flicker) than with 60 Hz power (120 Hz flicker). Flicker can also be observed from some LED systems, but can be reduced with careful power supply design.

Flicker index is a ratio that has been established to measure the variations in output of a source. It is defined as the ratio of the area of the waveform of light output that lies above the average light level divided by the total area of the waveform of light output over one cycle and is expressed as a number between 0 and 1. The Illumination Engineering Society of North America (IESNA) recommends that flicker index be held below 0.1 to minimize any perceptible flicker from light [47]. With the proper regulations and control of the output stage of a switch mode supply, solid-state lighting systems can easily be developed to achieve these levels.

Chapter 4. Expected Evolution of White LEDs

Because light emitting diodes technology is rapidly evolving, projections of solid-state lighting efficacy, cost and lifetime are frequently updated. Haitz and his co-authors [48] note that since the invention of the red LEDs in the late 1960s, light output has increased by roughly a factor of 20 every decade while the cost per lumen has fallen by about a factor of 10. The same trends seem to be followed by white LEDs. Several projections are available of how white LEDs are likely to perform in the near future (see Figure 66, Figure 67) [30], [31], [44], [45]. Today, in the laboratory, solid-state lightings have reached efficacies of 160 lm/W [49] whereas commercialized SSLs have efficacies of 20-56 lm/W, last between 30,000 and 50 000 hours and cost 47 $/klm [30], [31]. Figure 66 summarizes the efficacy values achieved by white LEDs as well as projections of the likely future efficacies.

According to DOE 2006 targets [30], the lifetime of commercial cold white lamps is expected to increase linearly from 30,000 hours to 50,000 hours between 2005 and 2008, and remain at 50,000 hours thereafter. There are also ranges of cost projections as shown in Figure 67. The prices and efficacies in DOE 2006 targets [30] assume that white LED devices are operating at a correlated color temperature (CCT) of approximately 5,000 K to 6,000 K and a color-rendering index (CRI) of 70 or higher.

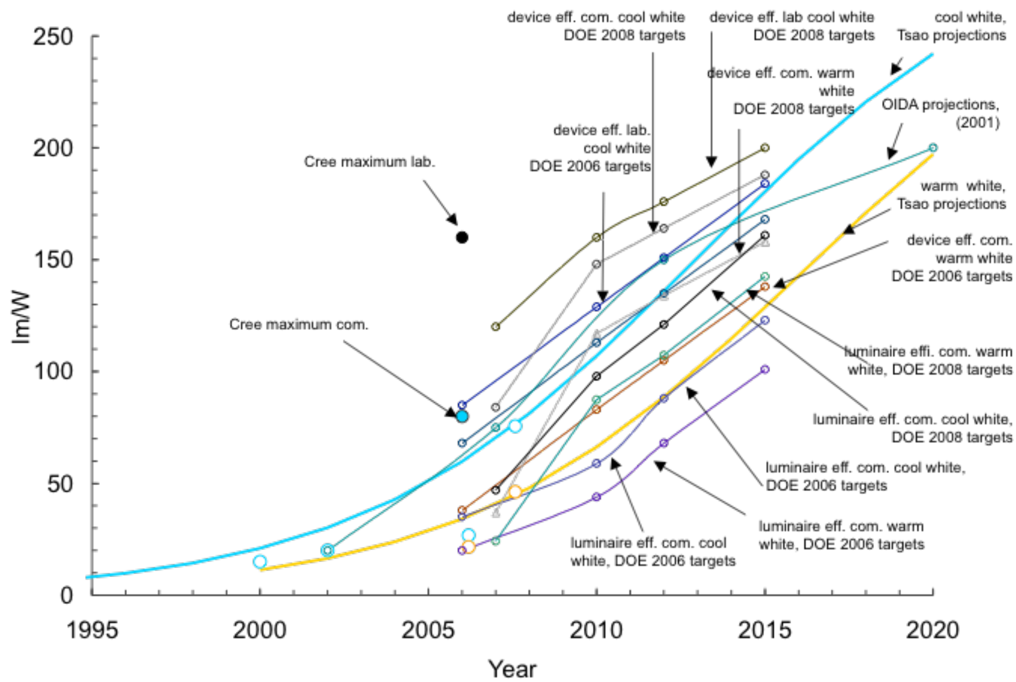

Figure 66 - Laboratory and commercial efficacy projections for cold and warm white LEDs. Constructed with from projections made by OIDA [45], DOE [30][31] and Tsao [44].

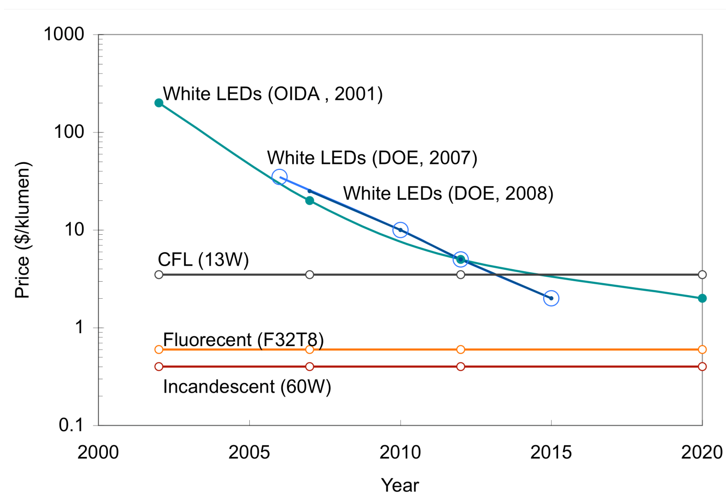

Figure 67 - White light LED OEM price targets for commercial applications. DOE efficacy and cost projections assume a CRI between 70 and 80, a CCT between 5,000 K and 6,000 K, a 350 ma drive current. Results are for devices alone (driver and luminaire costs are not included). Data adapted from [30], [31], [45].

Chapter 5. Choice of Lighting Technologies

There are several metrics that can be used to estimate the cost of light supplied by different lighting systems. DOE [30], [31] and participants in the solid-state lighting program generally refer to the upfront cost ($/klumen) and to the "cost of light" metric. The cost of light is defined as:

$$\mathit{Cost\ of\ light} = \left(\frac{10}{\mathit{lamp\ lumens}}\right) \times \left(\frac{\mathit{lamp\ cost} + \mathit{labor\ cost}}{\mathit{lifetime}} + \mathit{energy\ use} \times \mathit{energy\ cost}\right),$$

where *lamp lumens* is the light output of the lamp in lumens, *lamp cost* is the initial cost of the lamp in $/lamp, *labor cost* is the labor cost necessary to replace the lamp in $/lamp, *lifetime* is the theoretical lifetime of the lamp in thousands of hours, *energy use* is the power consumption of the lamp in W/lamp, and *energy cost* is the cost of electricity in $/kWh.

By this metric, today's solid-state lighting is already cheaper (20 $/Mlmh) than incandescent (27 $/Mlmh) or halogen lamps (23 $/Mlmh) [30], [50]. However, this metric is inadequate because it does not consider the hours of operation of the technology, or the time value of money.

Mishan [51] and Rubin and Davidson [52] provide descriptions of different decision rules and the appropriate discount rates to use under different circumstances. In a standard approach, the discount rate will depend on the alternative opportunities open to the decision maker. While the explanation provided by Mishan [51] and others is appropriate for investment choices by economically rational actors, it does not explain why decision makers at the commercial and residential level are often slow to voluntarily adopt energy efficient products such as CFLs.

To incorporate the time value of money, a discounted utility model can be used. However, the most widely used model, developed by Samuelson, lacks descriptive realism - which Samuelson himself acknowledged [53]. Other authors [54] argue that there is little empirical behavioral support for using the discounted utility model, although it continues to be widely used by economists. For example, Sanstad and Howarth [55], [56] argue that the mathematical formalism of economic rationality provides the basis for economic models of consumer behavior but is generally not subjected to empirical testing. The main argument for discounted utility theory comes from Friedman [57], who states that people may not actually solve complicated problems of utility maximization, they just behave *as if they do.* Thus, it is argued, that the models provide a good description of observed behavior. Goett [58] uses this argument to explain the use of the levelized annual cost calculations in modeling consumer decisions regarding energy-efficiency by stating that implicit discount rates "*do not simply reflect a conscious, mental calculation of the cost tradeoffs among alternative technologies. Rather, they summarize an amalgam of market forces that determine consumers' actual choices*".

In the analysis that follows, we separately assess private and societal costs. Additional considerations must be added when selecting lighting from a societal perspective, where important factors include reducing emissions of conventional pollution and CO_2, reducing need for new construction, and reducing dependence on imported fuels.

From behavioral studies on consumer choice it is possible to infer the effective discount rates employed. These implicit rates are typically *much* higher than market rates, as high as 300 % for residential consumers and up to 30 % for commercial consumers. In contrast, decisions made by government in the public interest, typically employ a discount rate that ranges between 2.5 % and 10 % [59].

Table 36 – Average implicit discount rates adopted by consumers for energy-efficiency investments (adapted from [54],[55]).

End use	**Implicit discount rate**
Air conditioners	17 % - 20 % [60]
Heaters	102 % [61]; 25 % [62]
Freezers	138 % [61]
Refrigerators	from 45 % to 300 % [63]; from 61% to 108 % [64]; from 34 % to 58 % [65]
Thermal shell measure	32 % [66]; 26 % [64]

There is mixed evidence on the role of income on the discount rates. As Socolow [70] complained, "we still know pitifully little about the determinants of durability of hardware and even less about the determinants of durability of attitudes and behavior" [16]. Hausman [60] found implicit discount rates that varied markedly with income. However, in another study, Houston [67] presented individuals with a decision of whether to purchase a hypothetical *energy-saving* device, and *no statistically significant role of income was observed* [54]. Implicit discount rates embody a variety of factors including:

- Lack of knowledge by consumers about available technologies and the cost savings that could be achieved [54];
- Disbelief among consumers that the cost savings will be as great as promised [54];
- Lack of expertise in translating available information into economically efficient decisions [54];
- Hidden costs of the more efficient appliances, such as reduced convenience or reliability [54];
- The role of the availability heuristic [68] when an earlier attempt by the consumer or others to use the technology did not fulfill expectations;
- The role of marketing and advertisement in promoting different technologies;
- Dominance of retail sales staff and issues of product selection and promotion [69];
- The tendency of many architects, designers and builders to only use products and processes with which they are already familiar; and,
- Lack of information concerning electricity prices and hours of use of the technology.

A recent NRC study [71] concluded that requirements for solid-state lighting to overcome market barriers include:

- An upfront cost of < 33 $/klumen - which according to DOE [30] should be reached in 2008; lifetimes of 50 000 hours – which again, according to DOE [30], should be reached by 2008; a 70% of lumen output by the end of life and a CRI between 80 and 100.
- "Building and lighting infrastructures available for installation, known standardized equipment specifications, information available to the lighting industry and information to support interior design needs".

In addition to their different time preferences, residential consumers typically use much of their illumination only few hours a day, while commercial consumers average 10h/day. Since the different illumination technologies considered have substantially different lifetimes, we compare them using levelized annual cost, rather than net present value. We define levelized annual cost (LAC) in dollars per year as:

$$LAC = I\frac{d}{(1-(1+d)^{-n})} + O\&M ,$$

where I is the initial capital investment in the lighting system in dollar, d is the discount rate, n is the number of years that the technology lasts, and $O\&M$ is the expected annualized cost of operation and maintenance in dollars.

Chapter 6. The Cost of Light

Given the expected performance of different lighting technologies over the period from 2008 to 2015, the choice of lighting technologies by rational economic actors will depend on conversion efficacy, upfront cost, lamp lifetime, and lamp usage. I assume DOE [30],[31] values for future white LED system efficacy, OEM upfront costs and lifetimes. Assumptions about alternative lighting technologies are shown in Table 42.

. I also assume that all technologies will be chosen so as to provide the same illumination level no matter the choice of the technology. Incandescent and fluorescent technologies are taken as mature and are not changed over the course of the analysis.

Lifetime depends on the amount of usage. For example, I assume that an incandescent lamp with a theoretical lifetime of 1,000 h that is used 2 h/day will last roughly one year and four months. In this calculation I also assume that the consumer replaces all old lamps with new lamps of the same kind.

In doing engineering-economic analysis from the perspective of a consumer driver costs should be included and OEM prices should be marked up to reflect retail prices.

However, the DOE OEM cost trends already appear to match full system retail LED prices (including driver and luminaire). Thus, I use the DOE projections as an estimate of future retail LED system prices. In the sensitivity analysis that follows we explore how additional markup prices as high as 30% on top of DOE's projected OEM prices would delay consumers' decisions to adopt white LEDs.

Table 37 – Assumptions of key characteristics of mature lighting technologies.

		Efficacy (lm/W)	Lifetime (h)	Lumen Output (lm)	Power (W/lamp)	Service Cost ($/thousand *lm*)	Lamp Cost ($/lamp)
Incandescent		14	1 000	926	65	0.5	0.5
Compact fluorescent lamp (CFL)		69	8 000	926	13	4.3	4
Fluorescent tube (T12)		69	5 000	926	13	2	2
Fluorescent tube (T8)		92	12 000	926	10	2	2
Fluorescent tube (T5)		104	20 000	926	9	2	2
Solid-State Lighting (System Level, Warm White)	Targets from DOE for 2008	47 (cool) 27 (warm)	50 000	926	13	25	23
	Targets from DOE for 2015	137 (cool) 117 (warm)	50 000	926	7	3	3

Note: sources for lamp typical characteristics from [30],[31],[44],[45] and, [50]. For solid-state lighting, we used OEM prices for the lamp retail costs. “Cool” and “Warm” mean “cool white” and “warm white” as defined by DOE [30],[31].

6.1 Rational Economic Actor

I start by looking at the engineering-economic analysis for lighting technology choice for a commercial building owner. For this case, I assume a daily operation of 10 h/day and a 5% market discount rate, Figure 68. The results show that the levelized annual cost of a cool white solid-state lighting investment today is less than half that of an incandescent and is about to reach that of CFLs and fluorescent tubes. The levelized annual cost for warm white light solid-state lighting is also substantially lower than incandescent lamps. Solid-state lighting is likely to reach the cost of the most competitive fluorescent technologies before 2015. Note that even assuming discount rates as high as 20%, solid-state lighting has a lower levelized annual cost than incandescent lamps, and is the same as the levelized annual cost of fluorescent lamps by 2009. However, if the commercial consumer only considers upfront costs (either in $/klm or $/lamp – assuming the lamps will provide the same total lumens), a switch to solid-state lighting will not be made in the near future, since the costs of solid-state lighting luminaries is only projected to reach that of fluorescent lamps by 2013 (Figure 69).

We conclude from this analysis that rational economic actors in the commercial sector now using incandescent bulbs would find it cost effective to switch to solid-state lighting today. Given that most of the illumination in the commercial sector is provided by fluorescent technology, commercial building owners should begin to think about switching to solid-state lighting in just the next few years.

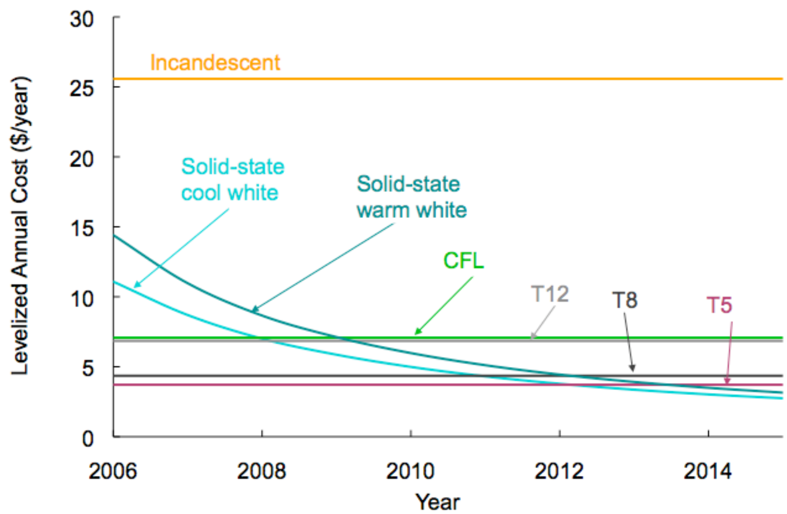

Figure 68 – Levelized annual cost for different lighting technologies (incandescent, CFLs, T12, T8, T5 and cool and warm white solid-state lighting). I assume an electricity retail price of 0.10 $/kWh, lamps are used 10 h/day and a discount rate of 5%.

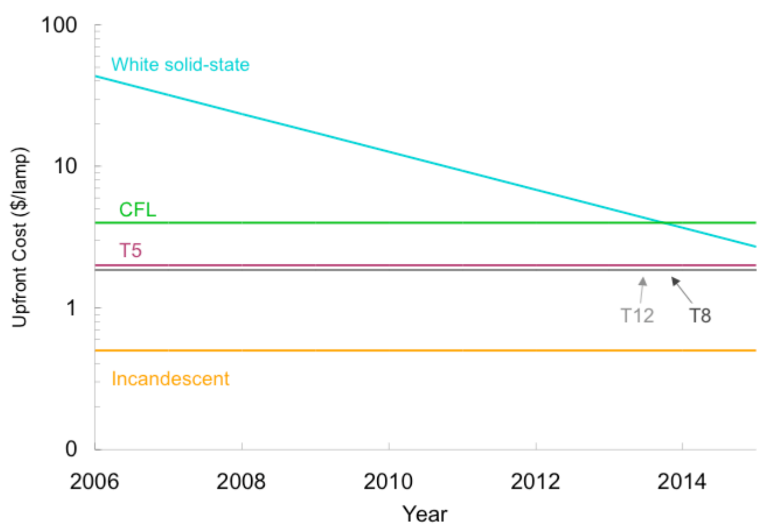

Figure 69 – Upfront cost for different lighting technologies (incandescent, CFLs, T12, T8, T5 and cool and warm white solid-state lighting).

6.2 Effect of High Implicit Discount Rates

In performing a similar analysis for an average household, we assume a discount rate of 20% in recognition of the body of literature on implicit discount rates. We conclude that considering high implicit discount rates, and a daily usage of 2 hours, solid-state lighting will have a lower levelized annual costs than incandescent lamps this year and lower than CFLs by 2012, if they can be purchased at DOEs' projected prices (stated as OEM, but today closer to retail). Retail markups above these prices will delay these times by a few years, as indicated in the sensitivity analysis that follows. We conclude that, in less than a decade, residential consumers should think about switching to solid-state lighting.

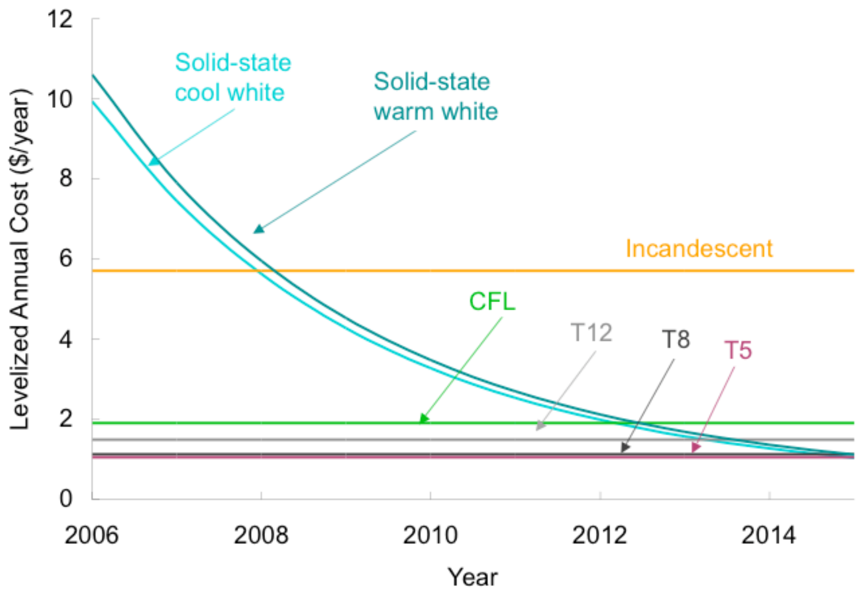

Figure 70 – Levelized annual cost for different lighting technologies (incandescent, CFLs, T12, T8, T5 and cool and warm white solid-state lighting). I assume an electricity retail price of 0.10 $/kWh, a discount rate of 20% and a daily usage of 2 h/day.

6.3 Sensitivity Analysis

There is large uncertainty about the likely future mix of luminaries, their wattage, hours of operation hours, future electricity prices, consumer adoption behavior, and how solid-state lighting cost and performance will evolve over time. Figure 71 reports the sensitivity of the levelized annual cost of white LEDs in 2010 to variations in luminous efficacy, lifetime, cost, electricity price, discount rate, and the number of hours of operation. Across the same range of values, Figure 72 reports the difference between the levelized annual cost of white LEDs and incandescent lamps. A negative levelized annual cost corresponds to a lower cost for, and less energy use by the consumer, since the levelized annual cost of switching to the new technology is lower then an investment in the current technology.

These results indicate that, across this wide range of assumptions, by 2010 solid-state light is a better investment than incandescent lamps even assuming a high discount rate (20%) and using a lamp only 3 h/day. The levelized annual cost of solid-state lighting is very sensitive to the luminous efficacy achieved by solid-state lighting for values lower than ~46 lumen/W, but changes less than a dollar after reaching that efficacy, a level already exceeded in 2006. Above a lifetime of 12,000 hours, the levelized annual cost becomes quite insensitive to the theoretical lifetime of solid-state lighting. Again, this threshold was reached in 2002. The feature that remains most critical to achieve a competitive level for solid-state lighting is the initial cost. Even assuming a markup as high as 50% on top of the projected price, by 2010 solid-state lighting is a better option then incandescent lamps (see Figure 72).

Some might argue that only solid-state lighting should be subjected to high implicit discount rates, since other technologies are well established in the market. In a simulation with this assumption, we found that if solid-state lighting is subjected to discounts rates as high as 30% with choices about the remaining technologies based on discount rates as low as 3%, the choices about solid-state lighting occurs with a lag of at most two years compared to the previous scenario. This result is largely due to the high upfront cost and the rapid rate at which the technology is evolving. For example, if a lamp is only used 2 hr/day, with a discount rate of 30% on just the new technology, the LAC of solid-state lighting is lower than that of incandescent by 2009 and reaches CFL and fluorescent levels by 2015.

Despite DOE targets [30],[31], there is considerable uncertainty about how commercial solid-state lighting technology will perform over time. For this reason we have performed a parametric analysis of the levelized annual costs for solid-state lighting technologies for different values of inputs using a matrix model as illustrated in Figure 73.

The advantage of the full parametric model is that it can account for new and unexpected pathways in the evolution of the technology and its economic performance. Given a set of initial inputs, the model provides a contour plots of the levelized annual cost (Figure

74), providing a very effective way to determine the implications of changes in the solid-state lighting technology performance in key characteristics.

In Figure 74 we present the levelized annual cost for solid-state lighting under different assumptions for efficacy (lm/W), theoretical lifetime (h), discount rate (%) and usage (h/day). Upper plots correspond to levelized annual cost surfaces and lower plots are the respective contour plots.

In (a) we present the levelized annual cost for a 926 lumen solid-state lighting bulb (typical light output of a 60 W incandescent bulb), as a function of efficacy (lumen/W) and theoretical lifetime (hours). For that case, we assumed that the upfront-cost of solid-state lighting remains at 14 $/klumen. In (b) we present the levelized annual cost for one solid-state lighting bulb with an illumination service of 926 lm, as function of efficacy (lumen/W) and upfront cost ($/klumen) for a theoretical lifetime of 30 000 hours. The joint results of (a) and (b) suggest that from the perspective of consumer adoption, increases in efficacy performance from solid-state lighting are likely to be more important then increases in lifetime. Moreover, after reaching efficacies of 40 lumen/W, reductions in cost are likely to be more important for reducing the levelized annual cost than increases in efficacy. We have assumed an electricity price of 0.10 $/kWh, a usage of 2 h/day and a discount rate of 10%.

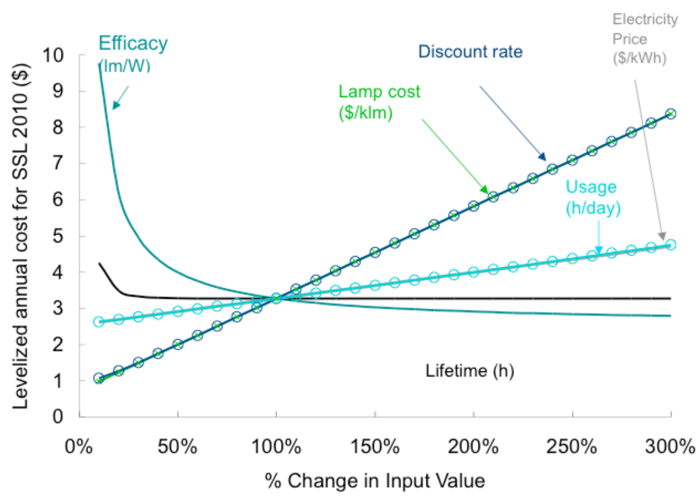

Figure 71 - Sensitivity analysis for the main parameters of the engineering-economic simulation of the levelized annual cost of cool white solid-state lighting in 2010. The 100% values correspond to an electricity price of 0.10 $/kWh, operation of 2 h/day, a 20% discount rate, a luminous efficacy of 92 lm/W and, a theoretical solid-state lighting lifetime of 50 000 hours.

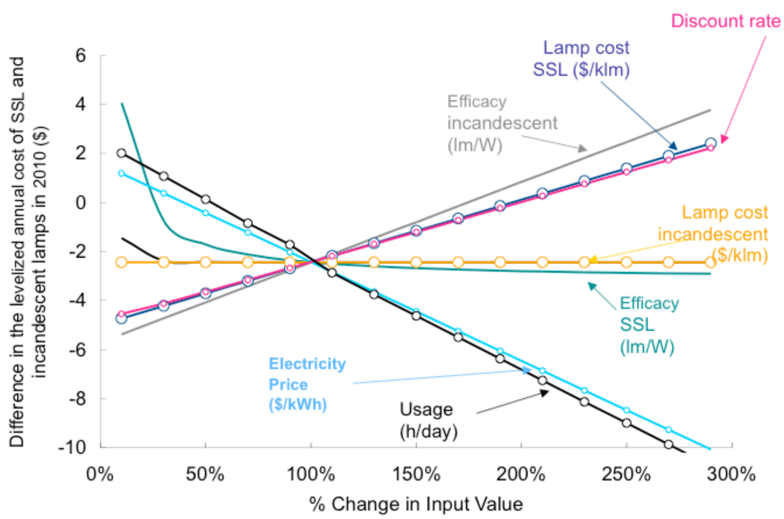

Figure 72 – Sensitivity analysis for the main parameters of the engineering-economic simulation of the difference between the levelized annual cost of cool white solid-state light and incandescent light in 2010. The 100% values correspond to an electricity price of 0.10 $/kWh, operation of 2 h/day, a 20% discount rate, a luminous efficacy of 92 lm/W and a theoretical solid-state lighting lifetime of 50 000 hours.

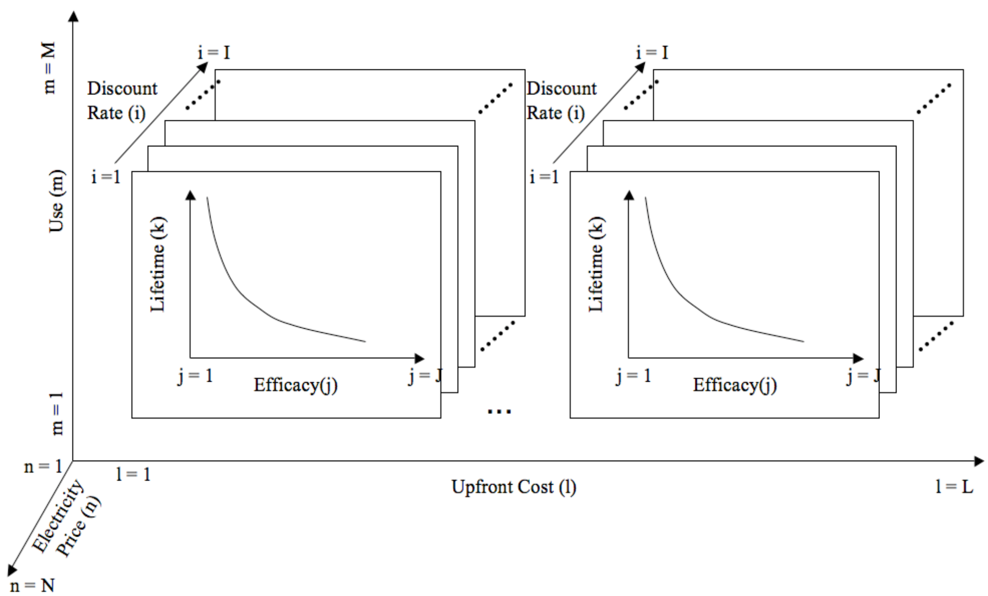

Figure 73 - Representation of the dimensions of the parametric model for levelized annual costs of solid-state lighting, which was designed based on matrices assuming a plausible range of values for electricity price, upfront cost, efficacy, lifetime and discount rate and hours of use. The curves correspond to levelized annual cost.

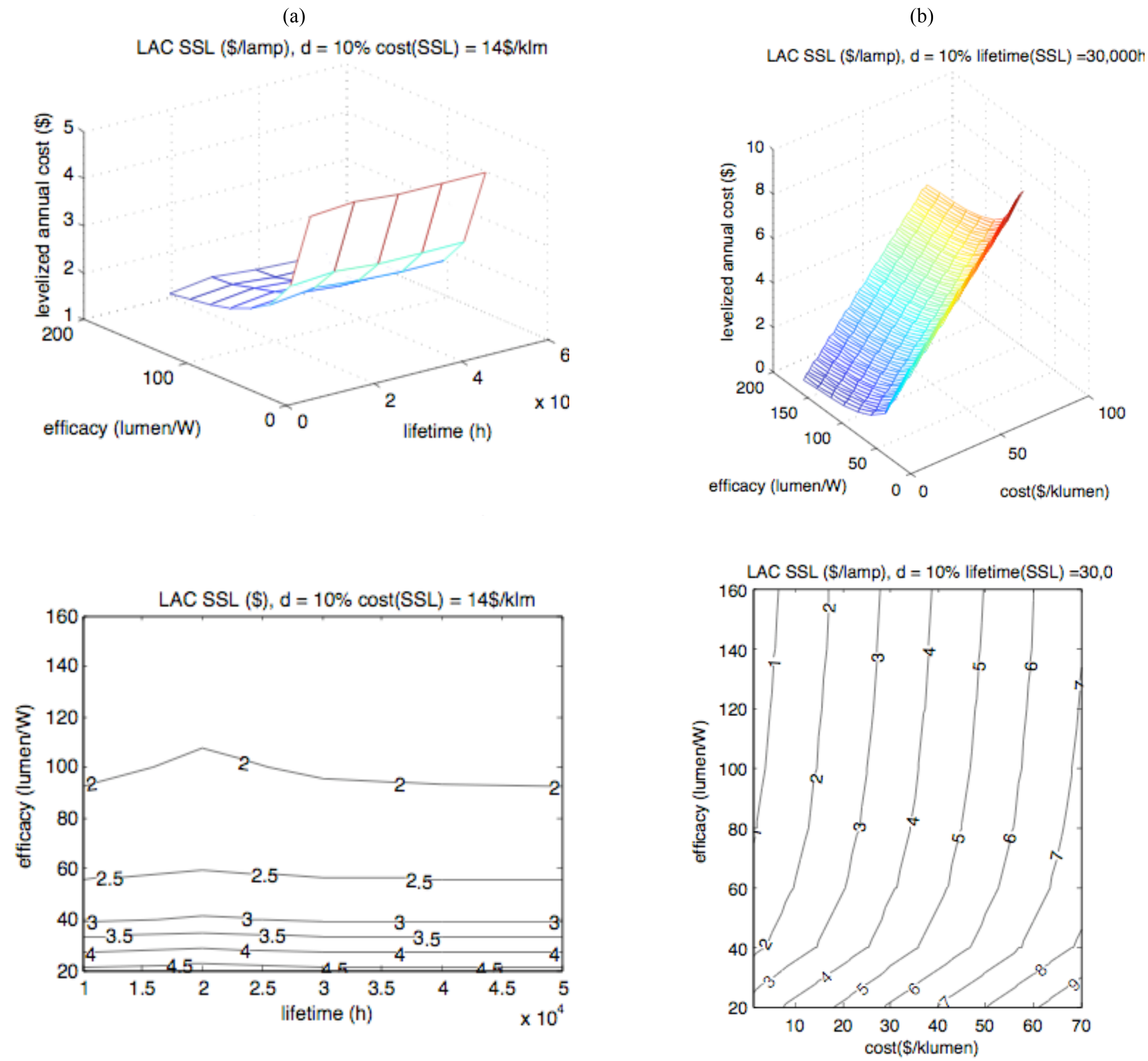

Figure 74 - Levelized annual cost for solid-state lighting under different assumptions for efficacy (lm/W), theoretical lifetime (h), discount rate (%) and usage (h/day). The upper plots correspond to levelized annual cost surfaces. The lower plots are the respective contour plots. In (a) we present the levelized annual cost for one solid-state lighting bulb with an illumination service of 926 lumens, as a function of efficacy (lumen/W) and theoretical lifetime (hours). We assume that the upfront-cost of solid-state lighting remains at 14 $/klumen. In (b) we present the levelized annual cost for one solid-state lighting bulb with a illumination service of 926 lumens, as a function of efficacy (lumen/W) and upfront cost ($/klumen) for a theoretical lifetime of 30 000 hours. We assume an electricity price of 0.10$ /kWh, usage of 2 h/day and a discount rate of 10%.

6.4 Daily Lighting Electricity Consumption Load Shapes

Assuming the low and high household lighting estimates found in the literature as well as our own estimates (Section Chapter 8), and the normalized hourly lighting profiles from the Building America program [72], average household hourly lighting profiles were constructed (Figure 75). Assuming average bulb wattages from [1], we then estimate a profile of the number of bulbs that are operating during each hour of the day is estimated.

This leads to 2 to 6 bulbs being used between 06:00 and 08:00, and between 2 and 13 bulbs being used during the evening lighting peak, between 16:00 and 23:00[53,54]. Focusing only on the evening peak, so as to not to double count the lamps, we estimate that there are 8 lamps being used for more than 3 hours a day. As shown in the previous section, at a usage rate of 3 hours a day, and using a 10% discount rate, the LAC of solid-state lighting is already lower than incandescent bulbs. On the basis of LAC, economically rational consumers would find it cost effective to switch those bulbs to solid-state lighting today. However, solid-state lighting lamps only become as competitive as CFL or other fluorescent technologies by 2010.

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[53] Since there is already a large uncertainty in the number of bulbs being used, seasonality was not included in this analysis.
[54] We assume that the bulbs are incrementally added when the lighting load demand is increasing, and incrementally switched off when the lighting load is decreasing.

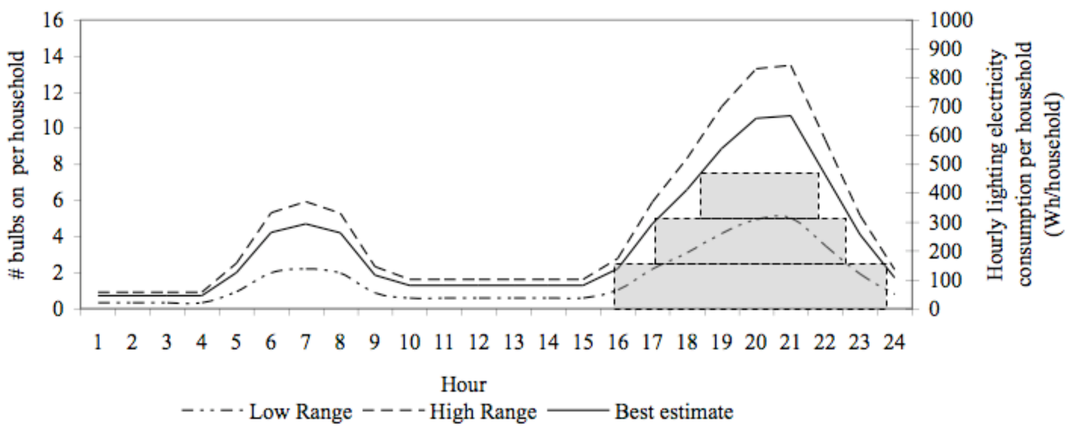

Figure 75 – Hourly lighting electricity consumption and bulbs usage of an U.S. average household. The typical household light use profile is based on normalized lighting profiles from [72], "Low range" profile is estimated using Vorsatz *et al.* [73] and the "high range" profile is obtained using Manclark and Nelson [74]. "Best estimates" is obtained using our estimates for 2005 lighting consumption, based on [1]. The curves on the figure can be read both in terms of the number of bulbs that are turned on (left axis) and the hourly electricity consumption from the household (on the right axis).

Chapter 7. Social Cost-Effectiveness of White LEDs

For a given lighting service, individuals largely make choices on the basis of cost. However, from a societal perspective, other considerations also enter into account. For example, if the focus is on reducing emissions of greenhouse gases while providing a similar energy service then a cost-effectivenes measure such as cost per kilogram of CO_2 avoided is appropriate. In the literature on energy efficiency, it is common to use the *cost of conserved energy* (CCE) [4]-[12]). Sathaye and Murtishaw [13] point out that earlier analysis of energy-efficiency options typically ignored effects such as changes in labor, material, and other requirements, which can be monetized. Subsequently Worrell [75] included these other costs and monetized benefits. In an analysis of the cost effectiveness of several carbon mitigation strategies for the residential sector, Brown [4] accounted for effects that could shift either the carbon savings potential or the cost effectiveness. This is sometimes called a take-back effect. Jaffe and Stavins [76] identified distinct notions of optimality in the context of different "energy efficiency-gaps" (the economists' economic potential, the technologists' economic potential, the hypothetical potential, the narrow social optimum and true social optimum) and argue that each corresponds to a different definition of the energy efficiency.

We evaluate the cost-effectiveness of a program that invests in solid-state lighting and explicitly compare the provision of the illumination service accounting for energy efficiency with the cost of additional generating capacity. The following definition is used for the cost of conserved energy (CCE):

$$CCE = \frac{LAC_{new\ tech} - LAC_{old\ tech}}{E_{old\ tech} - E_{new\ tech}},$$

where CCE is the cost of conserved energy (\$/kWh), LAC_i is the levelized annual cost of technology i, E_i is the annual electricity consumption from technology i, CCC is the cost of conserved greenhouse gas emissions (\$/tonCO_2 eq).

An energy service, such as lighting, heating or cooling, can be provided either through greater energy consumption or improved efficiency. In the case of lighting, one can either use incandescent bulbs, which are energy intensive, or solid-state lighting to provide the same service (illumination) while using less energy. Thus, it makes sense to compare the cost-effectiveness of a technology change (e.g., changing from incandescent to a solid-state lighting technology) with the levelized cost of providing electricity. In Figure 76, we compare the cost-effectiveness of changing from a mature technology (incandescent lamps or CFLs) to cool white solid-state lighting with the levelized cost of several electricity generation plants. In terms of cost-effectiveness for reducing energy consumption, solid-state lighting investments are already better than incandescent lamp investments. Improvements in solid-state lighting technology will make it more cost-effective than CFL lamps by 2010.

Investing in solid-state lighting becomes a better strategy than new generation capacity before 2010, even if the base case is already efficient CFLs. The implication is that solid-state lighting should be considered a key component of any policy to address climate change in a cost-effective way.

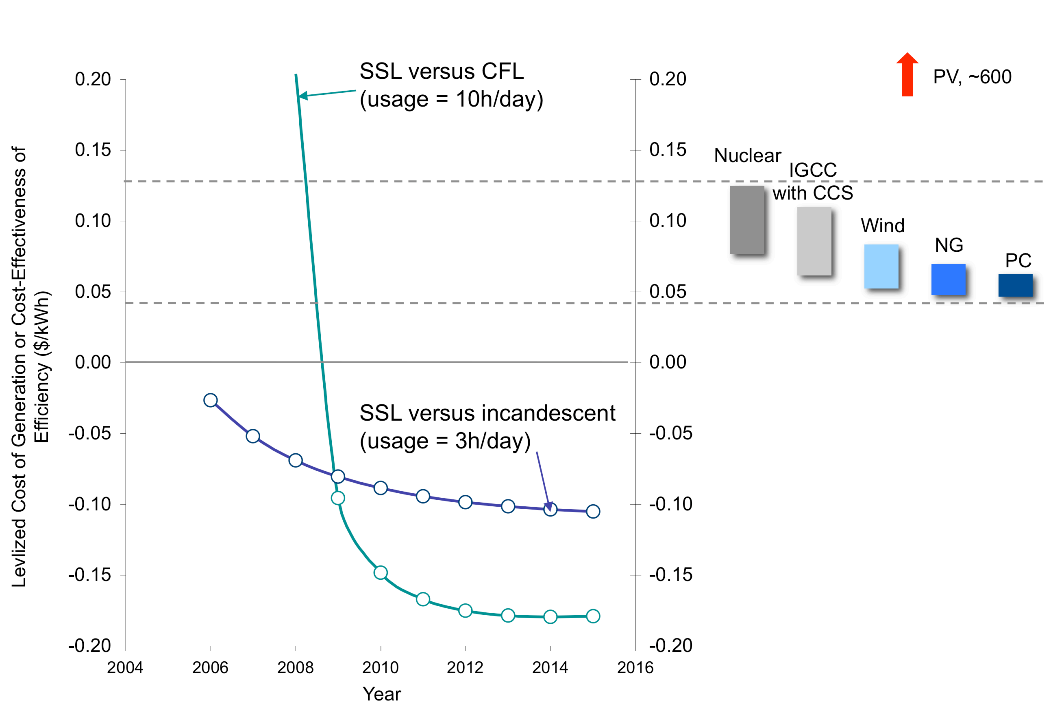

Figure 76 – Cost-effectiveness of solid-state lighting versus incandescent lamps (green line) and versus fluorescent lamps (blue line) ($/kWh). A discount rate of 10% is assumed. The green curve assumed the bulbs are used 3h/day all year. The blue curve assumes that the lamps are used 10h/day all year. The bars represent ranges of levelized cost from different electricity power plant types (ranges of values from [77]-[81]). *IGCC with CCS* stands for integrated gasification with combined cycle and with carbon capture and sequestration, NG stands for natural gas power plants and PC stands for pulverized coal power plants.

Chapter 8. Solid-State Lighting Potential for Energy and GHG Emissions Savings

Having shown that solid-state lighting investment is a more cost-effective strategy to achieve a certain demand level than an investment in new generation technologies, we next estimate the current and future lighting electricity and carbon savings consumption in the U.S. residential and commercial sector between 2007 and 2015 under several scenarios. We define a *status quo* scenario, where solid-state lighting fails to penetrate the general illumination market by 2015. We then simulate the likely savings for a voluntary and market driven adoption of solid-state lighting under various rates of technology adoption. Next we simulate the impacts of lighting standards applied in all new construction. Finally, we perform an analysis of a rebate or analogous subsidy policy to enhance adoption of solid-state lighting lamps.

8.1 U.S. Lighting Electricity Consumption

Only a few studies have estimated the level of U.S. lighting electricity consumption by different economic sectors and consistent time series data are lacking (Figure 77). EIA estimated that residential and commercial lighting electricity consumption were, respectively, 94 TWh and 340 TWh in 1995 [82],[83], whereas Vorsatz *et al.* [73] estimated use as 135 TWh and 280 TWh. The large range of estimated values reflects the urgent need of a better accounting of electricity consumption for lighting nationwide. Also, Mills [84] notes that while campaigns to promote efficiency and conservation usually target lighting, there is a substantial lack of systematic data on lighting energy consumption.

In order to account for uncertainty concerning lighting electricity consumption in the U.S. we use the ranges of estimates from previous studies (Figures 23 and 24) to forecast electricity consumption for lighting in the residential and commercial sector up to 2015 under different sets of assumptions (Figure 25 and 26).

I estimate the annual lighting electricity consumption in 2007 to be between 96 TWh and 257 TWh in the residential sector and between 415 TWh and 488 TWh in the commercial sector. Thus, residential lighting accounts for between 7 % and 19 % of residential electricity consumption, and commercial lighting accounts for between 31 % and 36 % of commercial electricity consumption. I estimate that lighting only in the residential sector accounts for yearly revenue for utilities of more than 20 billion dollars.

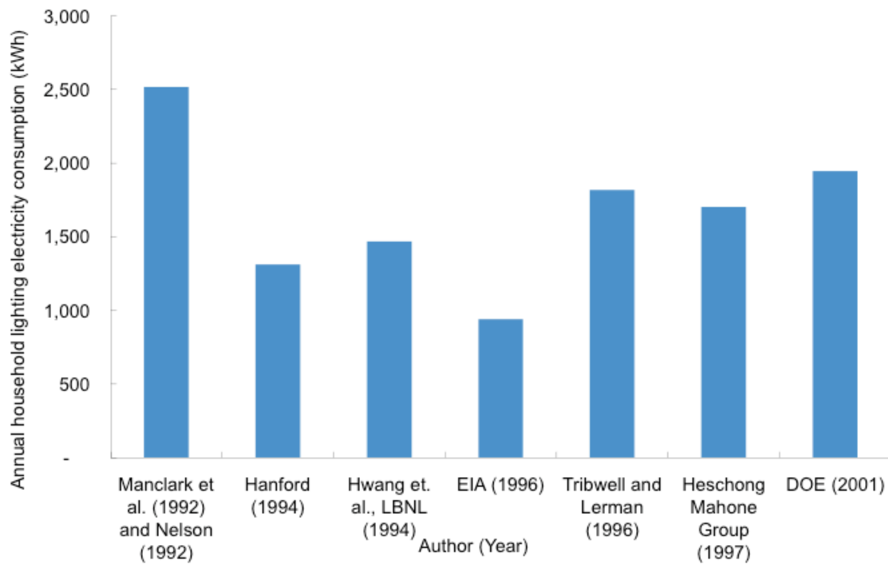

Figure 77 - Estimates of annual average household lighting electricity consumption (kWh) from previous studies. The year of publication is in brackets. While some of these are national and some regional, clearly there is great uncertainty even when regional factors are excluded. Sources: [85] - [89].

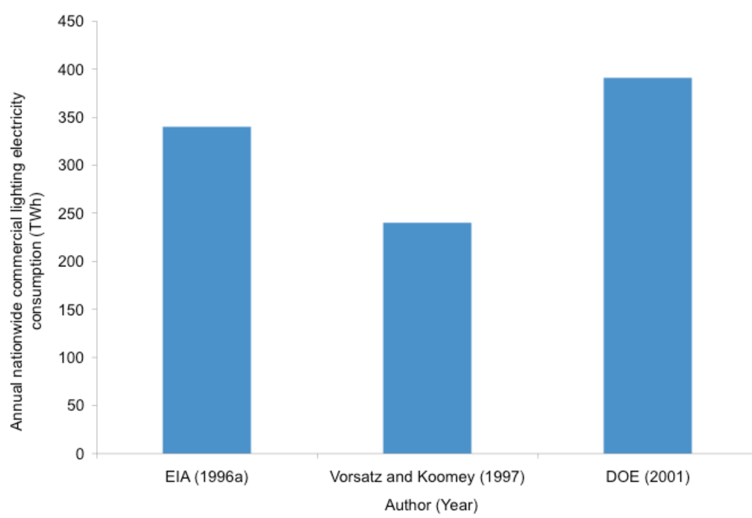

Figure 78 – Estimates of annual nationwide commercial lighting electricity consumption (TWh) from previous studies. The year of publication is in brackets. Source: [89].

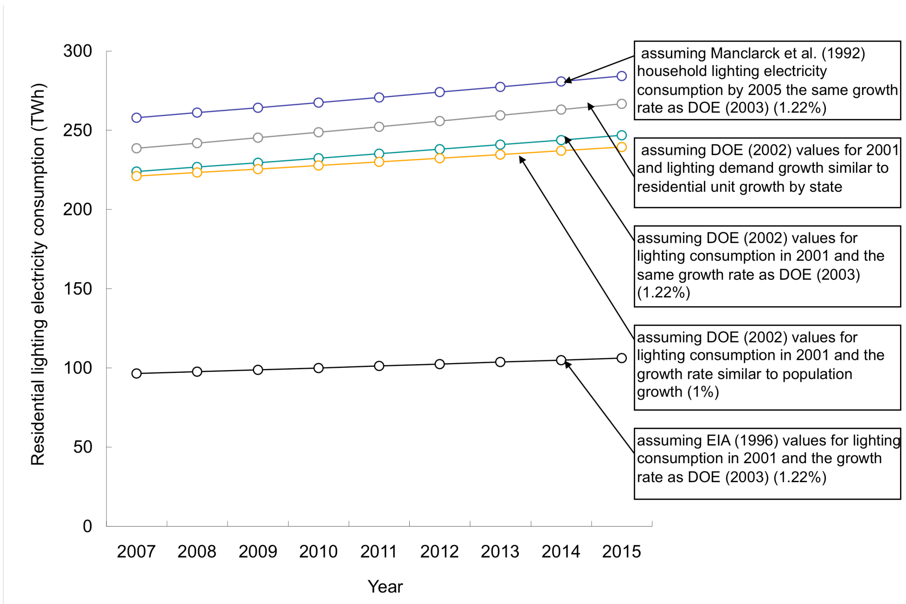

Figure 79 – Projections of residential lighting electricity consumption. Upper curve assumes that household annual lighting electricity consumption in 2005 is as in Manclark et al. [74] and a residential lighting growth rate as in [83]. The three following curves assume DOE [1] values and annual growth rates on residential lighting electricity consumption similar to the historical state residential housing units growth rates (estimated using census division data from 2001 to 2005), of 1.22 % (as in [83]) and 1 % (similar to population growth), respectively. The lower curve assumes the estimate for household annual average lighting electricity consumption from [82] and a growth rate of 1.22 % [83].

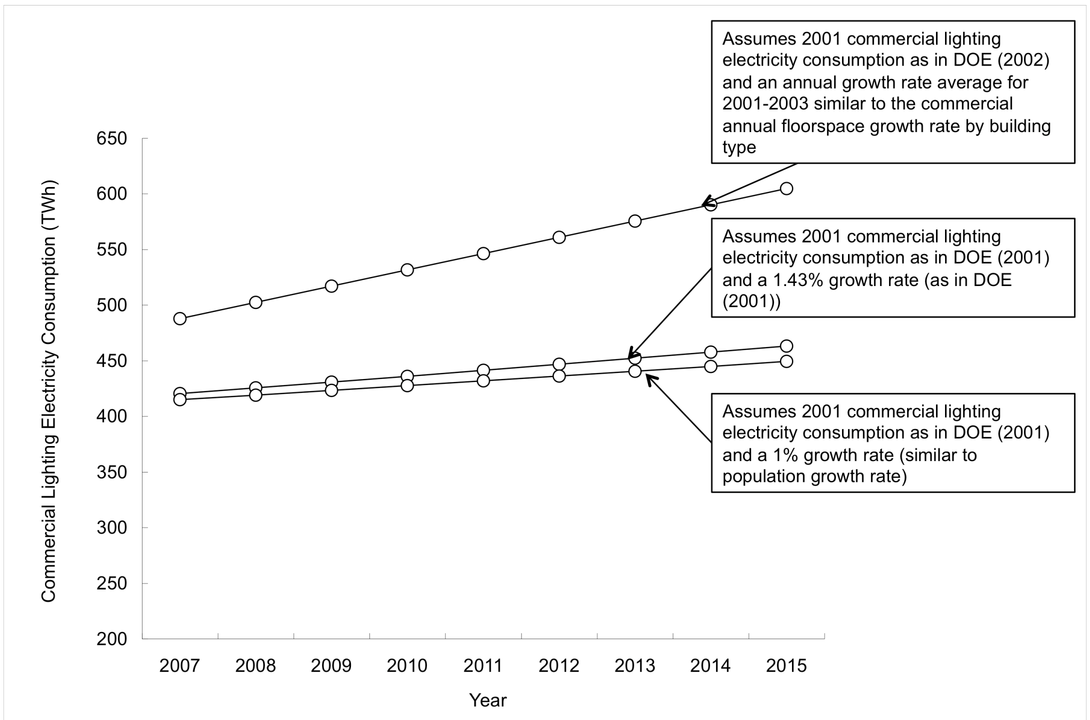

Figure 80 – Estimates of commercial annual lighting electricity consumption between 2007 and 2015 under different assumptions. Upper curve assumes values from [1] for 2001 DOE lighting consumption, and a commercial lighting demand growth rate similar to the annual floorspace stock growth rate by building type as in 2001-2003. The two lower curves assume initial values from [1] and a commercial lighting demand growth annual increase similar to [83] (1.43 %) and U.S. population increase (1 %).

8.2 Lighting Contribution to Greenhouse Gases Emissions

If we assume that lighting is responsible by 8% to 20% of residential and by 27% to 39% of commercial electricity consumption and thus CO_2 emissions (Table 38), then the CO_2 emissions due to lighting correspond to between 17% and 23% of total CO_2 emissions from electricity generation. CO_2 emissions due to lighting correspond to between 5% and 14% of the total CO_2 emissions of the residential sector and from 27% to 30% of the commercial sector. Carbon dioxide emissions due to lighting in the three sectors account for 7% to 9% of total U.S. CO_2 emissions. These estimates of carbon emissions due to electric lighting assume average national values for carbon intensity of electricity generation. They could be refined with a more detailed consideration of the time of day when consumption occurs, regional differences in the electricity generation mix, and regional differences in illumination needs, but given the large uncertainty in the basic use data, such refinements would change little.

Table 38 – Estimates of 2005 carbon emissions due to lighting use in the residential and commercial sectors in annual metric tons of carbon. The values in brackets correspond to the upper and lower estimates using upper and lower electricity consumption estimates from Figures 23 and 24. We assumed the national average carbon factor of 0.63 kg CO_2/kWh [90].

GHG Emissions from:	**Residential MMTC/year)**	**Commercial (MMTC/year)**
Lighting	38 (16 – 43)	71 (70 - 80)
Electricity	212	203
Total Emissions	312	264

Note: assuming U.S. electricity generation emissions of 600 MMTC per year [91] and total U.S. emissions of 1,579 MMTC per year [92]; MMTC = million metric tons of carbon.

8.3 Policy Designs for Enhancing Energy Efficient Lighting

8. 3. 1. Impact of Adoption of Solid-State Lighting on U.S. Electricity Consumption

The NRC recently developed a method for the DOE to perform a prospective evaluation of their applied energy research programs [71]. DOE's Energy Efficiency and Renewable Energy (EERE) lighting program was selected to test the methodology, and the DOE's National Energy Modeling System (NEMS) was used to estimate solid-state lighting penetration in the market. The panel notes "a simpler model [than NEMS] could have done much the same and given the panel the opportunity to run parametric analysis." Given that, we have developed a simple model that allows a parametric assessment of solid-state lighting penetration between now and 2015 as a function of the rate of penetration in the residential and commercial sectors.

In the technology diffusion literature, four different models (the *epidemic model*; the *probit model*; *legitimation and competition model*; and *information cascades model*) are commonly used to explain the market penetration of a technology [93]. We have adopted the most widely used model, a standard epidemic model as provided by Griliches [98].

We assume that the diffusion of solid-state lighting will follow the typical pattern of a logistic curve as follows:

$$P_i(t) = \frac{P_i^*}{1 + e^{(-\eta_i - \phi_i t)}},$$

where P_i* is the asymptotic level of use, η_i locates the diffusion curve on the horizontal axis and ϕ_i is a measure of the speed of diffusion. We define the potential market as illumination in the residential and commercial sectors and model annual Tlumen-hours provided. We use the model in a prescriptive form, assuming that in 2007 only 1% of the illumination energy service is provided by solid-state lighting and consider three scenarios for solid-state lighting market penetration in 2015: 5%, 50% and 99% (see Figure 81 and Figure 82).

In the residential sector, 90 % of the wattage (and 64 % of the lumens) is provided by incandescent lamps. Thus, the turnover of the lamps is less than once per year, even considering a usage of 2 h/day. In the commercial sector, 32% of the wattage is incandescent, 56% fluorescent and 12% HID. We assumed that the stock turnover is similar to that of the fluorescent bulbs with lights operating for an average 10 h/day. Assuming that bulbs have theoretical lifetimes of 10 000 hours, this roughly corresponds to a turnover of three years. Each year, the model assumes the prior cumulative adoption of the technology and takes into account solid-state lighting efficacy projections from DOE [31].

An solid-state lighting adoption of 5%, 50%, and 99% in terms of lumen demand would provide cumulative savings between 2007 and 2015 from 20 TWh to 50 TWh, from 125 TWh to 340 TWh and from 385 TWh to 1,030 TWh for the residential sector and from 25 TWh to 30 TWh, form 90 TWh to 110 TWh and from 430 TWh to 525 TWh for the commercial sector, depending on the assumptions made about future lighting demand.

A 99% adoption by 2015 (2018 in the case of the commercial sector) is unlikely to be achieved. However, a 50% penetration in the residential and commercial sectors (by 2015 and 2018, respectively) could be possible and would have significant impact on the overall U.S. electricity consumption and CO_2 emissions. DOE [89] estimated that within all economic sectors, solid-state lighting could save between 500 TWh and 1,850 TWh (for scenarios of moderate and accelerated investment, accordingly), cumulatively between 2010 and 2025. Our figures are in agreement with DOE findings, but are more optimistic in the early penetration of solid-state lighting in the market.

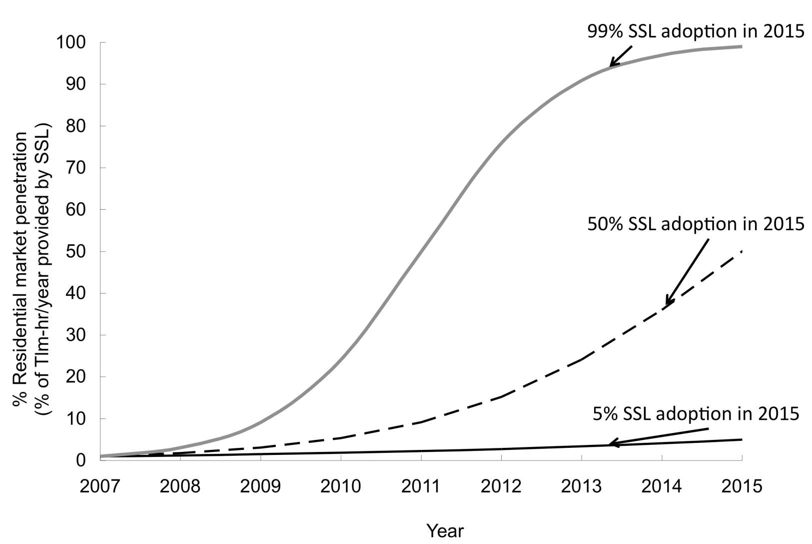

Figure 81– Percent of residential market penetration of solid-state lighting measured as illumination service provided (Tlm-hr/year), assuming a share of the illumination service from solid-state lighting of 5%, 50% or 99% by 2015. Similar curves were simulated for the commercial sector, but lagged by three years to account for the turnover of the fluorescent stock. A 1 % penetration of solid-state lighting in 2007 was assumed.

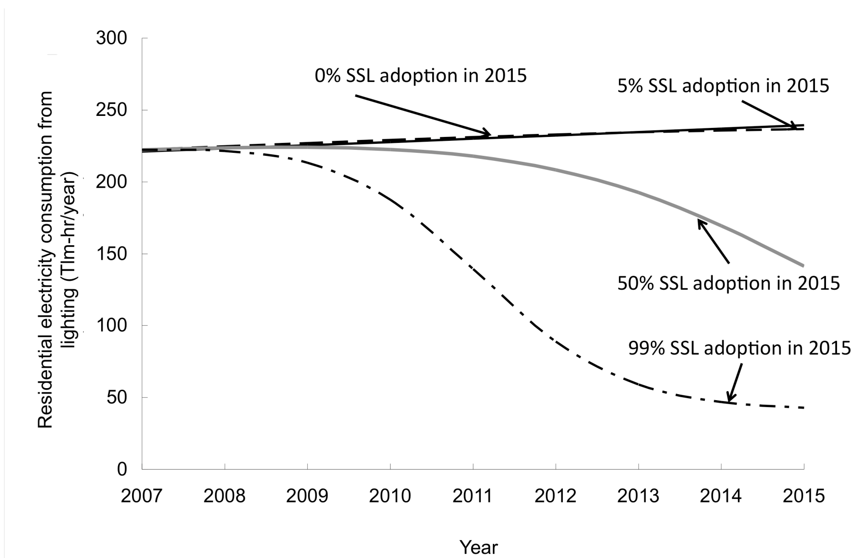

Figure 82 – Lighting electricity consumption in the residential sector between 2007 and 2015 assuming of the illumination service provided by solid-state lighting a share of 0%, 5%, 50%, and 99% in 2015. An initial 1% solid-state lighting penetration for 2007 was assumed.

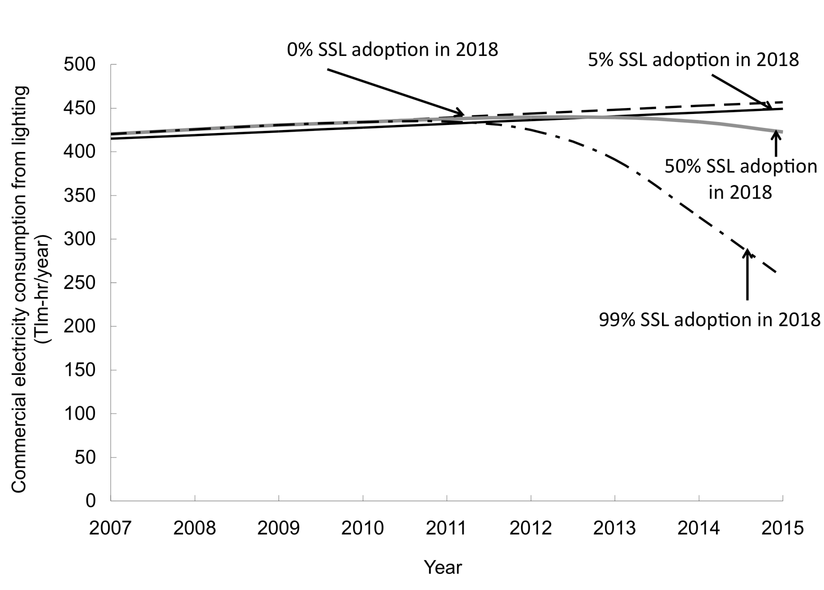

Figure 83 – Lighting electricity consumption in the commercial sector between 2007 and 2015 assuming that 0%, 5%, 50%, and 99% of solid-state lighting by 2018 provides the illumination service. An initial 1% solid-state lighting penetration for 2007 was assumed. Here, the 0% penetration in 2015 assumes lighting demand from [B] in Figure 81.

8. 3. 2. Nation-Wide Adoption of California's Title 24 Standards

As it often as in the past, today California is leading the nation in the development of energy efficiency standards. The 2005 Title 24 standards [17] that went into effect in October 2005 specify an allowed lighting power for commercial buildings, while they establish minimum efficacies for the luminaries in residential settings. According to Title 24, three methods can be used to estimate the allowed lighting power in a building: (i) the complete building method (see Table 4); (ii) the area category method; or (iii) the tailored method.

We estimate the impact that the standards would have if they were applied nationwide using the complete building method for the commercial sector and the minimum efficacies that comply with Title 24 with the residential sector.

However, a note of caution in what concerns the implementation of the standards in the residential sector should be made. Effectively, the design of standards of illumination will matter in terms of the potential energy savings that can be achieved. For example, in the case of Title 24 standards for the residential sector, all residential projects that apply for a building permit are required to have high efficiency luminaires or being controlled by sensors. The minimum requirements for what is considered a high efficacy luminaire is presented in Figure 84. The average power of incandescent lamps in the U.S. residential sector is roughly 65 W and an efficacy of 18 lm/W. This is presented as an X in Figure 84. Now, note that the standards impose a minimum efficacy on the lighting system, but do not set maximum wattages limits. Accordingly, under this standard an improvement in the efficiency of the lighting system may not result in large energy savings.

In Figure 84, an illustrative *iso-lumen* line corresponding to constant levels of light service is provided for the point marked X. Assuming an energy service that provides at least the same illumination as today, energy saving only occurs if the old luminaire is replaced by one that has lower wattage and lies to the right of the *iso-lumen* line. Only solid-state lighting, CFL and T6 will satisfy the minimum requirements, so it is likely that those technologies will prevail in new construction. The standards should be augmented with additional requirements that either (i) include power maximum allowances, or (ii) require that illumination (total lumens) provided by the technology would be in the same lumen isoquant as those already in place in the current construction stock. These different additional standard requirements are likely to lead to different outcomes in terms of technology mix, energy consumption and illumination levels in the buildings, but they guarantee two things: that the lighting system efficiency will increase and that energy savings compared to a situation without standards are going to occur.

We use the 2005 residential housing unit stock by state from U.S. Census Bureau data [100] and a distribution of annual construction change up to 2015 using a triangular distribution, were the minimum, maximum and average construction annual changes for the period 2000-2005 are assumed to apply over the period of the forecast. Cumulative distribution functions for the construction rates in 5 states are presented in Figure 85.

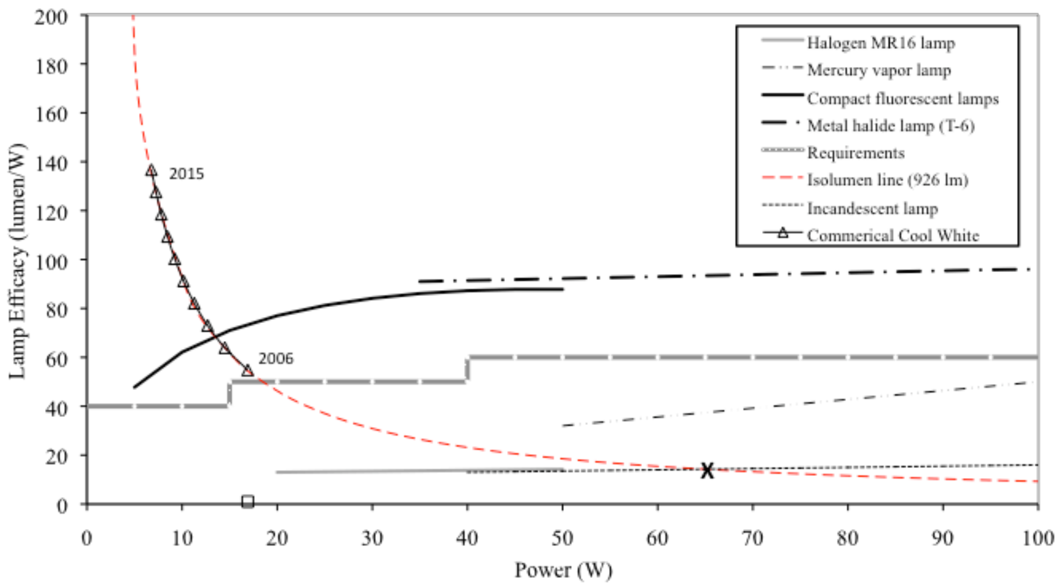

Figure 84 – Lamp efficacy in lm/W and wattage in W for current lighting technologies (halogen MR16, mercury vapor, CFL, metal halide and, incandescent lamps), adapted from Title 24 standards in California [17]. The dashed line corresponds to a lumen *isoquant* for a 65 W incandescent bulb with an efficacy of 18 lm/W. “Commercial cool white” corresponds to white solid-state lighting range of expected efficacies is also presented as projected by [30]. In new construction and retrofits, the luminaires are required to have efficacies above the requirements (grey line tick).

Table 39 - Assumptions the characteristics of the current stock of bulbs.

Input	Incandescent	Fluorescent	Notes
# of lamps by household	Triangular (0, 37,80)	Triangular (0, 6,15)	Based on data from the 2001 Residential Energy Consumption Survey (RECS) [99] and [1]
Wattage (W)	Triangular (40, 67, 100)	Triangular (5,38,100)	Based on data from the DOE [1]
Hours use (h)	Parametric: [0.5h, 2h, 4h, 8h]	Parametric: [0.5h, 2h, 4h, 8h]	Since the model was highly sensitive to the number of hours the lamps were used, it was modeled parametrically
Efficacy (lumens/W)	Uniform (13,16)	Uniform (48,96)	Typical efficacy ranges for each technology

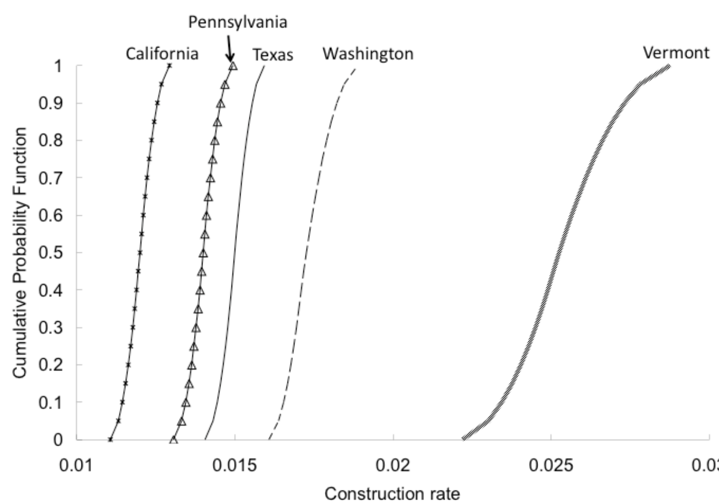

Figure 85 – Cumulative probability function of residential construction's annual changes for California, Pennsylvania, Texas, Vermont and Washington. We assumed the 2005 residential housing unit stock by state from the U.S. Census Bureau data [100] and a distribution of annual construction change for the period up to 2015 using a triangular distribution, were the minimum, maximum and average construction annual changes were considered to be the minimum, maximum and average observable annual changes in each state during the 2000-2005 period.

In order to see the effects of applying the policy nationwide, the potential energy savings up to 2015 for each U.S. state for the residential sector, and by building type for the commercial sector were modeled, assuming that the standards began to be applied in 2007. The key modeling assumptions are presented in Table 6. Household lighting electricity consumption is then expressed by:

$$\begin{aligned}&Household\ Lighting\ Cons[kWh/year] = \\ &\sum_{j=1}^{n}\left(\#\ Lamps_j \times Wattage_j[W] \times Usage[h/day] \times 365/10^3\right)\end{aligned}$$

Where *j* denotes a lamp type.

For simplicity and because of the lack of regional data, interstate differences in households lighting electricity consumption were not considered. Lighting demand increase by state was considered to be similar to the house unit annual change. Housing stock over time in each state was modeled as:

$$\begin{aligned}&Housing\ unit\ stock_{t+1} = \\ &Housing\ unit\ stock_t \times (1 + annual\ change)\end{aligned}$$

Under those assumptions, a projection of the mean housing units up to 2015 is obtained. The total state residential consumption in lighting in state *i* for year *t* is estimated as:

$$\begin{aligned}&Residential\ Lighting\ Electricity Consumption_{i,t}[kWh/year] = \\ &= Annual\ Household\ Lighting\ Electricity Consumption[kWh/year.household] \times \\ &\times (Unit\ Housing_{i,t})\end{aligned}$$

In order to model the effect of the standards, we assume that the illumination in lumens remain the same as under a *no standards* scenario, but that more efficient lighting is used in the new construction. The new residential construction is assumed to have luminaires with efficacies uniformly distributed between 60-100 lumen/W, thus complying with the Title 24 residential standards. The simulated mean lighting electricity consumption over time, with and without standards, is presented in Figure 86 for some illustrative states and for average total U.S. annual electricity savings up to 2015. Figure 87 provides a sensitivity plot for the average hours of lighting use by households.

For the simulations of lighting electricity consumption without standards in the commercial sector, we assumed the wattage per square foot in 2001 values from [1]. With the implementation of standards, new buildings wattage per square foot would follow the values from Title 24 standards. We assume the annual change in building stock by building type until 2015 would be similar to the average annual change in building stock for 2001 to 2003 estimated using the Commercial Energy Building Consumption Survey (CEBCS) data from 2001 and 2003 [101]. We used the average hours of operation by building type from [1]. We consider the square footage and number of building for each category as in [1].

The annual lighting electricity consumption in the commercial sector for each building type was estimated by:

$$\begin{aligned}&Lighting\ electricity\ consumption_{i,t} = \#\ buildings_{i,t}\\&\times hours\ of\ operation_i [h/year]\\&\times power\ per\ area_i [W/sqft] \times area_i [sqft]\end{aligned}$$

For each building type *i* and each year *t*. The estimated electricity savings between 2007 and 2015, by building type for some illustrative building types are presented in Figure 88.

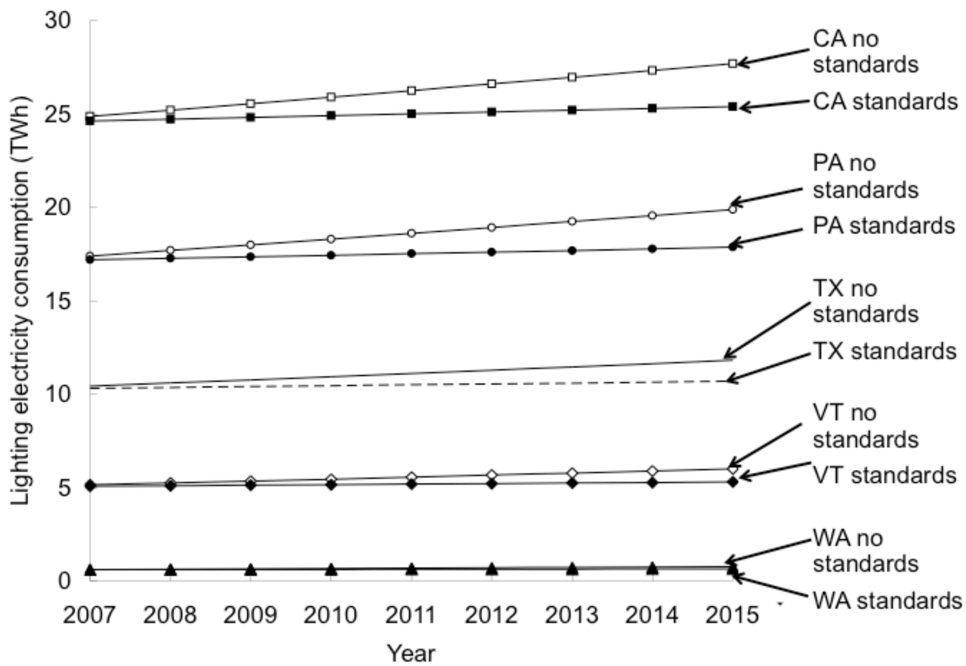

Figure 86 – Simulation of mean annual lighting electricity consumption in the residential sector for some illustrative states, with and without Title 24 standards, and assuming and average usage of 2 hr/day.

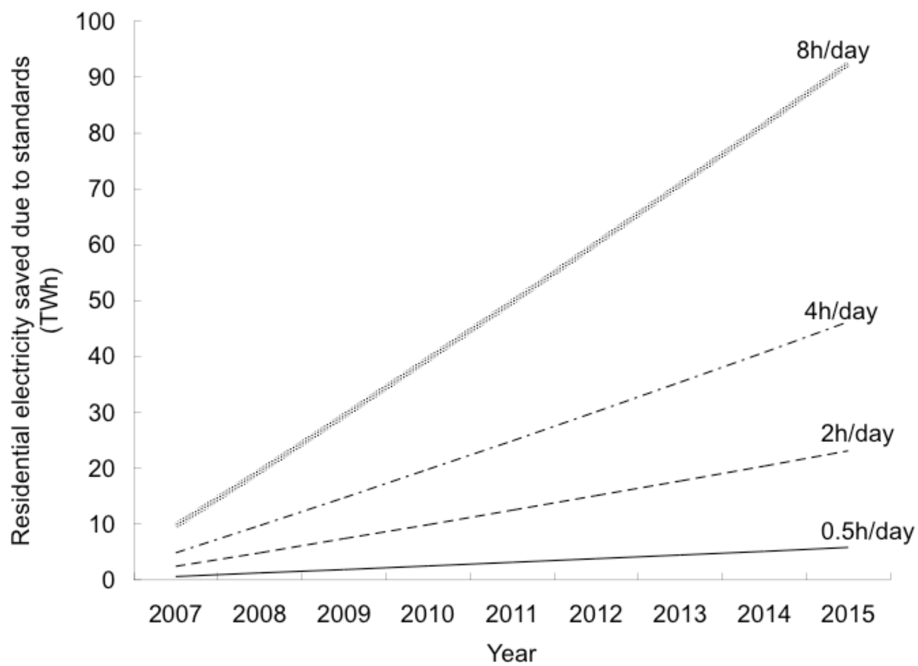

Figure 87 – Simulation of the electricity saved from the implementation of Title 24 lighting standards nation wide for the residential sector up to 2015. Sensitivity for different assumptions concerning the average operation hours of the bulbs: 0.5 hr/day, 2 hr/day, 4 hr/day, or 8hr/day.

Table 40 - Power allowed by building type according to the complete building method in Title 24 standards [17].

Type of Use	Allowed Lighting Power (W/sq ft)	Type of Use	Allowed Lighting Power (W/sq ft)
Auditoriums	1.5	Office buildings	1.1
Convention centers	1.3	Parking garages	0.4
Financial institutions	1.1	Religious facilities	1.6
General commercial and industrial work buildings	1.1 (high bay) 1.0 (low bay)	Retail and wholesale stores	1.5
Grocery stores	1.5	Restaurants	1.2
Hotel	1.4	School	1.2
Industrial and commercial storage buildings	0.7	Theaters	1.3
Medical buildings and clinics	1.1	All others	0.6

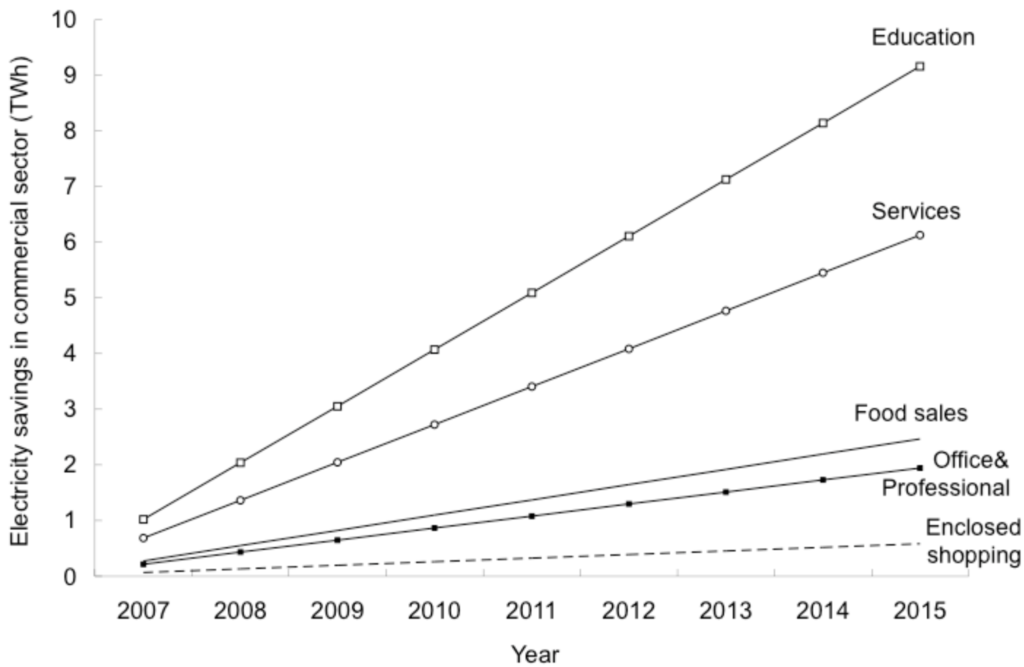

Figure 88 - Potential electricity savings in the commercial sector between 2007 and 2015 for various building types.

I conclude that given the current U.S. generation mix, the nationwide adoption of California's Title 24 illumination standards could lead by 2015 to cumulative savings of roughly 113 TWh for the residential sector and 232 TWh for the commercial sector, or a cumulative total of 217 million metric ton of CO_2 by 2015.

8. 3. 3. Rebates or Other Subsidies as a Policy to Enhance Solid-State Lighting Adoption

A number of rebate programs are in place for CFL, supported by state governments, NGOs, major retailers, and utilities that face capacity constraints. The design of a rebate program will influence its cost and effectiveness. Here we conduct a simulation to estimate the level of rebate (or other equivalent subsidy) for two rebate designs: (i) the difference between the levelized annual cost of solid-state lighting and another lighting technology (incandescent bulbs or CFLs); (ii) the difference between the upfront cost of solid-state lighting and another lighting technology (incandescent bulbs or CFLs). We present the simulations of the rebate amount over time accounting for the expected evolution of white LEDs (Figure 89). If we assume that the mental decision making process from consumers is based just on the comparison of the up-front cost of two illumination technologies that provide the same energy service, then a rebate of more than $20 per lamp would be needed today for a consumer to choose solid-state lighting over an incandescent bulb. However, if we assume that the mental decision process is based on the levelized annual cost, today's solid-state lighting bulbs would already be cheaper than incandescent lamps and no rebate would be necessary.

Also, if a consumer mental process only includes upfront costs, a rebate of $20 per lamp would be needed for the consumer to be indifferent between a solid-state lighting and

CFL. However, if we consider levelized annual cost, no rebate would be needed if the lamps were to be used more than 2h/day.

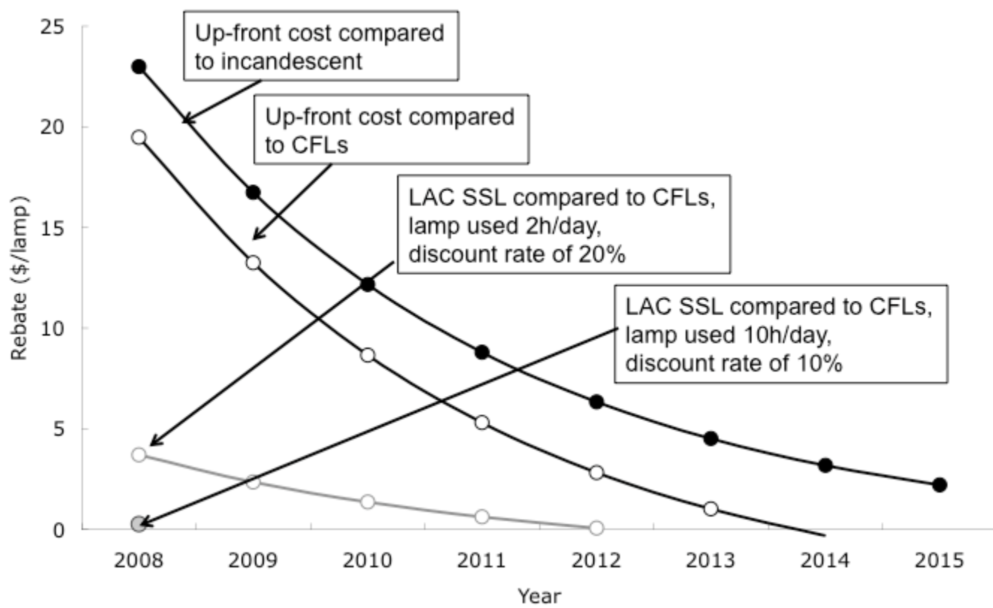

Figure 89 – Estimate of the rebate needed to make solid-state lighting LAC similar to incandescent or fluorescent bulbs, assuming 2h/day and 10h/day usage and discount rates of 5% and 20%.

A rebate or subsidy to set the LAC for solid-state lighting equal to that of incandescent lamps will only be required if the usage is less than 2h/day and consumers have implicit discount rates higher than 20%. Comparing with CFL, rebates of roughly 5$/luminary would be required if consumers are expected to discount solid-state lighting at 20%. Assuming a 10% discount rate, a rebate of less than 2.5 $/luminary would be needed starting in 2007, and would decrease over time, as solid-state lighting technology improves. By 2012, basing the rebate scheme only on the levelized annual cost, no rebate would be needed.

8. 3. 4. Utility Cost-Effectiveness

Using the preceding results, we can ask what CO_2 permit price or tax is necessary for a utility to prefer to invest in efficient lighting than to pay the permit price or tax. In this calculation, we assume the utility would pay the full cost of the lighting technology. Thus, the utility cost-effectiveness is the ratio of the levelized annual cost of each lighting technology and the amount of carbon dioxide emissions it would avoid. We compare each lighting technology with an incandescent bulb. Figure 90 and 37 present the estimates of cost-effectiveness assuming two extreme usages (2h/day and 10h/day).

For comparison, we also present the cost effectiveness of several other carbon mitigation strategies. The cost-effectiveness of carbon capture and sequestration for new power plants is estimated to range from 13 \$/ton CO_2 to 80 \$/ton CO_2 avoided [77] depending on the type of plant and fuel (Figure 90). These estimates do not account for transportation and storage.

Similarly, the levelized cost effectiveness for today solar photovoltaic's is roughly 980 \$/ton CO_2 and is estimated to range from 95 \$/ton CO_2 to 380 \$/ton CO_2 avoided in the near future. Wind power cost-effectiveness ranges from 56 \$/ton CO_2 to 110 \$/ton CO_2 avoided. Also, nuclear estimated cost-effectiveness ranges from 106 \$/ton CO_2 to 143 \$/ton CO_2 avoided.

According to our simulations, the cost-effectiveness of mature lighting technologies ranges from 4 \$/ton CO_2 to 28 \$/ton CO_2. Assuming a 10% discount rate, solid-state lighting cost-effectiveness for a utility ranges from 34 \$/ton CO_2 to 134 \$/ton CO_2 in 2008 and from 4 \$/ton CO_2 to 14 \$/ton CO_2 in 2015 making it among the more attractive investments available for large CO_2 abatement by the electricity sector.

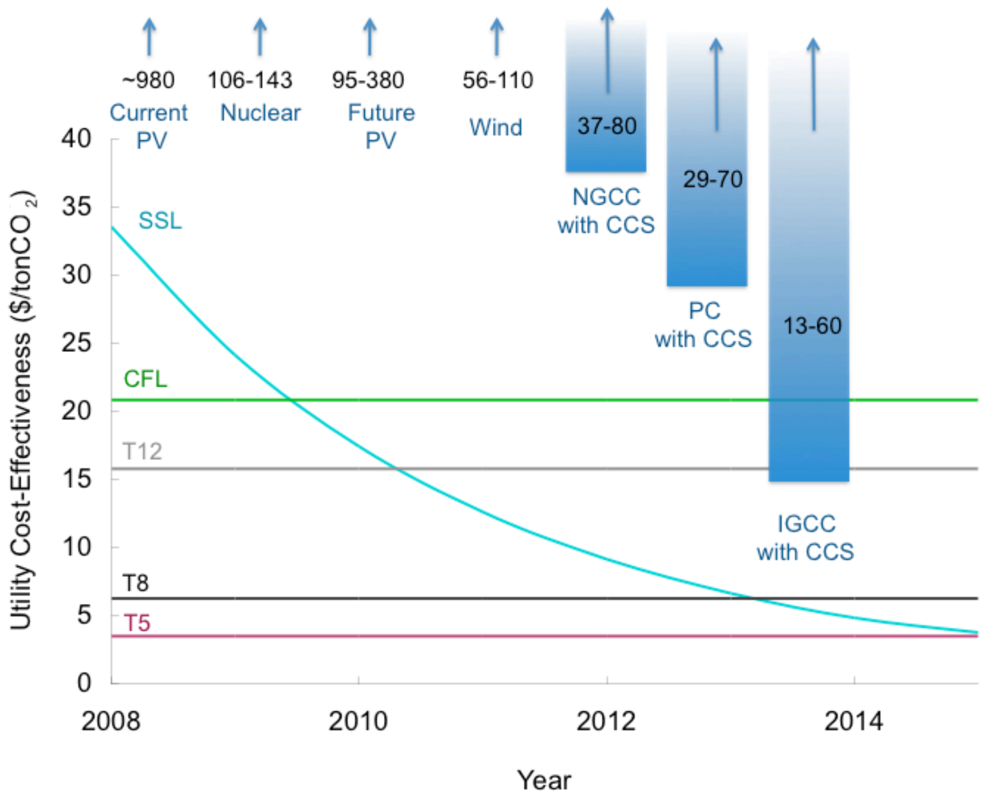

Figure 90 - Utility cost-effectiveness in $/ton CO_2 for solid-state lighting, CFL, T12, T8 and T5 lamps assuming the same illumination service is provided. The amount of carbon dioxide emissions avoided is estimated by comparing each lighting technology with an incandescent bulb. We assume a usage of 10 hr/day and a discount rate of 10 %. We include the cost-effectiveness of other mitigation strategies (current photovoltaics (PV), nuclear, future photovoltaics, wind, new natural gas combined cycle power plant with carbon capture and sequestration (NGCC with CCS), new pulverized coal power plant with carbon capture and sequestration (PC with CCS), and new integrated gasification combined cycle with capture and new gasification (IGCC with CCS)).

The cost-effectiveness of current incandescent bulbs will be highly depended on how much the lamps are used. Clearly, mature lighting technologies today and solid-state lighting in the near future provide a competitive alternative to carbon capture and sequestration or other carbon mitigation strategies and should be included in any future national climate change mitigation plan.

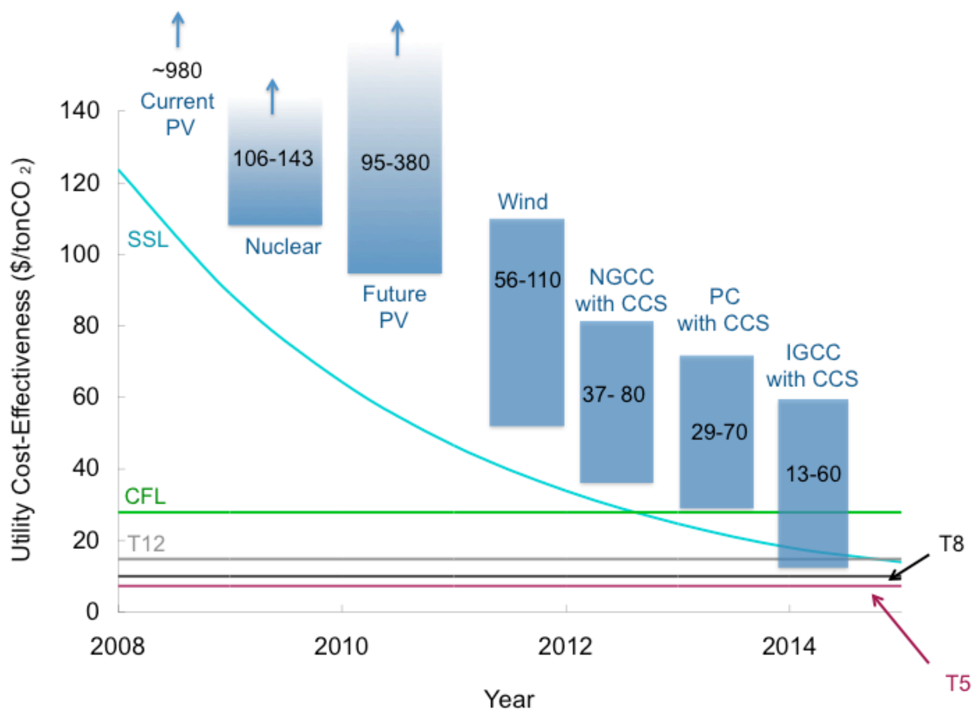

Figure 91 - Utility cost-effectiveness in \$/ton CO_2 for solid-state lighting, CFL, T12, T8 and T5 lamps assuming the same illumination service is provided. The amount of carbon dioxide emissions avoided is estimated by comparing each lighting technology with an incandescent bulb. We assume a usage of 2 hr/day and a discount rate of 10 %. We include the cost-effectiveness of other mitigation strategies (current photovoltaics (PV), nuclear, future photovoltaics, wind, new natural gas combined cycle power plant with carbon capture and sequestration (NGCC with CCS), new pulverized coal power plant with carbon capture and sequestration (PC with CCS), and new integrated gasification combined cycle with capture and new gasification (IGCC with CCS)).

Chapter 9. Conclusions and Policy Recommendations

Improving the energy efficiency of lighting technologies will lead to reduced energy use and associated emissions of CO_2 and conventional pollutants. However, as experience with CFLs clearly demonstrates, a variety of behavioral factors can limit the rate of adoption of new and efficient lighting technologies. Our analysis suggests that solid-state lighting will be competitive with conventional lighting technologies before 2015. White light solid-state lighting investments for general illumination may make sense right now for large customers, but the successful adoption of this technology will depend on the economic, institutional and regulatory context.

The upfront cost of solid-state lighting is the main barrier to high market penetration. R&D efforts should focus on bringing the upfront costs down, since other important features, such as efficiency, color balance, power supply, and controls are rapidly evolving and are not likely to be barriers to adoption.

Different product standards for the commercial and residential sector should be considered. Residential consumers might not benefit much from a further increase in the lifetime of the solid-state lighting bulbs, since lamps' lifetimes are already longer than the time the average household remains in the same housing unit. Thus, if product standards are to be developed for residential lighting, they might only require product lifetimes of 30,000 hours, but require higher lighting quality and lower upfront costs. Commercial decision makers might benefit from expected future solid-state lighting lifetimes, so a different product standard for commercial applications would be appropriate.

The marketing and information strategies of large retailers for different lighting technologies should be considered when addressing the adoption of solid-state lighting or other competing technologies. For example, Wal-Mart recently initiated a vigorous marketing strategy for CFL, with the aim to sell a hundred million CFL bulbs in 2007. This strategy is likely to lead to significant electricity savings for residential consumers. While the strategy will increase the time of the stock turn over, perhaps slightly delaying some solid-state lighting adoption, the impact will probably be small. On the other hand, in addition to the energy savings achieved, there may also be positive spillover effects in terms of information on potential energy savings from lighting to consumers, from which solid-state lighting may benefit. A gradual transition from incandescent to solid-state lighting through CFL might be an effective cost strategy, as it would offer customers the opportunity to benefit from rapid advances in solid-state lighting technology, rather than locking them in to current technology with the very long life expectancy of solid-state lighting luminaries.

Our analysis of the California Title 24 standard demonstrates that nationwide illumination standards for new residential and commercial construction would lead to large cumulative electricity savings if illumination service level remains constant. However, if lighting standards are to be implemented nationwide in new construction and retrofits, we recommend a residential standard that is based on power per area or add the requirement of providing new lighting systems that lie in the same *iso-lumen* line as the illumination service provided today.

There are other policy options such as rebates or subsidies, strategies that allow consumers to perceive the levelized cost of lighting, or product standards, which warrant future analysis. There are several aspects of solid-state lighting adoption that were not covered in this work, such as the implications of solid-state lighting adoption on air conditioning and heating demand, potential to flatten peak loads, and accordingly lower the marginal electricity price. Also, there are other technical options (*smart sensors*, OLEDs, greater use of sunlight,) that should be analyzed as the nation considers strategies to improve lighting efficiency.

Finally, this analysis has identified a number of fundamental methodological limitations in current methods for analyzing the adoption and diffusion of new technologies. Improved methods would be valuable to a wide range of analyses of future energy use technologies.

Chapter 9: Conclusions and Policy Recommendations

Chapter 10. References

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Appendix 1. Memo from Erica Myers (RFF)

Purpose

The NEMS Residential Demand Module tracks the stock of different appliances by equipment "class" i.e. clothes washers, dishwashers, etc. The flows of the appliances, however, are calculated at a finer level of detail, "type," i.e. clothes washer #1, clothes washer #2, etc. The numbering system does not refer to a specific make and model of an appliance, but rather an efficiency level; #1 being the least efficient with successively higher numbers getting more efficient. Here we calculate stock levels for each technology at the "type" level using the flow numbers for replacement and new equipment and a retirement function as specified in the NEMS Residential Demand Module.

Base Stock

The first simulation year for the Residential Demand Module was 2006. The base stock at the class level for 2005 is available in the Residential Detail file provided by John Cymbalsky for the Reference Case. We assumed that shares of the technology types within each class in the base stock were equivalent to the market shares of the replacement technologies. In other words, we used the market share from the first set of flow numbers for replacement equipment for the base stock.[55]

New and Replacement Equipment

We use the output from the NEMS Residential Demand Module for the flow of new and replacement equipment for each simulation year.

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[55] Using the market share from 2006 purchases as a proxy for base stock is likely an overestimation of the penetration of efficient technologies, as available efficient technologies become more affordable and newer, even more efficient technologies enter the market.

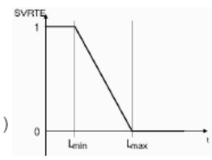
Retirement

We use the same linear retirement as the NEMS Residential Demand Module after a minimum age is reached up to a maximum lifespan. The minimum and maximum ages for equipment at the class level are available in the NEMS RTEKCL.TXT input file. The equation is as follows:

shown in the picture. Its mathematical description is as follows:

where,

$$SVRTE_{t,L_{\min},L_{\max}} = 1\,,\ if\ t < L_{\min}$$
$$SVRTE_{t,L_{\min},L_{\max}} = 0\,,\ if\ t > L_{\max} \qquad \text{(B-1)}$$
$$SVRTE_{t,L_{\min},L_{\max}} = 1 - \frac{t - L_{\min}}{L_{\max} - L_{\min}}\,,\ otherwise$$



$SVRTE_{y-t,L_{\min},L_{\max}}$	is the proportion of surviving equipment after time *t*,
t	is the age of the equipment in years,
L_{min}	is the minimum equipment lifetime in years, and
L_{max}	is the maximum equipment lifetime in years.

Unit Energy Consumption

In the NEMS Residential Demand Module, unit energy consumption (UEC) for new equipment is calculated at the class level as an adjustment to the UEC for base stock. For the heating and cooling there are additional adjustments for weather and square footage that are absent from other end uses. The calculation for heating is below:

Consumption and UEC Component

Final end-use fuel consumption is determined by the fuels demanded by the equipment to provide households with the demanded services. For each equipment class, the UEC for new equipment, replacement equipment, and the average of all equipment is computed. New equipment UEC values are calculated as:

$$\begin{aligned} EQCNUEC_{y,eg,b,r} &= EQCUEC_{r,eg,b} * WTEQCEFFN_{y,eg,b,r} * RTBASEFF_{2001,eg} * \\ &\qquad HDDFACT_{y,r} * SQFTADJ_{y,b,r},\ if\ WTEQCEFFN_{y,eg,b,r} > 0 \\ EQCNUEC_{y,eg,b,r} &= EQCUEC_{r,eg,b} * HDDFACT_{y,r} * SQFTADJ_{y,b,r} \qquad ,\ otherwise \end{aligned} \tag{B-44}$$

where,

$EQCNUEC_{y,eg,b,r}$	is the unit energy consumption for new equipment by forecast year, housing type and Census Division,
$WTEQCEFFN_{y,eg,b,r}$	is the equipment class efficiency weighted by the market share of the specific equipment as computed in the logistic function in the technology choice component by housing type and Census Division,
$RTBASEFF_{2001,eg}$	is the 2001 stock-average efficiency of the equipment class,
$EQCUEC_{r,eg,b}$	is unit energy consumption for original 2001 stock of the equipment class by Census Division and housing type,
$HDDFACT_{y,r}$	is the heating degree day adjustment factor by Census Division to correct to normal weather relative to the RECS survey year, and
$SQFTADJ_{y,b,r}$	is the adjustment for increasing floor area of new houses.

Replacement equipment UEC values are calculated as:

$$\begin{aligned} EQCRUEC_{y,eg,b,r} &= EQCUEC_{r,eg,b} * WTEQCEFFR_{y,eg,b,r} * RTBASEFF_{2001,eg} * \\ &\qquad HDDFACT_{y,r},\ if\ WTEQCEFFR_{y,eg,b,r} > 0 \\ EQCRUEC_{y,eg,b,r} &= EQCUEC_{r,eg,b} * HDDFACT_{y,r} \qquad ,\ otherwise \end{aligned} \tag{B-45}$$

For the end use water heating, there is an adjustment for changes in household size (people per household). Annual UEC for water heating is calculated as follows:

$$EQCNUEC_{y,eg,b,r} = EQCUEC_{r,eg,b} * WTEQCEFFN_{y,eg,b,r} * RTBASEFF_{2001,eg} * \left(\frac{HHSIZE_{y,r}}{HHSIZE_{2001,r}}\right)^{HHSELAS}, \text{ if } WTEQCEFFN_{y,eg,b,r} > 0 \quad \text{(B-88)}$$

$$EQCNUEC_{y,eg,b,r} = EQCUEC_{r,eg,b} * \left(\frac{HHSIZE_{y,r}}{HHSIZE_{2001,r}}\right)^{HHSELAS}, \text{ otherwise}$$

where,

$EQCNUEC_{y,eg,b,r}$	is the unit energy consumption for new equipment by year, housing type and Census Division,
$EQCUEC_{r,eg,b}$	is the unit energy consumption for the equipment class by housing type and Census Division,
$WTEQCEFFN_{y,eg,b,r}$	is the weighted average inverse efficiency for new water heating equipment types by year, class, housing type and Census Division,
$HHSIZE_{y,r}$	is the average household size by year and Census Division,
$HHSELAS$	is an elasticity parameter for the increase in hot water intensity due to increases in household size, estimated at .315, and
$RTBASEFF_{y,eg}$	is the efficiency of the water heating equipment classes.

The efficiency for equipment types are measured differently across equipment classes. Sometimes more efficient equipment has a higher number as with heating, where efficiency is measured as units of heat out per unit of energy in. For other end uses, such as refrigeration, lower numbers are more efficient (kWh/year) and UEC is a reciprocal calculation to the ones shown above where higher numbers are more efficient.

$$EQCNUEC_{y,eg,b,r} = EQCUEC_{r,eg,b} * \frac{WTEQCEFFN_{y,eg,b,r}}{RTBASEFF_{2001,eg}} \quad \text{(B-125)}$$

The UEC numbers for the base stock and the base efficiencies for equipment classes are available in the NEMS input files RSUEC10.TXT and RTEKCL.TXT respectively. The weighted average inverse efficiency in the equations above is determined by the market share of technology types within a class.

$$WTEQCEFFN_{y,eg,b,r} = \frac{\sum_{es}\left[\frac{NEQTSHR_{y,es,b,r}}{RTEQEFF_{y,es}}\right]}{\sum_{es} NEQTSHR_{y,es,b,r}}, if \sum_{es} NEQTSHR_{y,es,b,r} > 0$$

$$WTEQCEFFN_{y,eg,b,r} = \frac{1}{RTBASEFF_{eg}}, otherwise \qquad \text{(B-28)}$$

$$WTEQCEFFR_{y,eg,b,r} = \frac{\sum_{es}\left[\frac{REQTSHR_{y,es,b,r}}{RTEQEFF_{y,es}}\right]}{\sum_{es} REQTSHR_{y,es,b,r}}, if \sum_{es} REQTSHR_{y,es,b,r} > 0$$

$$WTEQCEFFR_{y,eg,b,r} = \frac{1}{RTBASEFF_{eg}}, otherwise \qquad \text{(B-29)}$$

where,

$WTEQCEFFN_{y,eg,b,r}$ is the weighted average efficiency of new equipment type within each equipment class by year, housing type, and Census Division,

$RTEQEFF_{y,es}$ is the efficiency of the equipment type,

$RTBASEFF_{eg}$ is the 2001 stock-average efficiency of the equipment class, and

$WTEQCEFFR_{y,eg,b,r}$ is the weighted average efficiency of replacement equipment types within each equipment class by year, housing type, and Census Division.

In order to calculate the implied UEC for each equipment type we used equation B-125, but instead of using a weighted average inverse efficiency, we used the inverse efficiency of each type. In other words, the implied UEC for a technology type is the UEC for the equipment class if that technology had 100% of the market share.

Note: For heating and cooling end uses, we used the heating degree day and cooling degree day adjustment parameters from the NEMS input file RMISC.TXT, but we did not make a square footage adjustment. For water heating, we did not make the housing size adjustment.

Appendix 1: Memo from Erica Myers

Appendix 2. Raw RREEM Database for 2009

Sim.	Region	End use	Tech Class	Tech Type	Stock	UEC	Max life (year)	Min life (year)	Avg life (year)	Capital cost ($/unit)	Retail cost ($/unit)	Fuel type	Base Stock	Base UEC	New Ship.	Ret.
4	1	1	1	1	60,451	28	25	10	17.5	1900	1200	4	222935.8597	29	15,661	16,370
4	1	1	2	1	8,875	21	21	7	14	3162	2700	4	0	21	2,272	21
4	1	1	2	2	3,748	19	21	7	14	3495	3500	4	0	21	974	9
4	1	1	2	3	615	17	21	7	14	4660	4250	4	0	21	118	2
4	1	1	2	4	355	15	21	7	14	5825	5000	4	0	21	68	1
4	1	2	12	1	1,216,111	1	16	8	12	310	275	4	3787003.32	2	340,849	341,698
4	1	2	12	2	122,050	1	16	8	12	450	325	4	376659.468	2	35,469	33,984
4	1	2	12	3	33	1	16	8	12	925	825	4	100.042355	2	11	9
4	1	2	13	1	174,693	6	21	7	14	3000	1800	4	236966.2256	10	43,912	19,622
4	1	2	13	2	64,865	6	21	7	14	3200	2000	4	206752.4218	10	17,258	16,907
4	1	2	13	3	38,487	5	21	7	14	3600	2400	4	123877.9508	10	10,396	10,129
4	1	2	13	4	4,027	4	21	7	14	6000	4000	4	6696.105447	10	988	552
4	1	2	14	1	8,875	4	21	7	14	638	0	4	0	6	2,272	21
4	1	2	14	2	3,748	3	21	7	14	705	0	4	0	6	974	9
4	1	2	14	3	615	3	21	7	14	940	0	4	0	6	118	2
4	1	2	14	4	355	3	21	7	14	1175	0	4	0	6	68	1
4	1	3	17	1	353,376	0	18	11	14.5	700	600	4	1959796.89	0	53,098	167,038
4	1	3	17	2	455,926	0	18	11	14.5	800	710	4	733700.2456	0	131,101	63,216
4	1	3	17	3	301,371	0	18	11	14.5	950	850	4	441577.8936	0	99,993	38,066
4	1	4	18	1	26,510	2	18	11	14.5	745	645	4	117538.3182	1	4,973	8,545
4	1	4	18	2	734,548	1	18	11	14.5	750	650	4	2322937.392	1	192,934	169,246
4	1	4	18	3	102	1	18	11	14.5	1200	900	4	203.245296	1	35	15
4	1	6	26	1	286,343	1	21	16	18.5	400	350	4	1478139.868	1	72,106	64,489
4	1	6	26	2	286,343	1	21	16	18.5	400	350	4	1478139.868	1	72,106	64,489
4	1	7	28	1	205,575	3	20	11	15.5	375	375	4	139772.9664	3	50,168	9,935
4	1	7	28	2	556,501	3	20	11	15.5	450	450	4	341287.7176	3	145,470	24,359
4	1	8	29	1	597,579	2	26	7	16.5	550	500	4	2222736.962	3	157,028	146,861
4	1	8	29	2	375,949	2	26	7	16.5	600	550	4	1376695.231	3	101,508	90,966
4	1	8	29	3	17,562	2	26	7	16.5	800	750	4	171564.3934	3	2,411	11,275
4	1	8	29	4	107	2	26	7	16.5	1050	1000	4	1339.074477	3	9	88
4	1	8	29	5	410,788	3	26	7	16.5	1400	1350	4	1563369.451	3	108,150	103,272
4	1	9	30	1	72,727	2	31	11	21	400	350	4	351950.5319	2	17,945	16,903
4	1	9	30	2	34,836	2	31	11	21	450	400	4	166555.0875	2	8,819	7,999
4	1	9	30	3	17,402	1	31	11	21	500	450	4	82124.05251	2	4,525	3,944
4	1	9	30	4	93,139	2	31	11	21	500	450	4	447645.0695	2	23,320	21,499
4	2	1	1	1	229,366	24	25	10	17.5	1900	1200	4	857754.3216	25	59,030	62,979
4	2	1	2	1	47,691	22	21	7	14	3015	2700	4	56448.92055	22	12,160	4,295
4	2	1	2	2	41,408	21	21	7	14	3332	3500	4	45587.9514	22	10,838	3,475
4	2	1	2	3	18,564	18	21	7	14	4443	4250	4	26361.5756	22	4,474	1,998
4	2	1	2	4	13,155	16	21	7	14	5524	5000	4	17275.61921	22	3,308	1,311
4	2	2	12	1	3,206,259	1	16	8	12	310	275	4	10308998.53	2	903,084	929,939
4	2	2	12	2	318,113	1	16	8	12	450	325	4	1008439.448	2	93,306	90,966
4	2	2	12	3	102	1	16	8	12	925	825	4	314.311367	2	34	28
4	2	2	13	1	873,244	5	21	7	14	3000	1800	4	1672751.952	8	224,148	137,637
4	2	2	13	2	437,437	4	21	7	14	3200	2000	4	1359393.864	8	116,257	111,191
4	2	2	13	3	243,892	4	21	7	14	3600	2400	4	759042.334	8	65,341	62,083
4	2	2	13	4	9,792	3	21	7	14	6000	4000	4	29673.45968	8	1,823	2,430
4	2	2	14	1	47,691	4	21	7	14	785	0	4	56448.92055	7	12,160	4,295
4	2	2	14	2	41,408	4	21	7	14	868	0	4	45587.9514	7	10,838	3,475
4	2	2	14	3	18,564	4	21	7	14	1157	0	4	26361.5756	7	4,474	1,998
4	2	2	14	4	13,155	3	21	7	14	1446	0	4	17275.61921	7	3,308	1,311

4	2	3	17	1	1,325,380	0	18	11	14.5	700	600	4	6830360.64	0	226,617	582,349
4	2	3	17	2	1,143,056	0	18	11	14.5	800	710	4	1150973.445	0	358,790	100,053
4	2	3	17	3	487,437	0	18	11	14.5	950	850	4	433706.322	0	171,311	37,768
4	2	4	18	1	90,678	2	18	11	14.5	745	645	4	398621.6456	1	17,818	28,979
4	2	4	18	2	1,646,777	1	18	11	14.5	750	650	4	5250824.901	1	434,226	382,540
4	2	4	18	3	150	1	18	11	14.5	1200	900	4	328.392553	1	51	24
4	2	6	26	1	547,509	1	21	16	18.5	400	350	4	2512156.198	1	136,657	109,757
4	2	6	26	2	547,509	1	21	16	18.5	400	350	4	2512156.198	1	136,657	109,757
4	2	7	28	1	430,519	3	20	11	15.5	375	375	4	936030.8368	3	105,354	64,237
4	2	7	28	2	1,047,656	3	20	11	15.5	450	450	4	2067291.278	3	272,596	142,055
4	2	8	29	1	1,719,263	2	26	7	16.5	550	500	4	6419188.047	3	451,980	424,124
4	2	8	29	2	995,747	2	26	7	16.5	600	550	4	3649347.726	3	267,982	241,141
4	2	8	29	3	42,157	2	26	7	16.5	800	750	4	411380.161	3	5,746	27,037
4	2	8	29	4	260	2	26	7	16.5	1050	1000	4	3130.499158	3	23	206
4	2	8	29	5	1,142,759	3	26	7	16.5	1400	1350	4	4344463.302	3	300,764	286,994
4	2	9	30	1	215,173	2	31	11	21	400	350	4	991963.6634	2	53,228	47,667
4	2	9	30	2	97,417	2	31	11	21	450	400	4	442941.514	2	24,634	21,286
4	2	9	30	3	45,764	1	31	11	21	500	450	4	204989.6858	2	11,843	9,852
4	2	9	30	4	267,059	2	31	11	21	500	450	4	1222087.831	2	66,852	58,727
4	3	1	1	1	342,231	19	25	10	17.5	1900	1200	4	1209052.495	19	87,946	89,586
4	3	1	2	1	158,496	18	21	7	14	3033	2700	4	200463.4908	18	41,164	15,389
4	3	1	2	2	98,007	17	21	7	14	3352	3500	4	143638.2829	18	26,902	10,979
4	3	1	2	3	32,787	15	21	7	14	4470	4250	4	56593.74066	18	7,256	4,316
4	3	1	2	4	20,568	13	21	7	14	5587	5000	4	34308.58898	18	4,648	2,618
4	3	2	12	1	1,688,054	2	16	8	12	310	275	4	5173305.873	2	470,276	470,255
4	3	2	12	2	166,024	1	16	8	12	450	325	4	499329.8601	2	47,793	45,392
4	3	2	12	3	50	1	16	8	12	925	825	4	142.828907	2	17	13
4	3	2	13	1	1,686,079	5	21	7	14	3000	1800	4	3725204.786	8	432,383	308,513
4	3	2	13	2	993,546	5	21	7	14	3200	2000	4	2883547.916	8	259,843	237,931
4	3	2	13	3	516,718	4	21	7	14	3600	2400	4	1540770.099	8	136,274	127,091
4	3	2	13	4	18,317	3	21	7	14	6000	4000	4	50600.74227	8	3,645	4,182
4	3	2	14	1	158,496	5	21	7	14	767	0	4	200463.4908	8	41,164	15,389
4	3	2	14	2	98,007	5	21	7	14	848	0	4	143638.2829	8	26,902	10,979
4	3	2	14	3	32,787	4	21	7	14	1130	0	4	56593.74066	8	7,256	4,316
4	3	2	14	4	20,568	4	21	7	14	1413	0	4	34308.58898	8	4,648	2,618
4	3	3	17	1	2,911,774	0	18	11	14.5	700	600	4	11092345.8	0	622,524	954,426
4	3	3	17	2	1,066,854	0	18	11	14.5	800	710	4	365194.3608	0	367,113	33,736
4	3	3	17	3	166,541	0	18	11	14.5	950	850	4	52801.9872	0	62,236	4,889
4	3	4	18	1	297,555	2	18	11	14.5	745	645	4	1131547.218	1	64,938	83,060
4	3	4	18	2	2,153,620	1	18	11	14.5	750	650	4	6501268.727	1	564,833	478,154
4	3	4	18	3	74	1	18	11	14.5	1200	900	4	171.837087	1	23	13
4	3	6	26	1	800,106	1	21	16	18.5	400	350	4	3970574.477	1	197,924	175,670
4	3	6	26	2	800,106	1	21	16	18.5	400	350	4	3970574.477	1	197,924	175,670
4	3	7	28	1	754,385	4	20	11	15.5	375	375	4	1349745.93	4	185,581	93,944
4	3	7	28	2	1,568,049	3	20	11	15.5	450	450	4	2590226.867	4	405,262	180,547
4	3	8	29	1	2,332,982	2	26	7	16.5	550	500	4	8559271.405	3	608,341	570,998
4	3	8	29	2	1,122,051	2	26	7	16.5	600	550	4	4076664.473	3	297,447	271,970
4	3	8	29	3	39,297	2	26	7	16.5	800	750	4	373470.6796	3	5,098	24,763
4	3	8	29	4	223	2	26	7	16.5	1050	1000	4	2586.888214	3	18	171
4	3	8	29	5	1,448,246	3	26	7	16.5	1400	1350	4	5392558.429	3	377,506	359,685
4	3	9	30	1	467,412	2	31	11	21	400	350	4	2215636.07	2	114,808	107,760
4	3	9	30	2	186,703	2	31	11	21	450	400	4	877546.3326	2	46,701	42,682
4	3	9	30	3	76,494	1	31	11	21	500	450	4	356281.3695	2	19,500	17,329
4	3	9	30	4	544,467	2	31	11	21	500	450	4	2570583.645	2	134,892	125,026
4	4	1	1	1	285,235	15	25	10	17.5	1900	1200	4	932328.3795	15	72,794	69,459

4	4	1	2	1	84,098	20	21	7	14	2997	2700	4	59548.0575	20	20,250	4,712
4	4	1	2	2	30,901	19	21	7	14	3313	3500	4	41187.19855	20	8,372	3,173
4	4	1	2	3	8,857	17	21	7	14	4417	4250	4	14930.67131	20	1,888	1,146
4	4	1	2	4	5,548	15	21	7	14	5521	5000	4	8849.884121	20	1,177	680
4	4	2	12	1	514,355	2	16	8	12	310	275	4	1641032.661	3	144,582	149,673
4	4	2	12	2	51,434	2	16	8	12	450	325	4	162099.1519	3	14,990	14,784
4	4	2	12	3	13	2	16	8	12	925	825	4	42.822953	3	4	4
4	4	2	13	1	801,315	6	21	7	14	3000	1800	4	1944236.215	8	208,231	161,494
4	4	2	13	2	485,200	6	21	7	14	3200	2000	4	1570263.144	8	126,937	129,952
4	4	2	13	3	259,912	5	21	7	14	3600	2400	4	871703.2308	8	68,720	72,110
4	4	2	13	4	9,777	4	21	7	14	6000	4000	4	33260.69488	8	1,863	2,754
4	4	2	14	1	84,098	6	21	7	14	803	0	4	59548.0575	8	20,250	4,712
4	4	2	14	2	30,901	5	21	7	14	887	0	4	41187.19855	8	8,372	3,173
4	4	2	14	3	8,857	5	21	7	14	1183	0	4	14930.67131	8	1,888	1,146
4	4	2	14	4	5,548	4	21	7	14	1479	0	4	8849.884121	8	1,177	680
4	4	3	17	1	1,367,765	0	18	11	14.5	700	600	4	4892984.255	0	300,953	422,886
4	4	3	17	2	404,783	0	18	11	14.5	800	710	4	114358.5935	0	141,806	10,828
4	4	3	17	3	49,539	0	18	11	14.5	950	850	4	13503.35935	0	19,074	1,276
4	4	4	18	1	184,268	2	18	11	14.5	745	645	4	665559.9536	1	41,107	49,102
4	4	4	18	2	1,067,053	1	18	11	14.5	750	650	4	3212725.369	1	280,006	237,401
4	4	4	18	3	24	1	18	11	14.5	1200	900	4	62.489492	1	7	5
4	4	6	26	1	440,142	2	21	16	18.5	400	350	4	2160206.528	2	108,531	96,264
4	4	6	26	2	440,142	2	21	16	18.5	400	350	4	2160206.528	2	108,531	96,264
4	4	7	28	1	407,876	4	20	11	15.5	375	375	4	408617.8698	4	100,572	29,135
4	4	7	28	2	775,862	3	20	11	15.5	450	450	4	731872.3872	4	199,898	52,285
4	4	8	29	1	1,065,111	2	26	7	16.5	550	500	4	3887218.758	3	277,510	260,624
4	4	8	29	2	490,549	2	26	7	16.5	600	550	4	1784261.856	3	129,985	119,624
4	4	8	29	3	16,452	2	26	7	16.5	800	750	4	156517.3706	3	2,128	10,425
4	4	8	29	4	86	2	26	7	16.5	1050	1000	4	1048.874349	3	7	70
4	4	8	29	5	651,567	3	26	7	16.5	1400	1350	4	2415720.383	3	169,763	161,935
4	4	9	30	1	273,694	2	31	11	21	400	350	4	1330680.912	2	67,313	65,117
4	4	9	30	2	106,291	2	31	11	21	450	400	4	513990.1311	2	26,714	25,152
4	4	9	30	3	42,230	1	31	11	21	500	450	4	203043.0465	2	10,853	9,936
4	4	9	30	4	314,647	2	31	11	21	500	450	4	1526019.755	2	78,159	74,675
4	5	1	1	1	1,821,110	5	25	10	17.5	1900	1200	4	6116554.836	5	468,184	452,512
4	5	1	2	1	3,048,307	7	21	7	14	1725	2700	4	1575098.3	7	753,178	125,526
4	5	1	2	2	814,845	6	21	7	14	1907	3500	4	1271616.03	7	225,920	96,809
4	5	1	2	3	431,590	6	21	7	14	2542	4250	4	879908.3439	7	94,122	66,737
4	5	1	2	4	311,005	5	21	7	14	3178	5000	4	608874.0885	7	69,674	46,208
4	5	2	12	1	1,422,634	2	16	8	12	310	275	4	4697640.688	3	400,629	425,974
4	5	2	12	2	145,980	2	16	8	12	450	325	4	473914.4866	3	42,610	42,975
4	5	2	12	3	46	2	16	8	12	925	825	4	128.761672	3	16	12
4	5	2	13	1	1,711,736	10	21	7	14	3000	1800	4	3772130.786	12	444,521	311,753
4	5	2	13	2	997,358	9	21	7	14	3200	2000	4	3313185.014	12	265,166	272,457
4	5	2	13	3	640,201	9	21	7	14	3600	2400	4	1984413.979	12	164,978	163,318
4	5	2	13	4	35,953	6	21	7	14	6000	4000	4	102451.8053	12	6,505	8,449
4	5	2	14	1	3,048,307	10	21	7	14	2075	0	4	1575098.3	12	753,178	125,526
4	5	2	14	2	814,845	10	21	7	14	2293	0	4	1271616.03	12	225,920	96,809
4	5	2	14	3	431,590	9	21	7	14	3058	0	4	879908.3439	12	94,122	66,737
4	5	2	14	4	311,005	8	21	7	14	3822	0	4	608874.0885	12	69,674	46,208
4	5	3	17	1	3,970,950	0	18	11	14.5	700	600	4	13080853.22	0	827,668	1,125,100
4	5	3	17	2	1,552,050	0	18	11	14.5	800	710	4	585380.085	0	529,161	53,512
4	5	3	17	3	264,299	0	18	11	14.5	950	850	4	101329.7064	0	97,840	9,225
4	5	4	18	1	442,196	2	18	11	14.5	745	645	4	1394945.613	1	98,476	102,386
4	5	4	18	2	3,758,948	1	18	11	14.5	750	650	4	9367446.841	1	966,979	689,286
4	5	4	18	3	157	1	18	11	14.5	1200	900	4	312.389845	1	46	23
4	5	6	26	1	1,882,207	2	21	16	18.5	400	350	4	7282891.454	2	462,074	322,310
4	5	6	26	2		2	21	16	18.5	400	350	4	7282891.454	2	462,074	322,310

					1,882,207										
4	5	7	28	1	1,552,437	3	20	11	15.5	375	375	4	298006.9501	4	380,972	24,439
4	5	7	28	2	3,109,262	3	20	11	15.5	450	450	4	565417.6461	4	792,944	46,704
4	5	8	29	1	3,197,132	2	26	7	16.5	550	500	4	9846305.156	3	824,088	656,764
4	5	8	29	2	1,569,446	2	26	7	16.5	600	550	4	4850831.239	3	409,732	323,525
4	5	8	29	3	58,288	2	26	7	16.5	800	750	4	462371.654	3	7,182	30,625
4	5	8	29	4	345	2	26	7	16.5	1050	1000	4	3293.09075	3	27	218
4	5	8	29	5	1,999,707	3	26	7	16.5	1400	1350	4	6283886.626	3	514,319	419,041
4	5	9	30	1	528,087	2	31	11	21	400	350	4	2190877.815	2	129,264	106,421
4	5	9	30	2	214,066	2	31	11	21	450	400	4	887826.9479	2	53,301	43,123
4	5	9	30	3	89,120	1	31	11	21	500	450	4	369582.987	2	22,582	17,950
4	5	9	30	4	619,481	2	31	11	21	500	450	4	2569711.12	2	152,880	124,818
4	6	1	1	1	552,823	9	25	10	17.5	1900	1200	4	1822762.224	9	142,464	136,124
4	6	1	2	1	534,308	9	21	7	14	2212	2700	4	323236.6462	9	132,810	25,906
4	6	1	2	2	160,237	9	21	7	14	2445	3500	4	248013.7208	9	43,870	19,089
4	6	1	2	3	68,250	8	21	7	14	3260	4250	4	135392.995	9	14,674	10,380
4	6	1	2	4	46,010	7	21	7	14	4074	5000	4	87953.065	9	10,312	6,747
4	6	2	12	1	625,430	4	16	8	12	310	275	4	2063210.93	4	176,341	188,511
4	6	2	12	2	66,873	4	16	8	12	450	325	4	216749.5131	4	19,434	19,805
4	6	2	12	3	19	3	16	8	12	925	825	4	57.110734	4	7	5
4	6	2	13	1	521,411	9	21	7	14	3000	1800	4	1299226.622	12	140,242	108,120
4	6	2	13	2	389,993	9	21	7	14	3200	2000	4	1141336.971	12	100,980	94,792
4	6	2	13	3	222,914	8	21	7	14	3600	2400	4	683732.1707	12	56,976	56,757
4	6	2	13	4	11,725	6	21	7	14	6000	4000	4	35327.16325	12	2,258	2,936
4	6	2	14	1	534,308	10	21	7	14	1588	0	4	323236.6462	12	132,810	25,906
4	6	2	14	2	160,237	9	21	7	14	1755	0	4	248013.7208	12	43,870	19,089
4	6	2	14	3	68,250	8	21	7	14	2340	0	4	135392.995	12	14,674	10,380
4	6	2	14	4	46,010	7	21	7	14	2926	0	4	87953.065	12	10,312	6,747
4	6	3	17	1	1,298,850	0	18	11	14.5	700	600	4	4479339.97	0	283,633	388,152
4	6	3	17	2	418,691	0	18	11	14.5	800	710	4	137193.9136	0	144,832	12,887
4	6	3	17	3	56,357	0	18	11	14.5	950	850	4	19001.64102	0	21,159	1,774
4	6	4	18	1	145,085	2	18	11	14.5	745	645	4	485744.5089	1	32,945	35,959
4	6	4	18	2	954,007	1	18	11	14.5	750	650	4	2690447.682	1	248,897	199,518
4	6	4	18	3	24	1	18	11	14.5	1200	900	4	46.800704	1	7	3
4	6	6	26	1	529,411	2	21	16	18.5	400	350	4	2368108.671	2	131,125	106,088
4	6	6	26	2	529,411	2	21	16	18.5	400	350	4	2368108.671	2	131,125	106,088
4	6	7	28	1	477,978	4	20	11	15.5	375	375	4	51201.78594	4	118,014	4,987
4	6	7	28	2	978,072	3	20	11	15.5	450	450	4	99483.81752	4	251,217	9,802
4	6	8	29	1	916,733	2	26	7	16.5	550	500	4	3080328.899	3	238,575	207,321
4	6	8	29	2	430,973	2	26	7	16.5	600	550	4	1456210.001	3	113,513	97,997
4	6	8	29	3	15,030	2	26	7	16.5	800	750	4	132249.7075	3	1,889	8,835
4	6	8	29	4	79	2	26	7	16.5	1050	1000	4	903.221606	3	5	60
4	6	8	29	5	564,797	3	26	7	16.5	1400	1350	4	1935260.676	3	146,702	130,220
4	6	9	30	1	220,168	2	31	11	21	400	350	4	976173.8271	2	54,195	48,002
4	6	9	30	2	86,683	2	31	11	21	450	400	4	384669.0024	2	21,702	18,914
4	6	9	30	3	34,956	1	31	11	21	500	450	4	155313.2155	2	8,903	7,636
4	6	9	30	4	254,727	2	31	11	21	500	450	4	1129860.726	2	63,196	55,557
4	7	1	1	1	1,146,615	8	25	10	17.5	1900	1200	4	3593958.951	7	294,111	273,659
4	7	1	2	1	568,942	9	21	7	14	1700	2700	4	139617.7483	8	146,822	12,832
4	7	1	2	2	138,419	8	21	7	14	1879	3500	4	116167.4843	8	29,670	9,416
4	7	1	2	3	52,494	7	21	7	14	2505	4250	4	87334.99059	8	11,762	6,866
4	7	1	2	4	47,092	6	21	7	14	3182	5000	4	61864.8509	8	10,283	4,905
4	7	2	12	1	1,311,530	4	16	8	12	310	275	4	4334659.381	5	369,574	402,158
4	7	2	12	2	142,472	4	16	8	12	450	325	4	469541.2839	5	42,050	43,554
4	7	2	12	3	48	4	16	8	12	925	825	4	142.2249	5	17	13
4	7	2	13	1	1,192,536	13	21	7	14	3000	1800	4	2376115.753	16	307,321	202,240
4	7	2	13	2	807,847	12	21	7	14	3200	2000	4	2442666.147	16	209,416	206,286
4	7	2	13	3	503,567	11	21	7	14	3600	2400	4	1693751.99	16	137,002	142,788
4	7	2	13	4	46,350	8	21	7	14	6000	4000	4	160383.2973	16	10,015	13,529
4	7	2	14	1	568,942	14	21	7	14	1868	0	4	139617.7483	16	146,822	12,832
4	7	2	14	2	138,419	13	21	7	14	2321	0	4	116167.4843	16	29,670	9,416

4	7	2	14	3	52,494	12	21	7	14	3095	0	4	87334.99059	16	11,762	6,866
4	7	2	14	4	47,092	11	21	7	14	3868	0	4	61864.8509	16	10,283	4,905
4	7	3	17	1	1,974,086	0	18	11	14.5	700	600	4	7113263.116	0	389,516	626,318
4	7	3	17	2	934,867	0	18	11	14.5	800	710	4	422946.4743	0	319,497	39,948
4	7	3	17	3	199,638	0	18	11	14.5	950	850	4	86488.12809	0	76,816	8,153
4	7	4	18	1	184,488	2	18	11	14.5	745	645	4	633754.4392	1	38,788	47,805
4	7	4	18	2	1,888,052	1	18	11	14.5	750	650	4	4917241.284	1	490,862	372,299
4	7	4	18	3	89	1	18	11	14.5	1200	900	4	155.278688	1	29	12
4	7	6	26	1	786,396	2	21	16	18.5	400	350	4	2812316.668	2	193,536	130,288
4	7	6	26	2	786,396	2	21	16	18.5	400	350	4	2812316.668	2	193,536	130,288
4	7	7	28	1	640,132	4	20	11	15.5	375	375	4	237258.8622	4	154,216	19,045
4	7	7	28	2	1,665,625	4	20	11	15.5	450	450	4	564783.276	4	430,439	45,743
4	7	8	29	1	1,637,873	2	26	7	16.5	550	500	4	5119974.126	3	422,891	352,161
4	7	8	29	2	835,526	2	26	7	16.5	600	550	4	2600242.419	3	220,533	178,839
4	7	8	29	3	32,020	2	26	7	16.5	800	750	4	256799.8571	3	4,089	17,492
4	7	8	29	4	185	2	26	7	16.5	1050	1000	4	1816.30151	3	15	124
4	7	8	29	5	1,038,399	3	26	7	16.5	1400	1350	4	3306657.824	3	268,355	227,362
4	7	9	30	1	300,945	2	31	11	21	400	350	4	1312695.144	2	73,619	66,296
4	7	9	30	2	125,197	2	31	11	21	450	400	4	543043.8577	2	31,368	27,425
4	7	9	30	3	53,625	1	31	11	21	500	450	4	231216.9264	2	13,773	11,676
4	7	9	30	4	357,537	2	31	11	21	500	450	4	1555244.69	2	88,503	78,545
4	8	1	1	1	280,927	8	25	10	17.5	1900	1200	4	995421.2058	8	72,107	74,550
4	8	1	2	1	238,601	4	21	7	14	1576	2700	4	144607.5181	3	60,070	11,657
4	8	1	2	2	105,964	3	21	7	14	1742	3500	4	113211.0932	3	28,860	8,855
4	8	1	2	3	43,508	3	21	7	14	2323	4250	4	76479.72887	3	9,304	5,905
4	8	1	2	4	33,142	3	21	7	14	2903	5000	4	53005.99554	3	7,020	4,103
4	8	2	12	1	346,508	2	16	8	12	310	275	4	621693.2253	2	88,858	57,507
4	8	2	12	2	36,528	2	16	8	12	450	325	4	67426.8676	2	9,585	6,233
4	8	2	12	3	4	2	16	8	12	925	825	4	0	2	2	0
4	8	2	13	1	660,253	13	21	7	14	3000	1800	4	988333.0374	15	163,903	83,434
4	8	2	13	2	297,522	12	21	7	14	3200	2000	4	955038.5913	15	79,405	79,491
4	8	2	13	3	194,295	11	21	7	14	3600	2400	4	622436.3841	15	52,420	51,806
4	8	2	13	4	23,545	8	21	7	14	6000	4000	4	44219.18622	15	3,276	3,725
4	8	2	14	1	238,601	13	21	7	14	2224	0	4	144607.5181	15	60,070	11,657
4	8	2	14	2	105,964	12	21	7	14	2458	0	4	113211.0932	15	28,860	8,855
4	8	2	14	3	43,508	11	21	7	14	3177	0	4	76479.72887	15	9,304	5,905
4	8	2	14	4	33,142	10	21	7	14	4097	0	4	53005.99554	15	7,020	4,103
4	8	3	17	1	1,414,185	0	18	11	14.5	700	600	4	4767808.284	0	293,014	414,670
4	8	3	17	2	539,436	0	18	11	14.5	800	710	4	161504.5501	0	184,848	15,417
4	8	3	17	3	90,831	0	18	11	14.5	950	850	4	23729.80693	0	33,481	2,288
4	8	4	18	1	164,793	2	18	11	14.5	745	645	4	570021.126	1	35,060	42,350
4	8	4	18	2	1,335,529	1	18	11	14.5	750	650	4	3322920.857	1	343,326	247,900
4	8	4	18	3	47	1	18	11	14.5	1200	900	4	77.914315	1	15	6
4	8	6	26	1	479,681	1	21	16	18.5	400	350	4	1858928.343	1	117,071	83,978
4	8	6	26	2	479,681	1	21	16	18.5	400	350	4	1858928.343	1	117,071	83,978
4	8	7	28	1	503,369	3	20	11	15.5	375	375	4	339719.1604	3	121,134	24,995
4	8	7	28	2	973,780	3	20	11	15.5	450	450	4	604139.7832	3	246,222	44,658
4	8	8	29	1	1,080,626	2	26	7	16.5	550	500	4	3364869.537	3	276,385	227,678
4	8	8	29	2	526,055	2	26	7	16.5	600	550	4	1607733.513	3	137,094	108,805
4	8	8	29	3	19,090	2	26	7	16.5	800	750	4	147813.699	3	2,377	9,921
4	8	8	29	4	104	2	26	7	16.5	1050	1000	4	1029.116996	3	6	69
4	8	8	29	5	673,817	3	26	7	16.5	1400	1350	4	2122472.558	3	172,348	143,588
4	8	9	30	1	240,958	2	31	11	21	400	350	4	969913.1076	2	58,252	48,025
4	8	9	30	2	96,930	2	31	11	21	450	400	4	384985.0631	2	23,844	19,065
4	8	9	30	3	40,027	1	31	11	21	500	450	4	156662.6409	2	10,027	7,759
4	8	9	30	4	281,635	2	31	11	21	500	450	4	1126462.863	2	68,654	55,780
4	9	1	1	1	926,442	9	25	10	17.5	1900	1200	4	3264858.719	8	239,265	243,780
4	9	1	2	1	263,110	7	21	7	14	2915	2700	4	183368.0669	7	66,922	14,581
4	9	1	2	2	87,116	7	21	7	14	3222	3500	4	122456.0877	7	22,926	9,460
4	9	1	2	3	22,683	6	21	7	14	4296	4250	4	42061.88352	7	4,638	3,233
4	9	1	2	4	15,338	5	21	7	14	5370	5000	4	25025.99893	7	3,541	1,928
4	9	2	12	1		1	16	8	12	310	275	4	2650522.323	1	273,049	242,942

					1,003,924											
4	9	2	12	2	95,224	0	16	8	12	450	325	4	251429.3437	1	26,016	23,045
4	9	2	12	3	24	0	16	8	12	925	825	4	71.234515	1	6	7
4	9	2	13	1	1,020,430	5	21	7	14	3000	1800	4	1993968.342	6	263,223	166,753
4	9	2	13	2	502,273	4	21	7	14	3200	2000	4	1647107.326	6	130,455	136,692
4	9	2	13	3	296,500	4	21	7	14	3600	2400	4	934346.6119	6	74,932	77,585
4	9	2	13	4	21,080	3	21	7	14	6000	4000	4	39209.24	6	3,621	3,290
4	9	2	14	1	263,110	5	21	7	14	885	0	4	183368.0669	5	66,922	14,581
4	9	2	14	2	87,116	4	21	7	14	978	0	4	122456.0877	5	22,926	9,460
4	9	2	14	3	22,683	4	21	7	14	1304	0	4	42061.88352	5	4,638	3,233
4	9	2	14	4	15,338	4	21	7	14	1630	0	4	25025.99893	5	3,541	1,928
4	9	3	17	1	2,264,669	0	18	11	14.5	700	600	4	8976853.931	0	462,876	777,352
4	9	3	17	2	1,146,143	0	18	11	14.5	800	710	4	575949.0776	0	375,690	52,593
4	9	3	17	3	262,377	0	18	11	14.5	950	850	4	123167.2709	0	88,269	11,286
4	9	4	18	1	223,471	2	18	11	14.5	745	645	4	837682.6156	1	49,255	61,974
4	9	4	18	2	2,412,749	1	18	11	14.5	750	650	4	6755667.309	1	622,781	501,403
4	9	4	18	3	125	1	18	11	14.5	1200	900	4	249.296391	1	37	19
4	9	6	26	1	806,563	1	21	16	18.5	400	350	4	3503200.999	1	198,393	157,175
4	9	6	26	2	806,563	1	21	16	18.5	400	350	4	3503200.999	1	198,393	157,175
4	9	7	28	1	599,477	3	20	11	15.5	375	375	4	1333038.645	3	147,531	93,210
4	9	7	28	2	1,294,476	3	20	11	15.5	450	450	4	2648923.418	3	330,369	185,494
4	9	8	29	1	2,161,599	2	26	7	16.5	550	500	4	7456614.707	3	562,984	502,046
4	9	8	29	2	1,118,551	2	26	7	16.5	600	550	4	3820234.809	3	293,425	257,238
4	9	8	29	3	42,951	2	26	7	16.5	800	750	4	381222.4645	3	5,369	25,484
4	9	8	29	4	388	2	26	7	16.5	1000	1050	4	2760.259196	3	66	185
4	9	8	29	5	1,377,352	3	26	7	16.5	1400	1350	4	4832582.421	3	357,174	325,307
4	9	9	30	1	296,015	2	31	11	21	400	350	4	1349574.626	2	72,864	66,398
4	9	9	30	2	124,026	2	31	11	21	450	400	4	561585.9786	2	30,718	27,632
4	9	9	30	3	53,541	1	31	11	21	500	450	4	240679.7051	2	13,347	11,843
4	9	9	30	4	352,932	2	31	11	21	500	450	4	1603606.63	2	87,141	78,899

Appendix 3. Historical and Projected Retail Fuel Prices by Census Division Level

Fuel prices were largely based on AEO 2008, with some modifications. Fuel price is taken as zero for solar and geothermal, since the capital costs of equipment installation are already included in the technology costs. The price of wood is taken to be the same as E85.

The price of coal is taken as the average price of non-metallurgical coal ("other coal") reported in the AEO 2008 detailed tables. The price of residential kerosene was assumed to be similar to the price of kerosene jet fuel in the AEO detailed tables.

Table 41 – Historical and estimated projections of distillate retail residential fuel price for each census division region between 2005 and 2030 (2006$/MMBTU).

DISTILLATE	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
YEAR/REGION	1	2	3	4	5	6	7	8	9	10
2005	16.67	17.32	16.39	15.81	17.21	17.45	15.43	16.94	17.31	16.98
2006	17.61	18.30	17.29	16.70	18.18	18.44	16.31	17.90	18.28	17.94
2007	19.11	19.47	18.65	18.42	19.35	20.62	18.23	19.52	21.48	19.32
2008	21.69	22.07	21.59	21.47	21.51	22.93	20.27	22.82	24.40	21.92
2009	17.96	18.11	17.13	16.33	17.86	17.63	16.64	16.50	15.86	17.86
2010	17.30	17.45	16.48	15.71	17.20	16.97	15.99	15.69	15.63	17.21
2011	16.60	16.76	15.73	15.16	16.51	16.18	15.29	15.23	14.73	16.50
2012	15.88	16.05	14.90	14.34	15.80	15.35	14.59	14.45	14.55	15.80
2013	15.18	15.35	14.20	13.66	15.10	14.69	13.90	13.76	14.42	15.12
2014	14.91	15.08	13.92	13.38	14.83	14.41	13.62	13.47	14.17	14.84
2015	14.33	14.50	13.31	12.76	14.25	13.79	13.05	12.86	13.76	14.27
2016	13.89	14.07	12.88	12.33	13.82	13.36	12.62	12.44	13.55	13.84
2017	13.90	14.08	12.89	12.35	13.83	13.37	12.63	12.47	13.60	13.86
2018	14.04	14.22	13.03	12.49	13.97	13.51	12.77	12.59	13.92	14.00
2019	14.20	14.37	13.18	12.63	14.12	13.66	12.92	12.73	14.20	14.16
2020	14.31	14.48	13.29	12.74	14.23	13.77	13.02	12.95	14.48	14.27
2021	14.41	14.59	13.39	12.85	14.33	13.88	13.13	13.01	14.61	14.38
2022	14.52	14.69	13.54	13.00	14.44	14.05	13.24	13.18	14.75	14.49
2023	14.72	14.89	13.74	13.19	14.64	14.24	13.43	13.45	15.08	14.69
2024	14.96	15.12	13.97	13.43	14.87	14.48	13.67	13.81	15.36	14.93
2025	15.16	15.33	14.18	13.64	15.08	14.69	13.87	13.98	15.53	15.14
2026	15.39	15.58	14.43	13.88	15.33	14.94	14.12	14.32	15.88	15.38
2027	15.59	15.76	14.60	14.06	15.50	15.12	14.29	14.45	16.23	15.57
2028	15.81	15.97	14.82	14.28	15.72	15.33	14.51	14.61	16.43	15.79
2029	16.06	16.23	15.07	14.53	15.97	15.59	14.76	14.88	16.72	16.04
2030	16.31	16.47	15.22	14.68	16.21	15.74	15.00	15.03	16.84	16.27

Table 42 – Historical and estimated projections of LPG retail residential fuel price for each census division region between 2005 and 2030 (2006$/MMBTU).

LPG	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
YEAR/REGION	1	2	3	4	5	6	7	8	9	10
2005	22.09	22.18	17.17	14.52	21.58	19.51	19.78	17.88	21.83	18.83
2006	27.69	27.31	20.03	20.03	25.46	24.65	24.65	21.29	25.70	23.08
2007	29.68	29.27	21.47	21.47	27.28	26.40	26.40	22.82	27.55	24.69
2008	32.20	31.75	23.30	23.30	29.60	28.66	28.66	24.76	29.90	26.80
2009	30.30	29.09	23.96	21.64	28.25	26.56	25.82	24.59	26.83	25.58
2010	29.78	28.64	23.64	21.23	27.92	26.21	25.38	24.18	26.41	25.21
2011	29.51	28.32	23.30	20.93	27.64	25.92	25.02	23.81	26.04	24.90
2012	29.24	28.07	23.07	20.72	27.46	25.73	24.82	23.65	25.85	24.70
2013	28.98	27.77	22.81	20.46	27.20	25.51	24.63	23.43	25.56	24.46
2014	28.69	27.55	22.61	20.26	26.99	25.31	24.43	23.33	25.42	24.27
2015	28.49	27.41	22.47	20.14	26.84	25.16	24.29	23.27	25.34	24.15
2016	28.41	27.36	22.42	20.10	26.78	25.11	24.24	23.23	25.29	24.11
2017	28.45	27.43	22.48	20.16	26.84	25.18	24.32	23.28	25.32	24.18
2018	28.49	27.49	22.55	20.22	26.92	25.26	24.40	23.33	25.35	24.26
2019	28.50	27.55	22.60	20.27	26.99	25.33	24.49	23.39	25.41	24.32
2020	28.39	27.46	22.48	20.08	26.97	25.31	24.47	23.07	25.29	24.23
2021	28.26	27.35	22.34	19.91	26.90	25.24	24.41	22.79	24.99	24.10
2022	28.36	27.48	22.48	20.07	27.03	25.37	24.54	22.95	25.03	24.24
2023	28.41	27.55	22.58	20.18	27.11	25.46	24.64	23.15	25.17	24.35
2024	28.52	27.67	22.72	20.32	27.24	25.59	24.78	23.36	25.34	24.50
2025	28.61	27.78	22.84	20.47	27.35	25.70	24.89	23.55	25.51	24.63
2026	28.72	27.90	22.98	20.63	27.44	25.79	24.98	23.77	25.72	24.78
2027	28.76	27.94	23.07	20.77	27.48	25.83	25.02	23.89	25.83	24.86
2028	28.98	28.17	23.30	20.98	27.72	26.09	25.29	24.12	26.04	25.10
2029	29.12	28.31	23.47	21.17	27.85	26.22	25.42	24.37	26.27	25.27
2030	29.25	28.45	23.63	21.35	27.99	26.35	25.56	24.57	26.48	25.43

Table 43 – Historical and estimated projections of natural gas retail residential fuel price for each census division region between 2005 and 2030 (2006$/MMBTU).

Natural Gas	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
YEAR/REGION	1	2	3	4	5	6	7	8	9	10
2005	15.53	14.35	11.77	11.88	15.65	13.90	12.59	10.92	11.79	12.85
2006	16.88	15.76	11.95	12.23	16.86	14.95	12.90	11.69	11.69	13.40
2007	15.16	13.94	11.51	11.74	14.31	13.05	11.80	11.39	12.18	12.52
2008	15.64	14.08	11.64	11.89	14.24	13.10	12.10	11.43	12.35	12.66
2009	15.80	14.19	11.59	11.86	14.35	12.89	11.99	11.43	12.23	12.65
2010	15.23	13.73	11.12	11.27	13.89	12.36	11.39	10.94	11.74	12.15
2011	14.99	13.47	10.82	10.99	13.66	12.09	11.09	10.65	11.41	11.86
2012	14.75	13.25	10.61	10.79	13.48	11.91	10.91	10.55	11.24	11.67
2013	14.55	13.02	10.38	10.57	13.31	11.74	10.77	10.39	11.00	11.46
2014	14.30	12.83	10.20	10.41	13.15	11.57	10.61	10.34	10.89	11.30
2015	14.14	12.72	10.08	10.30	13.03	11.43	10.48	10.32	10.83	11.20
2016	14.09	12.70	10.04	10.28	13.02	11.40	10.45	10.32	10.79	11.17
2017	14.18	12.82	10.14	10.39	13.15	11.50	10.58	10.45	10.86	11.28
2018	14.27	12.94	10.24	10.49	13.30	11.63	10.70	10.54	10.91	11.38
2019	14.33	13.03	10.32	10.58	13.43	11.73	10.82	10.65	11.01	11.48
2020	14.24	12.97	10.22	10.42	13.45	11.73	10.82	10.39	10.92	11.39
2021	14.15	12.91	10.12	10.31	13.45	11.68	10.79	10.17	10.67	11.29
2022	14.30	13.08	10.27	10.47	13.63	11.84	10.96	10.36	10.71	11.43
2023	14.40	13.20	10.41	10.63	13.78	11.97	11.10	10.60	10.88	11.58
2024	14.54	13.36	10.57	10.81	13.98	12.13	11.28	10.85	11.07	11.76
2025	14.69	13.52	10.72	10.98	14.17	12.28	11.43	11.09	11.27	11.94
2026	14.87	13.71	10.91	11.20	14.36	12.43	11.59	11.38	11.52	12.14
2027	14.92	13.78	11.00	11.32	14.44	12.46	11.64	11.53	11.63	12.23
2028	15.19	14.04	11.25	11.56	14.75	12.75	11.94	11.80	11.85	12.49
2029	15.39	14.25	11.45	11.80	14.97	12.93	12.13	12.11	12.11	12.72
2030	15.57	14.43	11.63	11.99	15.17	13.09	12.30	12.36	12.34	12.91

Table 44 – Historical and estimated projections of retail residential electricity prices for each census division region between 2005 and 2030 (2006$/MMBTU).

Electricity	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
YEAR/REGION	1	2	3	4	5	6	7	8	9	10
2005	40.71	37.84	25.48	23.56	26.75	22.49	30.42	26.27	31.25	28.52
2006	47.05	39.35	26.89	23.90	28.72	24.03	33.80	26.48	34.20	30.52
2007	45.21	39.89	27.57	24.52	28.81	25.81	30.93	28.24	32.77	30.36
2008	46.11	40.76	27.85	24.49	28.62	25.69	31.66	29.24	33.15	30.68
2009	47.72	41.98	28.84	25.75	29.83	26.83	33.12	29.85	33.33	31.74
2010	46.42	40.69	28.61	26.17	29.85	26.67	32.51	29.45	32.66	31.37
2011	46.42	40.05	28.24	25.89	29.13	26.17	31.91	28.80	31.78	30.77
2012	46.77	40.37	27.96	25.41	28.71	25.73	32.04	28.31	31.13	30.49
2013	46.39	40.05	27.67	25.46	28.44	25.47	31.99	28.44	31.15	30.31
2014	46.35	39.84	27.43	25.44	28.11	25.19	31.78	28.55	31.29	30.12
2015	45.87	40.05	27.47	25.15	27.88	24.99	31.90	28.68	31.30	30.04
2016	45.78	40.29	27.54	25.08	27.80	24.94	32.14	28.89	31.28	30.07
2017	46.10	40.59	27.67	25.12	27.82	24.98	32.30	29.09	31.35	30.17
2018	46.38	40.79	27.89	25.19	27.96	25.15	31.56	29.39	31.41	30.20
2019	46.42	40.65	27.84	25.16	27.97	25.19	32.19	29.72	31.47	30.30
2020	46.09	40.53	27.80	25.16	27.96	25.22	31.84	29.63	31.39	30.20
2021	45.76	40.15	27.70	25.09	27.86	25.13	31.97	29.47	31.30	30.09
2022	46.00	40.33	27.77	25.04	27.94	25.13	32.18	29.93	31.37	30.21
2023	46.17	40.52	27.82	25.03	28.00	25.07	32.05	30.28	31.30	30.24
2024	46.43	40.60	27.75	24.99	28.02	25.06	31.99	30.49	31.41	30.26
2025	46.38	40.76	27.70	24.94	28.06	25.09	32.07	30.94	31.60	30.33
2026	46.76	40.79	27.61	24.88	28.07	25.10	32.23	31.11	31.74	30.38
2027	46.59	40.80	27.56	24.83	28.06	25.12	32.16	31.18	31.78	30.36
2028	47.16	41.03	27.64	24.81	28.11	25.22	32.63	31.32	31.93	30.52
2029	47.52	40.93	27.68	24.86	28.18	25.33	32.47	31.54	32.13	30.57
2030	47.15	41.35	27.85	24.93	28.34	25.41	32.24	31.44	32.24	30.63

Table 45 – Historical and estimated projections of retail residential kerosene prices for each census division region between 2005 and 2030 (2006$/MMBTU).

Kerosene	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
YEAR/REGION	1	2	3	4	5	6	7	8	9	10
2005	13.49	13.23	13.01	13.23	12.98	12.95	12.69	13.76	14.00	13.30
2006	15.27	14.87	14.47	14.97	14.89	14.54	14.46	15.21	15.06	14.83
2007	15.43	15.05	14.65	15.14	15.06	14.70	14.63	15.37	15.24	15.00
2008	16.19	15.78	15.37	15.88	15.80	15.43	15.35	16.13	15.99	15.74
2009	17.24	16.38	16.03	16.63	16.97	16.17	16.08	16.88	15.83	16.27
2010	16.67	15.86	15.49	15.94	16.44	15.67	15.52	15.94	15.55	15.77
2011	16.19	15.41	15.08	15.51	15.99	15.23	15.04	15.97	15.63	15.50
2012	15.38	14.65	14.30	14.70	15.22	14.48	14.25	15.17	14.88	14.72
2013	14.73	14.04	13.64	14.02	14.60	13.87	13.60	14.48	14.22	14.08
2014	14.38	13.71	13.30	13.67	14.27	13.55	13.25	14.11	13.89	13.74
2015	13.78	13.14	12.73	13.09	13.70	12.99	12.67	13.51	13.31	13.16
2016	13.17	12.56	12.32	12.67	13.30	12.61	12.25	13.07	12.96	12.75
2017	13.18	12.59	12.34	12.68	13.33	12.64	12.26	13.06	13.17	12.82
2018	13.32	12.75	12.50	12.82	13.49	12.81	12.40	13.19	13.33	12.97
2019	13.49	12.93	12.66	12.98	13.66	12.99	12.56	13.33	13.49	13.13
2020	13.62	13.08	12.80	13.11	13.81	13.15	12.69	13.45	13.64	13.27
2021	13.77	13.24	12.96	13.26	13.97	13.32	12.84	13.58	13.79	13.42
2022	13.93	13.41	13.12	13.42	14.13	13.49	13.00	13.73	13.95	13.59
2023	14.10	13.59	13.30	13.59	14.31	13.68	13.17	13.89	14.13	13.76
2024	14.28	13.79	13.48	13.77	14.50	13.88	13.35	14.08	14.32	13.95
2025	14.48	13.99	13.68	13.96	14.70	14.08	13.54	14.27	14.52	14.15
2026	14.68	14.20	13.89	14.17	14.92	14.30	13.75	14.47	14.91	14.41
2027	14.91	14.44	14.12	14.40	15.15	14.54	13.97	14.69	15.22	14.66
2028	15.14	14.67	14.35	14.62	15.38	14.78	14.20	14.91	15.48	14.90
2029	15.37	14.91	14.58	14.85	15.62	15.02	14.43	15.13	15.79	15.15
2030	15.62	15.17	14.83	15.10	15.87	15.28	14.67	15.37	15.93	15.37

Table 46 – Historical and estimated projections of retail residential wood prices for each census division region between 2005 and 2030 (2006$/MMBTU).

Wood	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
YEAR/REGION	1	2	3	4	5	6	7	8	9	10
2005	23.89	23.89	23.89	23.89	23.89	23.89	23.89	23.89	23.89	23.89
2006	33.03	33.03	22.32	22.32	23.95	25.06	25.06	24.52	26.78	24.81
2007	26.75	26.75	24.95	24.95	24.89	24.36	24.36	24.86	27.20	25.49
2008	26.72	29.73	30.06	24.79	22.63	28.55	27.09	24.01	24.68	24.88
2009	26.45	29.43	29.76	24.55	22.40	28.27	26.82	23.77	24.43	25.16
2010	28.90	28.90	22.06	21.96	20.73	28.28	27.85	29.03	29.79	23.58
2011	28.62	28.55	21.87	21.76	19.77	26.89	19.36	27.63	29.92	22.11
2012	27.70	27.67	21.33	21.22	24.12	26.10	18.84	26.88	29.05	23.21
2013	26.83	26.85	20.86	20.75	18.84	25.40	18.37	26.14	28.24	21.21
2014	18.36	26.68	20.78	20.69	18.72	25.23	18.26	25.95	18.85	18.96
2015	17.98	25.87	20.25	16.53	18.62	24.46	22.21	25.18	18.55	17.61
2016	19.45	25.20	19.78	16.42	18.17	23.84	17.36	24.55	18.26	17.64
2017	17.46	25.29	16.48	16.11	19.37	23.93	17.44	24.67	21.70	16.55
2018	17.62	25.54	16.61	16.25	19.64	24.20	16.20	24.93	22.00	16.72
2019	18.93	26.39	17.94	17.59	20.31	25.03	18.75	25.74	19.44	18.54
2020	18.68	18.20	17.55	17.10	24.25	25.68	17.04	26.41	19.20	18.15
2021	17.36	17.93	16.97	16.87	16.75	16.20	19.45	17.16	17.70	17.28
2022	18.37	18.79	17.08	16.99	17.52	17.02	16.69	17.97	18.78	17.77
2023	18.92	19.35	17.77	17.45	20.21	17.59	17.26	21.02	19.37	18.36
2024	19.39	19.88	18.29	18.02	20.22	18.09	17.80	20.85	19.75	18.79
2025	19.28	22.72	18.18	17.88	20.43	18.07	17.70	20.78	19.56	18.50
2026	19.65	22.82	18.59	18.30	20.54	18.44	18.09	20.88	19.95	18.87
2027	19.82	23.00	18.73	18.46	20.66	18.60	18.24	20.81	20.11	19.02
2028	20.11	23.22	19.04	18.75	20.88	18.91	18.53	20.86	20.36	19.28
2029	20.42	23.41	19.38	19.09	21.08	19.23	18.85	21.00	20.70	19.58
2030	20.51	23.60	19.45	19.16	21.27	19.30	18.93	20.98	20.69	19.62

Table 47 – Historical and estimated projections of retail residential coal prices for each census division region between 2005 and 2030 (2006$/MMBTU).

Coal	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	US
YEAR/REGION	1	2	3	4	5	6	7	8	9	10
2005	3.40	2.07	2.36	1.22	2.93	2.73	1.48	1.68	2.25	2.22
2006	3.60	2.26	2.46	1.39	2.96	2.82	1.73	1.86	2.56	2.34
2007	3.76	2.29	2.55	1.46	3.03	2.92	1.81	1.93	2.68	2.42
2008	3.93	2.34	2.62	1.51	3.12	2.98	1.85	1.99	2.79	2.49
2009	3.92	2.33	2.61	1.50	3.09	2.96	1.83	2.02	2.78	2.48
2010	3.87	2.29	2.57	1.48	2.98	2.86	1.82	1.99	2.74	2.42
2011	3.90	2.30	2.55	1.51	2.89	2.80	1.82	1.95	2.75	2.39
2012	3.83	2.28	2.51	1.49	2.80	2.74	1.84	1.91	2.73	2.35
2013	3.82	2.29	2.49	1.50	2.76	2.71	1.85	1.90	2.75	2.34
2014	3.80	2.26	2.48	1.51	2.73	2.69	1.86	1.89	2.75	2.32
2015	3.74	2.24	2.46	1.52	2.69	2.67	1.88	1.88	2.73	2.31
2016	3.70	2.23	2.45	1.51	2.67	2.65	1.86	1.86	2.71	2.29
2017	3.67	2.21	2.44	1.52	2.64	2.63	1.87	1.86	2.72	2.29
2018	3.65	2.19	2.43	1.59	2.62	2.61	1.89	1.86	2.73	2.28
2019	3.64	2.18	2.42	1.59	2.61	2.59	1.90	1.87	2.74	2.28
2020	3.65	2.19	2.42	1.59	2.62	2.58	1.93	1.88	2.76	2.28
2021	3.65	2.19	2.42	1.58	2.62	2.58	1.92	1.88	2.78	2.28
2022	3.66	2.19	2.43	1.60	2.62	2.58	1.93	1.89	2.80	2.29
2023	3.65	2.19	2.43	1.61	2.62	2.58	1.95	1.90	2.83	2.30
2024	3.65	2.19	2.45	1.62	2.62	2.58	1.96	1.90	2.85	2.30
2025	3.64	2.18	2.45	1.63	2.61	2.57	1.97	1.91	2.87	2.30
2026	3.64	2.18	2.45	1.65	2.61	2.57	1.98	1.92	2.89	2.31
2027	3.65	2.18	2.45	1.66	2.61	2.57	1.99	1.93	2.90	2.31
2028	3.65	2.18	2.46	1.67	2.61	2.57	2.01	1.94	2.92	2.32
2029	3.66	2.18	2.46	1.67	2.62	2.57	2.01	1.95	2.94	2.32
2030	3.67	2.20	2.48	1.68	2.63	2.58	2.03	1.95	2.94	2.33