Disaggregation of the Energy Savings Achieved from Insulation in EESoP 3 and the Energy Efficiency Commitment.

Executive summary

Various research has been undertaken to investigate whether the energy savings from insulation measures, as predicted by theoretical models, are realised in practice. A consolidation of this research[1] has concluded that homes receiving insulation measures do not benefit from a significant proportion of the expected energy savings.

This has resulted in the application of a 'Reduction Factor' of 50% to the energy savings expected when installing such measures in domestic homes. A reduction factor can be described as:

"The amount by which the measured energy saving following refurbishment is less than the saving predicted from theory".

Previous analysis[2] had determined the total average reduction factor associated with the installation of various types of insulation measures in three sets of dwellings, initially containing approximately 500, 530 and 1000 cases respectively. The analysis was based on the evaluation of pairs of meter readings taken before and after the insulation measures were installed. The readings were subjected to degree day correction and then used to calculate annual energy consumption before and after refurbishment. The calculated energy saving was then compared to the expected theoretical saving generated by the BREDEM model. The A shortfall of that analysis was that many of the homes received more than one type of insulation (e.g. cavity wall plus loft insulation) and it was not investigated whether the reduction factor differed between different types of insulation.

The goal of the analysis described in this document was to recreate these original calculations, and determine whether reduction factor varies with the type of measure installed.

The conclusion of this further analysis was that there was no statistically significant difference in reduction factor between different types of insulation and therefore the same reduction factor should apply to all types of insulation.

[1] "Consolidation of the available information on the differences between measured and theoretical energy saving in housing"; Glasgow Caledonian University: 2006 (http://www.defra.gov.uk/environment/climatechange/uk/energy/research/pdf/insulationmeasures-review.pdf)

[2] "Monitoring Energy Savings achieved from Insulation Measures installed in Gas Heated Homes in SoP3 and EEC Schemes"; Energy Saving Trust: 2004. (http://www.defra.gov.uk/environment/climatechange/uk/energy/research/index.htm)

Summary of Analysis

The table below shows the number of cases remaining in each sample after the elimination of unsuitable records, and summarises the changes in unadjusted annual consumption for each of the three sub-samples and for the entire sample.

Sample	Cases	Before insulation (kWh/year)	After insulation (kWh/year)	Saving (kWh/year)	Reduction
2002D	401	20 958	17 399	3559	17%
2003P	352	25 618	23 281	2337	9%
2003NP	768	26 810	22 992	3818	14%
All	1521	24 991	21 585	3407	14%

The climate in which the buildings were operated inevitably changed between the periods before and after insulation, and a normalisation process, in conjunction with degree day data for the relevant periods, is used to account for this. The next table summarises the consumptions after normalisation.

Sample	Before insulation (kWh/year)	After insulation (kWh/year)	Saving (kWh/year)	Reduction
2002D	19 358	17 171	2187	11%
2003P	24 842	21 484	3358	14%
2003NP	25 557	22 855	2702	11%
All	23 757	21 039	2718	11%

The next table summarises the energy saving reduction factors, defined as 1-(observed saving/expected saving), again for the three sub-samples and for the whole sample.

Sample	Expected saving (kWh/year)	Observed saving (kWh/year)	Reduction factor	95% confidence interval
2002D	4815	2187	55%	± 5%
2003P	6262	3358	46%	± 8%
2003NP	5105	2702	47%	± 6%
All	5296	2718	49%	± 4%

It is noted that no sub-sample shows a reduction factor which is significantly different to that of any other, and that no sub-sample differs significantly from the whole dataset.

The sample dwellings received a range of combinations of cavity wall insulation, loft insulation upgrades to 200mm (from various starting thicknesses), draught stripping and hot water tank insulation. To remove the complexity associated with the effect of multiple measures, cases which had received more than one measure only were first excluded from the sample.

Only four dwellings had draught stripping alone fitted and the effect of this measure in isolation could therefore not be established. It was thought unlikely that tank insulation would significantly affect comfort levels. The only physical mechanism by which this could occur would be if the reduction in tank losses reduced unwanted overheating, but this effect will be small, and limited to a small part of the dwelling.

The table below summarises the results for the two remaining measures: cavity wall insulation and loft insulation. For completeness, the results originally obtained for the whole sample have also been included.

	Cases	Reduction factor	95% confidence interval
Cavity wall insulation only	765	43%	± 6%
Loft insulation only	353	30%	± 12%

The relatively large confidence intervals mean that it is not possible to draw the conclusion that the two reduction factors are significantly different. The factors for the two measures could differ by up to $\sqrt{(6^2+12^2)}$ = 13.4% purely by chance. The only way to resolve this question is to increase the size of the sample. It should be remembered that the confidence intervals will decrease only with the square root of the sample sizes: to halve the uncertainties the sample sizes would need to be increased by a factor of four.

1 Data cleaning

The first data file had already been cleaned to remove unsuitable records. The remaining two data files were not available in cleaned form. It was therefore necessary to recreate the data cleaning process which had been used prior to the previous analysis. This was done in a series of stages.

1.1 Change of tenancy

Cases where there had been a change of tenancy were eliminated from the samples.

1.2 Meter changes

Where meters had been changed the final reading on the old meter and the starting reading on the new meter were provided in the datasets. It was necessary to adjust the end of data collection reading to take account of the consumption logged on both meters.

1.3 Meter rollover

In some cases meters had ‘rolled over’, that is their reading had passed 99999 and gone back round to 00000. This effect is readily detected when the consumption over the measuring interval is calculated: the result is large and negative. It can be corrected by adding 100000 to the final meter reading.

1.4 Length of data intervals

The length of each monitoring period (before and after insulation) is calculated. Certain stages of the analysis process rely on this covering a period of approximately one year, and will lose accuracy if this is not the case. Accordingly, any site for which either the pre-insulation or post-insulation monitoring period was less than 200 days was excluded from the analysis.

1.5 Timing of test intervals in relation to measure installation

In a number of cases the indicated installation date was either ahead of the end of the before meter reading interval, or later than the start of the after period. Again, a few cases had obvious errors in the date entries, and these were corrected. Remaining cases were eliminated from the samples.

1.6 Addition of house type codes

The calculation of expected fuel saving is based on a matrix of dwelling types and the measure installed. Prior to using this matrix dwelling type must be coded as shown in the table below.

Dwelling type	Number of bedrooms	Code
Flat (2EW)	1	1
	2	2
	3	3
Flat (3EW)	1	4
	2	5
	3	6
Mid-terrace	2	7
	3	8
End terrace	2	9
	3	10
Semi-detached bungalow	2	11
	3	12
Detached bungalow	2	13
	3	14
	4	15
Semi-detached house	2	16
	3	17
	4	18
Detached house	2	19
	3	20
	4	21

The raw data file contains details of dwelling type and number of bedrooms, and these were used to associate a dwelling type number with each record. The raw data did not contain details of whether flats were 2EW or 3EW, and in all cases 2EW was assumed.

A small number of cases could not be classified, for example four bedroom semi-detached bungalows or five bedroom houses. The code for the nearest possible option was used in these cases.

1.7 Elimination of outlying consumptions

In some dwellings energy consumptions were unreasonably low. In the most extreme cases this was most likely due to errors in the transcription of readings. In other cases it may have indicated long periods of absence, or that fuel was used only for water heating. Although these may be real behavioural effects, the normalisation process assumes that each dwelling is heated, and either renders a data record unsuitable for inclusion in that analysis. The average consumption calculated for water heating depends on the number of bedrooms, and is in the range 4840 to 8940 kWh/year. Cases with consumption less than 6000 kWh/year either before or after insulation were therefore excluded from the samples.

In other cases consumptions were unreasonably high. This was most probably due to errors in the transcription of readings. It was noted that the correlation between before and after consumptions breaks down for cases with consumptions over about 150 000 kWh/year. Cases in which consumption, before or after insulation, was above 200 000 kWh/year were therefore removed from the datasets.

1.8 Elimination of outlying savings

This is probably the most controversial stage in the entire data cleaning process. Some dwellings displayed very large increases or decreases in consumption after insulation. It is remotely possible that some of these cases corresponded to real changes in comfort take. Householders may have opted to take very large increases in internal temperature, in the knowledge that their dwelling was now insulated. Alternatively, they may have adopted much lower temperatures as part of their energy saving activities. It is probably more likely that they were due to minor errors in data transcription which manages to make it through the less demanding tests outlined above. Accordingly, cases in which energy consumption changed by more than 35% were excluded from the samples.

2 Modifications to original data analysis spreadsheet

The original analysis carried out for EST was performed in a large and rather complex spreadsheet. A number of intermediary pieces of data inspection which did not contribute to the final conclusions remained in the sheet. Certain key constants were included with the raw data. Finally, a great many results were computed at the bottom of the main worksheet, making the insertion of new data rather hazardous.

In response to these observations, the analysis was split across a series of separate worksheets. The first, ‘data’, contains the selected consumption data. The worksheet ‘calcs’ contains all the calculations carried out for each dwelling, and ‘results’ generates the required summary of the whole data set. Where required, a worksheet ‘disaggregation’ contains the calculation to split out the effects of different measures. In order to carry out the analysis a number of fixed parameters are used. To simplify the calculation formulae and facilitate future adjustment of these parameters they are all now named and held in a separate worksheet, ‘tables’.

Before use, these modifications were checked by comparing the final results, and a great many intermediate quantities, with the original spreadsheet which was available for the first of the three datasets.

3 *Summary of worksheet ‘data’*

This worksheet contains the raw data used in the analysis. It is arranged as follows. Valid data records begin in row 8 of the worksheet.

Column	Data	
A	Case number	
B	Customer reference	
C	Postcode (outcode only)	
D	Property type	
E	Number of bedrooms	
F	House type code	
G	Tenure	
H	Cavity wall insulation applied	Pre 1976 construction
I		Post 1976 construction
J	Loft insulation applied	0-200 mm
K		25-200 mm
L		50-200 mm
M		75-200 mm
N	Tank insulation applied	
O	Draught stripping applied	
P	Other measures	
Q	Measure installation date	
R	Customer type	
S	Before measure meter readings	Start reading date
T		Type of reading
U		Reading
V		End reading date
W		Type of reading
X		Reading
Y	After measure meter readings	Start reading date
Z		Type of reading
AA		Reading
AB		End reading date
AC		Type of reading
AD		Reading

Note that the entries in columns H through to P must be a single “Y” if a measure is to be registered as in place in the calculation process.

4 *Summary of worksheet 'calcs'*

Worksheet 'calcs' contains the calculations required to normalise the consumption data for each individual case.

Column	Description	Units	Formula used in first row	Notes
Time periods				
A	Before measure monitoring duration	days	=data!V8-data!S8	Simple time/date arithmetic used to determine interval between readings taken before measure
B	After measure monitoring duration	days	=data!AB8-data!Y8	As above for period after measure
Consumptions				
C	Before measure gas consumption	kWh	=(data!X8-data!U8)*cuft2kwh	Difference between start and end readings. cuft2kwh contains conversion factor from 100cuft gas to kWh
D	After measure gas consumption	kWh	=(data!AD8-data!AA8)*cuft2kwh	As above for period after measure
E	Before measure consumption rate	kWh/day	=C8/A8	
F	After measure consumption rate	kWh/day	=D8/B8	
G	Percentage reduction in consumption	%	=1-E8/F8	
H	Not used			
Degree day calculations				
I	Index into degree day table for start of before period	None	=MATCH(data!S8,ddeom,1)	ddeom contains the dates at which each degree day period ends.
J	Preceeding start cumulative degree days	degree days	=INDEX(ddcum,I8,1)	ddcum contains cumulative degree days. This formula therefore returns the value at the time immediately before the meter reading was taken
K	Succeeding start cumulative degree days	degree days	=INDEX(ddcum,I8+1,1)	As above, this returns the next degree day value after the meter reading was taken
L	Preceeding start degree days date	dd/mm/yyyy	=INDEX(ddeom,I8,1)	This returns the date corresponding to the degree day value in column J

M	Succeeding start degree days date	dd/mm/yyyy	=INDEX(ddeom,I8+1,1)	This returns the date corresponding to the degree day value in column K
N	Interpolated cumulative start degree days	degree days	=J8+(K8-J8)*(data!S8-L8)/(M8-L8)	Simple linear interpolation is used to obtain a best estimate of the cumulative degree day value on the date of the first meter reading
O	Index into degree day table for end of before period	None	=MATCH(data!V8,ddeom,1)	The formulae in columns O through to T repeat the process described above to obtain the interpolated degree days value at the time the second before measure meter reading was taken
P	Preceeding end cumulative degree days	degree days	=INDEX(ddcum,O8,1)	
Q	Succeeding end cumulative degree days	degree days	=INDEX(ddcum,O8+1,1)	
R	Preceeding end degree days date	dd/mm/yyyy	=INDEX(ddeom,O8,1)	
S	Succeeding end degree days date	dd/mm/yyyy	=INDEX(ddeom,O8+1,1)	
T	Interpolated cumulative before degree days	degree days	=P8+(Q8-P8)*(data!V8-R8)/(S8-R8)	
U	Net before degree days	degree days	=T8-N8	The number of degree days during the data period before the measure was applied is obtained by differencing the two interpolated values
V	Before degree days per day	degrees	=U8/A8	Net degree days is divided by length of first data period
W	Index into degree day table for start of before period	None	=MATCH(data!Y8,ddeom,1)	The formulae in columns W through to AJ repeat the process described above to obtain the net degree days for the data period after measure was installed
X	Preceeding end cumulative degree days	degree days	=INDEX(ddcum,W8,1)	
Y	Succeeding end cumulative degree days	degree days	=INDEX(ddcum,W8+1,1)	
Z	Preceeding end degree days date	dd/mm/yyyy	=INDEX(ddeom,W8,1)	
AA	Succeeding end degree days date	dd/mm/yyyy	=INDEX(ddeom,W8+1,1)	
AB	Interpolated cumulative end degree days	degree days	=INDEX(ddeom,W8+1,1)	

AC	Index into degree day table for end of after period	None	=MATCH(data!AB8,ddeom,1)	
AD	Preceeding start cumulative degree days	degree days	=INDEX(ddcum,AC8,1)	
AE	Succeeding start cumulative degree days	degree days	=INDEX(ddcum,AC8+1,1)	
AF	Preceeding end degree days date	dd/mm/yyyy	=INDEX(ddeom,AC8,1)	
AG	Succeeding end degree days date	dd/mm/yyyy	=INDEX(ddeom,AC8+1,1)	
AH	Interpolated cumulative after degree days	degree days	=AD8+(AE8-AD8)*(data!$AB8-AF8)/(AG8-AF8)	
AI	Net after degree days	degree days	=AH8-AB8	
AJ	After degree days per day	degrees	=AI8/B8	
AK	Not used			
Water heating				
AL	Water	kWh/day	=wat0+wat1*data!E8	Water consumption is calculated using number of bedrooms and coefficients wat0 and wat1 derived from BREDEM
AM	Not used			
Consumption minus water (SH)				
AN	Space heating before	kWh	=C8-$AL8*A8	Fuel used for space heating in the data period before the measure is calculated as total used minus water heating per day times the number of days in the period
AO	Per day basis	kWh/day	=AN8/U8	Result is then converted to per day basis
AP	Space heating after	KWh	=D8-$AL8*B8	Columns AP and AQ repeat the process for the data period after the measure
AQ	Per day basis	kWh/day	=AP8/AI8	
AR	Not used			
Normalised consumptions				
AS	Normalised consumption before measure	kWh	=365*$AL8+AN8+alpha*AO8*(normdd-U8)	The total normalised consumption is obtained by combining the annual water heating requirement with the calculated space heating consumption. A

AT	Normalised consumption after measure	kWh	=365*$AL8+AP8+alpha*AQ8*(normdd-AI8)	correction is then made for the fact that the total
AU	Normalised reduction due to measure	kWh/year	=AS8-AT8	number of degree days over the data period may not be exactly equal to those assumed when the expected saving is calculated. Note that this is only precise if the data monitoring period covers the whole of the heating season.
AV	Not used			
Expected results				
AW	Expected saving	kWh/year	=INDEX(matrix,data!F8,1)*(data!H8="Y") +INDEX(matrix,data!F8,2)*(data!I8="Y") +INDEX(matrix,data!F8,3)*(data!J8="Y") +INDEX(matrix,data!F8,4)*(data!K8="Y") +INDEX(matrix,data!F8,5)*(data!L8="Y") +INDEX(matrix,data!F8,6)*(data!M8="Y") +INDEX(matrix,data!F8,7)*(data!N8="Y") +INDEX(matrix,data!F8,8)*(data!O8="Y")	This formula computes the total saving due to each of the measures installed. Note that is assumed that the savings are additive: if both CWI and loft insulation are installed the total saving is assumed to be the sum of the savings due to each of the measures separately.
AX	Expected consumption before measure	kWh/year	=INDEX(matrix,data!F8,9)	The 9th column of the matrix contains the predicted prior consumption
AY	Not used			
Statistical factors				
AZ	Cavity wall insulation installed		=OR(data!H8="Y",data!I8="Y")*1	The *1 causes result to display as a number, for ease of exporting factors to other packages
BA	Loft insulation installed		=OR(data!J8="Y",data!K8="Y",data!L8="Y",data!M8="Y")*1	
BB	Draught stripping installed		=(data!O8="Y")*1	
BC	Only cavity wall insulation installed		=AND(AZ8,NOT(BA8),NOT(BB8))*1	Only one measure is installed if that measure is in place and the remaining two are not
BD	Only loft insulation installed		=AND(BA8,NOT(AZ8),NOT(BB8))*1	
BE	Only draught stripping installed		=AND(BB8,NOT(AZ8),NOT(BA8))*1	
BF	Disadvantaged ?		=data!R8	

5 *Summary of worksheet 'results'*

Worksheet 'results' creates a summary of the results from the whole sample.

Cell	Description	Units	Formula	Notes
Sample details				
B4	Number of cases in analysis	None	=COUNT(data!A8:A5007)	Number of cases is determined by counting the case numbers in the data worksheet. This approach allows data to be added (up to a maximum of 5000 cases)
Consumption data before normalisation				
B7	Before measure gas consumption	kWh/dwelling	=365*AVERAGE(calcs!E$8:E$5007)	These values are obtained by scaling the observed daily consumption directly up to one year. As such they are not representative of real performance (consumption will be much lower during the summer). They are included here only to allow comparisons with results in existing report.
B8	After measure gas consumption	kWh/dwelling	=365*AVERAGE(calcs!F$8:F$5007)	
B9	Actual saving	kWh/dwelling	=B7-B8	
B10	Percentage reduction	%	=B9/B7	
Consumption data after normalisation				
B13	Normalised before measure consumption	kWh/dwelling	=AVERAGE(calcs!AS$8:AS$5007)	
B14	Normalised after measure consumption	kWh/dwelling	=AVERAGE(calcs!AT$8:AT$5007)	
B15	Actual saving	kWh/dwelling	=B13-B14	
B16	Percentage reduction	%	=B15/B13	
Reduction factor				
B19	Expected normalised annual saving	kWh/dwelling	=AVERAGE(calcs!AW$8:AW$5007)	
B20	Actual normalised annual saving	kWh/dwelling	=B15	
B21	Reduction factor	%	=1-B20/B19	See below for the derivation of these formulae
D21	95% confidence interval on reduction factor estimate	%	=1.96*STDEV(calcs!AU8:AU5007)/ SQRT(B4)/B19	

The reduction factor is defined as:

$$1-\frac{S_n}{S_e}$$

where:

S_n is the normalised observed saving

S_e is the expected saving.

When the whole dataset is considered S_e and S_o may be expressed as totals across the whole sample, or as average (per dwelling) values. Here the latter approach has been chosen. Thus the overall reduction factor is calculated using the formula:

$$1-\frac{\overline{S}_n}{\overline{S}_e}$$

where the bars denote averages across the sample. In this equation the mean observed energy consumption is a random variable. The estimated reduction factor is therefore also a random variable. The factor 1 and the mean expected saving are both numerical values, and contribute nothing to the uncertainty in the result. To determine the uncertainty in the result it is therefore necessary only to determine the uncertainty in the mean observed energy consumption, and to propagate it through the above equation.

Assuming that the variations in consumption between households are statistically independent and that there are *n* dwellings in the sample, the standard deviation of the estimate of the mean is given by:

$$stdev(\overline{S_n}) = \frac{stdev(S_n)}{\sqrt{n}}$$

The width of the corresponding 95% confidence interval is therefore:

$$1.96 \times \frac{stdev(S_n)}{\sqrt{n}}$$

when the value is incorporated into the reduction factor it is divided by the mean expected consumption, and thus this uncertainty is reduced to:

$$\frac{1.96 \times \frac{stdev(S_n)}{\sqrt{n}}}{\overline{S}_e}$$

6 Summary of worksheet 'tables'

This worksheet holds the constants used in the analysis. Some of the data, such as ddeom or ddcum, are in tabular form. Others, such as cuft2kwh are single constants.

To clarify the formulae used in the calcs worksheet, all of these data have been given descriptive names.

Name	Range	Data
ddeom	A3..A161	This column contains the date of the end of the month for each degree day month
ddcum	D3..D161	Cumulative degree days up to the date given in ddeom
matirix	I4..R24	Matrix of energy savings. Each row refers to one particular dwelling type, as defined in column F of the data worksheet. Columns 1 to 8 contain the expected savings due to the eight different types of measure tabulated in columns of the data worksheet. The last column (9) contains the expected annual consumption before the measure(s) were applied.
cuft2kwh	D29	Conversion from meter readings in units of 100cuft to kWh. Default value is 30.765
wat0	D31	These two coefficients describe the BREDEM equation for hot water heating requirement. Default values are 10.45 kWh/day and 2.81 kWh/day/bedroom respectively.
wat1	D32	
alpha	D34	Value of the constant alpha. Default value is 0.6
ddnorm	D35	Number of degree days used to normalise to standard year. Default value is 1946