Final Report

Low Income Single Family Program Impact Evaluation

Part of the Massachusetts Residential Retrofit and Low Income Program Area Evaluation

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ACRONYM GLOSSARY

Acronym	Full Name
AG	Attorney general
AHAM	Association of Home Appliances Manufacturers
AMP	Appliance Management Program
BTU	British thermal units
CAA	Community action agency
CAP	Community Action Program
CDD	Cooling degree day
CFL	Compact fluorescent light bulb
CLC	Cape Light Compact
CSA	Conditional savings analysis
DHCD	Department of Housing and Community Development
DHHS	Department of Health and Human Services
DHW	Domestic hot water
DOE	Department of Energy
DOER	Department of Energy Resources
DPU	Department of Public Utilities
DSM	Demand-side management
EISA	Energy Independence and Security Act
HDD	Heating degree day
HEARTWAP	Heating Emergency Assistance Retrofit Task Weatherization Assistance Program
HES	Home Energy Services
HVAC	Heating, ventilating, and air conditioning
kWh	Kilowatt hour
LEAN	Low Income Energy Affordability Network
MRET	Massachusetts Renewable Energy Trust
NMR	Nexus Market Research
PA	Program Administrator
pre-NAC	pre-retrofit normalized annual consumption
SAE	Statistically Adjusted Engineering
The Act	The Massachusetts Green Communities Act of 2008
TLC	Tender Loving Care (baseload energy savings kit)
TRM	Technical Reference Manual
TYM3	Typical meteorological year data set
WAP	Weatherization Assistance Program
WMECO	Western Massachusetts Electric Company
Wx	Weatherization

EXECUTIVE SUMMARY

This report summarizes the impact evaluation of the 2010 Low Income Program, conducted by The Cadmus Group, Inc., Opinion Dynamics, Navigant Consulting, Itron, and Energy and Resource Solutions, collectively referred to as The Cadmus Team. The Cadmus Team conducted an array of data collection activities and evaluation tasks, including billing and engineering analyses, to determine the evaluation findings, conclusions, and recommendations presented here.

Methodology

The Cadmus Team assessed the gross per-unit savings generated by each Low Income Program measure using two approaches: a billing analysis and an engineering analysis. A brief description of each is provided below, while significant detail is provided in the body and appendices of this report:

- ***Billing Analysis.*** The Cadmus Team specified a fixed-effects conditional savings regression model with paired pre- and post-participation months to estimate measure-level savings for measures installed by Program Administrators (PAs) who provide electricity and/or natural gas. We leveraged these weather-normalized models with detailed measure data and home characteristics we collected from the implementing agencies.
- ***Engineering Analysis.*** The Cadmus Team's engineering analysis utilized two approaches to estimate measure-specific savings for all three fuel types (electric, natural gas, and heating oil). For program measures known to generate interactive effects (i.e., those that increase or decrease the energy consumption of another end use), we estimated savings using a DOE-2-based simulation model calibrated using the average pre-program energy consumption of Low Income Program participants. For measures not typically subject to interactive effects, we estimated savings using standard industry engineering algorithms. Both engineering approaches were primarily informed by the same detailed measure data and home characteristics we utilized in the billing analysis.

The Cadmus Team used billing analysis results whenever measure- and fuel-specific results met a threshold of precision. Billing analysis captures actual changes in energy consumption within participating homes from energy-efficiency and behavioral improvements. Specifically, we used billing analysis results that had a precision of 20% or less at the 90% confidence level. The results met this threshold for insulation measures, including air sealing, and for heating system replacements in gas heated homes. We derived all the other savings presented in this report using the engineering analysis.

Results

The statewide per-unit gross *ex post* energy savings by measure and primary fuel type of treated homes are summarized in Table 1.

Table 1. Annual *Ex Post* Gross Savings by Measure and Primary Fuel Type of Treated Homes

Category	Measure	Natural Gas (Therms/year)	Electric (kWh/year)	Oil (MMBTUs/year)
Insulation and Air Sealing	Insulation and Air Sealing (overall)	263*	1,616	28.1
	Air Sealing	105	501	9.9
	Attic Insulation	83	1,071	11.6
	Wall Insulation	115	824	11.2
	Basement Ceiling Insulation	15	30	2.9
	Basement Wall Insulation	13	37	0.2
	Furnace Fan (due to weatherization)	206 (kWh)	--	224 (kWh)
	Cooling (due to weatherization)	138 (kWh)	--	153 (kWh)
Heating System	Heating System Replacement	199*	--	18.4
	Boiler Reset Controls	--	--	4.4
	Programmable Thermostat	--	--	3.1
	Furnace Fan (due to furnace replacement)	172 (kWh)	--	132 (kWh)
Appliances	Refrigerator Replacement	--	762	--
	Second Refrigerator Removal	--	1,180	--
	Freezer Replacement	--	239	--
	Window AC Replacement	--	204	--
Lighting	CFLs	--	45	--
	Torchieres	--	211	--
	Fixtures	--	140	--
Domestic Hot Water	Domestic Hot Water (overall)	5	128	0.7
	Low-Flow Showerhead	9	188	1.1
	Faucet Aerator	2	40	0.2
	Pipe Wrap	4	41	0.4
Distribution	Duct Insulation	55	--	4.3
	Duct Sealing	33	--	3.3
Other	Baseload (TLC Kits)	--	25**	--

* Indicates this number is based on billing analysis. We determined all other measure results through engineering analysis (simulation or algorithms).

** Reflects MA-wide average based on each PA's kit contents and participation. Details for computing kit-specific savings below.

INTRODUCTION

Program Overview

As is typical with most low income programs, the Massachusetts PA Low Income Program operates in conjunction with the U.S. Department of Energy's (DOE's) Weatherization Assistance Program (WAP) and is implemented by the agencies in the Massachusetts Low Income Energy Affordability Network (LEAN). The program offers free home energy audits and energy-efficiency measures to the participating PAs'[1] income-qualified residential customers. The program targets single family and two-to-four unit multifamily residential customers with a household income less than or equal to 60% of the State household median. For the three-year energy-efficiency planning period (2010-2012), the Massachusetts PAs allotted over $134 million and $72 million for low income electric and gas funding, respectively. The total Low Income Program funding allocated by the PAs for the three-year period was over $205 million.[2,3,4]

The Massachusetts Green Communities Act of 2008[5] (the Act) greatly affected activities in the PA-funded Massachusetts Low Income Program. The Act required that at least 10% of electric energy-efficiency program funds and at least 20% of gas energy-efficiency program funds be spent on comprehensive low income residential demand-side management (DSM) and education programs. Additionally, the programs are required to be:

- Cost-effective;
- Implemented through the existing low income weatherization and fuel assistance program network; and
- Coordinated with Cape Light Compact (CLC) and all electric and gas distribution companies in the State (to standardize implementation).

1 There are eight PAs in Massachusetts. Seven of the eight PAs are utilities, while Cape Light Compact is an inter-governmental organization created by 21 towns and two counties on Cape Cod and Martha's Vineyard.

2 These budgets include all customer sectors (including low income multifamily) and reflect the total low income program overall including all of the PA budget categories: Program Planning and Administration; Marketing and Advertising; Participant Incentive; Sales, Technical Assistance & Training; and Evaluation and Market Research.

3 Budgets for 2010 can be found in the three-year energy-efficiency plans on the Energy Efficiency Advisory Council Website:
Electric: http://www.ma-eeac.org/docs/DPU-filing/ElectricPlanFinalOct09.pdf
Gas: http://www.ma-eeac.org/docs/DPU-filing/GasPlanFinalOct09.pdf

4 Budgets for 2011 and 2012 were changed from the original three-year energy-efficiency plans during the mid-term modifications which took place in October 2010 and October 2011. NSTAR provided budget information from these modifications for all PAs.

5 Massachusetts Green Communities Act of 2008 (G.L. c. 25, sec. 19(c) (St. 2008, c. 169, sec. 11).

LEAN

LEAN was established in 1998 by the lead agencies of the low income weatherization and fuel assistance program network. The PAs coordinate program efforts through LEAN in order to: (1) ensure consistency throughout the State, and (2) provide services required for implementing the coordination requirements of the Act. This approach retains the advantages of central coordination while avoiding the creation of a new or central entity.

LEAN provides the following essential services:[6]

- Coordination among electric and gas PAs, the Energy Efficiency Advisory Council and its consultants, and the Department of Housing and Community Development (DHCD; administrator of US DOE and Department of Health and Human Services (DHHS) weatherization programs) with the objective of standardizing implementation.
- Coordination within the low income weatherization and fuel assistance program network, including among lead agencies and between lead agencies and sub-agencies.
- Coordination with potential vendors outside the low income weatherization and fuel assistance program network for certain segments of the low income residential market, (e.g., those that live in large multifamily buildings).
- Assistance in monitoring and evaluating existing programs to improve cost-effectiveness and develop new program features. This encompasses developing evaluation strategies, coordinating with evaluators, synthesizing statewide lessons from program evaluations, and coordinating a best practices effort.
- Support for the training of the low income weatherization and fuel assistance program network with the objectives of quality, cost-effectiveness, and consistency.
- Regulatory support in negotiations with and proceedings before the Department of Public Utilities (DPU) and the Department of Energy Resources (DOER).

The members of LEAN, including a representative of the DHCD as *ex officio*, meet regularly throughout the year. Additionally, representatives of the DPU, DOER, Massachusetts Renewable Energy Trust (MRET), and the State attorney general (AG) are frequent guests.

Lead Agencies and Sub-Agencies

Currently, more than 20 community action agencies (CAAs) deliver the Massachusetts Low Income Program to customers. Serving an integral role in program implementation, these CAAs provide the following services:

- Managing multiple funding sources (including the PAs and DOE funding),
- Determining participant eligibility,
- Scheduling and conducting audits,
- Arranging for the installation of energy-efficiency measures,

6 The Cadmus Team found this information on: www.democracyandregulation.com.

- Reporting progress and invoicing funding sources, and
- Conducting quality control.

In Massachusetts, the CAAs typically employ their own energy audit staff and manage a network of third-party installation contractors.

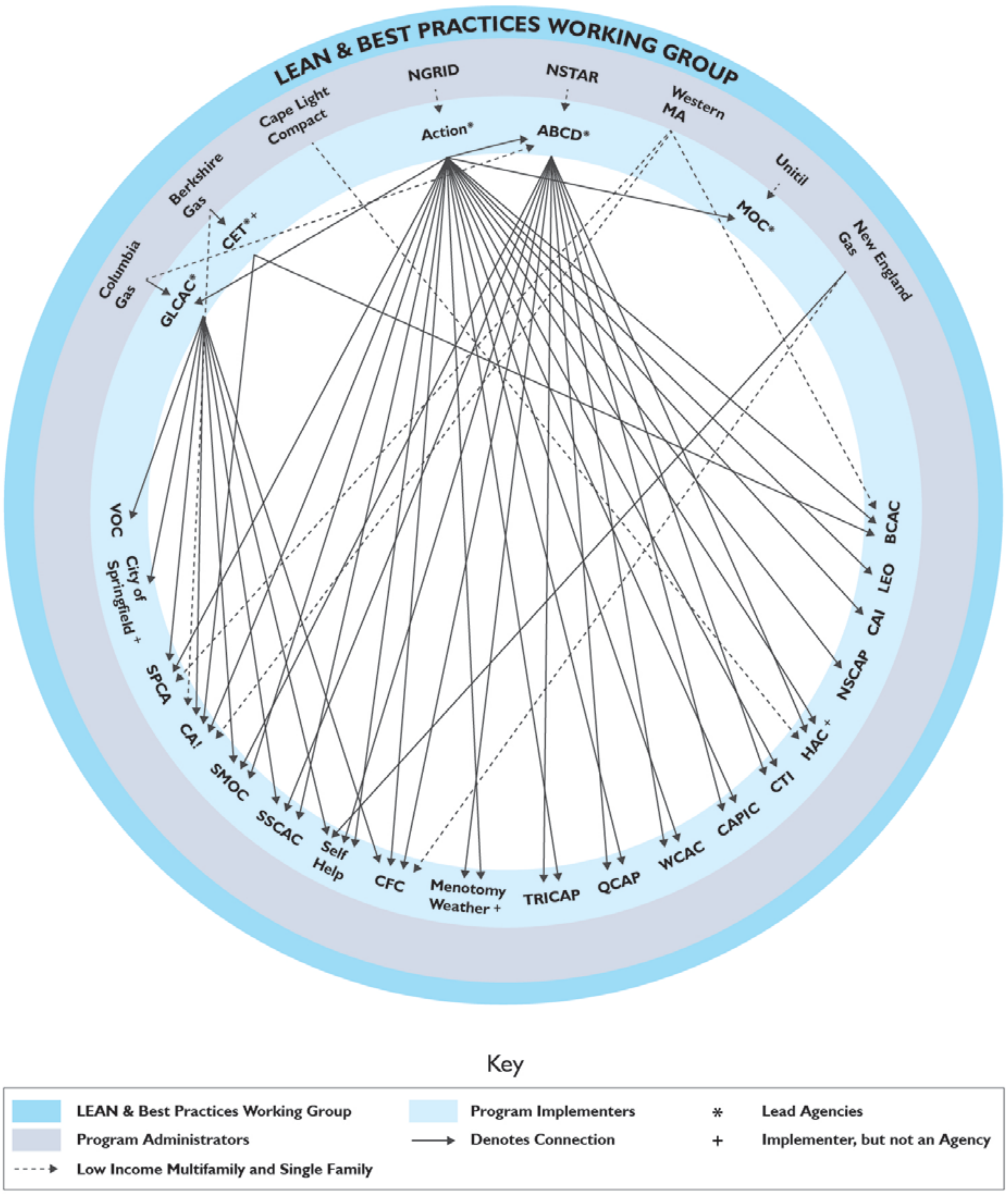
PAs with large services territories commonly work with a lead agency to streamline the management of numerous sub-agencies. In addition to implementing the program directly for customers within the region they serve, lead agencies contract with local sub-agencies to coordinate reporting, invoicing, budgets, and goals for the regions they serve. The lead agencies are responsible for reporting all necessary information from sub-agencies to their respective PAs, thus streamlining the program implementation and communications among numerous implementing agencies.

The sub-agencies are responsible for implementing the program in their region, working directly with the lead agencies.

Low Income Program participants work directly with CAAs in their local community for all aspects of the program, whether the agency is a lead vendor or a sub-agency.

Figure 1 illustrates the program's complex network with multiple stakeholders (PAs, lead agencies, and sub-agencies) and the larger coordination that occurs through LEAN and the best practices working group (discussed below). The arrows delineate implementer relationships.

Figure 1. Network of Low Income Program Stakeholders



As an example, National Grid's lead agency—Action Energy, Inc.—manages multiple sub-agencies and reports the program activities performed by themselves and on their behalf by the sub-agencies to National Grid. Action Energy, Inc. also implements the program for some of the other PAs, and it reports those program activities to those other lead agencies.

Some PAs—such as Western Massachusetts Electric Company (WMECO), CLC, and New England Gas—do not contract with a lead agency. Instead, they work directly with one or multiple agencies. In these cases, the PAs essentially assume the role of lead agency. Table 2 provides a list of acronym definitions associated with Figure 1.

Table 2. Program Implementer Acronyms

Acronym	Full Name
Action*	Action Energy, Inc.
ABCD*	Action for Boston Community Development
BCAC	Berkshire Community Action Council
CA!	Community Action of the Franklin Hampshire & North Quabbin Regions, Inc.
CAI	Community Action, Inc.
CAPIC	Community Action Programs Inter-City
CET**	Center for Ecological Technology
CFC	Citizens for Citizens
CTI	Community Teamwork, Inc.
GLCAC*	Greater Lawrence Community Action Council
HAC***	Housing Assistance Corporation
LEO	Lynn Economic Opportunity
MOC*	Montachusett Opportunity Council
NSCAP	North Shore Community Action Programs
QCAP	Quincy Community Action Programs
SMOC	South Middlesex Opportunity Council, Inc.
SPCA	Springfield Partners for Community Action
SSCAC	South Shore Community Action Council, Inc.
TRICAP	Tri-City Community Action Programs, Inc.
VOC	Valley Opportunity Council
WCAC	Worcester Community Action Council, Inc.

* Is a lead agency.

** Is a lead, but not an agency.

*** Is a housing assistance corporation (not an agency), but implements the program for PAs.

Best Practices Working Group

The best practices working group is a forum for communication between PAs and agencies regarding program consistency and measure standardization. The purposes of the best practices group meetings include: (1) provide a forum for technical standardization and coordination between funding sources (i.e., PAs, DOE, DHCD); (2) discuss strategies for addressing any program issues that pose barriers to installation (such as knob-and-tube wiring and combustion safety); (3) review potential new measures; (4) conduct training; and (5) coordinate with other programs.

This group consists of numerous stakeholders, such as: PA Low Income Program managers, agency program managers, and representatives from other funding sources (including DHCD). However, the meetings are open to any stakeholders that want to participate. During these meetings, LEAN communicates any concerns expressed by sub-agencies to the PAs and vice versa.

Program Offerings

As listed in Table 3, the Massachusetts Low Income Program consists of three components that are paid for by the PAs. Measures from each component are recommended by an auditor or, in some cases such as CFLs, installed during the program audit(s). All of the measures recommended are fully subsidized and installed with the customer's permission.[7]

Table 3. Program Components

Low Income Program Component	Measure Description
Insulation and Weatherization	Insulation (attic, wall, pipe, floor); air sealing; health and safety; and repair measures
Base Load	Refrigerator/freezer replacement and/or removal; addition of CFLs and efficient lighting; waterbed mattress replacement; domestic hot water measures replacement; and window AC replacements
Heating Emergency Assistance Retrofit Task Weatherization Assistance Program (HEARTWAP)	Heating system repair and/or replacement

Customer Eligibility

All residential customers with a household income less than or equal to 60% of the State median income level are eligible for the Low Income Program. This includes all customers who are on fuel assistance and/or utility-discounted rate codes. Customers who are renters must have written approval from their landlord.

Once deemed eligible, the CAA scores customers using DOE's priority system to determine where they fall on the list of those waiting to receive audits and services. The CAAs serve customers with more priority points first, giving priority points to customers who:

- Are elderly or disabled
- Have children in the home aged six or younger
- Are Native American Indian
- Have high energy consumption

The CAAs may also place a customer at the top of the priority system if they have an urgent situation, such as a broken window or door during freezing temperatures.

[7] For at least two PAs, in a minimal number of cases, a customer co-pay may be requested to help with heating system replacement costs. This may occur for heating system replacements when the maximum funds allowed per home have been exhausted and the customer can help bridge a (small) gap in funding.

As the CAAs determine measure funding ***after*** a home receives program services,[8] CAAs prioritize all jobs based on government prioritization, regardless of funding source. A CAA's decisions regarding the leveraging of funds are dependent on the specific needs of a household and the PA service territory. The number of customers waiting to be served is specific to each agency; there is not a statewide inventory. The PAs do not have an established priority system for services; however, it is possible for a low income eligible home to be served using only one funding source, such as PA funding.

Report Organization

The remaining report sections are outlined in the following order:

- ***Methodology***, which explains the impact evaluation tasks and how The Cadmus Team collected and analyzed data for this project.
- ***Findings***, which detail the key results from the impact evaluation.
- ***Appendices,*** which contain detailed measure-specific methodologies for the engineering analysis, including engineering algorithms and simulation modeling methodology. Additionally, we provided the on-site agency data collection tool.

[8] LEAN notes that this is by agreement with the PAs who have adopted the DOE protocols.

METHODOLOGY

The Cadmus Team assessed the gross per-unit savings generated by each Low Income Program measure using two approaches: a billing analysis and an engineering analysis. A brief description of each is provided below, while significant detail is provided in the body and appendices of this report:

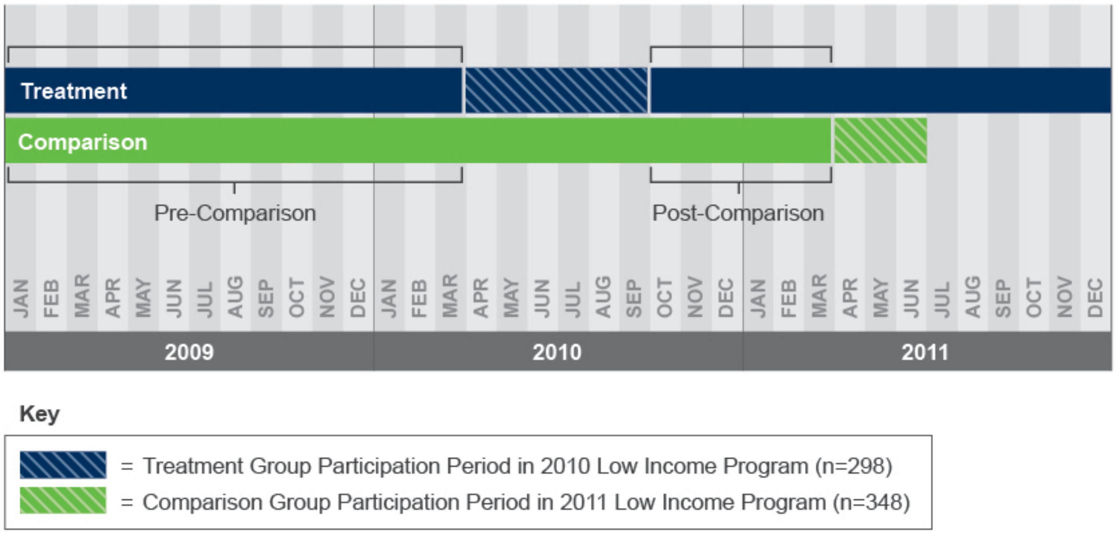
1. ***Billing Analysis.*** The Cadmus Team specified a fixed-effects conditional savings regression model with paired pre- and post-participation months to estimate measure-level electric, natural gas, and oil energy savings statewide. In order to account for macro-economic factors and naturally occurring trends in usage, we also included a control group in the model composed of future 2011 participants. We leveraged these weather-normalized models with detailed program data we collected from the implementing agencies.
2. ***Engineering Analysis.*** The Cadmus Team used two approaches for the engineering analysis. For program measures known to generate interactive effects (i.e., those that increase or decrease the energy consumption of another end use), we estimated savings using a DOE-2-based simulation model calibrated using the average pre-program energy consumption of Low Income Program participants. For measures not typically subject to interactive effects, we estimated savings using standard industry engineering algorithms. Both engineering approaches were primarily informed by the same detailed program data we utilized in the billing analysis.

After completing the billing and engineering analyses, The Cadmus Team identified the most reliable savings estimate for each measure from both approaches. We used the billing analysis whenever measure- and fuel-specific results were sufficiently precise, due to its ability to capture actual changes in energy consumption within participating homes from energy-efficiency and behavioral improvements. Specifically, we used any billing analysis results with a precision of 20% or less at the 90% confidence level to report this evaluation's *ex post* savings. The billing analysis results met this threshold for insulation measures, including air sealing and heating system replacements in natural gas heated homes. We derived all other savings presented in this report using the engineering analysis.

Analysis Period

For the analysis, The Cadmus Team focused on changes in customers' energy consumption between January 2009 and August 2011. We demarcated these changes into pre- and post-periods based on the date of each participant's audit and the date the last measure was installed. First, we designated any billing data months occurring before the earliest participation date as pre-period, and any billing data months occurring after the latest measure installation date as post-period. Figure 2 shows the general pre- and post-period assignments for the participants and the comparison group.

Figure 2. Billing Analysis Period Definitions



For customers with less than 12 months of pre- or post-period billing data, we paired the pre- and post- months. For example, if a customer participated in September 2010 and the available post-billing data was from October 2010 through August 2011, then we only the corresponding pre-period months from October through August. This ensured that we used the same months in both the pre- and post- periods. In order to ensure that there was only one month of pre- and post-period paired data for any given month during the analysis period, we systematically search for and removed duplicate records. For example, if the pre-period included both February 2010 and February 2009 billing data, we only used the February 2010 billing data. We selected the months closest to the install dates as it best represents the participant's pre-conditions at the time of participation. This ensured that there was no bias introduced from uneven month distributions between the pre- and post-periods and that each paired month is represented only once in the pre- and post-periods. Overall, 80% of the sample had a minimum of 10 months that matched for the pre- and post-periods. Half of the analysis sample had all 12 months of both pre-audit and post-measure installation data.

Sampling

We defined the group of participants for analysis as follows:

- Single family low income households that received a program measure in Q2 or Q3 of 2010. We selected the two middle quarters to allow for available (non-archived) billing data from a minimum of one complete heating season pre- and post-installation.
- Participants' billing data must not include outliers (annual electric usage should be between 360 and 30,000 kWh, and annual gas usage should be between 30 and 3,000 therms). These ranges represent approximately 98% of customers (effectively removing the top and bottom 1%).

Table 4 summarizes the process The Cadmus Team followed to define the population or sample frame; that is, to define all Q2 and Q3 2010 participants from which we could sample and include in the analysis.

Table 4. 2010 Participant Population Attrition

PA	Service	PA Tracking	Participated in Q2 or Q3 2010	Installed Major Measure	Successfully Joined to Billing	Non-Outlying Usage	Sufficient Pre- and Post-Records	Population (Sample Frame)
National Grid	Gas	1,861	543	537	510	449	437	437
	Electric	6,662	2,056	587	587	581	498	498
NSTAR	Gas	478	129	123	121	116	112	112
	Electric	3,510	1,244	371	355	348	294	294
Berkshire	Gas	71	14	14	13	13	13	13
CLC	Electric	843	195	188	187	161	161	161
Columbia	Gas	747	144	143	127	124	122	122
NE Gas*	Gas	78	48	48	N/A	N/A	N/A	N/A
Unitil	Gas	29	4	4	4	4	4	4
	Electric	77	20	20	20	18	18	18
WMECO	Electric	2,254	691	253	205	115	115	115
Total		16,610	5,088	2,288	2,129	1,929	1,774	1,774

* We did not receive billing data from this PA in time for analysis.

Since the electric program tracking data provided by the PAs was insufficient for completing our impact analysis, The Cadmus Team collected the majority of the data needed to inform the evaluation directly from the CAAs during on-site visits to the agencies. Specifically, the significant on-site data collection effort was necessary for us to attempt to collect the following data:

- The pre-installation conditions of the homes.
- Additional installations attributable to non-utility funding.
- Federal dollars spent on each home.
- Participants' household and demographic information.

To limit the scope of the on-site data collection efforts, we further refined the sample population as follows:

- There was some overlap in gas weatherization and gas heating system replacement, as some customers had both measures installed. Thus, the sum of the Grand Total row in Table 5 (n=1,058) only represents 988 unique participating households.
- When the sample of participants available for any PA and measure/fuel combination was less than 100, we included a census of available participants in the analysis sample.
- When the sample of participants available for any PA and measure/fuel combination was greater than 100, we selected a random sample of 100 participants from this sample size population.

The Cadmus Team requested detailed audit records from the relevant CAP agencies for the sample of participants presented in Table 5. Table 5 further expands the information in Table 4 by measure and heating fuel type.

Table 5. Proposed Analysis Sample

PA	Weatherization			Gas Heating System	Minor Measure Group*
	Electric Heat	Oil Heat	Gas Heat		
Berkshire	N/A	N/A	3	1	0
CLC	83	41	N/A	N/A	6
Columbia	N/A	N/A	88	40	0
NE Gas**	N/A	N/A	N/A	N/A	N/A
National Grid	6	100	100	100	100
NSTAR	7	94	64	64	100
Unitil	1	4	3	2	0
WMECO	5	40	N/A	N/A	6
Grand Total	102	279	258	207	212

* This column includes measures such as refrigerator/freezer replacement and/or removal; the addition of CFLs and efficient lighting; the installation of kit measures and domestic hot water measures; and window AC replacements.

** We did not receive billing data from this PA in time for the on-site agency data collection.

To facilitate the data collection process, The Cadmus Team worked with the PAs, LEAN, and the CAAs prior to the first on-site data collection visit to refine the list of requested information for each sampled participant. The specific data fields we identified as most critical included the following:

- Energy-efficiency measures installed from all funding sources, including installation dates;
- Baseline conditions observed during audit visit (e.g., home size, pre- and post-insulation levels, and heating fuel type);
- Participant contact information; and
- Participant demographic information (e.g., number of occupants).

Agency Data Collection

The Cadmus Team completed on-site data collection visits at 21 agencies in February and March 2012. As we needed additional data to supplement the electronic data provided by the PAs, we reviewed physical files from each agency that oversaw the implementation of efficiency measures at the homes of sample participants. The Cadmus Team visited the agencies listed in Table 6 to attempt to collect data about the participants.

Table 6. Agency Site Visits

Agency	Number of Participants
Action for Boston Community Development, Inc.	186
Action Energy, Inc.	35
Berkshire Community Action Council, Inc.	18
Citizens for Citizens	91
Community Action of the Franklin Hampshire & North Quabbin Regions, Inc.	11
Community Action Programs Inter-City, Inc.	58
Community Action, Inc.	22
Community Teamwork, Inc.	40
Greater Lawrence Community Action Council, Inc.	70
Housing Assistance Corporation	142
Lynn Economic Opportunity, Inc.	11
Menotomy Weatherization	14
Montachusett Opportunity Council, Inc.	24
North Shore Community Action Programs, Inc.	20
Quincy Community Action Programs, Inc.	19
Self Help, Inc.	47
South Middlesex Opportunity Council, Inc.	46
South Shore Community Action Council, Inc.	25
Springfield Partners for Community Action, Inc.	48
Tri-City Community Action Programs, Inc.	14
Worcester Community Action Council, Inc.	47

Prior to the site visits, The Cadmus Team developed a Microsoft Excel® data collection tool. The spreadsheet included cells to capture information about the participants, the building science and the measures installed, and the funding source. A complete list of the data fields included in the data collection tool is provided in Appendix C.

The Cadmus Team contacted the leads at each CAA to arrange a convenient day and time for collecting data. Throughout this process, the CAAs were very cooperative and did their best to assist with the data collection process. While on-site, we reviewed each sampled customer's file, and captured all the pertinent data to determine all the participants' pre- and post-installation conditions. Many of the forms we used and the data we collected was consistent amongst the agencies. While on-site, The Cadmus Team noted the following key observations:

- There were often multiple funding sources for a single participant.
- Participants often installed measures from multiple Low Income Program components (WAP, HEARTWAP, and electric baseload through the Appliance Management Program (AMP)).
- The CAAs grouped their files by program and PA, rather than by customer.

- Discrepancies often existed between the tracking database provided by the PAs and the documentation we found during the site visits (e.g., the database indicated that a customer participated in WAP and HEARTWAP only, while we found on-site that the customer participated in AMP as well).
- Pre-existing conditions for certain measures were not always documented in the audit reports.

The Cadmus Team ensured quality control with the data entry process. For instance, two staff reviewed the same participant files. One read the file and the second entered the data (with each responsible for reviewing the others work). After collecting the data, we uploaded it to a secure FTP site each night, where an automated program transferred all the data files into a combined SAS dataset that was stored on a secure Cadmus server.

The final count of unique participants we collected data for during our on-site efforts (the analysis sample) is presented in Table 7. In total, we successfully collected information for 891 of the 988 sampled participants.

Table 7. Final Analysis Sample (Unique Participants)

PA	Service Type	Wx Only	Heating System Only	Minor Measure Only	Wx & Heating System	Wx, Heating System, & Minor Measure	Wx & Minor Measure	Heating System & Minor Measure	Total
Berkshire	Gas	0	0	0	0	1	2	0	3
CLC	Electric	5	0	5	0	8	107	0	125
Columbia	Gas	2	10	0	2	22	72	1	109
National Grid	Electric	5	0	65	3	30	92	1	196
	Gas	11	53	0	8	45	56	5	178
NSTAR	Electric	2	0	14	3	35	61	1	116
	Gas	2	23	0	6	35	41	1	108
Unitil	Electric	1	0	0	0	1	3	0	5
	Gas	0	1	0	0	2	1	0	4
WMECO	Electric	4	0	2	0	3	38	0	47
Total		32	87	86	22	182	473	9	891

Analysis Weights

Once we completed data collection at participating CAP agencies, The Cadmus Team weighted the analysis sample to reflect the population of customers that participated in 2010, by PA and by measure category. Weighting is needed for two reasons. First, the analysis sample was composed of only Q2/Q3 2010 participants and needs to represent the entire 2010 program year. Second, a random sample of National Grid participants was selected from the available frame because of their larger number of participants. As a result, the relative influence of National Grid on statewide values resulting from our analysis needed to be increased.

The Cadmus Team developed a weighting scheme to correct for over and under selecting the PAs in the sample frame. The best available standard unit to weight participation across the PAs was the amount of incentive provided to each participant. An incentive amount existed for all of the participants and measures for each PA within each tracking database, and could be tied directly to each participant. A participant/measure energy savings value did not exist for all PAs within the tracking data, and therefore we could not use energy savings as the weighting unit.

The distribution of dollars across PAs represented the sample frame and reported in the annual tracking databases are listed in Table 8. The resulting weights shown in the table were applied to every participant.

Table 8. PA-Based Analysis Weights

Fuel Type	Gas			Electric			Oil		
PA	2010 Tracking Database	Sample	Weights	2010 Tracking Database	Sample	Weights	2010 Tracking Database	Sample	Weights
National Grid	40.30%	65.30%	162%	13.30%	25.70%	194%	36.90%	52.20%	142%
NSTAR	25.20%	16.20%	64%	32.00%	14.70%	46%	40.10%	30.80%	77%
Berkshire	1.30%	1.70%	131%	NA	NA	NA	NA	NA	NA
CLC	NA	NA	NA	45.30%	49.70%	110%	15.20%	6.40%	42%
Columbia	31.70%	15.70%	50%	NA	NA	NA	NA	NA	NA
Unitil	1.50%	1.10%	70%	4.60%	2.00%	44%	2.90%	1.60%	56%
WMECO	NA	NA	NA	4.80%	7.90%	162%	5.00%	9.00%	181%

Control Group

To account for macro-economic factors and other influences on pre- and post-program energy consumption that are unrelated to the installation of program measures (such as the number of household occupants changing), The Cadmus Team utilized a control group composed of 348 future year participants (2011). We only used the billing data from January 2009 through the earliest 2011 installation date in the billing analysis (i.e., only pre-program consumption). The control group was subject to the same data screens as the sample of 2010 customers included in the analysis.

Since the distribution of control group customers was different from that of participants in the population, we also created separate PA-specific weights for the control group. These weights, which were utilized only for the natural gas billing analysis, are summarized in Table 9.

Table 9. PA-Based Control Group Distribution and Weights

PA	Gas Tracking Database Distribution (Population)	Gas Control Group Billing Sample Distribution (Sample)	Control Group Weights (Population / Sample)
Berkshire	2%	0%	NA
Columbia	16%	16%	0.99
National Grid	65%	49%	1.32
NSTAR	16%	31%	0.53
Unitil	1%	4%	0.25

Other Data Sources

In addition to the data we collected from the CAAs, we also utilized data from the following sources for our analysis:

- Billing data from PAs
- Tracking system data from PAs
- Weather data
- Massachusetts Technical Reference Manual (TRM)
- Other TRMs

PA Data Tracking

The Cadmus Team performed a gap analysis after the agency site visits to ensure that we had captured all the measure installation data. In the event that participant data were not available while on-site, we supplemented the on-site data using the PA tracking data, when possible. The primary reasons we did not capture data for a participant while on-site include files not being available that would show the installation of the measure, illegible entries, or data entry errors. For example, if we were unable to collect any information on a furnace replacement, but had flagged the participant as having had a furnace replaced (based on information provided in the

PA tracking data), then we left the customer designated as the recipient of a furnace replacement in the analysis sample.

Electric Measure Data

While most of the Low Income Program data required on-site data collection due to being maintained in hard copy format, the electric baseload (AMP) data are stored electronically. The engineering analysis in particular encompassed measures beyond those in the billing analysis, such as air sealing and insulation for oil heated homes, refrigerator replacement, and showerheads. In particular, the baseline conditions for many electric measures are stored electronically (e.g., they are stored in an electronic database for the AMP for National Grid and NSTAR), and are thus more accessible than program data at the agencies. Table 10 details the electronically available AMP data provided to Cadmus.

Table 10. Electric AMP Data Provided

PA	Provided Detailed AMP Data
National Grid	Yes
NSTAR	Yes
Unitil	No
WMECO	Yes
CLC	No

Billing Data

For our billing analysis, we utilized participants' energy consumption records for the time periods shown in Table 11. Although some PAs provided data for 2008, we only included data from 2009 through the latest available month in the billing analysis, as noted in the analysis period definitions.

Table 11. Dates of Billing Data Analyzed, by PA

PA	Electric	Natural Gas
National Grid	September 2008 – August 2011	September 2008 – August 2011
NSTAR	July 2008 – September 2011	July 2008 – September 2011
Berkshire	--	December 2008 – August 2011
CLC	March 2009 – June 2011	--
Columbia	--	January 2008 – December 2011
NE Gas	--	None
Unitil	August 2008 – September 2011	August 2008 – September 2011
WMECO	December 2008 – August 2011	--

Weather Data

We collected weather data from the National Climatic Data Center for 32 stations across the State to account for weather impacts in our billing analysis. For each station, we calculated the base 65 heating degree days (HDDs) and cooling degree days (CDDs). We matched each billing data period for the associated HDDs and CDDs based on the nearest weather station using participants' ZIP codes.

Massachusetts TRM

When audit data were not available to inform engineering analysis assumptions, The Cadmus Team first turned to the Massachusetts TRM as a secondary source for input assumptions.[9] The Cadmus Team valued the TRM as a source of Massachusetts-specific information, but also recognized that some data in the TRM was not appropriate. For example many savings estimates in the TRM come from past billing analyses, which make it difficult to extract the underlying assumptions. In cases where the TRM did not provide adequate information, we used other resources.

Other TRMs and Secondary Sources

In cases where the Massachusetts TRM and audit data from the CAAs did not provide adequate inputs, The Cadmus Team used the following other TRMs and published studies (more details on the sources for each measure are outlined in Appendix B):

- 2010 Vermont TRM
- 2010 Ohio TRM
- 2012 Pennsylvania TRM
- Federal efficiency standards

Engineering Analysis

For the engineering analysis, The Cadmus Team utilized two approaches: simulation modeling and standard engineering algorithms. Both approaches were primarily informed by the same detailed program data that we utilized for the billing analysis. Table 12 shows the approach we used for each major measure category. Note that we used the billing analysis results for two gas measure categories, insulation and weatherization and heating system replacement.

Table 12. Summary of Engineering Methodology by Measure Category

Measure Category	Engineering Approach
Insulation and Weatherization	Simulation
Heating System Replacement	Algorithm
Appliances	Algorithm
Lighting	Algorithm
Domestic Hot Water	Algorithm

Simulation Modeling

For program measures known to generate interactive effects, such as insulation and air sealing (weatherization), we estimated savings using a DOE-2-based simulation model calibrated to the average pre-program energy consumption for Low Income Program participants. This approach

[9] 2011 Massachusetts Electric and Gas Energy Efficiency Program Administrators. *Massachusetts Technical Reference Manual for Estimating Savings from Energy Efficiency Measures: 2012 Program Year—Plan Version.* October 2011.

is more accurate than standard engineering algorithms at capturing the interactive effects and savings attributed to the improved efficiencies for those measures that tend to increase or decrease the energy consumption of another end use.

The following bullets detail the advantages of simulation modeling over a simple algorithmic approach:

- Simulation modeling accounts for internal gains, thermostat set-point variations due to occupant behavior, and solar gains within the modeled structure.
- Energy modeling accounts for the thermal mass of a building assembly, instead of exclusively examining the heat transfer through the assembly.

To perform the simulation modeling on the select program measures that are subject to interactive effects, we created individual simulation models for each participant category (gas, oil, and electric). To accomplish this, we leveraged the CAA data we collected during the audit process to accurately inform the building characteristics. Next, we calibrated each model to the various end-use consumption values (heating, cooling, domestic hot water (DHW), lighting, and plug loads/appliances) to match the pre-retrofit normalized annual consumption (pre-NAC) as determined through billing analysis. Appendix A offers a detailed explanation of our DOE-2-based simulation modeling approach and calibration techniques.

Engineering Algorithms

For measures that are not typically subject to interactive effects, we estimated savings using standard industry engineering algorithms. To accomplish this, The Cadmus Team relied on several TRMs and technical studies, as well as on engineering methods used in past evaluations. Where appropriate, we estimated baseline and energy-efficient scenarios with engineering algorithms to calculate savings. For some measures, the many factors that influence savings could not be captured by straightforward algorithms. In these cases, The Cadmus Team estimated savings as a percentage of the calculated baseline consumption. We set baseline consumptions equal to the average heating portion of the pre-NAC as determined through billing analysis and simulations. Details on these measures and the percentages we used can be found in Appendix B.

The Cadmus Team used audit data for as many inputs as possible. As the data permitted, we averaged each input within the pool of participants installing each measure. Due to the small sample of audit data for this program, we used overall program averages in several instances. Please see Appendix B for a complete description of the algorithms and assumptions we used for each measure.

Billing Analysis

The Cadmus Team evaluated several different specification options to model savings before selecting the fixed-effects conditional savings analysis (CSA), paired-months modeling approach detailed in this section. Other specification options we considered, but were not as explanatory or reliable, included a Statistical Adjusted Engineering (SAE) model and account-level Princeton Scorekeeping Method model. Neither of these model types was as statistically significant as the CSA approach. Furthermore, for gas measures, the CSA model has an added advantage: when the savings are interacted with HDDs, it is straightforward to obtain the normal year savings estimates.

Our model selection process was dictated largely by the number of available sample points, the level of detail available for certain measures, and the wide range of PA-specific savings estimates. Each Low Income Program participant does not have a specific savings estimate, as all *ex ante* savings estimates are based on the PA-specific deemed values. Further, some utilities do not have separate measure-specific *ex ante* estimates (but instead use a single household value). The very large variation in *ex ante* definitions and savings for the same measure also posed an issue (for example, gas weatherization ranged from 137 to 324 therms). Running a combined SAE model using these estimates confused the model. Furthermore, because participants received both air sealing (97%) and the individual insulation measures (over 80%) and due to high collinearity, it was not possible to include separate model indicator variables or additional information, such as ACH values or U-values. The fixed-effects CSA model we employed generated the average savings for the average participant, without being influenced by any small or large usage participants or the magnitude of the *ex ante* savings.

Billing Data Screening

The Cadmus Team reviewed the pre- and post-paired monthly billing data for each participant with this data available in the original group of 351 participant accounts to check for any potential problems. We plotted their average daily consumption over time and compared it to customer-specific, weather-normalized usage estimates from the PRISM-based method. Since it was very important that only the highest quality data be included in the analysis, we screened out a total of 53 sites based on the criteria detailed in Table 13. This screening criterion led to a final group of 298 participants, an attrition of only 15% of the original sample (that had sufficient billing data). Furthermore, we also screened out any control group customer with less than one year of billing data from the analysis.

Table 13. Billing Data Screening Criteria

Screening Criteria	Number of Sites Removed
Insufficient data, or had less than two winter months of billing data	18
Contained outliers, data gaps, outlier data readings, or mismatched months (such as the pre-audit data ending on December 30 and the post-audit data ending on December 1)	14
Failed PRISM screening by having negative slopes	8
Contained inoperable heating units or had vacancies that were not related to data quality screening. These were dropped as follows: • We identified three sites in the audit data as having inoperable heating systems. • Five additional participants had inoperable heating systems based on ABCD and other agency review of the billing data. • We dropped five sites because they had vacant periods in the billing data.	13
Total Billing Accounts Screened	53

The number of unique households, by measure, we used in the final natural gas billing analysis is presented in Table 14.

Table 14. Billing Analysis Sample Sizes

Measure	Billing Analysis* Natural Gas
Heating System Replacement (Furnaces)	52
Heating System Replacement (Boilers)	91
Insulation and Air Sealing - Overall (Air Sealing and Any/Multiple Insulation Types)	225
Air Sealing	215
Attic Insulation	196
Wall Insulation	189
Floor Insulation	107
Other Miscellaneous Measures**	254
Lighting	-
Refrigerators	-
Freezers	-
Appliance Removal	-
Room AC	-
Water Heating	60
TLC Kit (Base Load/Education)	-

*Billing analysis was attempted for electric measures but did not yield reliable results. Sample sizes for viable natural gas model shown here. Billing analysis was not attempted to customers with oil as their primary heating fuel because of lack of data
**Includes roof replacements, windows, heating system tune-ups, heating system distribution measures, door kits

Model Specification – Natural Gas

After screening the billing data and obtaining the final group of 298 participants and 348 control group customers, The Cadmus Team used the following fixed-effects model specification to obtain gas measure savings:[10]

$$ADC_{it} = \alpha_i + \beta_1 * HDD_{it} + \beta_2 * Insulation\_Weatherization * HDD_{it} + \beta_3 * Furnace\_Replacement * HDD_{it} + \beta_4 * Boiler\_Replacement * HDD_{it} + \beta_5 * MISC\_DHW * HDD_{it} + \beta_6 * MISC\_Measures * HDD_{it} + \beta_7 * Insulation\_Weatherization * POST * HDD_{it} + \beta_8 * Furnace\_Replacement * POST * HDD_{it} + \beta_9 * Boiler\_Replacement * POST_{it} + \beta_{10} * MISC\_DHW * POST_{it} + \beta_{11} * MISC\_Measures * POST_{it} + \varepsilon_{it}$$

[10] We also attempted a similar model specification for electric measures; however, the errors around the modeled measure savings were very high, ranging from ±52% to ± 632%. As a result, we did not present those results, and obtained the savings estimates for electric measures only from the engineering analysis. The main contributing factors to the high errors were the low expected savings (for example, lighting and weatherization had expected savings less than 5% of pre usage) and low sample sizes (for example, only 83 homes had insulation/weatherization measures installed).

Where, for customer ‘i’ and billing month ‘t’:

ADC_{it} = The average daily therm consumption in the pre- and post-period

$POST_{it}$ = An indicator variable that is 1 in the post-installation period and 0 in the pre-installation period

β_1 = The average usage per HDD for non-participants

HDD_{it} = The average daily base 65 HDD for the nearest weather station based on location

β_2 = The incremental average usage per HDD for insulation and weatherization participants

Insulation_Weatherization * HDD_{it} = An interaction between the insulation weatherization participant flag and average daily HDD

β_3 = The incremental average usage per HDD for furnace replacement participants

Furnace_Replacement * HDD_{it} = An interaction between the furnace replacement flag and average daily HDD

β_4 = The incremental average usage per HDD for boiler replacement participants

Boiler_Replacement * HDD_{it} = An interaction between the furnace replacement flag and average daily HDD

β_5 I = The incremental average usage per HDD for water heater measure participants (showerheads, aerators, and tank wrap)

MISC_DHW * HDD_{it} = An interaction between the water heater measure participants (showerheads, aerators, and tank wrap) and average daily HDD[11]

β_6 = The incremental average usage per HDD for water heater measure participants (showerheads, aerators, and tank wrap)

MISC_Measures* HDD_{it} = An interaction between the miscellaneous measure participants and average daily HDD

β_7 = The savings per HDD for air sealing and insulation measure participants

Insulation_Weatherization * POST * HDD_{it} = An interaction between the insulation weatherization participant flag, the $POST_{it}$ indicator, and average daily HDD

[11] Note that although the weather sensitive component of water heating is minor, this term captures the difference in base heating usage between the control group and the measure. Since all water heating participants also received insulation measures, it is important to include this term.

β_8 = The savings per HDD for furnace heating system replacement measure participants

$Furnace\_Replacement * POST * HDD_{it}$ = An interaction between the furnace heating system replacement participants, the $POST_{it}$ indicator, and average daily HDD

β_9 = The savings per day for the boiler heating system replacement measure participants

$Boiler\_Replacement * POST_{it}$ = An interaction between the furnace heating system replacement participants and the $POST_{it}$ indicator

β_{10} = The savings per day for water heater measure participants (showerheads, aerators, and tank wrap)

$MISC\_DHW * POST_{it}$ = An interaction between the water heater measure participants (showerheads, aerators, and tank wrap) and the $POST_{it}$ indicator

β_{11} = The savings per day for the miscellaneous measure participants

$MISC\_Measures * POST_{it}$ = An interaction between the miscellaneous measure participants and the $POST_{it}$ indicator

ε_{it} = The model error term

The following calculations show how we derived the final savings estimates from the model coefficients:

$\beta_7 * 5{,}971$[12] = Annual **insulation/weatherization** savings using normal typical meteorological year (TMY3) HDDs

$\beta_8 * 5{,}994$ = Annual **furnace heating system replacement s**avings using normal TMY3 HDDs

$\beta_9 * 365 * (6{,}016 / 5{,}634)$ = Annual weather-normalized **boiler heating system replacement** savings. The average boiler participant HDD in the billing analysis was 5,634 and the normal TMY3 HDD was 6,016. This adjusts the boiler savings accordingly.

We ran the above model by applying the weights so that all savings estimates account for the PA-specific weighting. This ensured that the savings reflect true statewide estimates. All the model coefficients and statistics can be found in Appendix D.

12 5,971 is the weighted average of the typical meteorological year (TMY3; 1991-2005) series HDDs across all the gas PAs in the final low income billing sample.

FINDINGS

This section presents gross *ex post* savings estimates for all Low Income Program measures, covering electric, natural gas, and oil fuel types. The results are grouped by measure type and primary heating fuel type, although some measures have savings for more than one fuel type (these cases are noted in the tables where applicable).

Ex Post Energy Savings – Natural Gas

Insulation and Air Sealing

As shown in Table 15, the most common gas weatherization measure was air sealing: 96% of weatherization participants had this measure installed. Most participants also had attic and wall insulation installed. Very few participants installed basement insulation on the ceiling or walls. On average, participants had 2.7 insulation and air sealing measures installed per home.

Table 15. Distribution of Natural Gas Weatherization Measures (Billing Analysis)

Measure	n	Percent Installed
Air Sealing	215	96%
Attic Insulation	196	88%
Wall Insulation	189	85%
Total	223	269%

The Cadmus Team calculated the average insulation levels (weighted by square footage installed) using the agency on-site data (Table 16). We used an assumed pre-R-Value of 3.4 where no pre-existing insulation was indicated in the audit data and no assembly R-Value was provided by the CAAs.[13] For this measure (for gas and other fuel types), The Cadmus Team weighted input averages for each PA to ensure having a sample representative of all statewide installations.

The number of observations by insulation type differs between Table 15 and Table 16. These types of disparities between the samples used in the billing analysis and the samples used in the engineering estimations occur throughout this report as a result of the different data requirements imposed by each estimation method. For example, while the billing analysis required a minimum number of post-program billing records, the engineering analysis had no similar requirement. Conversely, the engineering analysis relied heavily on detailed inputs, such as household square footage, which was unnecessary for the billing analysis due to the fixed-effects model specification we employed. To maximize the limited sample available, we leveraged each estimation method with all the valid customer records (as opposed to reducing the analysis sample for both estimation methods to only those records meeting the requirements of both).

[13] This assembly R-Value is consistent with eQuest modeling assumptions (http://doe2.com/equest/). An R-Value of zero is not physically possible, as all materials have a non-zero R-value. This assembly R-Value is also consistent with the baseline observed in the HES audit data, and it represents the typical R-Value of framing only (no existing insulation).

Table 16. Average R-Values and Installed Square Feet for Natural Gas Customers

Measure	n	Original Pre-R-Value	Modified Pre-R-Value	Post-R-Value	Square Feet Installed per Customer
Attic Insulation	248	0.0	8.2	27.0	944
Wall Insulation	210	0.0	3.4	14.4	1,243
Basement Ceiling Insulation	11	0.0	3.4	23.3	197
Basement Wall Insulation	3	6.6	6.6	23.6	287

Table 17 summarizes the billing analysis results for insulation and air sealing. We conducted a billing analysis for this measure category because the precision level is less than ±20% of the estimated value. With the average weather-normalized pre-period usage of 1,168 therms, the insulation and air sealing measures represent 22% savings over the pre-installation usage. With the average heating pre-period usage of 891 therms, the gas insulation and air sealing savings represent 29% savings over the heating pre-replacement usage.

Table 17. Billing Analysis *Ex Post* Energy Savings Results for Natural Gas Insulation and Air Sealing*

Measure	n	Billing Analysis (Therms/Year)	Relative Precision at 90% Confidence Level	Average Household Pre-NAC	Average Household Percent Savings	Average Heating Pre-NAC	Average Heating Percent Savings
Insulation and Air Sealing	223	263	± 8%	1,168	22%	891	29%

* The Cadmus Team also estimated the model including the 13 units identified as having inoperable heating systems or were vacant prior to the program. The insulation savings drop slightly to 258 therms using this sample of participants.

In order to verify the reliability of the billing analysis, we also ran separate models for each pre-period usage. As expected, the savings increase as the pre-installation usage increases. Even the smallest quartile shows significant savings of 157 therms, or 21% of the pre-installation usage (Table 18). As expected, the higher usage quartiles (Q3, Q4) show a higher percentage of savings than the two lower usage quartiles.

Table 18. Billing Analysis Natural Gas Insulation and Air Sealing Savings by Pre-NAC Quartiles

Quartile	n	Pre-NAC	Savings	Precision	Savings as % of Pre-NAC
Q1: 391 - 927 therms	55	752	157	12%	21%
Q2: 927 - 1,124 therms	57	1,021	200	12%	20%
Q3: 1,124 - 1,399 therms	55	1,253	305	9%	24%
Q4: 1,399 - 2,406 therms	56	1,688	393	11%	23%
Overall*	223	1,168	263	8%	22%

* Note that the weighted average from the individual quartile models will not necessarily sum to the final value for the overall model. They are very close but not identical.

While the billing analysis was unable to provide insight into the separate savings specific to attic, wall, and basement insulation (primarily due to collinearity), the simulation modeling we employed as part of the engineering analysis produced insulation-type specific estimates. Table 19 shows both measure-specific and aggregated savings for these measures. As evident in the table, the billing analysis (which revealed 263 therms of savings overall) and engineering analysis (which revealed 253 therms of savings overall) produced similar estimates of savings for the average participant who received air sealing and one or more insulation measures. The Cadmus Team also used the simulation model to estimate electric savings due to reduced furnace fan run times.

Table 19. *Ex Post* Natural Gas Energy Savings for Insulation and Air Sealing (therms/year)

Category	Measures	PA 2010 Reported	Evaluated
Insulation and Air Sealing	Insulation and Air Sealing (Overall 2.7 average installations)	245	263*
	Air Sealing (96% installed)	30 – 190**	105
	Attic Insulation (88% installed)	70 – 240**	83
	Wall Insulation (85% installed)	80 - 190**	115
	Basement Ceiling Insulation (2% installed)	--	15
	Basement Wall Insulation (2% installed)	--	13
	Furnace Fan (due to weatherization)	--	206 (kWh)
	Cooling (due to weatherization)	--	138 (kWh)

* Result of the billing analysis.

** These ranges are based on averages found in tracking data, not on Benefit Cost Reports.

The Cadmus Team made the following two observations with respect to insulation and air sealing measures, both with regard to a similar concurrent impact evaluation for the Home Energy Services (HES) Program (the PA's non-low income weatherization program):

1. Evaluated wall insulation savings were higher than the PA-reported savings for two primary reasons:
   a. On average, low income participants had 1,243 square feet of insulation installed. This value is higher than the 1,092 square-foot average for the market-rate HES Program participants heating with natural gas. As a result, savings are higher for this program than for HES.
   b. There was a relatively high average post-retrofit R-Value of 14.4, compared to the HES Program average of 11.4 R-Value.[14]
2. Evaluated basement ceiling insulation savings are relatively low because in Massachusetts, the majority of heating systems are in the basement, making that space semi-conditioned. The added floor insulation cuts the home off from heat

[14] The width of walls in low income areas are sometimes wider than the average width for HES Program participants (who live in non-low income areas) due to the age of the home, allowing more insulation to be blown in.

generated by the heating system and duct leakage, and thus theoretical savings are not typically realized.

Heating Systems

Boiler/Furnace Replacements

The Cadmus Team analyzed savings for replaced boilers and furnaces at sites where the new equipment efficiencies and the heating equipment matched the replaced measure description. Table 20 lists the system efficiencies by heating system type, showing the number of participants for each. Although the audit data provided average existing efficiency and installed efficiency, the CAAs indicated that these values were higher than the actual program averages because contractors do not always record baselines, especially for the oldest and most inefficient units. The Cadmus Team adjusted our baseline estimates downward based on input from LEAN and kept the audit data averages for installed efficiencies.

Table 20. Natural Gas Heating System Efficiencies

Heating System Measure Replaced	n	Existing Efficiency*	Installed Efficiency
Boiler	87	71%	86.4%
Furnace	53	72%	93.1%

* The existing efficiency of the replaced unit is not often capture by the contractor, especially for older systems. Therefore, the existing efficiencies listed in the table may not truly represent the entire participant population.

Table 21 summarizes the results of our billing analysis of gas heating system replacements. We conducted a billing analysis for this measure category because the modeled precision level is less than 20%. With the average household weather-normalized pre-period usage of 1,148 therms, the gas heating system replacement savings represent 17% savings over the household pre-replacement usage. With the average heating pre-period usage of 878 therms, the gas heating system replacement savings represent 23% savings over the heating pre-replacement usage.

Table 21. Billing Analysis *Ex Post* Energy Savings Results for Natural Gas Heating System Replacement

Measure	n	Billing Analysis Savings (Therms/Year)	Relative Precision at 90% Confidence Level	Average Household Pre-NAC	Average Household Percent Savings	Average Heating Pre-NAC	Average Heating Percent Savings
Heating System Replacement	143	199	± 16%	1,148	17%	878	23%

Table 22 shows the individual results of the furnace and boiler heating system replacements. The actual therm savings between furnaces and boilers are similar; however, the furnaces represent a higher percentage of savings over the pre-replacement usage (19%) compared to the boilers (16%).

Table 22. Billing Analysis Natural Gas Heating System Replacement Savings by Heating System Type (therms/year)

System Type	n	Savings	Relative Precision at 90% Confidence Level	Household Pre-NAC	Heating Pre-NAC	Savings as Percent of Household Pre-NAC	Savings as Percent of Heating Pre-NAC
Furnaces	52	207	15%	1,069	822	19%	25%
Boilers	91	194*	21%	1,191	908	16%	21%
Overall	143	199	16%	1,148	878	17%	23%

* We employed a PRISM-based savings model estimate to look only at the participants who received a heating system boiler. The outcome only showed savings of 196 therms ±26%, which is very similar to the estimate in this table. We also re-estimated the model to include the 13 inoperable units and vacant sites, which dropped the boiler savings to 176 therms.

In some cases, the low income tracking data provided by the PAs denoted whether an integrated space and water heating system was installed. Although the detailed system boiler installation information was largely incomplete, we were able to compare non-integrated system boiler savings to the integrated space and water heating system savings. Not surprisingly, the billing analysis revealed higher percent savings for integrated systems. The smaller sample size for integrated systems resulted in less precise model results.

Table 23. Billing Analysis of Natural Gas Heating System Replacement Savings for Integrated vs. Non-Integrated Heating Systems (therms/year)

Boiler System Type	n	Pre-NAC	Savings	Relative Precision at 90% Confidence Level	Savings as % of Pre-NAC
Integrated	10	1,031	210	47%	20%
Non-integrated	81	1,217	187	22%	15%
Overall	91	1,191	194	21%	16%

Similar to air sealing and insulation, the engineering analysis-based statewide savings (which revealed 182 therms of savings overall) largely corroborated the results of the billing analysis (which revealed 199 therms of savings overall).

We also calculated the electric savings from reduced furnace fan run-times (Table 24). As this reduction corresponds to the reduction in gas use, the evaluated savings value is lower than the reported number.

Table 24. *Ex Post* Energy Savings for Natural Gas Heating System Replacement (savings/year)

Category	Measures	PA 2010 Reported	Evaluated
Heating System Replacement	Heating System Replacement	209 therms	199 therms*
	Furnace Fan (electric savings due to furnace replacement)	194 kWh	172 kWh

* This value is the result of the billing analysis.

Distribution

The Cadmus Team calculated savings estimates for two distribution measures: duct sealing and duct insulation. Details on the calculation method are included in Appendix B. Table 25 shows the estimated therm savings for each measure.

Table 25. Ex Post Energy Savings for Distribution Measures (Therms/year)

Category	Measure	PA 2010 Reported	Evaluated
Distribution	Duct Insulation	--	55
	Duct Sealing	--	33

Domestic Hot Water

We used the engineering algorithm approach to calculate savings for DHW measures (aerators, showerheads, and pipe wrap) based on a combination of audit data inputs and researched assumptions. The audit data provided the total number of each measure installed in the sample, which we used to determine weighted average savings for the measure category (Table 26). The average participant had 1.2 DHW measures installed. No audit data was available for existing or new flow rates.

Table 26. Weighting of Natural Gas Domestic Hot Water Measures

Measure	n	Amount Installed per Site	Percent of Participants Receiving Measure (Weight)
Showerheads	5	1.0 units	7%
Aerators	18	1.1 units	28%
Pipe Wrap	56	31 feet	84%
Overall	67		119%

Table 27 summarizes our evaluation findings for natural gas DHW measures.

Table 27. *Ex Post* Natural Gas Energy Savings for Distribution and Domestic Hot Water Measures (therms/year)

Category	Measures	PA 2010 Reported	Evaluated
Domestic Hot Water	Domestic Hot Water (1.2 measures per household)*	10	5
	Low-Flow Showerhead (7% installed)	--	9
	Faucet Aerator (28% installed)	--	2
	Pipe Wrap (84% installed)	--	4

* These are the average savings for a household that received at least one DHW measure.

Summary of Natural Gas Savings

Table 28 summarizes the overall evaluation findings for all natural gas measures.

We also completed a household-level analysis to compare to our measure-specific analysis. The household-level model showed an average household savings of 239 therms. This value is slightly less than the weighted average of our measure-specific savings (249 therms). This information indicates the measure-specific values maybe slightly overstated. However, there is no way to adjust them given the insignificance of the DHW measures and the collinearity associated with the other measure category. Because the measure-specific savings somewhat exceed those observed at the household-level, behavior-based base load savings are not reported separately.

Table 28. *Ex Post* Energy Savings for All Natural Gas Measures (therms/year)

Category	Measures	PA 2010 Reported	Evaluated
Insulation and Air Sealing	Insulation and Air Sealing (Overall 2.5 average installations)	245	263*
	Air Sealing (96% installed)	30 - 190**	105
	Attic Insulation (88% installed)	70 - 240**	83
	Wall Insulation (85% installed)	80 - 190**	115
	Basement Ceiling Insulation (2% installed)	--	15
	Basement Wall Insulation (2% installed)	--	13
	Furnace Fan (electric savings due to weatherization)	--	206 (kWh)
	Cooling (electric savings due to weatherization)	--	138 (kWh)
Heating System Replacement	Heating System Replacement	209	199*
	Furnace Fan (electric savings due to furnace replacement)	194 (kWh)	172 (kWh)
Distribution	Duct Insulation	--	55
	Duct Sealing	--	33
Domestic Hot Water	Domestic Hot Water (1.2 measures per household)	10	5
	Low-Flow Showerhead (7% installed)	--	9
	Faucet Aerator (28% installed)	--	2
	Pipe Wrap (84% installed)	--	4

* These values reflect the results of the billing analysis.

** These ranges are based on averages found in tracking data, not on Benefit Cost Reports.

Ex Post Energy Savings – Electric

As noted in the Methodology section, we could not reliable estimate savings for any electric measures through a billing analysis. As a result, we obtained all the savings presented in this section through engineering analysis.

Insulation and Air Sealing

The Cadmus Team used the same calibrated simulation approach to evaluate insulation and air sealing measures for electrically heated homes as we used to evaluate gas heated homes. We adjusted the model using the home characteristics from the electrically heated home sample, and calibrated the model to align with the pre-NAC value determined through the billing analysis.[15] We weighted the resulting savings values using the sample installation rates shown in Table 29. As with the gas weatherization measures, we adjusted these installation rates to ensure a

[15] Although the electric sample was not large enough to discern measure savings via billing analysis, we were able to determine the average normalized consumption.

representative sample across PAs. This adjustment explains the differences between Table 29 and Table 30.

Table 29. Distribution of Electric Insulation and Air Sealing Measures

Measure	n	Measure Weight
Air Sealing	27	100%
Attic Insulation	23	86%
Wall Insulation	6	23%
Basement Ceiling Insulation	7	26%
Basement Wall Insulation	0	0%
Total Participants	27	234%*

* This value is greater than 100% because participants installed multiple measures; 234% indicates that each participant had an average of 2.34 measures installed.

The Cadmus Team calculated average insulation levels (weighted by square footage installed) using the agency on-site data (Table 30). We used an assumed pre-R-Value of 3.4 where no pre-existing insulation is indicated in the audit data, but gave no assembly R-Value.

Table 30. Average R-Values and Installed Square Feet for Electric Customers

Measure	n	Original Pre-R-Value	Modified Pre-R-Value	Post R-Value	Square Feet Installed per Customer
Attic Insulation	19	8.0	8.0	26.7	905
Wall Insulation	6	0.0	3.4	14.4	949
Basement Ceiling Insulation	5	11.0	11.0	23.3	647
Basement Wall Insulation	0	6.9	6.9	25.5	162

With the average household baseline consumption of 11,357 kWh, the insulation and air sealing measures represent 14% savings. With the average baseline heating consumption of 5,340 kWh, the insulation and air sealing savings represent 26% savings (Table 31).

Table 31. *Ex Post* Electric Energy Savings Results for Insulation and Air Sealing

Measure	Engineering Analysis (kWh/Year)	Average Household Baseline Consumption (kWh/Year)	Average Household Percent Savings	Engineering Analysis Heating Savings (kWh/Year)	Average Baseline Heating Consumption (kWh/Year)	Average Household Percent Savings
Insulation and Air Sealing	1,616	11,357	14%	1,412	5,340	26%

The average electric insulation and air sealing participant had 2.3 measures installed, whereas the average gas insulation and air sealing participant had 2.5 measures installed. The electric weatherization savings estimates include cooling savings (Table 32).

Table 32. *Ex Post* Electric Energy Savings for Insulation and Air Sealing (kWh/year)

Category	Measures	PA 2010 Reported	Evaluated
Insulation and Weatherization	Insulation and Air Sealing (Overall 2.3 average installations)	374	1,616
	Air Sealing (100% installed)	--	501
	Attic Insulation (86% installed)	--	1,071
	Wall Insulation (23% installed)	--	824
	Basement Ceiling Insulation (26% installed)	--	30
	Basement Wall Insulation (0% installed)	--	37

The PA 2010 reported value of 374 kWh for electric weatherization came from the Massachusetts TRM and is based on savings from a previous evaluation.[16] The previous evaluation included a billing analysis of 24 low income customers from National Grid's Massachusetts and Rhode Island territories that had electric weatherization measures installed in 2007. At that time, electric weatherization measures were not a large part of the overall low income assistance programs, which focused on appliances (AMP). The PAs did not report individual measures (air sealing, insulation, etc.) for that evaluation, and The Cadmus Team does not know exactly which unique measures were included. We based the current evaluated savings of 1,616 kWh for overall insulation and air sealing on more detailed, known measures from audit documents, and can break that number out precisely by the type of weatherization measure.

It should be noted the evaluated savings are based on a relatively small sample of homes (n=27), approximately half of which were located within CLC's service territory (which had the greatest participation of electric weatherization of all the PAs).

Appliances

Agency auditors use one of two approaches to determine whether a participant's refrigerator and/or freezer is eligible to be removed and/or replaced by the program. The first way is for auditors to install metering equipment at the beginning of the audit. While the auditor inspects the remainder of the house over the next couple of hours, the metering logger records the appliance's energy consumption. Upon completing the audit, the auditor removes the logger and converts the observed hourly energy consumption to daily and annual values. The auditor then will compare these values to the program's current efficiency thresholds to determine its eligibility for replacement. If the auditor determines that a refrigerator or freezer is less efficient than the program threshold, they remove the appliance and replace it with a comparably sized ENERGY STAR® model. The second way auditors determine appliance eligibility is by looking up the appliance make and model in the Association of Home Appliance Manufacturers (AHAM) database, which details the estimated annual energy consumption for a cross-section of refrigerator and freezers.

The metering process described as the first of two approaches above results in participant-specific primary data for estimating the savings generated by refrigerator replacement, freezer replacement, and the removal of a secondary refrigerator. However, energy consumption

[16] The Cadmus Group, Inc. *Impact Evaluation of the 2007 Appliance Management Program and Low Income Weatherization Program.* Prepared for National Grid; Table 1. 2009.

information of the existing (or replaced) appliance only informs half of the savings calculation for replaced units (all primary refrigerators or stand-alone freezers). To calculate savings for the new measures, we also factored in information regarding the energy consumption of the replacement appliance.

Our review of the PA-provided data shows that their details regarding the energy consumption of the existing appliance and the replacement appliance differed greatly. In addition, the PAs did not denote whether the metered value was for a *replaced* primary refrigerator or a *removed* (and not replaced) secondary refrigerator. A summary of the information available from each electric PA is provided in Table 33.

Table 33. Refrigerator and Freezer Data Provided by Electric PAs

PA	Differentiated Between Replaced and Removed Refrigerators	Included Metering Data for Existing Appliance	Included Information Regarding Replacement Appliance
National Grid	Yes, both	No	Yes* (model information and estimated consumption)
NSTAR	Replacement only	Yes	Yes (model information, but no usage)
CLC / Unitil	Replacement only	No	No
WMECO	Could not be determined	No	Yes (model information, but no usage)

* This PA provided the estimated consumption in a separate file.

NSTAR provided the most complete information regarding the metering values of replaced appliances, thus we limited our assessment of the existing appliances' energy consumption to only NSTAR customers. Specifically, The Cadmus Team utilized the actual metered value. Unfortunately, the NSTAR data did not include the new unit's consumption (replacement unit), so we used this sample (n=227)as the proxy for existing appliance consumption only for the refrigerator replacement and removal scenarios. National Grid provided the most detailed data regarding replacement appliances (newly installed units, refrigerator n=597, freezer n=119), so we used the sample of National Grid participants to calculate the average savings for refrigerator and freezer replacement scenarios (Table 34).

Table 34. Refrigerator and Freezer Electric Energy Consumption and Savings Estimates (kWh/year)

Measure	Existing Appliance Consumption	Replacement Appliance Consumption	Energy Savings
Refrigerator Replacement	1,180 (n=227)	439 (n=597)	741
Secondary Refrigerator Removal	1,180 (n=227)	N/A	1,180
Freezer Replacement	696 (n=33)	458 (n=119)	238

To calculate savings from window air conditioner replacements, The Cadmus Team used the engineering algorithm approach, based on estimated operating hours, unit capacity, and pre- and post-SEER ratings as shown in the following equation:

$$\boldsymbol{Savings\ per\ Unit} = \frac{\frac{\boldsymbol{BTU}}{\boldsymbol{hr}} \times \left(\frac{\boldsymbol{1}}{\boldsymbol{EER_{BASE}}} - \frac{\boldsymbol{1}}{\boldsymbol{EER_{EFF}}}\right) \times \boldsymbol{EFLH_{COOL}}}{\boldsymbol{1,000}}$$

The inputs we used to inform our estimate of savings are provided in Table 35.

Table 35. Window Air Conditioner Savings Calculation Summary

Parameter	Value	Source
Hours (EFLHcool)	360	Massachusetts TRM
Capacity (BTU/hr)	10,000	ENERGY STAR calculator
Baseline Efficiency (EERbase)*	6.7	Laboratory testing of older, but operable window air conditioners
Measure Efficiency (EEReff)	10.8	ENERGY STAR calculator
Savings (kWh/year)	204	Calculated

* The Cadmus Group, Inc. *OPA Keep Cool Metering Study.* 2008. (http://www.powerauthority.on.ca/sites/default/files/2008%20OPA%20Every%20Kilowatt%20Counts%20PowerSavings%20Event%2C%20Keep%20Cool%2C%20and%20Rewards%20for%20Recycling%20Evaluation%20Retailer%20Names%20redacted.pdf)

Table 36 shows the savings results for all four appliance measures.

Table 36. *Ex Post* Electric Energy Savings for Appliances (kWh/year)

Category	Measures	PA 2010 Reported	Evaluated
Appliances	Refrigerator Replacement	1,122	762
	Second Refrigerator Removal	1,321	1,180
	Freezer Replacement	637	239
	Window AC Replacement	100	204

Lighting

The Cadmus Team used the following standard engineering equation to estimate first-year savings for CFLs installed in 2010:

$$kWh\ saved = \frac{(Watts_{base} - Watts_{ee})}{1000} \times HOU$$

We used numerous data sources to inform the equation. First, The Cadmus Team used agency and PA tracking data to establish pre- and post-retrofit lamp wattages, as shown in Table 37. Without CFL metering as part of this evaluation, we used the default of 2.8 hours-of-use recommended by the Massachusetts TRM. The average installed quantity was 11 CFLs per household.

As shown in Table 37, we calculated the evaluated per-CFL savings to be 45 kWh/year.

Table 37. CFL Energy Savings Calculation Summary*

Parameter	Estimate	Source
Average Pre-retrofit Wattage (2011)	68	Tracking Data
Average Post-retrofit Wattage	17	CAP Audit Data
Delta Watts	51	Calculated
Annual Hours-of-Use (based on 2.8 hours-of-use per day)	1,022	MA TRM
In-Service Rate	90%	MA TRM
Savings (kWh/year)	45	Calculated

* This calculation also included a weighted average of interactive terms across fuel types with and without air conditioning. See Appendix B for details.

In order to estimate the effects of the new federal Energy Independence and Security Act (EISA) standards on first-year CFL savings, The Cadmus Team projected a possible baseline shift scenario from 2011 to 2016. Our goal with this analysis was to predict the change in Watts_{base} over the course of implementing the EISA standard. For this simple scenario, we made basic assumptions about the lag in market adoption, but did not attempt to account for customers changing to different types of incandescent or halogen bulbs as the standards come into effect.

Nexus Market Research (NMR) is conducting a broader analysis of how EISA standards will affect residential lighting programs in Massachusetts. They will use a sensitivity analysis to estimate additional and more complex repercussions (e.g., customers shifting to CFLs, customers bin-jumping to purchase halogen incandescents). The Cadmus Team spoke to NMR and confirmed that our approach to estimating the CFL baseline shift aligns with their respective baseline assumptions. Since a more complex analysis was outside the scope of the current effort, The Cadmus Team has provided these values for context only.

We determined the CFL baseline shift from three main factors:

1. New EISA baselines
2. EISA effective dates for each incandescent wattage
3. Assumed market lag factors

Table 38 summarizes the EISA standards for each rated lumen range and their effective dates.

Table 38. Summary of EISA Standards and Timelines

Rated Lumen Range	Typical Current Lamp Wattage	Maximum Rated Wattage	Effective Date
1,490 – 2,600	100	72	1/1/2012
1,050 – 1,489	75	53	1/1/2013
750 – 1,049	60	43	1/1/2014
310 - 749	40	29	1/1/2014

Table 39 summarizes the estimated percentage of the baseline share for EISA-compliant lamps each year after a given component of the standard takes effect. The Cadmus Team used these factors to project the baseline for each wattage range over a five-year period, then used a weighted average of the wattages replaced to determine a single baseline for each year.[17]

Table 39. Estimated EISA Market Lag Factors

Years Since Effective Date	Estimated EISA Baseline Share
Year 1	30%
Year 2	80%
Year 3	90%
Year 4	100%
Year 5	100%

This baseline information resulted in an estimated baseline shift from 68 watts in 2011 to 50 watts in 2016, and a corresponding change in savings from 45 kWh in 2011 to 29 kWh in 2016, as illustrated in Table 40.

Table 40. Potential CFL Baseline Shift and Corresponding Savings Estimates

Year	Baseline (Watts)	Savings (kWh)
2011	68	45
2012	67	43
2013	63	41
2014	58	36
2015	51	30
2016	50	29

Table 41 summarizes the evaluated *ex post* energy savings for lighting. We determined the evaluated savings for torchieres and fixtures by applying the realization rate between PA reported and evaluated savings for CFLs (45/41 = 1.10). The Cadmus Team did not investigate the effects of the EISA standards on torchieres or fixtures.

Table 41. *Ex Post* Electric Energy Savings for Lighting (kWh/year)

Category	Measure	PA 2010 Reported	Evaluated
Lighting	CFLs	41	45
	Torchieres	194	213
	Fixtures	128	141

Domestic Hot Water and Other Measures

As with gas hot water heating measures, The Cadmus Team used an algorithm approach and sample installation rates to weight the overall DHW measure category savings. We did not evaluate baseload TLC kits as a stand-alone measure. Table 42 summarizes the DHW and baseload TLC results.

17 We estimated this weighted average based on typical residential uses, which we adjusted to match the average Low Income Program baseline of 68 watts.

Table 42. *Ex Post* Energy Savings for Domestic Hot Water and Other Measures (kWh/year)

Category	Measures	PA 2010 Reported	Evaluated
Domestic Hot Water	Domestic Hot Water (1.7 measures per home)*	134	128
	Low-Flow Showerhead (40% installed)	--	188
	Faucet Aerator (80% installed)	--	40
	Pipe Wrap (50% installed)	--	41
Other***	Baseload (TLC kits)**	138	25
	Faucet Aerator****	--	24
	LED Nightlight	--	11
	Drip Gauge	--	0
	Hot Water Thermometer	--	18
	Refrigerator/Freezer Thermometer	--	0
	Refrigerator Coil Brush	--	0
	Wall Plate Stoppers	--	4

* This row reflects the average savings for a household that received at least one DHW measure.

** This row reflects statewide averages based on each PA's kit contents and participation levels.

*** All measure savings are reported per-unit and account for installation and/or adoption rates.

**** Faucet aerators in the other category save less than those in the domestic hot water category because of a lower in-service rate (61%, Assessment of Washington Energy Education in Schools: 2010-2011 Program Year).

Summary of Electric Savings

Table 43 summarizes the overall electric energy savings estimates for the Low Income Program. Due to the small sample size of customers with electric heating (n=100), we estimated all heating measure savings using the calibrated simulation approach. Similarly for electric non-heating measures (such as appliance and CFLs), the percentage of savings was too small and/or the sample size was not sufficiently large enough to reliably evaluate savings via a billing analysis. Thus, for electric non-heating measures, we used engineering algorithms to evaluate savings.

Table 43. *Ex Post* Energy Savings for All Electric Measures (kWh/year)

Category	Measures	PA 2010 Reported	Evaluated
Insulation and Weatherization	Insulation and Air Sealing (Overall 2.3 average installations)	374	1,616
	Air Sealing (100% installed)	--	501
	Attic Insulation (86% installed)	--	1,071
	Wall Insulation (23% installed)	--	824
	Basement Ceiling Insulation (26% installed)	--	30
	Basement Wall Insulation (0% installed)	--	37
Appliances	Refrigerator Replacement	1,122	762
	Second Refrigerator Removal	1,321	1,180
	Freezer Replacement	637	239
	Window AC Replacement	100	204
Lighting	CFLs	41	45
	Torchieres	194	211
	Fixtures	128	140
Domestic Hot Water	Domestic Hot Water (1.7 measures per home)*	134	128
	Low-Flow Showerhead (40% installed)	--	188
	Faucet Aerator (80% installed)	--	40
	Pipe Wrap (50% installed)	--	41
Other***	Baseload (TLC kits)**	138	25
	Faucet Aerator	--	24
	LED Nightlight	--	11
	Drip Gauge	--	0
	Hot Water Thermometer	--	18
	Refrigerator/Freezer Thermometer	--	0
	Refrigerator Coil Brush	--	0
	Wall Plate Stoppers	--	4

* This row reflects the average savings for a household that received at least one DHW measure.

** This row reflects statewide average savings based on each PA's kit contents and participation levels.

*** All measure savings are reported per-unit and account for installation and/or adoption rates.

**** Faucet aerators in the other category save less than those in the domestic hot water category because of a lower in-service rate (61%, Assessment of Washington Energy Education in Schools: 2010-2011 Program Year).

Ex Post Energy Savings – Oil

Insulation and Air Sealing

As with electric insulation and air sealing, The Cadmus Team used a calibrated simulation model to estimate oil savings. The average oil participant installed 2.7 measures, which is similar to gas participants who averaged 2.5 installations. As with the gas participants, air sealing was the most common measure, with 93% of oil participants receiving the measure. Table 44 shows the number of installations and measure weights for each oil weatherization measure.

Table 44. Distribution of Oil Insulation and Air Sealing Measures

Measure	n	Measure Weight
Air Sealing	249	93%
Attic Insulation	216	81%
Wall Insulation	221	83%
Basement Ceiling Insulation	14	5%
Basement Wall Insulation	13	5%
Overall	267	267%

We calculated the average insulation levels (weighted by square footage installed) using the on-site data. Similar to natural gas, attic, wall, and basement insulation accounted for 94% of the area insulated by the program. Also similar to our natural gas analysis, we used an assumed R-Value of 3.4 where no pre-existing insulation was indicated in the audit data and no assembly R-Value was shown in the data we collected from the CAAs (Table 45).

Table 45. Average R-Values and Installed Square Feet for Oil Heating Customers

Measure	Number of Customers	Original Pre-R-Value	Modified Pre-R-Value	Post R-Value	Square Feet Installed per Customer
Attic Insulation	188	5.9	5.9	27.2	968
Wall Insulation	158	3.9	3.9	14.3	1,305
Basement Ceiling Insulation	11	0.0	3.4	19.8	396
Basement Wall Insulation	2	6.5	6.5	24.6	36

With the average household baseline consumption of 28 MMBTU, the insulation and air sealing measures represent 26% savings. With the average baseline heating consumption of 83 MMBTU, the insulation and air sealing savings represent 34% savings (Table 46).

Table 46. *Ex Post* Oil Energy Savings Results for Insulation and Air Sealing

Measure	Engineering Analysis Total Savings (MMBTU/Year)	Average Baseline Consumption (MMBTU/Year)	Average Household Percent Savings	Average Baseline Heating Consumption (MMBTU/Year)	Average Household Percent Savings
Insulation and Air Sealing	28	108	26%	83	34%

Table 47 shows the results of the calibrated simulation model, including furnace fan savings.

Table 47. *Ex Post* Oil Energy Savings for Air Sealing and Insulation (MMBTU/year)

Category	Measures	PA 2010 Reported	Evaluated
Insulation and Air Sealing	Insulation and Air Sealing (Overall 2.7 average installations)	13.70	28
	Air Sealing (93% installed)	--	10
	Attic Insulation (81% installed)	--	12
	Wall Insulation (83% installed)	--	11
	Basement Ceiling Insulation (5% installed)	--	2.9
	Basement Wall Insulation (5% installed)	--	0.2
	Furnace Fan (due to weatherization) Cooling (due to weatherization)	-- --	224 (kWh) 153 (kWh)

Heating System Measures

Table 48 shows the oil heating system replacement assumptions we used for the evaluation. The values present weighted averages of boiler and furnace installations. As with gas heating systems, The Cadmus Team overrode the baseline efficiencies reported in the audit data based on input from LEAN. For detailed results on furnaces, boilers, and indirect water heaters, please see Appendix B.

Table 48. Oil Heating System Replacement Assumptions

Parameter	Evaluation Assumption	Evaluation Source
Baseline Efficiency	69%	Engineering Estimate
New Efficiency	85.2%	Agency Data, n=51 participants
Pre-Retrofit Annual Heating Usage (therms)	879	PA billing data for gas heating system participants
Savings (MMBTU)	18.4	Calculation

The Cadmus Team conducted a literature review to inform a percent savings estimate for boiler reset controls and programmable thermostats. Details regarding this review are provided in Appendix B. We then applied this factor to the base heating load we had determined in the gas billing analysis.

Table 49 summarizes the *ex post* energy savings for oil heating system measures.

Table 49. *Ex Post* Energy Savings for Oil Heating Systems (MMBTU/year)

Category	Measure	PA 2010 Reported	Evaluated
Heating System	Oil Heating System Replacement	12.2	18.4
	Boiler Reset Controls	7.9	4.4
	Programmable Thermostat	7.7	3.1
	Furnace Far (electric savings due to furnace replacement)	--	132 (kWh)

Distribution

The Cadmus Team calculated savings estimates for two distribution measures: duct sealing and duct insulation. Details on the calculation method are included in Appendix B. Table 50 shows the estimated MMBTU savings for each measure.

Table 50. *Ex Post* Energy Savings for Distribution Measures (MMBTU/year)

Category	Measures	PA 2010 Reported	Evaluated
Distribution	Duct Insulation	--	4.3
	Duct Sealing	--	3.3

Domestic Hot Water

As with gas hot water heating, we used an algorithm approach and sample installation rates to weight the overall measure category savings for oil hot water heating. Table 51 and Table 52 show the installation rates and savings associated with each measure, respectively.

Table 51. Weighting of Domestic Hot Water Measures for Oil Heating Customers

Measure	n	Amount Installed per Site	Percent of Participants Receiving Measure (Weight)
Showerheads	19	1.1 units	23%
Aerators	37	1.6 units	67%
Pipe Wrap	58	23 feet	64%
Overall	90		154%

Table 52. *Ex Post* Oil Energy Savings for Domestic Hot Water (MMBTU/year)

Category	Measure	PA 2010 Reported	Evaluated
Domestic Hot Water	Domestic Hot Water (1.5 measures per household)*	1.1	0.7
	Low-Flow Showerhead (23% installed)	--	1.1
	Faucet Aerator (67% installed)	--	0.2
	Pipe Wrap (64% installed)	--	0.4

* The values in this row reflect the average savings for a household that received at least one DHW measure.

Summary of Oil Savings

Table 53 summarizes the overall *ex post* energy savings for all oil fuel measures. Due to the nature of oil billing data, we used an engineering algorithm approach for all oil measures. However, we leveraged the gas customer model to estimate oil savings, changing the input assumptions where necessary (such as heating efficiency).

Table 53. *Ex Post* Energy Savings for All Oil Measures (MMBTU/year)

Category	Measures	PA 2010 Reported	Evaluated
Insulation and Air Sealing	Insulation and Air Sealing (Overall 2.7 average installations)	13.70	28.1
	Air Sealing (93% installed)	--	9.9
	Attic Insulation (81% installed)	--	11.6
	Wall Insulation (83% installed)	--	11.2
	Basement Ceiling Insulation (5% installed)	--	2.9
	Basement Wall Insulation (5% installed)	--	0.2
	Furnace Fan (due to weatherization)	--	224 (kWh)
	Cooling (due to weatherization)	--	153 (kWh)
Heating System	Oil Heating System Replacement	12.20	18.4
	Boiler Reset Controls	7.90	4.4
	Programmable Thermostat	7.70	3.1
	Furnace Fan (due to furnace replacement)	--	132 (kWh)
Distribution	Duct Insulation	--	4.3
	Duct Sealing	--	3.3
Domestic Hot Water	Domestic Hot Water (1.5 measures per household)	1.10	0.7
	Low-Flow Showerhead (23% installed)	--	1.1
	Faucet Aerator (67% installed)	--	0.2
	Pipe Wrap (64% installed)	--	0.4

APPENDIX A. SIMULATION MODELING METHODOLOGY

The Cadmus Team's simulation modeling approach consisted of four tasks:

1. First, **analyzing participant billing data** for each fuel type (gas, oil, and electric).
2. Next, **disaggregating billing data into end-uses** for model calibration targets.
3. Then, **calibrating the model** using participant audit data to inform building characteristics.
4. Finally, **deriving measure-level savings** by running simulation models with baseline and efficient values pulled from the audit data.

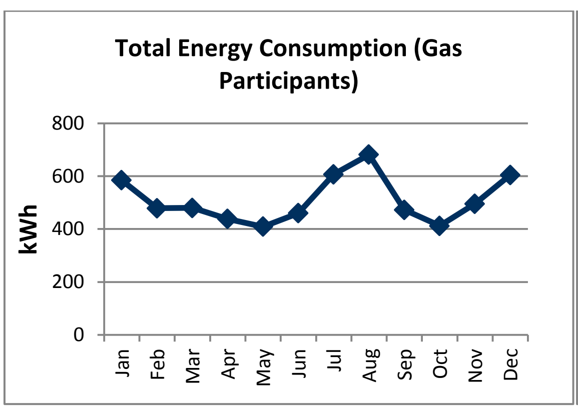
Analysis of Participant Billing Data

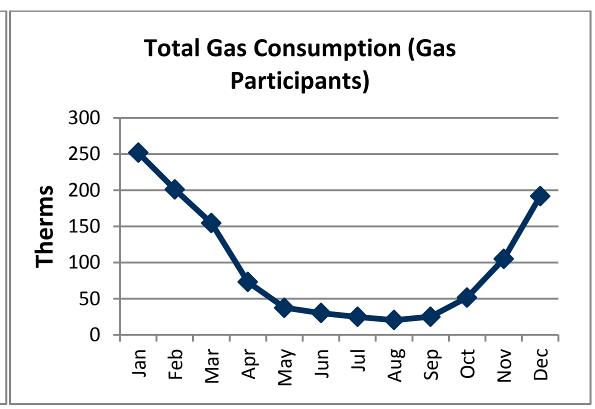
In order to determine energy consumption targets for the model calibrations, The Cadmus Team analyzed billing data provided by each PA on a per-site basis. The PAs delivered this data in the form of a spreadsheet showing rows with energy consumption data for the past billing period, along with the billing date. We cleaned and then converted the data into energy consumption values for each calendar month using the following process:

1. Summed all consumption values for a particular month and year for each site to remove erroneous data and possible duplicates.
2. Determined consumption for each calendar month by adjusting the monthly billing data by billing date to reflect the actual consumption used each month.
3. Removed program years 2010 and 2011 to ensure pre-install consumption.
4. Calculated the average monthly consumption for each fuel type.

We plotted the average consumption for each fuel type (gas is shown in therms) and examined the results to ensure there was a linear slope between calendar months.

Figure 3. Average Annual Consumption for Gas Participants (kWh and Therms)





We established that the annual consumption and monthly breakdowns were suitable for the calibration process.

Disaggregate Consumption Data into End Uses

Once The Cadmus Team determined the average monthly consumption for each fuel type, we broke those monthly total values down by end use using the Navigant billing data end-use disaggregation method. This method is Navigant's standard practice, and has been used for numerous residential evaluations nationwide. The basic steps are as follows:

1. **Determined the average monthly consumption** for each model group by aggregating monthly participant billing data (as described above).
2. **Estimated lighting and DHW usage** based on the U.S. DOE's Building America Research Benchmark and based on a lighting usage study conducted for the California investor-owned utilities (KEMA IOU).[18] To create this estimate, we used the average building size and electric hot water heater saturation for each region of Massachusetts.
3. **Calculated the remaining consumption,** which is attributable to HVAC and miscellaneous equipment (all uses other than lighting and DHW), by subtracting lighting and DHW consumption from the monthly average.
4. **Calculated miscellaneous equipment consumption** by:
   a. Identifying the base month, defined as the month with the lowest remaining consumption per day, assuming that heating and cooling (HVAC) consumption accounts for a small fraction of the base month total (usually 10% to 15% in colder climates with both heating and cooling).
   b. Subtracting the HVAC consumption in the base month from the remaining consumption, assuming that this miscellaneous equipment consumption per day is constant throughout the year.
5. **Calculated HVAC consumption** by subtracting lighting, DHW, and equipment consumption from the monthly average.

[18] KEMA, Inc. *CFL Metering Study, Final Report.* Prepared for Pacific Gas and Electric, San Diego Gas and Electric, and Southern California Edison. February 25, 2005.

6. **Split the HVAC consumption into heating and cooling** by assigning all winter season HVAC consumption (November through March) to heating and all summer season HVAC consumption (June through August) to cooling. We then split the swing season HVAC consumption by assuming that heating and cooling are proportional to the HDDs and CDDs in each month.[19]
7. **Adjusted the heating and cooling consumption** in each month by multiplying the ratio of average HDDs or CDDs for that month's billing period to those same months in a typical year.[20]

The first step to disaggregate monthly energy consumption into end-uses is to break out the uses that can reliably be calculated using engineering algorithms and primary research: in this case, lighting and DHW.

Lighting

The Cadmus Team estimated annual lighting consumption per household using an equation from the U.S. DOE's Building America Research Benchmark (BARB), which gives lighting consumption as a function of square footage of floor area as follows:

$$\boldsymbol{Annual\ Lighting\ Consumption\ (kWh) = 0.8 * Floor\ Area\ (sf) + 805}$$

To break the annual consumption into monthly values, it was necessary to derive a seasonal load profile, due to the fact that lighting use increases during the winter months when there is less daylight. We derived the seasonal lighting variation profile from a CFL monitoring study performed for the California investor-owned utilities KEMA IOU. The basic steps are as follows:

1. **Determine the percent of total hours and weighted average hours per lamp** that are daylight-sensitive; assume family, kitchen/dining, and living rooms are daylight sensitive. These input data and calculated result are shown in Table 54 and Table 55.

[19] We determined the HDDs and CDDs from www.degreedays.net, a Website that aggregates data from the Weather Underground (www.wunderground.com).

[20] We determined HDDs and CDDs for a typical year from the EnergyPlus Simulation software available at: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=4_north_and_central_america_wmo_region_4/country=1_usa/cname=USA.

Table 54. Number of Fixtures in KEMA Study and Average Daily Usage by Room Type

Room	Daylight Sensitivity	Number of Fixtures in KEMA Study	Percent of Household Fixtures	Average Daily Hours per Lamp
Bedroom	No	669	27%	1.6
Bathroom	No	400	16%	1.5
Family	Yes	194	8%	2.5
Garage	No	72	3%	2.5
Hallway	No	184	7%	1.6
Kitchen/dining	Yes	484	19%	3.5
Living	Yes	342	14%	3.3
Laundry/utility	No	68	3%	1.2
Other	No	94	4%	1.9

* Column may not add to 100% due to rounding.

Table 55. Percent of Total Annual Hours and Weighted Average Daily Usage by Daylight Sensitivity

Sensitivity	Percent of Total Annual Hours	Weighted Average Daily Hours per Lamp
Daylight Sensitive	58%	3.24
Non-Daylight Sensitive	42%	1.65
All Lamps	100%	2.57

2. **Calculate an average percent "night adder"** by assuming an average adder of 0.75 hours per day for daylight-sensitive lamps and 0.25 hours per day for non-daylight-sensitive lamps; divide these values by the average hours per day and weight by the percent of total hours to get an average night adder (which The Cadmus Team calculated to be 20% for this evaluation).
3. **Determine the relative daily usage factor for each month** by assuming that usage varies linearly from a minimum of (1-Night Adder) in June to a maximum of (1+Night Adder) in December; add an additional 20% to December to account for an observed spike in energy consumption in this month, which is assumed to be from holiday lighting.
4. **Calculate relative monthly usage** by multiplying the relative daily usage factor times the number of days in the month.
5. **Derive the monthly variation profile** by dividing each month's relative usage by the average monthly relative usage for the whole year (30.93). Steps 3, 4, and 5 are shown in Table 56.

Table 56. Daily Usage, Monthly Usage, and Lighting Variation Profile

Month	Relative Daily Usage Factor	Days/Month	Relative Monthly Usage	Lighting Variation Profile
January	113%	31	34.43	1.11
February	107%	28	32.42	1.05
March	100%	31	30.42	0.98
April	93%	30	28.41	0.92
May	87%	31	26.40	0.85
June	80%	30	24.39	0.79
July	87%	31	26.40	0.85
August	93%	31	28.41	0.92
September	100%	30	30.42	0.98
October	107%	31	32.42	1.05
November	113%	30	34.43	1.11
December	140%	31	42.58	1.38

The Cadmus Team then calculated the average monthly lighting electricity consumption by multiplying the lighting variation profile by the annual lighting consumption estimate.

Domestic Hot Water

The starting point we used for determining seasonal DHW end usage was the DHW end-use profiles from the 2008 BARB. The BARB details the average gallons per day of DHW used each month for the dishwasher, clothes washer, baths, showers, and sinks, along with the average temperature of the water mains (i.e., inlet/supply water). An example of this data for Massachusetts is shown in Table 57.

Table 57. Domestic Hot Water Profile for Massachusetts (gallons/day)

Month	Mains Temp (ºF)	Dishwasher	Clothes Washers	Baths	Showers	Sinks	Total
January	43.3	3.0	8.3	5.6	22.5	20.1	59.5
February	41.7	3.0	8.4	5.7	22.6	20.2	59.9
March	42.8	3.0	8.3	5.6	22.6	20.1	59.6
April	46.5	3.0	8.0	5.6	22.3	19.9	58.8
May	51.7	3.0	7.6	5.5	21.9	19.5	56.2
June	57.1	3.0	7.1	5.3	21.3	19.0	54.4
July	61.3	3.0	6.6	5.2	20.9	18.6	52.9
August	63.2	3.0	6.4	5.2	20.6	18.4	52.3
September	62.2	3.0	6.5	5.2	20.7	18.5	52.8
October	58.7	3.0	6.9	5.3	21.2	18.9	54.2
November	53.6	3.0	7.4	5.4	21.7	19.3	56.0
December	48.2	3.0	7.9	5.5	22.2	19.8	57.5

To calculate the total monthly DHW consumption, we multiplied the consumption of each end use by the saturations of that end use among participants.[21]

Next, we calculated the monthly electricity consumption for homes with electric DHW using the total monthly gallons of hot water and the seasonally adjusted mains water temperatures. This consumption was composed of two parts: the water heating load and the standby heat loss coefficient (UA load), which is equal to the amount of heat required to compensate for heat loss from the water heater tank. The equations we used are as follows:[22]

$$\begin{aligned}Heating\ Load\ (kWh/day)\\ &= Consumption\ (gal/day)\ *\ 8.31\ (Btu/(gal\ ^\circ\mathrm{F}))*(Water\ Temp\\ &- Mains\ Temp)(^\circ\mathrm{F})/(Heating\ Efficiency*3412\ (Btu/kWh)\ )\end{aligned}$$

$$\begin{aligned}UA\ Load\ (kWh/day)\\ &= Tank\ UA\ (Btu/(hr\ ^\circ\mathrm{F}))*(Water\ Temp - Ambient\ Temp)(^\circ\mathrm{F})\\ &*\ 24\ (hr/day)\ /(Heating\ Efficiency*3412\ (Btu/kWh)\ )\end{aligned}$$

Similar to the lighting variation profile, we then calculated the DHW variation profile by finding the average consumption for each month divided by the average consumption for all months. Table 58 shows these results for Massachusetts.

Table 58. Domestic Hot Water Electricity Consumption and Variation Profile for Massachusetts

Month	Gal/Day	Mains Temp	Heating Load (kWh/day)	UA Load (kWh/day)	Days/ Month	Total kWh/ month	DHW Variation Profile
January	57.2	43.3	11.4	3.1	31	448.7	1.2
February	57.5	41.7	11.7	3.1	28	413.7	1.1
March	57.3	42.8	11.5	3.1	31	451.4	1.2
April	56.5	46.5	10.8	3.1	30	416.7	1.1
May	54.0	51.7	9.6	3.1	31	394.6	1.0
June	52.3	57.1	8.6	3.1	30	352.2	0.9
July	50.9	61.3	7.9	3.1	31	340.6	0.9
August	50.2	63.2	7.6	3.1	31	330.5	0.9
September	50.7	62.2	7.8	3.1	30	325.6	0.8
October	52.1	58.7	8.4	3.1	31	356.6	0.9
November	53.8	53.6	9.4	3.1	30	373.4	1.0
December	55.3	48.2	10.3	3.1	31	416.5	1.1

Next, we derived the average household monthly DHW electric consumption by multiplying the monthly DHW electricity consumption by the electric hot water saturation. The Cadmus Team

[21] We assigned 100% saturation to dishwashers because we assumed that households without a dishwasher use the same amount of hot water for washing dishes by hand.

[22] We assumed for following variables for this calculation: Hot Water Temp = 120, Heating Efficiency = 0.75, Tank UA = 7, Ambient Temp = 70.

utilized this same procedure for a sample of homes with gas water heaters, and then converted the units to therms.

Miscellaneous Equipment

After subtracting the DHW and lighting end uses from the monthly household electricity consumption, the remaining consumption is composed of HVAC and miscellaneous equipment, which includes appliances and plug loads. To determine the portion of the remaining consumption that is used by miscellaneous equipment, The Cadmus Team calculated the remaining consumption per day for each month, and identified the month with the minimum daily remaining consumption. This month is generally during the spring or the fall, and corresponds to the time of lowest HVAC use.

Next, The Cadmus Team assumed that during this minimum consumption month, HVAC accounted for 10% of the total consumption for electric-only customers and 5% for natural gas customers. We split the HVAC consumption evenly between heating and cooling, then estimated the daily equipment consumption for this minimum month by subtracting the total consumption per day from the consumption used for lighting, DHW, and HVAC. The Cadmus Team assumed that the equipment consumption per day remains constant throughout the year.

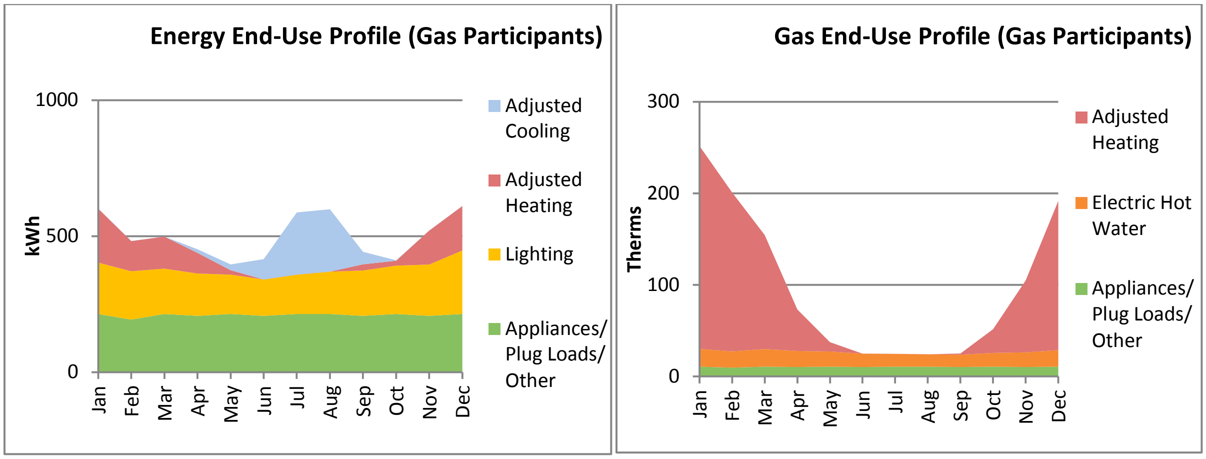
Heating and Cooling

The Cadmus Team's experience has shown that heating and cooling energy still makes up 10% of the total electricity consumption in typical homes during the minimum consumption month. After assuming that the minimum consumption month included 5% heating and 5% cooling, we calculated the monthly heating and cooling electricity by subtracting the DHW, lighting, and base end uses from the total for each month.

For June through September, we assumed that all the HVAC electricity was for cooling. For December through March, we assumed that all of the HVAC electricity was for heating. For the shoulder months (April, May, October, and November), we split the HVAC consumption in half by assuming that heating and cooling are proportional to the HDDs and CDDs in each month. We then calculated the annual heating and cooling end-uses by summing the monthly heating and cooling end uses. The Cadmus Team utilized the same methodology for gas homes, but modified the percent of HVAC consumption used during the baseline month to 20% instead of the 10% we used for electricity.

Figure 4 shows the disaggregated end-use profiles for gas participants.

Figure 4. Disaggregated End-Use Profile for Gas Participants (kWh and Therms)



Model Calibration Process

With established monthly end-use profiles, The Cadmus Team constructed and adjusted the models to represent the actual functions of the average participant home. The following sections detail the intricate processes involved in model alterations.

Create Energy Simulation Models

We built the energy models we used for this evaluation using the DOE-2.2 engine, based on models Navigant has created previously for an impact evaluation. Each of the models consists of four buildings: two each of single- and two-story homes, oriented north-south and east-west. We created one base model for each model group, with differing HVAC types specific to each participant fuel type; see for corresponding HVAC types by participant.

Table 59. Simulation Modeling HVAC Types for the Each Fuel Participant

Participant Type	HVAC Type
Gas	Gas Furnace and Central Air Conditioning
Oil	Oil Furnace and Central Air Conditioning
Electric	Air-Source Heat Pump with Electric Resistance Supplemental*

* Due to the multiple types of heating systems in Massachusetts (wood burning fireplaces, electric baseboard heat, electric furnaces, heat pumps, etc.), we used a heat pump for the electric model but decreased the duct losses and moved 50% of the ducts into a conditioned space. This approach attempts to capture characteristics present for each variation of participants. Since we adjusted the total consumption to match actual participant billing data, the results are not skewed from these HVAC adjustments.

The Cadmus Team altered these models to match the participants in each model group by changing the average building size and other characteristics when participant audit data was available. When the audit data did not contain building characteristics, such as for window specifications and typical insulation values, we used the Building America Benchmark[23] spreadsheet to inform the models.

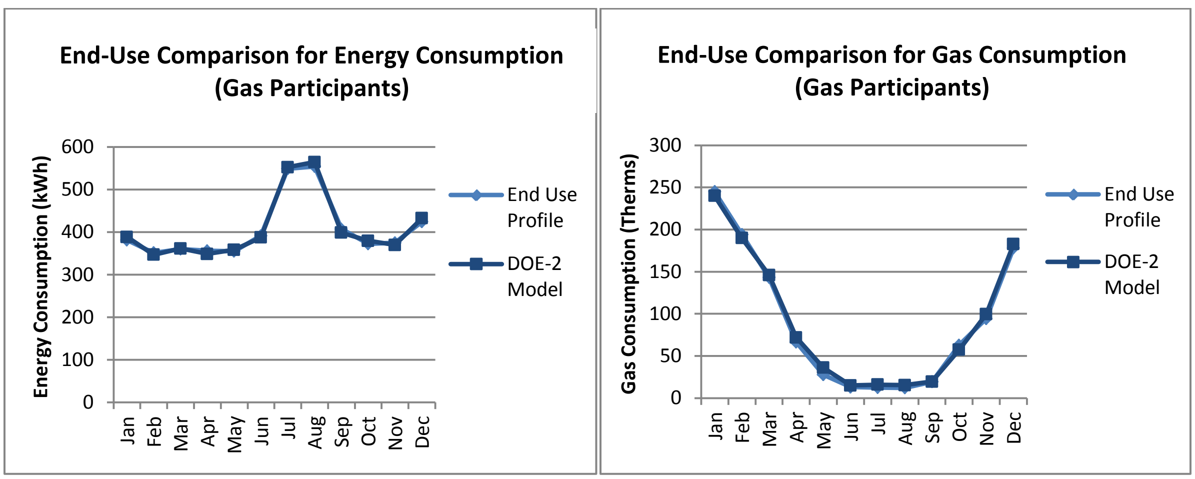
Calibrate Energy Simulation Models

The Cadmus Team calibrated each model group in order to match the modeled energy consumption to the end-use targets for that group. This calibration was an iterative process, involving the following steps:

1. **Derived modeled end-use consumption for each model group** by weighting the two sets of results (single- and two-story homes) from each simulation run in each participant group.
2. **Compared the modeled end-use consumption to the calculated participant end-use consumption.**
3. **Adjusted calibration parameters and re-ran the models**.

We repeated the above process until the monthly error and total annual error in each end-use was no more than 1% of the annual end use target. Figure 5 shows a comparison of the end-use targets and final calibrated model.

Figure 5. Comparison of End-Use Profile Targets to the Calibrated DOE-2 Model



We adjusted the calibration parameters to within pre-determined reasonable ranges, in order to avoid getting unrealistic building characteristics. After the models were properly calibrated and producing the same consumption values as the average participant homes, we adjusted the models to calculate savings for the desired measures. This meant that when we calibrated a model, we used different parameters as knobs (e.g., insulation values, temperature set-points, shading schedules) in order to adjust our consumption to match the actual participant billing data. These knobs have reasonable ranges that we do not adjust above or below unless we have

[23] The Building America Resources for Energy Efficient Homes spreadsheet detailing the existing homes can be found at http://www1.eere.energy.gov/buildings/building_america/analysis_spreadsheets.html.

hard evidence that abandoning these pre-defined ranges makes sense. One example is the temperature setpoint for heating. Our range is 64-72 degrees, as it would be unreasonable to assume that someone would have their thermostat set at 80 or 50 degrees for an extended period of time. We use this approach to simulate occupant behaviors, and these ranges keep us within reasonable actual behaviors.

Derive Measure-Level Savings

The Cadmus Team used the simulation model approach to estimate savings for program measures that are known to generate interactive effects, such as insulation and air sealing (weatherization). The following sections outline how we modeled each measure and the methodology we used to calculate savings.

Altering Model Parameters

Utilizing the calibrated models, we ran a parametric model for each model group by altering the measure parameters in the calibrated models while leaving all other parameters constant. We created baseline and efficient parametrics to model the home's pre- and post-installation energy usage. This alteration of the parametric runs for each measure varied; the following list details the individual adjustments we made:

- ***Air Sealing (weatherization).*** We only adjusted the whole-house infiltration rate.
- ***Attic Insulation***. We adjusted the baseline and efficient R-Values, along with the whole-house infiltration rate.

Deriving Savings from Model Results

Another approach was necessary to model the insulation upgrades due to unknown parameters for the rest of the home. Although the audit data provided both pre- and post-values for insulation measures, these values typically dealt with a portion of the entire home, therefore leaving an unknown value for areas that did not receive upgrades. Consequently, we simulated the building as if the entire attic, wall, or floor area received insulation in order to determine the overall whole-house savings. We then normalized these savings on a per-square-foot basis by dividing the overall savings by the percentage of the total area that received insulation (attic, wall, or floor). Finally, we applied this value to the installed quantity listed in the audit data to derive measure-level savings for each of the insulation types offered by the Low Income Program.

APPENDIX B. ENGINEERING ALGORITHMS

This appendix provides detailed explanations of the algorithms The Cadmus Team used to calculate energy impacts for measures that were not covered by our billing analysis or calibrated simulation. The measures are all listed Table 60, along with the approach we used for each.

Table 60. Summary of Analysis Approach by Measure and Heating Fuel Type

Category	Measure	Natural Gas	Electric	Oil
Insulation and Air Sealing	Insulation and Air Sealing (Overall)	Billing	Simulation	Simulation
	Air Sealing	Simulation	Simulation	Simulation
	Attic Insulation	Simulation	Simulation	Simulation
	Wall Insulation	Simulation	Simulation	Simulation
	Basement Ceiling Insulation	Simulation	Simulation	Simulation
	Basement Wall Insulation	Simulation	Simulation	Simulation
	Furnace Fan (due to weatherization)	Simulation	Simulation	Simulation
Heating System	Heating System Replacement	Billing	N/A	Engineering
	Oil Boiler Replacement	N/A	N/A	Engineering
	Boiler Reset Controls	N/A	N/A	Engineering
	Programmable Thermostat	N/A	N/A	Engineering
	Furnace Fan (due to heating system/boiler replacement)	Engineering	N/A	Engineering
Appliances	Refrigerator Replacement	N/A	Engineering	N/A
	Second Refrigerator Removal	N/A	Engineering	N/A
	Freezer Replacement	N/A	Engineering	N/A
	Window AC Replacement	N/A	Engineering	N/A
Lighting	CFLs	N/A	Engineering	N/A
	Torchieres	N/A	Engineering	N/A
	Fixtures	N/A	Engineering	N/A
Domestic Hot Water	Domestic Hot Water (Overall)	Engineering	Engineering	Engineering
	Low Flow Showerhead	Engineering	Engineering	Engineering
	Faucet Aerator	Engineering	Engineering	Engineering
	Pipe Wrap	Engineering	Engineering	Engineering
Distribution	Duct Insulation	Engineering	N/A	Engineering
	Duct Sealing	Engineering	N/A	Engineering
Other	Baseload (TLC Kits)	N/A	Engineering	N/A

The following sections summarize the engineering approaches we used for each measure.

Heating System

This measure category includes four measures: oil heating system replacement (furnaces and boilers, including furnace fan savings), oil boiler reset controls, and programmable thermostats for oil-heated homes.

Heating System Replacement (and associated furnace fan)

The Cadmus Team used the following algorithm to calculate the impacts of heating-only system replacements:

$$MMBtu\ Save = Baseline\ Consumption \times \left(1 - \frac{AFUE_{ee}}{AFUE_{base}}\right)$$

We set the baseline consumption equal to the heating pre-NAC of corresponding gas customers.

Although the audit data we collected provided averages for both baseline and retrofit efficiencies, LEAN indicated that many auditors did not record baseline efficiencies when units were clearly old and inefficient. Based on input from LEAN, we revised the baseline efficiency estimates as shown in Table 61. The Cadmus Team kept the audit data averages for installed efficiency.

Table 61. Summary of Oil Heating System Replacement Inputs

System Type	Base Consumption, Btu	Baseline Efficiency	Measure efficiency
Oil Furnace	82,200	70%	85%
Oil Boiler	90,800	69%	85%

The Cadmus Team also estimated savings for boilers with indirect water heaters. We calculated the water heating component of the savings as follows:

$$Total\ Savings = Standby\ Save + Combustion\ Efficiency\ Save - Summer\ Loss$$

Where:

$$Standby\ Save, MMBtu = \Delta T_{tank,ambient} \times 8{,}760 \times \left(\frac{UA_{base}}{CE_{base}} - \frac{UA_{ee}}{CE_{ee}}\right) \times 10^{-6}$$

$$Combustion\ Efficiency\ Save, MMBtu = Gallons\ per\ year \times \Delta T_{cold,tank} \times \left(\frac{1}{CE_{base}} - \frac{1}{CE_{ee}}\right) \times Energy\ Conversion$$

$$Summer\ Loss = Gallons\ per\ summer \times \Delta T_{cold,tank} \times \left(\frac{1}{EF_{summer,ee}} - \frac{1}{EF_{ee}}\right) \times Energy\ Conversion$$

$$EF_{summer,ee} = Summer\ De-rating\ Factor \times EF_{ee}$$

$$EF_{ee} = Boiler\ AFUE - 0.0019 \times Storage\ Volume$$ [24]

Table 62 presents the inputs we used to calculate savings.

Table 62. Indirect Water Heater Savings Inputs

Input	Value	Source
$\Delta T_{ambient,\ tank}$	50	Calculated: 120°F tank, 70°F ambient temperature
UA_{base}	2.38	Calculated based on storage volume, R-8 insulation
UA_{ee}	1.35	Calculated based on storage volume, R-16 insulation
Base Thermal Efficiency	0.59	Federal standard
Base Combustion Efficiency, CE_{base}	0.59	Calculated
EE Combustion Efficiency, CE_{ee}	0.86	Low income audit data: the average installed boiler AFUE
Annual Hot Water Use, Gallons	23,470	ENERGY STAR: 64.3 gallons per day
$\Delta T_{cold,\ tank}$	64	Calculated: 120°F tank, 56°F entering cold water temperature
Standard Storage Factor	-0.0019	Federal standard
Storage Volume, Gallons	42.2	HES DHW average
EF_{base}	0.510	Calculated
EF_{ee}	0.78	Calculated
Summer Derating Factor	20%	Assumption: EF decreases due to additional boiler mass heating unnecessarily in summer months, variability in performance due to settings
$EF_{summer,ee}$	0.63	Calculated
Summer Length, Days	122	June through September

Table 63 summarizes the savings for each type of oil heating system replacement, as well as the weighted average savings for broader measure categories that were informed by the audit data and billing analysis.

Table 63. Summary of Oil Heating System Savings

Category	MMBTU Savings	Weighting
Oil Heating System	18.4	33% furnaces, 67% boilers
Oil Furnace	14.3	100% furnaces
Oil Boiler	20.4	55% heating only, 45% with indirect
Oil Boiler (heating only)	17.5	100%
Oil Boiler (with indirect)	24.0	100%

[24] This equation is per the current federal method to calculate EF standards for oil: EF = 0.59 – 0.0019 x storage volume.

For forced air systems, we also calculated associated fan savings. We assumed that the bulk of these systems are furnaces, and thus used the above furnace savings to inform the analysis. The Cadmus Team assumed that fan savings are proportional to heating system fossil fuel savings:

$$Fan\ Savings = Fan\ Base\ Load \times Percent\ Heating\ System\ Savings$$

We calculated the fan base load as follows:

$$Fan\ Base\ Load = \frac{Fan\ Motor\ Horsepower \times Fan\ Run\ Hours \times 0.746}{Fan\ Motor\ Efficiency}$$

Table 64 shows the inputs we used to calculate the fan base load.

Table 64. Furnace Fan Calculation Inputs

Input	Value	Source
Furnace Fan Run Hours	1,014	2012 Massachusetts Brushless Motors Fan Study*
Fan Motor Horsepower	0.5	2012 Pennsylvania TRM**
Fan Motor Efficiency	0.5	2012 Pennsylvania TRM**
Base Fan Load (kWh)	756	Calculation

*Massachusetts Residential Retrofit Brushless Fan Motors Impact Evaluation. 2012.
**Pennsylvania Public Utility Commission. "Technical Reference Manual." 2012.

Programmable Thermostats (Oil Only)

The key inputs for programmable thermostats are listed in Table 65.

Table 65. Programmable Thermostat Assumptions

Measure	Percent Savings	MMBTU Savings	Source
Evaluation Estimate	3.6%	3.1	Conservative estimate based on literature review
Current PA Estimate	6.2%	7.7	2012 Massachusetts TRM*

*"Massachusetts Technical Reference Manual for Estimating Savings from Energy Efficiency Measures: 2012 Plan Year—Plan Version." October 2011.

The Cadmus Team reviewed several programmable thermostat studies for both heating and cooling climates. Because these studies have conflicting results, we recommend using a conservative estimate of 3.6% to calculate savings. We again used the pre-NAC from the billing analysis (average of all participants) to calculate savings.

The current TRM value is based on a 2007 study by RLW Analytics[25] which claims that programmable thermostats save, on average, 6.2% of heating load in gas heated homes. However, this study does not include all sources of uncertainty in their confidence intervals, so the true confidence interval could cross zero, making the result not statistically significant. Furthermore, estimated savings resulting from the use of a participation indicator—which is

[25] RLW Analytics. "Validating the Impact of Programmable Thermostats." 2007.

more common in billing analyses—resulted in a much lower point estimate of between 1.7 and 1.8%.

The Cadmus Team reviewed the following additional studies (with some high level outcomes listed). While some sources indicate high savings, such as ENERGY STAR, most empirical studies showed more conservative results.

- GDS Associates. *Programmable Thermostats. Report to KeySpan Energy Delivery on Energy Savings and Cost Effectiveness*. Marietta, Georgia. 2002.
  - ➢ Savings of 3.6% by using programmable thermostats based on metering study, which accounts for variability of actual setback/setup settings.
  - ➢ Savings from programmable thermostats account for 56% of realization rate.
- KEMA Inc., Southern California Edison, and Quantum Consulting. *Can Programmable Thermostats Be Part of a Cost-Effective Residential Program Portfolio?* 2007. Based on 2004 evaluation results from a California statewide single family rebate program.
  - ➢ There is an increased market penetration of programmable thermostats (which have a dominant share of contractor thermostat installations and represent about half of retail thermostat sales).
  - ➢ Programmable thermostats have high levels of free-ridership.
  - ➢ There is evidence that customers are not using programmable thermostats to save energy.
  - ➢ There has been negligible savings from programmable thermostats in California.
- Energy Center of Wisconsin. *Programmable Thermostats That Go Berserk? Taking a Social Perspective on Space Heating in Wisconsin*. 1999.
  - o Study of energy use in 299 single family homes in Wisconsin.
  - ➢ Homes with programmable thermostats have 2.5% lower heating energy usage (there is large uncertainty in this estimate).
  - ➢ The potential for savings from programmable thermostats is low: out of the two-thirds of homeowners that do not already have one installed, most either already set back their thermostats manually or are resistant to doing so.
- ENERGY STAR equipment calculator
  - ➢ Programmable thermostats lead to 16% savings for central cooling and 14% savings for heating.
- ENERGY STAR programmable thermostat calculator
  - ➢ Programmable thermostats lead to 2.4 MMBTU/degree of savings (703 kWh/degree) for heating and lead to 0.2 MMBTU/degree (59 kWh/degree) of savings for central cooling.

- Southern California Edison. *Programmable Thermostats Installed into Residential Buildings: Predicting Energy Saving Using Occupant Behavior & Simulation*. 2004.
    - ➢ Programmable thermostat savings are based on combining the RASS analysis on usage with DOE-2 simulation results.
    - ➢ Cooling savings for Climate Zone 16 (coldest zone in California) are approximately 2%.
    - ➢ Programmable thermostats lead to negative heating savings.
    - ➢ Referenced by 2005 California DEER Database, main source of deemed savings for California.
- California Energy Commission: http://www.consumerenergycenter.org/home/heating_cooling/thermostats.html.
    - ➢ Estimates that programmable thermostats lead to 15-25% savings for cooling and 20-75% for heating.

Boiler Reset Controls (Oil Only)

The key inputs for programmable thermostats are listed in Table 66. The Cadmus Team reviewed the 2006 ACEEE report[26] on the measure. The report concludes that "*for conventional boilers, adequate add-on controls may cost from $150 (time-delay relay) to over $1,000 (reset with automatic post purge) and save up to 6-8% or more of fuel used.*" Given that the type of controls is not specified and the TRM has no guidelines as to whether retrofitted boilers must be condensing or cold-start (where savings are maximized), The Cadmus Team recommends a more conservative estimate of 5% of heating load. We used the pre-NAC from the billing analysis (average of all participants) to calculate savings for this measure.

Table 66. Boiler Reset Control Assumptions

Measure	Percent Savings	MMBTU Savings	Source
Evaluation Estimate	5%	4.4	Conservative estimate based on literature review
Current PA Estimate	6-8%	7.9	TRM cites ACEEE study; the exact source of the current TRM value is unclear

Appliances

This section presents The Cadmus Team's approaches to calculating savings for refrigerator replacement and removal, as well as for freezer and window air conditioner replacements.

Refrigerator Replacement

The Cadmus Team used the following algorithm to calculate energy savings from refrigerator replacements:

[26] The American Council for an Energy Efficient Economy. "Emerging Technology Report: Residential Boiler Controls." May 2006.

$$kWh\ saved = kWh\ Usage_{existing} - \ kWh\ Usage_{new}$$

Table 67 shows the input assumptions we used to calculate savings.

Table 67. Refrigerator Replacement Inputs

Input	Value	Units	Source
Usage Existing	1,180	kWh	CSG audits per NSTAR
Usage New	418	kWh	National Grid's invoiced new units

Second Refrigerator for Removal

The Cadmus Team used the following algorithm to calculate energy savings from secondary refrigerator removals:

$$kWh\ saved = kWh\ Usage_{existing}$$

Table 68 shows the input assumptions we used to calculate savings.

Table 68. Refrigerator Replacement Inputs

Input	Value	Units	Source
Usage Existing	1,180	kWh	CSG audits per NSTAR

Freezer Replacement

The Cadmus Team used the following algorithm to calculate energy savings from freezer replacements:

$$kWh\ saved = kWh\ Usage_{existing} - \ kWh\ Usage_{new}$$

Table 69 shows the input assumptions we used to calculate savings.

Table 69. Freezer Replacement Inputs

Input	Value	Units	Source
Usage Existing	696	kWh	CSG audits per NSTAR
Usage New	458	kWh	National Grid's invoiced new units

Window AC Replacement

The Cadmus Team used the following algorithm to calculate energy savings from window air conditioner replacements:

$$kWh\ saved = Full\ load\ hours \times Capacity \times \left(\frac{1}{SEER_{base}} - \frac{1}{SEER_{ee}}\right)$$

Table 70 shows the input assumptions we used to calculate savings.

Table 70. Window Air Conditioner Replacement Inputs

Input	Value	Units	Source
Full load hours	360	hours	MA TRM
Capacity	10	kBTU	ENERGY STAR standard assumption
Baseline efficiency	6.7	EER	Cadmus' OPA Keep Cool Metering Study
Measure efficiency	10.8	EER	MA Multifamily Low Income Program average (no data for Low Income Single Family)

Lighting

This section presents the approach The Cadmus Team used to determine savings for the three lighting measures: CFLs, torchieres, and fixtures.

CFLs

The majority of the PAs claim the energy savings specified in the TRM for CFLs. These savings assumptions are shown in Table 71, along with corresponding audit data averages, where available. The Cadmus Team used low income data for both the pre- and post-retrofit wattages.

Table 71. TRM and Evaluation Lighting Inputs

Input	2012 TRM Value	Evaluation Value
ΔkW*	Not Listed	0.051
Hours Per Day	Not Listed	2.8**
In-Service Rate	100% LI, 90% HES	90%
ΔkWh	41	45***
Summer Coincidence Factor+	0.11	0.11
Winter Coincidence Factor+	0.22	0.22

* The TRM only includes winter peak demand savings of 0.011.

** This number is the single family hours-of-use from 2012 MA TRM.

*** This number incorporates electric interactive effects with a weighted average by heating fuel type and assumes the presence of air conditioning. The source for interactive factors was the NY GasTech Manual[27].

+ The TRM lists higher coincidence factors for the measure "CFL Bulb" than for "Screw-in Bulb," at 0.35 for summer and 1.00 for winter. The Cadmus Team prefers the listed values, which are consistent with other programs.

Most of the implementation contractors collected data on the wattage of the retrofit and pre-retrofit light bulbs in participants' homes. The Cadmus Team elected to use 2.8 hours-of-use per day as listed in the current Massachusetts TRM. In order to properly account for interactive effects, we calculated a weighted average of savings per bulb using the overall percentage of customers with each fuel type. This average also accounted for the approximate percentage of homes with air conditioning. The average wattages and breakdown of fuel types are shown in Table 72. Neither the 2011 TRM nor the 2012 TRM accounts for interactive effects.

[27] New York Evaluation Advisory Contractor Team. "New York Standard Approach for Estimating Energy Savings from Energy Efficiency Programs." October 2010.

Table 72. Lighting Inputs by Heating Fuel Type, Presence of Air Conditioning

HVAC Type	Pre-Retrofit Wattage	Post-Retrofit Wattage	Percentage of Customers	Heating Interactive Factor	Cooling Interactive Factor
Gas Heating	68	17	52%	-0.025	n/a
Oil Heating	68	17	36%	-0.025	n/a
Electric Heating	68	17	11%	-0.577	n/a
Air Conditioning	68	17	9%	n/a	0.06

Details on the impacts of the EISA standards can be found in the report.

Torchieres and Fixtures

The Cadmus Team applied the realization rates from the CFL analysis to both torchieres and fixtures. The resulting savings estimates are presented in Table 73.

Table 73. Torchiere and Fixture Savings

Measure	kWh Savings
Torchieres	211
Fixtures	140

Domestic Hot Water

This section reviews the methodology The Cadmus Team used to estimate savings from the following DHW measures:

- Low-flow showerheads
- Faucet aerators
- Water heater pipe wrap

Generally, we were not able to compare our evaluation inputs with PA-specific values, because most PAs only provided deemed savings values, rather than algorithms and specific inputs. The majority of PAs currently claim a single deemed value for all of these measures. The Cadmus Team calculated a unique value for each measure.

Low-Flow Showerheads

The Cadmus Team began this portion of the evaluation by reviewing the low income audit data for the key inputs to the low-flow showerhead energy savings algorithm. Table 74 shows the inputs for low-flow showerheads, indicating both the original audit data inputs and final assumptions. Where low income data did not exist, we used HES data where possible.

The following algorithm is identified by a report from the Lawrence Berkeley National Lab and Summit Blue Consulting submitted to Union Gas and Enbridge Gas Distribution in Ontario[28]:

*Shower water use (gallons/year) = household members * showers per capita per day * shower length * proportion of showering activity affected by replacement * as-used water flow rate*

In that equation, we set the as-used water flow rate as equal to the maximum rated flow rate, after scaling it back linearly to account for water pressure at the residence that is less than the 80 psi rating pressure. That rating pressure is meant for limiting the flow by throttling back (closing) the control valve during the shower, and due to partial clogging in household pipes. That led to the following equation:

Shower water energy saved = shower water use reduction (Temperature of shower - Temperature of incoming cold-water) *conversion to energy / water heater recovery efficiency*

Table 74 shows the input assumptions we used to calculate savings.

Table 74. Low-Flow Showerhead Inputs

Input	Audit Data Values	Values Used in Calculations	Source
Household Members	2.3	2.3	Low income audit data
Showers (pcpd)	-	0.7	Default is 0.7; 2 (3)
Shower Length (min)	-	8.2	1 (3)
Proportion Affected	0.73	0.73	HES audit data
Baseline Rated Flow	-	2.5	Federal standard
Baseline As-used Flow (linear)	-	2.05	2; calculated from rated flow*
Retrofit Rated Flow	1.7	1.7	HES audit data
Retrofit As-used Flow (linear)	1.61	1.61	2; calculated from rated flow
Shower Temperature (F)	-	105	1
Cold Water Temperature (F)	-	56.04	4; average of Massachusetts locations
Water Heater Recovery Efficiency	-	Electric: 0.97 Gas: 0.67 Oil: 0.59	Federal standard; varies by fuel type

* For linear adjustments, we used the following equation: as-used flow = 0.542 * (Rated Flow) + 0.691.

1. Biermayer, Peter J. *Potential Water and Energy Savings from Showerheads.* Lawrence Berkeley National Laboratory. 2006.
2. Cook, G. and B. Barkett. *Resource Savings Values in Selected Residential DSM Prescriptive Program.* Summit Blue Canada Inc. 2008.
3. Mayer, P.W., et al. *Residential End Uses of Water.* AWWA Research Foundation. 1999. Referenced by Biermayer 2006.
4. US Department of Energy. Building America Benchmark Program Database. 2010.

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Biermayer, Peter J. *Potential Water and Energy Savings from Showerheads.* Lawrence Berkeley National Laboratory. 2006.
Cook, G. and B. Barkett. *Resource Savings Values in Selected Residential DSM Prescriptive Program.* Summit Blue Canada Inc. 2008.

Faucet Aerators

The Cadmus Team used the following algorithm to calculate faucet aerator savings:

Faucet energy savings	=	Water savings per year * (average faucet mix temperature - temperature of incoming cold water) * conversion to energy/water heater recovery efficiency

Where:

*Water savings per year (gallons/year) = Household water use * flow reduction*

Household water use	=	Household members * total daily household faucet use per capita * 365 days * % of use affected by replacement
Flow reduction	=	% flow rate reduction * % of straight-down-the-drain use
Straight-down-the-drain use	=	Percent of water that flows straight down the drain (since water volume that fills a sink for batch use is not affected by the flow rate)

Table 75 shows the values we used for each input. Because faucets are rarely used at their rated flows, The Cadmus Team recommends that the PAs determine actual flow rates through water metering studies. Several studies have been conducted nationwide using flow-trace analysis, a method which can disaggregate metered water use data by end-use fixture (e.g., faucets, dishwaters, showerheads). The values we recommend (as shown in) represent an average of the values presented by those nationwide studies. Audit data was only available for two inputs: number of household members (from participants in the Low Income and HES Programs) and percentage of faucet use affected. The Cadmus Team used both of those values without modification.

Table 75. Faucet Aerator Inputs

Input	Assumed Values	Source*
Bath Baseline Flow (gpm)	1.3	3
Kitchen Baseline Flow (gpm)	1.3	3
Bath Retrofit Flow (gpm)	1	3
Kitchen Retrofit Flow (gpm)	1	3
Household Members	2.3	Low income audit data
Total Daily Faucet Use (gallons per capita per day)**	10.9	3
% Down the Drain Use (kitchen)	0.5	2
% Down the Drain Use (bath)	0.7	2
% Kitchen Use	0.65	2
% Bath Use	0.35	2
% of Kitchen Use Affected	1.00	Assumes that 1 of 1 kitchen faucets were retrofitted
% of bath Use Affected	0.62	HES audit data: # installed / # bathrooms
Average Faucet Temperature (F)	90	2
Cold Water Temperature (F)	56.04	4
Water Heater Recovery Efficiency	Electric: 0.97 Gas: 0.67 Oil: 0.59	Federal standard that varies by fuel type; no audit data was available

* For the list of source references, see notes from Table 74.

** This value assumes use for 365 days per year.

Water Heater Pipe Wrap

The Cadmus Team used the following engineering algorithm to estimate savings from DHW pipe wrap:

$$Savings\ per\ linear\ ft = \frac{\left(\frac{1}{R_{pre}} - \frac{1}{R_{post}}\right) \times Pipe\ Circ. \times \Delta T \times 8{,}760}{Hot\ Water\ Recovery\ Efficiency} \times Energy\ Conversion \times Thermal\ Regain\ Factor$$

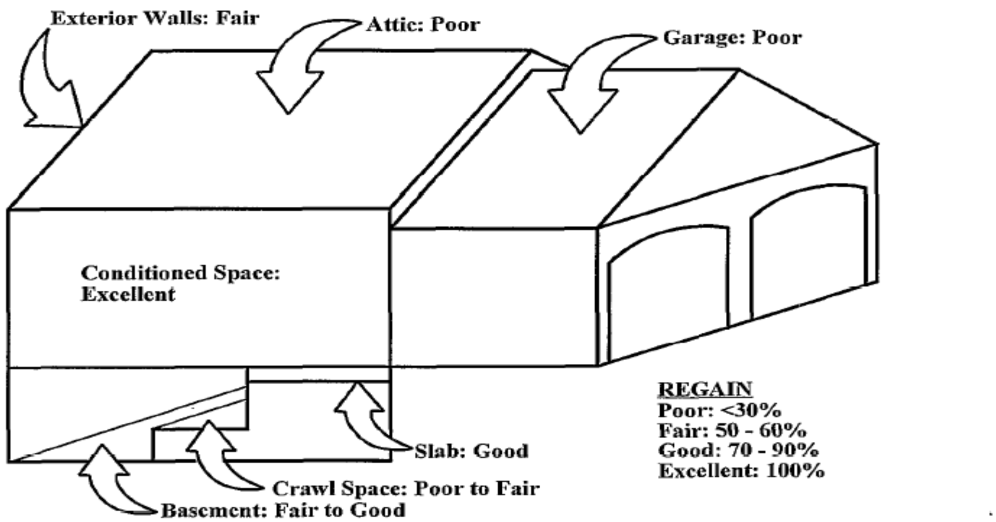
Table 76 shows the assumptions we used to calculate savings.

Table 76. Domestic Water Heater Pipe Wrap Savings

Input	Value	Source
R_{pre}	1	Navigant Consulting Inc. *Measures and Assumptions for Demand Side Management Planning*. Appendix C Substantiation Sheets, pp. 77. April 2009.
R_{post}	5	Low income data observed in tracking data from Berkshire Gas
Pipe Circumference (feet)	0.13	Calculated assuming typical diameter of 0.5"
ΔT	55	Calculated assuming ambient temperature of 65°F and hot water temperature of 120°F
Thermal Regain Factor	42% Gas 33% Electric 41% Oil	Calculated based on typical system location, as found in HES audit data.
Water Heater Recovery Efficiency	Electric: 0.97 Gas: 0.67 Oil: 0.59	Federal standard that varies by fuel type; no audit data was available.

As with duct sealing and duct insulation, we estimated thermal regain effects, which accounts for the increased heat load in the home due to a reduction in losses from the energy saving measures installed (see for an illustration of this process).

Figure 6. Illustration of Thermal Regain by Location



Source: Andrews, John. *Better Duct Systems for Heating and Cooling.* US Department of Energy. 2001.

As shown in , thermal regain varies based on the system location. In conditioned spaces, 100% of reductions in losses are added to the heating system load, effectively cancelling out savings. In semi-conditioned spaces, such as basements, a smaller percentage of losses (50% to 90%) directly impact the heating system. In unconditioned spaces, none of the heat losses from pipes or ducts contribute to heating the home, making the insulation more effective.

The Cadmus Team defined thermal regain factors using the following equation, where it is the percentage of theoretical insulation savings that are captured, depending on location. For example, in a conditioned space where regain is equal to 100%, the thermal regain factor is zero.

$$Thermal\ Regain\ Factor = 1 - Regain$$

Table 77 and Table 78 summarize the thermal regain factors we assigned to each system location found in the HES audit data. Due to the lack of hot water-specific information, The Cadmus Team assumed that hot water systems are typically in the same area of the participant's homes as the heating systems.

Table 77. Location Category Assignments

System Location Specified	Assigned Location Category
Attic	Unconditioned
Crawlspace	Unconditioned
Basement	Basement
Garage	Unconditioned
Other Rooms (kitchen, living room, etc.)	Conditioned

Table 78. Assumed Thermal Regain Factors

System Location	Assumed Regain	Thermal Regain Factor
Unconditioned	15%	85%
Basement	60%	40%
Conditioned	100%	0%

Finally, The Cadmus Team used the known amounts of pipe insulation installed to calculate total average savings for each fuel type. We assumed a maximum of 10-feet of pipe insulated in unconditioned or semi-conditioned spaces. These results are shown in .

Table 79. Installed Lengths and Savings by Fuel Type

Input	Oil Value	Gas Value	Electric Value
Typical Amount Installed (linear feet)	23	31	8
Length Used in Calculation (linear feet)	10	10	8
Savings	4.3 therms	3.9 therms	41 kWh

Distribution

This section presents The Cadmus Team's savings estimates for two distribution measures, duct insulation and duct sealing. We did not calculate overall distribution savings because the measure definition did not specify which measures to include.

Duct Insulation

The Cadmus Team used a combination of low income and HES programs' audit data to calculate duct insulation savings. The low income data provided the average number of linear feet of insulation installed and its heating efficiency, and the HES data provided installed R-values. We calculated the savings used the following algorithm:

$$MMBtu\ Savings = \frac{\left(\frac{1}{R_{pre}} - \frac{1}{R_{post}}\right) \times Fan\ Run\ Hours \times Area \times \Delta T \times Thermal\ Regain\ Factor \times 10^{-6}}{Heating\ Efficiency}$$

Table 80 shows the input assumptions we used to calculate savings.

Table 80. Duct Insulation Inputs Based on HES Audit Data Averages

Heating Savings	Input: Unconditioned Space	Source
Fan Run Hours (heating)	1,014	2012 Massachusetts Brushless Motors Fan Study***
Area Insulated (square feet)*	446.1	Low income audit data
R-value (pre-installation)	1.2	Assumed
R-value (post-installation)	7.06	HES audit data
Average Duct Temperature (F; 1/2 supply, 1/2 return)	87	Assumed: 105°F supply, 69°F return
Ambient Temperature	55	Assumed
ΔT	32	Calculated based on duct and ambient temperatures
Heating Efficiency	100% Gas 77% Gas 77% Oil	Low income audit data for gas and oil; electric assumed due to lack of data
Thermal Regain Factor	41% Electric 42% Gas 33% Oil	Audit data from US DOE report**

* We calculated this value assuming a typical duct diameter of 12" and using the audit data average length insulated of 142 feet.

** Andrews, J. *Better Duct Systems for Heating and Cooling.* US Department of Energy. 2001. Online: Accessed 2/22/2012. http://www.energycodes.gov/training/res_wbt/pdfs/DOEducts.pdf

*** Massachusetts Residential Retrofit Brushless Fan Motors Impact Evaluation. 2012.

Duct Sealing

We did not collect any useable data from the audits related to duct sealing; presents the key assumptions we used to calculate energy savings for this measure. We used the pre-NAC heating load from the billing analysis as the base consumption. Due to the low percentage of participants with air conditioning, we did not calculate cooling savings.

Table 81. Duct Sealing Assumptions

Input	Pre-Retrofit Value	Post-Retrofit Value	Source
Supply Leakage	9.0%	2.6%	Proctor 1996 APS study*
Return Leakage	8.0%	2.4%	Proctor 1996 APS study
Cooling Supply Temperature (F)	55	55	Engineering estimate
Heating Supply Temperature (F)	105	105	Engineering estimate
Cooling Return Temperature (F)**	78	78	Engineering estimate
Heating Return Temperature (F)**	69	69	Engineering estimate
Heating Savings (unconditioned space)***	-	9.1%	Calculated
Cooling Savings (unconditioned space)+	-	10.7%	Calculated

* Blasnik, M., T. Downey, J. Proctor, and G. Peterson. *Assessment of HVAC Installations in New Homes in APS Service Territory: Final Report.* Prepared for the Arizona Public Service Company by Proctor Engineering Group. 1996.

** These temperatures are theoretical (assuming no duct leakage); we calculated actual values based on assumed leakage.

*** This value is for a ventilated crawlspace.

+ This value is for an attic.

For duct sealing and duct insulation, The Cadmus Team also considered the effect of heating system location. We used HES audit data to determine the percentage of heating units in each location, as no low income data was available.

Table 82. Heating System Location (forced air systems only)

Location of Heating System	Electric Systems	Gas Systems	Oil Systems
Basement	62.0%	84.2%	55.7%
Unconditioned Space*	19.4%	9.9%	13.0%
Conditioned Space	18.5%	5.9%	31.2%

* These values are for a crawlspace or attic.

We calculated a weighted average of savings, assuming different levels of thermal regain for different heating system locations and different levels of thermal regain for duct insulation versus DHW pipe wrap (Andrews 2001).

Other

For the Other category, Cadmus calculated the savings for the Baseload TLC Kit. Contents of the kit varies by PA. Table 83 shows the percent of statewide savings by PAs who offer the kit, and the savings for each PA. Table 84 then provides details regarding the origin of these savings values.

Table 83. Baseload TLC Kit Population and Savings by PA and Overall

PA	Percent of MA-Wide 2010 LI Participation	Savings (kWh/Year)
CLC	6%	126
NGRID	50%	21
NSTAR	26%	11
WMECO	17%	21
Weighted Average	100%	25

Table 84. Baseload TLC Kit Savings by PA

Measure	Per-Unit Savings (kWh/ Year)	Reference	CLC			National Grid			NSTAR			WMECO		
			Quantity	Installation/ Adoption Rate	Savings (kWh/ Year)	Quantity	Installation/ Adoption Rate	Savings (kWh/ Year)	Quantity	Installation/ Adoption Rate	Savings (kWh/ Year)	Quantity	Installation/ Adoption Rate	Savings (kWh/ Year)
Faucet Aerator	40	1,2	2	0.61	49									
LED Nightlight	19	2	1	0.56	11	2	0.56	21	1	0.56	11	2	0.56	21
Drip Gauge	0		1		-									
Hot Water Thermometer	67	2	1	0.27	18									
Refrigerator/Freezer Thermometer	0	3				1		-	1		-	1		-
Refrigerator Coil Brush	0	4				1		-						
Wall Plate Stoppers	8	5	12	0.50	48									
Total Savings			17		126	4		21	2		11	3		21

References
1. Massachusetts Low Income Single Family Program Impact Evaluation (Table 1, per aerator electric savings)
2. Assessment of Washington Energy Education in Schools: 2010-2011 Program Year
3. Iowa Energy Wise 2005-2006 Program Analysis
4.http://www.cee1.org/eval/db_pdf/588.pdf
5. Joint Utility Low Income Energy Efficiency Program, 2005 Costs and Bill Savings Report

APPENDIX C. AGENCY DATA COLLECTION FIELDS

Table 85. On-Site CAA Data Collection Fields

Field Name	Field Description
Site	
SITEID	Site ID (unique dwelling identifier)
NAME	Name of occupant on the account
ADDRESS	Street address of unit
CITY	City address of unit
ZIP	ZIP code of unit
PHONE	Occupant phone number
ELECTRIC_PA	Electric provider (PA)
ELECTRIC_ACCT_ID	Account ID of occupant at electric PA
ELECTRIC_ALT_ID	Alternative customer ID at electric PA
GAS_PA	Gas provider (PA)
GAS_ACCT_ID	Account ID of occupant at gas PA
GAS_ALT_ID	Alternative customer ID at gas PA
AUDIT_DATE	Date initial audit performed
LIHEAP_OCCUPANTS_2011	Number of people living in unit in 2011 (LIHEAP)
LIHEAP_OCCUPANTS_2010	Number of people living in unit in 2010 (LIHEAP)
LIHEAP_OCCUPANTS_2009	Number of people living in unit in 2009 (LIHEAP)
HOUSE_TYPE	Building type description
HEATED_SQFT	Square footage of unit that is heated
BEDROOMS	Number of bedrooms in unit
BATHROOMS	Number of bathrooms in unit
NO_UNITS	Number of units in building
CENTRAL_AC	Unit has central AC (yes/no)
ROOM_AC	Number of room ACs in unit
HEATSYS_FUEL	Primary heating fuel
DHW_FUEL	Primary hot water fuel
Space Heating System	
HEATSYS_YEAR	Year existing system manufactured / installed
HEATSYS_EX_DISTTYPE	Distribution type used by existing system
HEATSYS_EX_EFFRATED	Rated efficiency of existing system
HEATSYS_EX_EFF	Measure efficiency of existing system
HEATSYS_INSTALL_MEASURE	Services provided to improve system
HEATSYS_INSTALL_DATE	Install date of new high efficiency system
HEATSYS_INSTALL_EFF	Rated efficiency of new system
BOILER PIPE INSULATION INSTALL	New boiler pipe insulation installed (yes/no)
BOILER PIPE INSULATION QTY	Linear feet of new boiler pipe insulation
Domestic Hot Water	
INSTALL_DATE	Install date of new DHW
MEASURE	Type of new equipment
LOCATION	Location of new equipment
EX_QTY	Existing quantity

Field Name	Field Description
EX_GPM	Existing gallons per minute
INSTALL_QTY	New quantity installed
INSTALL_GPM	New gallons per minute
Air Sealing	
INSTALL_DATE	Install date of new air sealing
LOCATION	Location
EX_CFM50	Existing air leakage (cubic feet per minute at 50 Pa)
INSTALL_QTY	Hours of air sealing performed
INSTALL_CFM50	New air leakage (cubic feet per minute at 50 Pa)
Insulation	
INSTALL_DATE	Install date of new insulation
LOCATION	Location
EX_RVALUE	R-value of existing insulation
INSTALL_QTY	Quantity of new insulation
UNIT_QTY	Quantity used to measure new insulation
INSTALL_RVALUE	R-value of new insulation
WALL_SIDING	Siding on outside wall of home (yes/no)
Lighting	
INSTALL DATE	Install date of new bulbs / fixtures
INSTALL MEASURE	Type of lighting measure
DAILY USE HRS	Estimated daily hours-of-use of measure
EX QTY	Quantity of bulbs replaced
EX WATTS	Wattage of bulbs replaced
INSTALL QTY	Quantity of bulbs installed
INSTALL WATTS	Wattage of bulbs installed
Refrigeration	
INSTALL_ DATE	Install date of new refrigerator or freezer
METERED_VALUE	Value of spot measurement by auditor
EX_QTY	Quantity of refrigerators or freezers removed
INSTALL_ QTY	Quantity of refrigerators or freezers installed
Miscellaneous Items	
INSTALL DATE	Install date of measure
MEASURE	Name of measure
INSTALL QTY	Quantity installed
NOTES	Notes

APPENDIX D. BILLING ANALYSIS MODEL OUTPUTS

Table 86. Gas Savings Measure-Level Model Output After Screening (n=298 participants, n=348 non-participants)

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.14212	0.00081554	174.26	<.0001
MISC * HDD	1	-0.00048908	0.00286	-0.17	0.8644
DHW * HDD	1	0.00607	0.0027	2.25	0.0244
INS * HDD	1	0.02639	0.00284	9.28	<.0001
BOILER * HDD	1	0.00963	0.00257	3.74	0.0002
FURNACE * HDD	1	0.0051	0.00306	1.67	0.0954
INS * HDD * POST	1	-0.04397	0.00212	-20.78	<.0001
FURNACE * HDD * POST	1	-0.03459	0.00321	-10.79	<.0001
BOILER * POST	1	-0.49799	0.06484	-7.68	<.0001
DHW * POST	1	0.12161	0.07355	1.65	0.0983
MISC * POST	1	0.10803	0.05352	2.02	0.0436

Table 87. Gas Savings Overall Model Output After Screening (n=298 participants, n=348 non-participants)

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.14341	0.0006555	218.78	<.0001
POST	1	-0.62226	0.02849	-21.84	<.0001

Table 88. Gas Savings Measure-Level Model Including 13 Inoperable Units and Vacancies (n=311 participants, n=348 non-participants)

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.14191	0.00081503	174.12	<.0001
MISC * HDD	1	0.00029873	0.00278	0.11	0.9145
DHW * HDD	1	0.00592	0.00268	2.21	0.0271
INS * HDD	1	0.02594	0.00277	9.38	<.0001
BOILER * HDD	1	0.00933	0.00251	3.72	0.0002
FURNACE * HDD	1	-0.00044367	0.00294	-0.15	0.8799
INS * HDD * POST	1	-0.04318	0.00207	-20.88	<.0001
FURNACE * HDD * POST	1	-0.03172	0.00308	-10.31	<.0001
BOILER * POST	1	-0.45106	0.06355	-7.1	<.0001
DHW * POST	1	0.09253	0.07331	1.26	0.2069
MISC * POST	1	0.10968	0.05216	2.1	0.0355

Table 89. Gas Savings Overall Model Including 13 Inoperable Units and Vacancies (n=311 participants, n=348 non-participants)

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.14305	0.00065037	219.96	<.0001
POST	1	-0.59465	0.02793	-21.29	<.0001

Table 90. Gas Savings Measure-Level Model for Quartile 1 of Insulation Participants

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.09425	0.00060626	155.46	<.0001
MISC * HDD	1	-0.00822	0.0024	-3.43	0.0006
DHW * HDD	1	0.00588	0.00276	2.13	0.0332
INS * HDD	1	0.02011	0.00242	8.31	<.0001
BOILER * HDD	1	0.01825	0.00272	6.71	<.0001
FURNACE * HDD	1	0.01613	0.0023	7.01	<.0001
INS * HDD * POST	1	-0.02642	0.00197	-13.38	<.0001
FURNACE * HDD * POST	1	-0.02255	0.00239	-9.42	<.0001
BOILER * POST	1	-0.22881	0.06666	-3.43	0.0006
DHW * POST	1	-0.02931	0.07341	-0.4	0.6897
MISC * POST	1	0.11036	0.05068	2.18	0.0295

Table 91. Gas Savings Measure-Level Model for Quartile 2 of Insulation Participants

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.14732	0.00107	138.17	<.0001
MISC * HDD	1	-0.0156	0.00334	-4.67	<.0001
DHW * HDD	1	-0.00706	0.00294	-2.4	0.0163
INS * HDD	1	0.02304	0.00338	6.81	<.0001
BOILER * HDD	1	-0.00876	0.00282	-3.11	0.0019
FURNACE * HDD	1	-0.0068	0.004	-1.7	0.0893
INS * HDD * POST	1	-0.03397	0.00243	-13.98	<.0001
FURNACE * HDD * POST	1	-0.03615	0.00425	-8.51	<.0001
BOILER * POST	1	-0.4708	0.0696	-6.76	<.0001
DHW * POST	1	-0.03234	0.078	-0.41	0.6785
MISC * POST	1	0.14366	0.05926	2.42	0.0154

Table 92. Gas Savings Measure-Level Model for Quartile 3 of Insulation Participants

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.17528	0.00122	143.79	<.0001
MISC * HDD	1	-0.01537	0.00441	-3.49	0.0005
DHW * HDD	1	0.00242	0.00392	0.62	0.5373
INS * HDD	1	0.0211	0.00432	4.88	<.0001
BOILER * HDD	1	0.00002511	0.00349	0.01	0.9943
FURNACE * HDD	1	-0.00356	0.00464	-0.77	0.4424
INS * HDD * POST	1	-0.0509	0.00291	-17.5	<.0001
FURNACE * HDD * POST	1	-0.03099	0.00479	-6.47	<.0001
BOILER * POST	1	-0.42396	0.08731	-4.86	<.0001
DHW * POST	1	0.27644	0.10773	2.57	0.0103
MISC * POST	1	-0.00812	0.07033	-0.12	0.9081

Table 93. Gas Savings Measure-Level Model for Quartile 4 of Insulation Participants

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.25193	0.00205	122.98	<.0001
MISC * HDD	1	-0.01986	0.00656	-3.03	0.0025
DHW * HDD	1	0.01359	0.00498	2.73	0.0064
INS * HDD	1	0.00669	0.00621	1.08	0.2812
BOILER * HDD	1	0.00048007	0.00497	0.1	0.9231
FURNACE * HDD	1	0.0176	0.00685	2.57	0.0102
INS * HDD * POST	1	-0.06463	0.00416	-15.52	<.0001
FURNACE * HDD * POST	1	-0.06721	0.00724	-9.28	<.0001
BOILER * POST	1	-0.70046	0.12755	-5.49	<.0001
DHW * POST	1	0.36121	0.14042	2.57	0.0102
MISC * POST	1	0.14796	0.11264	1.31	0.1891

Table 94. Gas Savings Measure-Level Model for Non-Integrated Boiler Systems

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.14228	0.00081588	174.39	<.0001
MISC * HDD	1	0.00387	0.00293	1.32	0.1876
DHW * HDD	1	0.00566	0.0027	2.1	0.0359
INS * HDD	1	0.02202	0.00292	7.53	<.0001
BOILER * HDD	1	0.0118	0.00259	4.55	<.0001
FURNACE * HDD	1	0.00513	0.00306	1.68	0.0936
INS * HDD * POST	1	-0.04414	0.00213	-20.72	<.0001
FURNACE * HDD * POST	1	-0.03458	0.00321	-10.78	<.0001
BOILER * POST	1	-0.4889	0.06665	-7.34	<.0001
DHW * POST	1	0.11857	0.07367	1.61	0.1075
MISC * POST	1	0.11179	0.05377	2.08	0.0376

Table 95. Gas Savings Measure-Level Model for Integrated Boiler Systems

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
HDD	1	0.14253	0.00083095	171.53	<.0001
MISC * HDD	1	0.00908	0.00391	2.32	0.0202
DHW * HDD	1	0.00799	0.00305	2.62	0.0089
INS * HDD	1	0.01355	0.00399	3.4	0.0007
BOILER * HDD	1	-0.03122	0.00644	-4.85	<.0001
FURNACE * HDD	1	0.00587	0.00309	1.9	0.0577
INS * HDD * POST	1	-0.04026	0.0025	-16.08	<.0001
FURNACE * HDD * POST	1	-0.03566	0.00325	-10.96	<.0001
BOILER * POST	1	-0.53693	0.15443	-3.48	0.0005
DHW * POST	1	0.11781	0.08392	1.4	0.1604
MISC * POST	1	0.05799	0.05967	0.97	0.3312