# Policy implications for the performance gap of low-carbon building technologies

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## Abstract

It is widely-recognised that the actual impact of low-carbon technologies is often lower than predicted by models alone, a phenomenon which has been coined the “performance gap”. Still, in many instances, estimates of both energy savings and renewable energy generation in domestic buildings continue to rely on engineering models and building energy simulations rather than approaches that are based on measured parameters. And there are good reasons for this - evaluation budgets are often limited, with policy makers needing timely results for reporting purposes, whereas high quality measurement can be complex and is often associated with a substantial time lag. . Much of the existing literature on the performance gap focuses on energy efficiency and is concerned with the quantification of the scale of the performance gap. This article adds to this body of evidence by drawing retrospectively on a range of grey literature evaluations of low-carbon technologies (including energy efficiency measures, renewable heat, and renewable electricity) in the UK household sector done by Energy Saving Trust in collaboration with a range of private and public partners. The paper focuses not only on the quantification of the performance gap but also qualitative factors often overlooked, such as installation issues or installer/user behaviour.  The article concludes by recommending policy changes including the development of evaluation standards, the experimentation with pay-for-performance programmes, ensuring that installation standards for low-carbon technologies are being enforced, and taking reasonable steps to ensuring that end users are able to use any new technology effectively.

**Keywords**: performance gap; energy efficiency; field trial; heat pump; boiler; wind turbine; solar thermal; water; energy; sustainability; renewables; retrofit

# Introduction

Across the globe, efforts are under way to reduce the energy consumption of buildings by increasing the amount of renewable electricity generated on-site and decarbonising heating and cooling systems. For example, in the European Union (EU), the Energy Efficiency Directive is a key driver for improving the energy efficiency of the existing residential building stock (Rosenow et al., 2016). Much of the discussion in the EU has focused on the energy efficiency targets and the types of policies chosen by Member States (Bertoldi et al. 2015; Forster et al. 2016). Going forward, a robust evaluation, monitoring and verification system will need to be developed in all Member States to ensure that the expected impact of the policies implemented will materialise (Schlomann et al. 2015). This requires not only a sophisticated reporting framework, but also the ability to monitor the achieved impacts with a reasonable degree of certainty to ensure reported carbon and energy savings are realised (Vine et al. 2012). If the impacts of low-carbon technologies are significantly over- or under-estimated it is very difficult to track policy impacts reliably and assess whether or not additional efforts are needed to achieve carbon and energy targets (ibid). Another potential result of poor evaluation and verification leading to false conclusions regarding low carbon technologies is the erosion of public credibility towards these technologies and their ability to deliver energy savings and low-carbon energy (*sensu* the "Cry-Wolf" effect documented in Breznitz, 1984). In many instances, estimates of both energy savings and renewable energy generation in domestic buildings still rely on engineering models and building energy simulations rather than approaches that are based on measured parameters (Wade and Eyre 2015). And there are good reasons for this - measurement is costly and often associated with a substantial time lag (Cooney, 2017), while evaluation budgets are limited and policy makers require timely results for reporting purposes (Vine et al., 2014). However, there is a large body of literature (see Borgstein et al. (2016) and de Wilde (2014) for a detailed literature review) that demonstrates the existence of a performance gap - where the actual measured performance of low-carbon technologies is often lower than predicted by pre-installation modelling . The reasons reported for this are manifold and include poor quality of installation (Bordass, 2004; Bordass et al., 2001; Zero Carbon Hub, 2014), unrealistic manufacturers' specifications of a technology's performance not reflecting in situ conditions (Zero Carbon Hub 2014), unintended user interaction (Branco et al., 2004; Buso et al., 2015; Guerra Santin & Itard, 2012, 2010; Haas et al., 1999; Linden et al., 2006), the use of incorrect models (de Wilde, 2014), and inaccurate assumptions on the ex-ante situation (Rosenow & Galvin, 2013; Sunikka-Blank & Galvin, 2012). The extent to which these factors are taken into account in policy evaluation varies across different geographies (see for example Rosenow and Galvin 2013 who compare evaluation practices in Germany and the UK). Evaluators are often contracted by the same authorities responsible for delivering a specific sustainable energy programme which can result in a structural bias towards overly optimistic results (this has been well-documented in other policy areas such as public accounting, see for example Brown and Klerman 2012) and thus a tendency to ignore the performance gap in evaluations.

This paper is a retrospective summary of six of the most recent grey literature evaluations of low-carbon technologies in the household sector carried out by a range of consortia. These consortia are generally comprised of public and private organisations including Energy Saving Trust (EST), a British organization devoted to promoting energy efficiency, energy conservation, and the sustainable use of energy. The other members of the consortia are listed in the acknowledgements. These fields trials are not easily found by academics, having never been published in the peer-reviewed literature. This review rectifies this issue, ensuring that their contribution to our understanding of the performance gap is synthesised and assimilated into current theory. These data cover a range of technologies including energy efficiency measures, renewable heat, and renewable electricity, all of which are still in circulation and use today. Most of the existing literature on the performance gap focuses on energy efficiency and is concerned with the quantification of the scale of the performance gap, although there are now some contributions focusing also on renewable energy (Boyd & Schweber, 2018; Frances & Stevenson, 2018). This paper has a wide scope that includes renewable energy technologies as well as energy efficiency improvements and examines not only on the quantification of the performance gap but also qualitative factors often overlooked. Finally, energy efficiency policy in the United Kingdom has been neglected recently (Eyre et al. 2016), with a severe policy vacuum being left due to the failure of the Green Deal, a flagship policy intended to deliver energy efficiency retrofits (Rosenow & Eyre, 2016). In this vacuum it is easy to find UK examples providing estimates of a performance gap in energy savings from single measures and/or combinations of those in domestic buildings with some based on actual measured data (Adan and Fuerst 2016; Gupta et al. 2015; Gupta and Gregg 2016; Hamilton et al., 2013; Hong et al., 2006; Johnston et al., 2015; 2016; Wyatt 2013; Zero Carbon Hub 2014) and others on modelled data (Loucari et al., 2016). Reviewing the literature, Adan & Fuerst (2016) conclude that “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.” Whilst there are uncertainties around the data, the current literature clearly suggests the existence of a performance gap, finding that in some cases the performance gap exceeds 100% (Johnston et al., 2015, 2016; Zero Carbon Hub 2014). In short, the wealth of field trials presented here highlights that that performance gap is an ongoing problem in the UK, and should create a sense of urgency amongst the relevant policy makers.

In summary, this paper aims to: (1) review some of the existing causes of the performance gap; (2) bring a range of field trials published as grey literature in to the academic literature, (3) synthesize the insights from these field trials in an analysis of why the performance gap is a recurring problem, (4) highlight the ubiquity of the performance gap in UK energy efficiency activities; and (5) make preliminary suggestions for the policy steps that can be taken by the UK and other countries to address the issue.

## Understanding the performance gap

The performance gap can be defined as the difference between the predicted and observed energy performance (Borgstein et al. 2016; Gram-Hanssen and Georg 2018; Lowe et al. 2017). This is usually discussed in the literature with regard to energy use of the whole building rather than specific elements (de Wilde 2014) and mostly in the context of building fabric improvements, although more recently research on the performance gap related to on-site renewable energy technologies has been published (e.g. Boyd and Schweber 2018). With a focus on the construction of new buildings, de Wilde (2014) carries out a comprehensive literature review and analyses the root causes of the performance gap and groups them into three categories including:

- *causes linked to the design stage* including inaccurate modelling of expected performance (de Wilde, 2014; Rosenow & Galvin, 2013; Sunikka-Blank & Galvin, 2012).
- *causes linked to the construction stage* such as poor construction of buildings and/ or installation of specific measures (Bordass, 2004; Bordass et al., 2001; Zero Carbon Hub, 2014); and

*causes linked to the operational stage* including inappropriate operation of technologies, and unintended user interaction (Branco et al., 2004; Buso et al., 2015; Guerra Santin & Itard, 2012, 2010; Haas et al., 1999; Linden et al., 2006).It is contested which of the different types of factors is the most critical and some scholars have argued that a contextual analysis of expectations and practices regarding energy performance is much needed (see for example Gram-Hanssen and Georg 2017). Each of the three categories is now discussed in turn.

## Causes linked to the design stage.

Inaccurate modelling of expected performance is a common issue observed in the literature (de Wilde, 2014; Menezes et al., 2012). This can be caused by the model itself, but also the people involved in the modelling (Dwyer, 2013). For example, a common issue with building models is the overestimation of the ex-ante energy consumption based on unrealistic assumptions. This phenomenon that has been coined the ‘prebound effect’, such as when residential building models typically overestimate heating energy consumption prior to an intervention by as much as 30% (Sunikka-Blank & Galvin, 2012). A reason for this is sometimes that the energy performance of the walls of old buildings is underestimated (Hens et al., 2007). This can lead to overestimates of the amount of energy saved through refurbishment, as householders cannot save energy that was not already being consumed prior to the intervention (Rosenow & Galvin, 2013).

## Causes linked to the construction stage.

Even if technologies achieve the expected performance under laboratory conditions there is a range of potential factors that can lead to underperformance at the operational stage. Dependent on the installer's level of training and attention to detail, poor workmanship can result in the inappropriate installation of technology which may hamper performance or even cause operational failure. A good example is cavity wall insulation whereby poor distribution of the insulation can result if the cavity is not carefully inspected for areas blocked off by debris (BRE, 2016). Another example is in photovoltaics, when panels are overshadowed by trees and as a result generate less renewable electricity (Frances & Stevenson, 2018). After the installation of low-carbon technologies regular maintenance is required for some types of technologies. Poor maintenance of technologies can result from insufficient instructions and training (Bordass, 2004), thus potentially leading to additional performance issues. These recurring issues might be addressed by the application of a thorough audit and approval process after the installation, as seen for the success of audits in encouraging the adoption of energy efficiency measures in enterprises across the world (for example, in Germany in Fleiter et al., 2012; Australia in Harris et al., 2000; Nigeria in Kabir et al., 2010; China in Shen et al., 2012; Sweden in Thollander et al., 2007).Currently the performance gap is not addressed appropriately within building industry processes Tuohy and Murphy (2015a). In the UK, work is under way to address this issue, for example through the Soft Landings process, which aims to smooth the transition from the from the construction to occupation stage and feedback of post-occupancy evaluations for future projects (BSRIA, 2014).

## Causes linked to the operational stage.

Unfamiliarity with a new technology and old habits may prevent users from interacting with the technology in the way intended. Many examples of this phenomenon exist, such as in Hong et al. (2006) where people continued to use inefficient single room heaters even after a more efficient heating system was installed, or in households that override modern ventilation systems by ventilating the house through opening windows, with strong consequences for performance (Anderson et al., 2013). A recent study by Zero Carbon Hub (2016) on new mechanical ventilation systems found that out of 13 cases analysed all 13 occupants had turned off their ventilation systems after a while due to noise issues. This results in poorer air quality with potential health implications. Or even more simply, is that when controls are misunderstood users may avoid more energy efficient features in favour of incorrect manual control, such as seen in how householders use programmable thermostats (Meier et al., 2011). Occupancy and the number of occupants in particular is a key factor that is often overlooked, although studies clearly show that the importance of this factor for energy use (Guerra Santin et al., 2009). Recognising the issues set out above, recent research has increasingly focused on the role of the user or the occupant (see for example Gram-Hanssen 2013; Gram-Hanssen and Darby 2018; Wilson et al. 2015) and revealed that most research treats users as a homogeneous and largely passive group. This literature demonstrates that there is considerable user heterogeneity and that an 'install and forget' mentality which has often been applied in the past is deeply problematic.

# Methodology

Amongst their work on energy efficiency and conservation, EST and its partners offer a bespoke verification service, by which manufacturers receive independent evaluation of their product's performance claims. Whilst each service is different, depending on the needs and context of each individual product, the verification process broadly comprises of a replicated field trial where quantitative product performance data (e.g. energy or water use and environmental variables such as temperature) are monitored for 12 months from the installation of the technology/start of the trial and interpreted in combination with contextual information, such as the reported behaviour of users. For analysis, the actual performance (and underlying environmental conditions) monitored as part of these field trials is compared to the modelled performance (and the assumed environmental conditions used therein).

To find relevant studies for this research, EST's internal server was searched for any field trials that that met the following criteria: (1) that the trial examines a technology that is still in use as of 2017; (2) that the trial comprises at least 12 months of monitoring; (3) that the field trial stakeholders have been evaluated qualitatively; and (4) that there was at least some level of replication, a minimum threshold for which was not set. Nine studies were found, of which three were excluded from the final analysis (a retrofit trial which had already been published in Gupta et al. 2015, a solid wall insulation field trial for which there was no reporting done and an exploration of domestic hot water use, for which no metered data was collected; EST, 2015). From this process six of the most recent field trials done by EST and partners were selected., These field trials cross a range of domestic technologies/upgrades (condensing boilers, heat pumps, solar thermal, solid wall insulation and small scale wind turbines) across three utilities (electricity, gas and water). The specific methodologies for each trial are taken from their respective grey publications and given in Table 1. Finally, content analysis was done on the six fields trials to ascertain what they concluded with regard to the presence of any kind of performance gap, and whether the causes of those performance gaps could be attributed to factors that are contextual, related to the installation of the technology or dependent somehow on the end user.

# Results/Discussion

## Performance gap

A performance gap was identified in all seven field trials (Table 2). The largest performance gap was seen for building mounted wind turbines which often fell short of a load factor (the amount of energy used as a proportion of the total possible energy that could be used) of 10% (which is commonly quoted by manufacturers of these sorts of turbines), with no urban or suburban building mounted sites achieving load factors of more than 3% (EST, 2015). In some cases performance was so poor that the installation was found to be a net consumer of electricity due to the inverter taking its power from the mains supply while the turbine was idle. In the hot water field trial (EMC & EST, 2008) delivery temperature was found to be much lower (52.9°C ± 1.5°C 95% confidence interval for regular boilers and 49.5 ± 2.0°C for combi boilers) than the value of 60°C, which was assumed by the UK Government's Standard Assessment Procedure at the time (Shorrock 2008). Furthermore, the average temperature rise of water as it passes through the system was reported as consistently lower (36.7°C) than the 50°C that was assumed in the BRE Domestic Energy Model at the time, that is, the approximate difference between a target temperature of 60°C and average English air temperatures (Met Office, 2018), leading to predictions being inflated by approximately 35%. Condensing boilers were found to perform closer to prediction than in the hot water field trial, albeit 5.3% less efficient than manufacturers' claimed performance with 75% of boilers recording annual electrical consumption of greater than the BRE standard assessment procedure assumption of 175kWh/year (Orr et al., 2009). For heat pumps, the issue was not whether they could meet the manufacturer's assurances, but that their system efficiencies (the amount of useful heat the heat pump produces compared with the amount of energy used to run the system) were considerably varied (air source heat pump range = 1.2 - 2.2; ground source heat pump range 1.55 - 3.47), meaning that many systems did not perform as well as expected (Dunbabin & Wickins, 2012; EST, 2013). Similarly, performance in solar thermal systems was found to be extremely variable, with the solar fraction (the amount of energy provided by the solar heat collector divided by the total energy input required, in this case not including heat loss from the primary circuit) provided ranging from 9 - 98% with a median of 39% (EST 2011). This variability was also evidenced in the solar thermal trial by the wide range of parasitic energy consumption (the electricity needed to run the system) from zero (in those systems supported by photovoltaic infrastructure) up to 180kWh per annum (EST, 2011). In terms of a performance gap, the delivery temperatures (i.e. the output temperature) from solar thermal systems were much lower than 60°C at 49.1°C, showing values similar to those observed in the condensing boiler trial (EST, 2011). These are similar to the issues found in a retrofit trial the performance gap (Gupta et al. 2015) manifested through the actual opportunity scope being smaller than assumed in original forecasts (a "prebound" effect, *sensu* Sunikka-Blank & Galvin, 2012) based on the information supplied by applicants as part of the application process (TSB, 2013). This is because most properties actually had lower air infiltration rates than suggested (most less than 10 $m^3/m^2/hr$ @ 50Pa). Conversely, 13 of the 87 pre-retrofit had considerably higher air infiltration rates (greater than 15 $m^3/m^2/hr$ @ 50Pa) which meant that these properties had greater scope for performance than initially anticipated (TSB, 2013).

## Contextual factors

According to the field trials presented here, performance gap can be caused when something in the physical environmental of the installation differs from what was expected/modelled, or functions as an entirely unanticipated key factor. For example, discrepancies in the hot water trial were partly caused by the initial cold water feed being cooler than anticipated (EMC & EST, 2008). In the solar thermal trial it was found that the solar fraction was also directly affected by the demand on water, which, among other things, is a function of how many other cold water appliances are sharing the same domain (EST, 2011). In the least, solar thermal performance is of course affected by insolation, which is dependent on weather, which can be unpredictable (Kreith & Kreider, 1978). Many similar issues were found in the Gupta et al. 2015 retrofit trial, where performance was indirectly hampered by issues that affected the installation of the new infrastructure including internal and external spaces issues (i.e. accommodation space for larger hot water cylinders, or the need to retain alleyways, bin storage space or delivery access) and delays caused by local phenomena such as bat infestation, asbestos and wet rot (TSB, 2013).

## Installation factors

The performance gap can also be exacerbated when the quality of the installation is low. All of the boilers installed as part of the condensing boiler trial were oversized (i.e. bigger than necessary for the space being serviced) by factors ranging from approximately 1.5 to 10, potentially causing flue heat loss (i.e. heat escaping through the chimney) and purge losses from cycling (i.e. where heated residual gases are replaced with cooler ambient air as a safety practice each time the boiler restarts) to increasingly result in a reduced efficiency (Orr et al., 2009). Orr et al. (2009) suggests that if installation guidance for optimal boiler size is followed, there should be a correlation between installed boiler size and heat demand. Orr et al. (2009) did not observe this pattern, suggesting that the boiler installer likely chooses which size boiler is installed, suggesting that their decision is based on personal beliefs that might be independent of house size, household usage patterns and heat loss. Installation issues were particularly prevalent in the Gupta et al. 2015 retrofit trial, primarily due to the fact that retrofits tend to need bespoke services of which the installation team has no direct experience (TSB, 2013). Nearly a quarter of the homes upgraded as part of the retrofit trial (22 of 100) reported a lack of the skills needed as a challenge for their particular retrofit (TSB, 2013).

## User factors

Another factor influencing whether the performance gap is realised is in how the technology is ultimately used. If the technology is used incorrectly, a reduction in efficiency and performance is often inevitable. For example, parasitic energy consumption in the solar thermal trial can become prohibitively great (up to 180 kWh/annum) in households that have their pumps at an unnecessarily high setting (EST, 2011). In that trial, one particular household was found to have their backup heating source set to input a large amount of energy in the morning. An expert site visitor applied the correct setting but reported that they were confident that the householder would return it to their previous setting, highlighting how the human factor can veto good performance, even in spite of clear instruction and guidance. Similarly, the analysis of electrical and gas consumption of boilers carried out as part of the condensing boiler trial indicated that a key factor in electrical consumption are the pump operating times which are dependent upon the settings of the thermostat, thermostatic radiator valves and/or other controls that can be manipulated by the user (Orr et al., 2009). The literature supports the idea that the human factor is important in how water and energy are used in the home, with consumption being influenced by a range of factors including occupancy and occupants' age, income and space heating preferences (Harlan et al., 2009; House-Peters et al., 2010; Santin et al., 2009), all of which might ultimately differ from the specifications in the designers' energy use models.

Given the role of the human factor in the function of efficient technologies, and that many home owners may not have, either in principle or as a part of their home in particular, knowledge of how a new technology works (which indirectly affects behaviour as reviewed in Huijts et al., 2012) or how much of a resource they actually use (EST, 2011), it is likely that behaviour can explain at least some of any observed performance gap. Ultimately, this highlights the need for a clear, simple and compelling engagement with users during the installation process for optimal building performance to be achieved. In the heat pump trial, customers exhibited varying levels of understanding of how to best use the various controls in order to achieve the best performance from the equipment (EST, 2013). Similarly, based on the comments made by householders in the solar thermal trial, the level and quality of the advice given by installers to householders on how to modify their water use in response to the installation did not appear to be very consistent, though this did not seem to affect peoples' satisfaction with the system itself (EST, 2011). Thus, the heat pump and solar thermal trials indicated that the inductions received were sometimes inadequate, which may also explain some of the performance gap.

## Methodological influences

The field trials done by EST and partners have many strengths, particularly in the holistic approach to monitoring (by considering environmental and performance variables in conjunction with qualitative evaluation), which allows the analytical team to compare and contrast the performance of the technology of interest. These have allowed the clear measurement of the performance of the technology (and the subsequent performance gap), which is their primary function. That said, there is a suite of areas where they can be strengthened. For example, the majority of measurements taken tend to focus directly on the technology being evaluated. It would be good to increase the range of measurements made to allow a better understanding of the dwellings involved in the project as this could generate more insight on the factors that can influence performance. Additional measurements could include thermal imagery, in-situ measurements of wall U-values, air tightness measurements, humidity measurements, wall surface temperatures, endoscopic investigation of cavity walls to assess insulation levels, increased resolution of energy consumption measurements and more granular monitoring of building occupancy, all of which might give additional insight or are known to affect energy use in the home (Branco et al. 2004; Yohanis et al. 2008; Santin et al. 2009). Another weaknesses in the approach is that as the field trials involve simply monitoring the technology once it has been installed they are correlative in nature, involving no randomly assigned or manipulated treatments and no control group. This is not uncommon for these sorts of trials, which represent what is generally accepted as they most realistic and efficient way of conducting larger scale field work (for example, Carstens et al. 2017). As a third weakness, the participants in these field trials opt in to participation, meaning that the sample of homes included in the trial is not likely to be representative of the UK more broadly, with many of the participants utilizing these innovative schemes and technologies likely to be early adopters as defined by the Rogers' Bell Curve (Rogers, 2003; Caird and Roy, 2008). Given that early adopters tend to be informed and interested with regard to the innovative technology in focus (Keirstead, 2007; Lane and Potter, 2007; Caird and Roy, 2008; Schelly 2014), it is likely that the performance gaps due to user behaviour reviewed here will be much larger and thus represent a more substantively significant problem to households in the UK more generally. More effort should be made to ensure that the profiles of the households used fields trials are broadly more representative of the whole target market for the innovation being tested. This could be achieved by an increase in sample sizes, which are generally limited by the project budget (J. Russill, 2018, personal comms), presumably rather than a lack of willing participants. Finally, while these field trials reviewed here were long enough to detect the performance gap (12 months or more), that project funding is often tied to annual budgets within financial years means that longitudinal studies of two years or more are rare, meaning that there are a whole raft of potential longer term effects (such as degradation of infrastructure or changes in the ages or identities of the occupants) that are not being adequately considered. Addressing these relatively minor weaknesses will require more resource being earmarked for future verification trials, a need which is covered in more detail in the next section: policy recommendations.

# Policy recommendations

The question of how to deal with the performance gap through policy has so far only received limited attention. Policy makers have a tendency to "oversell expectations of policy outcomes" (Foxell and Cooper 2015, 405) - a good example of this is the Green Deal, an energy efficiency on-bill finance mechanism which the UK government had launched in 2013 to retrofit homes. The Green Deal achieved less than 0.1% of the expected impact in terms of the number of homes (Rosenow and Eyre 2016). A great deal of political capital was invested in the Green Deal and failure was not politically conceivable which resulted in government officials presenting data in such a way that it supported rather than undermined the policy approach chosen (ibid). Similarly, building codes for new buildings are often based on estimated energy performance and assume unrealistic level of energy consumption (Cohen and Bordass 2015) and more realistic standards are likely to result in policy makers having to potentially report significantly fewer energy savings which in turn risks achieving official targets. As Foxell and Cooper (2015) put it, "greater realism will undoubtedly deflate many of the high claims and ambitions of those on both the supply and demand sides of built environment production". The following sections present a number of suggestions for how the performance gap can be dealt with through policy design. Those should be understood as explorative rather than prescriptive, and further research is needed to better understand both the dynamics between existing policies and the performance gap as well as potential ways of moving towards a more realistic approach that moves away from calculated to measured performance.

## Accounting for the performance gap in evaluation and policy

The results of the verification services documented here clearly evidence the need for robust and replicated field trials of all new and current technologies where ever they have not yet been done. This will help consumers, manufacturers and energy suppliers understand how new technologies work once they have been integrated in to homes, not just in an ideal context (i.e. in the laboratory). At the moment, there is substantial heterogeneity across the world when it comes to evaluating energy efficiency and renewable energy policies (see for example Wade & Eyre, 2015). This includes practices of how to account for the performance gap. The inconsistent approach to measuring energy savings and monitoring and verification leads to considerable uncertainties as to whether the benefits of energy efficiency and renewable energy policies will materialise to the extent anticipated by policy makers. In particular, this could make the task of end use energy demand managers more difficult, as they try to grapple with the vagaries of human behaviour in the context of unreliable technical data..

In the energy efficiency field, following the implementation process of the Energy Services Directive in 2006, similar issues were discussed in the literature (Boonekamp, 2006; Thomas et al., 2012). There are also detailed global standards for monitoring and verification such as the International Performance Measurement and Verification Protocol (IPMVP; EVO, 2014) that address the performance gap, but those standards are mainly being used for larger projects rather than in the residential sector. Given that manufacturers' estimates can be wrong (as seen in the performance gaps presented here) and that the methodologies that manufacturers use to predict performance can vary so widely (for example, the power curves and ratings of turbines presented in EST, 2009 were calculated using different methods) it is virtually impossible for customers to compare the performance of different products and make an informed decision on how to invest.  This literature can form the basis of a clear and consistent approach to monitoring and verification of energy savings across the EU. Rather than specifying in detail how exactly the performance gap should be accounted for, a set of high-level principles for policy evaluation would be a good starting point. Such high-level principles would need to set out the key parameters to be analysed in evaluations, quality standards for carrying out monitoring of low-carbon technologies once installed, key aspects to be covered by post-installation audits, and appropriate methods for evaluation, monitoring and verification. In the United States, there is a common approach (e.g. TecMarket Works Framework Team, 2004). If applied in Europe, such principles would ensure that awareness for the performance gap is increased and, over time, policy evaluations account for it more systematically.

In recent years there has been accelerated experimentation with so called “pay-for-performance” energy efficiency programmes (Szinai et al., 2017), although mainly in the United States and particularly in California. Pay-for-performance programmes reward actual measured energy savings based on metered energy consumption. Many, but not all, of such approaches evaluate savings using some form of meter data or utility bill data collected before and after an energy efficiency intervention. Payments of any subsidy are linked to the savings achieved over time - this minimises the risk of providing upfront payments for technological interventions that do not deliver energy savings in line with expectations. Traditionally, energy efficiency programmes reward specific technologies assuming a certain amount of savings. The incentives offered do not differentiate between the actual outcomes achieved. In a world of increasing digitalisation and with more abundant energy data (for example from smart meters) and new innovative monitoring and verification methods discussed under the heading M&V 2.0 (Franconi et al., 2017), pay-for-performance programmes provide a promising policy approach to reward real savings rather than just modelled savings. By definition, such a framework would set incentives to reduce the performance gap. So far, most of the savings delivered through pay-for-performance programmes stem from interventions on the commercial, public, and industrial sectors (Szinai et al., 2017). However, with the costs for both obtaining and analysing energy data come down there is the potential to also use pay-for-performance programmes in the residential sector. First examples of pay-for-performance programmes targeting residential buildings have begun to emerge in Europe: Germany recently launched the *Einsparzaehler* (energy savings meter) programme, a pilot scheme to test the feasibility of a pay-for-performance programme in Germany (http://www.bafa.de/DE/Energie/Energieeffizienz/Einsparzaehler/einsparzaehler_node.html). Policy makers should continue to experiment with such instruments given the increasing coverage of buildings with smart meters.

Finally, innovative retrofit programmes such as *Energiesprong* (Visscher et al., 2016) use performance guarantees to ensure the performance of the improvements over a long-term (minimum 30-year) period. This is based on the Dutch net zero-energy renovation concept (Rovers 2014), which has been applied in social housing. Tenants pay an increased rent but are not charged any energy costs at all after retrofit if their energy consumption remains within certain specified bounds. This approach only works if the performance gap is small.

### Installer standards and user training

A recurring theme throughout these field trials is the role that the installer plays in the performance gap with the domestic wind turbine trial pointedly concluding that industry standards must be agreed and implemented so that customers can realistically assess the potential for building mounted turbines to generate energy (EST, 2009). In the first phase of the heat pump trial, heat pump performance was found to be dependent on the specification, design, installation and commissioning practices (Dunbabin & Wickins, 2012), which led to a thorough review of installation and training guidance and the eventual revision of the Microgeneration Certification Scheme (MCS) installer standards (an industry-led and nationally recognised quality assurance scheme) to good effect (EST, 2013). Generally, customers and policy makers should treat all novel technologies with caution, in particular domestic scale wind, until such a time that the product they are considering receives MCS accreditation or equivalent (EST, 2009). The content of these accreditation schemes should be considered particularly carefully in terms of installer training, so that the pitfalls of having unprepared installers as observed in the more bespoke retrofitting projects (TSB, 2013) are likely to be seen less often, assuming that the effectiveness of accreditation schemes documented for performance in engineering (Volkwein et al., 2007) translate to the retrofitting context. This is particularly relevant for more complex technologies such as heat pumps, where short courses without formal educational qualifications are simply not good enough (Gleeson, 2016). Furthermore, minimum standards of user engagement and induction beyond a user manual should also be included if efficiency claims are to be allowed. This is because quality advice and understanding can help minimise the performance gap as seen here in the solar thermal trial where better advice on heating patterns, use of back up heating and the correct function of controls might have helped householders make the most of the new system (EST, 2011) and encourage householders to capitalise on other low carbon opportunities (Owen et al., 2014).

## Future research

This paper draws on a number of case studies from the UK. There are similar analyses focusing on other geographies and future research should undertake comparative studies of how the performance gap is taken into account and addressed in different jurisdictions. Particularly, the role of field trials deserves attention. This paper also demonstrates that the role of the installer is of importance for the significance of the performance gap. Further work is required to better understand how installation standards are already addressing performance issues related to the installation process and whether and how such standards can be used to address the performance gap. A third avenue of research should investigate the potential policy design options and monitoring and verification framework that would address the performance gap more systematically. This includes both more streamlined and reliable evaluation, monitoring and verification frameworks but also innovative policy instruments such as pay-for-performance programmes. Others have called for an Institute for

Building Performance to be founded to address such issues (Bordass & Leaman, 2013). Furthermore, future research should investigate to what extent existing regulatory frameworks create conditions associated with practices that neither acknowledge nor address the performance gap.

# Conclusion

The evaluations presented here corroborate with the literature in concluding that the performance gap is a common phenomenon that can have considerable impact on the ultimate effectiveness of energy efficient technologies. It is clear that structured guidance on how to measure the performance of products is needed to assist manufacturers in providing accurate and transparent advice to consumers on what technologies are appropriate for achieving any desired outcome.  Such an evaluation framework, whether encouraged through regulation or an optional standard (such as IPMVP; EVO, 2012) should aspire towards international application and contain enough methodological flexibility to evaluate any technologies designed to improve the efficiency of buildings.  Secondly, similar action should be taken to ensure that a) manufacturers develop installer standards for their products and b) end users are engaged with proper guidance on how to use the technology effectiveness. Until steps such as these or similar are taken the potential for technological innovation to help society achieve a sustainable future will continue to be undermined by the performance gap. Finally, innovative approaches such as pay-for-performance programmes deserve to be tested also in jurisdictions outside of the United States and in the residential sector. Rewarding energy savings based on standardised analysis of metered data potentially offers a policy solution to the complex evaluation, monitoring and verification problems that the performance gap creates.

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- EST & EST 2008: The Department for Environment; Food and Rural Affairs; and Energy Monitoring Company
- Orr et al. 2009: Gastec at CRE Ltd; AECOM; EA Technology; and Carbon Trust
- EST 2009: EDF Energy; RWE nPower; NIE Energy; Centrica plc; Scottish Power Ltd; Scottish and Southern Energy plc; E.ON Engineering Ltd; The Scottish Government; The Department of Energy and Climate Change; B & Q plc; and The University of Southampton
- EST 2011: The Department of Energy and Climate Change; The Scottish Government; the Welsh Assembly Government; the North West Regional Development Agency; E.On UK; EDF Energy; Scottish Power; Centrica; Firmus Energy; Sustainable Energy Ireland; Worcester Bosch; and Good Energy
- Dunbabin & Wickins 2012, EST 2013: EA Technology Ltd; KIWA Gastec; The Department of Energy and Climate Change; The Scottish Government; The North West Regional Development Agency; EDF Energy; Npower; British Gas; Scottish Power; Scottish & Southern Energy; E.On UK; NIE Energy; Danfoss UK; NIBE; Mitsubishi Electric; Mimer Energy; Worcester Bosch; Baxi Group; The Energy Technologies Institute; Calorex; Dimplex; Heat King; Ice Energy; IVT; Mitsubishi; NIBE.

**Table 1: Methodologies for seven fields trials examining various energy and water efficiency technologies in domestic homes. All trials involved monitoring performance for 12 months after the installation/beginning of the trial and some degree of qualitative engagement with installers and users.**

| Citation | Subject | Sample | Data Collected |
|---|---|---|---|
| EMC & EST, 2008 | Amount of hot water used (and the energy used to heat it) | 68 regular boilers and 39 combi boilers in 107 houses of unspecified type | Water use and temperature |
| Orr et al., 2009 | In-situ efficiency of condensing boilers | 67 condensing boilers in a mixture of house types including 18 flats with the remainder terrace or stand alone buildings | Energy use, heat output and internal/external temperature |
| EST, 2009 | domestic wind turbine performance | 38 roof mounted turbines, 19 pole mounted turbines | Energy use, energy generation, wind speed |
| EST, 2011 | performance of solar thermal hot water systems | 88 terrace or stand alone homes | Solar radiation, solar collector temperature, input/output water temperature, output volume and energy, energy use |
| Dunbabin & Wickins, 2012 | Seasonal performance factors of air and ground source heat pumps (Phase 1) | 54 ground source heat pumps and 29 air source heat pumps | Energy use, loop temperature, heat and hot water output, internal/external temperature |
| EST, 2013 | Seasonal performance factors of air and ground source heat pumps (Phase 2) | 21 ground source heat pumps and 21 air source heat pumps, 15 of which were also used in Phase 1 | Energy use, loop temperature, heat and hot water output, internal/external temperature |

**Table 2: Performance gaps observed in seven field trials of domestic energy efficiency technologies and home improvements.**

| Citation | Subject | Metric | Performance gap |
|---|---|---|---|
| EMC & EST, 2008 | Amount of hot water used (and the energy used to heat it) | Delivery temperature[1] | Much lower than the widely assumed value of 60°C: 52.9°C ± 1.5°C for regular boilers; and 49.5 ± 2.0°C for combi boilers. |
| Orr et al., 2009 | In-situ efficiency of condensing boilers | Efficiency | 5.3% less efficient than manufacturers' claimed performance; 75% of boilers had an annual electrical consumption of greater than an assumed 175kWh/year |
| EST, 2009 | domestic wind turbine performance | Load factor[2] | Technology often fell short of the commonly quoted load factor of 10%, with no urban or suburban building mounted sites achieving load factors of more than 3%. |
| EST, 2011 | performance of solar thermal hot water systems | Solar fraction[3] | Considerable variation ranging from 9 - 98% with a median of 39% |
|  |  | Parasitic energy consumption[4] | Considerable variation ranging from 0 - 180 kWh per annum |
| EST, 2011 | performance of solar thermal hot water systems | Delivery temperature[1] | Much lower than the widely assumed value of 60°C: 49.1°C |
| Dunbabin & Wickins, 2012; EST, 2013 | Seasonal performance factors of air and ground source heat pumps (Phase 1) | System efficiency[5] | Performance was considerably varied: ASHP range = 1.2 - 2.2; GSHP range 1.55 - 3.47 |

Notes: 1: the output temperature; 2: amount of energy used as a proportion of the total possible energy that could be used ; 3: the amount of energy provided by the solar heat collector divided by the total energy input required, in this case not including heat loss from the primary circuit; 4: the electricity needed to run the system; 5: the amount of useful heat the heat pump produces compared with the amount of energy used to run the system.

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