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**Title:** Do Energy Efficiency Measures Really Reduce Household Energy Consumption? A Difference-in-Differences Analysis

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# Do Energy Efficiency Measures Really Reduce Household Energy Consumption? A Difference-in-Differences Analysis

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# Do Energy Efficiency Measures Really Reduce Household Energy Consumption? A Difference-in-Differences Analysis


**Abstract**

The aim of this study is to investigate the impact of energy efficiency measures installed through the Carbon Emissions Reduction Target (CERT) and the Community Energy Saving Programme (CESP) on domestic gas and total energy consumption. The recently released National Energy Efficiency Data-Framework (NEED) database is used to examine the changes in domestic gas and total energy consumption for the dwellings in the sample relative to the changes in gas and total energy consumption for a comparable control group in the year after installation. By using a matched difference-in-difference methodology, cavity wall insulation, loft insulation and a new efficient boiler are all statistically observed to reduce domestic gas and total energy consumption for the sample. The single most effective energy efficiency measure when installed alone is found to be cavity wall insulation, reducing annual gas consumption by 10.5% and annual total energy consumption by 8% in the year following installation. Considering the impact of combining different energy efficiency measures, dwellings retrofitted with both cavity wall insulation and a new efficient boiler are found to experience the largest reductions in annual gas and total energy consumption of 13.3 % and 13.5%, respectively. This is followed by a mean annual reduction of 11.9% and 10.5% in gas and total energy consumption for dwellings with all three energy efficiency measures installed in the same year. Interestingly, installing cavity wall insulation on its own is found to be more effective than combining loft insulation and a new efficient boiler.



**Keywords:** *Energy Consumption*, Energy Savings Obligations, Energy Efficiency Policy, National Energy Data-Framework (NEED),Rebound Effect.

## 1. Introduction

A major policy target for many developed countries is to reduce energy demand in every sector of the economy. Particularly, it is envisaged that lower consumption levels in buildings through increased energy efficiency eases dependence on energy imports and improves its trade balance (Umbach 2010). Lower energy demand is also recognised to be a major linchpin in the effort to minimise environmental impacts such as ozone layer depletion, global warming and climate change associated with energy use and exhaustion of energy resources. For these reasons, policymakers across developed economies have gradually shifted their attention to energy efficiency efforts. In the UK, energy consumption used for space heating contributes to approximately 26% of final energy consumption and 25% of UK`s greenhouse gas emissions (IEA, 2012).

The Energy Savings Obligation has become the principal instrument of reducing energy used for space heating in UK homes. This policy instrument was introduced in the mid-1990s, around the time of energy markets liberalisation and has evolved to become the second most important climate policy mechanism after the EU Emissions Trading Scheme (Rosenow, 2012). The savings targets are set for the major energy suppliers by the Department of Energy and Climate Change (DECC) and are administered and enforced by the energy regulator, the Office of Gas and Electricity Markets (OFGEM). The targets are then achieved at the customer end of operations. The focus has therefore been on substantial energy efficiency measures in buildings such as cavity wall insulation, loft insulation and installation of condensing boiler. In the past few years, these measures were predominately delivered via major refurbishment schemes for the existing dwelling stock, notably the most recent version of the energy suppliers' obligations, the Carbon Emissions Reduction Target (CERT), and the Community Energy

Saving Programme (CESP). Both schemes were running between 2008 and 2012. Among many other targets, the CERT's foremost objective was to legally oblige energy companies to cut down carbon emissions by 293 million lifetime tonnes through energy efficiency measures in domestic dwellings across the UK. Professional loft insulation was the most common retrofit measure installed in homes, with approximately 3.9 million dwellings undergoing installations (OFGEM, 2013). Privately installed loft insulation was second on the list, with nearly 2.8 million homes undergoing such retrofit. Cavity wall insulation was third most common measure installed, with over 2.5 million properties benefitting (OFGEM, 2013). A large number of the properties targeted also installed a new efficient boiler via the scheme. All these figures exclude carryovers from CERT`s predecessors, the Energy Efficiency Commitment (EEC) and the Energy Efficiency Standard of Performance (EESoP). The CERT came to an end in December 2012 with energy companies having achieved 296.9 million lifetime tonnes of carbon dioxide. In addition to CERT, during the same period, the CESP was running. This complementary scheme required gas and electricity suppliers to reduce carbon emission by approximately 19 million lifetime tonnes of carbon dioxide through area-based schemes. This was to primarily be achieved by delivering energy efficiency measures to households in targeted low income neighbourhoods defined by the Index of Multiple Deprivation in the UK (OFGEM, 2013). CESP came to an end in December 2012 with energy companies having achieved a reduction of 16.3 million lifetime tonnes of carbon dioxide, almost 85% of the overall target. Yet, the above cited emission reductions achieved by CERT and CESP are defined in terms of lifetime savings achieved by the measures promoted via the obligations and do not necessarily entail reductions in final energy use. Along with this measurement challenge, the energy savings obligations under CERT and CESP were also based on self-reporting as OFGEM were unable to check each individual case due to the administrative challenges of such verification efforts. This gives room for inaccurate self-reporting, although the potential fine of up to 10% of global turnover may have deterred such conduct to a certain extent (Rosenow, 2012).

A further regulatory feature of the UK`s housing market is the government commitment to meet the standards required by the EU’s Energy Performance of Buildings Directive (EPBP, 2010). Under the directive, all residential buildings in the UK are required to undergo Energy Performance Certification before they are sold or let, in order to meet the requirements of the Directive. The Energy Performance Certificates compiles information on current energy consumption and energy costs of the dwelling as well as potential recommendations on how to reduce energy demand. The EPC rating ranges from an A rating (most efficient) to a G rating (least efficient), with almost half of dwellings in England being rated D in 2012 (EHS, 2013).

The present study analyses the extent to which household gas and total energy consumption are reduced by installing energy efficiency measures through the CERT and/or the CESP. Natural gas is the most widely used heating fuel in the UK and it is also the cheapest option available to households. Although not all UK homes are on the gas network, all dwellings in the sample are connected to the gas network and have access to grid gas. Likewise, a large majority of UK`s households use a combination of gas and electricity to heat their homes. These two main sources of domestic energy use covering space heating, lighting and hot water are, therefore, examined. Electricity consumption alone is not analysed here due to its sensitivity to usage of individual electrical appliances. Furthermore, the impact of the three main measures mainly delivered by CERT and CESP ,cavity wall insulation, loft insulation and condensing boiler, are investigated in this paper. Empirical estimations are made by comparing the observed changes in gas and total energy consumption of pre- and post-installation for a sample of properties undergoing efficiency measure(s) relative to the changes experienced by a comparable control group of properties with no record of improvements under the CERT and CESP. This analysis provides one of the first empirical estimations of the link between energy efficiency efforts and actual metered energy consumption in the UK`s residential housing market. By matching the data based on key building characteristics prior to applying a difference-in-differences estimation, we are able to use around three million dwellings in our database EPC ratings of dwellings prior to the energy efficiency upgrade are also controlled for and all dwellings in the sample had an EPC valid for 10 years. The key data source used in this study is the National Energy Efficiency Data-framework (NEED). NEED is a government administrated data framework enabling researchers to understand and explain energy consumption in buildings and to identify potential energy efficiency improvements from a national targeting perspective.

## 2. Background

Research on the impact of energy efficiency measures on consumption is largely ex-ante and prospective rather than based on actually measured ex-post consumption. Several of these empirical studies including Siller et al, 2007; Skea, 2012; Nord et al, 2014 etc. provide valuable insights. Yet, one possible complication is that they may overestimate the true impact of energy efficiency improvements as circumstances of individual installations may vary and other factors including households` characteristics and their behaviour may change. These studies are also difficult to compare due to inconsistencies in approaches, parameter choices and definitions of both the dependent and independent variables, see Sorrell et al (2009) for a discussion. Similarly, some studies use simple before-after comparisons to evaluate the cost-effectiveness of energy efficiency measures. In the absence of a comparison group or controls for confounding variables, counterfactual analysis is not undertaken in these studies and results are hence prone to bias.

A more robust approach to estimating future energy savings is through an econometric analysis of the ex post effectiveness of energy efficiency measures. Such regression analyses require billing data or meter reading information to categorise drivers of residential energy consumption (Swan & Ugursal, 2009). One of the first ex post analyses investigating the relationship between energy efficiency retrofits and energy consumption was conducted by S.H. Hong et al (2006) which examined the impact of cavity wall insulation, loft insulation and energy efficient heating system installed on domestic space heating fuel consumption. By monitoring a sample of English dwellings before and after installation of energy efficiency measures, the authors report that cavity wall and loft insulation reduce heating demand by 10% in centrally heated properties and 17% in non-centrally heated dwellings. This is supported by Scheer et al (2013) evaluating the energy savings realised by households participating in a government sponsored residential retrofit scheme in Ireland. Their study uses an ex post billing analysis to examine the change in gas consumption for a sample of Irish households pre- and post- scheme participation relative to the change in gas consumption for a control group. An average gas reduction of about 3664 kWh or 21 % following installation of energy efficiency measures is reported. When compared to an ex-ante estimation of energy savings, a shortfall of approximately 36 ± 8 % between technical potential and ex-post measured savings is reported. However, these studies may be vulnerable to selection bias as households chose to participate in the retrofit scheme as opposed to being randomly assigned.

In one of the studies closely related to the research presented here, Wyatt (2013) uses annualised electricity and gas consumption data as well as information on installed energy efficiency improvements obtained from the Homes Energy Efficiency Database, a subset of the National Energy Data-Framework used in this study. The author concludes that realised gas reductions for cavity wall insulation and installation of a new condensing boiler are broadly equivalent with median savings in the range 13.5%-19.5%. The effect of installing loft insulation is found to be somewhat lower between 8.4% and 12.2% in the year following installation. Using the same data source, Hamilton et al (2013) also report that energy savings are achieved following the installation of loft and cavity insulations as well as the installation of double glazing and a new efficient boiler in the dwelling. The scope of these studies is limited by the data sets used as they were unable to conduct matching on key explanatory variables, making the results sensitive to latent differences in the characteristics of treatment and control groups. More importantly, both studies focus on the impact of installing a single energy efficiency measure, disregarding the impact of installing a combination of different energy efficiency measures.

In this paper, we exploit a new data source made available through the National Energy Efficiency Data-framework (NEED) in order to estimate changes in actual gas and total energy consumption when dwellings are retrofitted with one or more of the following energy efficiency measures; cavity wall insulation, loft insulation and a new efficient boiler. A sub-sample of NEED has been used previously by DECC (2014) to produce a preliminary report investigating the impact of energy efficiency measures on energy consumption. However, the report only considers the impact on gas consumption and excludes flats from the sample. A rather generic matching procedure is also used as opposed to the one used in this study. The analytical differences between the DECC report and the study presented here are further elaborated in the methodology and the discussion sections.

## 3. Method

A quasi-experimental approach is the most appropriate estimation method to quantify the causal effect of a treatment on an outcome variable (Meyer 1995). In order to estimate the impact of energy efficiency measures on gas and total energy consumption, we compare the performance of a sample of dwellings pre- and post-treatment relative to the performance of some control group pre- and post-treatment. Properties receiving energy efficiency measure (s) in the treatment year represent the treated group and the non-upgrading properties in the sample make up the control group. In essence, variation in gas and energy consumption is explained across time and groups. This research design is superior to most other estimation methods used in previous studies. For instance, the ex-ante analysis of energy savings relies on treated properties to serve as their own controls and the simple before–after evaluation does not account for changes in socio-economic, environmental and behavioural factors. A difference-in-differences analysis, on the other hand, controls for external factors affecting both the sample and the control group between periods by using trends in the control as the baseline. In this study we also apply a Coarsened Exact Matching (CEM) procedure to control for the confounding influence of pre-treatment control variables in the data. The idea is that by creating a better distributional balance between the treated and control groups, a simple difference in means on the matched data or more robustly a difference-in-differences approach can be used to estimate the causal effect. Such matching procedure is far more powerful than one used in previous studies. For instance, in the DECC report (2014), a simple matching algorithm seeking to restrict aspects of the variance and hence the matched sample size is applied, leaving the impact of much bigger problems of statistical bias and model dependency uncertain and to ad-hoc ex-post diagnosis. Equally worrying, properties of a simple matching algorithm only holds on average across samples and rest on strong unverifiable assumptions about the data generation process, see Iacus et.al 2011 for a discussion. CEM, on the other hand, yields a relatively larger matched sample size, is less model-dependent and does not require assumptions about the data generation process. For these reasons, we adopt a matched difference-in-difference approach to estimate the ex post effectiveness of energy supplier obligation programs (CERT and CESP) implemented in the UK by comparing changes in gas and total energy consumption of dwellings retrofitted relative to the changes experienced by an analogous non-retrofitted group of dwellings. The change in average consumption for non-retrofitted properties over the same period represents the counterfactual, i.e. changes in gas and energy consumption unobserved for the treated but would have been observed in the absence of the retrofit (Scheer et al 2013, Frondel and Schmidt 2005). This proposed methodology requires data measured at two or more time periods in order to estimate the "normal" difference in the outcome variable between the treated and the control groups. That is, the difference that would still exist if neither group experienced energy efficiency improvement(s). In this respect, time-trends factors such as changes in weather conditions, energy prices and socio-economic characteristics over time as well as behavioural factors directly or indirectly affecting energy consumption are controlled for and assumed to affect both groups in the same way. This would reduce potential biases in post-treatment period including trends or inherent differences between the treated and the control groups (Wooldridge, 2007). Needless to say, studies using robust matching procedure such as CEM are better able to produce a consistent unbiased estimator relative to studies applying a difference-in-differences estimation on an unmatched data sample as in the case of Hamilton et al (2013) & Wyatt (2013).

We present the following identifying equation for the difference-in-differences estimation:

$$y_{it} = \beta_0 + \beta_1 T_{it} + \beta_2 A_{it} + \beta_3 T_{it} A_{it} + \epsilon_{it} \qquad (1)$$

$y_{it}$ is the outcome variable of interest, i.e. mean annual gas or total energy consumption for dwelling i in time t. $T_{it}$ is equal to unity if dwelling i belongs to the group of dwellings that will eventually be treated (retrofitted) and thus $\beta_1$captures the differences between the treated dwellings and the ones in the control group prior to the energy efficiency treatment. $A_{it}$ is equal to unity in the period after when treatment occurs and hence $\beta_2$ captures aggregate factors that would cause changes in gas or energy consumption in the absence of the treatment. The interaction term $\beta_3$ is the coefficient of interest and is equal to unity for treated dwellings after the intervention. That is, it identifies the causal effect of the treatment, the impact of energy efficiency measure(s) on gas or energy consumption. $\beta_3$ can be obtained by directly estimating Equation (1) or simply by calculating the change in average gas or energy consumption for the treated dwellings pre and post treatment less the change in average gas or energy consumption for dwellings in the control group pre and post treatment as shown in Equation 2.

$$\widehat{\beta_3} = (\overline{y}_{A=pre} - \overline{y}_{A=post})_{Treatment} - (\overline{y}_{A=pre} - \overline{y}_{A=post})_{Control} \qquad (2)$$

In this study, the first method of directly estimating the three parameters of interest ($\beta_1, \beta_2$ *and* $\beta_3$) is used. The crucial identifying assumption in Equation (1) is that $\beta_3$ is equal to zero in the absence of the treatment. That is, without any record of energy efficiency measures installed, the co-efficient identifying the causal impact on gas or energy consumption would be zero. Statistically, the zero conditional mean of errors, $\mathrm{E}(\varepsilon_{it}|T_{it}) = 0$, is required. This assumption is most plausible when the non-participating control group is very similar to the treatment group (Meyer, 1995). As discussed in earlier paragraphs, this can be achieved by applying a CEM matching algorithm ensuring that the empirical distributions of the covariates in the groups are more similar. Matches are made on the basis of key explanatory variables including property type, size and age as well as the region in the UK the dwelling is located in. In essence, statistical twins are created by pairing treated dwelling with recorded energy efficiency installations with comparable non-upgrading dwellings in the control group to isolate the causal effect of energy efficiency measure. The results may still be open to an omitted variable bias in the form of idiosyncratic differences in socio-economic characteristics of households as well as a selection bias in receiving retrofit though CERT and CESP. Yet, the matching procedure applied and the robustness of the difference-in-differences estimation is likely to considerably reduce risks of such biases.

## 4. Data

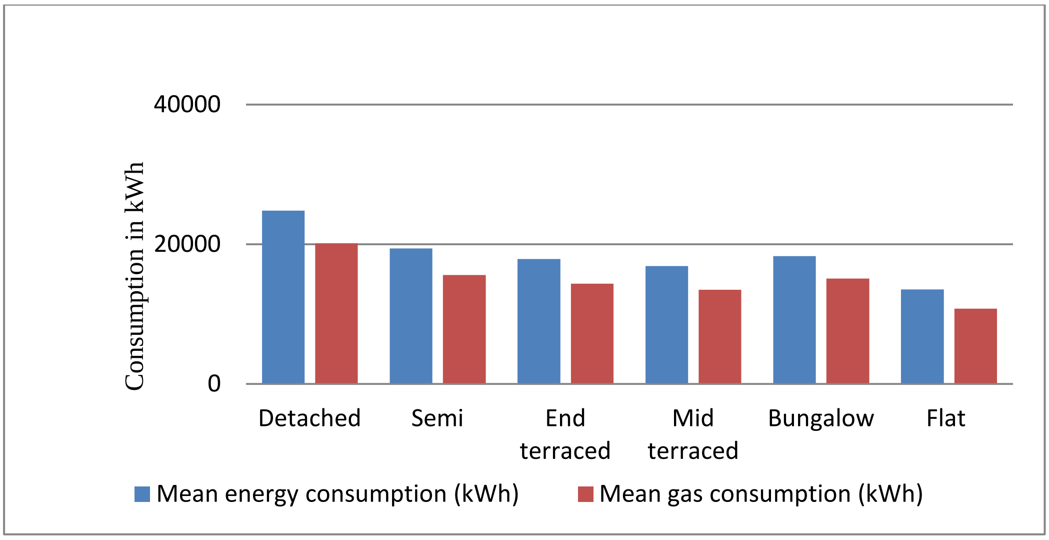
As discussed in the previous section, if the treated and the control groups are analogous across the covariates, the matched difference-in-differences estimation achieves high internal validity**,** an instrument of reflecting the extent to which a causality effect is justified. For this reason, a comprehensive data framework which tracks energy efficiency features, physical building characteristics and actual energy consumption of dwellings both with and without recorded installations of energy efficiency measures is required. An important building block for compiling such databases is the recently released UK`s National Energy Efficiency Data-framework (NEED) which comprises of annualised electricity and gas consumption meter readings obtained from Xoserve, a company managing financial transactions between the gas transporters, as well as readings obtained from groups of independent gas transporters. These meter readings are then weather-corrected using historic and forecasts from the Met Office and are aligned with information on the specific location of the meters. Annual data between 2008 and 2012 is used in this study. More importantly, NEED draws together information on energy efficiency measures installed in dwellings from the Homes Energy Efficiency Database (HEED) and information on physical property characteristics obtained from the Valuation Office Agency (VOA). HEED is a national database which tracks the energy efficiency characteristics of the UK's housing stock and records the uptake of energy efficiency measures across the country. VOA, on the other hand, is responsible for allocating all properties in the UK to the appropriate Council Tax band. It maintains a property database covering information on the age of a dwelling, property type and floor area. The address information in each of these data sources is used to combine them into one comprehensive database by assigning a unique property reference number to each record.

The unmatched sample used in this study is made up of approximately three million properties created using random sampling of residential properties in England and Wales. This sample contains valid records defined as properties with electricity consumption value between 100 and 25,000 kWh and gas consumption value between 3000 and 50,000 kWh. Electricity and gas consumption of the majority of households in the UK falls within these thresholds. Outliers are excluded to minimise the risks of including invalid consumption data or records from non-domestic properties. Similar to the DECC study (2014), estimated meter readings and dwellings with unreasonable changes in gas and electricity consumptions are also excluded from the sample. Unreasonable changes are defined as annual changes in gas or electricity consumption of over 50% as such deviations are likely to be due to data errors or factors other than the installation of energy efficiency measures. For instance, a large change in gas or total energy consumption is likely to be observed if there is a change in occupants or their circumstances which we cannot control for given the data available. The final integrated sample is used to set out the matched difference-in-differences methodology. That is, estimating the changes in gas and total energy consumption following observed installation of energy efficiency measures in the dwelling relative to a comparable control group of properties. Consistent with previous ex-post analysis (Hamilton et al, 2013 and Wyatt 2013), a retrospective treated-control method is adopted by assigning dwellings to the treatment group if they had undergone one or more energy efficiency improvements in 2011 and to the control group if they had no record of installation under the CERT and/ or CESP. However, dwellings in the control group may include those with insulations installed by the homeowner themselves or dwellings which had their installation when built. A separate control group is created for each measure and all criteria applied to the treated group are also applied to the control group, except the installation of the energy efficiency measure being analysed. Table 1 displays summary statistics for the sample. It gives the breakdown of annual average gas and energy consumption in kWh for the treated dwellings known to have installed one or more energy efficiency measures in 2011 (intervention year) and for the ones in the control group with no record of energy efficiency measures installed through CERT and/or CESP. For instance in Model 1, mean gas and energy consumption is shown to be higher in 2010 (pre-intervention) relative to 2012 (post-intervention) for both the treated and control groups. A close inspection of Model 1 reveals that the treated group had a higher gas and energy consumption in 2010 but that the fall in gas and energy consumption after the intervention (installation of cavity wall insulation) is larger for treated dwellings compared to the dwellings in the control group. A similar trend is observed in the other models of Table 1.

Table 1: Descriptive statistics

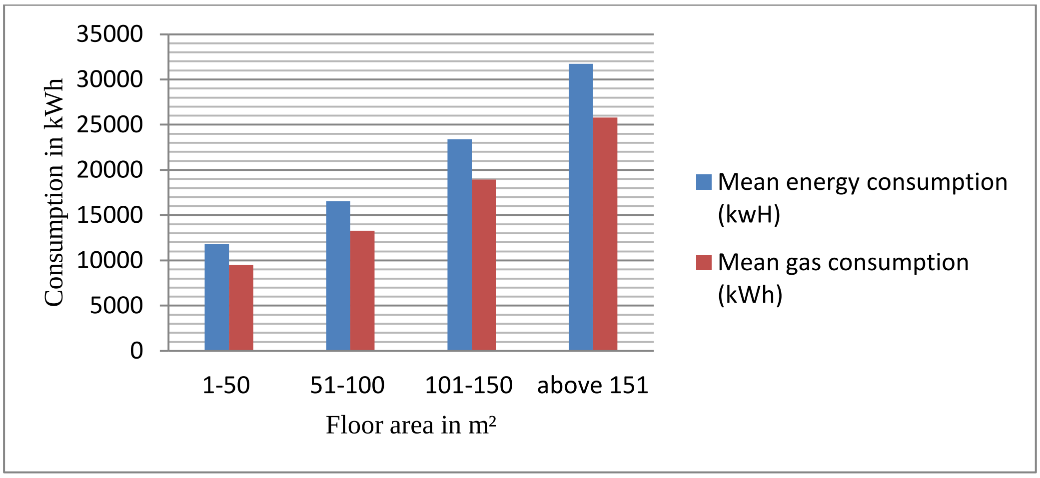
| | Mean Gas use (kWh/yr) | | Mean Energy use (kWh/yr) | |
|---|---|---|---|---|
| | **Treated** | **Control** | **Treated** | **Control** |
| **Model 1: Cavity Wall insulation** | | | | |
| 2010 | 16,279 | 15,902 | 20,022 | 19,709 |
| 2012 | 13,551 | 14,863 | 17,212 | 18,590 |
| Sample size | 36,362 | 1,214,385 | 36,362 | 1,214,385 |
| **Model 2: Loft insulation** | | | | |
| 2010 | 15,900 | 15,914 | 19,462 | 19,730 |
| 2012 | 13,959 | 14,866 | 17,487 | 18,600 |
| Sample size | 56,555 | 1,194,192 | 56,555 | 1,194,192 |
| **Model 3: New boiler** | | | | |
| 2010 | 16,043 | 15,903 | 19,704 | 19,719 |
| 2012 | 14,082 | 14,865 | 17,791 | 18,591 |
| Sample size | 64,245 | 1,186,502 | 64,245 | 1,186,502 |
| **Model 4: Cavity wall + loft insulations** | | | | |
| 2010 | 16,168 | 15,910 | 19,745 | 19,721 |
| 2012 | 13,198 | 14,885 | 16,730 | 18,618 |
| Sample size | 15,313 | 1,173,143 | 15,313 | 1,173,143 |
| **Model 5: Cavity wall insulation + boiler** | | | | |
| 2010 | 16,364 | 15,896 | 19,866 | 19,710 |
| 2012 | 12,884 | 14,901 | 16,505 | 18,628 |
| Sample size | 3,263 | 1,153,403 | 3,263 | 1,153,403 |
| **Model 6: Loft insulation + boiler** | | | | |
| 2010 | 15,891 | 15,911 | 19,264 | 19,729 |
| 2012 | 13,153 | 14,902 | 16,616 | 18,636 |
| Sample size | 5,274 | 1,135,221 | 5,274 | 1,135,221 |
| **Model 7: Cavity wall & loft insulation + boiler** | | | | |
| 2010 | 16,180 | 15,899 | 19,467 | 19,721 |
| 2012 | 12,601 | 14,920 | 16,070 | 18,654 |
| Sample size | 1,489 | 1,115,946 | 1,489 | 1,115,946 |

To control for confounding factors of energy consumption, we match dwellings undergoing energy efficiency measures with comparable dwellings on the basis of property type, size and age as well as region. As shown in Figure 1 detached homes consume the largest amount of gas and total energy and flats consume the least.  Consistent with Wyatt (2013) findings, bungalows and semi-detached homes exhibit similar gas and total energy consumption levels, perhaps unsurprisingly as these property types are likely to be comparable in floor areas.



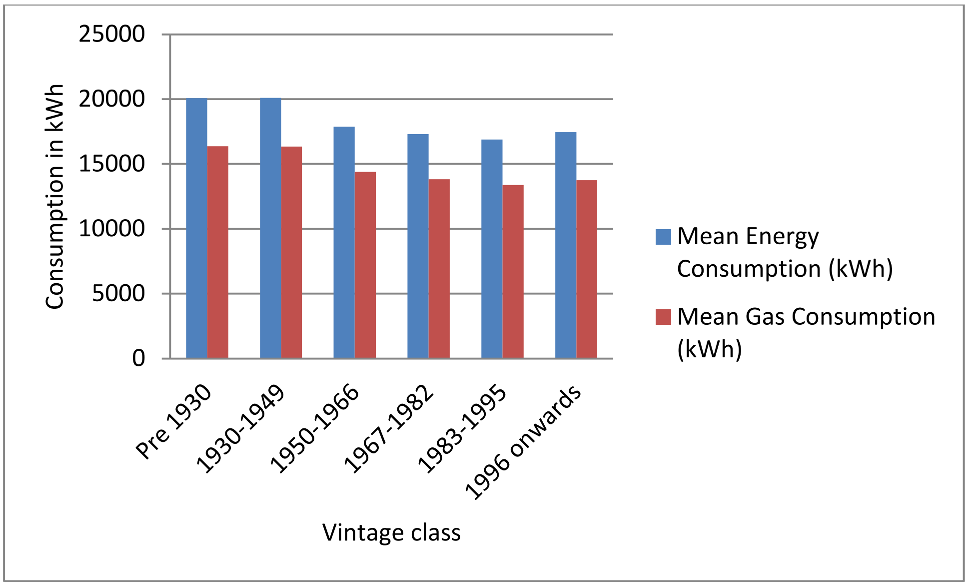

.Figure 1: Average annual gas and total energy consumption in kWh by property type for dwellings in the sample (n=3 million, 2008-12).

Similarly in figure 2, average gas and total energy consumption appears to increase with the size of a property, suggesting that larger homes are more likely to require more energy to heat.



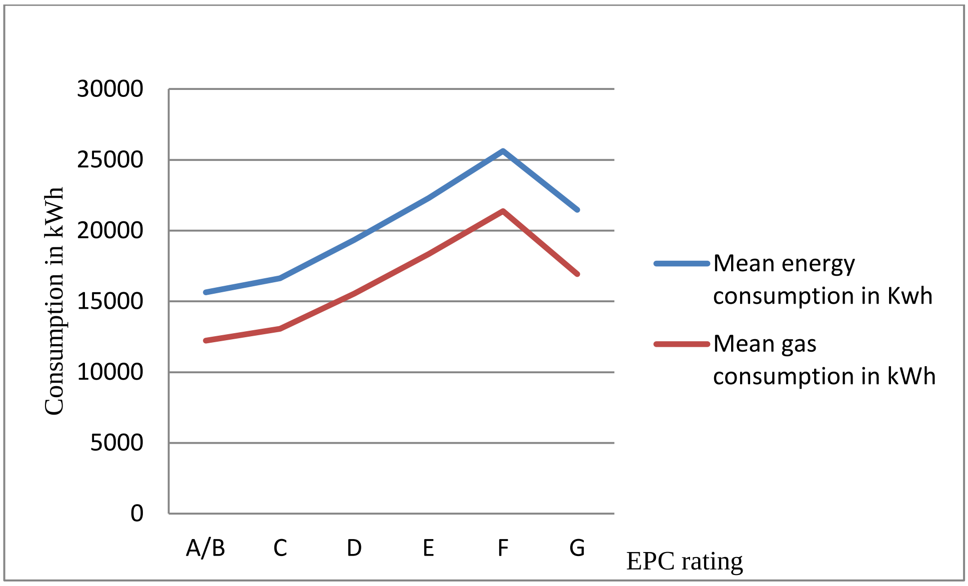

.Figure 2: Average annual gas and total energy consumption in kWh by floor size for dwellings in the sample

Newer properties on the other hand, are shown to consume less gas and total energy than older properties. In figure 3, with decreasing building vintage, there is a corresponding reduction in gas and total energy consumption. This could be explained by the lower level of fabric insulation found in older homes leading to lower energy efficiency relative to well insulated modern homes (S.H. Hong et al 2006). Figure 3 shows that properties constructed before 1930 in the sample have similar consumption levels as properties constructed between 1930 and 1949. A plausible explanation for this is that properties constructed prior to 1930 are typically Victorian and Edwardian houses which are likely to have undergone structural renovations affecting their energy consumption (Wyatt 2013 and Zhao & Magoulès 2012).




.Figure 3: Average annual gas and total energy consumption in kWh by vintage class for dwelling in the sample.

Furthermore, in addition to matching observations on the basis of building characteristics, we control for the Energy Performance Certificate (EPC) rating of the dwellings. As shown in Figure 4, gas and total energy consumption prior to the energy efficiency upgrade appear to vary with the EPC ratings. With increasing ratings, there is a corresponding decrease in the gas and total energy consumption, except for properties with the least energy efficiency rating (G).




.Figure 4: Average gas and total energy consumption in kWh by EPC rating for dwellings in the sample prior to energy efficiency upgrade.

**5. Results**

To establish a causal relationship between installation of energy efficiency measure(s) and gas and total energy consumption, observed differences in gas and total energy consumption of the treated dwellings between 2010 (pre-treatment) and 2012 (post-treatment) are estimated by using trends in the control group with similar characteristics as the baseline. Table 2 presents summary of the difference-in-differences regression estimating the percentage change in annual gas consumption given the installation of a single energy efficiency measure relative to a comparator group of properties with no record of ever having had considered energy efficiency measures installed. Model 1a displays the effect of installing cavity wall insulation alone; Model 2a shows the effect of loft insulation and Model 3a the effect of installing a new efficient boiler in the dwelling. A statistical significant impact at an acceptable level of confidence is observed for all three energy efficiency measures considered. The first row of Table 2 indicates that gas consumption in treated dwellings is higher than for dwellings in the control group in all three models. This row is captured by $\beta_1$ in the econometric model of 3.2. The next row presents the change in gas consumption in both treated dwellings and in the ones in the control between the two periods (2010 and 2012). A reduction of about 5-7 % in gas consumption is observed between 2010 and 2012 depending on the specification. This row is represented by $\beta_2$ in the econometric model. Finally, the last row of table 1 presents the estimation of the difference-in-differences coefficient, $\beta_3$ in the econometric model. That is, the differential effect of installing single energy efficiency measure on gas consumption. The most effective energy efficiency measure is shown to be cavity wall insulation with an observed change of 10.5% gas consumption in the year after installation. This is followed by the installation of a new boiler, found to reduce annual gas consumption by 4.1%. Loft insulation is the least effective retrofit measure among the three energy efficiency measures considered with an estimated reduction in gas consumption of 3.1% in the year following installation.

Table 2: The impact of a single energy efficiency measure on annual mean gas consumption

| **Dep. variable: Log( gas use in kWh/yr)** | **Cavity Wall insulation**<br>(1a) | **Loft insulation**<br>(2a) | **New boiler**<br>(3a) |
|---|---|---|---|
| Treated | 0.0536***<br>(-11.21) | 0.0156***<br>(-4.2) | 0.0186***<br>(-5.89) |
| Post treatment | -0.0534***<br>(-11.19) | -0.0647***<br>(-17.52) | -0.0669***<br>(-21.6) |
| Treated*Post treatment (diff-in-diff) | -0.105***<br>(-15.76) | -0.0305***<br>(-5.85) | -0.0407***<br>(-9.30) |
| N | 78,380 | 151,250 | 231,460 |

*t-statistics are indicated in brackets. Significance at the 0.10, 0.05, and 0.01 levels are marked *, **, and *** respectively.*

Table 3, presents the difference-in-differences estimation of the impact of installing a combination of the energy efficiency measures considered on gas consumption. The largest reduction in gas consumption is achieved by combining a cavity wall insulation with a new efficient boiler; an average annual reduction of about 13.3% in the year following installations. This is followed by a 12.5% reduction in annual gas consumption for dwellings with both cavity wall insulation and loft insulation. Next, dwellings with all energy efficiency measures considered installed are observed to have 11.9% lower gas consumption in the year following installations. Likewise, the least effective combination is achieved by a combination of loft insulation and a new efficient boiler, with a 7.7 % reduction in gas consumption. Interestingly, this reduction is lower than the one observed for dwellings with cavity wall insulation alone.

Table 3: The impact of a combination energy efficiency measure on annual mean gas consumption

| **Dep. variable: Log( gas use in kWh/yr)** | **Cavity wall & loft insulations** | **Cavity Wall insulation & new boiler** | **Loft insulation & new boiler** | **Cavity wall insulation, loft insulation & new boiler** |
|---|---|---|---|---|
| | **(4a)** | **(5a)** | **(6a)** | **(7a)** |
| Treated | 0.0617*** | 0.0648*** | 0.0371** | 0.05671*** |
| | (-10.71) | (-3.77) | (-3.00) | (2.87) |
| Post treatment | -0.0696*** | -0.0688*** | -0.0631*** | -0.1026*** |
| | (-12.07) | (-4.11) | (-5.24) | (-5.47) |
| Treated*Post treatment (diff-in-diff) | -0.125*** | -0.133*** | -0.0765*** | -0.1194*** |
| | (-15.40) | (-5.65) | (-4.51) | (-4.53) |
| | 56,564 | 7,322 | 15,350 | 6,162 |

*t-statistics are indicated in brackets. Significance at the 0.10, 0.05, and 0.01 levels are marked *, **, and *** respectively.*

Table 4 presents adjusted coefficients, when the EPC ratings of the dwellings prior to the treatment are controlled for. As show in the table, there are no sizable differences in the figures reported and the ones in Tables 2 and 3. Yet, controlling for EPC ratings adds a new insight to the analysis. Particularly, annual gas consumption is found to vary with the EPC ratings of dwellings. For instance, those dwellings with excellent to good EPC ratings (A/B or C) are found to have lower gas consumption relative to average EPC rated dwellings (D). On contrary, below average E and F rated dwellings are found to consumer more gas relative to average rated dwellings. So far this is intuitive. However, there are two interesting findings in Table 4. Firstly, although some of the coefficients of A/B rating are insignificant, it is shown that C-rated dwellings appear to consume less energy than A/B rated Dwellings. Secondly, despite the fact that only the coefficient of model 4b is marginally significant, there seems to be a clear indication that those dwellings in the worst EPC classifications (G) may consume less gas than initially anticipated. These findings are consistent with the descriptive statistics of Figure 4.

Table 4: The impact of energy efficiency measure(s) on annual mean gas consumption adjusted for EC rating of dwellings

| **Dep. variable: Log( gas use in kWh/yr)** | **Cavity Wall insulation**<br>**(1b)** | **Loft insulation**<br>**2(b)** | **New boiler**<br>**(3b)** | **Cavity wall & loft insulations**<br>**(4b)** | **Cavity Wall insulation & new boiler**<br>**(5b)** | **Loft insulation & new boiler**<br>**(6b)** | **Cavity wall insulation, loft insulation & new boiler**<br>**(7b)** |
|---|---|---|---|---|---|---|---|
| Treated | 0.048*** | 0.0157*** | 0.0199*** | 0.0521*** | 0.0432* | 0.0231 | 0.0290 |
| | (10.22) | (4.38) | (6.5) | (9.21) | (2.55) | (1.91) | (1.48) |
| Post treatment | -0.053*** | -0.0659*** | -0.0675*** | -0.0679*** | -0.0689** | -0.0702*** | -0.1022*** |
| | (-11.39) | (-18.34) | (-22.51) | (-12.06) | (-4.21) | (-6.02) | (-5.55) |
| Treated*Post treatment (diff-in-diff) | -0.106*** | -0.0293*** | -0.0401*** | -0.1267*** | -0.1339*** | -0.0694* | -0.1201** |
| | (-16.13) | (-5.79) | (-9.43) | (-15.95) | (-5.79) | (-4.22) | (-4.62) |
| Control for EPC | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| EPC = D vs: | | | | | | | |
| A/B | -0.085** | -0.114*** | -0.142*** | -0.0171 | -0.1034 | -0.1163* | 0.0776 |
| | (-4.34) | (-7.15) | (-11.01) | (-0.82) | (-1.38) | (-2.65) | (1.39) |
| C | -0.140*** | -0.176*** | -0.175*** | -0.1516*** | -0.1456*** | -0.1980*** | -0.1163*** |
| | (-32.75) | -49.32 | (-62.64) | (-27.78) | (-9.44) | (-17.34) | (-6.25) |
| E | 0.112*** | 0.152*** | 0.161*** | 0.1184*** | 0.0987*** | 0.1454*** | 0.1339*** |
| | (-26.88) | (50.66) | 61.99 | (24.59) | (7.07) | (14.84) | (8.82) |
| F | 0.171*** | 0.28*** | 0.29*** | 0.1726*** | 0.1926*** | 0.2961*** | 0.1213* |
| | (-13.96) | (40.12) | (51.18) | (12.54) | (6.09) | (14.71) | (3.56) |
| G | -0.089 | -0.013 | 0.016 | -0.1470* | 0.0650 | -0.1806 | -0.0245 |
| | (-1.29) | (-0.33) | (0.03) | (-2.15) | (0.32) | (-1.46) | (-0.16) |
| N | 78,380 | 151,250 | 231,460 | 56,564 | 7,322 | 15,350 | 6162 |

*t-statistics are indicated in brackets. Significance at the 0.10, 0.05, and 0.01 levels are marked *, **, and *** respectively.*

In Table 5, we present the difference-in-differences estimation of the impact of a single energy efficiency installation on average total energy consumption. The first row of Table 5 shows the difference between the treated dwellings and the ones in the control, with treated dwellings observed to have higher energy consumption prior to undergoing the upgrade in Models 8a and 9a. It should be noted that no such difference can be observed in model 10a as the coefficient is insignificant. On the other hand, in the second row the coefficient capturing the change in energy consumption between pre – (2010) and post- (2012) periods is significant in all three models of Table 5.  A 4-6% drop in energy consumption is observed for dwellings in both groups depending on the specification. More importantly, as shown in the last row of Table 5, the differential effect of each energy efficiency measure is found to be significant at an acceptable level of confidence. Particularly, Cavity wall insulation is found to reduce energy consumption by approximately 8%, loft insulation by about 1.8% and a new boiler installation by 5.2% relative to dwelling with no record of installation.

Table 5: The impact of a single energy efficiency measure on annual mean energy consumption

| **Dep. variable: Log( Energy use in kWh/yr)** | **Cavity wall insulation (8a)** | **Loft insulation (9a)** | **New Boiler (10a)** |
|---|---|---|---|
| Treated | 0.0445*** | -0.0086* | -0.0040 |
| | (-9.79) | (-2.52) | (-1.47) |
| Post treatment | -0.0421*** | -0.0566*** | -0.0489*** |
| | (-9.20) | (-16.51) | (-18.53) |
| Treated*Post treatment (diff-in-diff) | -0.0800*** | -0.0184*** | -0.0517*** |
| | (-12.66) | (-3.85) | (-13.83) |
| N | 104,139 | 183,598 | 332,231 |

*t-statistics are indicated in brackets. Significance at the 0.10, 0.05, and 0.01 levels are marked *, **, and *** respectively.*

Table 6 displays the difference-in-differences estimation of the impact of a combination of energy efficiency improvements on average total energy consumption. Installations of cavity wall insulation and a new efficient boiler during the same year are found to reduce energy consumption by 13.5%.  This is followed by installing all three measures considered in the same year, found to reduce energy consumption by approximately 10.5%. Next, installing both cavity wall insulation and loft insulation is found to reduce energy consumption by 7.2%. Finally, installation of loft insulation and a new efficient boiler is found to reduce energy consumption by 5.2% in the year following installation. Consistent with the results for gas consumption in Table 3, savings realised under a combination of cavity wall insulation and loft insulation as well as loft insulation and a new efficient boiler are lower than energy savings realised by installing cavity wall insulation on its own.

Table 6: The impact of a combination energy efficiency measure on annual mean energy use

| Dep. variable: Log( Energy use in kWh/yr) | Cavity wall & loft insulation (11a) | Cavity Wall insulation & boiler (12a) | Loft insulation & boiler (13a) | Cavity wall insulation , loft insulation & boiler (14a) |
|---|---|---|---|---|
| Treated | 0.0132* | 0.0176 | -0.0300** | -0.0177 |
| | (-2.41) | (-1.12) | (-2.68) | (-1.02) |
| Post treatment | -0.0756*** | -0.0279 | -0.0686*** | -0.0847*** |
| | (-13.77) | (-1.82) | (-6.34) | (-5.04) |
| Treated*Post treatment (diff-in-diff) | -0.0724*** | -0.135*** | -0.0517*** | -0.105*** |
| | (-9.51) | (-6.34) | (-3.41) | (-4.46) |
| N | 64,696 | 8,912 | 18,114 | 7,055 |

t statistics in parentheses * p<0.05, **p<0.01, *** p<0.001

Table 7 shows the difference-in-differences coefficients adjusted for the EPC ratings of the dwellings prior to the treatment. Again, there are no sizable differences in these coefficients and the ones in Tables 5 and 6. Yet, the impact on total energy consumption differs depending on whether a single energy efficiency measure or a combination of measures is installed in the property. When a single energy efficiency measure is installed, dwellings in the highest EPC classification of A/B are found to have approximately 40% lower total energy consumption relative to average D-rated dwellings. Next, C-rated dwellings are found to have about 22% lower total energy consumption in comparison to D-rated Dwellings. Depending on the specification, below average rated dwellings in the E and F classifications are found to consume between 8-13% more in total energy relative to D-rated dwellings. Interestingly, the worst G-rated dwellings are found to consume between 13-16% less in total energy in comparison to D-rated dwellings, depending on the specification. Considering the impact of combining different measures, similar observations are made. Particularly, G-rated dwellings appear to consume less energy than anticipated given their EPC rating.

Table 7: The impact of energy efficiency measure(s) on annual mean total energy consumption adjusted for EC rating of dwellings

| **Dep. variable: Log( total energy use in kWh/yr)** | **Cavity Wall insulation** | **Loft insulation** | **New boiler** | **Cavity wall & loft insulations** | **Cavity Wall insulation & new boiler** | **Loft insulation & new boiler** | **Cavity wall insulation, loft insulation & new boiler** |
|---|---|---|---|---|---|---|---|
| | **(8b)** | **(9b)** | **(10b)** | **(11b)** | **(12b)** | **(13b)** | **(14b)** |
| **Treated** | 0.0418*** | 0.0084* | 0.0092** | 0.0084 | 0.0139 | -0.0265* | -0.0254 |
| | (-9.44) | (-2.6) | (3.53) | (-1.55) | (-0.89) | (-2.41) | (-1.46) |
| **Post treatment** | -0.043*** | -0.0559*** | -0.0495*** | -0.0762*** | -0.0303* | -0.066*** | -0.085*** |
| | (-9.68) | (-16.24) | (-19.37) | (-14.12) | (-2.01) | (-6.22) | (-5.13) |
| **Treated*Post treatment (diff-in-diff)** | -0.0795*** | -0.0172* | -0.052*** | -0.072*** | -0.1326*** | -0.0536** | -0.1034** |
| | (-12.92) | (-2.96) | (-14.39) | (-9.57) | (-6.31) | (-3.6) | (-4.41) |
| **Control for EPC** | | | | | | | |
| EPC = D vs: | | | | | | | |
| A/B | -0.4064*** | -0.4047*** | -0.4082*** | -0.1494*** | -0.2297** | -0.1424** | 0.002 |
| | (-27.29) | (-35.19) | (-49.82) | (-6.04) | (-3.64) | (-3.34) | (-0.03) |
| C | -0.2233*** | -0.2342*** | -0.2254*** | -0.1494*** | -0.1769*** | -0.1748*** | -0.1047*** |
| | (-57.8) | (-65.65) | (-99.85) | (-29.12) | (-12.68) | (-16.45) | (-6.03) |
| E | 0.0789*** | 0.1203*** | 0.1307*** | 0.0746*** | 0.0888*** | 0.1176*** | 0.0945*** |
| | (-19.88) | (-68.76) | (-57.02) | (-16.42) | (-7.07) | (-13.47) | (-6.91) |
| F | -0.0125 | 0.1188*** | 0.127*** | 0.0101 | 0.0703* | 0.0995*** | 0.0154 |
| | (-1.4) | (-23.44) | (-28.56) | (-0.95) | (-2.75) | (-6.04) | (-0.62) |
| G | -0.1607*** | -0.1284*** | -0.1385*** | -0.202*** | -0.1777** | -0.1826*** | -0.2004** |
| | (-8.34) | (-13.16) | (-14.78) | (-8.61) | (-3.22) | (-5.33) | (-3.84) |
| N | 104,139 | 183,598 | 332,231 | 64,696 | 8,912 | 18,114 | 7055 |

**6. Discussion**

The results presented in this study suggest that considerable energy savings are statistically observed for dwellings with energy efficiency measures installed through the CERT and the CESP schemes. Considering the impact of installing a single energy efficiency measure, results reported in this study are aligned with findings from previous analysis of ex-post effectiveness of energy efficiency measures in the UK, (Hong et al, 2006; Hamilton et al, 2013, Wyatt, 2013 and DECC,2014). However, an interesting and divergent insight is found when more than one energy efficiency installation is undertaken. Particularly, we find mostly sub-additive gains from combining different energy efficiency measures. Though, combining two measures (cavity wall insulation and a new efficient boiler) is found to be more effective than installing all three energy efficiency measures considered. Additionally, installing cavity wall insulation on its own is found to be more effective than combining loft insulation and a new efficient boiler. These findings are less straightforward and appear to suggest existence of the "prebound effect" discussed by Sunikka-Blank and Galvin (2012). The prebound effect refers to the situation where energy consumption prior to energy efficiency installation is lower than the calculated figure for pre-installation consumption, based on the building's physical characteristics. This can lead to overestimation of the amount of energy saved when combining two or more energy efficiency measures, as householders cannot save energy that was not already being consumed (Rosenow & Galvin, 2013). The NEED data framework used in this study does not allow for estimation of the prebound effect. However, as shown in Tables 4 and 7, households inhabiting dwellings with the lowest energy performance rating (G) prior to the energy efficiency installations are found to consume, on average, less energy than households inhabiting average EPC rated dwellings (D). This may imply a prebound effect in that households living in poorly insulated homes in the sample seem to have had low energy consumption prior to the energy efficiency installations and hence installing, for example, three different energy efficiency measures may not have led to large energy savings for them. The objectives of the CERT and the CESP also imply that the least energy efficient dwellings in the sample were also likely to have received several energy efficiency installations in order to raise their energy efficiency to an acceptable level. For this reason, the CEM matching procedure applied to the data prior to the difference-in-differences estimation, arguably, enabled us to re-adjust energy savings by conceivably capturing the prebound effect. For instance, a mean reduction in gas consumption of 11.9% is found following installation of cavity wall insulation, loft insulation and a new efficient boiler in contrast to a 17.1 % reduction in gas consumption found in the DECC report (2014). While this is not conclusive, some coefficients of A/B-rated dwellings were also found to have higher gas consumption relative to C-rated dwellings.

A data framework without flaws is a rarity; the National Energy Efficiency Data Framework (NEED) used in this study is based on a rich, well-structured and reliable data of good quality, enabling a robust estimation of ex-post effectiveness of energy efficiency measures. An important caveat is that some measures not supported by CERT or CESP could well have been installed by the control group which could explain the higher effectiveness of some of the measures. For instance, a DIY loft insulation undertaken by the control group or a replacement of a broken boiler without support from the schemes could explain the higher savings achieved by installing cavity wall insulation alone in comparison to a combination of cavity wall insulation and loft insulation. More importantly, despite the fact that some of the variations in gas and total energy consumption appear to be explained by building characteristics contained within NEED, there are other factors to consider such as performance of heating systems, building construction, and appliances. However, important factors such as household composition, income profiles, age etc. are implicitly controlled for by the use of the difference-in-differences estimation in this study and add robustness to the results.

## 7. Conclusion

This study presents an econometric analysis of the ex-post effectiveness of energy supplier obligation programs (CERT and CESP) implemented in the UK. Access to a new comprehensive data source made available through the National Energy Efficiency Data-framework (NEED) allowed us to adopt a convincing matched difference-in-differences estimation. The results suggest that a significant drop in gas and energy consumption is statistically observed following installation of different energy efficiency measures. Particularly, cavity wall insulation, loft insulation and installation of a new efficient boiler are all found to reduce gas and total energy consumption when installed separately or in different combination packages. The single most effective energy efficiency measure when installed alone is found to be cavity wall insulation, reducing annual gas consumption by 10.5% and annual total energy consumption by 8% relative to a comparable control group of dwellings with no record of considered energy efficiency measures. Next, reductions of 4.1% in gas and 5.2% in total energy consumption are observed following installation of a new efficient boiler on its own. Loft insulation is found to be the least effective energy efficiency measure when installed alone with a 3.1% reduction in gas and a 1.8% reduction in total energy consumption in the year following installation. Turning to different combination of these measures, dwellings retrofitted with both cavity wall insulation and a new efficient boiler experience the largest reductions in annual gas and energy consumption of 13.3 % and 13.5%, respectively. This is followed by a mean annual reduction of 10.5% or 11.9% in gas and total energy consumption for dwellings with all three energy efficiency measures installed in the same year. Lastly, the least effective combination is loft insulation and a new efficient boiler with 7.7% reduction in gas consumption and 5.2% reduction in total energy consumption in the year following installations. Nevertheless, the impact of a combining cavity wall insulation and loft insulation is inconclusive. A mean reduction in gas consumption of 12.5% is found, making it the second most effective combination and a reduction in total energy consumption of 7%, making it the second least effective combination. Descriptive statistics also reveal that dwelling type, age and size appear to vary strongly with gas and energy consumption, justifying their inclusion in the matching procedure prior to the estimation.

The above findings have wider policy implications. Particularly, policy measures focusing on the physical and technical structure of dwellings as determinants of energy consumption are justified in this paper. Equally, behavioural aspects such as the prebound effect, often ignored in the analyses of household energy use, are found to be important.

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