A Preliminary Analysis of Energy Impacts from Partial Deep Energy Retrofit Projects in National Grid's Jurisdiction

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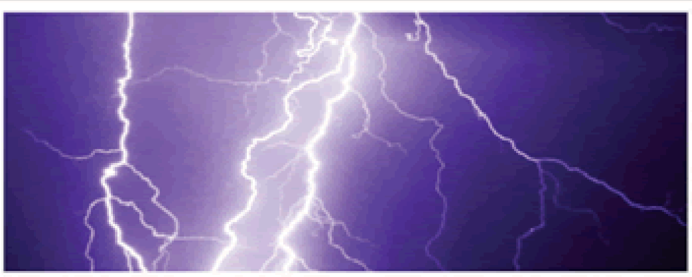

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1. Executive Summary

As part of its 2013 to 2015 Three-Year Energy Efficiency Program Plan, National Grid is proposing to offer a new program to promote partial deep energy retrofit (DER) projects in Massachusetts, based on its experience with the DER pilot program since 2010. National Grid's filing for the proposed program must include estimates of *energy savings* and *costs* associated with partial DER projects.

This study, conducted by Synapse Energy Economics and independent consultants Dave Legg and Mike Duclos (the Synapse project team), provides the *energy savings* estimates required by National Grid for its filing. These data can also be measured against the incremental cost of partial DER projects in order to evaluate net benefits or benefit/cost ratios associated with the projects to be supported by National Grid's partial-DER program between 2013 and 2015.

The partial DER projects considered in this study include projects for a home's attic, above-ground walls, windows, and basement walls. This study focuses on energy savings related to heating, exclusively (not cooling).

Study Approach

The Synapse project team began the study by developing a "model house" with characteristics typical of a Massachusetts home that might undertake a partial DER project under National Grid's proposed program for 2013 to 2015. National Grid's DER pilot project database was used as a resource to identify "typical" house characteristics; for most of these characteristics (except insulation), we used the median values or values most frequently occurring in the database to identify "typical" conditions. The resulting model house is essentially a two-story, single family home, built around 1920, with a natural gas heating system with AFUE 75.

Two "baseline scenarios" were developed to reflect differing insulation levels for the model house under pre-DER project conditions: a "worst existing condition" (WEC) case, which assumed little pre-existing insulation in the model house; and a "better existing condition" (BEC) case, which assumed better insulation in the model house. Details on the insulation assumptions for the WEC and BEC cases are provided in Section 2 of this report. The air leakage rate for both of these baseline scenarios was assumed to be the same.

Next, we developed "Improved" case insulation levels and air leakage reduction rates for the model home under post-DER project conditions. Air leakage reduction rates were developed for each partial DER component (i.e., attic, above-grade walls, windows, and basement walls) based on data from two National Grid partial-DER projects, several other partial DER projects, a literature review, and consultation with expert DER practitioners.

Using these assumptions, we calculated the energy consumption for the model home under each partial DER project scenario (i.e., attic, above-grade walls, windows, and basement walls) using a simple spreadsheet model developed by the Synapse project team for this study. These "post-DER project" energy consumption values were then compared to the energy consumption of the model house under the "pre-DER" baseline scenarios (WEC and BEC) to determine energy savings associated with each of the partial DER projects.

Energy savings for the WEC and BEC scenarios were also compared against each other, in order to help clarify a range of possible energy savings that may result from National Grid's partial DER projects.

Key Findings

Absolute Energy Savings

This study found that above-grade wall partial DER projects provide the greatest absolute energy savings, followed by attic, basement, and windows (in that order). Absolute energy savings for the WEC case were significantly higher than savings for the BEC case for all components except windows; the WEC-case energy savings for a window project were only slightly better than the BEC-case savings.

Relative Energy Savings

Table 1-1, below, shows the relative energy savings achieved by each partial DER project. Relative savings is calculated by dividing the absolute energy savings for a partial DER project by the total energy consumption for the model house prior to improvement.

Table 1-1. Percent Energy Savings Achieved by Partial DER Projects

Partial DER Project	% energy savings relative to WEC-case energy consumption	% energy savings relative to BEC-case energy consumption
Above-grade walls	39%	32%
Attic	23%	17%
Basement walls	12%	9%
Windows	7%	11%

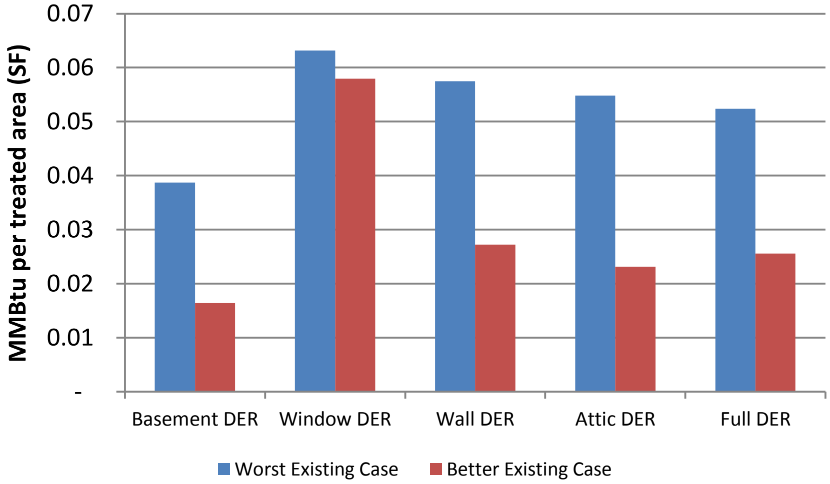
As shown in Table 1-1, the relative savings from window projects is higher for the BEC case than for the WEC case. This is because:

- The numerators used to calculate relative savings for the WEC and BEC cases (i.e., absolute energy savings for a partial DER window project) are similar; and
- The denominator (total energy consumption prior to improvement) is much smaller for the BEC case than the WEC case, due to better insulation levels.

Savings per Treated Square Foot

While above-ground wall projects provide the greatest absolute and relative energy savings, window projects provide the greatest savings per treated square foot, followed by above-ground walls, attic, and basement (in that order). Figure 1-1, below, shows annual energy savings per treated square foot for the WEC and BEC cases.

Figure 1-1. Annual Heating Energy Savings of Partial DER Projects for WEC and BEC cases (MMBtu per treated area)



Recommendations for Further Analysis

The simple spreadsheet (SS) model developed by the Synapse project team for this study offers a useful, first-cut analysis of energy savings for partial DER projects. The reasonableness of this SS model was affirmed, as part of this study, by conducting a rough comparative analysis of energy consumption using the REM/Rate model and actual consumption data for two DER projects (see Section 3 of this report).

However, as discussed in Section 2 (below), existing data on air leakage reduction rates by component (i.e., attic, above-grade walls, windows, and basement walls) is very limited; and the SS model relies on these data for its calculations. Therefore, while the SS model appears to be a reasonable tool for estimating energy savings from partial DER projects at this time, the Synapse project team recommends testing the model over a larger set of actual, partial-DER projects as more data becomes available, and adjusting the SS model to improve accuracy, if necessary.

2. Assumptions & Scenarios

Developing the "Model House"

In order to forecast energy savings from partial DER projects, the Synapse project team began the study by developing a "model house" with characteristics typical of a Massachusetts home that might participate in National Grid's proposed program. More specifically, we defined the model house in our study as "a house that is likely to undergo one partial DER project between 2013 and 2015."

To develop the model house characteristics, the Synapse project team relied on National Grid's DER pilot project database, the REM/Rate NEHERS Alliance model library, and our own experience and judgment.

For most of the characteristics (except insulation levels), we used the median values or values most frequently occurring in the National Grid DER pilot database to identify "typical" conditions. For non-quantitative values, such as the type of HVAC system and fuel type, we chose the variables that occurred most frequently. For quantitative values (again, excluding insulation values), we used the median values.

As detailed in Table 2-1, below, the resulting model house was essentially a two-story, single family home, built around 1920, with a natural gas heating system with AFUE 75. The total surface area is 5325 square feet, and the total conditioned floor area is about 2000 square feet. These areas were estimated from the National Grid DER database as being "typical" for each component, and represent an approximation to a building, not any specific actual building. In both the WEC and BEC cases (discussed in detail below), the model house has an assumed infiltration rate of 4600 CFM50.[1]

While many of the full-DER projects participating in National Grid's pilot program expanded existing enclosure space, our analysis assumed no change for the total surface area in order to simplify the analysis of energy savings of partial DER projects.

Table 2-1. Model House Characteristics for a Partial DER Project in National Grid Jurisdiction

Characteristic	Value
Year House Built	1920
Existing Air Leakage per Enclosure Area (CFM50 Pa/SF)	0.864
Existing Air Leakage @ CFM50	4603
Total No. of Eligible Dwelling Units	1
Total Conditioned Usable Floor Space for Building (SF)	2050
Total Enclosure Surface Area (SF)	5325
Existing AFUE of Heating Equipment	75
Existing Primary Fuel/Energy Type	Natural Gas
Stories in Building (Excluding Basement)	2
Total Number of Building Occupants in Winter	4
Proposed Total Enclosure (SF)	5325
Proposed Attic or Roof Area (SF)	1191
Proposed Above Grade Walls w/ Windows (SF)	2227
Proposed Total Windows (SF)	296
Proposed Foundation Wall Below Grade (SF)	651
Proposed Foundation Wall Above Grade, w/ Windows (SF)	221
Proposed Slab (SF)	997
Proposed Area Basement Walls COMBINED (%)	16%
Proposed Area of Above Grade Walls (%)	42%
Proposed Area of Windows (%)	6%
Proposed Attic or Roof Area (%)	22%
Proposed Area of Slab (%)	19%
Proposed Area of Insulated Foundation Wall Below Grade (%)	12%
Proposed Area of Insulated Foundation Wall Above Grade (%)	4%

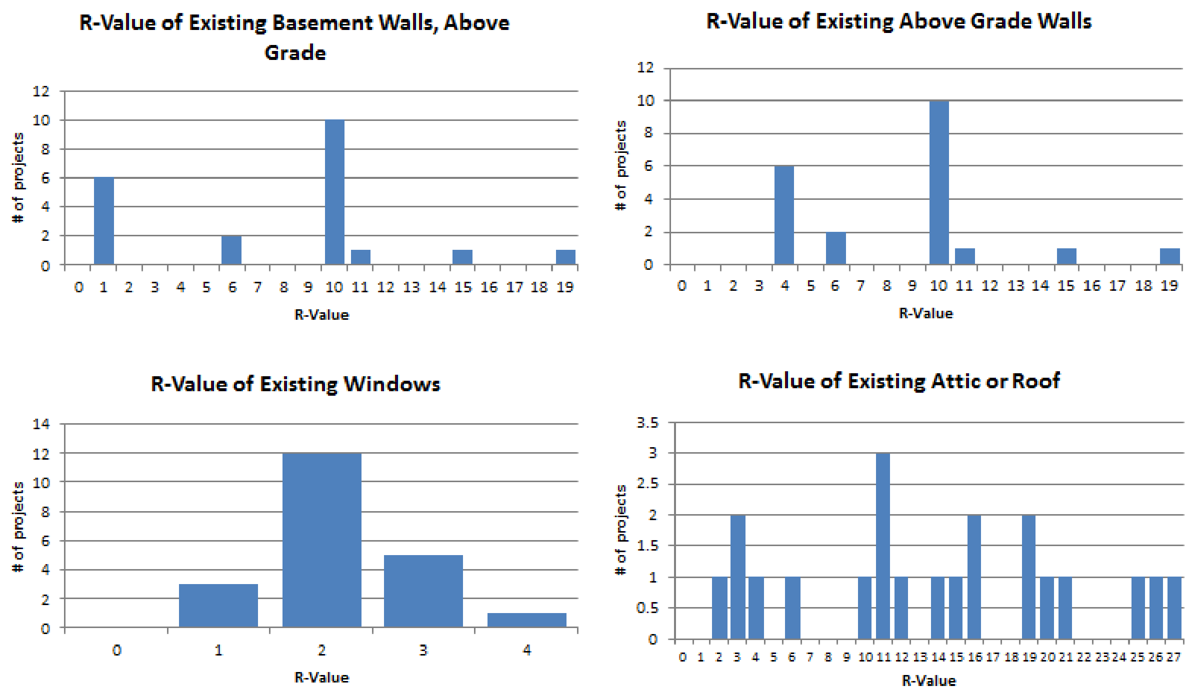
[1] "CFM50" is the airflow, in Cubic Feet per Minute, needed to create a change in building pressure of 50 Pascals. CFM50 is the most commonly used measure of building airtightness.

Insulation Scenarios

To determine the level of insulation by component for the model house, we reviewed the existing insulation conditions of National Grid's DER pilot program participants. Figure 2-1, below, presents a histogram of insulation levels by building component.

Based on this review, which identified distinct trends in insulation levels for basement walls and above-grade walls, we developed two "baseline scenarios" to reflect differing insulation levels for the model house under pre-DER project conditions. The "worst existing condition" (WEC) case assumed little (or no) pre-existing insulation for components in the model house; and the "better existing condition" (BEC) case assumed better insulation in the model house.

Figure 2-1. Histogram of Reported Insulation Levels, by Building Component, of Houses that Participated in the National Grid DER Pilot



The insulation levels for the "Improved" case, which represent conditions at the model home *after* the partial DER project is complete, correspond to the current DER targets in National Grid's program.

Table 2-2, below, presents the insulation levels assumed for the WEC, BEC, and Improved cases.

Table 2-2. R Values for Baseline and Improved Cases

Insulation Scenario for Partial DER	WEC Case	BEC Case	Improved Case
Basement Wall Insulation	0.0	10.0	20.0
Above-Grade Wall Assembly	3.7	9.6	40.0
Window Assembly	2.0	2.2	5.0
Existing Foundation Windows Assembly	1.1	1.1	5.0
Attic Floor Assembly	1.9	14.9	60.0

Additional information about the insulation assumptions for the WEC and BEC cases, by component, are discussed below:

- **Above Grade Wall Assembly:** The R value of an un-insulated 2x4 stud cavity at 16" on center (O.C.) is likely around R-4 because of the thermal resistance of air films on the inside wall area (also called "inside surface resistance") as well as an effect called a "dynamic heat exchanger," in which air-porous, above-grade walls exchange heat flowing out of the wall with air flowing into the wall. The REM/Rate NEHERS Alliance model library uses U 0.27 (R-3.7) for an empty wall cavity and U 0.104 (R-9.6) for a wall cavity with poor common insulation (FG3). Based on our review of National Grid database, the REM/Rate NEHERS Alliance library data, and our experience, we concluded that the most likely wall assemblies will be either R-4 (WEC case) or R-10 (BEC case) effective.
- **Attic/Roof**: The National Grid DER database did not provide clear trends to help determine typical attic/roof insulation values, as it did for other building components. As such, we developed attic U values based on our own experience and judgment. The WEC case for the attic assumes no insulation. An empty cavity attic floor has an insulation value of about R-2 (U 0.53). The roof itself is assumed to have a thermal resistance value of about U 0.4.[2] While the roof U value is not incorporated in Table 2-2, it is incorporated in our calculation of energy consumption and savings for the WEC, BEC, and Improved cases. The BEC case for the attic assumes some modest R-15 insulation, which implies the presence of either: fiberglass batts of a relatively high R value and typical installation quality, or a typical blown cellulose insulation. More specifically, the BEC case assumes R-38 rated fiberglass insulation, or 5" of loose cellulose properly installed in an attic with 2x6 joists.[3] There are two reasons for the difference between the rated and actual R values for fiberglass: (1) it is very difficult to install it properly; and (2) insulation quality degrades the most due to improper installation compared to other insulation materials.
- **Windows**: For the WEC case, we assume existing above-grade windows are single pane wood windows with storm windows; and for the BEC case, we assume inexpensive double pane vinyl windows. The U and SHGC values for these two cases are based on

[2] This assumes one inside air film, one air film outside, framing, and 1" wood board sheathing (R Value 1.2). Other attic components (e.g., gable end walls, chimneys) are not considered. The total U value of this thermal resistance is estimated at 0.41

[3] For R-38 fiberglass batts in the attic, the effective R value ranges from R-15 to R-26 depending on the quality of installation. According to NEHERS Alliance, R-38 batts with more than 5% voids (which we believe represent a typical installation) are effectively R15 (U0.067), less than half the "'rated" insulation value of the product.

the NEHERS Alliance library. According to the REM/Rate NEHERS Alliance library, single pane wood windows with storm windows have U 0.49 (R-2) / SHGC 0.71, and double pane vinyl windows have U 0.46 (R-2.2) / SHGC 0.57. Our review of the National Grid DER database was consistent with these estimates; R-2 is the most frequently reported value for the existing window condition in the database. For basement windows, we assume that both the WEC and BEC cases have single wood frame windows. The U value for the basement windows is 0.9.

- **Basement/Foundation Wall**: Based on our review of the National Grid database and our judgment, we assumed that the foundation wall has un-insulated masonry for the WEC case, and has some kind of insulation (e.g., fiberglass R-11) in 2x4 framing with total effective R-10 insulation in the BEC case. The thermal resistance of foundation materials (i.e., concrete) and air films on the foundation wall are incorporated separately in our calculation of energy savings.

Infiltration Rates

The air leakage rate for both of the baseline scenarios (WEC and BEC) was assumed to be 4600 CFM50, based on the pilot data and model house as shown in Table 2-1, above. This rate was determined based on the median air leakage rate per enclosure area observed in National Grid's DER project database.

Air leakage reduction rates for the model home under post-DER project, "improved conditions" were calculated for each partial DER component (i.e., attic, above-grade walls, windows, and basement walls). One significant challenge for this task was that National Grid's pilot projects completed to date are almost entirely full DER projects; thus, key data on partial retrofits—such as energy savings and CFM50 reductions by building component—were not readily available.

With limited partial-DER data to draw on, the Synapse project team calculated air leakage reduction rates for the Improved case based on data from two National Grid partial-DER pilot projects, a literature review on air leakage reduction techniques and results, and data obtained from consultation with expert DER practitioners. After reviewing many submissions, we identified useful case data (that included component surface area data) for at least two and up to 22 projects for each component type.[4] These data included cases from the *Summary Report - Hot Roofs Pilot Program* prepared for National Grid by CSG in January, 2010. This is the largest known sample (19 records) where blower door test results were available for work approximating a partial attic DER.

Table 2-3, below, summarizes the partial DER projects and components investigated by the Synapse project team. Appendix A explains how we derived our assumptions on air leakage reduction rates based on these sample data. Appendix B presents the development of partial DER scenarios with a focus on air infiltration.

[4] For example, we had two cases for the basement partial DER, and 22 cases for the roof partial DER.

Table 2-3. Selected Partial DER Cases

Project	Component(s)	Order *
Jamaica Plain, MA	Basement and roof – spray foam (pre pilot)	first
Jamaica Plain, MA	Walls w/4" polyisocyanurate and replacement windows (DER pilot)	last
Lexington, MA	Basement rim joist - open cell foam	first
CSG Hot Roof Pilot (19 sites)	Attic slopes w/ open cell foam	only
Bath, ME	Walls w/cellulose and foam	first
Bath, ME	Basement walls foamed	last
Concord, MA	Roof w/ rigid foam, rim w/ open cell foam, repl. 7 windows	only
Jamaica Plan, MA	Basement wall w/ OC foam, roof w/ 12" CC foam	only

** "First" represents a component treated first as part of a more comprehensive retrofit that treated more than one building component. "Only" represents a case where a given partial DER is the only project. "Last" represents a component treated last as part of a DER project that treated more than one component.*

Our assumptions on air leakage reduction rates for the Improved case are presented in Table 2-4, below. The above-grade wall section saw the largest *total* CFM 50 reduction (about 1,660 CFM50) compared to the WEC and BEC cases for the model house, with the attic area having slightly lower reduction, and the basement having less than half the reduction of the above-grade wall. The window CFM50 reduction was the smallest.

In contrast, the largest air leakage reduction rate *per square foot of treated area* was found in the attic/roof component, followed by above-grade wall, basement wall, and windows.

Table 2-4. Proposed Air Leakage Reduction Rates and Total Reduction for "Partial" DER Projects for the Model House

Partial DER Project	Component Area (SF)	CFM@50Pa Reduction per sf. of treated area	CFM@50Pa Reduction	Estimated Final Building CFM@50Pa
Basement Walls*	873	0.80	701	3,902
Above Grade Walls	1903	0.87	1,657	2,946
Existing Windows	296	0.49	146	4,457
Existing Attic or Roof	1191	1.06	1,257	3,346

**Basement walls include rim joists.*

It is important to note that the values in Table 2-4 represent our preliminary estimate of air leakage reduction rates for partial DER projects based on limited available data.

As explained in detail in Appendix A, we believe partial DER projects present the opportunity to gain significant air leakage reduction by carefully treating the transition between two components at the time of the first treatment (e.g., partial DER as the first component). With effective guidelines and requirements, this approach is likely to provide more air leakage reduction than just the leakage associated with a specific component. To represent this effect, we have included a 10% adder to the reduction rates we developed from the sample data, except in the rates for basement walls. Detailed methodologies for air leakage reduction rates are presented in Appendix A.

3. The Energy Consumption Model

Heat Load and Consumption Modeling Methods

A primary goal of this study was to develop a simple spreadsheet (SS) model for National Grid to use in estimating energy consumption and savings for partial DER projects. This SS model was intended to serve as an alternative to commercially available models, such as REM/Rate, and to be customized to National Grid's specific uses.

The SS model and REM/Rate compare as follows:

- **Simple spreadsheet-based model**: The SS model requires U values for various building components and building air leakage data, as well as actual HDD and CDD data for the nearest locations to the DER project sites and for the period actual energy consumption was measured.
- **REM/Rate building energy software**: REM/Rate™ is a widely used building energy model utilized for code compliance purposes and the ENERGY STAR program. It takes into account insulation, infiltration, solar heat gain through windows, and internal heat gain from appliances.

These features are summarized in Table 3-1 below. An important difference between the two models, as shown in Table 3-1, is that the SS model does not take into account internal heat gains (e.g., heat from lights and appliances). While internal gains can be a significant portion of heat that offsets heating load, this factor is less important to our present study (and the SS model), which is focused on energy savings associated with *just* envelope and air sealing.

Table 3-1. Comparison of Modeled Factors between SS model and REM/Rate

Factor	SS Model	REM/Rate
Insulation, UA values	Yes	Yes
Infiltration	Yes	Yes
Internal heat gains	No	Yes
Solar heat gains	No	Yes

The SS model also does not take into account solar heat gain. Whether the inclusion of solar heat gain in a model over-projects or under-projects energy consumption depends upon how the SHGC values of the *existing* windows are different from the SHGC value of the *new* windows. Traditional triple pane windows in the U.S. generally have low SHGC values, similar to double pane windows, while triple pane windows with high SHGCs (e.g., SHGC 0.5) have recently become available in the U.S. market.

Below, we provide an overview of the SS model methodologies and sources by component.

- **Attic, above-grade walls, windows, and above-grade foundation walls**: Heating energy load for these components are estimated using a simple heat transfer calculation based on a building component-specific U value (heat transfer rate in BTU/square foot/degree F/hour) and area (also called "UA").[5] This UA value is then multiplied by heating degree days (HDDs) in a given area to estimate annual total heating load.
- **Below-grade foundation walls and slab:** The calculations of heat load transfer rates for these components are based on complex equations provided in ASHRAE Fundamentals. The formula for the below-grade wall U factor is found in Equation 39 in ASHRAE Fundamentals on page 18.31, which uses parameters such as soil thermal conductivity, total resistance of wall, insulation and inside surface, and depths of top and bottom of wall segment. The formula for the slab floor U factor is found in Equation 40 in ASHRAE Fundamentals on page 18.31, which relies on the same parameters used for the below-grade foundation U factor, as well as basement width and floor depth below grade. These U factors are multiplied by given areas to estimate UA values. The UA values are then multiplied by effective heating degree hours in the ground.
- **Air infiltration and ventilation**: To estimate heat load through air leakage and ventilation, we rely on ASHRAE Fundamentals as well as a study by Lawrence National Laboratory (LBNL).[6] To estimate natural air infiltration rates, we first use a method developed Max Sherman of LBNL because his method uses CFM at 50 Pa air leakage data that have been collected by National Grid's DER pilot program, whereas ASHRAE's method does not use this parameter.[7] Sherman's method estimates air changes per hour at 50 Pascals (ACH50),[8] which essentially attempts to account for annual temperature, wind speed, building stack effect associated with building height, and building-specific leakiness. The estimated ACH50 is then converted into CFM natural (or natural air infiltration rate in CFM) using CFM50 data. The rest of the methods rely of ASHRAE Fundamentals' equations, and combine air leakage and ventilation rates together as follows:
    - The estimated air infiltration is combined with unbalanced air ventilation based on Equation 14 on page 17.7 of ASHRAE Fundamentals 2009.[9]
    - A sensible infiltration and ventilation load heat transfer coefficient (hourly rate) is estimated using ASHRAE Fundamentals' Equation 15 on page 17.7.[10]

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[5] The insulation value (thermal resistance) of a building component depends on the types and amount of insulation material, building assembly (e.g., wood, concrete, etc.), and air "films" of inside and/or outside surface areas of the component.

[6] Max Sherman (1987). "Estimation of Infiltration for Leakage and Climate Indicators," in Energy and Buildings, 10, 1987, p.81.

[7] This method is provided in an online article "ACHN: Just ACH 50 divided by 20?", available at http://www.homeenergy.org/show/article/nav/blowerdoor/id/1015; Also see http://epb.lbl.gov/blowerdoor/BlowerDoor.html

[8] ACHN_Coeff = Climate Coefficient * Height Coefficient * Wind Coefficient * Leakiness Coefficient

[9] Qvi = max (Qunbal , Qi + 0.5Qunbal) where
Qvi = combined infiltration/ventilation flow rate (not including balanced component), cfm;
Qi = infiltration leakage rate assuming no mechanical pressurization, cfm

[10] Cs[Qvi + (1 – εs)Qbal, hr + Qbal, oth] where
Qvi = air ventilation and infiltration rates estimated in the equation above
Cs = Air sensible heat factor = 1.1 btu/hr/cfm/°F
εs = HRV/ERV sensible effectiveness

- Annual heating load is estimated by multiplying the hourly heat transfer coefficient by heating degree hours in a given location.

Evaluating the Reasonableness of the Model

As noted above, a primary goal of this study was to develop a simple spreadsheet (SS) model for National Grid to use in estimating energy consumption and savings for its partial DER projects. However, because building energy modeling can be extremely complex, and because there are many factors that cannot be easily modeled in a spreadsheet, we devised a method to evaluate the SS model's accuracy as compared to both REM/Rate and actual energy consumption data from two full DER projects.

To begin, the Synapse project team collected additional data on two National Grid DER projects: one in Millbury, and one in Belmont. The Synapse team conducted a site visit at each location, and contacted customers to obtain the most recent usage information and data.[11]

These two projects were selected from a pool of four cases where pre- and post-DER consumption data were available. The Millbury (1.5 story) and Belmont (two-family) projects had the advantage of being "more typical" of the mix of projects in National Grid's pilot, and being better known to Synapse's project team.[12] These two DER projects are summarized as follows:

- **Belmont**: Completed in September of 2010, the Belmont DER project was part of a whole-house renovation that included converting the attic of an 85-year-old, two-family home. Highlights of this project include a HERS rating index of 32, final air leakage of 590 CFM50, R-5 windows, plus an R-60 roof with 6 inches of cellulose and 6 inches of rigid polyiso foam added to the exterior. Both the above-grade walls and basement walls were insulated to R-40. The mechanicals included a gas forced-air heating system at 95% AFUE, a heat recovery ventilation with an ERV, and a Solar DHW system with electric back-up.
- **Millbury**: Completed in December 2010, the Millbury DER project was done in conjunction with re-siding and re-roofing. It included a visual upgrade of a 1952 Cape house by adding overhangs and adding roof dormers for more space. Highlights of this project include an R-62 roof and R-40 walls with R-13 fiberglass and 4 inches of polyiso rigid foam on the exterior. Basement walls were insulated to R-20 and windows are R-4 triple glazed, argon-filled, low-E. Heating and cooling are provided by a ducted mini-split with an exhaust-only integrated ventilation system and a pellet stove heating system as back-up heat. Water is heated with an EF .82 tankless propane unit.

Energy consumption data for both projects were obtained directly from the property owners. For the Belmont house, we received natural gas usage data for the entire year in 2011. We used this

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Qbal,hr = balanced ventilation flow rate via HRV/ERV equipment, cfm
Qbal,oth = other balanced ventilation supply airflow rate, cfm

[11] National Grid is expecting to receive more post-project consumption data in several months. At that point, we could conduct similar analyses to further evaluate our model results and consider adjusting the algorithms for energy savings estimates.

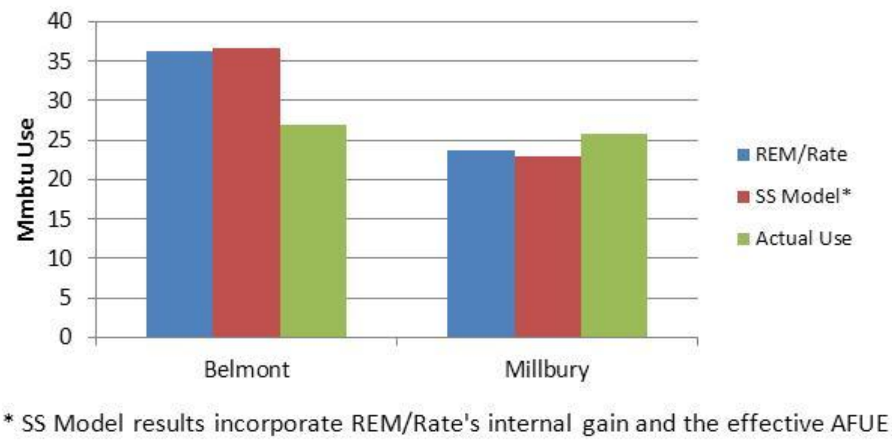
[12] A Belchertown project was considered for inclusion, but was less desirable due primarily to unusual initial air leakage conditions.

data as the home's total heating energy usage because the site's heating system uses natural gas forced hot air. For the Millbury house, we combined the property's consumption of wood pellets and an estimate of the electricity used by its mini-split heat pump system in 2010 and 2011. In order to determine heating-related electricity usage, we reviewed electricity usage during the non-heating seasons, determined the baseline electricity usage for non-heating purposes (e.g., cooling, appliances, lighting, etc.), and subtracted the baseline usage from the winter usage. The heating-related electricity usage was then converted to MMBtu and combined with the MMBtu usage from wood pellet use to estimate the total heating energy usage for the Millbury house.

This energy consumption data was then compared to the heating energy consumption projected for the two projects by the SS and the REM/Rate models. As mentioned above, REM/Rate's energy load and consumption results incorporate buildings' internal heat gains. For the purpose of estimating the reasonableness of our model for heating energy load and consumption, we adjusted the SS model results using the same internal heat gains produced by REM/Rate.[13] In addition, the SS model uses the same AFUE that the REM/Rate model is using. The results of this analysis are shown in Figure 3-1 and Figure 3-2 below.

Figure 3-1 provides energy consumption results assuming complete shading (i.e., no solar heat gains) for both REM/Rate and the SS model. The results from both models are very similar for both DER projects. However, it is important to note that REM/Rate uses heating degree day (HDD) data from TMY2 data sets, and does not incorporate actual HDD data. The actual HDD for Millbury and Belmont in 2011 turned out to be 4 to 8% lower than the HDD provided by TMY2. As such, if using the actual HDD data, the REM/Rate results probably would have been lower by about 4 to 8% than the current estimates shown in Figure 3-1. Nonetheless, the SS model estimates are reasonably close to REM/Rate's estimates. Compared to actual consumption, the model results are close to the actual consumption for Millbury, but are higher than actual consumption for Belmont.

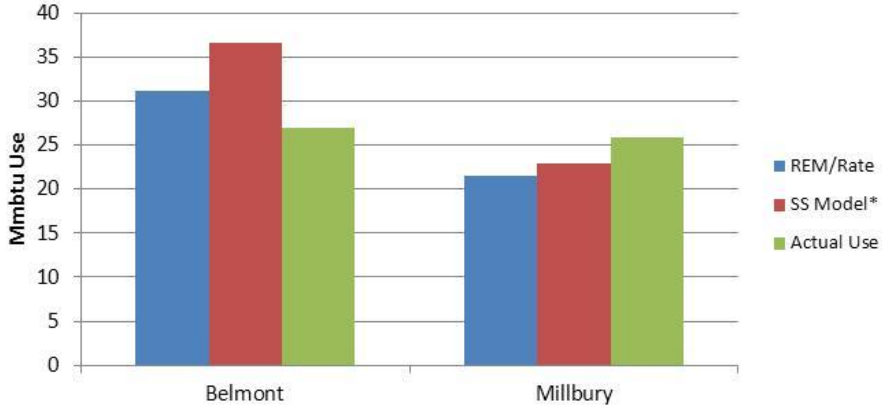
Figure 3-1. Comparison of Space Heating Use: Model Prediction vs. Actual Use (with complete shading for REM/Rate)



[13] Note the ultimate purpose of using our model is to estimate energy "savings," for which we could assume internal gains are equal before and after DER treatment; thus, we do not need to model internal gains.

Since REM/Rate is capable of incorporating solar heat gain, we ran the REM/Rate model for a second time with an assumption of “some shading” (instead of complete shading, as modeled above). Figure 3-2, below, shows the results of the “some shading” REM/Rate model run. The data for the SS model and actual use in Figure 3-2 are the same as in Figure 3-1.[14]

Figure 3-2. Comparison of Space Heating Use: Model Prediction vs. Actual Use (with some shading for REM/Rate)



* SS Model results incorporate REM/Rate's internal gain and the effective AFUE

As shown in Figure 3-2, REM/Rate’s predicted heating energy consumption is lower for both the Belmont and Millbury houses assuming “some shading” instead of “complete shading.” Interestingly this adjustment puts the REM/Rate results closer to the actual consumption for the Belmont house, but further away from the actual consumption for the Millbury house.

In general, both models overestimated consumption for the Belmont house, and underestimated consumption for the Millbury house, compared to the actual consumption data. While finding the causes of these discrepancies is beyond the scope of this study, factors that may have contributed include: the accuracy of our building characterization; the accuracy of heating-related energy consumption by the wood pellets and mini-split heat pump for the Millbury house; the discrepancy between the model thermostat setting and the actual thermostat settings; and modeling inaccuracies.

Based on this rough comparative analysis—and with the limited data currently available on actual consumption pre- and post-DER projects—the SS model appears to be a reasonable tool for estimating energy savings from DER projects at this time. However, as more DER project data becomes available, it would be valuable to test the SS model over a larger set of actual projects, and to make adjustments to the model as necessary.

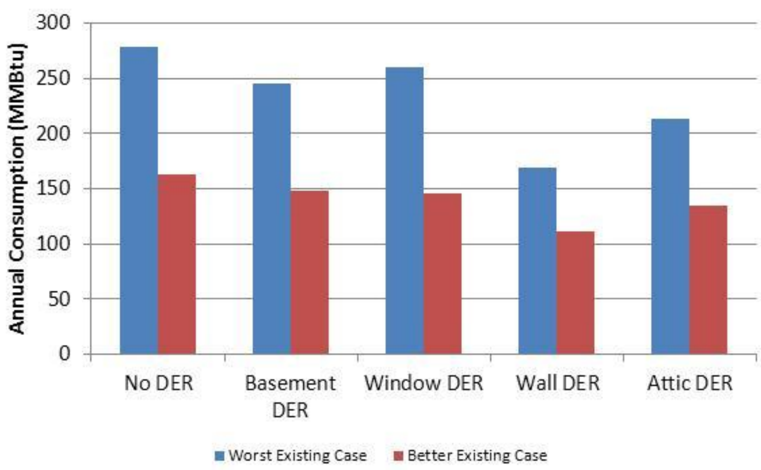
[14] Based on our site visit to these places, “some shading” characterizes these two locations more accurately than complete shading. Unfortunately, the SS model cannot incorporate solar heat gains. However, note the impact of solar heat gains on energy “savings” is not likely to be significant for future DER projects, as mentioned above in footnote 13.

4. Energy Savings from Partial DER Projects

Using the SS model, we analyzed energy savings for partial DER projects treating the basement, windows, above-grade walls, and attic. For each component, we developed two "baseline scenarios" to reflect differing insulation levels for the model house under pre-DER project conditions. As discussed in Section 2, the "worst existing condition" (WEC) case assumed little or no pre-existing insulation in the model house components; and the "better existing condition" (BEC) case assumed greater pre-existing insulation in the model house components. The insulation levels for the "Improved" case, which represent conditions at the model home *after* the partial DER project is complete, correspond to the current DER targets in National Grid's program.

The SS model estimated energy consumption for the WEC, the BEC, and the Improved case for each component. The delta in consumption between the WEC and the Improved case provided the energy savings for the WEC case; and the delta in consumption between the BEC and the Improved case provided energy savings for the BEC case. Figure 4-1, below, shows annual energy consumption at the model house for the WEC and BEC scenarios assuming no DER, and assuming separate, partial DER projects for each of the studied components (i.e., basement, windows, above-grade walls, and attic).

Figure 4-1. Annual Heating Energy Consumption for Partial DER Projects (MMBtu)

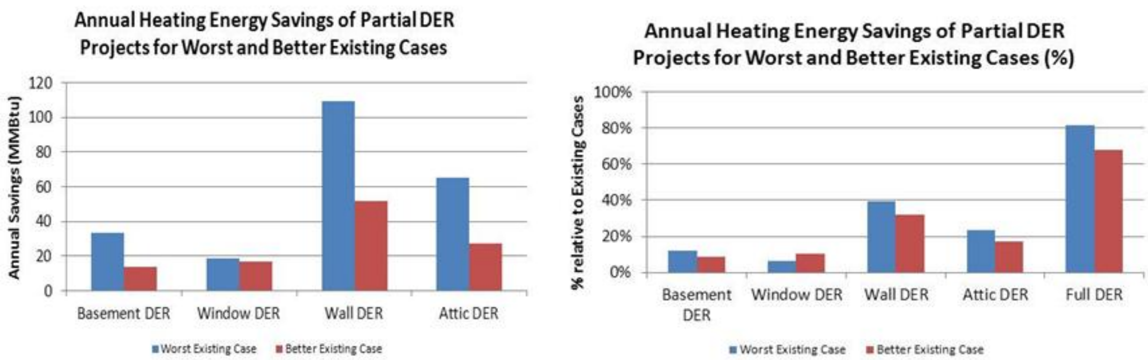


Absolute and Relative Energy Savings

Figure 4-2, below, presents the energy savings for both scenarios in terms of absolute savings (on the left) and relative savings (on the right).

In terms of absolute energy savings, Figure 4-2 indicates that "above-grade wall" partial DER projects provide the greatest savings, followed by attic, basement, and windows (in that order). Absolute energy savings for the WEC case were significantly higher than savings for the BEC case for all components except windows; the WEC-case energy savings for a window project were only slightly better than the BEC-case savings.

Figure 4-2. Annual Heating Energy Savings of Partial DER Projects in MMBtu (left) and % relative to the base case (right)



Relative savings (shown in the right-hand chart in Figure 4-2) is calculated by dividing the absolute energy savings for a partial DER project by the total energy consumption for the model house prior to improvement. Interestingly, the relative savings from window projects is higher for the BEC case than for the WEC case. This is because:

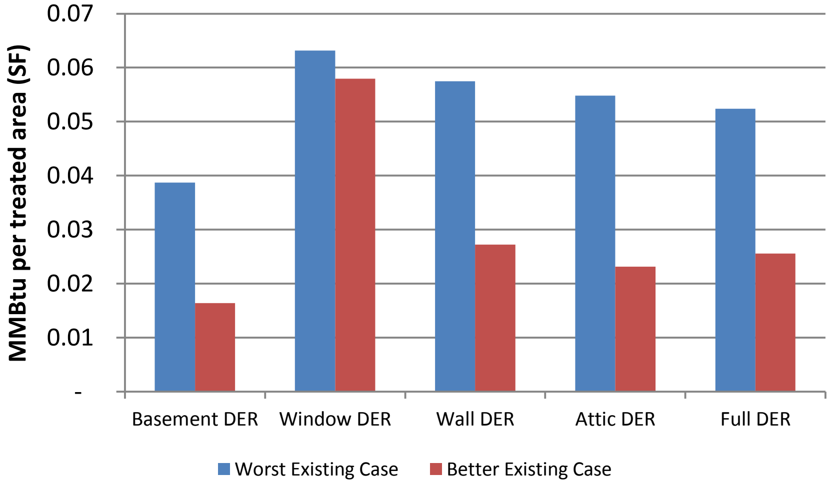
- The numerators used to calculate relative savings for the WEC and BEC cases (i.e., absolute energy savings for a partial DER window project) are similar; and
- The denominator (total energy consumption prior to improvement) is much smaller for the BEC case than the WEC case, due to better insulation levels.

Also shown in Figure 4-2, the relative energy savings for *all* partial DER projects (totaled together) is about 68% for the BEC case and 80% for the WEC case, which fall in the range of estimated or actual energy savings for existing full-scale DER projects funded by National Grid. However, it is important to note that, because all of the partial DER projects assume that they also treat adjoining components, simple summing of savings from each DER project slightly overstates the total energy savings for an entire house.

Savings per Treated Square Foot

While above-ground wall projects provide the greatest absolute and relative energy savings, window projects provide the greatest savings per treated square foot, as shown in Figure 4-3, below. Savings per square foot are significantly higher for the WEC case than for the BEC case for all components except windows; the WEC-case energy savings (per treated square foot) for a window project were only slightly better than the BEC-case savings.

Figure 4-3. Annual Heating Energy Savings of Partial DER Projects for WEC and BEC cases (MMBtu per treated area)



5. Recommendations for Further Analysis

The simple spreadsheet (SS) model developed by the Synapse project team for this study offers a useful, first-cut analysis of energy savings for partial DER projects. The reasonableness of this SS model was affirmed, as part of this study, by conducting a rough comparative analysis of energy consumption using the REM/Rate model and actual consumption data for DER projects.

However, as discussed in Section 2, existing data on air leakage reduction rates by component (i.e., attic, above-grade walls, windows, and basement walls) is very limited; and the SS model relies on these data for its calculations. Therefore, while the SS model appears to be a reasonable tool for estimating energy savings from partial DER projects at this time, the Synapse project team recommends testing the model over a larger set of actual, partial-DER projects as more data becomes available, and making adjustments to improve the accuracy of the model, if necessary. Below, we summarize components of the SS model and the present study that may benefit from additional analysis and testing:

- **The SS model**: The reasonableness of the SS model was tested against two sample DER projects as part of this study. As full-DER project data become more available, it would be valuable to run the SS model against a larger set of full DER projects that have actual consumption data available for a full year before, and a full year after, the DER project.
- **Baseline insulation levels**: While we are comfortable with our assumptions of insulation levels for the WEC and BEC cases, it may be worthwhile to reexamine these assumptions as additional DER data become available.
- **Cooling savings**: The SS model is not capable of estimating cooling savings. While we could consider developing this capability, actual DER projects may not produce significant cooling energy savings. It may be worthwhile to investigate this issue further.
- **Air leakage**: The air leakage reduction rates developed in this study are based on limited sample projects, and are adjusted for the total leakage reduction attained by several

National Grid full DER projects.[15] Again, it may be worthwhile to reexamine these assumptions as additional DER data become available.

- **Ducts and HVAC in attics:** Multiple studies have found savings from reducing the significant air leakage and conductive losses from heating equipment duct-work that is located in an attic outside of the thermal and air leakage boundary. Bringing leaky ductwork inside the envelope is common with DER attic retrofits, especially those done in conjunction with re-roofing. Analysis of this aspect was not included in this study due to modeling complexity. Further investigation, including a review of studies already done, may show increased savings.
- **Other building energy models**: Other building energy models (in addition to REM/Rate), such as the U.S. Department of Energy's EnergyPlus model, could be used to test the reasonableness of the SS model. This would increase confidence in the use of the SS model.

[15] The Synapse project team assumed that, like National Grid's DER pilot, the partial DER initiative will include stringent infiltration reduction standards, incentives for air leakage control, and effective guidance and verification. Absent those, the air leakage reductions may not be as great.

Appendix A. Preliminary Analysis of Air Infiltration Reduction for Partial DER Projects

In this appendix, we describe our analysis of air infiltration reduction for partial DER projects. The primary objective of this analysis was to determine coefficients for air infiltration reductions for the wall, basement wall, attic/roof, and window components of partial DERs. A secondary objective was to investigate what additional air leakage reductions may be attributable to a component when it is the first installed DER component.

Methodology

One significant challenge for this analysis was that National Grid's pilot projects to date are almost entirely full DER projects, and thus key data on partial retrofits—such as energy savings and CFM50 reductions by building component—were not readily available. Methods used to address this challenge included: examining air leakage data from DERs in National Grid's Deep Energy Retrofit and Hot Roofs Pilots, and other partial DERs; and conducting a literature review on air leakage reduction techniques and results.

Review of DER Partial Case Example Data

The Synapse project team investigated data from two National Grid partial DER pilot projects and data obtained from an appeal to expert practitioners. In reviewing the submissions, we identified useful case data (that included component surface area data) for at least two and up to 22 projects of each component type. These data included cases from the *Summary Report - Hot Roofs Pilot Program* prepared for National Grid by CSG in January, 2010. This is the largest known sample (19 records) wherein blower door test results were available for work approximating a partial attic DER. Table A-1 summarizes the partial DER projects and components investigated by the Synapse team. (Table A-1 is identical to Table 2-3 in this report; it is duplicated here for reference.) Below, we explain how we developed our assumptions on air leakage reduction rates based on these sample data.

Table A-1. Summary of Partial Case Examples

Project	Component(s)	Order
Jamaica Plain, MA	Basement and roof – spray foam (pre pilot)	first
Jamaica Plain, MA	Walls w/ 4" polyisocyanurate and replacement windows (DER pilot)	last
Lexington, MA	Basement rim joist - open cell foam	first
CSG Hot Roof Pilot (19 sites)	Attic slopes w/ open cell foam	only
Bath, ME	Walls w/ cellulose and foam	first
Bath, ME	Basement walls foamed	last
Concord, MA	Roof w/ rigid foam, rim w/ open cell foam, repl. 7 windows	only
Jamaica Plan, MA	Basement wall w/ OC foam, roof w/ 12" CC foam	only

Literature Review

The team conducted a literature review focused on investigating infiltration rates by component and treatment modalities likely to impact the first component treated. The literature review not only filled gaps in test data on partials, but also showed the potential benefits of robust first-component treatment (i.e., continuity between building components is of far greater importance than just the components themselves). The sources reviewed included the following:

1. Oser, R., (2011) “Research Report - 1107 Final Retrofit Pilot Community Evaluation Report,” prepared for Building America, Building Technologies Program, Building Science Corporation[16]
2. Ueno, K., (2010). “Residential Exterior Wall Superinsulation Retrofit Details and Analysis,” Building Science Corporation[17]
3. *Summary Report - Hot Roofs Pilot Program*, prepared for National Grid by CSG
4. ASHRAE Fundamentals 2006 Chapter *27.14 Air Leakage of Building Components*

Results of Air Leakage Reduction Analysis

Our estimates of coefficients for air leakage reduction per square-foot are based on air leakage estimates before and after DER projects observed in limited data sets, but are also adjusted upward to reflect the best practices or the experiences gained in National Grid’s pilot programs (e.g., chainsaw retrofit) as well as the enhanced nature of air leakage reduction by partial DER.

The Synapse project team took the following steps to derive coefficients for CFM50 reductions per square foot for partial DERs. First, we estimated a median air leakage reduction value for each component among the selected DER projects (presented in Table A-1 above). We then made two types of adjustment to these median values.

The first adjustment shifted our air leakage coefficients upward by 20%; this adjustment was intended to provide a rough representation of the best practices in air leakage reduction experienced in National Grid’s DER pilot projects, as compared to our samples of partial DER projects, which were not as rigorously renovated.[18] The 20% factor was derived by testing and adjusting our air leakage reduction rates per square foot against a set of actual full DER projects under National Grid’s pilot program. More specifically, we first applied our leakage reduction rate to each component (e.g., roof, wall, window, and basement) of each DER project and estimated the total CFM50 for each of 10 full DER projects out of 21 full DER projects.[19] We then adjusted our CFM50 reduction rates in a way that the sum of total CFM50 reductions from the 10 DER projects became close to the sum of the final CFM50 rates measured by National Grid. We found that the derived air infiltration rates have a fairly large variability, but are reasonably consistent given the variety of air sealing methods applied.[20]

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[16] Available at http://www.buildingscience.com/documents/reports/rr-1107-final-retrofit-pilot-community-evaluation-report

[17] Available at http://www.buildingscience.com/documents/reports/rr-1012-residential-exterior-wall-superinsulation-retrofit

[18] For example, CSG’s Hot Roof Pilot used open spray foams, while many National Grid DER pilot projects used other insulation strategies such as a combination of XPS rigid foam and spray foam or cellulose, and/or a chain-saw roof retrofit.

[19] About half of the DER projects were excluded from this project as outliers because they show extremely high or low initial blower door test.

[20] For an example, there is a large difference between a chainsaw retrofit and using open cell spray foams in the rafters and eave areas in terms of air sealing efficacy.

The second adjustment is a 10% adder for partial DER projects. This factor was applied to all components except the basement partial DER, for which we think there is little difference in air leakage reduction between a partial DER and a full DER. While we have seen a much higher leakage reduction for some partial DER projects being done as a first component (e.g., 30%), our data sample is quite limited. Thus, we decided to use a conservative value of 10% to account for the enhanced air reduction nature of partial DER projects. Further investigation beyond this preliminary analysis is needed to determine the extent of air leakage reduction per component.

The results of our analysis are presented in Table 2-4 of this report. The above-grade wall section saw the largest total CFM 50 reduction (about 1,660 CFM50) for the model house, with the attic area having slightly lower reduction, and the basement having less than half the reduction of the above-grade wall. The window CFM50 reduction was the smallest. In contrast, the largest air leakage reduction rate *per square foot of treated area* was found in the attic/roof component, followed by above-grade walls, basement walls, and windows.

Appendix B. Development of Robust Partial DER Scenarios

General Infiltration Reduction Baseline

Based on input from National Grid, the Synapse team assumed that, like National Grid's DER pilot, the partial DER initiative will include stringent infiltration reduction standards with effective guidance\verification—which may not be as costly or robust as the DER pilot—plus impactful incentives for air leakage reduction. We assumed that the first DER partial component deployed in each home will be installed so as to: (1) facilitate installation of high performance adjacent components in the future; and (2) seal a high percentage of the leaks at the transition to the adjacent components, e.g. wall-to-roof juncture.

CFM50 testing by Building Science Corporation (BSC) shows significantly better air leakage results in the DER pilot than non-pilot projects they tested in Massachusetts.[21] The BSC case examples reviewed and the CFM50 data indicate that, within the pilot sample, projects with more robust approaches tested better. Our review of the DER case studies by BSC points to more sophisticated techniques such as "chain saw retrofits," dual airflow control layers, and high quality workmanship as contributing factors.

The reference baselines for determining the coefficients for CFM50 per component and for the scenarios below were (1) the average CFM50 reductions, and (2) average mix of methods deployed in the National Grid comprehensive DER projects.

Overarching Arguments

The DER pilot data show outstanding CFM50 reductions,[22] a strong indicator that there is a knowledge base and capacity among at least a handful of contractors for achieving comparable infiltration reductions in partial DER's as well.

However, capacity does not assure similar performance in the future if other conditions change. The DER pilot had excellent overall CFM50 reductions, but it offered multiple types of robust supports to projects including BSC with US DOE's Building America funding for technical guidance and inspections; incentives over $30,000 in all cases; and a bonus incentive for air sealing and a penalty for falling too short of the air sealing ideal. It should be noted that DER project CFM50 readings improved for projects after the air sealing incentive was in play. Absent sufficient robust supports, the partial DER initiative may be more likely to achieve final building air sealing results like non-pilot projects.

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[21] The average final air leakage tests for four non-pilot projects evaluated by Osr (page 39) and Ueno (page 10) was 0.34 CFM50 per square foot enclosure area. The DER Pilot database average final reading was 0.134 CFM50\sf. Note: The whole Building Air Sealing Target in the pilot guidelines is "sealed to achieve 0.1 (zero point 1) CFM 50 /sq. ft. of thermal enclosure surface area (6 sides)..."

[22] See previous footnote. Six projects to date have reached National Grid's very stringent CFM50\sf standard, most after the air sealing incentive was added. The pilot air leakage reductions have "exceeded expectations" according to Joe Lstiburek PhD. of Building Science Corporation, speaking at a December 2010 workshop on Deep Energy Retrofits.

However, since we are looking at infiltration savings for partial DERs, there is another offsetting "change" factor to consider. The first partial component installed may be able to achieve more of the infiltration reduction potential at the transitions to the adjacent components. Our investigation of this aspect looked both at CFM50 data for actual partial DER projects and at the literature.

1. The literature, comparison test data and expert opinions of team members indicate that the transitions are vital aspects to address to achieve deep CFM50 reductions. (An example of this is provided in the roof\wall section below.)
2. The available sample of partial DERs showed up to 30% better CFM50 reductions per square foot for a particular component when it is deployed first. However, the sample was very small.

Given the assumption that some form of bonus incentive for air leakage reductions is planned for partials—and that the first component treated, if done well, has a reasonable chance to capture "transition" area CFM50 reductions—the team used average pilot CFM50 reduction results as a baseline with a 10% first component adder as explained in Appendix A.

Next we describe the work methods for air leakage control in brief and findings from pilot review and trends showing which methods led to better leakage reduction for transitions. Awareness and reinforcement of these methods is essential to help ensure that work by future contractors will build on what has been learned in the pilot, and to help ensure robust savings.

Attic – Treatment Scenario

In the pilot all comprehensive DER projects used interior applied spray foam and/or rigid foam on the roof deck for insulation and to control air leakage. Spray foam such as Icenyne applied between rafters creates what is often called a "hot roof," wherein one insulates a vented attic, seals it, and seals the ventilation bringing the entire attic inside the thermal and air flow enclosure. Pilot projects undertaken at the time of re-roofing typically installed at least two layers of 2" rigid, foil faced polyisocyanurate foam with staggered joints on top of a membrane such as water and ice-shield applied to roof sheathing.

Either spray or rigid foam installed at the plane of the rafters, unlike standard attic air sealing, offer the additional benefits of gaining usable space and bringing HVAC equipment inside the enclosure, including the almost always "leaky" ductwork. However, our analysis does not incorporate fully the benefit of eliminating duct leaks to outside, nor conductive losses from heating equipment duct-work that is often located in an attic outside of the thermal boundary in a pre-DER condition.

Wall – Treatment Scenario

The common approach for walls in the DER pilot was two layers of rigid polyisocyanurate foil faced foam with joints offset and taped installed "outboard" of wall sheathing with a 2x4 wall cavity filled with foam, cellulose or fibrous insulation. Air-flow control layers were either the taped exterior face of the foil, or house-wrap on sheathing. In one case (Belchertown) the contractor installed 5.5" spray foam in a double staggered-stud wall. The DER projects that approached or met National Grid's stringent air leakage guideline used the outboard approach combined with chain saw retrofits and "cut-aways" at porch roof and porch floor connections to walls to allow rigid foam to be applied continuously to the walls. Projects that had less than average results included cases with intersecting porches that didn't cut the joining porch roof or floor back or didn't address all the transitions at walls and windows.

Roof (Attic)\Wall Transition

Projects with better CFM50 reductions typically deployed "chain saw" retrofits here as well for more effective treatment of the transitions from attic to wall. A chain saw retrofit involves sawing away the exterior roof overhangs and trim at rakes and eaves to allow access to bring rigid insulation on both wall and roof into contact. No longer separated by wood and trim materials, the resulting foam joints are then sealed with tape and or sealants. The BSC case examples underscore the importance of this type of detail for creating continuity between components. Ueno, K., (2010) cites other sources for this as well, and states "[t]his assembly appears to be extremely sensitive to workmanship and builder comprehension of the vital connection between air barrier elements. In addition, the presence of two layers of insulation (with staggered seams) appears to do little to ensure air barrier effectiveness: its continuity between building components is of far greater importance, which is consistent with the Straube and Burnett's (2005) recommendations."

Basement Wall Treatment Scenario

All but a few of the projects we reviewed included foundation wall insulation strategies. Each of these employed either closed-cell spray foam extending up into the rim joist cavities at 2-5" thickness, or rigid polyisocyanurate. Basement ceilings were not considered as a component for estimating savings as the DER projects that opted for just insulating and sealing the basement ceiling instead achieved significantly lower CFM50 reductions.

Rim Joist Area, the Transition from Basement to Above-Grade Walls

Although on average CFM50 reduction per SF is modest for basement walls, for basement rim only it is the highest. However rim only was not a separate component measure for incentives per se and may be best deployed with the full basement wall insulation to reduce cold condensing surfaces in the basement, as it's best to exercise caution in terms of water management.

Window Treatment Scenario

The scenario assumed for the windows again was based upon stringent DER pilot guidelines that call for "Window and Doors - target R5 (U ≤ 0.2) whole-unit thermal performance, infiltration resistance performance of ≤ 0.15 CFM/sq ft. of air leakage, per AAMA11 standard infiltration test." Windows were replaced unless relatively new, in which case tight exterior storms were added. Non-expanding foam or other sealant applied around the outer frame of windows created a connection between the windows and the wall air barrier. In many instances very leaky single glazed basement windows were replaced or blocked-off and foamed.

Window Leakage Assumptions and Window-to-Wall Transitions

ASHRAE Fundamentals air leakage rates by component (section 27.14) helped to inform our understanding of CFM50 reductions for windows and doors where we lack CFM50 reduction measurements for this component. Though one might expect (especially since 90% of overall leakage is reduced in the pilot) to see the fraction of air leakage reduction by TREATED component to be close to the fraction of air leakage rate by component, we've seen a need to consider other factors based on the measurements and observations of DER methods. Baseline for fenestration leakage is ASHRAE infiltration of 15% attributable to windows and doors. We assumed that in terms of treatment that 50% of leakage reductions at junctures of wall and window are due to wall treatments with the rest due to window replacement with tighter windows. This assumption, along with ASHRAE's 15% air leakage attribution to windows and doors, leaves 8% for window treatments and 92% of wall\fenestration reductions for wall treatment for the average "whole house" case. Examples of such wall\fenestration juncture treatments include taping of rigid insulation to window flanges or "bucks," as well as foaming and sealing window weight boxes in the wall. It is assumed given the fact that operability of windows is depending upon the existence of seams that in a nearly perfectly sealed wall the remaining leaks may be mostly through windows.